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NGMA/PESA OTWAY BASIN SYMPOSIUM MELBOURNE, 20 APRIL 1994: EXTENDED ABSTRACTS

compiled by

D. M. FINLAYSON
Australian Geological Survey Organisation, Canberra.

National Geoscience Mapping Accord (NGMA) Otway Basin Project:
- participating organisations:

- **Australian Geological Survey Organisation (AGSO), Canberra.**
- **Department of Mines and Energy, South Australia (DMESA), Adelaide.**
- **Geological Survey of Victoria (GSV), Melbourne.**
- **Victorian Institutes for Earth and Planetary Sciences (VIEPS) at Monash and LaTrobe Universities, Melbourne.**

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The NGMA Otway Basin Project: aims and objectives

D. M. Finlayson[1], B. Simons[2], C. D. Cockshell[3], K. C. Hill[4] and K. A. Hill[5]

1 - Australian Geological Survey Organisation, Canberra
2 - Geological Survey of Victoria, Melbourne
3 - Department of Mines and Energy, S.A., Adelaide
4 - School of Earth Sciences, LaTrobe University, Melbourne
5 - Department of Earth Sciences, Monash University, Melbourne

Background

The Otway Basin is one of a number of basins formed on the southern margin of Australia at the time of rifting and eventual breakup with Antarctica during Late Jurassic to Early Cretaceous times (Fig. 1). Various datasets from southern Australia in recent years have demonstrated the complex nature of the early rifting events and a number of different models have put forward for the history of these events. An improved understanding of the rifting process is essential to assist resource evaluation along the whole southern margin.

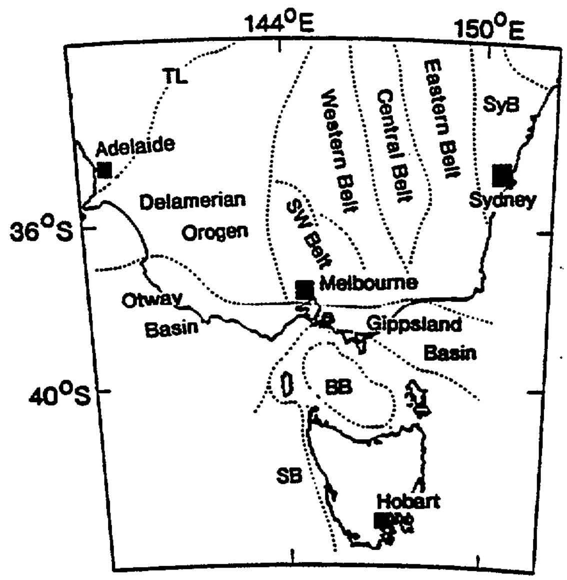

Figure 1 - Location of the Otway Basin and simplified major geological provinces (belts) of the Lachlan Orogen (adapted from Glen et al. 1992). BB = Bass Basin; SB = Sorell Basin; SyB = Sydney Basin; TL = Tasman Line.

In the Otway Basin significant natural resources have been identified but, to date, exploration for hydrocarbons has not been as successful as in the neighbouring Gippsland Basin, partly because of structural complexity recognised in the basin sequences. Geothermal and industrial gas resources have also been identified. Pressures on these various resources and competing interests in the management of them are issues which cannot be divorced from any study of the Otway Basin. Hence a study of the basin's development is regarded as being both timely and desirable to enable informed debate.

Aims

The National Geoscience Mapping Accord (NGMA) Otway Basin Project aims to provide new data on the early (mainly onshore) structures of the basin and improve knowledge of the tectonic events that resulted in its development and evolution.

The project (1991-94) is a co-operative research program involving the Australian Geological Survey Organisation (AGSO), the Department of Mines and Energy, South Australia (MESA), the Geological Survey of Victoria (GSV), and the Victorian Institute of Earth and Planetary Sciences (VIEPS) at Monash and LaTrobe Universities. The project addresses some of the problems associated with the limited knowledge of the early basin-forming events and their influence on later basin development.

Strategies

1. Improve information on the deep basin (Otway Group) sequences and basement structures using deep seismic sounding techniques.

2. Use complementary industry seismic data acquired across the basin to develop a better understanding of early basin evolution.

3. Integrate interpretations from gravity, aeromagnetic, fission track analyses, and other geoscience disciplines to improve tectonic models for the basin's early history.

Research plan and methods

AGSO undertook to acquire about 450 km of deep seismic data (20 s recording time) in four key target areas of the basin. The seismic lines crossed specific sedimentary and structural targets which have an important bearing on the interpretation of early basin evolution. AGSO and GSV acquired detailed gravity data along the seismic lines.

The NGMA project undertook to interpret selected data from the large number of exploration industry seismic lines throughout the basin and map four seismic horizons - base Tertiary, top Eumeralla Formation, top Crayfish Sub-group, and top basement. This horizon mapping was undertaken in three sectors - the western basin (MESA), the central basin (GSV), and the eastern basin (AGSO, VIEPS and Monash University).

MESA and GSV undertook to review sedimentary facies and stratigraphic nomenclature used for Otway Group sequences. This included the drilling of a stratigraphic hole in the Victorian part of the Penola Trough (Bus Swamp No.1).

VIEPS staff and students at LaTrobe and Monash Universities undertook fission track and vitrinite reflectance analyses to improve understanding of the thermal history of various parts of the basin.

AGSO undertook airborne magnetic survey work in the western Otway Basin to complete regional coverage of the basin and extend it offshore to the Crayfish Platform. The program aimed to improve structural interpretations in the region.

AGSO undertook to acquire and integrate U.S. Navy Geosat data from the Southern Ocean with gravity data in continental Australia so that regional geological trends could be identified.

Results from the NGMA project have appeared in a number of published papers listed in the bibliography. Data and mapping products are available from the appropriate organisations.

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Further information

Further information on the NGMA Otway Basin Project and its results can be obtained from the contacts listed below:

D. M. Finlayson
Australian Geological Survey Organisation
PO Box 378
Canberra ACT 2600
Ph. 06 249 9761
Fax. 06 249 9972

B. Simons
Geological Survey of Victoria
PO Box 98
East Melbourne VIC 3002
Ph. 03 412 7825
Fax. 03 412 7803

J. G. G. Moreton
Department of Mines and Energy, S.A.
PO Box 151
Adelaide SA 5063
Ph. 08 274 7565
Fax. 08 373 3269

K. C. Hill
VIEPS, School of Earth Sciences
LaTrobe University
Bundoora VIC 3083
Ph. 03 479 1273
Fax. 03 479 1272

K. A. Hill
VIEPS, Department of Earth Sciences
Monash University
Clayton VIC 3168
Ph. 03 565 5773
Fax. 03 565 4903

Geology of the onshore Torquay Sub-Basin: a sequence stratigraphic approach

S. A. Reeckmann
Esso Australia Ltd., 360 Elizabeth Street, Melbourne, Vic., 3000

The Mesozoic to Cainozoic Otway, Bass and Gippsland Basins, which occur along the SE Australian Margin, owe their origin and development to the evolution of the rifting system between Australia and Antarctica, and to a lesser extent, the opening of the Tasman Sea. The Torquay Sub-basin lies between the Otway and Bass Basins (Figure 1). It is connected to the Otway Basin proper around the northern nose of the Otway Ranges, and is separated from the Bass Basin by the Mornington Peninsula - King Island high. Although considered as an extension of the Otway Basin because of this northern connection, the stratigraphic succession in the Torquay Sub-basin most closely resembles the sequence which occurs in the Bass Basin.

During Late Cretaceous times, the sea flooded eastwards into the Otway Basin but was blocked from the Torquay Sub-basin and Bass Basin by the Otway Ranges uplift and the Otway - King Island high (Figure 1). Marine sediments were deposited in the Otway Basin proper during this time, coeval with the deposition of the non marine Eastern View Coal Measures (Singleton, 1973) in the northern Otway, Torquay and Bass Basins. The Eastern View Coal Measures consist of thick beds and lenses of cross-bedded quartz gravels and sands interbedded with beds of clay and lenticular deposits of brown coal. They were deposited in a fluvial to coastal plain environment during a time of uplift and erosion of the Otway Ranges and Victorian Highlands. An angular unconformity is exposed between the Otway Group and Eastern View Coal Measures in places around the flanks of the Otway Ranges (Figure 2).

By Eocene times the on-shore Torquay Sub-basin and Bass Basin were restricted marine environments with deposition of marine, carbonaceous Anglesea Sand (Singleton, 1973).

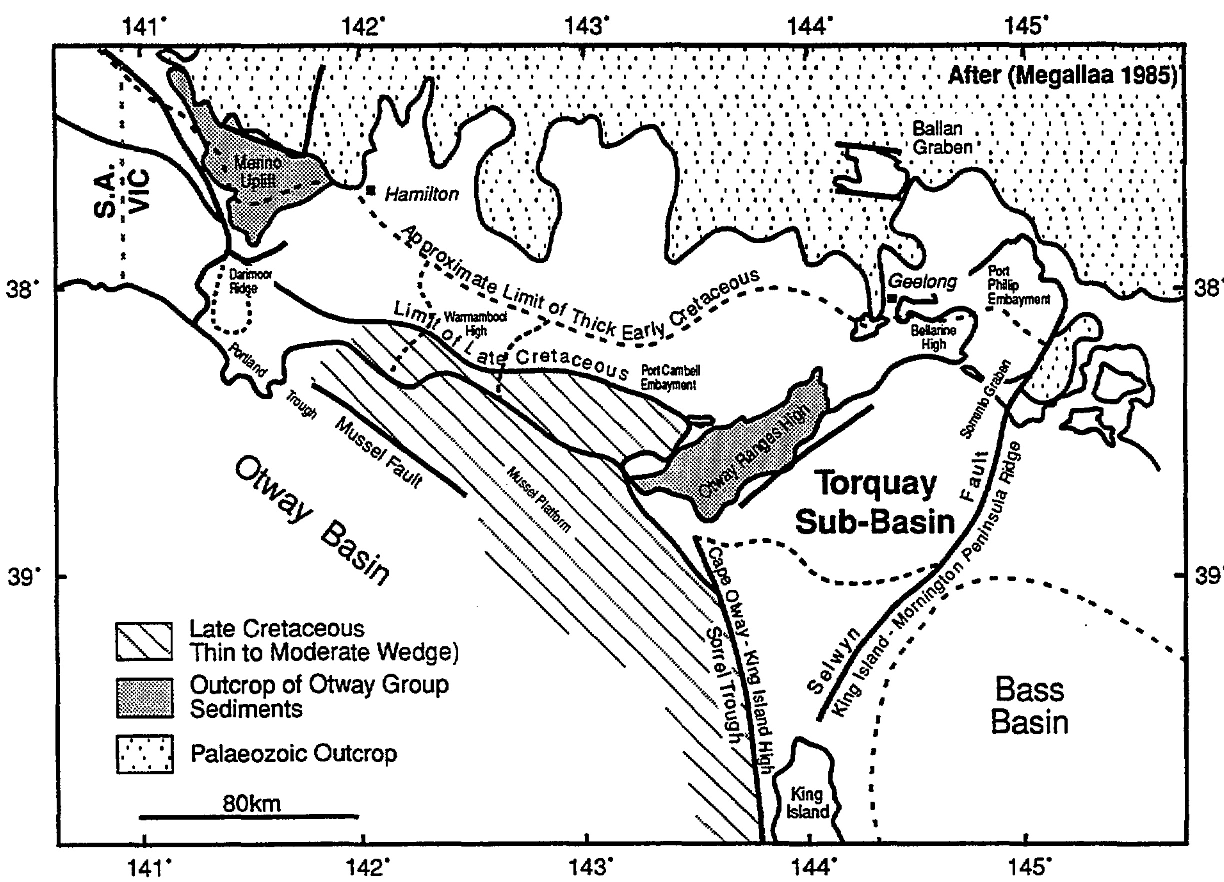

Figure 1 - Tectonic setting and location of the Torquay Sub-Basin.

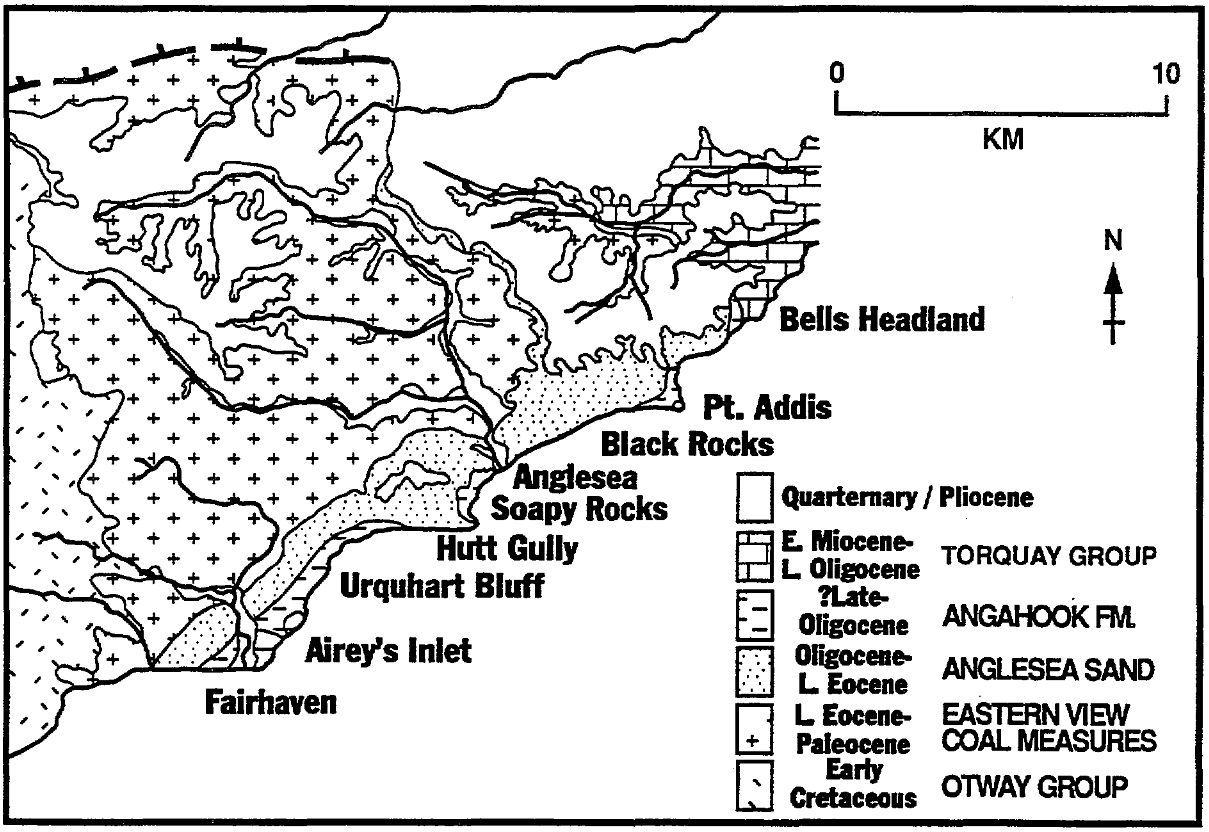

Figure 2 - Onshore geology, Torquay Sub-basin.

This formation is a homogeneous, poorly stratified, dark grey, carbonaceous sand, extensively burrowed and bioturbated, with common pyritic concretions. Marine fossils are rare but foraminifera, ostracods, molluscs and sharks teeth have been reported (Raggatt and Crespin, 1955; Reeckmann, 1979). Towards the top of the Anglesea Sand, large channel cuts believed to represent sequence boundaries have been recognised in the coastal cliffs near Anglesea (Figure 2). The channel complex at Soapy Rocks is filled with clays which coarsen upwards to sandstones interpreted to represent an aggradational shelf to estuarine (tidal) complex. The Anglesea Sand is dated as Late Eocene to Oligocene in the Torquay Sub-basin based on foraminifer and spore/pollen assemblages (Reeckmann, 1988). Evidence of shallowing-upwards at the top of the formation is evident in a number of outcrops along the Torquay coastal section with the appearance of beds of coarse-grained, quartzose and limonitic sands interbedded with the finer, carbonaceous silts and clays.

During the Oligocene, the Otway Ranges were rejuvenated and a complex series of marine and non marine sediments and volcanics of the Angahook Formation (Singleton, 1973) were deposited in the Torquay Sub-basin overlying the sequence boundary at the top of the Anglesea Sand. The Angahook Formation consists of complex non-marine, marginal marine and marine sediments which crop out in isolated locations in the coastal cliffs between Airey's Inlet and Bells Headland (Figure 2). Evidence of marine influence within the formation increases basinward, away from the uplifted Otway Ranges which were probably emergent at this time. Episodes of basaltic volcanism occurred during Angahook times and is represented by basalts and pyroclastic sediments within the Angahook Formation, both in the coastal outcrops and inland at Waurn Ponds (Abele, 1976; Reeckmann, 1979). Volcanic material believed to have emanated from an eruptive centre at Airey's Inlet forms a time-synchronous zone throughout the Angahook Formation along the coastal section enabling correlation between isolated outcrops. K/Ar dating of altered basalts at Airey's Inlet provide ages of 26.5 m.y to 27 m.y for this material (Abele and Page, 1974).

The basin-margin Oligocene Angahook Formation and overlying Oligo-Miocene shallow marine Point Addis Limestone and Jan Juc Marl provide sensitive records for relative sea level changes. These changes can be interpreted by constructing a sequence stratigraphic framework for the sediments preserved based on evidence of erosion, downlap and vertical sediment stacking patterns, including the recognition of maximum flooding surfaces within the sections. An attempt has been made to fit the sequence boundaries recognised in the section to the global cycle chart (Figure 3), and assign an age to each sequence boundary which honours available biostratigraphic and chronostratigraphic data.

The 30 m.y. sequence boundary is assigned to the erosion surface identified at the base of the Angahook Formation. This surface is exposed at Hutt Gully (Figure 3) where it is overlain by a conglomerate containing rounded pebbles of limonitic-cemented quartz sandstone believed to have been deposited on a beach. Evidence of uplift and erosion of the Otway Ranges at this time is provided by heavy mineral concentrates occurring in the overlying upper shoreface sands (Reeckmann, 1979). Elsewhere in the section the 30 m.y. sequence boundary is represented by evidence of erosion or the sudden appearance of coarse-grained sediment overlying the fine, uniform silts and sands of the Anglesea Sand.

Within the Angahook Formation at Airey's Inlet, on-lap of marine re-worked pyroclastic sediments occurs, representing the next transgressive sequence and surface of maximum flooding prior to erosion at the overlying sequence boundary.

The upper sequence boundary within the Angahook Formation is also indicated by evidence of erosion and identification of conglomeratic layers in outcrops at Airey's Inlet and Soapy Rocks (Figure 2). Extensive erosion of basaltic lava and deposition of a shoreline conglomerate is seen at Airey's Inlet providing evidence of marine transgression on the margin of the Otway Ranges at the end of Angahook times in the Late Oligocene.

Evidence of these relative sea level changes and associated sequence boundaries which occurred during Angahook times are more difficult to define in the Bell's Headland section where the Angahook Formation has remained marine throughout its deposition.

Following the transgression in the Late Oligocene at the end of Angahook Formation deposition, the Torquay sub-basin became a region of open marine, shallow shelf deposition.

A temperate shelf bryozoan carbonate, the Point Addis Limestone, was deposited in high energy, near shore environments surrounding the Otway Ranges and Barrabool Hills. The Point Addis Limestone passes basinwards into

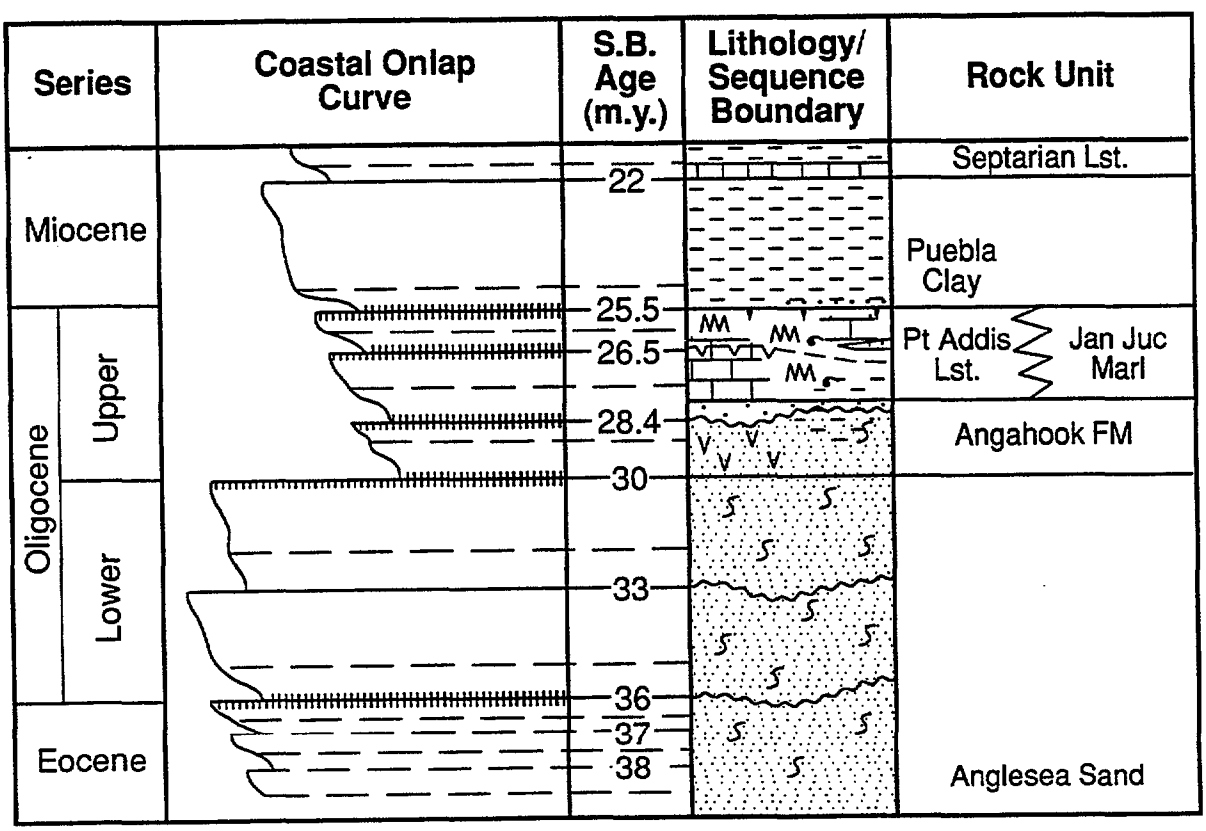

Figure 3 - Sequence stratigraphic interpretation, onshore Torquay Sub-basin.

the finer grained Jan Juc Marl (Ref: Figure 2) and this lateral facies transition is exposed in the cliffs between Bells Headland and Jan Juc. Downlap of Point Addis Limestone as it prograded across the shelf can be seen in the cliffs at Airey's Inlet and Point Addis where it overlies the Angahook Formation. A succession of coarsening-upward parasequences of mixed carbonate-clastic material forms the Jan Juc Marl, which built up further out on the shelf. At least one sequence boundary has been recognised in the Point Addis Limestone associated with subaerial exposure, cementation and erosion.

The Jan Juc Marl can be seen to onlap this sequence boundary in the cliffs between Bells Headland and Jan Juc and a condensed deposit rich in glauconite has been interpreted to represent the maximum flooding surface associated with transgression following this sea level fall. A further sequence boundary is believed to occur at the top of the Point Addis Limestone and Jan Juc Marl prior to maximum marine transgression represented by the overlying Miocene Puebla Clay (Figure 3).

A sequence stratigraphic approach to the subdivision and correlation of the sediments of the onshore Torquay Sub-basin has provided a means of correlating diverse lithologies which occur in isolated outcrops where biostratigraphic age control is poor. Correlation is by the means of time synchronous flooding surfaces and sequence boundaries. Numerous changes in relative sea level are evident in the sequence because of its proximity to the shoreline. Further work is required to tie the outcrop geology into the sub-surface for future seismic stratigraphic interpretation.

Tighter age control will improve the confidence in the sequence stratigraphic relationships proposed based on this study.

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Towards a unified stratigraphy for the Otway Basin

J.G.G. Morton[1], A.J. Hill[1], G. Parker[2], and A. Tabassi[3]

1. Mines and Energy - South Australia, P.O. Box 151, Eastwood SA 5063
2. Geological Survey of Victoria, P.O.Box 98, East Melbourne, VIC 3002
3. Tabassi and Associates Pty Ltd, 28 Sunline Ave., Noble Park North, VIC 3174

Introduction

Stratigraphic nomenclature in the Otway Basin has been in a state of considerable confusion for over 30 years. There are over 200 formational names defined for the Otway Basin (Thompson and Walker, 1985), and in at least one case the type section for a unit has been changed as many as seven times. The reasons for this confusion are complex, and were first noted by Glenie (1971), who among them noted an emphasis on correlation of units based on palaeontology (i.e. time) rather than lithology by early stratigraphers in the basin. This is still a problem, a recent example being the subdivision of the Eumeralla Formation into Upper, Middle and Lower units by Kopsen and Scholefield (1990), which were essentially defined on palynological zones and seismic character. Other reasons were definition of units in outcrop which were subsequently shown from subsurface data to be incomplete sections, and a lack of appreciation for lateral facies changes in units. In addition, the scale of the formations in the Cretaceous section are an order magnitude greater than the Tertiary, and 1 to 200 or 500 scale petrophysical logs are too large to appreciate the significant lithology contacts. We have found that a scale of 1 to 5000 or smaller is needed to determine formation contacts within the Sherbrook Group. Because of extensive downhole contamination in most wells, cuttings are not a good indicator of lithology, and in practice petrophysical logs are the only reliable method of picking formation boundaries. However, difficulties are experienced in relating new wells to original type or reference sections, as most of these old wells have SP and resistivity logs only available for correlation, and do not have gamma ray or sonic logs. Gamma ray and sonic logs are superior for well correlation as they have better vertical resolution, and are calibrated against standard scales that are independent of individual borehole conditions.

In the intervening 23 years since Glenie's review, there has, unfortunately, been little improvement in the situation. The problem has in fact been made worse by subsequent definition of palynological zones with essentially the same zone names, but representing different intervals. There are eleven palynological zonal schemes for the Cretaceous in Australia, at least four of which are still in current use by palynologists (Alley, 1993). In addition, most petroleum companies and state and federal departments have developed their own lithostratigraphic nomenclatures that may use similar names to describe conceptually different units; this has hindered geoscientists who are unfamiliar with the basin to fully understand the complex geology. A major objective of the NGMA project was to resolve these nomenclature differences, or at least improve communication between the various organisations so that work towards a unified stratigraphy could be more coordinated. The nomenclature proposed in this paper (Figure 1), whilst a compromise between the various existing nomenclatures, and in the case of the Crayfish Group, a simplification, we believe provides a sound basis for further subdivision as new wells and new data become available. Figure 1 has been drawn to emphasise the correlation of units in an east - west sense to resolve the variations in nomenclature usage between Victoria and South Australia, however most of these units show significant north - south variations that could not be shown on this chart.

Casterton Formation

An essentially pre-rift (or earliest syn-rift) sequence, the Casterton Formation consists of interbedded carbonaceous shale, with minor feldspathic sandstone and siltstone and basaltic volcanics. The unit has been previously known informally as Casterton beds, and recently was defined as a Group (without formations) by Kopsen and Scholefield (1990). The Type Section has not been formally defined but we suggest the interval 2220m to 2450m (all depths are quoted as below KB) in Casterton 1; this differs from the intervals used as reference sections by Wopfner et al (1971) and Kopsen and Scholefield (1990), who included a sandstone at the top of the sequence that we consider to be basal Crayfish Group. The presence of volcanics is characteristic of wells which have intersected Casterton Formation in the eastern Otway Basin, but a carbonaceous shale facies is more usual in the western Otway Basin, where it is now confined to relatively deep parts of early half grabens, either as an erosional remnant or as a primary depositional fill. Seismic work by the Geological Survey of Victoria has suggested that Casterton Formation deposition may have preceded rifting. The upper boundary of the unit is an unconformity. In Bus Swamp 1, (a Geological Survey of Victoria Stratigraphic well drilled in early 1993), the upper *C. australiensis* zone of Morgan (1993 usage) is absent due to onlap after the uplift associated with the top Casterton Formation unconformity. Other wells may not show a major time break. In addition, seismic data suggest an angular unconformity at this level in both Victoria and

South Australia. This formation is the most poorly known of the Otway Basin, and further deep drilling is required before more a more detailed subdivision into members can be formally established.

Crayfish Group

Kopsen and Scholefield (1990) introduced the name for the early syn-rift, graben fill megasequence, above the Casterton Formation, but below the Eumeralla Formation, and within the Otway Supergroup. The name had been in common usage by industry before that, and was included on a stratigraphic column by Sprigg (1986). Morton (1990) revised the name to Crayfish Subgroup within the Otway Group. We believe that the term Otway Supergroup is now of limited usefulness. The unconformity at the contact with the Eumeralla Formation is a strong angular unconformity in the western Otway Basin, but is not obvious in the eastern Otway, where more gradational contacts are observed. Without doubt, the nomenclature of the formations in this group have been the most difficult to standardise. It is likely that each half graben may have it's own unique stratigraphy. The sparse drilling density, particularly of wells that have fully penetrated the sequence, and a lack of a fine biostratigraphic subdivision (there are only three palynological zones for the Crayfish Group), has made well correlations somewhat ambiguous. Correlation from the deep trough to the northern margin in hampered by significant erosion at the top Crayfish unconformity level, which is often apparent on seismic, but due to a lack of biostratigraphic control, is not quantifiable on well sections. As a consequence, it has been difficult to resolve nomenclature differences.

Pretty Hill Formation

The lower sequence we have called Pretty Hill Formation, with a new reference section defined as 1472m to 2220m, in Casterton 1 due to some uncertainty in correlating with the type section in Pretty Hill 1 further to the east. The definition of a single formation is in fact an over- simplification, as the Pretty Hill Formation can show diverse sequences of sand and shale in individual wells. These sequences appear to be distinct units which cannot as yet, be confidently correlated basin wide. The greatest well density over this part of the sequence is in the Penola Trough, where SAGASCO have a subdivided the Pretty Hill Formation into members. Further drilling over the next year may lead to formal publication of this subdivision. It is clear that the twofold sandstone subdivision proposed by Kopsen and Scholefield (1990) is too simplistic to be a basin-wide model, as it is clear that there are significant shale units in the lower Crayfish Group. It will probably be necessary, as more drilling data become available, to define members in each half graben.

The "Geltwood Beach Formation", although never formally defined, has been used, even relatively recently (Laing et al 1989), for a shale facies of the Crayfish Group. However it has been known for some years that Geltwood Beach 1 did not penetrate below the Eumeralla Formation. The name "Geltwood Beach Formation" should be dropped from usage.

In an attempt to improve biostratigraphic correlation within the Crayfish Group, a collaborative project between industry, Mines and Energy - South Australia, and the Geological Survey of Victoria is currently under way. The project is investigating local subdivision of established palynological zones for the western Otway Basin, and establishing a plant cuticle based biostratigraphic zonation. The results of this project will be made available to project sponsors in July, 1994.

Katnook Sandstone and Laira Formation

The upper Crayfish Group is better understood, at least over the Penola Trough area, where the Katnook Sandstone and Laira Formation are easily recognised and correlated, with type sections defined in Katnook 2 by Morton (1990). Regional correlation clearly shows that the Katnook Sandstone and Laira Formation can be lateral facies variants of each other, but that the top Pretty Hill Formation is probably reasonably synchronous. The diachroneity of the Laira and Katnook has made seismic mapping of these units difficult, as seismic reflectors tend to be synchronous surfaces, and lithological boundaries are too subtle to be unambiguously recognised on conventional seismic sections.

Eumeralla Formation

The name Eumeralla Formation was introduced by Reynolds (1966) for the predominantly shaly megasequence below the Sherbrook Group and above the Crayfish Group. The section 947m to 2777m in Eumeralla 1 was nominated as a reference section by Reynolds, who also wanted to include the outcrop sections of the Otway Ranges as part of the definition. There was a significant change in depositional and structural style following deposition of the Crayfish Group. The reasons for this change are still not universally agreed; three scenarios were discussed by Perincek et al (1994). Eumeralla Formation facies are less diverse, and the unit generally thickens in a broad wedge to the south towards the rift axis. The formation of a narrow rift to the south resulted in some erosion of the Crayfish Group on the tilted northern margins, and deposition of a coarse grained basal sandstone in the axes of the pre Eumeralla troughs. This was defined as the *Windermere Sandstone Member* by Kopsen and Scholefield (1990), with the type section 3187m to 3292 m in Windermere 2. The subdivision into Upper, Middle and Lower Eumeralla Formations proposed by Kopsen and Scholefield (1990) are not however generally accepted by industry and are not based on unique lithological criteria. The Heathfield Sandstone Member has never been formally defined although it is in wide usage. No type section has been defined, but presumably refers to the sand in the mid Eumeralla Formation occurring between 1254m and 1263m in Heathfield 1. Due to a meandering fluvial to lacustrine palaeoenvironment, we believe that there are numerous minor sands within the Eumeralla Formation, and it is not possible to correlate with confidence any of these sands between wells. For this reason we suggest that the Heathfield Sandstone Member be discarded.

Sherbrook Group

Glenie (1971) did not recognise the Sherbrook Group as a separate sequence from the Wangerrip Group. Subsequent work has shown the distinct character of each sequence and later use has been Sherbrook Group for the Late Cretaceous sequence and Wangerrip Group for the Early Tertiary sequence.

The nomenclature of the formations within the Sherbrook Group is relatively stable compared to the Early Cretaceous. The major problems are associated with the lack of definition and fixed type sections for each of the formations. As deposition was dominated by very large scale deltas, significant problems arise in correlating deeper parts of the post rift sequence in the south, with the condensed, sandy sequence in the north. In the north, the term undifferentiated Sherbrook Group is suitable nomenclature, and Kalangadoo 1, 544 to 765m had been designated a reference section by Morton (1990). However, new foraminiferal data indicate that the upper boundary is higher, at approximately 519m. Most of the units show strong diachroneity, and as a consequence, there are difficulties in relating well formation picks to seismic sections. The Sherbrook Group is perceived to be essentially conformable, but local unconformities may exist within the sequence. Sequence stratigraphy could improve our understanding of the Late Cretaceous, although the intense faulting may make this difficult. At least one petroleum company involved in the Otway Basin is taking this approach, but this work has not yet been made public. Glenie (1971) reviewed type sections for all Sherbrook Group formations, and South Australian reference sections were established by Morton (1990).

Copa Formation

The Copa Formation was defined by Morton (1990) for the shaly unit below the Waarre Sandstone unconformably above the top Eumeralla Formation. This unit occurs in several wells in South Australia, but has not been recorded from Victoria, except possibly in Mussel 1. It is likely to occur in most areas south of the Tartwaup Hinge Line, but few wells have fully penetrated the thick Sherbrook Group sequence, particularly in western Victoria. The type section was defined in Copa 1, but subsequent palynological work has cast doubt on whether the well fully penetrated the Sherbrook Group. Reference sections are Caroline 1, 2841m to 2892m and Burrungule 1, 2268m to 2337m. It is not clear if this formation is non marine or marine, and further palynological work is necessary.

Waarre Sandstone

The Waarre Sandstone was defined as the basal non-marine formation of the Sherbrook Group by Glenie, (1971). On small scale (greater than 1 to 5000) petrophysical logs, the unit is a distinct, clean sandstone, with only minor shale compared to the units above and below. In spite of the unambiguous appearance on logs, the type section has changed many times, and was redefined by Glenie (1971) as 2494 to 2675m in Port Campbell 2 appears to be valid. Reference sections were assigned in Nullawarre 3, 1599m to 1634m, and Flaxmans 1, 2096m to 2166m. The reference section for South Australia is 2789m to 2841m in Caroline 1. Buffin (1989) reviewed the Waarre Sandstone in the Port Campbell area, and subdivided the formation into four units. However, no reference was made to the type section, and Mehin and Link (1994) incorrectly interpreted the unnamed example used by Buffin as a "General Type Section".

Flaxman Formation

The Flaxman Formation is defined as the initial marine transgressive unit of the lower Sherbrook Group. It is relatively distinct on small scale logs, appearing as a interbedded sand/shale unit. The type section has been changed seven times by various authors and was redefined by Glenie (1971) as 2340m to 2494m in Port Campbell 2. Reference sections were assigned in Nullawarre 3, 1984m to 2096m and Flaxmans 1, 1984m to 2096m, as the Port Campbell section is considered to be atypical. Caroline 1, 2466m to 2789m is the South Australian reference section.

Belfast Mudstone

The Belfast Mudstone is defined as the pyritic marine (prodelta) shale of the middle Sherbrook Group, although in the past it has been considered the basal member of the Paaratte Formation. The type section is Port Campbell 1, 1501 to 1685m. Reference sections are Flaxmans 1, 1697 to 1984m and Belfast 4, 1361 to 1498m. The South Australian reference section is Caroline 1, 2161 to 2465m.

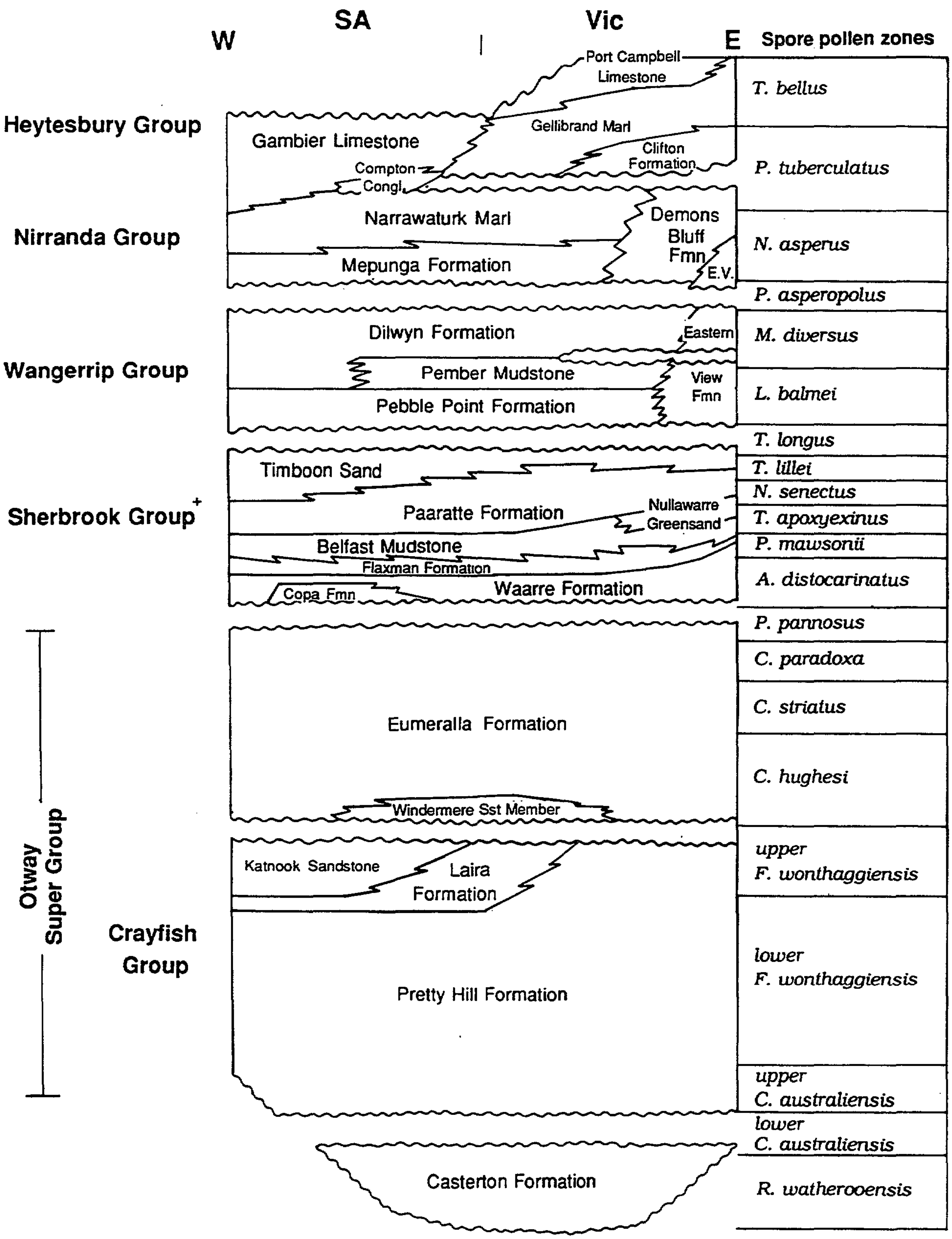
Paaratte Formation

The Paaratte Formation is a regressive paralic deltaic unit, with a log response similar to the Flaxman Formation. The type section is defined as Port Campbell 1, 1295 to 1503m. Reference sections for the Paaratte Formation in Victoria are Flaxmans 1, 1071 to 1984m, and 1008 to 1549m in Nullawarre 3. The reference section in South Australia is Caroline 1, 1740m to 2161m. Glenie (1971) observed that, where the deeper water Belfast Mudstone is absent in the northern part of the basin, the Paaratte and Flaxman Formations may be indistinguishable, and suitable terminology would be "Paaratte/Flaxman Formation". The *Skull Creek Mudstone Member*, published recently by Laing et al (1989) and Buffin (1989), is of uncertain definition, and does not appear to be used by industry generally.

Nullawarre Greensand

Previously considered to be a member of the Parratte Formation, the formation occurs near the base of the Paaratte Formation, and is a glauconitic, or where weathered, limonitic, sandstone unit. There has been some

OTWAY BASIN STRATIGRAPHIC NOMENCLATURE



+ Condensed sandy sequence occurs in northern areas.

Note: Pliocene and younger sediments have not been reviewed.

Figure 1.

MESA 94-251

dissent over the nature of this unit as Hawkins and Dellenbach (1971) suggested it was a chloritic sandstone. Further work is necessary to more firmly establish the validity of this unit, and in particular determine the petrophysical characteristics. The type section is 1344 to 1514m in Nullawarre 3. The unit has not been identified in South Australia, and occurs only in some wells in Victoria. It has not been recognised in the Paaratte Formation Type Section in Port Campbell 1.

Timboon Sandstone

Timboon Sandstone is defined as the non marine sandstone of the upper Sherbrook Group. In South Australia usage is as a full formation, (Morton, 1990), but in Victoria it is considered the upper member of the Paaratte Formation. The name Curdies Formation is still incorrectly used by some authors, (e.g. O'Brien et al, 1994) in spite of the name Timboon Sandstone having clear priority. The type section is Port Campbell 1, 886 to 1295m. Reference sections are Timboon 5, 1006 to 1144m, Nullawarre 3, 1186 to 1275m and Glenelg 1, 1142 to 1615m. The South Australian reference section is Caroline 1, 930 to 1740m.

Wangerrip Group

The Wangerrip Group represents the first of a series of transgressive-regressive units that comprise the Tertiary sequence in the Otway Basin area. In South Australia, the Tertiary is considered to be part of the overlying Gambier Basin, but in Victoria is still considered to be part of the Otway Basin. This difference still remains to be resolved. A sequence stratigraphic approach will probably help resolve nomenclature differences and improve our understanding of relationships between units. There has traditionally been a significant difference in the level of investigation into Tertiary sedimentation on either side of the Victorian/South Australian border . This has been due to the fact that only the very uppermost units outcrop on the South Australian side, whereas there are many well studied complete sections of these units in Victoria. There have been few studies of the subsurface Tertiary, and there is a general perception that it is unprospective. Whilst this may be true for generation of hydrocarbons, the Tertiary may host reservoirs for petroleum generated lower in the sequence, and Tertiary deposition and structuring have influenced the timing and extent of generation from the Cretaceous units, particularly from the Eumeralla Formation and Crayfish Group. To review Tertiary nomenclature in context of subsurface data is a initiative currently being pursued by the NGMA members.

An easterly condensed sandy sequence, equivalent to Wangerrip and lower Nirranda Groups has been named the *Eastern View Formation* in Victoria. A similar sequence may occur in the northern areas of South Australia, but perhaps better terminology is to refer to this simply as undifferentiated Wangerrip/Nirranda Groups, particularly as there are two major unconformities within this sequence

Pebble Point Formation

The Pebble Point Formation comprises ferruginised conglomerates and grits, with occasional oolitic intervals, deposited in shallow marine conditions. The type section is defined from outcrop and no subsurface reference section has been designated. It is not readily recognisable on petrophysical log character alone, although it is recognised in several wells in South Australia and Victoria.

Pember Mudstone

This formation has been previously defined as a basal marine member of the Dilwyn Formation, but is now regarded as a separate formation. In South Australia the upper contact appears to be conformable. However in the eastern Otway Basin in Victoria, seismic evidence shows an unconformity (probably a sequence boundary) at the top of the Pember Mudstone (Perincek et al, 1994), and thus cannot be regarded as a lateral facies variation of the Dilwyn formation as previously thought. Further work is underway by the Geological Survey of Victoria to clarify this relationship. The subsurface reference section is 287.4m to 343.5m in La Trobe 1.

Dilwyn Formation

The Dilwyn Formation is a paralic-regressive unit comprising highly variable sequences of sand silt and clay. The type section has been defined in outcrop, and La Trobe 1, 70 to 287m has been cited as a subsurface reference section. The top is a basin-wide disconformity, with the *P. asperopolus* zone generally absent.

Nirranda Group

The Nirranda Group comprises a major marine transgression, and consists of a lower ferruginous sand (*Mepunga Formation*), overlain by glauconitic marl, (*Narrawaturk Marl*). The top may be a regional unconformity, but in some South Australian wells the Narrawaturk Marl clearly grades laterally into the lower Gambier Limestone .

Heytsbury Group

The lowermost formation of the Heytsbury Group is the *Compton Conglomerate*, seen only in South Australia, which appears to be a marine shelf channel fill deposit, and may be equivalent in age to the regional unconformity with the Nirranda Group observed in Victoria. In Victoria, the Group comprises the *Clifton Formation*, a carbonate sand, overlain by the *Gellibrand Marl*, and succeeded by the *Port Campbell Limestone*. In South Australia, the Gellibrand Marl is present, but is relatively thin compared to that observed in to Victoria. The Gambier Limestone and Gellibrand Marl are lateral equivalents, while the Port Campbell Limestone is not represented in South Australia.

Conclusions and Further Work

In reviewing most of units used in the Otway Basin, the NGMA participants have developed a nomenclature that has resolved some of the previously existing anomalies, and provides a framework for further co-operative refinement. Further work will concentrate on the subdivision of the Pretty Hill Formation, after more drilling in South Australia and improvements to biostratigraphic correlation. The Tertiary sequence will also be reviewed in more detail to resolve differences, and subsurface reference sections will be established in both South Australia and Victoria to aid petroleum exploration.

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Deep Seismic Profiling: basement controls on Otway Basin development

D. M. Finlayson, D. W. Johnstone, A. J. Owen and K. D. Wake-Dyster
Australian Geological Survey Organisation, GPO Box 378, Canberra A.C.T. 2601, Australia

Key words: reflection seismic, Otway Basin, basement, structural development

Deep seismic profiling across the Colac-Otway Ranges, Port Campbell-Tyrendarra Embayment, Penola-Ardonachie Trough, and Gambier Embayment areas of the onshore Otway Basin has shown that pre-Aptian rift segments with half-graben geometry have a variety of trends and that the bounding faults dip predominantly, but not exclusively, towards the continent. The basin sequences in these half-graben are imaged at greater than 4 s two-way time in places and the bounding faults sole along detachments with ramp and flat geometry at mid crustal levels. The trend variations indicate that extensional strain direction varied along the rift system, probably controlled by pre-existing Palaeozoic geology. Basement highs such as the Merino and Framlingham highs are interpreted as accommodation zones between the rift segments. Multiple bounding faults on the northern margin of the Penola Trough mirror features within basement and probably indicate a component of strike-slip during early rifting. Crustal thickness is interpreted to be 31 km (10.3-10.5 s two-way time) near Lake Bullen Merri in the Port Campbell Embayment, an area of recent volcanism where crustal and upper mantle xenoliths provide some geological control on the interpertation of intra-crustal reflections. South of the Tartwaup Fault Zone, crustal thinning (to about 9 s two-way time) coincides with a significant increase in post-Albian deposition and is interpreted to be the landward limit of rifting along a lower plate margin which ultimately separated Australia from Antarctica. Crustal thinning under the Otway Ranges in the eastern Otway Basin probably accounts for the major gravity high in that region.

Introduction

The processes responsible for the initiation and development of sedimentary basins are intimately associated with the dynamics of the lithosphere. Hence, when the structural evolution of a basin is investigated, it is necessary to examine the deeper parts of the crust and the upper mantle to identify features which may be controlling basin structures. The style of structural development will, to a large extent, determine the geothermal and depositional histories of the basin and have a bearing on its prospectivity. Lithospheric extension, compression and strike-slip all affect a basin's structural evolution and hence hence affect the development of source rocks, their maturation history, hydrocarbon migration paths, the development of reservoirs and their subsequent structural integrity.

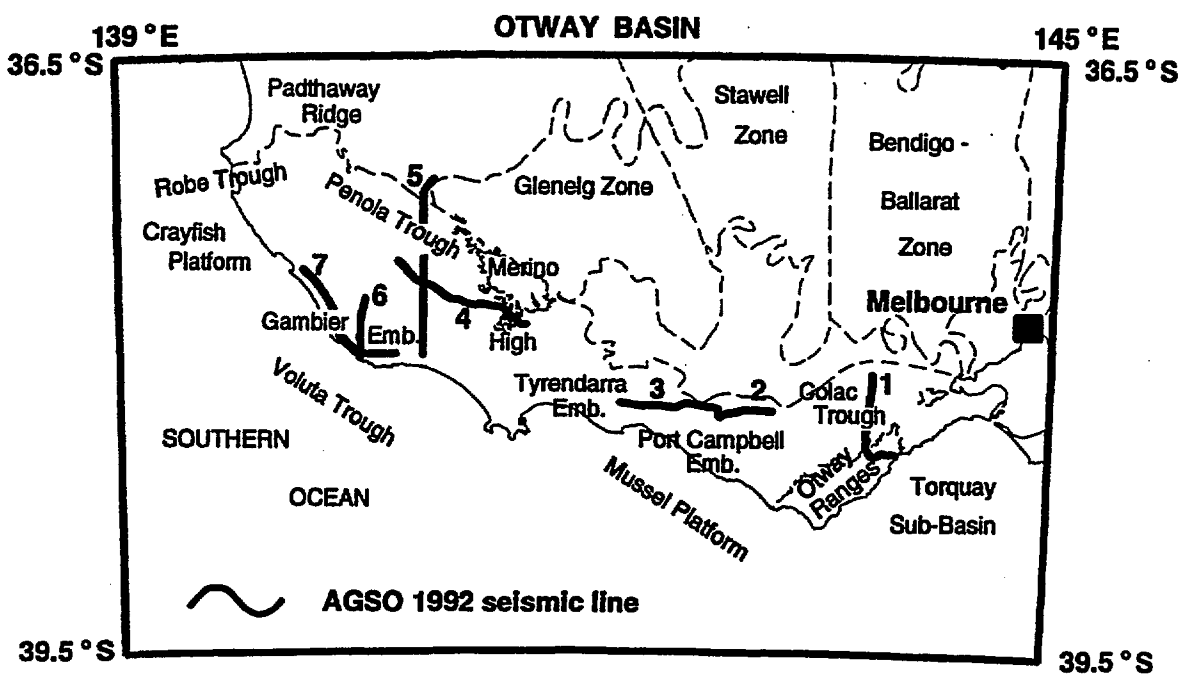

Figure 1 - Location of 1992 AGSO deep seismic profiling lines across onshore target areas of the Otway Basin.

This paper discusses the results of deep seismic profiling conducted during 1991-92 in the onshore parts of the Otway Basin aimed at examining significant features of basin structure and the possible geological processes within basement which led to their development. The Australian Geological Survey Organisation (AGSO) seismic profiling in the Otway Basin provided data on the geology of the deeper parts of the basin, the middle and lower crust, and the upper mantle which are not normally acquired in the course of commercial exploration for hydrocarbons.

The tectonic development, structural elements and the sedimentary units encountered in the Otway Basin are described elsewhere in this volume of symposium preceedings and hence will not be described in this paper. However, it is important to have a conceptual model for basin development in the intra-continental setting which probably existed in this part of Gondwanaland prior to separation of Australia from Antarctica. Appropriate models for the formation of early rift segments have been described by various authors including Rosendahl (1987), Morley (1989) and Nelson et al. (1992). Such models, based largely on the east African rift system, probably apply to early Otway Basin development.

Four target areas in the Otway Basin were identified for examination in co-operation with State surveys and the exploration industry. These were 1) the Colac Trough and Otway Range structures, 2) the structures between the Port Campbell and Tyrendarra Embayments, 3) the eastern Penola Trough and its connection across the Merino High to the Ardonachie Trough, and 4) the Gambier Embayment and the Tartwaup Fault Zone (Fig. 1).

Seismic profiling

The deep seismic profiling conducted by AGSO in the Otway Basin during 1991-92 is described in detail by Wake-Dyster et al.(1993); only a brief description of acquisition and processing is given here. Acquisition difficulties were expected from near-surface geological variations associated with extensive limestones, recent volcanics, and paleo-sand dunes. Seismic lines were confined largely to existing roads and tracks. Because targets were in the middle and lower crust as well as in the deep sedimentary sequences, test surveys were conducted during 1991 to determine shooting parameters (Wake-Dyster et al. 1994).

Most of the data acquired during 1992 used the following general specifications - Sercel 368 recording system; 120 channel split spread; dynamite source (10 kg); average shothole depth 29 m; group interval 50 m; 20 s record lengths; nominal 5-10 fold CMP; 2 ms sampling interval.

Data were processed by AGSO using Disco software. The processing sequence was as follows - demultiplex to SEGY format; crooked line geometry definition; trace editing; spherical divergence correction; uphole static corrections; common mid-point (CMP) sort and brute stack; velocity analysis, normal moveout (NMO) correction; prestack NMO mute; time-varying equalisation; CMP stack; bandpass filter; coherency enhancement and display.

Basement geology

The basement to the Otway Basin comprises Late Proterozoic and Palaeozoic rocks of the Delamerian and Lachlan Orogens. Parker (1986), Brown et al. (1988), Wellman (1994), and Glen (1992) give summaries of the geological and geophysical constraints on the basement terranes and their boundaries.

In this short paper it is sufficient to emphasise the strong N-S and NW-SE trends evident in the basement rocks adjacent to the Otway Basin. Wellman (1994) indicates that these trends are "tectogenic" i.e. based on the latest deformation episode. The NW-SE trends are seen in the Padthaway Ridge adjacent to the Robe and Penola Troughs; these trends were established during the mid- to late Cambrian Delamerian Orogeny. This trend persists along the northern margin of the central and western parts of the basin in the form of prominent gravity highs probably associated with subsurface Cambro-Ordovician mafic volcanics.

The basement trends change to more N-S farther east within the southern parts of the Stawell and Bendigo-Ballarat structural zones (Fig. 1) and at their common boundary, the Avoca Fault. The Middle Devonian Tabberabberan Orogeny probably set many of these trends (Wilson et al. 1992). There is continuing debate on how far east the Delamerian Orogen extends in the subsurface. Glen (1992) and Wilson et al. (1992) place the eastern limit of Delamerian basement rocks at the Avoca Fault; others place it farther west (Gibson & Nihill, 1992).

Seismic images - general observations

AGSO seismic profiling was designed to examine a range of targets of regional significance not examined by industry profiling. Modern industry high-fold vibroseis data can usually image the sedimentary sequences to 3-3.5 s TWT very well. However, AGSO experience shows that explosive sources are a cost-effective means of producing a source signal that is not band limited and can produce images of deep basin sequences and basement structures down to Moho depths.

Generally the upper crustal basement beneath basin sequences is transparent (few reflectors) at two-way times in the range 3-5 s, but there are locations where fault-plane reflectors are interpreted cutting basement, and mid-crustal ramps can be inferred from the geometry of prominent reflection bands. The lower crust is generally more reflective and the Moho is interpreted as being at 9-12 s TWT where the lower-crustal reflectivity decreases dramatically (Finlayson et al. 1993). Below this the upper mantle is largely non-reflective although there are some significant events at two-way times greater than 12 s; without further data acquisition there is no way of telling whether or not these events are from within the plane of recording.

Line diagrams of interpretations along the AGSO lines are contained in poster-scale Figures 2 and 3 accompanying this abstracts volume. The 6 s TWT sections are interpreted in conjunction with adjacent industry seismic lines and exploration well data. The 16 s TWT line drawings are

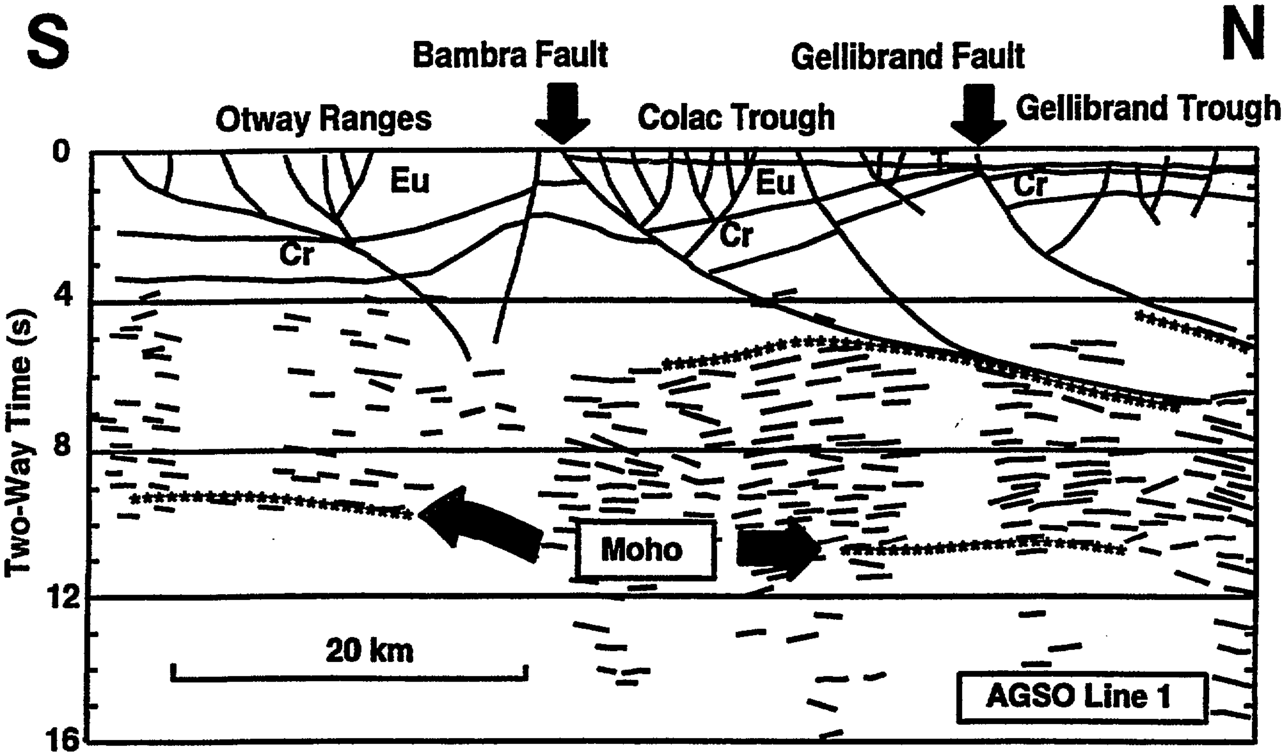

Figure 4 - Line diagram of basin interpretation and basement reflections across the Colac Trough and Otway Ranges. All prominent basement reflectors which have been digitized are represented in the diagram. The Moho is interpreted as the base of lower crustal reflectors where amplitudes decline markedly within the upper mantle. Features interpreted within the crust, such as prominent ramp and flat structures and possible detachments are indicated by stars.

based on digitized reflectors in the middle and lower crust.

Colac Trough and Otway Range

AGSO seismic line 1 was designed to examine the deep basin and basement structures across the Colac Trough and Otway Ranges. No seismic data were available from the northern limits of the Early Cretaceous Otway Group sequences or across the Otway Ranges which present considerable logistic problems for seismic crews. The final location of the seismic line across the ranges was determined by the available timber tracks and hence the shooting geometry is far from ideal.

Four wells provide control on the the interpretation of the sedimentary sequences - Warracburunah No.2, Ingleby No.1, Murroon No.23, and Olangolah No.1. Industry seismic data provide ties from the first two wells to AGSO line 1.

Within the Colac Trough area AGSO Line 1 imaged the Otway Group sequences farther north than previous surveys but still did not reach the northern limit of the Early Cretaceous sedimentation. The half-graben geometry of the Gellibrand Trough and Barwon Downs Graben were demonstrated, with over 3 s TWT of sedimentary section being imaged NW of the Bambra Fault.

The deep seismic data show many reflectors in the middle and lower crust. Some ramp structures at 5-6 s TWT under the Gellibrand High strongly suggest that they acted as detachment surfaces during early basin evolution (Fig. 4). The Moho is interpreted at about 11 s TWT under the Colac Trough.

A tentative interpretation of reflectors under the Otway Ranges suggests over 3.5 s TWT of sedimentary section. The deformation and uplift of these Otway Group sequences is evident from surface mapping. Reflectors in the mid and lower crust are not well defined because of crooked line geometry but the Moho is interpreted as shallowing to about 9 s TWT, which is probably the cause of the associated gravity high across the Otway Ranges.

Port Campbell and Tyrendarra Embayments

The Warrnambool gravity high between the Port Campbell and Tyrendarra Embayments has been a puzzling feature of the Otway Basin for some time. AGSO lines 2 and 3 were designed to extend across the gravity high to give a better indication of its structure and influence on basin development. The Port Campbell Embayment is an area of established gas production and prospectivity. Because of water pipeline infrastructure it was not possible to connect lines 2 and 3 along existing roads; however the offset is small compared to the structural features being investigated. It was also regarded as desireable to locate line 2 near Lake Bullen Merri, a recent volcanic centre where the geochemistry of crustal and upper mantle xenoliths was well established.

Stratigraphic control along AGSO lines 2 and 3 is provided by tie lines to a number of wells, - Ballangeich No.1, Garvoc No.1, Terang No.1, Tandarook No.1, Hawkesdale No. 1, and Pretty Hill No.1.

The significant results from AGSO line 2 and 3 are, 1) the magnitude of early rifting within the Tyrendarra Embayment (about 4 s TWT) (Fig. 5); 2) the northwestern boundary of the Port Campbell Embayment formed along what we have called the Yaloak Fault; 3) the Warrnambool gravity high coincides with the deepest rift sequences, not a basement high; 4) eastward dipping ramp structures at mid-crustal levels played a part in determining the basin geometry; and 5) the Moho boundary determined from seismic data near Lake Bullen Merri corresponds to the crust-mantle boundary determined from petrological and petrophysical measurements on xenoliths at 31 km (10.3-10.5 s TWT) (Finlayson et al. 1993).

The basement high between the Port Campbell and Tyrendarra Embayments on lines 2 and 3, which we call the Framlingham High, has many of the characteristics of an accommodation zone (as defined by Rosendahl, 1987) between early rifts segments.

Penola Trough, Merino High and Ardonachie Trough

The structures of the Merino High separating the Penola and Ardonachie Troughs have been the subject of debate for some time. The Penola Trough has known gas fields and the structures of the area are regarded as an important factor in determining hydrocarbon migration paths and trap geometries. AGSO seismic lines 4 and 5 were designed to investigate the structures across the Merino High and also the nature of basin features from the Palaeozoic basement (the Padthaway Ridge) in the north to the sea in the south across known major faults associated with the Penola Trough, Mumbannar High and Tartwaup Fault Zone.

In the region of AGSO Lines 4 and 5 stratigraphic control is available through seismic tie lines to the following wells: - Mocamboro No.11, Casterton No.2, McEachern No.1, Bus Swamp No.1, Penola No.1, Katnook No.1, Ladbrook Grove

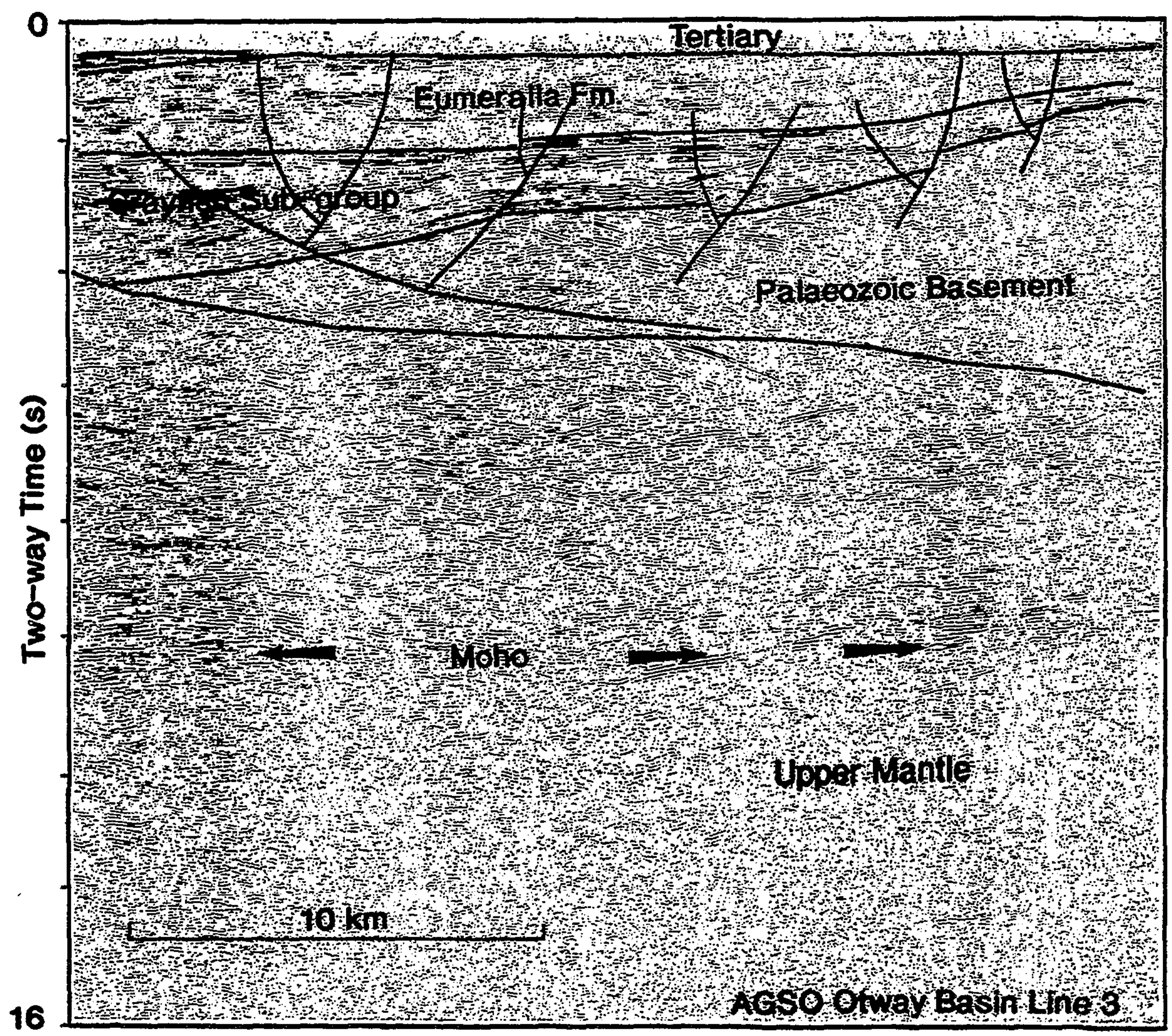

Figure 5 - Deep seismic reflection record (16 s two-way time) from 1992 AGSO Line 3 across the Tyrendarra Embayment.

No. 1, Caroline No.1, Palpara No.1, Ardno No.1, Malanganee No.1, Werrikoo No.2, Kaladbro No.2, Sawpit No.1, Mumbannar No.1, and Fahley Nos.1 and 2.

Along AGSO line 4 the significant features are, - 1) the thinning of the Crayfish sequence over the Merino High between the Penola and Ardonachie Troughs, 2) the changing polarity of the bounding faults in the two troughs, 3) the relatively uniform thickness of Eumerella Formation across the Merino High, 4) the Penola South Fault Zone identified, and 5) a mid-crustal ramp structure identified under the Merino High.

The Merino basement high, as with the Framlingham High farther east, has many of the characteristics of an accommodation zone between early rift segments with opposing boundary faults, the Penola and Ardonachie Troughs.

AGSO line 5 trends north-south along the South Australian-Victoria border. Major features along the line from north to south are as follows - 1) small graben are evident in the Padthaway Ridge to the north of the Penola Trough, 2) multiple faults on the northern margin of the Penola Trough with the south dipping Kanawinka and Kanawinka South Fault Zones (soling at about 7 s TWT) controlling early deposition, 3) multiple ramp structures within basement under the Kanawinka Fault Zones, 3) complex faulting within the Penola Trough suggesting a component of strike-slip movement during early rifting, 4) the Penola South Fault Zone is a complex later feature and was active throughout the later history of the basin along north-dipping fault planes, 5) north-dipping faults are pervasive across the Mumbannar High, 6) the Tartwaup Fault Zone has fault planes dipping to the southwest, 7) the Moho is interpreted at about 11 s TWT under most of line 5, and 8) the southern end of AGSO line 5 in the Gambier Embayment may be a strike line separating Palaeozoic basement blocks.

Overall, the interpretation along AGSO lines 4 and 5 in conjunction with industry data from the same area is that the early southeast Penola Tough is not a simple half-graben but instead has a component of strike-slip associated with the early-rift Merino High accommodation zone. The Penola South and Tartwaup Fault Zones are fundamental structures associated with the later history of the basin.

Gambier Embayment and Tartwaup Fault Zone

The thickening of Sherbrook Group sequences south of the Tartwaup Fault Zone has long been recognised but there have always been difficulties in imaging the underlying Otway Group sequences through limestone and palaeo-dune cover rocks. The targets for AGSO Lines 6 and 7 included the deeper basin sequences and the structures within basement which seemed to play a key role in determining the nature of the deposition and the development of hydrocarbon plays.

In the region of AGSO Lines 6 and 7 stratigraphic control is available from the following drillholes through seismic tie lines: - Kalangadoo No.1, Mt. Salt No.1, Knights Dome No.1, Burrungule No.1, Kentgrove No.1, Lake Bonney No.1, Geltwood Beach No.1, Hatherleigh No.1, and Douglas Point No.1.

The northern end of AGSO line 6 is on the Kalangadoo High where basement is interpreted at about 1 s TWT (Fig. 6). To the south AGSO line 6 crosses the Tartwaup Fault Zone and the basement image is lost. The fundamental nature of the Tartwaup Fault Zone is evident by the dramatic increase in two-way times to the base Tertiary (1 s TWT) and top Eumeralla horizons (3 s TWT). Along the same line the two-way time to Moho reflectors decreases from about 11 s TWT under the Kalangadoo High to about 9 s TWT near the coast.

The region southwest of the Tartwaup Fault Zone is interpreted to be part of a zone of crustal thinning which ultimately resulted in the separation of Australia from

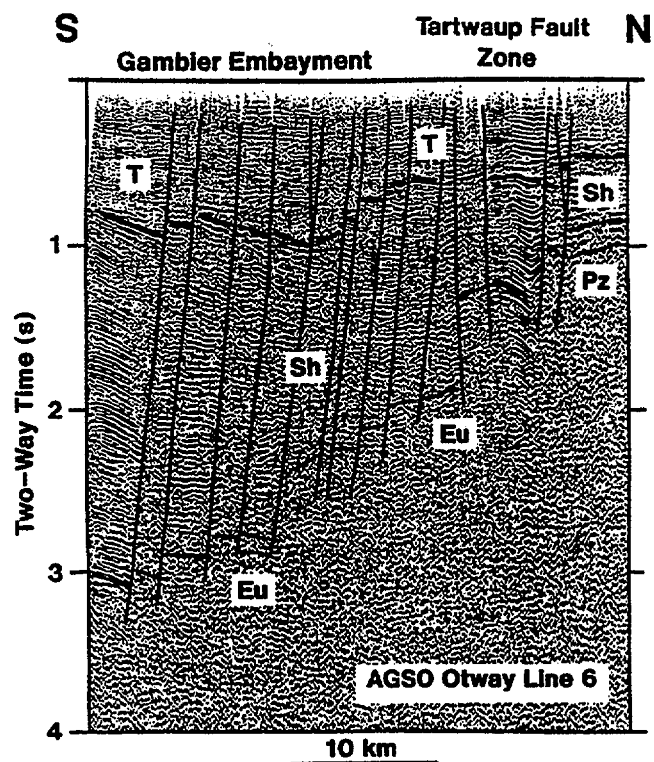

Figure 6 - Seismic record section of AGSO Line 6 across the Tartwaup Fault Zone and the Gambier Embayment showing the significant increase in Tertiary and Late Cretaceous sequences.

Antarctica. The importance of the Tarwaup Fault Zone has been previously emphasised by, among others, Tupper et al. (1993). It may represent the continental limit of a lower plate margin described by Etheridge et al. (1989) along other parts of Australia's southern margin. Multiple block rotation soling in the lower crust probably accounts for the poor imaging of the early basin sequences both by AGSO and the exploration industry.

AGSO line 7 trends northwest-southeast, crossing the Tartwaup Fault Zone near where it extends offshore and providing data emphasizing the structural importance of the fault zone. Early Cretaceous Otway Group sequences and basement are imaged northwest of the zone but not to the southeast. The Late Cretaceous sequences are shown to increase significantly in thickness towards the southeast, and, as on line 6, the two-way time to the Moho reflections is again seen to decrease to about 9 s TWT in the region of crustal thinning.

Comments

Studies of present-day rift systems such as the East African Rift system indicate that the initial stages of rifting and basin formation are complex. Early rift segments occur with varying trends and can be widely separated, suggesting that extensional strain direction varies throughout the rift system (Morley, 1989). A lithospheric heating process and magma injection are thought to result in the upper crust responding brittlely to local extension controlled by pre-existing geological trends.

It is therefore not surprising that the early Otway Basin rift segments mapped in the onshore part of the basin should have a variety of trends. Half-graben geometry for the rift segments is evident in both AGSO and industry seismic data and the deep AGSO profiling indicates that the basin bounding faults dominantly, but not exclusively, sole towards the continent at mid- to lower crustal levels.

Since the direction of early tectonic transport can vary locally within the rift system, early Otway Basin trends in the basin rift sequences need not necessarily be linked to trends seen elsewhere along Australia's southern margin. N-S and NW-SE trending features identified from gravity and aeromagnetic data as corresponding to Palaeozoic trends in the Delamerian and Lachlan Orogens probably influenced basin developments within the Otway-Sorell microplate defined by Finlayson et al. (1994).

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The authors wish to acknowledge many others in AGSO involved in the acquisition and processing of seismic data and others within the NGMA project who have contributed discussion and ideas on the interpretation of deep seismic data.

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Key horizon mapping and spatial basin evolution

C.D. Cockshell[1], D. Perincek[2], D.M. Finlayson[3], G.R. Pettifer[2], K.A. Hill[4].

1. Mines and Energy - South Australia, (MESA), P.O. Box 151, Eastwood SA 5063
2. Geological Survey of Victoria, (GSV), P.O. Box 98, East Melbourne, VIC 3002
3. Australian Geological Survey Organisation, (AGSO), P.O. Box 378, Canberra, ACT 2601
4. Victorian Institute of Earth and Planetary Sciences, Earth Sciences Department, Monash University, Clayton, VIC 3168

Introduction

Seismic mapping of the whole onshore Otway Basin (Fig. 1) was undertaken by four NGMA partners. VIEPS and AGSO combined to map the eastern Colac sheet, GSV the central Hamilton sheet and MESA the Gambier sheet (Fig. 2). The mapped area extends from Kingston in South Australia to Geelong in Victoria, a distance of 500 km, with an average width of 70 km. The onshore area thus covered is 35 000 sq.km which is approximately one quarter of the whole Basin.

Previous basin wide studies include Wopfner and Douglas (1971), Reynolds (1978), Megallaa (1985), Cockshell (1986), Pettifer *et al.*, 1991 and Perincek *et al.*, 1994. Most of these studies provided the broad geometry of the basin but were hampered by limited seismic data coverage and quality.

The main aim of the project was to display the regional geometry of the basin to assist in definition of its tectonic history and hydrocarbon prospectivity. A key element was conformable mapping of horizons throughout the basin, so that integrated structural maps could be prepared.

Some company interpretations were used to initially guide the project, but as most were of small areal extent, independent interpretation of seismic sections by the NGMA partners were the prime method of investigation. Some companies have prepared semi-regional maps recently, however they remain confidential. A total of 872 seismic lines were interpreted (402 MESA, 178 GSV, 242 VIEPS/AGSO). Most lines were 1981-1992 vintage of good quality, although some earlier lines were used in Victoria in more sparsely covered areas. Data quality is also spatially dependant, showing particularly poor coverage and penetration in the southern karst lands, volcanic districts, and uplifted Otway Ranges.

Mapped horizons

Geological control was taken from 125 petroleum exploration and stratigraphic wells within the basin as well as outcrop mapping in the Otway Ranges in the east. Formation top picks for wells were correlated using lithological, palynological and seismic stratigraphic controls during the project. This ensured the highest accuracy of the picks.

Four horizons are regionally mapped:

Top Sherbrook Group (Late Cretaceous/Base Tertiary).
Top Eumeralla Formation (Early Cretaceous).
Top Crayfish Group Unconformity (Early Cretaceous).
Basement (Palaeozoic)

which represent the megasequence boundaries within the post-Palaeozoic sequence.

Pre-Mesozoic basement rocks consist of Palaeozoic intrusives and metasediments associated with the Lachlan Fold Belt. Basement outcrops to the north of the Otway Basin in much of Victoria and along the Padthaway Ridge in SA but is only known in a few deep wells within the Basin. The basement reflector is a high amplitude, low frequency event showing strong angular unconformity onto an erosional or faulted surface. The event is readily correlated in the shallower parts of the basin but becomes unreliable to undiscernible in the deeper parts of the basin, particularly where seismic quality is poor.

The Late Jurassic to Early Cretaceous Casterton Formation infills the deepest depressions in the basement. However this pre-rift (or earliest syn-rift) sequence of carbonaceous shales, feldspathic sandstones and volcanics is thin and poorly defined by drilling or seismic and is not regionally mappable. However, it is often characterised by high amplitude sub-parallel reflectors.

The overlying Early Cretaceous Crayfish Group is a widespread, syn-rift sequence which infills most of the rifted grabens. At least 5 000 m of fluvial and lacustrine clastics and coals were deposited in the initial rifting stage. Thick sand units within this sequence are the prime target for hydrocarbon exploration in much of the onshore Basin. However to the south and offshore they are too deep to be economic targets. A marked regional unconformity occurs at the top of this sequence which is associated with the close of the earliest known phase of rifting in the Aptian. A marked regional event occurred over much of the basin prior to deposition of the overlying Eumeralla Formation, with significant erosion in many areas. This unconformity has a distinct high amplitude seismic character over much

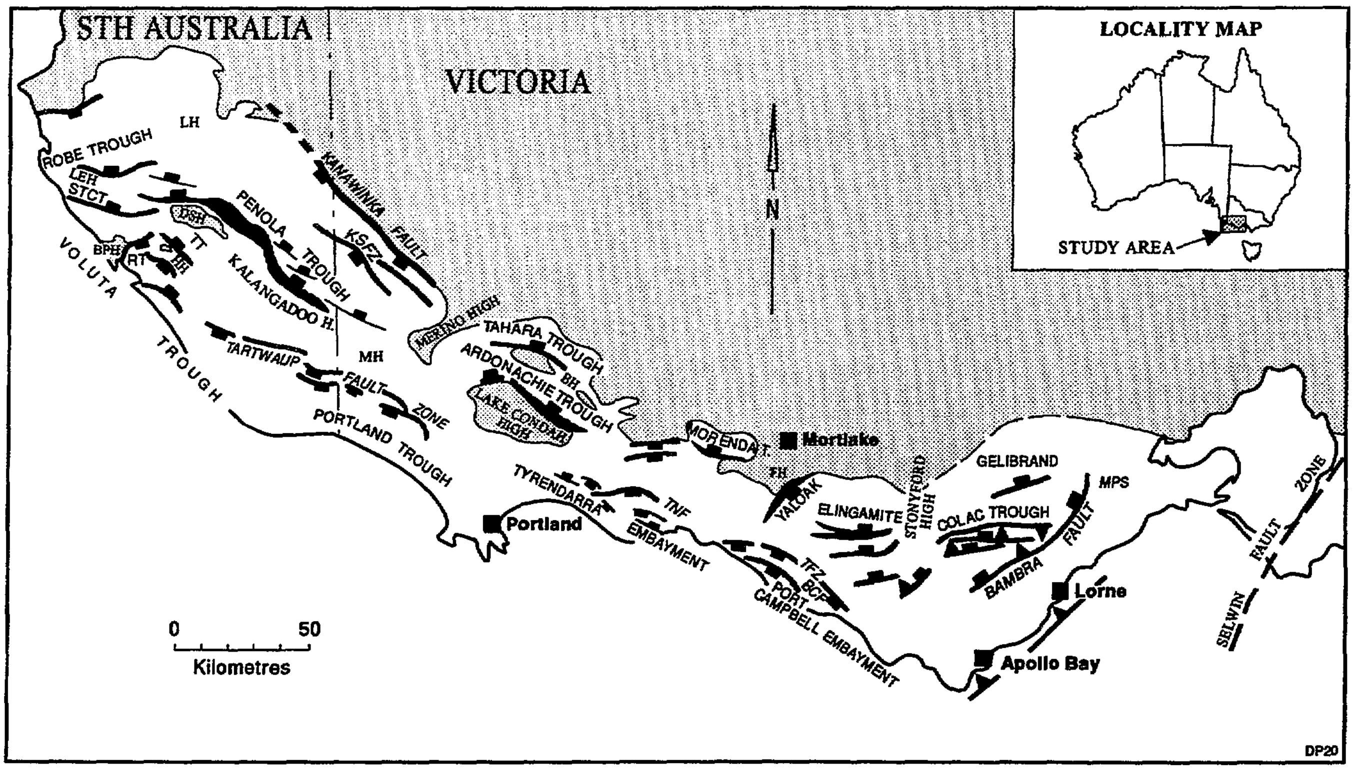

Figure 1 - Location map for the study area showing the location of major faults, depocentres, and basement highs. (BCF = Boggy Creek Fault, BH = Branxholme High, BPH = Beachport High, DSH = Diamond Swamp High, FH = Framlingham High, HH = Hatherleigh High, KSFZ = Kanawinka South Fault Zone, LEH = Lake Eliza High, LH = Lucidale High, MH = Mumbannar High, MPS = Mt. Pollock Structure, RT = Rivoli Trough, STCT = St. Clair Trough, TFZ = Timboon Fault Zone, TNF = Tyrendarra North Fault, TT = Tantanoola Trough).

of the basin, however its correlation becomes poorer to undiscernible in the deeper southern areas.

The Eumeralla Formation is a thick lacustrine shale and low energy fluviatile siltstone sequence. Near the base of the sequence the higher energy Windermere Sandstone and other interbedded sand units are prime hydrocarbon targets while interbedded coals provide sources of hydrocarbons and high amplitude seismic events. The late syn-rift formation onshore blankets the Crayfish Group and exposed basement inliers. The sediment forms the final phase of syn-rift deposition, which is more pronounced in the south as the rift axis moved south in the Albian. The top of the Eumeralla Formation is marked on most seismic records as an unconformity with the overlying Late Cretaceous Sherbrook Group. This unconformity is often difficult to pick and in many areas is taken at the top of a uniform low amplitude zone. This boundary correlates with thermal uplift and erosion associated with continental breakup (Yu, 1988).

The Sherbrook Group south of the Tartwaup Fault Zone (Fig. 1) is characterised by thick deltaic sediments with significant hydrocarbon potential. The Sherbrook Group is condensed by non deposition, bypass or erosion in the northern margins of the Otway Basin. Its deposition is associated with thermal subsidence and slow drift of Australia from Antarctica during Cenomanian to Maastrictian times. The Top Sherbrook event is a distinct high amplitude, low angle unconformity, which is clearly evident throughout the basin.

Slow drift continued in the Paleocene-Eocene with deposition of deltaic clastics and mudstones forming the Wangerrip Group. Rapid drift started in the Mid Eocene with deposition of marine clastics and carbonates of the Nirranda and Heytesbury Group. No regional mapping of Tertiary units was undertaken due to the limited petroleum interest at these levels (except for the southernmost onshore areas).

Map preparation

Interpreted horizons and faults were digitized and mapped primarily using the Petroseis system, with some work using Encom, ECS and ERMapper software.

Horizon pick misties were generally less than 30 msec, although some larger misties remain to be resolved in the easternmost map area. An apparent mistie at the South Australia-Victoria border south of the Tartwaup Fault Zone seems to be a geological reality, although poor data quality in this area limits mapping confidence.

The greatest difference between interpreters is in fault pattern interpretation and style. The intensity of faulting in the basin makes tying fault cuts from one line to the next difficult. Considerable effort was expended in merging the various fault sets together to form a conformable regional picture. However, as Figure 3 shows, individual styles are still visible.

Horizon time values were gridded in three separate map areas, interpreted by the three interpretation groups. Grids in Victoria were derived from seismic line based data while in South Australia hand drawn contours were digitized and regridded for final product display. Individual grids were then merged together. Regional horizon map products include coloured contour maps, isometric displays, sunshaded coloured and greyscale images.

Isochron (two-way time thickness) maps were prepared holistically from line based data without using fault datasets. A similar range of products is available for these maps. Examples of these map products are shown in Figures 3 and 4, which have been simplified for small scale presentation.

Mapping results

A brief discussion of the overall basin geometry follows. Discussion on other mapping results, including structural and tectonic history, sequence stratigraphy and hydrocarbon prospectivity are covered by other presentations at this seminar (Morton *et al.*, Finlayson *et al.*, Perincek *et al.*, Hill *et al.* and Summon *et al.*). The geometry of the main sequences in the basin is displayed in the four horizon structure and three isochron maps.

Mappable seismic basement structure is shown in Figure 3. The main elements are a series of half-grabens, complexly linked or isolated (such as the Tahara and Morenda Troughs), forming a failed rift segment. Many grabens, such as the Penola (SA), St Clair, Ardonachie, Elingamite and Colac Troughs (Fig. 1) are bounded to the south by large, north dipping faults. Many intervening half-grabens such as the Penola (Vic) Trough and Tyrendarra and Port Campbell Embayments have the opposite geometry of large north bounding, south dipping faults. This alternation, plus the apparent offsetting of adjacent grabens indicates involvement of transfer faulting or accommodation in the development of the rift system (Perincek *et al.*, 1994).

Mapping at this level has been the focus of AGSO seismic and aeromagnetic acquisition (Finlayson *et al.*, 1994). The Crayfish Isochron Map (Fig. 4) also reflects the main features of the basement structure map.

Individual units within the Crayfish Group have been mapped locally by many interpreters due to their hydrocarbon potential. However regional agreement on stratigraphy and structure has not yet been possible due to localised deposition of units within the deeper grabens.

Mapping of the Crayfish Group is possible throughout most of the onshore Otway Basin, however increasing depth to the south severely limits the extent of reliable

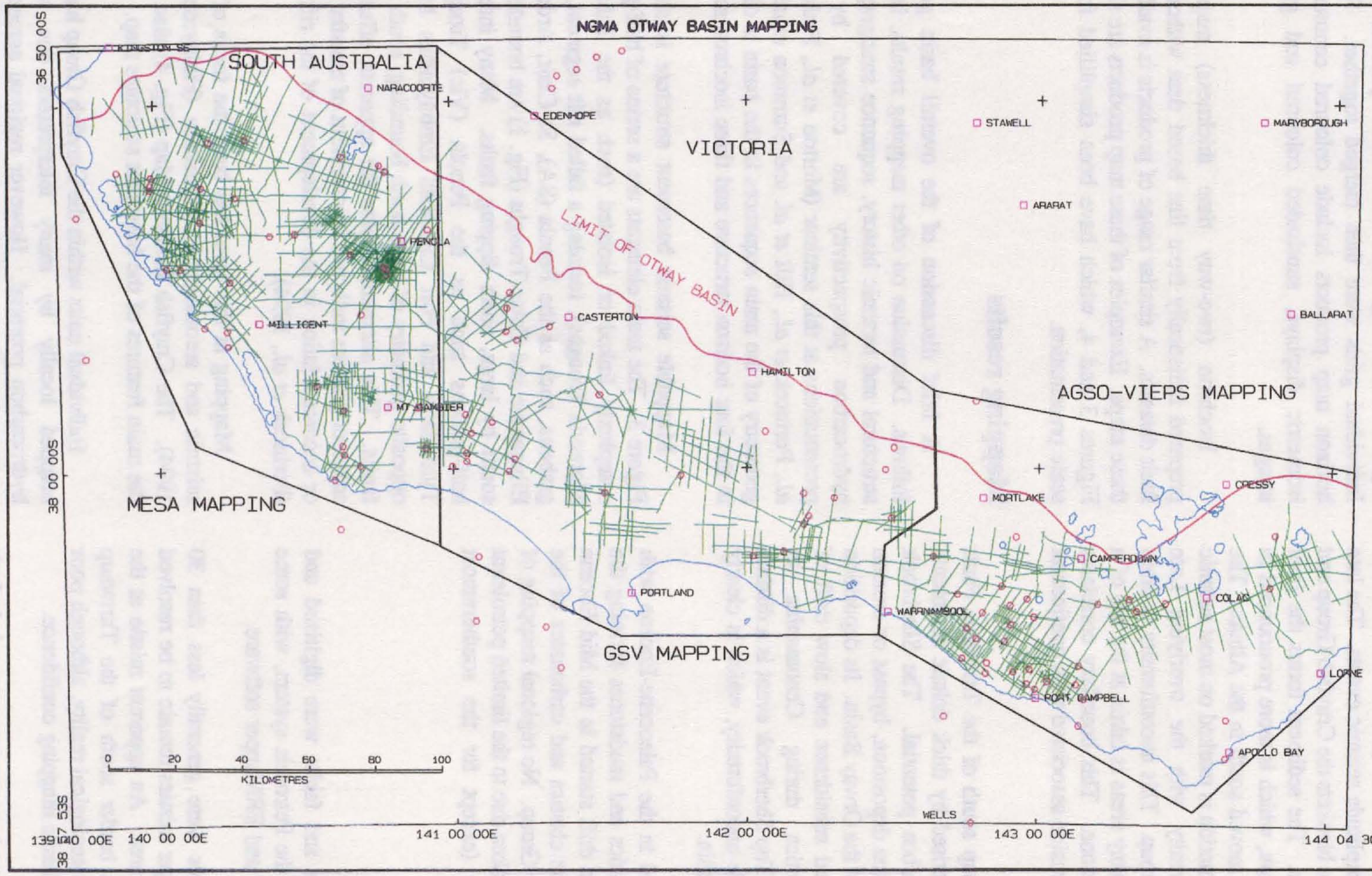

Figure 2 - Otway Basin mapping area and data location map.

mapping. The Crayfish Isochron Map (Fig.4) starkly highlights the graben infilling nature of these sediments. Over 4 000 m (2.4 sec TWT) have been deposited in the Penola Trough with thinner sediment infilling the many other half grabens developed in the northern part of the basin. Offsetting of depocentres within and between these grabens is clearly shown.

The overlying Eumeralla Formation is at least 3 000 m (2.5 sec TWT) thick in the northern Otway Ranges. It has also significant thickness in the Port Campbell Embayment and most southern mapped areas extending to the offshore portion of the basin. The unit thins towards the northern margin of the basin. Rapid thickness changes across the basin reflect deposition on an unconformity surface with significant tectonically controlled relief. Basement inliers such as the Diamond Swamp and Lake Condah Highs were onlapped and blanketed by Eumeralla Formation sediments.

The Sherbrook Isochron Map clearly shows the thin, bypass margin depositional setting of this group across the onshore Otway Basin. Throughout the Colac and Gellibrand Troughs it is virtually absent. The sequence is particularly well developed in the Portland Trough, south of the Tartwaup Fault Zone and, to a lesser extent in the Port Campbell Embayment. The unit is best developed offshore, where the basal Waarre Formation is the prime hydrocarbon target.

The Top Sherbrook horizon indicates the depth of burial of the Late Cretaceous sequence as well as the thickness of Cainozoic sediments. The Cainozoic sequence reaches a maximum time thickness of 1.8 sec in the Portland Trough south of Lake Condah High. Other embayments with thick Tertiary sequences occur in the south from Mt Gambier to Port Campbell. These units thin to the north throughout the basin, but can be traced north into the Murray Basin in the western Otway Basin. Eocene-Recent compression has caused significant uplift and erosion particularly in the Beachport and Merino Highs, Colac Trough and Otway Ranges.

Products available

Basin-wide onshore time structure (TWT) and isochron (TWT thickness) maps at 1:500 000 scale are available in various versions including coloured contours, perspective views, coloured and greyscale images. Digital files of seismic line-based digitized horizon values and mapping grids are also available. Customised products are also available upon request from MESA or GSV. More detailed maps are available for individual map areas from individual interpretators.

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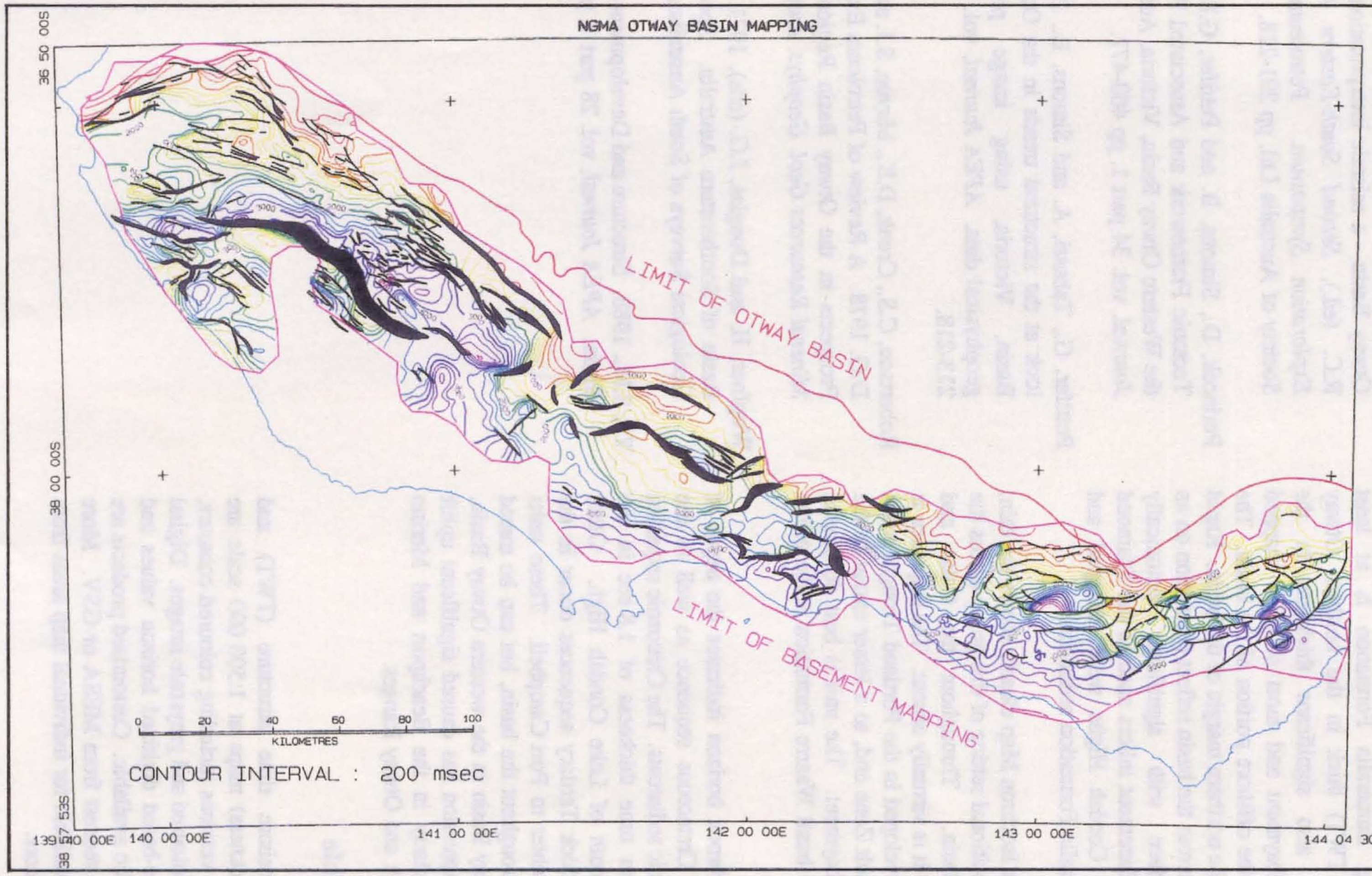

Figure 3 - Top basement time structure map.

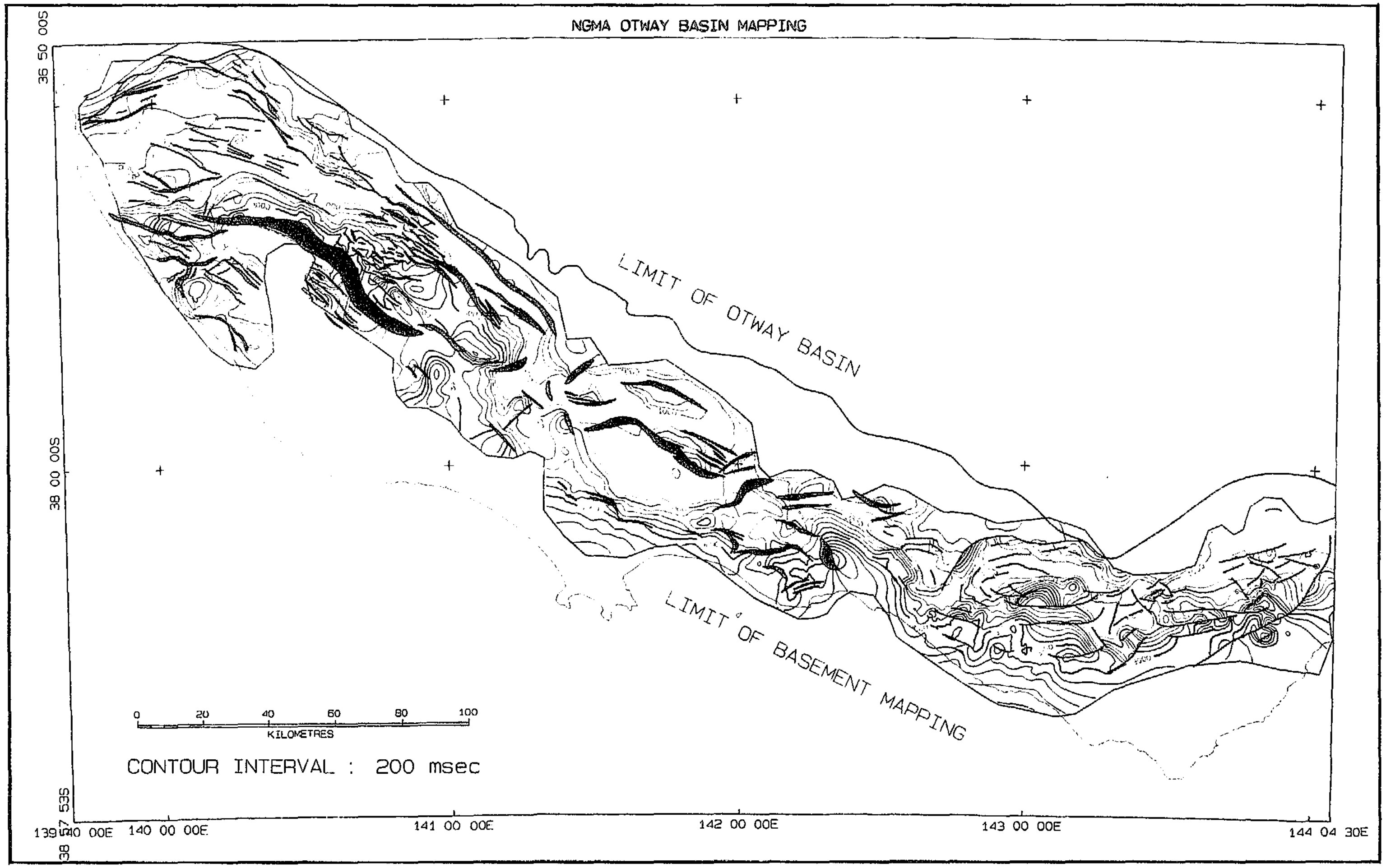

Figure 3 - Top basement time structure map.

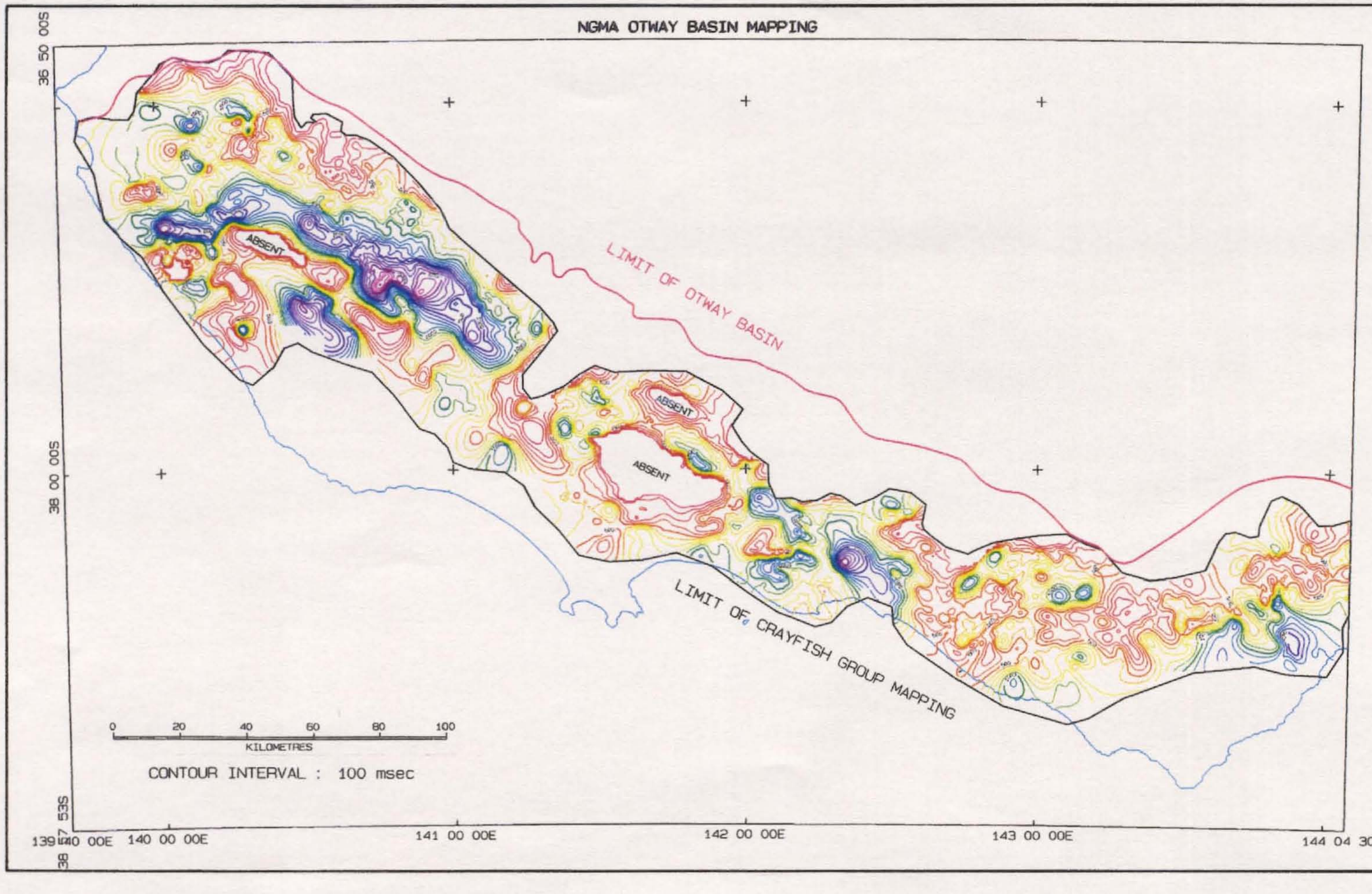

Figure 4 - Crayfish Group isochron map.

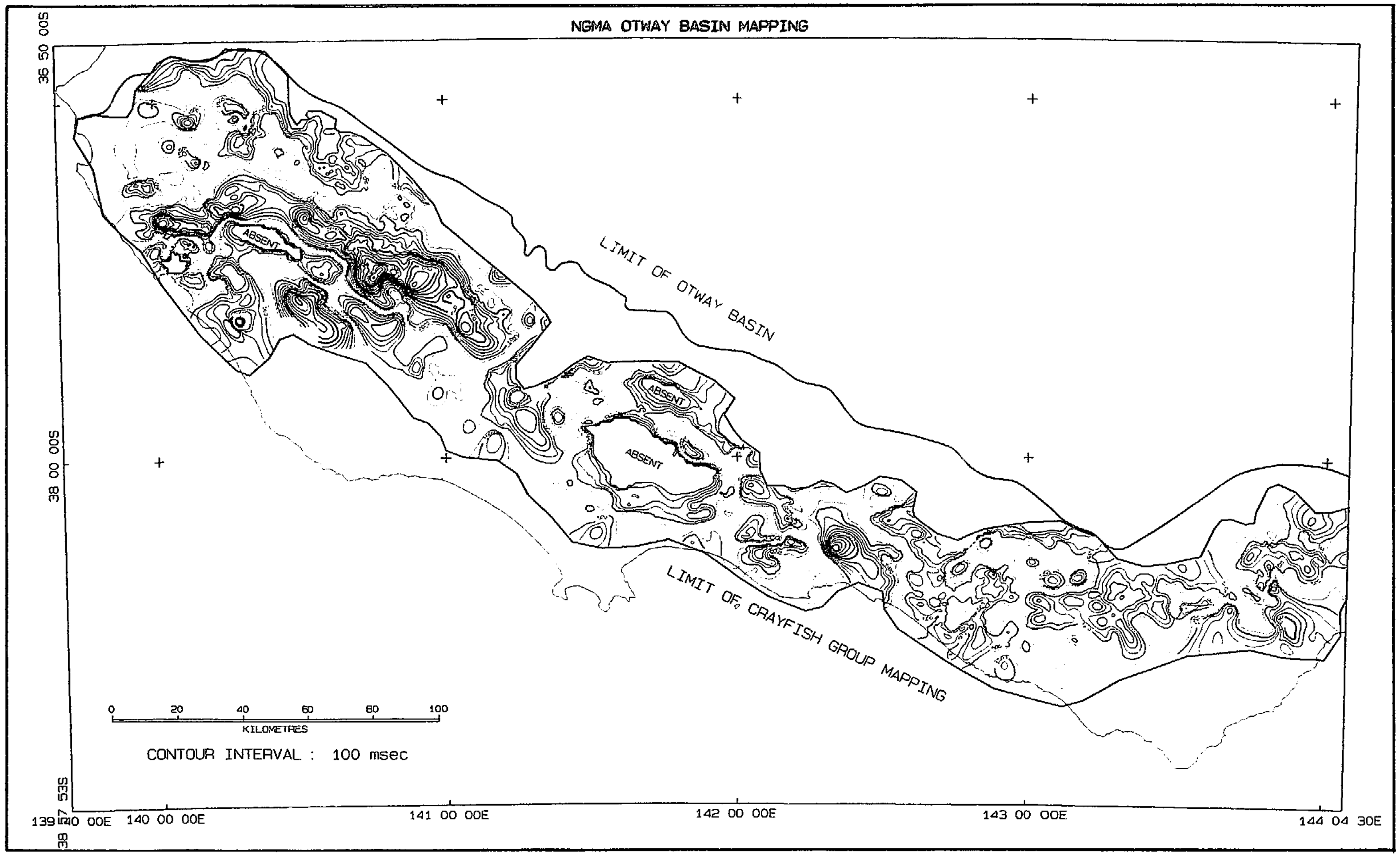

Figure 4 - Crayfish Group isochron map.

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The Otway Basin: Early Cretaceous rifting to Miocene strike-slip

Dogan Perincek[1], C. David Cockshell[2], Douglas M. Finlayson[3] and Kathy A. Hill[4]

1 - Geological Survey of Victoria (GSV), Department of Energy and Minerals, PO Box 98, East Melbourne, Vic. 3002
2 - S.A. Department of Mines and Energy (MESA), PO Box 151, Eastwood, SA 5063
3 - Australian Geological Survey Organisation (AGSO), PO Box 378, Canberra, ACT 260
4 - VIEPS, Department of Earth Sciences, Monash University, Clayton, Vic. 3168

Key words: Otway Basin, structure, half-graben, inversion, transfer/accommodation zone, Penola Trough, Colac Trough

Regional seismic interpretation of the onshore Otway Basin has produced a structural elements map showing the ages of faulting. This interpretation has improved our understanding of the tectonic events controlling the evolution of the basin and associated hydrocarbon plays.

The early development of the basin involved rifting during Late Jurassic - Early Cretaceous times, producing a number of half-graben. The rifting conforms with rift development models, in which half-graben of alternating vergence are separated by transfer or accommodation zones displaying complex folding and faulting patterns. These half-graben were filled and rifting ceased prior to the Aptian, within the northern margin of the basin. Compression, resulting in right-lateral wrenching and inversion of previous faults, occurred during the Miocene - Recent.

Based on the structural mapping, a number of hydrocarbon play types have been identified. These play types include anticlines associated with transfer/accommodation zones, tilted fault blocks, buried basement highs, stratigraphic traps, post-Albian horst structures, syn-depositional roll-over structures and post-Oligocene normal and reverse fault related structures.

Introduction

This paper presents the results of a regional seismic interpretation of the onshore portion of the Otway Basin (Fig. 1) as part of a National Geoscience Mapping Accord project which aims at mapping the onshore basin to improve our understanding of early tectonic events controlling the basin's evolution.

The structural elements in South Australia were mapped by MESA (C.D. Cockshell and B. Finlayson) (Fig. 2), in western Victoria by the Geological Survey of Victoria (D. Perincek) (Fig. 3), and in eastern Victoria by AGSO (D. Finlayson) and VIEPS (K.A. Hill, M.J. Richardson and C.J. Lavin) (Fig. 4).

In this paper we analyse the structure and history of basin development, including timing of fault activity and look at a number of resulting hydrocarbon play types.

Geological setting

The Otway Basin is a Late Jurassic - Recent basin on the southern margin of Australia, formed by the rifting and continental break-up of Australia and Antarctica. The basin was initiated as a series of half-graben (Sprigg, 1986) separated by basement highs. There are a significant number of inferred Palaeozoic basement blocks which play a part in basin development (e.g. Merino and Framlingham highs, Figs. 3 and 4).

Sedimentation in the Otway Basin commenced during the Tithonian? - Berriasian with the deposition of the Casterton Formation and continued during the Berriasian - Barremian with Crayfish Group deposition, characterized by half-graben development. Top basement faulting clearly shows the predominance of major faults controlling Crayfish Group distribution and thickness. The asymmetric half-graben character indicated by thickening toward the bounding fault, can be seen in the Crayfish Group thickness image, particularly in the St. Clair Trough (up to 2.1 s TWT), south Penola Trough (up to 2.4 s TWT), southeast Ardonachie Trough (up to 1.4 s TWT) and Elingamite Graben (up to 1.3 s TWT). The thickness of the Early Cretaceous sequences under the eastern Otway Basin is up to 4 s TWT.

The western part of the Otway Basin (Fig. 2) is characterised by the E-W to ENE-WSW trending Robe Trough and bounded by the ENE-WSW trending faults. North and northeast dipping faults bound the southern margin of the St. Clair, Tantanoola and Penola troughs. The southwestern bounding fault of the Penola Trough, dies out towards Victoria. The Penola Trough shows opposite polarity within Victoria, and is bounded to the north by the southwest dipping Kanawinka Fault and Kanawinka South Fault Zone. These faults form a complex of NW - SE trending northern bounding faults active during Crayfish Group deposition.

The NE dipping Ardonachie South Fault bounds the southern margin of the Ardonachie Trough and is clearly of Crayfish Group age (K_1), with no evidence of syn-depositional Eumeralla Formation faulting. Crayfish Group onlaps basement to the north. The polarity of the Ardonachie Trough half-graben is opposite to that of the eastern portion of Penola Trough.

The Tahara, Morenda, Elingamite, Colac and Gellibrand troughs (Figs. 3 and 4) show similar half-graben polarity to the Ardonachie Trough, whereas the Penola Trough within Victoria and Tyrendarra and Port Campbell embayments show opposite half-graben polarity. East of the Stoneyford High in the Colac Trough, the major faults trend NE-SW with bounding faults dipping towards the NW. The Crayfish Group fills these syn-depositional half-graben.

The Crayfish Group is thin, onlapping or absent on the Beachport, Diamond Swamp, Lake Condah, Branxholme and Merino basement highs, and on the northern margin of the basin.

Top Crayfish Group faulting (Ke) is clearly less significant than top basement faulting and much of the top basement topography is lost by top Crayfish time due to the Crayfish Group filling the half-graben. Faults active during Crayfish Group deposition have generally not controlled Eumeralla Formation distribution. The Eumeralla Formation thickens basinward gradually and then rapidly across the Tyrendarra North Fault, the Bambra Fault, the NW bounding fault of the Rivoli Trough, and the St. Clair Trough bounding fault from south (fig. 2). The Tyrendarra North Fault is the major fault controlling deposition of the Eumeralla Formation in the Tyrendarra Embayment. The remainder of the faults shown on Figures 2, 3, and 4, with the exception of minor faults to the west of the Ardonachie Trough and to the northeast of Ferguson Hill Anticline (Fig. 4), were not active until the Late Cretaceous (K_2).

Sherbrook Group sequences thicken from NE to SW, with rapid thickening across the syn-depositional Tartwaup Fault Zone into the Portland Trough (Figs 2 and 3). The Tartwaup Fault Zone is interpreted as the cratonic boundary for a lower plate margin during the episode of lithospheric extension which eventually resulted in separation of Australia from Antarctica (Finlayson et al. 1994). New graben formation within the Ardonachie, Penola and Morenda troughs and the Tyrendarra, and Port Campbell embayments indicates reactivation along previous Crayfish Group faults and creation of new Late Cretaceous faults. The NE and E trending faults in the SE corner of the Tyrendarra Embayment have become inactive and been sealed by Sherbrook Group. This trend has been replaced by WNW trending K_2 faults (Fig. 3).

Tertiary units generally thicken from NE to SW, with rapid thickening across the Tartwaup Fault into the Portland and Voluta troughs, which continue to be syn-depositional during the Tertiary. Late Cretaceous graben in the northern troughs continued to subside, narrowing and tending to die out, although some smaller new graben also developed.

Within the Tyrendarra Embayment, a number of WNW trending faults, which were initiated in the Late Cretaceous, were linked by NNW trending faults in Miocene time.

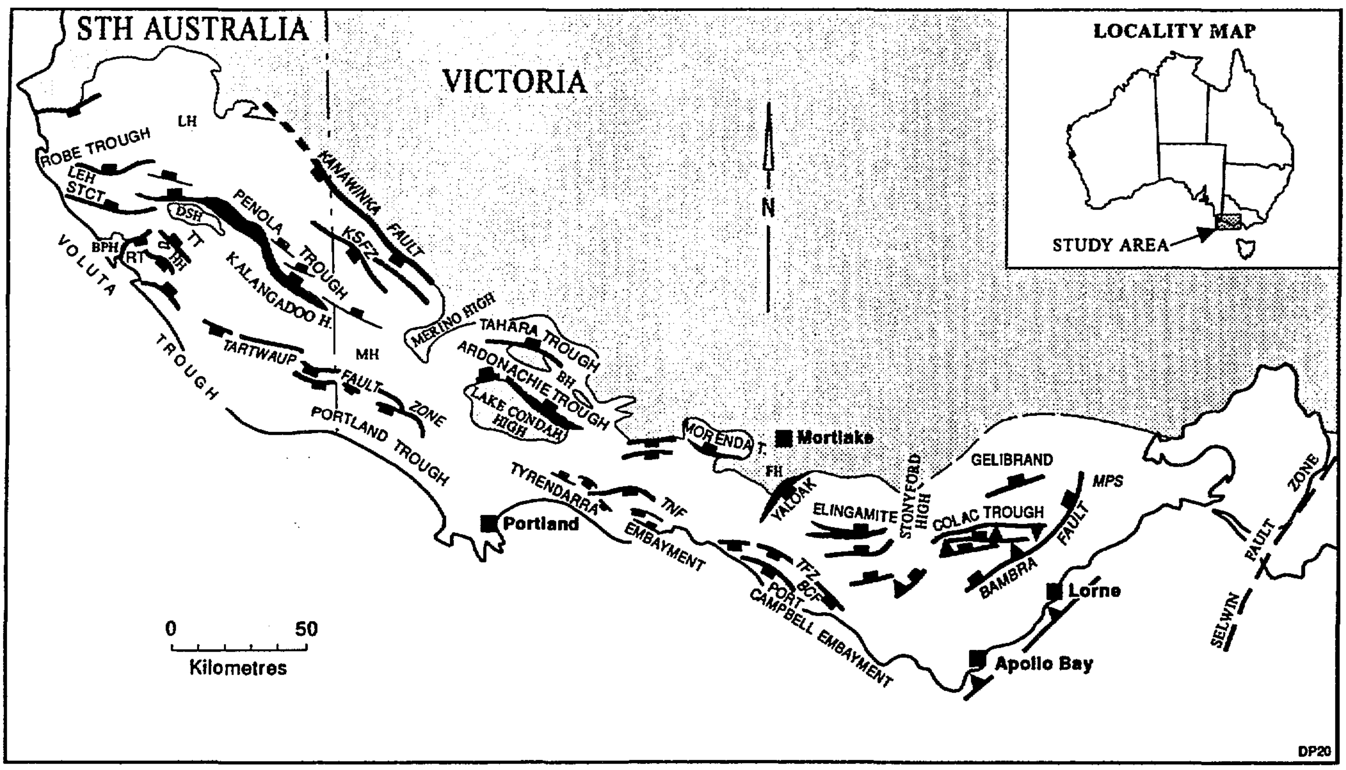

Figure 1 - Location map for the study area showing the location of major faults, depocentres, and basement highs. (BCF = Boggy Creek Fault, BH = Branxholme High, BPH = Beachport High, DSH = Diamond Swamp High, FH = Framlingham High, HH = Hatherleigh High, KSFZ = Kanawinka South Fault Zone, LEH = Lake Eliza High, LH = Lucidale High, MH = Mumbannar High, MPS = Mt. Pollock Structure, RT = Rivoli Trough, STCT = St. Clair Trough, TFZ = Timboon Fault Zone, TNF = Tyrendarra North Fault, TT = Tantanoola Trough).

Major faulting occurred at the NW trending Penola South Fault Zone during post-Oligocene time. This fault zone indicates reactivation along previous, minor K_1 faults within Victoria and joins the major K_1 fault in South Australia north of the Kalangadoo High. On the northern flank of the Diamond Swamp High this latter post-Oligocene fault maintains a NW trend, rather than the westerly trending K_1 fault system.

Structural elements maps

The structural elements maps (Figs. 2, 3 and 4) display areas of structural highs and lows representing varying Crayfish Group sediment deposition and limits, and faults showing their trends and age of movement: K (Cretaceous - undifferentiated), K_1 (Berriasian - Barremian), Ke (Aptian - Albian), K_2 (Late Cretaceous), T (Tertiary) and M (Miocene - Recent) or combinations of these. High areas during Crayfish Group deposition were later buried by the Eumeralla Formation.

Pre-Aptian faulting

Borehole data and a high amplitude seismic reflector overlying basement, interpreted to be Casterton Formation, suggest there has been minor syn-depositional faulting of the Casterton Formation. With the onset of rifting, major syn-rift faulting (K_1) controlled Crayfish Group deposition within the half-graben.

Within the eastern portion of Penola Trough , the northern

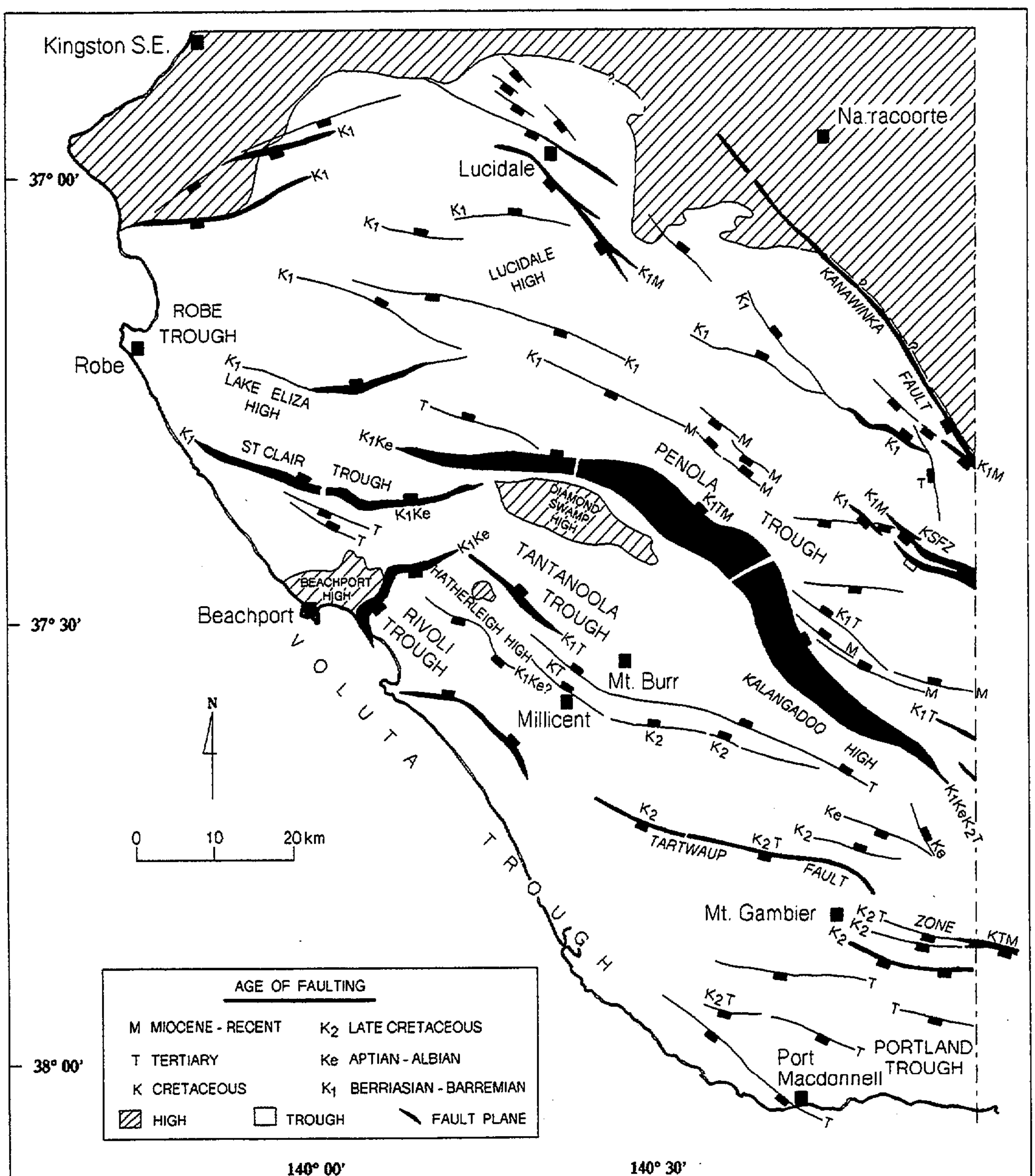

Figure 2 - Structural elements map of the Western Otway Basin (C. D. Cockshell and B. Finlayson) showing age of the major faults (fault timing by D. Perincek).

extent of the Crayfish Group is controlled by the major SW dipping Kanawinka South Fault Zone and Kanawinka Fault. Minor faulting and onlap occurred at the Penola South Fault Zone (Fig. 2).

The NE dipping Ardonachie South Fault defines the southern margin of the Ardonachie Trough (Fig. 3). Minor faulting and onlap occurred to the north of the Ardonachie Trough against the Branxholme High. The Tahara Trough north of the Branxholme High has a south bounding fault similar to the Ardonachie Trough.

The Tyrendarra Embayment is a half-graben bounded in the north by four south-dipping bounding faults. The Tyrendarra North Fault is the southernmost of these (Fig. 3). The Morenda Trough, separated from the Tyrendarra Embayment by a basement high (Fig. 3), shows similar geometry to the Ardonachie Trough with a northerly dipping, south bounding fault. The faulting in the Tyrendarra and northern Port Campbell embayments mostly strikes E-W (Figs. 3 and 4). To the east of an area centered around the Stoneyford High the strike of Early Cretaceous faults gradually changes from E-W to NNE-SSW (Hill et al. submitted).

The change in polarity of the half-graben and vergence of the major bounding faults between the various troughs is accounted for by the presence of transfer or accommodation zones which are discussed in detail later in this paper. Most of the Crayfish Group faults are sealed by deposition of the Eumeralla Formation.

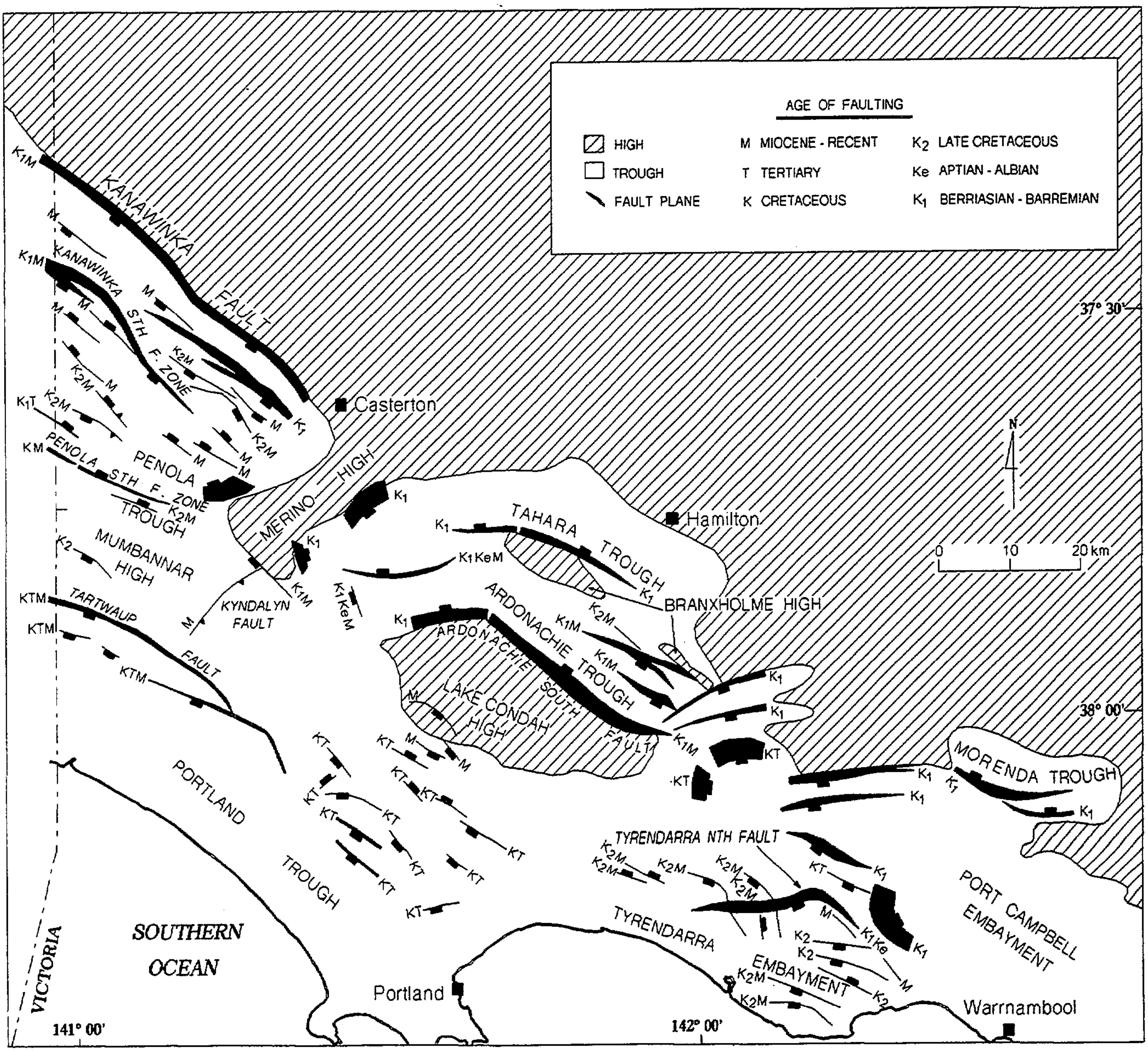

Figure 3 - Structural elements map of the Casterton-Portland-Warrnambool area showing the age of the major faults (Perincek et al. 1994)

Aptian - Albian faulting

Faulting related to rifting is interpreted to have ceased prior to the Aptian. Aptian - Albian age faulting (Ke in Figs 2, 3 and 4) is syn-depositional Eumeralla Formation faulting. This is mostly confined to the SE Tyrendarra Embayment, St. Clair Trough and Rivoli Trough. The Tyrendarra North and, possibly, Tartwaup faults (K_1Ke and K respectively) continued to be active after the rifting phase. The Kyndalyn Fault was also active at this time.

Cenomanian - mid Early Eocene faulting

Cenomanian - mid Early Eocene faulting (K_2 and KT) covers the period of deposition of the Sherbrook Group through to the Pember Mudstone deposition. This period was characterized by major activity on the Tartwaup Fault (Figs. 2 and 3) and reactivation of some northern margin faults of the basin which returned to an extensional regime. The reactivation of the earlier Crayfish Group faults produced shallow Late Cretaceous and Early Tertiary graben in the Ardonachie, Penola and Morenda troughs. New half-graben were also created during Sherbrook Group deposition and sealed by Wangerrip Group deposition.

The fault orientation within the Tyrendarra Embayment during this time changes from E-W and NE-SW to NW-SE (Fig.3). The WNW-ESE fault trends seen in the Port Campbell Embayment were initiated in the Cenomanian - Santonian (Hill et al. submitted). Within the Tyrendarra Embayment and Penola Trough a number of syn-depositional Palaeocene faults were sealed by the Dilwyn Formation. This coincides with the change in spreading rates observed in the Early Eocene and has been recognised as an unconformity within the Wangerrip Group (Perincek et al. 1994).

Miocene - Recent faulting

This period of faulting (designated M) is characterized by a new generation of normal faulting and reactivation of major bounding faults.

In addition to the normal faulting, there are several phenomena consistent with right lateral strike-slip movement

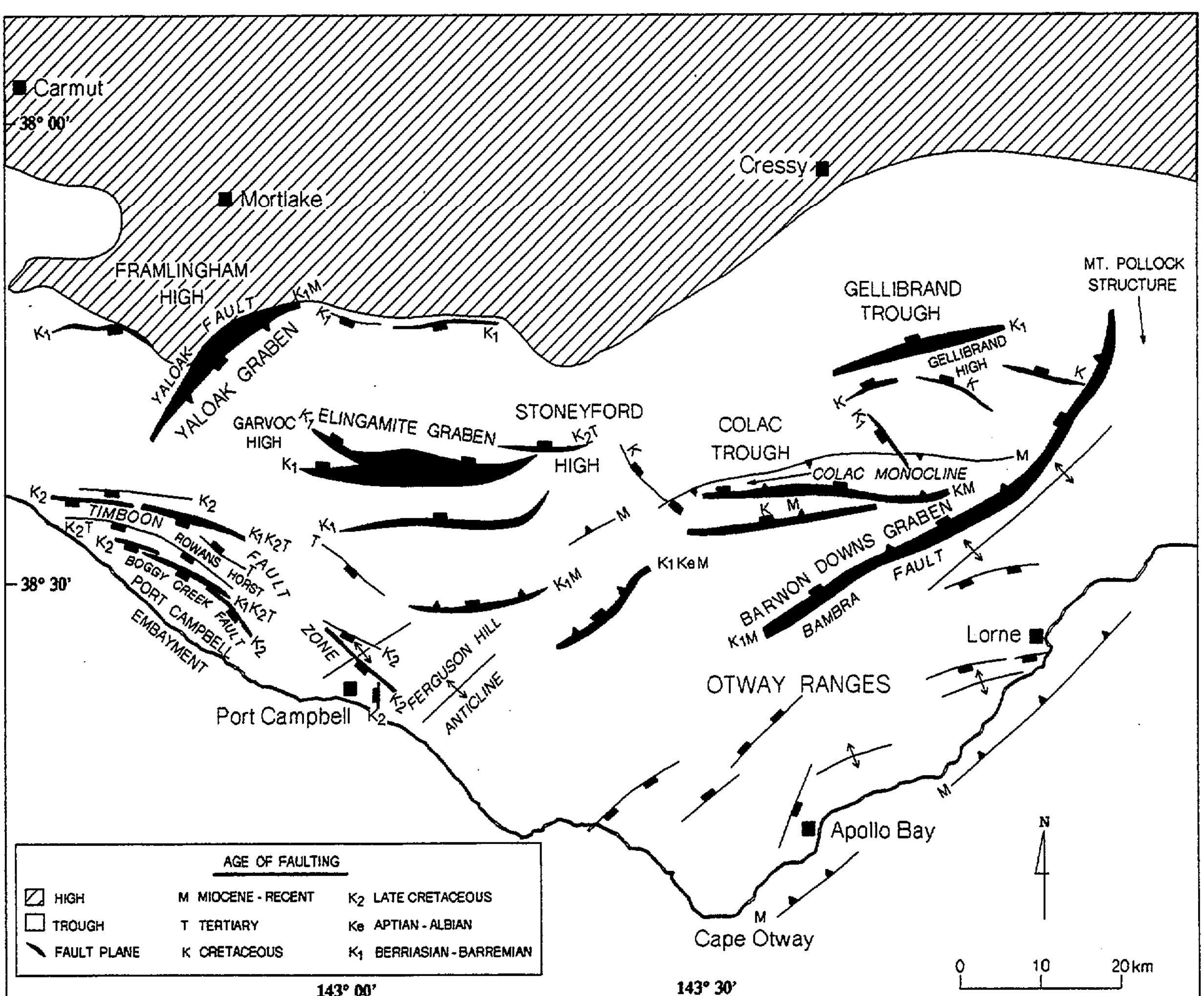

Figure 4 - Structural elements map of the Eastern Otway Basin (D. M. Finlayson, M. J. Richardson, C. J. Lavin, and K. A. Hill) showing age of the major faults (fault timing by D. Perincek).

at this time. The easternmost Miocene faults within the Tyrendarra Embayment exhibit flower structures on seismic data and 'dogleg' faults have developed in the Tyrendarra Embayment due to right stepping, releasing-bend, extensional structures. In addition, inversion of the Kyndalyn Fault is consistent with right lateral strike-slip movement oriented roughly NW-SE. The seismic interpretation indicates the timing of this inversion to be post-Oligocene. Inversion of faults within the Penola Trough, on the Tartwaup Fault and in the eastern Otway Basin also occurred at this time. Geological mapping (Tickell et al. 1992), topography, radiometric (Pettifer et al. 1991) and coastal geomorphology provide evidence that these faults come to the surface.

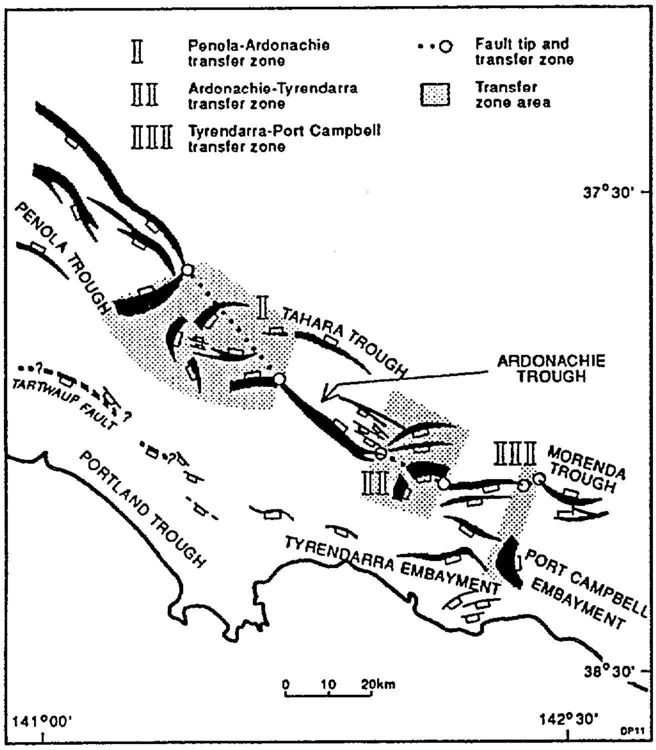

Figure 5 - Major half-graben faults and transfer zones within the western Victoria region (Perincek et al. 1994)

The present-day direction for the maximum compressive stress is close to NW-SE within the Otway and Gippsland Basins (Denham and Windsor, 1991), which is consistent with the observed right-lateral strike-slip and related inversion of previous faults. The stress regime within the Australian lithospheric plate is thought to be associated with collision on the northern and eastern margins of the plate (Veevers et al. 1991).

Transfer/accommodation zones

The polarity of the pre-Barremian fault-bounded half-graben changes a number of times along the northern margin of the basin (Fig. 1). These changes occur within transfer/accommodation zones (Fig.5) of complex faulting and folding and are not defined by single transfer faults. The architecture of rifting and basin formation in a region of lithospheric extension has been described by Rosendahl (1987) in terms of linked half-graben and accommodation zones. Subsequently Morley et al. (1990) and Nelson et al. (1992) described the rifting process in terms of rift segments and intervening transfer zones. Rosendahl (1987) indicates that in the East African Rift system, high relief accommodation zones almost always follow prerift structural trends very closely.

In western Victoria, Perincek et al. (1994) described the transfer zones as the Penola-Ardonachie transfer zone, Ardonachie-Tyrendarra transfer zone and Tyrendarra-Port Campbell transfer zone (Fig.5). Half-graben polarity changes and associated accommodation zones have also been suggested for the Otway Basin within South Australia (Hill and Durrand, 1993). Evidence presented by Hill and Durrand indicates that the western end of the Penola Trough in South Australia has a reversed half-graben polarity to the trough in Victoria.

East of the northeast trending Yaloak Fault (K_1) (Fig.4) further half-graben exist, including the Elingamite Graben, and half-graben within the Colac area which have a similar geometry to the Ardonachie Trough and Tahara Trough pair, with north dipping, south bounding faults (Fig.4). This area is bordered to the west and separated from the Tyrendarra Embayment by a transfer/accommodation zone, which extends to the Framlingham High in the north (Fig. 4).

Play types

The structural complexity of the basin has led to a number of structural play types being identified. These include anticlines associated with transfer/accommodation zones, tilted fault blocks, buried basement highs, stratigraphic traps, post-Albian horst structures, syn-depositional roll-over structures and Oligocene-Miocene normal and reverse fault related structures (Perincek et al. 1994).

Conclusions

As a result of seismic interpretation of the onshore Otway Basin, a structural elements map has been produced showing age of faulting.

Rift related extension in Late Jurassic - Early Cretaceous times, produced a number of half-graben on the northern margin of the basin. The rifting conforms with rift development models in which half-graben of alternating vergence are separated by transfer/accommodation zones displaying complex folding and faulting patterns.

During the Miocene and possibly earlier, compression resulted in right-lateral wrenching and inversion of previous faults.

Acknowledgments

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The Otway Basin: Thermal, Structural, Tectonic and Hydrocarbon Generation Histories

Ian R. Duddy

Geotrack International Pty Ltd, PO Box 4120
Melbourne University 3052

Introduction

The results summarised here represents the outcome of accumulated work in the Otway Basin begun with a study of the general geology, provenance, sedimentation, diagenesis and geochemistry of the Otway Group volcanogenic sediments (Duddy, 1983). In more recent years, development and application of integrated fission track and vitrinite reflectance studies by Geotrack International Pty Ltd has lead to elucidation of key features of the thermal, structural and tectonic histories of the south-eastern Australia as reported here and in several other studies (Duddy et al., 1991; Duddy and Green, 1992).

Application of fission track studies in sedimentary basin analysis was born in the Otway Basin over a decade ago (Gleadow and Duddy, 1981), culminating in the use of Apatite Fission Track Analysis (AFTA™) as a prime technique in thermal history reconstruction (e.g. Green et al. 1986; Laslett et al. 1987; Duddy et al. 1988; Green et al. 1989a & b) by all major oil exploration companies world-wide. Despite this background, quantitative interpretation of AFTA data from the Otway Group volcanogenic sediments has proved extremely difficult, only becoming possible in the last couple of years with the development of a quantitative understanding of the role of apatite composition on annealing kinetics. Similarly, it has only been since 1989 that a rigourous kinetic model for the interpretation of vitrinite reflectance (VR) data in terms of paleotemperature has been available (Burnham and Sweeney, 1989).

In this extended abstract key aspects of the thermal, structural, tectonic and hydrocarbon generation history of the Otway Basin and illustrated by reference to key well and outcrop sections.

Interpretation of thermal history

Details of the integrated methodology developed for reconstructing thermal histories using AFTA and VR data have been published elsewhere (e.g. Bray et al. 1992) and are only covered in broad terms here. The methodology has now been applied to a large number of wells and outcrops in the Otway Basin with only a few key localities (Figure 1) described in the following sections.

Thermal history reconstruction involving interpretation of AFTA and VR data ($R_o$max) requires accurate paleontology and present temperatures. In the Otway Basin, knowledge of the age of the youngest Otway Group is key information, as are details of the Tertiary stratigraphy. For well samples, BHT data must be assessed and appropriate correction applied before interpretation can proceed.

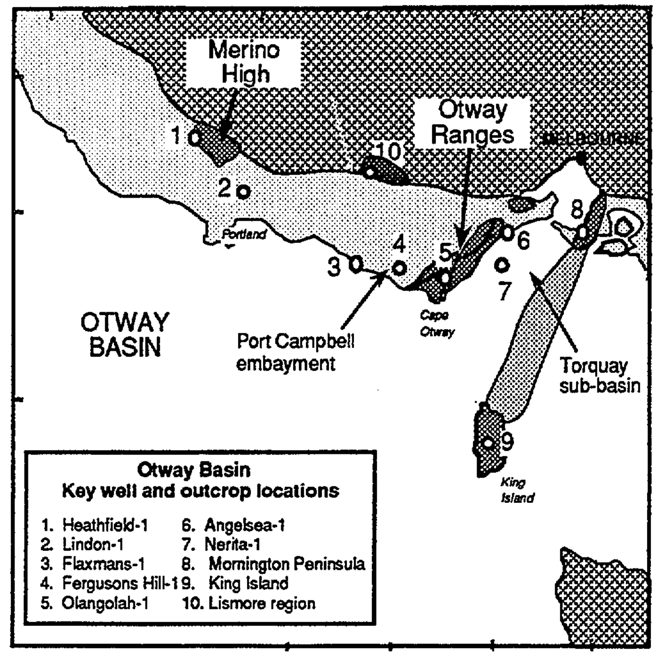

Figure 1: Key outcrop and well locations referred to in the text relevant to understanding thermal, structural and hydrocarbon generation histories in the Otway Basin.

VR data and AFTA each allow maximum paleotemperature to which a sediment has been subjected to be determined, while AFTA also provides the time at which cooling from maximum paleotemperature began, as well as some details of the style of cooling (Bray et al., 1992). Paleotemperature estimates from each technique are directly interchangeable for the same heating rate due to the similar underlying kinetic response to temperature and time (Duddy et al., 1991).

A vertical sequence of maximum paleotemperature estimates in samples from a deep well allow the paleogeothermal gradient at the time of cooling from maximum paleotemperatures to be determined and the cause of heating, in terms of increased heat flow, uplift and erosion or any other reason, to be sought. If a linear paleogeothermal gradient is determined, then the magnitude of missing section can be determined by assumption of linear extension of the measured paleogeothermal gradient through the "removed section" (Bray et al., 1992).

No direct estimate of paleogeothermal gradient can be made for individual outcrop locations, so assessment of the amount of removed section can only be approached from a regional assessment of the range of paleogeothermal geothermal gradient at this time. In the Otway Basin, this regional assessment is well advanced and fairly confident determinations of the amount of section eroded from "within basin" and basin margin structures can be made.

Thermal history reconstruction in key Otway Basin wells

Results of thermal history reconstruction in Olangolah-1, Fergusons Hill-1, Heathfield-1, Anglesea-1, Nerita-1 and Lindon-1 (Figure 1) are summarised in Table 1, with a brief summary of their respective contributions to our regional understanding of the Otway Basin evolution given below.

Table 1: Thermal history analysis summary for Otway Basin wells

Well	Time Otway Group cooled from maximum paleotemperatures*1	Paleogeothermal gradient*2 (°C/km)	Total section removed in mid-Cretaceous event (km)	Total section removed since the Eocene (km)
Olangolah-1	Mid-Cretaceous	~60	~3.0	?
Fergusons Hill-1				
- upper Otway Grp	Post-Eocene	~33	-	~1.0
- basal Otway Grp	Mid-Cretaceous	~65	0*3	-
Heathfield-1	Mid-Cretaceous	~60	0*3	?
Anglesea-1	Mid-Cretaceous	~50	~2.2	~1.0
Nerita-1				
- upper Otway Grp	post Mid-Miocene	~33	-	~1.0 to 2.0
- basal Otway Grp	Mid-Cretaceous	~60*4	~1.0	-
Lindon-1	Maximum temperatures at present day	up to ~70*5	0*3	~0

*1 Mid-Cretaceous is shown by AFTA to be ~95 to 100 Ma. Post-Eocene cooling may have commenced in either the late Eocene-early Oligocene of post-Middle Miocene for AFTA, although the later timing is favoured by the available seismic data.
*2 Determined from the VR data at the time the Otway Group cooling from maximum paleotemperatures
*3 Cooling due to decline in paleogeothermal gradient only, confirmed by the presence of P. pannosus in these wells.
*4 Based on regional data as available VR data give poor control on paleogeothermal gradient.
*5 A high mid-Cretaceous paleogeothermal gradient is inferred from regional data, but subsequent burial beneath late Cretaceous and Tertiary sediments has resulted in maximum temperatures in the Otway Group at the present day.

Thermal history reconstruction in **Olangolah-1, Fergusons Hill-1, Heathfield-1, Anglesea-1, Nerita-1** and **Lindon-1** are illustrated in Figures 2 to 7, respectively.

Data from Olangolah-1 demonstrates that mid-Cretaceous (~95 to 100 Ma) time of cooling corresponds with major folding in the Ranges, and the end of Otway Group volcanism across southern Victoria (Duddy, 1983), linking the geological evidence for a major tectonic reorganisation at this time to the radiometric time scale.

Direct evidence for elevated mid-Cretaceous paleogeothermal gradients is observed in Olangolah-1, Anglesea-1, Heathfield-1 and Fergusons Hill-1, demonstrating a broad regional feature that an reasonably extended to nearby wells. This has been done in reconstructing the thermal histories in Lindon-1, which is at maximum temperatures at the present-day, and in Nerita-1 where the available data are insufficient to constrain the gradient.

A post-Middle Miocene structuring episode is clear in Nerita-1 and may be the same event responsible for post-Eocene cooling observed in the Anglesea-1 and Fergusons Hill-1 well flanking the Otway Ranges. Tertiary structuring occurred under essentially normal geothermal gradient conditions, and evidence from Heathfield-1 suggests that decay of elevated mid-Cretaceous geothermal gradient to present values was near completion by ~80 Ma.
Hydrocarbon generation from potential early Cretaceous source rocks was complete and beyond dry gas by the time cooling commenced at ~95 Ma in Olangolah-1, and in the basal Otway Group in Anglesea-1, Fergusons Hill-1 and possibly Nerita-1. The interplay between declining geothermal gradient an late Cretaceous-Tertiary burial results in two periods of hydrocarbon generation from potential Early Cretaceous source rocks; the first from deeper Otway Group and terminated in the mid Cretaceous and the second from shallower Otway Group and terminated in the late Miocene-Pliocene. The latter period is the likely source of hydrocarbons in the Port Campbell embayment and at Lindon-1.

Thermal history reconstruction in the Otway Ranges

Time of cooling from maximum paleotemperatures

Perhaps perversely in the light of the birth of AFTA in the Otway Basin, AFTA data obtained from numerous Otway Group <u>outcrop</u> samples contribute little to the assessment of maximum paleotemperature in the Otway Ranges. This is due to a combination of factors relating to the contemporaneous volcanogenic source of the majority of the Otway group detritus (Gleadow and Duddy, 1981; Duddy, 1983), the huge thickness accumulated over a relatively short period of time (>100 m/Ma) and the structural history of the ranges themselves.

On the other hand, the time of cooling determined from the AFTA results provides the key knowledge on the time of major structuring in the Otway Basin, unlocking the understanding of basin development across Southern Victoria from the early Cretaceous to the present day.

Thus, the AFTA data show that almost without exception, the maximum paleotemperatures and therefore the source rock maturity in the Otway Ranges were reached immediately prior to the massive, rapid Mid-Cretaceous cooling episode, put at ~95±5 Ma in Olangolah-1 (Duddy and Gleadow, 1982; other evidence for this timing in the broader Bass Strait region is summarised in Duddy and Green, 1992). Olangolah-1 is located on the structural ridge

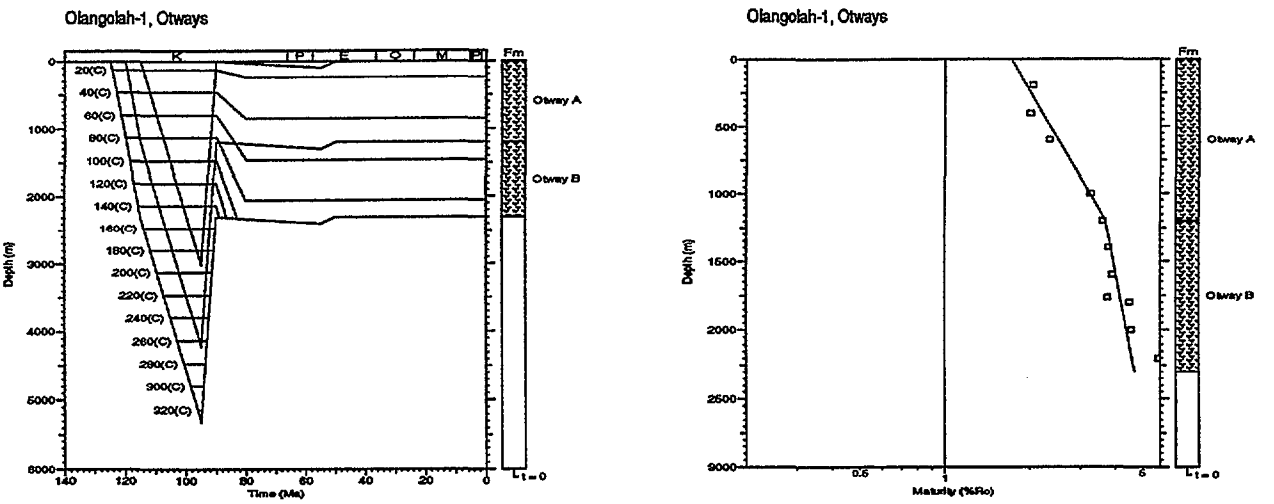

Figure 2: Reconstructed burial history based on data in Table 1 for Olangolah-1 with isotherms superimposed (left diagram) and match of predicted VR profile to measured VR data for this history (right diagram).

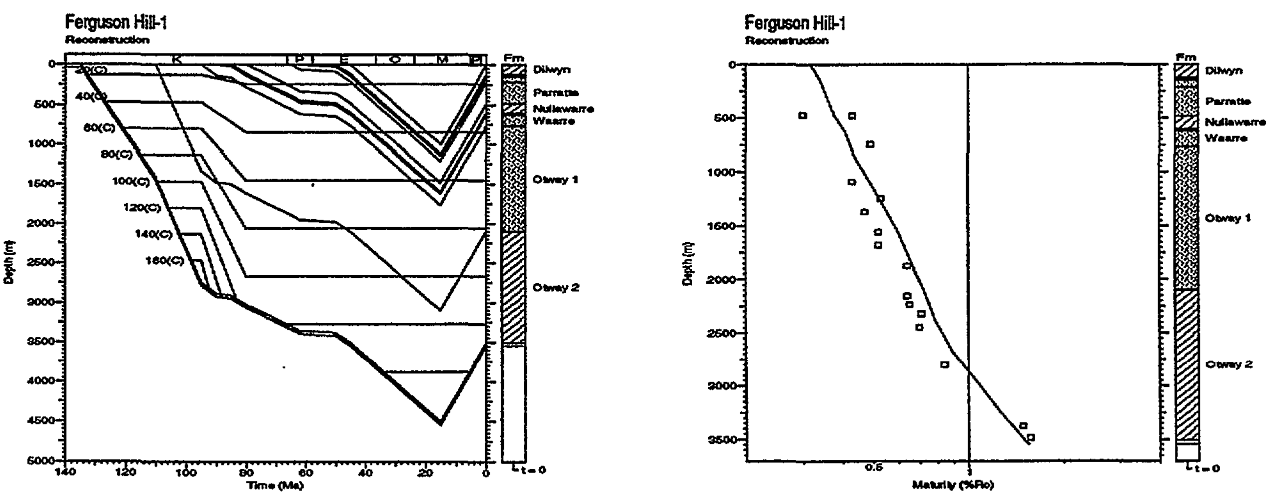

Figure 3: Reconstructed burial history based on data in Table 1 for Fergusons Hill-1 with isotherms superimposed (left diagram) and match of predicted VR profile to measured VR data for this history (right diagram).

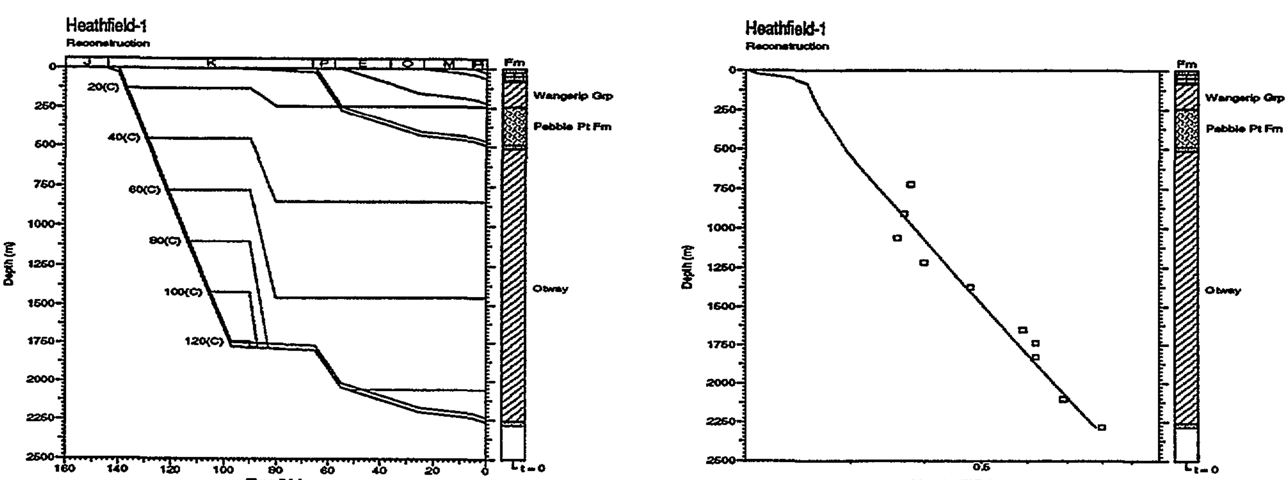

Figure 4: Reconstructed burial history based on data in Table 1 for Heathfield-1 with isotherms superimposed (left diagram) and match of predicted VR profile to measured VR data for this history (right diagram).

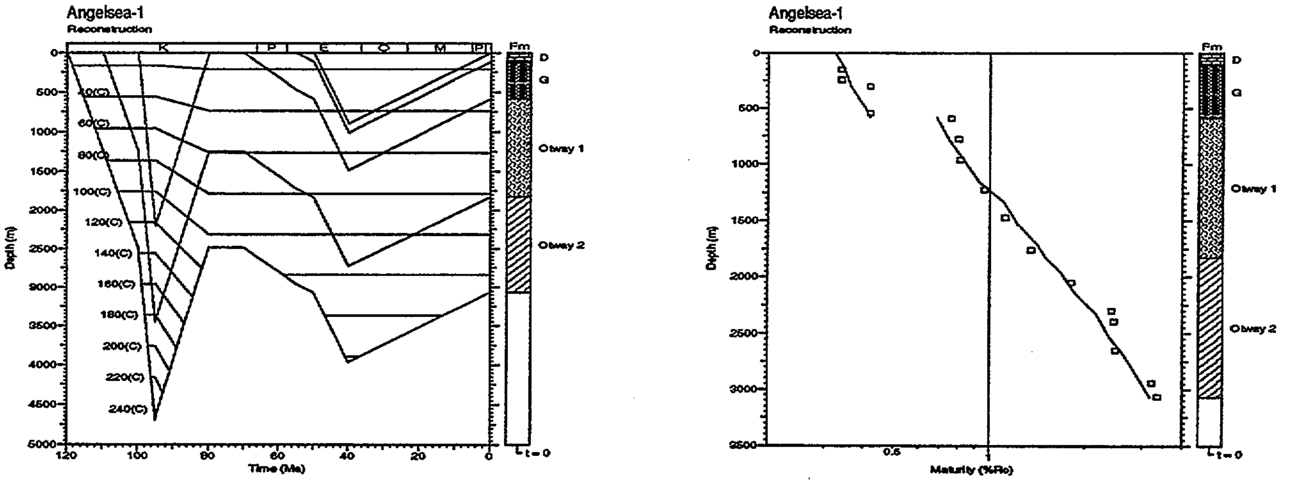

Figure 5: Probable burial history based on data in Table 1 for Anglesea-1 with isotherms superimposed (left diagram) and match of predicted VR profile to measured VR data for this history (right diagram).

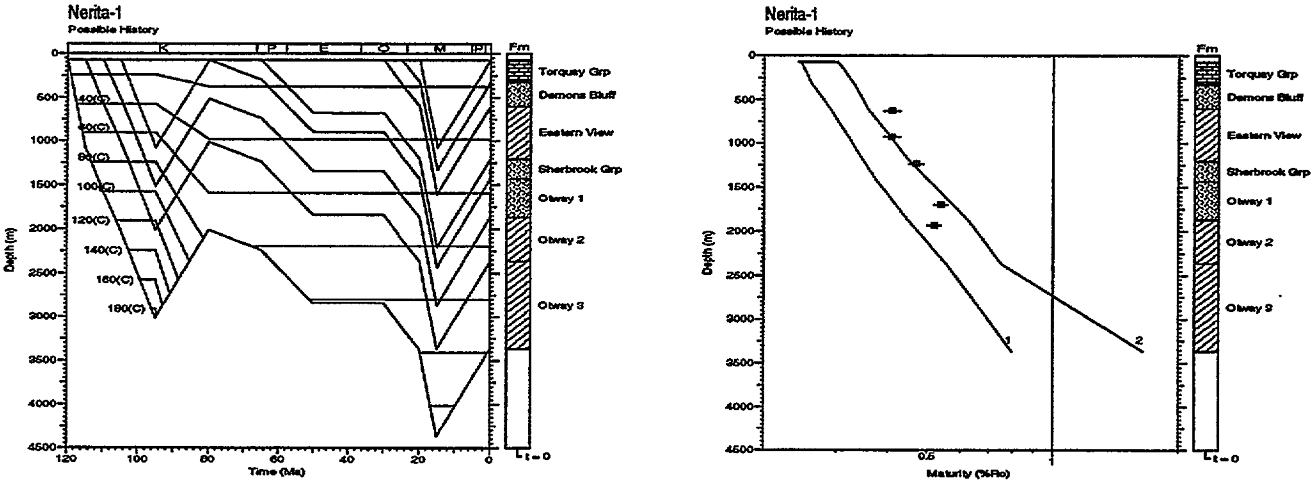

Figure 6: Possible burial history based on data in Table 1 for Nerita-1 with isotherms superimposed (left diagram) and match of predicted VR profile to measured VR data for this history (right diagram).

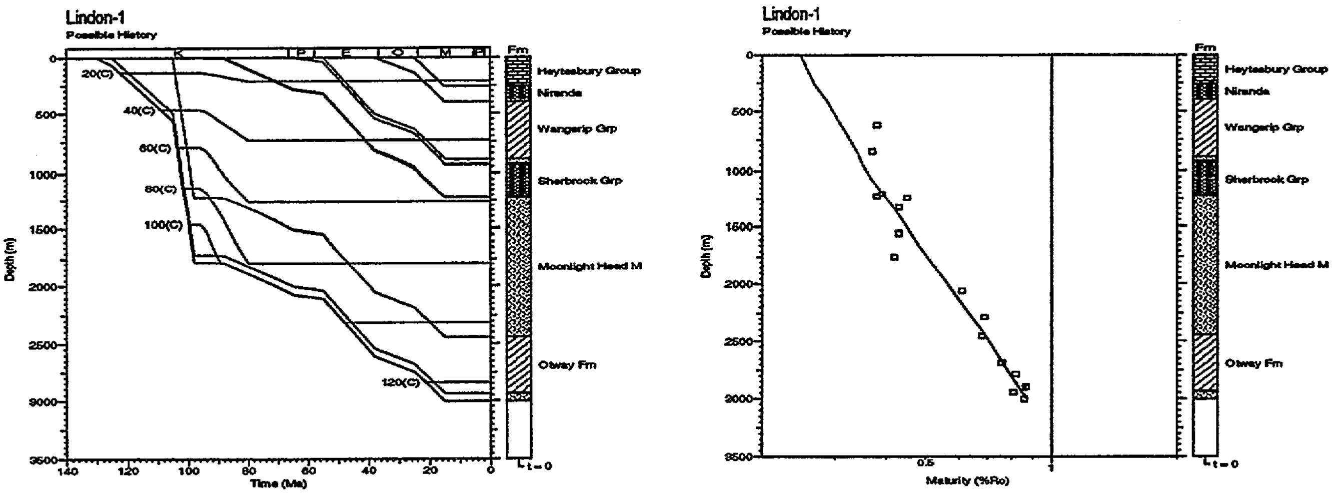

Figure 7: Probable burial history based on data in Table 1 for Lindon-1 with isotherms superimposed (left diagram) and match of predicted VR profile to measured VR data for this history (right diagram).

immediately to the west of, or perhaps within, the Wild Dog shear Zone. Similar timing, is clearly revealed by samples from the Skenes Creek Monocline and the Cape Otway-Pt. Flinders region, and in fact in all outcrops where the VR levels exceed ~1.0% (paleotemperatures >~155°C).

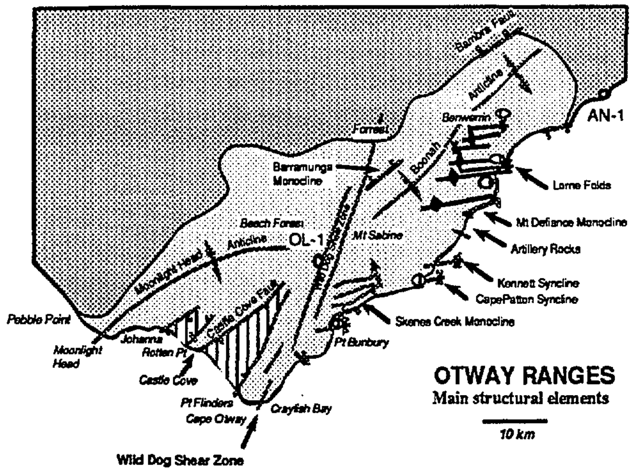

Figure 8: Main structural elements in the Otway Ranges (after Duddy, 1983). OL-1 = Olangolah-1; AN-1 = Anglesea-1; vertical hatching main Tertiary outcrops.

Maximum paleotemperatures

The relationship between the major folds and monoclines is essential knowledge in interpreting this paleotemperature pattern. The basic pattern is of a bipartite uplift composed of two main anticlines (the Moonlight Head and Boonah anticlines), flanked by steep-dipping monoclines and, separated from each others by a broad roughly linear zone of faulting and shearing between Cape Otway and Forrest that cuts across the folding at a high angle, the Wild Dog shear zone (of Duddy, 1983). Numerous smaller folds have been mapped in the the Lorne area (Edwards, 1962), and the outcrops are cut by numerous faults of uncertain magnitude (Figure 8, after Duddy, 1983). In broad terms, the present day topographic expression of the ranges reflects this underlying structure, as a response to post-middle Miocene rejuvenation (Singleton, 1968).

The distribution of maximum paleotemperatures in relation to the major structures of the Otway Ranges based on interpretation of VR data is shown in Figure 9. The region west of the Wild Dog shear zone is relatively less eroded than that to the east, with the Late Albian Zone D megaflora (Douglas, 1969), the P. pannosus microfloral zone (Burger, pers comm, 1991), and the heulandite-andesine diagenetic zone, preserved in outcrop on the flanks of the Moonlight Head Anticline and in the core of the Johanna Syncline (Duddy, 1983).

Maximum paleotemperatures vary from ~60°C to over 350°C, from which can be inferred the existence of major structural boundaries. The highest values indicate greenschist facies conditions.

The largest paleotemperature break occurs at Cape Otway, where the Wild Dog Shear zone separates maximum paleotemperatures of >350°C at Cape Otway from values of ~120°C at Crayfish Bay. North along the same structure, a break of ~60°C (170 to 102°C) is observed in shallowly dipping sandstones between road cuts on the Great Ocean Road. Indeed, the section between Olangolah through Cape Horn to Cape Otway-Pt Flinders records uniformly high mid-Cretaceous paleotemperatures (generally 170 to over 200°C). These values are higher than those recorded along the axis of the south plunging Moonlight Head anticline only a little to the west at Beech Forest. The Moonlight Head Anticline is not traceable between Beech Forest and the extension of the Wild Dog Shear Zone, the area being comprised on highly weathered shallow dipping sandstones.

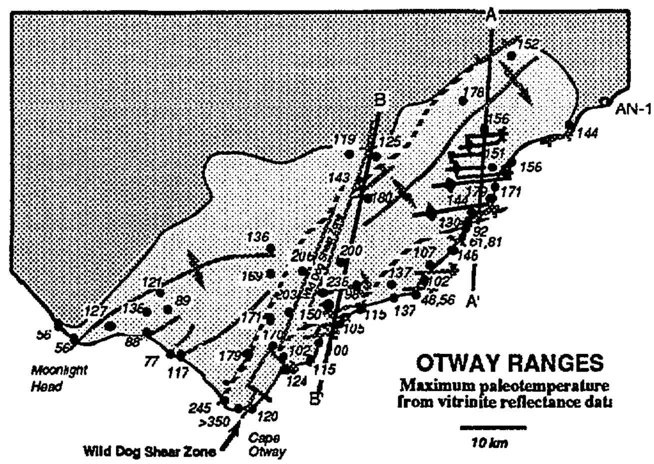

Figure 9 : Distribution of maximum paleotemperatures in the Otway Ranges in relation to major structures. The dashed lines delineate the core of the main uplift, with partly thrust boundaries.

Similar although lower magnitude breaks are observed between the steep dipping (overturned) and the shallow dipping section at southern end of the Skenes Creek Monocline, in the area from flat dips to steep dips in the shore platform at the mouth of the Wild Dog Creek, and in the change from steep dips to shallow dips in the section between the Mt Defiance Monocline (130 to 144°C) and Artillery Rocks (~61 to 92°C).

The highest paleotemperature recorded east of the Wild Dog shear zone is in the flat dipping section on the Wild Dog Road on the axis of the anticline at the northern end of the Skenes Creek monocline. Further north, paleotemperatures of around 200°C are recorded near the present topographic high at Mt Sabine, 180°C within the Barramunga Monocline and declining to ~120°C near the unconformity with the Tertiary deposits at Forrest. Paleotemperatures in the tightly folded sandstone section between Lorne and Benwerrin (Edwards, 1962) are uniformly high, 151 to 166°C, with 178°C recorded near the axis of the Boonah anticline, and 171 to 179°C along the coast between Mt St George and Cumberland River.

The lowest paleotemperature values east of the Wild Dog shear zone occur in the southern limbs of the synclinal "drag" structures along the coastal outcrops from Artillery Rocks, (61 and 81°C), Cape Patton (48 and 56°C) and Apollo Bay (71 to 115°C at Marengo and Point Bunbury). Eocene marine units are recorded in the Apollo Bay and Cape Patton Synclines (data discussed in Carter, 1958; Medwell, 1971) while the base of the Tertiary section occurs not far offshore from Artillery Rocks (open file "Shell" seismic). Interpretation of AFTA data from samples in the Skenes Creek monocline that have cooled from maximum temperatures in the mid Cretaceous also shows a significant component of cooling that may have commenced as early as the Eocene. These data suggest the southern flank of the Otway Ranges, at least, has undergone post-Eocene uplift and erosion.

To the west of the Wild Dog shear zone, the paleotemperature pattern generally conforms to the diagenetic mineralogy and paleontology, with high values along the main Moonlight Head Anticline axis and lower values on the limbs of the Johanna Syncline. Complexity is present however around the poorly exposed Wangerrip and other monoclines, where cooling appears to be enhanced. The section across the Aire River Tertiary basin demonstrates the magnitude of differential denudation. At the Castle Cove Fault-Monocline, steep dipping Otway Group cooled from ~117°C in the mid Cretaceous, while Eocene clays cooled from ~70°C, in either the late Eocene-Oligocene or post-middle Miocene structuring episodes. On the south east side of the basin at Point Flinders, Otway Group that cooled from ~245°C is unconformably overlain by Eocene sediments that have essentially suffered no burial heating (VR~0.28%). The Tertiary sediments along the coast here are clearly folded (e.g. Carter, 1958) and appear to have been significantly uplifted and eroded by reverse movement on the Castle Cove structure, while showing little or no post-Eocene uplift at Pt Flinders.

The exception to the mid-Cretaceous timing of maximum paleotemperatures occurs in the Moonlight Head coastal region. Identical VR levels of 0.32% in the Otway Group and the overlying Dilwyn clay show that cooling from maximum paleotemperatures occurred post-early Eocene. Furthermore, the occurrence of P.pannosus in this section indicates that little, if any, Otway Group was eroded in the mid Cretaceous structuring event. Thus, this part of the Otway Ranges was effectively within the Port Campbell embayment until structural inversion that may have occurred in either the late Eocene-early Oligocene or post-middle Miocene structural events. It seems likely that much of the western flank of the Otway Ranges where the uppermost zeolite zone (Duddy, 1983) and late Albian sediments outcrop also cooled from maximum paleotemperatures in such a post-early Eocene event.

These data allow construction of a thermal histories for key Otway Ranges outcrops as shown in Figure 10.

Regional Synthesis

Thermal history: Thermal history reconstruction in the Otway Basin are consistent with the concept of three periods of structuring: Mid-Cretaceous, Late Eocene-Oligocene and post-middle Miocene (Singleton, 1968). The importance of this mid-Cretaceous event in Gippsland Basin development and its association with initial separation of Australia and Antarctica has been discussed elsewhere (Duddy and Green, 1992), and it obtains similar importance in the Otway Basin. High geothermal gradients (~50 to 65°C/km) extant at this time contributed to extensive early hydrocarbon generation over much of the basin, although the pervasive permeability destruction during diagenesis of the volcanogenic components dominating the bulk of Otway Group Sandstones (Duddy, 1983).

Tertiary cooling is generally minor compared with that in the mid-Cretaceous, but is clearly important in the Port Campbell and Torquay Basins flanking the Otway Ranges. Tertiary cooling in the Otway Ranges themselves is difficult to resolve, but is clear at Moonlight Head from VR results on Tertiary sediments and from AFTA in the steep dipping Otway Group of the Skenes Creek Monocline. Cooling results from significant erosion (under normal geothermal gradient conditions associated with folding in the Late Cretaceous-Tertiary cover, probably as a response to reverse movement on early Cretaceous extensional faults in the underlying Otway Group.

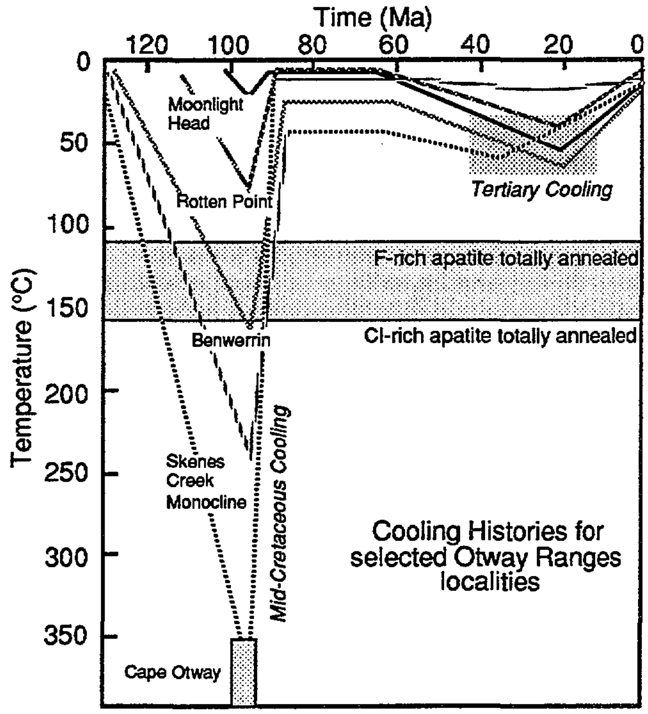

Figure 10 : Thermal histories derived from integration of AFTA and VR data from some key Otway Ranges outcrops.

From the results presented above, the interpretations of Cooper et al. (1993) regarding the thermal and structural history of the eastern Otway Basin cannot be supported. The approach used by these authors is flawed on several grounds. Firstly, two mutually exclusive methodologies for interpretation of vitrinite reflectance data were used. The Karweil method was used to calculate "paleotemperature and uplift" from the VR data, while the "thermal" history was "determined' from the same VR data using the Burnham and Sweeney (1989) algorithm. Both methods implicitly interpret VR data in terms of paleotemperature but are based on different "kinetics" and therefore cannot be combined. Further, the calculation of eroded section fails to take into account the time of cooling and subsequent reburial. Even if correct, their estimate of ~160 m of eroded section in Anglesea-1, for instance, must be adjusted by the amount of reburial that has occurred since cooling. It is little wonder that even modifying heat flow through a range of values from 10 to 150 mW/m^{-2} failed to achieve a good fit to the VR data (cf Fig 6 of Cooper et al. 1993). In addition the Otway Ranges thermal history interpreted from their fission track data is incompatible with paleotemperatures from the VR data, primarily due to inadequacies in the model used for interpreting the fission track results.

Otway Ranges structure: The basic structure of the eastern Otway Ranges can be interpreted as a broad anticline, bounded by reactivated steeply dipping zones giving the appearance of a box-like uplift. Direct evidence of overturning is seen at two locations, and combined with the break in paleotemperatures, a thrust can be interpreted as through the synclinal limb at Skenes Creek. The time of this thrusting is not currently constrained, and may involve components of movement in all three structural episodes, but probably dominant in the mid-Cretaceous. What seems clear is that shortening by mid-Cretaceous folding and associated erosion was of greatest magnitude between Skenes Creek and Barramunga Monoclines, compared with the region between the Mt Defiance and Bambra structures (Figure 11). This is may be a result of the lower strength of the flood plain dominated units exposed in the former structures, compared with the thick sandstones in the latter. At the western end of this uplift, shortening transferred to strike slip movement along the Wild Dog shear zone, with massive uplift and erosion to the west (Olangolah-Cape Otway), and relatively less to the east, forming a scissor-like structure.

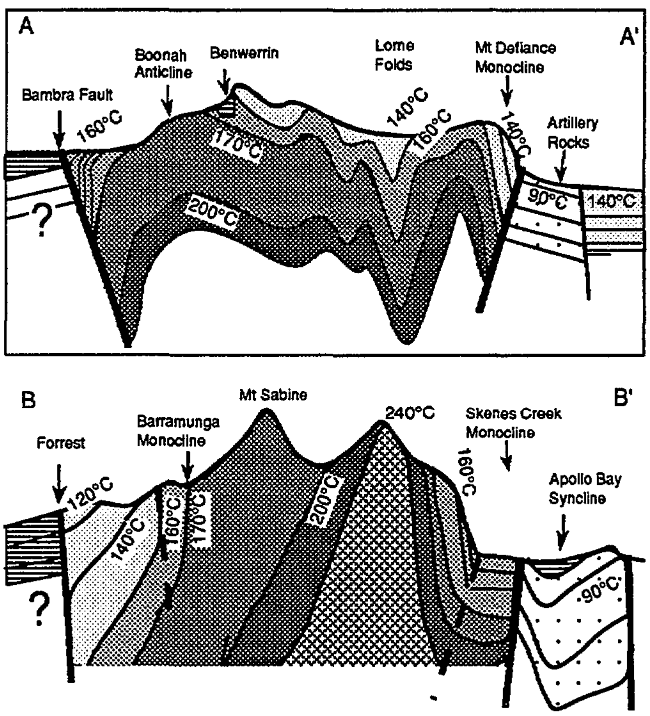

Figure 11 : Schematic Otway ranges cross-sections showing thermal structure interpreted from VR data. Dip of faults interpreted based on thermal offsets and surface structure.

Regional tectonics: The distribution of mid-Cretaceous basin inversions and basement block uplifts in the Bass Strait region was a major control on Late Cretaceous to Tertiary Basin configuration, with the creation of physical barriers between the northern basin margin (the Otway Ranges) and King Island preventing access of fully marine conditions into the Torquay and Bass Basins until the late Eocene-Oligocene. A similar mid-Cretaceous uplift between the Mornington Peninsula and King Island along the line of Selwyns Fault probably also divided the Torquay from the Bass Basin.

These uplifts are not distributed randomly, but appear to be readily accommodated within the extensional basin forming structure concept of Etheridge and co-workers (e.g. Etheridge et al., 1985; 1987). Thus, segmentation of the early Cretaceous graben implied by the presence of transfer faults (or accommodation zones) approximately orthogonol to rotational normal faults, is revealed by the location of the subsequent uplifts, resulting from compressional stresses across the graben in the mid-Cretaceous (Etheridge et al., 1985 considered that compression commenced in the Tertiary and that the Mornington Peninsula-King Island high is a Tertiary structure, but the AFTA data clearly show the initial and major development phase was mid-Cretaceous).

Figure 11 shows the fault pattern of Etheridge et al (1987) developed largely from offshore seismic data, superimposed on the uplift pattern mid-Cretaceous uplift pattern discussed here. In particular, the Port Campbell embayment can be understood as a basement block depressed against the surrounding uplifts during mid-Cretaceous compression, presumably as a response to the attitude of the main bounding transfer faults (as illustrated in Fig. 14 of Etheridge et al , 1985). The Wild Dog shear zone can be understood as a transfer fault zone, which acted as a similar loci for differential uplift in the Otway Ranges. The boundary between the uplifted Lismore basement and the remarkably stable basement to the west and extending at least to the Merino High, is explained as the point where the "Warrnambool Transfer" (identified by Etheridge et al, 1985 as an obvious large structure) impinges on the northern basin margin. This structure may have also focussed a large alluvial system responsible for deposition of the basement derived Pretty Hill and Waarre Sandstones in this area.

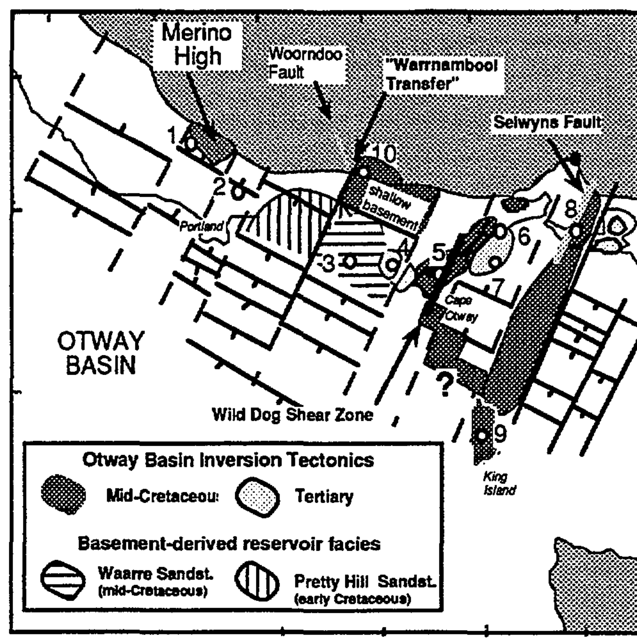

Figure 11 : Distribution of quantified Mid-Cretaceous and Tertiary inversions in relation to the extensional fault geometry of Etheridge et al (1985) and the distribution of key Otway Basin reservoir targets. The data do not support the major role of the Woorndoo Fault in Otway Basin evolution as surmised by Foster and Gleadow (1992). Rather the mid-Cretaceous uplift and erosion of the Lismore basement block is best understood in terms of differential reactivation across a major transfer zone separating upper and lower plate rift segments.

The data are not consistent with the proposal of Foster and Gleadow (1992) that the fission track results in basement of the northern margin in this area can be explained by reactivation of an older Paleozoic structure, the Woorndoo Fault. Unpublished AFTA from granitic basement in the Eilyar-3 well to the east of the Woorndoo Fault show that it is a part of the stable western block, indicating that the fault does not have the controlling effect envisaged by these authors. The significance of the volcanic signatures and the Paleozoic terrain boundaries used in support of the break in fission track ages is therefore somewhat diminished. There is also a lack of any discernible effect on the patterns of either Early or Late Cretaceous sedimentation that might be expected if such a fundamental structure crossed the basin on such a trend. On the contrary, the distribution of the Albian-Cenomanian Waarre Sandstone (Figure 11) is clearly controlled by a basin formed by reactivation of the early Cretaceous extensional fault system. Similar arguments apply to the margin of the west coast of Tasmania, which may also be more reasonably related to an early Cretaceous fault system than to direct reactivation of Paleozoic structures.

HC generation and preservation: Reservoiring significant hydrocarbons from potential Otway Group source rocks would seem to depend upon preservation of low maturities beyond the mid-Cretaceous, with generation delayed until the mid- to late Tertiary. In areas of thick Upper Cretaceous deposition generation from this upper Otway Group is probably too early, prior to formation of the more favourable Tertiary structures. Thus, a reasonable model is to focus on those areas surrounding the late Tertiary depocentres that do not correspond to underlying mid-Cretaceous uplifts nor thick late Cretaceous. The producing hydrocarbon provenance in the Port Campbell embayment conforms to this model. The potential for significant hydrocarbons from deeper Jurassic source rocks would appear limited to areas of thinnest Otway Group deposition, where there may be a small chance of holding these source rocks relatively cool (and immature) until generation under a thicker Tertiary cover.

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The Otway Basin: pre-drift tectonics

Kathy A. Hill[1], Douglas M. Finlayson[2], Kevin C. Hill[3], Dogan Perincek[4] and Bruce Finlayson[5]

1 - Victorian Institute of Earth and Planetary Science, School of Earth Sciences, Monash University, Clayton Vic. 3168
2 - Australian Geological Survey Organisation GPO Box 378 Canberra, ACT Australia 2601
3 - Victorian Institute of Earth and Planetary Science, School of Earth Sciences, La Trobe University, Bundoora Vic. 3083
4 - Geological Survey of Victoria, Department of Energy and Minerals, PO Box 98, East Melbourne Vic. 3002.
5 - Department of Mines and Energy, PO Box 151, Eastwood, S. A. 5063.

Introduction

The aim of this paper is to discuss the Tectonics of the Otway Basin, concentrating on the Late Jurassic and Early Cretaceous rift phase, on which the Otway National Geoscience Mapping Accord was focussed. The regional structural, stratigraphic and thermochronological syntheses are presented elsewhere in this volume so this paper emphasises tectonic models for the early rifting, including analogies to other 'simple' rift systems and to experimental models. Some analogues are presented first and the determination of extension direction is considered in some detail as this is one of the most contentious issues for the early rift history of the Otway Basin.

The Otway Basin is part of the southern margin rift system which led to the separation of Australia from Antarctica. This area has had a long history of continental extension from the Late Jurassic until the present day, with local rejuvenation of basement-involved faulting. The main period of significant extension onshore was in the pre-Aptian, as demonstrated from reflection seismic data (e.g. Davidson & Morrison 1986; Kopsen & Scholefield 1990; Hill & Durrand 1993; Perincek et al. 1994). In the Eastern Otway Basin, in the Port Campbell--Torquay Embayments area, extension persisted into the Aptian. This early stage of extension is emphasised here. Subsequent inversion, basement rejuvenation and strike slip faulting are discussed elsewhere in this volume and by Hill, K. C. et al. (submitted), Finlayson et al. (1994), Perincek et al. (1994) and Hill, K. A. et al. (submitted).

Direction of extension

The East African Rift analogue

One of the most studied early stage current rift systems is the East African Rift (EAR). There, a wide scatter of fault orientations can be seen on the PROBE reflection seismic data (e.g. Versfelt and Rosendahl 1989) and is inferred to be controlled in part by pre-existing basement structural fabric.

In the EAR, earthquake data suggest that most *present day* extension is taking place in a NW-SE direction, with faults striking in that direction accommodating differential extension. Detailed cross-cutting relationships have not been recognised, thus it cannot be assumed that these faults are concurrent. Differential timing and a change in stress orientations have been presented for the EAR as an alternative to a linked extension accommodation fault system (Pollitz 1991).

Although the EAR is a highly analysed, well exposed, young rift basin system, there is considerable disagreement as to the orientation of stresses, the mechanisms of accommodation of differential extension and changes in master fault polarity. For example, Morley (1988), favours E-W extension, perpendicular to the overall trend of the basins whereas Versfelt and Rosendahl (1989) and Scott et al. (1992) infer NW-SE extension, oblique to the overall N-S trend of the basins. Scott et al. (1992) in their study of the Lake Tanganyika and Malawi Rifts proposed that extension took place at an oblique angle to the major bounding faults. Seismic profiles that were at a low angle or sub-parallel to the inferred direction of extension were unrestorable and displayed steep faults and a wide scatter of fault orientations.

Determining Extension Orientation

Estimating a single extension direction in a previously undeformed medium can be accomplished from the heaves of major faults using geometrical methods (e.g. Williams & Vann 1987). However unless the cross-section (or seismic section) is within 15° of the extension direction, heave will be overestimated as the fault separation will be measured along an apparent dip of the fault plane. One problem with imaging faults is spatial aliasing of faults on sparse data sets. If line spacing is not less than that of fault spacing, erroneous fault orientations can result (e.g. Walsh et al. 1993). Providing that spatial aliasing of faults is not a problem and the faults with larger throw are used, the extension direction can be estimated from the orientation of the faults in map view as being roughly perpendicular to the strike of the major faults. The *amount* of extension however will be underestimated from fault heaves by 40% or more due to much of the extension being taken up at below the scale of observation (Walsh 1991).

Physical models suggest that in a *homogeneous medium* fault orientations in oblique or pure extension cluster perpendicular to the extension direction (Tron & Brun 1991). However, as the continental lithosphere is

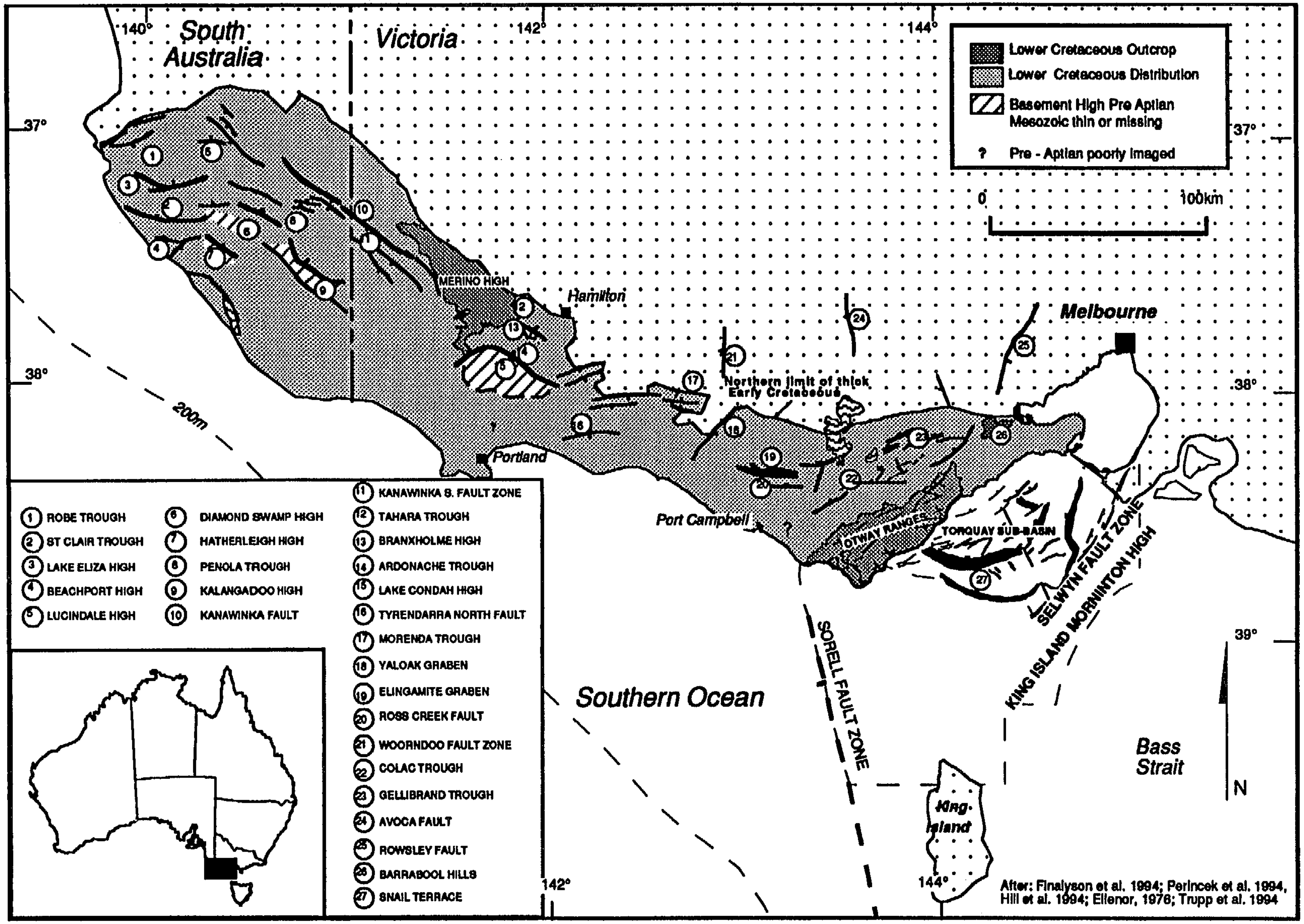

Figure 1 - Early Cretaceous synrift faults in the Otway Basin. Three trends can be discerned: 1) E-W (e.g. Robe Trough [1], Morenda Trough [17], Elingamite Graben [19]); 2) NW-SE (e.g. Penola Trough, Ardonachie Trough); 3) NE-SW (e.g. Colac Trough [22], Yaloak Graben [18]).

structurally heterogeneous and relatively weak in extension, the basement fabric can play a very important role in focussing extension. For instance basins of the EAR develop in the weak mobile belts between stable Precambrian cratonic blocks (Versfelt & Rosendahl, 1989) and such a mechanism has been applied to the northwest shelf of Australia (Hill, G. 1994). The relative weakness of each discontinuity and their angle with the direction of extension will influence how the basement responds to extension.

If the basement fabric is strongly influencing the orientation of the faults, which may be more the rule rather than the exception (Scott et al. 1992), estimating the original direction of extension using the orientation of the fault strikes at the maximum heave may give an inaccurate answer. Scott et al. (1992) have proposed plotting apparent basement (pre rift surface) dips from profile data at line intersections on rose diagrams and estimating the direction of extension from the resultants, thus removing the interpretive prejudice of fault trending and contouring.

Extension Directions in the Otway Basin

In the Otway Basin we are presented with an overprinted ancient rift system, in an area with a highly heterogeneous pre-rift basement and with generally quite sparse seismic coverage of variable vintage and quality. Given the problems determining the extension direction in a 'simple' rift, it is no wonder that there is a lack of agreement as to the orientation of extension in the Otway Basin. It is not surprising that the initial extension direction has been inferred to be N-S (e.g. Mehin & Link 1994), NE-SW (Etheridge et al. 1985, 1987; Perincek et al. 1994) or NW-SE (Willcox & Stagg 1990; O'Brien et al. 1994). Willcox et al. (1992) have inferred that the Torquay Embayment and Eyre Basin half graben may have initiated in the Late Jurassic and that they were linked by a NW-SE accommodation zone, with the major sub-basins of the Otway Basin opening up as "transtensional" or oblique slip basins. O'Brien et al. (1994) developed this model further proposing that the Ardonachie and Penola Troughs developed as part of a transtensional, sinistral strike slip system, similar to the style observed by Gibbs (1987) for the Moray Firth Basin and later applied to the Gippsland Basin by Willcox et al. (1992).

Fault Orientations in the Otway Basin

Early Cretaceous faults cluster into two general strike orientations (Fig. 1): E-W as in the Robe and Morenda Troughs and NW-SE in the Penola and Ardonachie Troughs (Williamson et al. 1990; Perincek et al. 1994). Recent mapping commissioned by Mines and Energy of South Australia of the onshore South Australian Otway Basin (Perincek et al. this volume, Finlayson et al. 1994) suggests that the Robe Trough trends approximately 80°E, more E-W than previously inferred from regional gravity data and portrayed on generalised tectonic maps (e.g. Sprigg 1986). A third orientation is seen to the east in the Torquay Sub-basin and Colac Trough where some of the faults strike NE-SW to NNE-SSW. The Yaloak Fault mapped by D. Finlayson on the eastern flank of the Waarnambool Gravity High also strikes NE-SW, as do some of the faults with pre-Aptian movement in Perincek et al. (1994).

Cross-cutting relationships are notably absent or unclear on the current data onshore so dating the timing of the faults relative to one another has not yet been possible. If the faulting is concurrent it implies that movement along at least one of the fault sets was oblique. If we assume a consistent stress field and that the E-W and NW-SE striking faults are concurrent we are probably dealing with a N-S to NE-SW overall direction of extension. The timing of the faulting in the Colac Trough and Torquay Basin is poorly controlled; however the NE-SW trends show significant Aptian and later movement and would appear to postdate the E-W to NW-SE trending faults (Trupp et al. 1994; Cooper pers. comm.).

N-S to NE-SW extension

Several observations favour a N-S to NE-SW direction of early extension over the NW-SE direction proposed by Willcox et al. (1992) and O'Brien et al. (1994). First a relatively consistent variation in throw is observed along the major faults of the Penola and Ardonachie Troughs. The faults do not change in their sense of throw, or show high frequency variation in the amount of throw. Second, the basin-bounding faults on the troughs generally do not exceed 60° dip generally observed at high angles of obliquity in the Tron and Brun (1991) models. There are exceptions (for example on the southern margin of the Hatherleigh High (Fig. 6 in Hill and Durrand 1993), but most of these features are antithetic to the overall basin bounding faults. Third, the predominance of the NW-SE striking faults as well as their consistency in dip supports an extension direction in the N-to-E quadrant, in accord with Tron and Brun (1991) physical models. However, the orientation of the bulk of the seismic data is NNE-SSW, so the fault orientations may be biased. Finally the seismic line of the Robe Trough shown in O'Brien et al. (1994; their figure 13) displays faults that dip at least 55°. An alternative interpretation by Williamson et al. (1990) of the same line shows steeper faulting. Thus it would appear that the faults on the Robe Trough are generally steeper than those in the Penola Trough, for example. The steeper faulting would imply that ENE striking Robe Trough faults may be more oblique to the direction of extension.

If the widths of the graben are examined, the basins controlled by NE trending faults such as the Yaloak fault (see Perincek et al. this volume) tend to be narrower implying an oblique slip component of extension whilst those associated with NW-SE striking faults tend to be broader in extent.

Regional Considerations

Gondwana is inferred to have had a major subduction zone present through much of the Mesozoic as shown in the pre-rift restoration (Fig. 2; modified from Veevers et al. 1991 and Elliot 1991). Eumeralla volcaniclastics are andesitic (Gleadow & Duddy 1981), probably associated with arc volcanism (Veevers et al. 1982) rather than rifts.

Limited dating of volcanic material in the Otway Ranges at ~115 Ma suggests that deposition took place very soon after crystallisation (Gleadow & Duddy, 1981) and recent paleocurrent work by Constantine (1992) suggests an eastern provenance. The volcanic arc responsible for the influx of Eumeralla sediments has not been identified and is probably at depth offshore southeast of the Lord Howe Rise, or as part of the Rise itself.

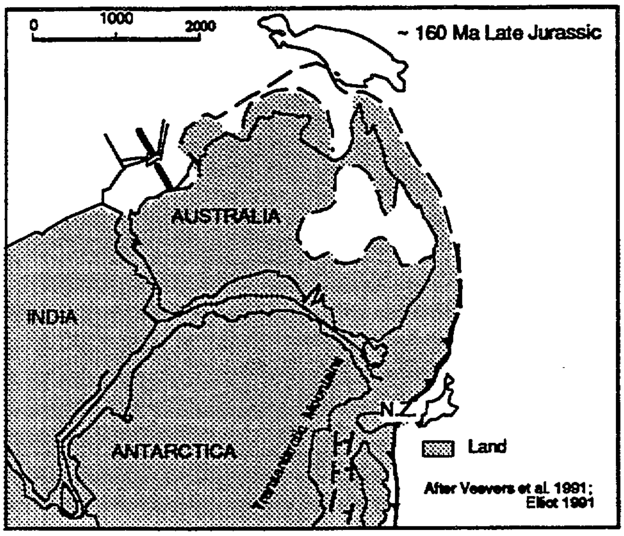

Figure 2 - The pre-rift setting of the Otway Basin as part of Gondwana. Whilst initial sea floor spreading was beginning in the Argo Abyssal plain northwest of Australia, a subduction system was active to the south and east of Australia. Subduction and the influx of arc volcaniclastics may have persisted until the end of the Albian.

This relatively sudden and voluminous influx of sediment blanketing much of the southern margin of Australia and extending into Antarctica and New Zealand must signify a major change in the balance of stresses in the late Aptian. Figure 2 illustrates that subduction occurred along the eastern margin of Australia at least as late as 165 Ma. Renewed or accelerated subduction along this volcanic arc flooded the subsiding Otway rift valley with volcaniclastics and quickly filled the available relief as far east at least as Cape Jaffa causing accelerated subsidence due to the sediment load. Deposition remained fluvial largely as sheet flood complexes (Constantine, 1992).

The metamorphic core complex in Fjordland in New Zealand is now considered to be associated with continental extension (Hill, E., 1994) but its development post dates Eumeralla deposition by 25 my and is inferred to be associated with formation of the Tasman Sea. Given the Triassic - Early Cretaceous history of subduction east of Antarctica and Australia (Elliot 1991) coupled with the rapid transition from continental extension to sea floor spreading in the Tasman Sea over 15 my, it is possible that the early evolution of the Tasman Sea may have been as a backarc basin with the final stage of stretching in 96-84 Ma ultimately rupturing already attenuated crust. Such backarc spreading in the Tasman Sea has been suggested by Karig (1971) and Veevers et al (1991).

Timing of Breakup

Thus the Eumeralla Formation may have originated from volcanic arc material sourced from subduction to the east. This phase of subduction implies that the cessation of rapid crustal extension under the Otway Basin may be in part controlled by a change to compression on a plate scale during the Apto-Albian. The time of initial plate rupture between Australia and Antarctica has been estimated as occurring from 125 Ma (Stagg and Willcox 1992) to 50 Ma (Falvey 1974). The recent consensus in the literature has breakup of the southern margin at ca 95 Ma, based on Cande and Mutter's (1982) modelling and Veevers (1986) subsequent work. The timing is indirectly constrained by the authors' own admissions. Minor crustal extension persisted into the Tertiary as evidenced by movement along basement involved faults. By the onset of rapid oceanic spreading at 49 Ma the Otway Basin has clearly evolved into a mature passive margin.

Diachroneity in the breakup has been proposed by Mutter et al. (1985) and supported by Moore et al. (1992) with the rupture progressing eastward to the Tasman Fracture Zone, along which spreading jumped to south of Tasmania. The Torquay Sub-basin remained intracratonic and faulting in the region east of the Stoneyford High persisted into the Aptian. Minor basement-involved and detached faulting is seen within the eastern Otway Basin until the Miocene.

Conclusions

Determining the orientation for early extension in the Otway Basin is hampered by the 1) lack of resolution and well control on the dating within the late Jurassic to Early Cretaceous section, 2) lack of cross-cutting relationships between the major fault trends to discern timing, 3) insensitivity of apparent dips and section restoration to the azimuth of extension, 4) multiple phases of faulting and subsidence, 5) bias of preferred 2d seismic section orientation, 6) heterogeneity of basement and the potential for rejuvenation of pre-rift fabrics, and 7) the relative weakness of the lithosphere in extension. As there is almost a 90° spread in inferred extension directions in the young East African Rift, it is not surprising that a larger range of extension directions is recorded in the literature for the Otway Basin.

Having stated those considerable limitations some refinement of current extension orientations may be achieved by attempting an apparent dip azimuthal study of section data as presented in Scott et al. (1992) in several of the areas better covered by reflection seismic data, preferably some distance away from accommodation features. The central Penola Trough is a potential study area as is the central Mussel platform offshore where basement can be imaged. Computer restoration of sections will help with filtering out later stage faulting and subsidence. Careful mapping of fault heave, throw and dip variation will also help.

Based on geological and physical analogues, the breadth of the Penola and Ardonachie Troughs, and the relatively low dips of the bounding faults during pre-Aptian extension, it is unlikely that they formed as near pure sinistral strike slip basins. Appropriate map projections should be employed for larger scale analyses (e.g. Lambert).

Although the age of continental breakup is generally accepted to be end Albian, it too is underconstrained. The Apto-Albian Eumeralla Formation is probably the product of arc rather than rift volcanism. The rapid influx of sediment in a largely sag style basin implies a change in the relative stresses on a plate scale during its deposition.

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Burial, heat pulses, inversion and denudation in the Otway Basin

Kevin C. Hill[1], Gareth T. Cooper[2] and Melinda M. Mitchell[1]
Victorian Institute of Earth and Planetary Science, School of Earth Sciences at
1 La Trobe University, Melbourne, Vic, Australia 3083
2 Monash University, Melbourne, Vic, Australia 3168

Introduction

The aim of this part of the National Geoscience Mapping Accord study of the Otway Basin is to compare and contrast the thermochronology of the eastern and westernmost Otway Basin to aid interpretation of the structural history. The work was carried out by Mitchell and Cooper as part of their PhD studies.

The thermochronology was determined from vitrinite reflectance (VR) and apatite fission track (FT) analysis and interpreted with the aid of field mapping and interpretation of reflection seismic data. Apatite FT and VR analyses help constrain the amounts and timing of cooling and denudation and reveal regional uplift events not apparent from seismic data. The Otway Basin is particularly suited to such analysis due to 1) the large volume of recently acquired high quality reflection seismic data, particularly the NGMA AGSO deep seismic lines, 2) the prevalence of onshore Palaeozoic granites for apatites and 3) basin sediments rich in both apatite and plant fossils for FT and VR measurements.

Apatite FT thermochronology has advantages over other techniques that record peak temperature, because the time of cooling from elevated temperatures may be assessed. The combination of FT thermochronology and VR data can elucidate rather precise tectono-thermal histories in basins because they independently measure the integrated time-temperature history of rocks. The resolution of complex thermal histories using apatite FT thermochronology is discussed in greater detail by Green et al. (1989a, b) and Gleadow et al. (1986) and the integration of VR by Bray et al. (1992).

The Otway Basin was formed as part of the Mesozoic and Tertiary separation of Australia from Antarctica, the timing of which is summarised in Table 1. The northern margin of the Basin straddles a major tectonic lineament marked onshore by differential uplift of Palaeozoic basement northwest of Cape Otway (Foster & Gleadow 1993) and offshore by the Sorell Fault and Tasman Fracture Zone (see Fig. 1 in Hill KA et al. this volume). The lineament separates the western Otway Basin, which proceeded to seafloor spreading, from the failed rift in Bass Strait including the Torquay Embayment, Otway Ranges and Colac Trough of the eastern Otway Basin. West of the lineament, previous fission track data from Palaeozoic granites along the northern basin margin suggest minimal regional uplift, but to the east the granites of the basin margin record rapid cooling at ~95 Ma due to regional uplift and denudation (Dumitru et al. 1991; Foster & Gleadow 1993). This study is focussed on two areas in the Otway Basin from either side of the lineament, with contrasting thermochronologies, the Otway Ranges and the Gambier Embayment (Figs 1 & 2).

Thermochronology of the western Otway Basin.

Mitchell has determined the apatite FT dates and completed preliminary analysis of the FT and VR data for seven wells in the Gambier Embayment, the western section of the Otway Basin. The wells examined were from the various structural domains of the Gambier Embayment (Fig. 1) and the results are discussed below. The Otway Basin sediments are derived from multiple source terrains containing different detrital apatite ages and lengths at the time of deposition. Variations in apatite composition, track lengths and original age of individual apatite grains must be taken into consideration when modelling a thermal history for any sample with this complex thermal evolution. Such modelling is now under way, but the provisional results, summarised here, indicate thermal variations in the Late Cretaceous and Tertiary during the time often described as a passive thermal subsidence phase in the Otway Basin (Hegarty et al. 1988; Pettifer et al. 1991).

TABLE 1:- Summary of the main tectonic events in the Otway Basin, after Willcox et al. 1992, Veevers et al. 1991, Cande & Mutter 1982, Davidson & Morrison 1986.

AGE		TECTONIC EVENT	
NEOGENE	PLIO	EAST OTWAY INVERSION + NEWER VOLCANICS	
NEOGENE	MIO	REGIONAL SUBSIDENCE	OLDER VOLCANICS
PALEOGENE	OLIG		OLDER VOLCANICS
PALEOGENE	EOC	COMMENCE RAPID SPREADING OF SOUTHERN OCEAN	
PALEOGENE	PAL		
CRETACEOUS	U	WEST OTWAY SLOW DRIFT-SUBSIDENCE	
CRETACEOUS	97.5 Ma	INITIAL BREAKUP + EAST OTWAY INVERSION	
CRETACEOUS	L	REGIONAL SUBSIDENCE	
JURASSIC	U	RIFTING	
JURASSIC	M	TASMANIA + OTWAY? DOLERITES	
JURASSIC	L		

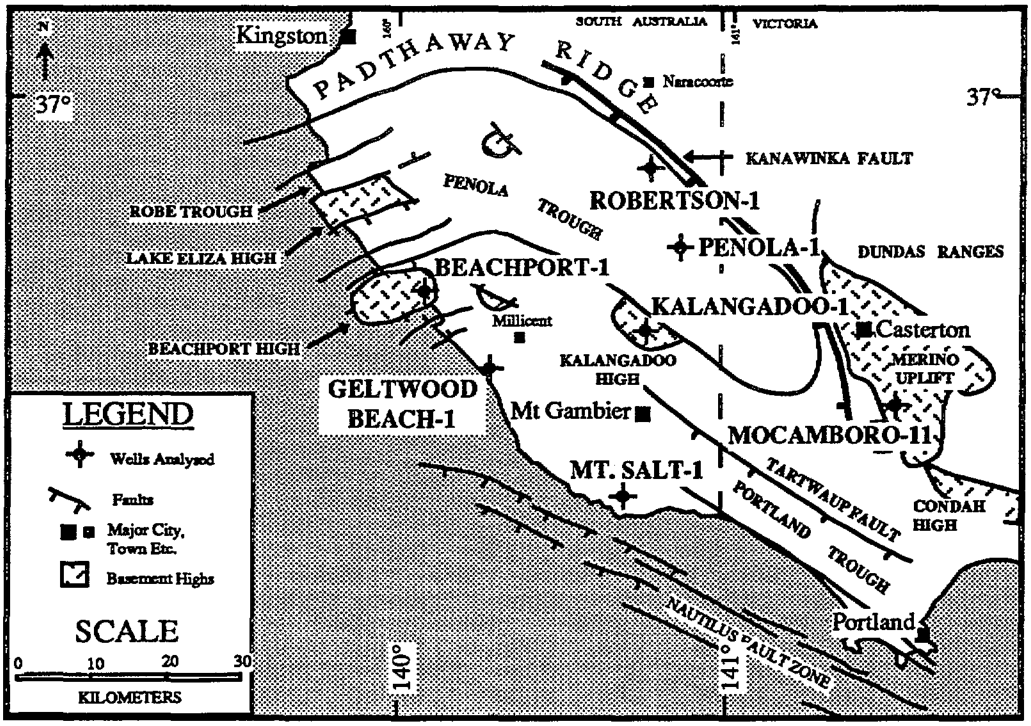

Figure 1. Location map of the Gambier Embayment section of the western Otway Basin, showing structural domains and well localities.

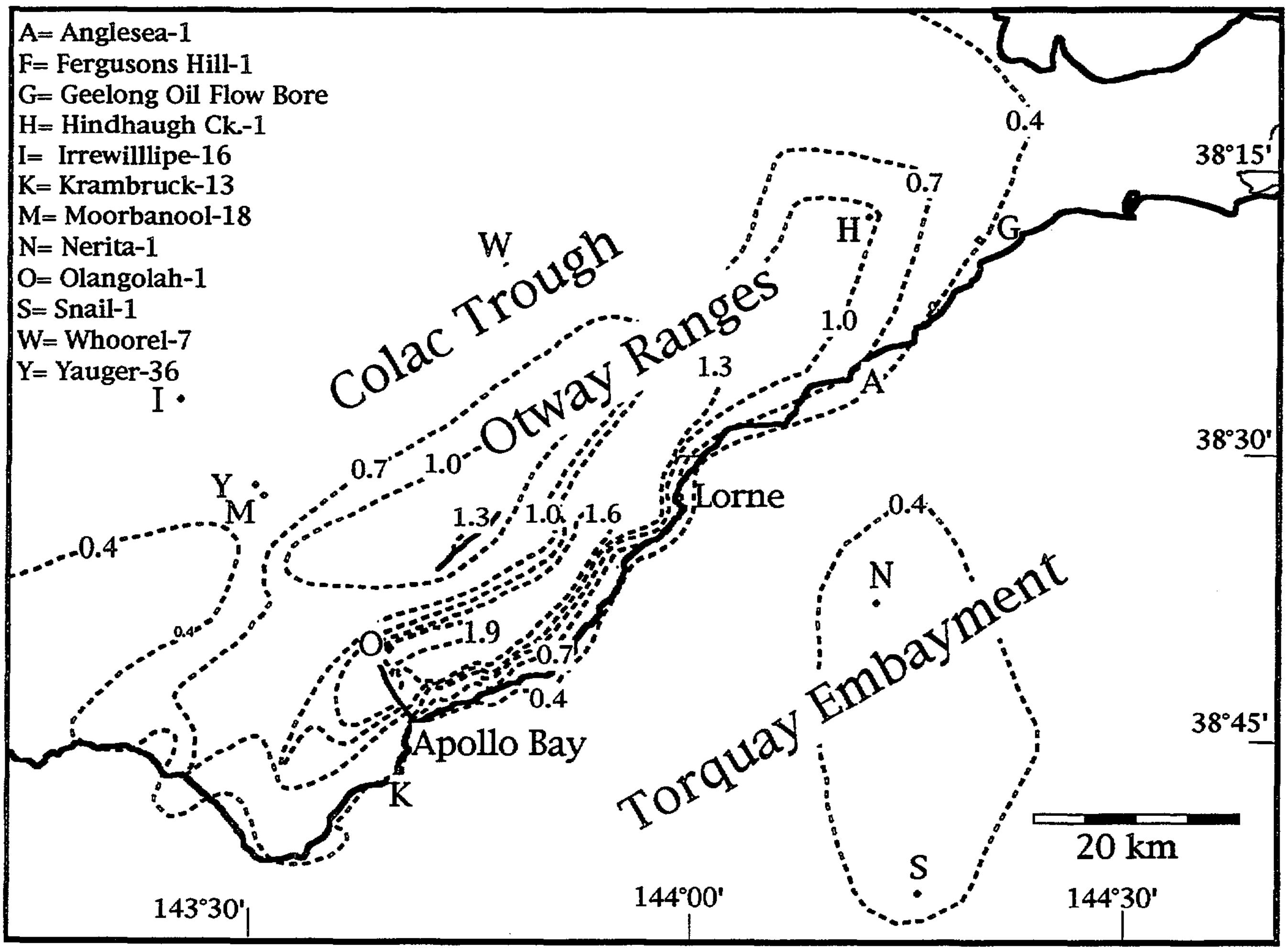

Figure 2. Isoreflectors Rv max% measured on Cretaceous surface coals and detrital organic matter. Based on 91 datapoints, 14 from Struckmeyer (1988)

Penola-1 and Robertson-1

These wells, within the Penola Trough adjacent to the northern margin of the basin (Fig. 1) record similar sediment provenance, but suggest different thermal histories despite the close proximity of the two wells.

Sediment provenance

Mesozoic(?) trachytic basement intersected at the base of Robertson-1 (presently at 97°C) has an apatite FT age of 104±11 Ma and a confined mean track length of 10.4 mm. The apatite FT data are consistent with the trachyte having a Jurassic crystallisation age, equivalent to the dated mid-Jurassic volcanics of the Coleraine-Casterton region (Harding 1969). FT data from both Penola-1 and Robertson-1 indicate that detritus in the Lower Otway Group is derived from multiple source regions, with Palaeozoic basement derived apatite grains dominating until ~112 Ma, when contemporaneous volcanogenic material became abundant. Volcanogenic material is the most common constituent of Otway Group sediments, particularly the Eumeralla Formation, in the eastern section of the Basin (Gleadow & Duddy 1981).

Thermal history

Integration of VR results (Struckmeyer 1986a & b) and apatite FT data suggests that Penola-1 experienced a decline in heat flow in the Tertiary, and negligible denudation. However, Robertson-1, close to the basin margin, underwent uplift and ~1 km of erosion, probably in the mid-Cretaceous.

Beachport - Kalangadoo High

Apatite FT results from Geltwood Beach-1 and Beachport-1 are consistent with the present temperatures being the maximum since deposition, with the deepest samples from Geltwood Beach-1 retaining Mesozoic single grain ages for chlorapatite at temperatures of ~105°C. Thus at the western end of the Beachport - Kalangadoo High no significant cooling events are recorded.

However, in the Kalangadoo-1 well, at the east end of the Beachport - Kalangadoo High (Fig. 1), the apatite FT data and VR results indicate that heat flow was elevated in the Early Cretaceous prior to cooling, provisionally interpreted to have occurred in the mid-Cretaceous. High heat flow prior to the Tertiary, is suggested by VR data (Struckmeyer 1986c) with a change in geothermal gradient in the Cretaceous facilitating greater cooling at depth such that basement (?Palaeozoic metasediments) samples have cooled more than Otway Group samples. Cooling of 45-60°C is suggested for the section examined by apatite FT thermochronology. Modelling of the basement results suggests additional cooling of ~20°C in the Tertiary, possibly following localised heating associated with volcanism (Table 1).

Merino Uplift

Mocamboro-11 on the Merino Uplift in western Victoria spudded in Otway Group sediments and metasedimentary basement was intersected at 1374 m. Thermal history modelling suggests removal of ~750 m of section at Mocamboro-11 since the Early Cretaceous, with a significant component of this erosion in the Early Tertiary.

Mount Salt -1

Mt Salt-1 is located to the south of the Tartwaup fault, a major normal fault which accommodates basin extension in the Late Cretaceous and Tertiary (Hill & Durrand 1993). The Late Cretaceous Sherbrook Group increases substantially in thickness from typically 600 m or less to the north of the fault, to 3-4 km south of the fault and the Otway Group is not penetrated in Mt Salt-1 at a bottom hole depth of 3063 m. Modelling of the VR data (Watson 1984) indicates a palaeogeothermal gradient of 15-20°C/km suggesting uplift and erosion of 2-3 km. Reflectance values of Ro 0.74% at 3250 m (Watson 1984) suggests palaeotemperatures of ~120°C. However, for samples at or near 3,000 m, apatite FT single grain ages are older or within error of the depositional age, indicating that the samples have not experienced the temperatures of >110°C suggested by the VR results. Indeed, the apatite FT ages are more consistent with the present day temperatures of ~80°C. Apatite FT analysis of samples from the Late Cretaceous and Tertiary at Mt Salt-1 suggest that the well is at present day maximum temperatures with a low geothermal gradient (22°C/km) resulting from the restricted thermal conductivity effects of the thick Sherbrook Group sediments.

Western Otway Basin Summary

The Gambier Embayment region was subjected to Jurassic volcanism prior to rifting and the initial Early Cretaceous sediments were dominated by basement-derived detritus. Around 112 Ma, this was replaced by contemporaneous volcanogenic material (Eumeralla), suggesting an expanding volcanic source region or increase in volcanism as rifting proceeded in the Early Cretaceous. In the Late Cretaceous and Tertiary there was major subsidence and deposition south of the Tartwaup Fault (Hill & Durrand 1983) resulting in low temperature gradients and maximum burial now (from FT data). At the same time, Gambier Embayment subsidence continued, but at very slow rates and the thermochronology of the area was highly variable.

The variable thermochronology is illustrated by a comparison of the Beachport-1, Kalangadoo-1 and Mocamboro-11 wells on structural basement highs. Beachport-1 on the coastal margin, has remained stable with continual burial and is presently at maximum temperatures. Kalangadoo-1 underwent mid-Cretaceous cooling from elevated temperature gradients and subsequent Tertiary cooling and Mocamboro-11 was subject to early Tertiary uplift and denudation. In addition, the Robertson-1 well indicates mid-Cretaceous uplift and erosion of the northern basin margin. Several of the wells suggest Tertiary thermal events, possibly associated with volcanism.

In summary, the results show that the western section of the Otway Basin underwent episodes of uplift and erosion, and fluctuations in geothermal gradient throughout the Late Cretaceous and Tertiary. The basin did not become thermally and tectonically stable following 'break-up' but continued to undergo tectonic readjustments probably in response to major plate re-organisations and changing stress fields.

Thermochronology of the Otway Ranges

The Otway Ranges comprise a broad topographic high which is 20-30 km wide, ~70 km long and up to 600 m high. They strike NE-SW and separate the offshore Torquay Embayment to the SE from the Colac Trough to the NW (Fig. 2). The present topographic expression of the Ranges is clearly due to Pliocene or Late Miocene uplift as indicated by the deformed Mio-Pliocene sediments recorded on reflection seismic data on both flanks (Hill et al. submitted) and geomorphically by the oversteepened creek profiles, mass movement and fans along the coast. Based on interpretation of reflection seismic data and structural mapping by Cooper, the Pliocene uplift is interpreted to be due to minor compressional reactivation of previously extensional faults.

However, for the Otway Ranges, Cooper has determined the vitrinite reflectance (Rv max and Ro) values from ~100 surface samples of the Lower Cretaceous Eumeralla Formation. Typical Rv max values along the SE coast are 0.4-0.5% increasing systematically to ≥1.0% inland along the crest of the ranges and nearly 2.0 % at the Olangolah well (eg Cooper et al. 1993; Fig. 2). The Rv max values then decrease to the NW into the Colac Trough, such that the Rv max values map as an elongate dome broadly coincident with the Ranges (Fig. 2). Maximum palaeotemperatures from the core of the structure are estimated to have been >150°C and Cooper's analysis of VR data from wells using BasinMod™ indicates palaeotemperature gradients of up to 60°C/km (Olangolah well) suggesting up to 3 km of previous burial and erosion, decreasing to 1-1.5 km on the flanks.

Thus the VR data indicate that there was previously a large, asymmetric anticline at the site of the Otway Ranges, that has subsequently been eroded (Fig. 3). This large structure could not have been uplifted and eroded as part of the Pliocene event, as there is no evidence for such Pliocene detritus. However, the maximum palaeotemperatures estimated from VR data for the centre of the Ranges are well in excess of the 110-130°C required to reset apatite fission track ages (Green et al. 1989a and b), so the FT age of those samples should reflect the cooling age due to uplift and erosion.

Five inland Eumeralla samples and eight along the coast yield apatite FT cooling ages of ~90 Ma, reflecting a rapid cooling event from ~95-90 Ma (Cooper et al. 1993; Hill et al. submitted). This is consistent with the regional FT dating of basement to the north (Foster & Gleadow 1993) and FT dating of the Olangolah well (Duddy & Gleadow 1982). The dating also agrees with a regional mid-Cretaceous unconformity in the Colac Trough and a smaller unconformity in the Torquay Embayment interpreted from reflection seismic data (Richardson 1993; Hill et al. submitted).

Interpretation of reflection seismic data from the Torquay Embayment and the Colac Trough show dominantly Early Cretaceous extension on steep, deep-seated, northwest dipping faults (Hill et al. submitted). Thus the mid-Cretaceous event is interpreted to be due, at least in part, to inversion of these faults creating the large anticlinal structure of the Otway Ranges (Fig. 3). Cooper is currently testing this concept by rigorous construction and restoration of regional balanced and restored cross sections across the Colac Trough, the Otway Ranges and the Torquay Embayment.

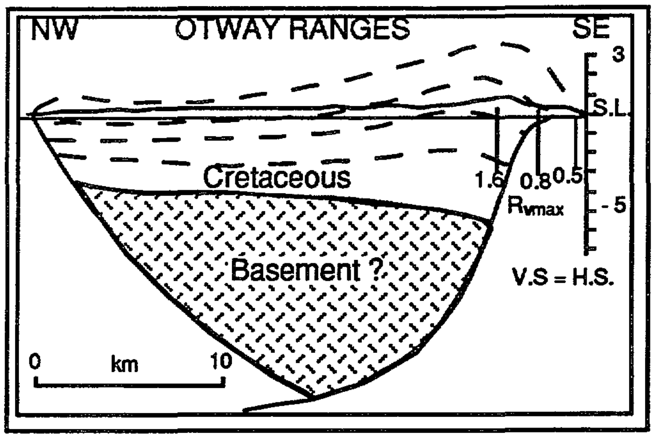

Figure 3. Sketch section of the structure of the Otway Ranges. The amount denuded is indicated by the VR values (Rv max) and FT data indicate denudation at ~95 Ma.

Otway Ranges problems and complexities

Maximum palaeotemperatures

Two FT samples from within the Ranges record grains that retain their Palaeozoic age suggesting that the maximum palaeotemperature was <120°C (Hill et al. submitted). These coincide with relatively high VR values suggesting that some of the latter may have been raised by weathering/oxidation. This is currently being investigated by Fluorescent Alteration Multi-Maceral analysis (FAMM) at CSIRO (Ellacott et al. 1994). However, the highest VR and hence palaeotemperature estimates are from the wells, which have not been subject to oxidation. The juxtaposition of samples with different maximum palaeotemperatures indicates some structural complexity, possibly locally down-faulted areas.

Early Tertiary event

Along the coast near Lorne, FT ages of 78 and 72 Ma are recorded, suggesting the possibility of an additional Late Cretaceous-Early Tertiary cooling event in that area, which is consistent with an unconformity observed on seismic data (Hill et al submitted). The event is also consistent with an Early Tertiary cooling recorded from FT data in the Gambier Embayment and in NE Tasmania (O'Sullivan 1992). The nature of this cooling event is uncertain. It is unlikely to be due to Late Cretaceous burial followed by uplift as the Upper Cretaceous section is thin throughout the Torquay Embayment. The ages need further confirmation and the possibility of local intrusives is still to be investigated.

Summary of Otway Ranges thermochronology

Rifting and inundation by volcanogenic sediment led to rapid subsidence from 120-~95 Ma, associated with elevated temperature gradients. Relaxation of high thermal gradients and 1-3 km of regional uplift and erosion, including inversion of the Otway Ranges, led to rapid cooling at ~95±5 Ma. Most of the Otway Ranges rocks have remained below ~60°C since the mid Cretaceous, but local Late Cretaceous heating and Early Tertiary cooling may have occurred, although the cause in uncertain. Late Miocene-Pliocene cooling is not recorded, although 500-1,000 m of inversion and uplift is clearly apparent from reflection seismic data, structural and geomorphic analyses.

Tectonic Interpretation of the Thermochronology of the Otway Basin

Jurassic volcanism in the Otway Basin area was a prelude to Late Jurassic - Early Cretaceous rifting. Detritus was originally largely from the Palaeozoic margins, but the basin was inundated with enormous volumes of contemporaneous volcanogenic sediment in the Aptian-Albian, causing regional subsidence and rapid deposition and burial of the Eumeralla Formation. Deposition in an extensional environment resulted in elevated heat flow of up to 60°C/km.

Around ~95 Ma, the rapid subsidence ceased in the onshore Otway Basin area and Torquay Embayment, as did the input of volcanogenic detritus. In the western Otway Basin local cooling and uplift occurred north of the Tartwaup Fault whilst to the south there was major Late Cretaceous subsidence and deposition associated with breakup (Veevers et al. 1991). Extension and breakup propagated south of Tasmania at ~95 Ma leaving the eastern Otway Basin as part of a failed rift. Compression across the failed rift and possibly thermal uplift of the margins resulted in both inversion of the Otway Ranges and regional denudation of the margins at ~95 Ma.

Early Tertiary, local, cooling and denudation events are indicated in the eastern and western Otway Basin as well as NE Tasmania, although the cause is uncertain. The events may be related to plate realignment associated with the onset of rapid spreading in the Paleocene-Eocene. Deposition and/or intrusion of the Older and Newer Volcanics caused Tertiary thermal anomalies in the western Otway Basin, but the main event in the eastern Otway Basin was the Pliocene inversion of the Otway Ranges. This is interpreted to be due to Late Miocene, arc-continent collision along the northern margin of the Australian craton (eg Cooper & Taylor 1987) and transpression in New Zealand resulting in compression of the entire craton, continuing to the present day (eg Etheridge et al. 1991; Denham & Windsor 1991).

Acknowledgments

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TOWARDS A STRUCTURAL HISTORY FOR THE OTWAY BASIN

THE VIEW FROM THE SOUTHEAST

Michael Hall
BHP Petroleum

The structural history of the Otway Basin appears to vary considerably from area to area along its length. Features typifying one part of the basin many be absent or unrecognisable in another, and it is gradually becoming clearer that different tectonic events have had markedly different effects in different areas. Also, it should be stressed that the "basin" really consists of an early Cretaceous intracontinental rift system overprinted in part by a late Cretaceous "passive margin" and followed by a Tertiary "subsidence phase" which was locally terminated by mid Tertiary - Recent compressional deformation.

Probably the most complex area occurs in the southeast of the basin, along the southern end of the Otway Ranges and in the offshore area from between Warrnambool and Cape Otway. The geology of this area has been interpreted from onshore mapping and an extensive offshore seismic grid with, at best, a one kilometre line spacing, and the drilling of four new exploration wells and one appraisal well. To date this work has resulted in significant gas discoveries at Minerva and La Bella.

Lower Cretaceous Otway Group sediments are exposed along the coastline from east of Port Campbell to Cape Otway, but offshore they become deeply buried and are strongly deformed. Depositional troughs, clearly recognisable in the western Otway Basin and Torquay Embayment, are largely overprinted by later structures in the southeast, and none can be recognised with certainty. By inference from surrounding areas, the Otway Group was probably deposited in east to northeast trending troughs, with a thickness of up to 7km accumulating in the vicinity of Cape Otway.

Upper Cretaceous sediments rest uncomfortably on the Otway Group and were deposited in a series of northwest trending fault blocks superimposed on the early Cretaceous structures. The thickness of the largely fluvial Shipwreck Group is strongly controlled by these faults, although the distribution of the group indicates that there was extensive interconnection between the different half graben systems.

The Shipwreck Group is locally truncated by the overlying, dominantly marine Sherbrook Group. Faulting continued well into the Cretaceous, following initial Cenomanian extension, and a younger more northerly trending system of normal faults cut across the slightly older northwest trending faults. The younger faults probably represent the northernmost limit of the fault system that extends southwards along the west coast of Tasmania.

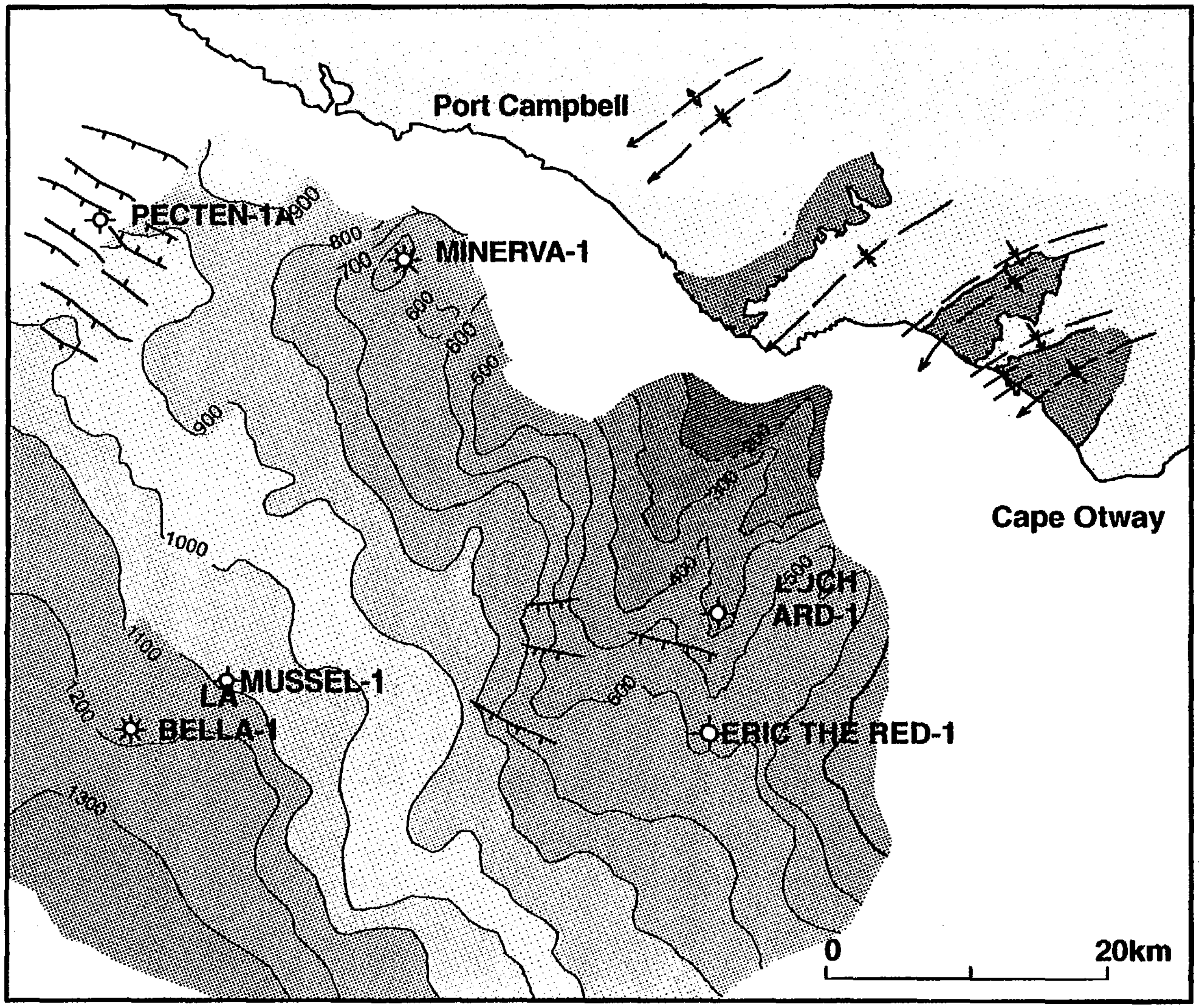
To further complicate the structural history, the area was subjected to a period of compressional deformation towards the end of the Cretaceous. The folds that developed trend northeast and clearly grew in a syndepositional setting. Some are associated with northeast trending reverse faults.

The late Cretaceous structures, both folds and normal faults, are truncated at an extensive erosional surface on which the Tertiary sediments were deposited. Minor normal faulting during the early Tertiary, commonly on reactivated Cretaceous faults, locally controlled an extensive estuarine depositional system. Throughout the Tertiary the shelf edge prograded generally southwards, with sea level changes causing some spectacular downlap and onlap relationships, as well channel cutting and filling.

Further compressional deformation during the middle Tertiary rejuvenated many of the northeast trending late Cretaceous folds and caused inversion of some early Tertiary depositional basins. The folds were again truncated before continuing to grow during the late Tertiary to Recent. Numerous low angle thrusts and reverse faults cutting the Tertiary sediments and locally involving Pliocene-Pleistocene sands testify to the youthfulness of the most recent deformation.

Southeast Otway Basin
Base Tertiary Contours (Time)

BHP



March 1994

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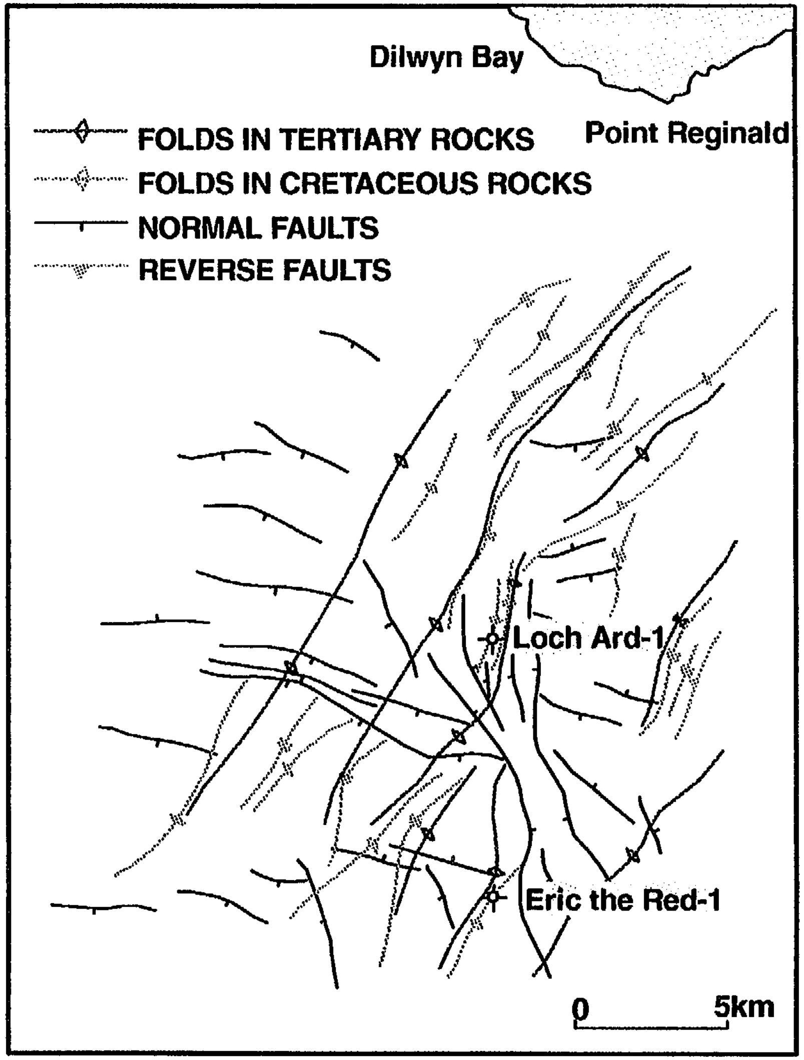
Australia Division
BHP Petroleum

Southeast Otway Basin
Structural Trends



Spectacular maps and images of an area of seabed south and west of Tasmania, three times the size of the island

N. F. Exon[1], P. J. Hill[1], J-Y Royer[2] and R. V. *L'Atalante* shipboard scientific party.

1 - Australian Geological Survey Organisation, PO Box 378, Canberra 2601
2 - Laboratoire de Geodynaique Sous-Marine, BP 48, 06230, Villefranche-sur-mer, France

Introduction

From 19 February to 27 March 1994, the large French Research Vessel *L'Atalante*, as part of a French-Australian scientific cooperation program, carried out a major mapping exercise south and west of Tasmania (Fig. 1), in waters beyond the continental shelf. It used one of the most sophisticated mapping systems in the world, a system of a type that Australia does not possess. The work will provide the equivalent of the onshore topographic maps and satellite images that we all take for granted. The Australian Geological Survey Organisation (AGSO), for which the work was done, has been given the task of mapping offshore Australia, with the primary aim of helping industry find and develop new petroleum and mineral deposits.

This present project also has wider aims in finding out how and when Australia and Antarctica split apart, and what effects this had on Tasmanian geology, and also in documenting climatic change in the last 50 million years. The work started with cruises of the German vessel *Sonne* and AGSO's vessel *Rig Seismic* off Tasmania in the 1980s, and will continue with *Rig Seismic* seabed sampling and reflection seismic cruises next year. The cruise was led by Neville Exon and Peter Hill of AGSO, with Jean-Yves Royer from France as a senior collaborator. University staff and students from Australia and France participated in the cruise, and three will write theses on aspects of the results.

Shipborne systems

The *L'Atalante* used its multibeam sonar system for detailed mapping of almost 200 000 km^2 of the continental margin in the Tasmanian region and the adjacent abyssal plain (three times the size of Tasmania). The "Tasmante" cruise (name derived from Tasmania and L'Atalante) employed the SIMRAD EM12D system to map an area along each ship track, up to 20 km wide, at a speed of 10 knots or nearly 20 km/hour. Average pixel size is of the order of 100x100 m. The system provides bathymetric maps with 20 m contours, and images of the sea bed texture, with a degree of accuracy and rate of coverage unobtainable in any other way. In addition, the ship records seismic reflection profiles with penetration of up to 2.5 seconds (two-way time) that show the structure several kilometres below the sea floor, and magnetometer and gravity data.

Regional geology

The region's structural pattern and geological history is largely controlled by the separation of Australia and Antarctica from 130 to 40 million years ago and thus has a bearing on the history of the entire southern margin of Australia. The southeastern part of the Australian continental margin is already a major producer of petroleum from the Gippsland Basin, and the Otway Basin is the scene of major recent BHP offshore gas discoveries. The Sorell Basin west of Tasmania is a southward prolongation of the Otway Basin and is also prospective for petroleum (Moore et al. 1992). The Strahan Sub-basin of the Sorell Basin is under active exploration. The very accurate bathymetric maps and sonar images from this survey allow the mapping of any fault patterns that come to the surface, and faults are often a key component of petroleum traps.

South Tasman Rise

The continental South Tasman Rise, a submerged continental block larger than Tasmania, extends from south of Hobart to 50° S. We mapped about 150 000 km^2 (three-quarters) of it (Fig. 2). It is bounded on three sides by oceanic crust of Late Cretaceous and Palaeogene age. Spectacular faults and giant fault blocks have been mapped by *L'Atalante*, in water depths of 2500-4500 m, on its western and eastern sides. The submarine cliffs dwarf anything on Australia, reaching 2300 m high in one place (Fig.3). The South Tasman Rise only sank completely below the ocean in the last 20 million years, and parts of it are less than 1000 m deep. It is current-swept and hence Neogene sediment cover is thin or absent. It gives a similar impression on the imagery to much of inland eastern Australia, with similar proportions of outcrop and sedimentary cover, and outcrops of schist and gneiss, granite, Palaeozoic and Mesozoic sediments, and Tertiary basalts.

The complexity of the South Tasman Rise geology will surely rival that of Tasmania, and the basement is sliced to form deep transpressional/tensional basins by faults trending N to NW. What is interpreted as the eastern limb of a NNW-trending anticline in Palaeozoic sediments is of the order of 100 km long and 40 km wide, and is bounded by cuestas hundreds of metres high. The western side of the structure is faulted out, with large rotated blocks there. The petroleum potential of the South Tasman Rise is not known, but the existence of thick

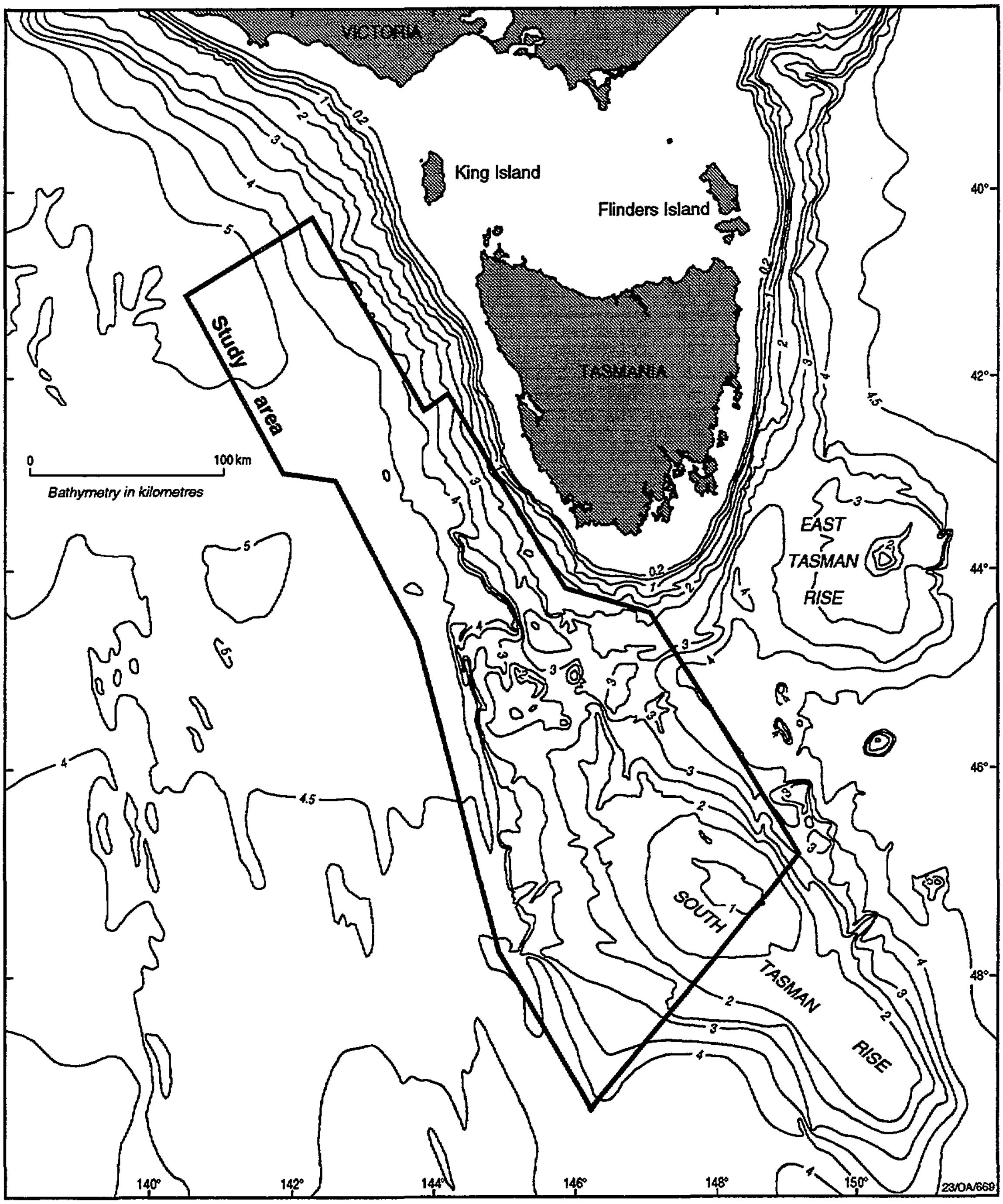


Figure 1 - The area surveyed by R. V. *L'Atalante* off Tasmania during the "Tasmante" swath-mapping and reflection seismic cruise. The total area is about 200 000 km^2.

sections in strike-slip basins, and the geochemical evidence that thermogenic hydrocarbons are being generated, suggests that it does have some potential (Hinz et al. 1985).

Sorell Basin

The Sorell Basin off west Tasmania is a remarkable contrast to the South Tasman Rise, being very heavily sedimented in Tertiary times. Therefore the swath-mapping of this area has been more restricted than the South Tasman Rise, but still covers about 50 000 km^2. On the shelf are several basement blocks that separate four strike-slip related depocentres containing more than 3000 m of Cretaceous and Tertiary sequences much like those in the Otway Basin. Some of the basin-forming faults have been imaged, as has a 2500 m high fault scarp trending NNW on the lower slope, from which Cretaceous shallow marine sediments have been dredged. The area needs a careful review using all existing data, including the excellent *L'Atalante* regional seismic grid, to reassess its petroleum prospects. The existence of a thick sedimentary section, oil and gas shows, and some structuring, suggests that it has considerable petroleum potential (Hinz et al. 1986; Moore et al. 1992).

Australia-Antarctic breakup

The oceanic basalts on the abyssal plain, 4500-5000 m deep west of Tasmania and around the South Tasman Rise, record much of the history of the breaking apart of Australia and Antarctica that started perhaps 130 million years ago, with Antarctica grinding slowly past Tasmania and finally clearing it about 40 million years ago. Thereafter, what had been dry land or a shallow marine embayment west of Tasmania, subsided thousands of metres below the sea, as did the South Tasman Rise. At the same time the easterly flowing Circum-Antarctic Current, that had previously flowed north of Australia, broke through in the south, leading to major climatic changes. The "Tasmante" sonar mapping gives us more detail of how these things happened. In addition, it will enable future sampling to be precisely targeted to resolve the important scientific question of where and how the continent ends and the oceanic crust begins.

The "Tasmante" mapping of sedimentary patterns on the continental slope will help document the changes as the slope subsided following the departure of Antarctica. The mapping of rocky outcrops and sedimentary patterns is invaluable in planning next year's AGSO seafloor sampling cruise, using R.V. *Rig Seismic*. Dredged older rocks will provide information on the history of the area before it subsided. Cores of marine sediments will be used to study changes in oceanic circulation and climate as Australia moved steadily north away from Antarctica. The *L'Atalante* mapping cruise is the key to a treasure house of information about Tasmania's ancient history, as it gradually became separated from land masses to the west, east and south.

The poster display presented at the NGMA Otway Basin Symposium includes images and contour maps at 1:250 000 and 1:1 000 000 scale derived from the "Tasmante" cruise.

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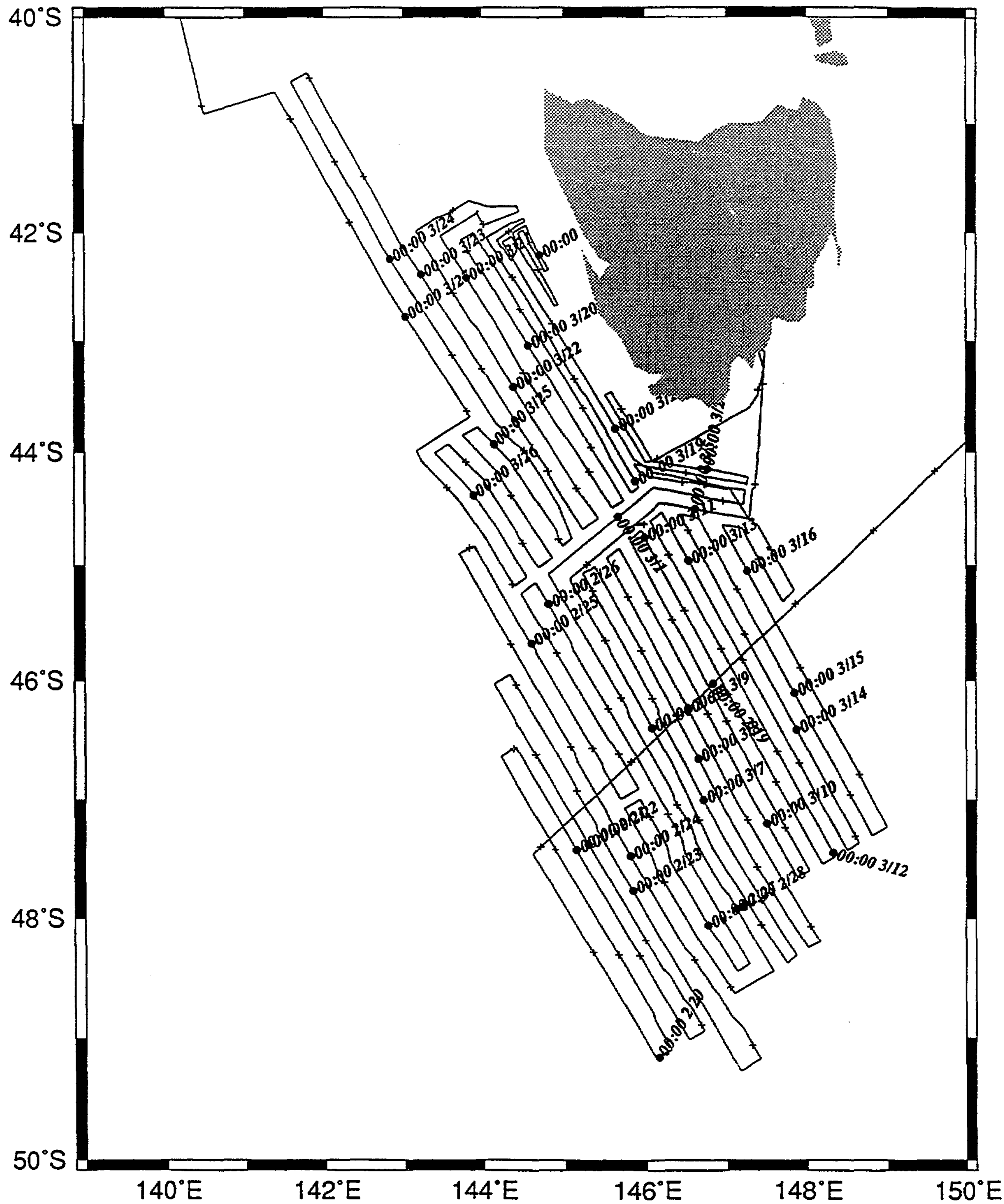

Figure 2 - The tracks of *L'Atalante* for the area surveyed on the South Tasman Rise and off west Tasmania. Coverage of swath-mapping is essentially 100%.

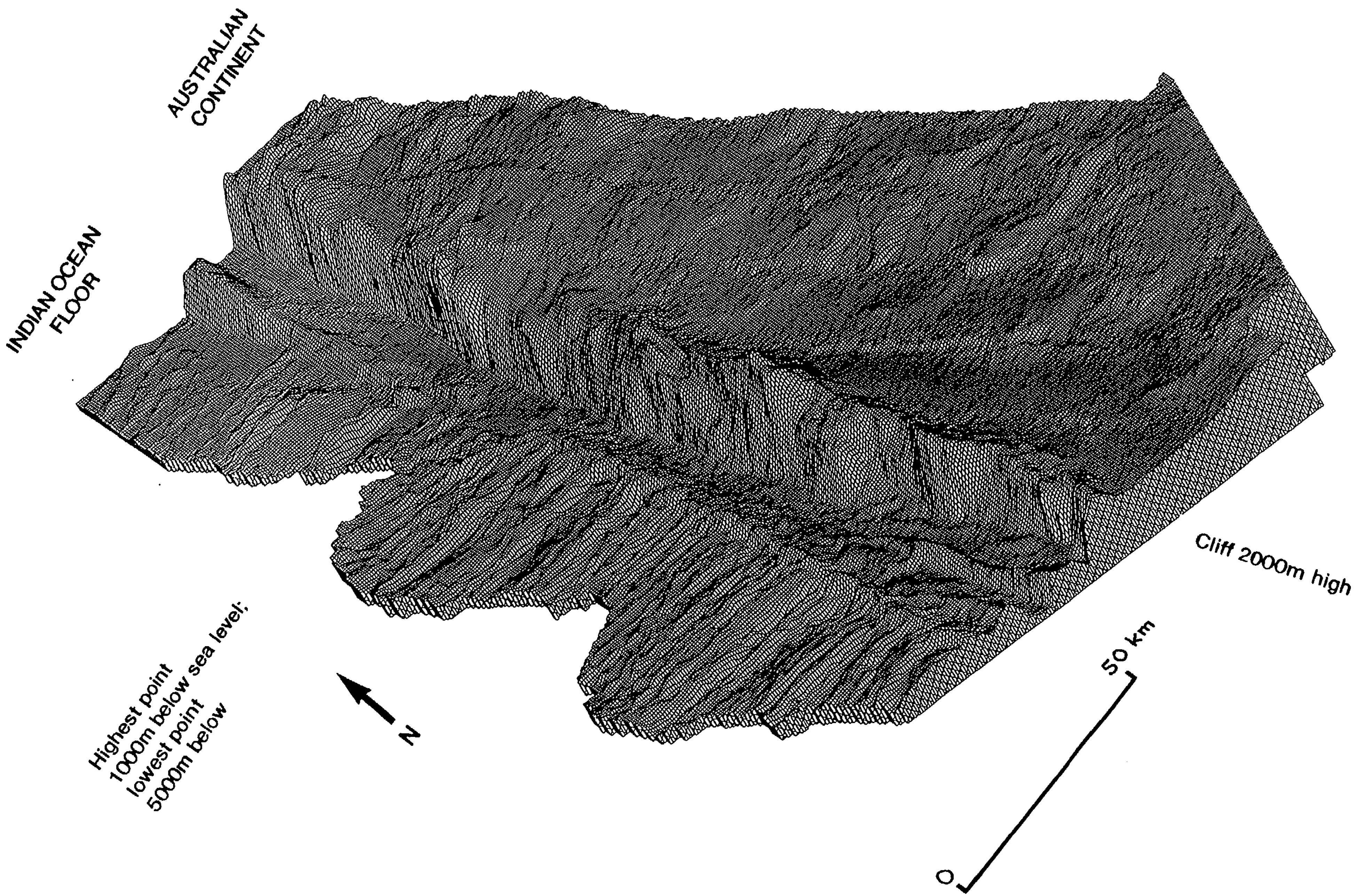

Figure 3 - Block diagram of part of the western margin of the South Tasman Rise, showing the continental cliff 2000 m high above the abyssal plain with its spreading fabric.

Improvement of Hydrocarbon Reserve Estimation, Otway Basin

Bridget Little
Department of Applied Geology, University of South Australia, The Levels, SA, 5095

The Katnook field in the onshore part of the Otway Basin produces gas from the Early Cretaceous Pretty Hill Sandstone. Log analysis has proven to be inaccurate in detecting the transition between gas and water in the field and this may be a result of complex mineralogy. It is necessary to provide an alternative method to determine reserves. Petrophysical equations such as those published by Waxman and Smits (1968) need to be used and adapted to suit this particular formation. For these to be meaningful, correct values for Qv must be used. These values are obtained via laboratory measurement of Cation Exchange Capacity (CEC). In the past, a standard 'wet chemistry' method has been used to measure this value, however due to the core plug having to be crushed, it is not an ideal way to measure it. A new method has been developed by Austin and Ganley (1991) by which organic fluids are pumped through the core plug. This method is currently being tested and adapted.

The Pretty Hill sandstone mineralogy includes potassium feldspar, chlorite, quartz, laumontite, plagioclase and volcanic lithic fragments. As part of this project, a more detailed understanding of the mineralogy is required so as to apply it to log and laboratory interpretation. Conventional thin section analysis has previously been applied. As an extra tool, new thin sections have been made which are stained for potassium feldspar. This has aided the recognition of potassium feldspar as grains and as crystals within volcanic lithic fragments. It has also confirmed that fine crystalline authigenic feldspar cement is plagioclase. The staining has also shown that the potassium concentration is higher than first observed in unstained thin sections which is important when considering wireline log responses.

Acknowledgments

This work is part of a Masters research project at the University of South Australia. It is sponsored by an APRA (Industry) Award and by ACS Laboratories. Extra data and assistance is generously provided by SAGASCO Resources and the Department of Mines and Energy, South Australia (MESA). It is expected that the project will be completed by April, 1995.

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Trapping of oil and gas in the Otway Basin, Victoria, Australia

Kourosh Mehin
Petroleum Development, Department of Energy and Minerals, Melbourne

Alby Link
Department of Civil and Geological Engineering, RMIT, Melbourne

Studies of isotopic analyses of gases, sedimentary facies distribution, tectonic structural patterns and salinity variation in the onshore Port Campbell Embayment revealed a close relationship between trapped hydrocarbons and high salinity; coarse, angular fluvial sands; and transfer, rift and re-activated Palaeozoic faults. The latter provided a mosaic of migration conduits from Eumeralla source to Waarre Formation traps. The two most recent gas discoveries in the region offshore from Port Campbell probably indicate similar relationships.

Initial studies of geothermal and other data from the Tyrendarra Embayment/Portland Trough indicate that there is a similar salinity, fault and fluid migration relationship in the western Otway Basin. Current drilling results also show that the western Otway Basin is prospective for not only gas but also oil.

The Victorian portion of the Otway Basin contains up to 7.5km of Mesozoic and Tertiary rift-filling clastic and carbonate sediments. These rocks are divided into five groups (Douglas and Ferguson, 1988) (Fig. 1), – the Otway and Sherbrook Groups being of particular interest here. Many onshore oil and gas shows have been noted and discoveries have been made in these Early and Late Cretaceous rocks (Sprigg, 1986); some significant gas discoveries have also been made offshore.

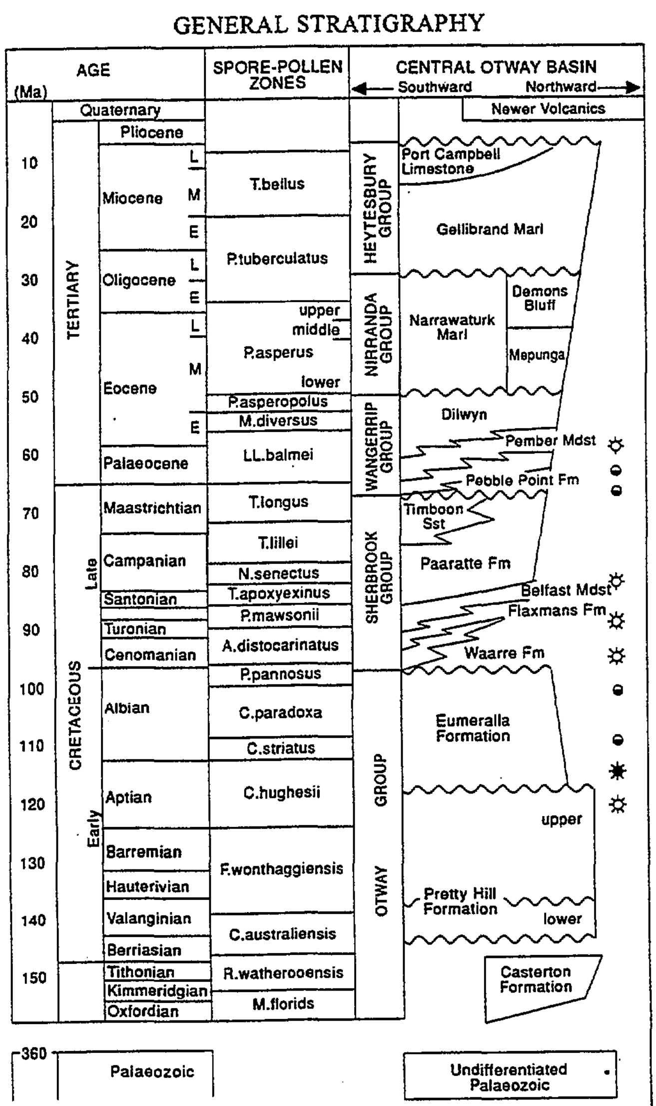

Figure 1 – Late Mesozoic to Tertiary stratigraphic sequence in the Otway Basin, Victoria.

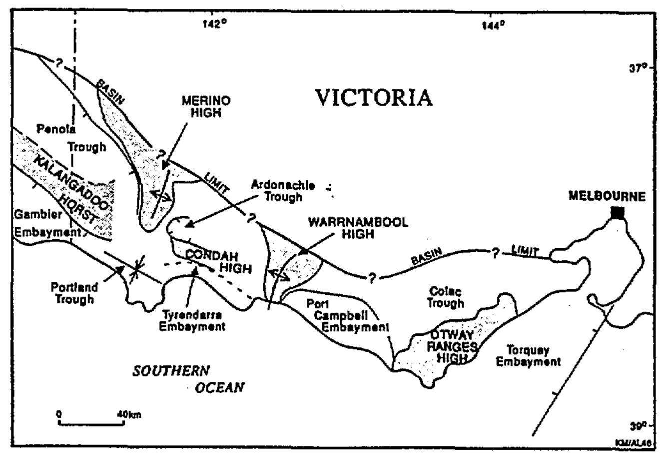

Figure 2 – Major structural elements, Otway Basin.

Structurally, the onshore comprises an E-W succession of horsts and grabens (Fig. 2). Interpretation of magnetic and gravity data (Pettifer et al, 1991) and seismic (eg. in the Port Campbell Embayment) (Fig. 3) shows a complex arrangement of WNW trending rift faults (the main structure-producing traps), NE-SW transfer faults and re-activated N-S Palaeozoic faults.

Isopach trends in the Otway, Sherbrook and Wangerrip Groups (Fig. 4) suggest that blocks within the rift system

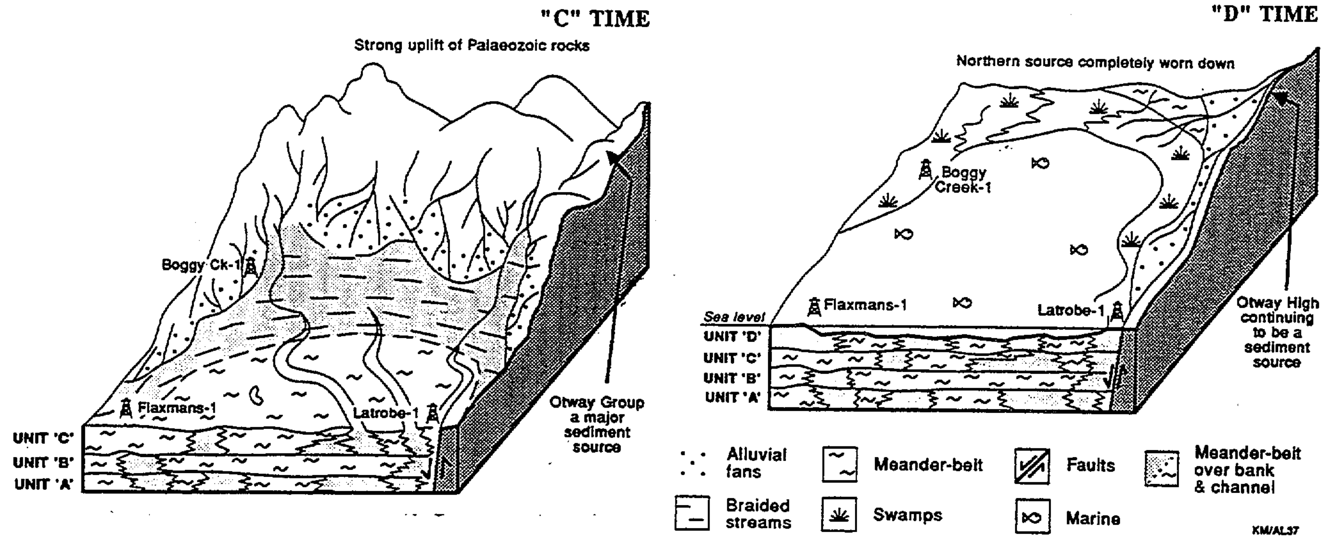

Figure 5 (b) – Schematic block diagrams showing the general distribution of the depositional environments in the Port Campbell Embayment during Units C & D times of the Waarre Formation.

Unit C within the onshore Port Campbell Embayment is a very porous coarse sand and contains the major gas reserves.

From a plot of the gas isotopic and vitrinite reflectance data (Fig. 6), the probable depths of the rocks sourcing hydrocarbon reserves are deduced to be within the Eumeralla Formation (Mehin and Link, 1994).

The large volumes at some wells of carbon dioxide (Fig. 7) – interpreted to be of volcanic origin, and geothermal data (after King et al, 1985) (Figs. 8 & 9) coupled with faulting patterns, revealed a probable connection between upwardly migrating, hot, deep-seated fluids and the vertical conduits of the re-activated Palaeozoic fault system.

Also, a plot of salinity distribution overprinted with the major faults strongly suggests a connection between high

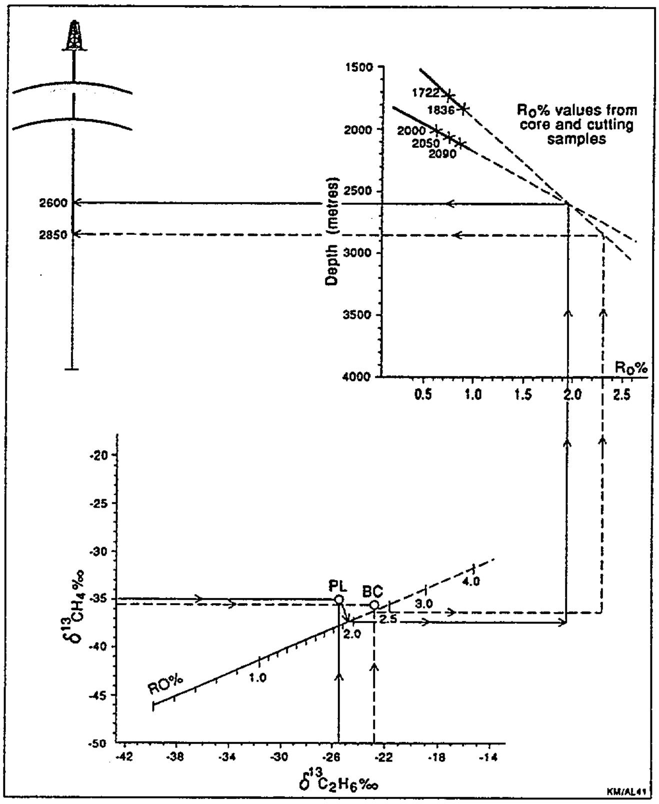

Figure 6 – The combined Faber plot and depths versus vitrinite reflectance indicates source rock depths of 2600m and 2850m at Pine Lodge 1 and Boggy Creek 1.

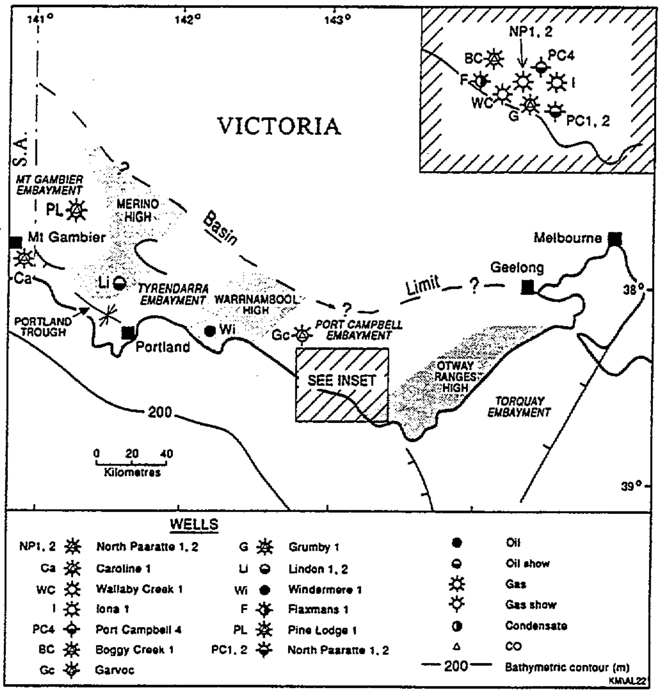

Figure 7 – Locations of carbon dioxide wells.

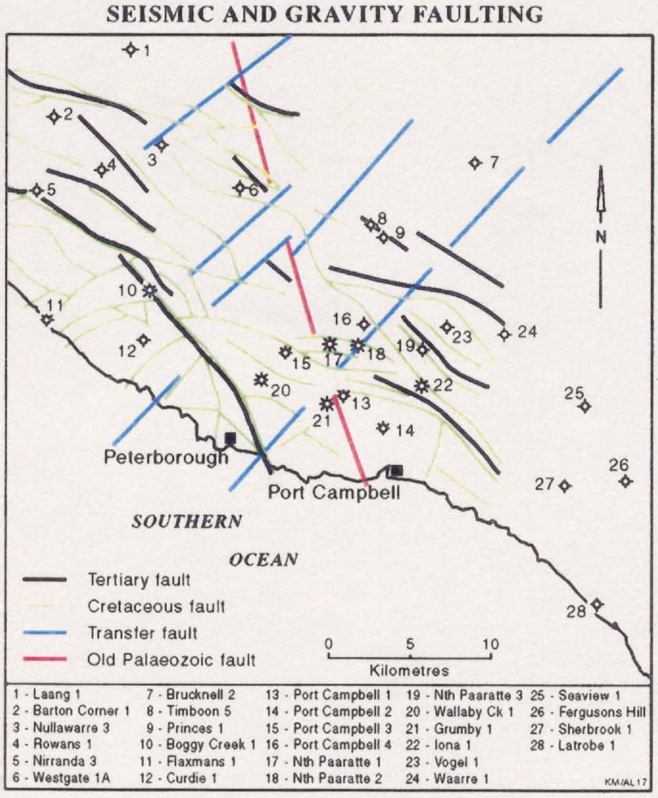

Figure 3 -- Port Campbell Embayment showing WNW rift valley, transfer and re-activated Palaeozoic faulting.

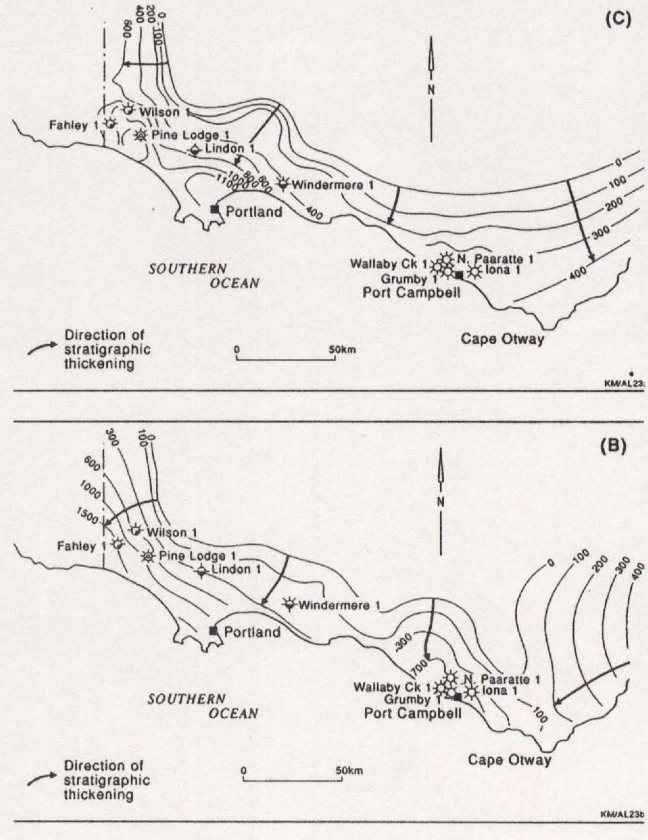

Figure 4 -- Isopachs showing drainage directions within (a) Otway, (b) Sherbrook, and (c) Wangerrip Groups.

subsided at different rates, some were tilted and possibly rotated. These different movements are thought to have played an important role in the positioning of the thickest reservoir sands and cap rocks.

For example, the distribution of the depositional systems of the Waarre Formation (Fig. 5) supports the notion that rapid block movement resulted in substantial lateral shifts of the sedimentary facies in each of the four units. (These four units were defined from log profile by Buffin, 1989).

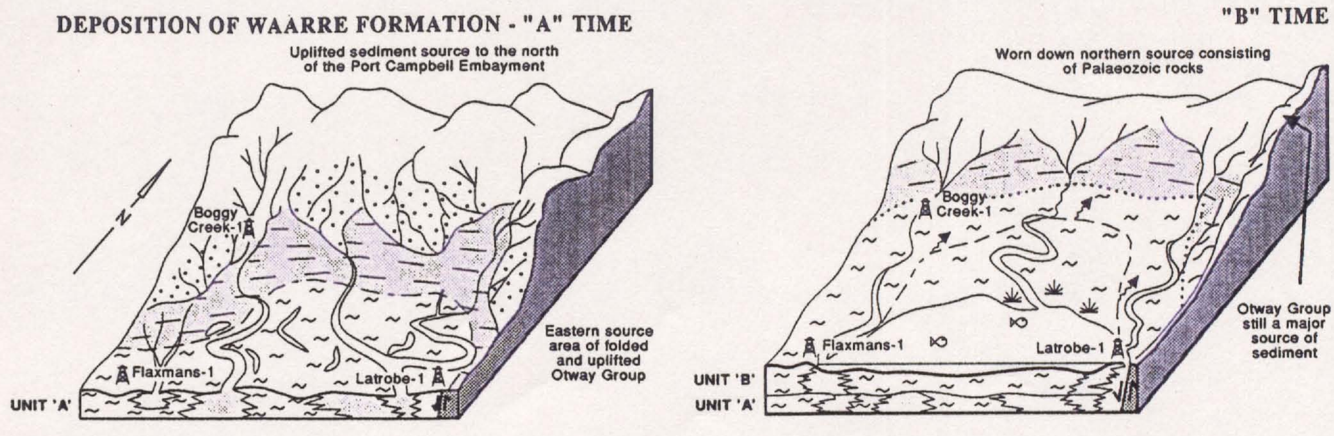

Figure 5(a) -- Schematic block diagrams showing the general distribution of the depositional environments in the Port Campbell Embayment during Units A & B times of the Waarre Formation.

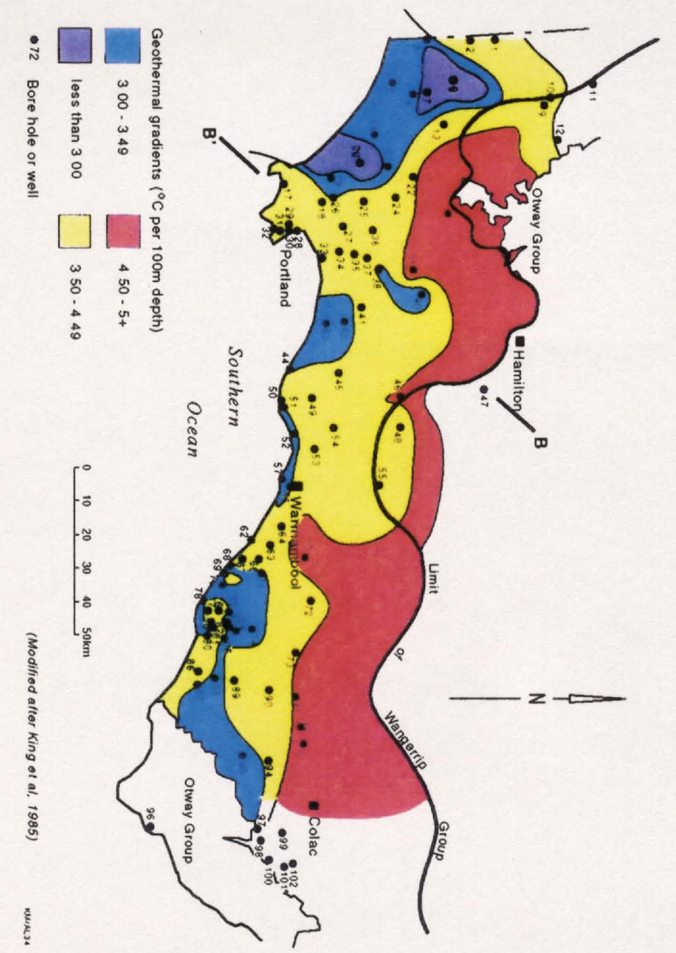

Figure 8 -- Distribution of thermal gradients - note the general increase towards the northern margin of the rift.

salinities and fault type (Fig. 10).

In fact, there appears to be a link between areas of high salinity, gas entrapment and rift faulting as at Boggy Creek 1, Wallaby Creek 1, North Paaratte 1 etc. A schematic model interpreting migration pathways of hydrocarbons generated from the Eumeralla source rocks and migrating to the Waarre Formation reservoir sands is presented in Figure 11.

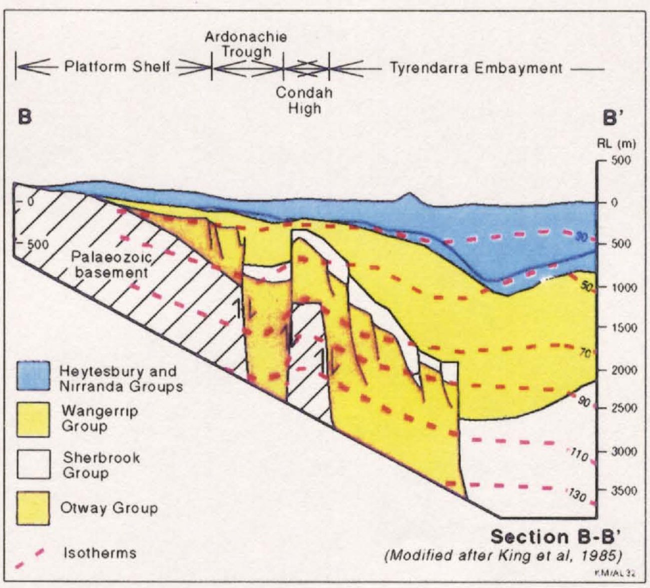

Figure 9 -- Cross-section showing elevated isotherms near faulted structural highs.

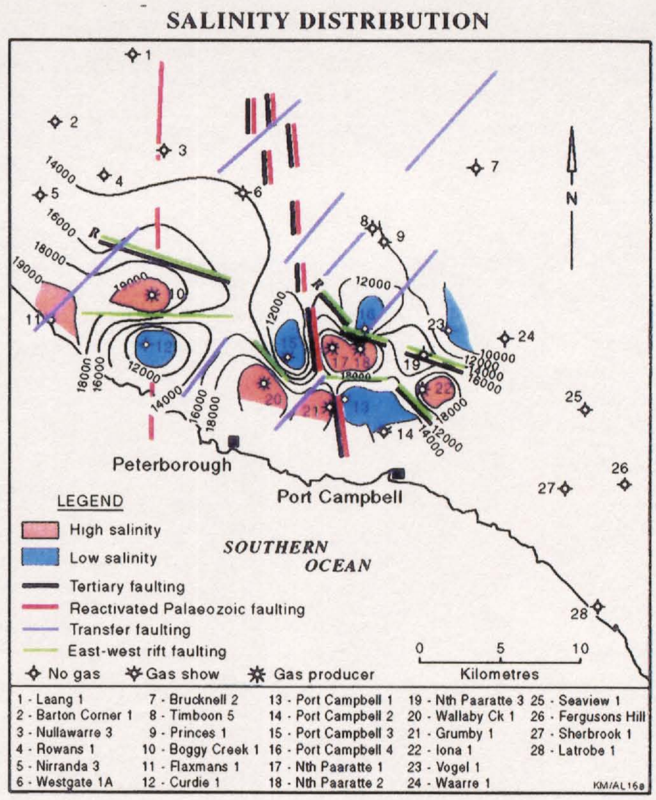

Figure 10 -- Major fault trends and areas of high and low salinity values.

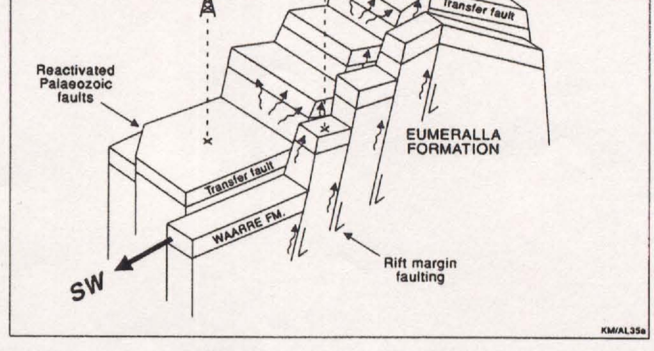

Figure 11 -- Schematic model depicting possible hydrocarbon and carbon dioxide migration pathways.

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NGMA Otway Basin Project - papers, products and presentations

Listed below are some of the papers, presentations and products which have been produced by the National Geoscience Mapping Accord (NGMA) partners as contributions to the Otway Basin Project.

- *1992 AGSO onshore Otway seismic Lines 1 - 7* : - data release, Oct 1992- Feb. 1993. Paper and film 6 s TWT seismic sections available, together with stack tapes (up to 20 s TWT), associated 1:100 000 scale maps, and shotpoint data disc in UKOOA fixed format.

  Enquiries - D. M. Finlayson, Australian Geologcal Survey Organisation, PO Box 378 Canberra ACT 2601, Ph. 06 2499761, Fax. 06 2499972.

- Finlayson, D. M., Owen, A., Johnstone, D. W., & Wake-Dyster, K. D., 1993. *Moho and petrologic crust-mantle boundary coincide under southeastern Australia.* Geology, 21, 707-710.

- Wake-Dyster, K. D., & Leven, J., 1992. *Pre-survey seismic testing: techniques and results.* Abstracts, Australian Society of Exploration Geophysicists 9th Geophysical Conference and Exhibition, 68.

- Finlayson, D. M., 1992. *NGMA Otway Basin Project.* AGSO92, Yearbook of the Australian Geological Survey Organisation, 1992, 23-25.

- Cooper, G. T., Hill, K. C., & Wlasenko, M., 1993. *Thermal modelling in the eastern Otway Basin.* Australian Petroleum Exploration Association Journal, 33, 205-214.

- Sherry, K. C., & Pettifer, G. R., 1993. *NGMA Otway Project gravity survey (9230), western Victoria, 1992, operational report.* Department of Energy and Minerals, Victoria, Report 1993/19.

- Reeves, C. V., O'Brien, G. W., Finlayson, D. M. Milligan, P. R., Morse, M. P., Brodie, R. C., & Willcox, J. B., 1993. *Western Otway Basin 1992 aeromagnetic dataset: images and interpretation.* Australian Geological Survey Organisation Record 1993/14.

- Brodie, R. C., 1993. *Penola (western Otway Basin) airborne geophysical survey, 1992 - operations report.* Australian Geological Survey Organisation Record 1993/16.

- *AGSO Western Otway Basin aeromagnetic and radiometric data*
  AGSO has released a range of products from 1992 airborne survey work in the western Otway Basin - maps, digital data, images, and survey reports and interpretations. These are listed below.

  Contour maps - 1:250 000 scale:
  Total magnetic intensity
  Spectrometer - total count
  Bouguer gravity field (density 2.67 t.m^3)

  Survey operations and profile maps - 1:250 000 scale:
  Total magnetic intensity profiles
  Spectrometer profiles - total count channel
  Spectrometer profiles - gamma-ray, potassium channel
  Spectrometer profiles - gamma-ray, uranium channel
  Spectrometer profiles - gamma-ray, thorium channel
  Flight path
  Radio altimeter profiles

  Digital data:
  Position-located aeromagnetic data and position-located, gamma-ray spectometric data - total count, potassium, uranium, and thorium channels.

Total magnetic intensity - 15" grid.
Gamma-ray spectrometric grids - total count, potassium, uranium, and thorium channels.

Enquiries - I. Hone, Australian Geological Survey Organisation, PO Box 378, Canberra ACT 2601, Ph. 06 2499306.

- ***Bass Strait - Encounter Bay area: digital aeromagnetic data***
These data have been derived from 1960-61 analogue data. The survey was flown by Aero Services Ltd for Haematite Explorations Pty. Ltd. at flightline spacings of 3 and 10 km at 600 m elevation. Digitising of the data was coordinated by the Geological Survey of Victoria (GSV) and jointly funded by GSV, AGSO, SADME, and Tas. Dept. of State Dev. & Resources.

The data are available as 1) point located data, 2) digital grids in ERmapper format, and 3) contour maps at 1:500 000 scale.

Enquiries - Bruce Simons, Geological Survey of Victoria, PO Box 98, East Melbourne Vic 3002, Ph. 03 412 7825, Fax. 03 412 7803.

- Hill, K. A., & Durrand, C., 1993. ***The western Otway Basin - an overview of the rift and drift history using serial profiles.*** Petroleum Exploration Society of Australia Journal, 21, 67-78.

VIEPS Symposium, LaTrobe University, Melbourne, 2 July, 1993
- K. C. Hill - ***Thermochronology of the Bass Strait region and environs.***
- D. Perincek - ***Structural elements of the western Otway Basin, Victoria***
- K. A. Hill - ***An overview of the rift-drift history of the western Otway Basin, South Australia.***
- G. R. Pettifer - ***Image processing case history - eastern Otway Basin.***

- Richardson, M. J., 1993. ***Tectono-stratigraphy of the Colac Trough (Otway Basin), southwestern Victoria.*** A project report submitted in partial fulfilment of the requirements for Masters Preliminary examination, Monash University, August 1993.

- Hill, K. C., Hill, K. A., Cooper, G. T., O'Sullivan, A. J., O'Sullivan, P. B., & Richardson, M. J., 1993. ***Inversion around the Bass Basin, SE Australia***. Proceedings of Basin Inversion Symposium, Oxford (1993), (Editor, Buchanan J.) Geological Society of London Special Publication, in press.

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- Finlayson, D. M., O'Brien, G. W., & Reeves, C. V., 1993. ***The Otway Basin - a complex margin in southeastern Australia***. 2nd AGSO Petroleum Group Seminar, Australian Geological Survey Organisation Record 1993/83, 8-9.

- Wake-Dyster, K. D., Owen, A. J., & Finlayson, D. M., 1993. ***Otway Basin seismic survey 1992: operational report***. Australian Geological Survey Organisation Record 1993/97.

- Mehin, K. & Link, A. G., 1994. ***Source, migration and entrapment of hydrocarbons and carbon dioxide in the Otway Basin, Victoria.*** Australian Petroleum Exploration Association Journal, 34, 439-459.

- Perincek, D., Simons, B., & Pettifer, G. R., 1994. ***The tectonic framework and associated play types of the western Otway Basin, Victoria, Australia.*** Australian Petroleum Exploration Association Journal, 34, 460-478.

- O'Brien, G. W., Reeves, C. V., Milligan, P. R., Morse, M. P., Alexander, E. M., Willcox, J. B., Zhou, Y., Finlayson, D. M., & Brodie, R. C., 1994. ***New ideas on the rifting history and structural architecture of the western Otway Basin: evidence from the integration of aeromagnetic, gravity and seismic data.*** Australian Petroleum Exploration Association Journal, 34, 529-554.

- Hill, K. A., Cooper, G. T., Richardson, M. J., & Lavin, C. J., 1994. ***Structural framework of the eastern Otway -Torquay Basins: inversion and interaction between two major structural provinces.*** Exploration Geophysics, in press.

- Wake-Dyster, K. D., Johnstone, D. W., & Owen, A. J., 1994. ***Otway Basin seismic test survey, 1992: operational report.*** Australian Geological Survey Organisation Record, in press.

- ***Western Otway Basin - Interpreted seismic sections and horizon maps***
The Department of Mines and Energy, South Australia, has released a number of products based on the interpretation of seismic sections in the western Otway Basin. These are listed below.

Displays and maps:
Interpreted seismic sections over 36 wells.
Colour contour maps of two-way times to four horizons at 1:250 000 and 1:100 000 scale covering onshore South Australia. The four horizons are - base Tertiary, top Otway Group, top Crayfish Sub-group, and top basement.
Black and white contour maps of four horizons listed above.
Isometric displays of four horizons.
Image displays of four horizons at approximately 1:250 000 scale, coloured and greyscale.
Customised colour contour maps, isometric displays and images of above data.

Digital data:
Digitized interpretation of 419 seismic lines.
Grid files of time depth and velocity datasets of four horizons (Petroseis gridding including fault files or ER Mapper gridfiles).
Basic petroleum datasets (e.g. well data, seismic shotpoints).

Enquiries - Well data, J. G. G. Moreton, Ph. 08 274 7565; Geophysical data, C. D. Cockshell, Ph. 08 274 7671, Department of Mines and Energy, SA, PO Box 151, Eastwood SA 5063; Fax. 08 373 3269.

- Parker, G., & Rooney, S., 1993. ***Well completion report - Bus Swamp No. 1.*** Geological Survey of Victoria Report No. 1993/23 (unpublished).

NGMA OTWAY BASIN PROJECT - CRUSTAL PROFILES

AGSO
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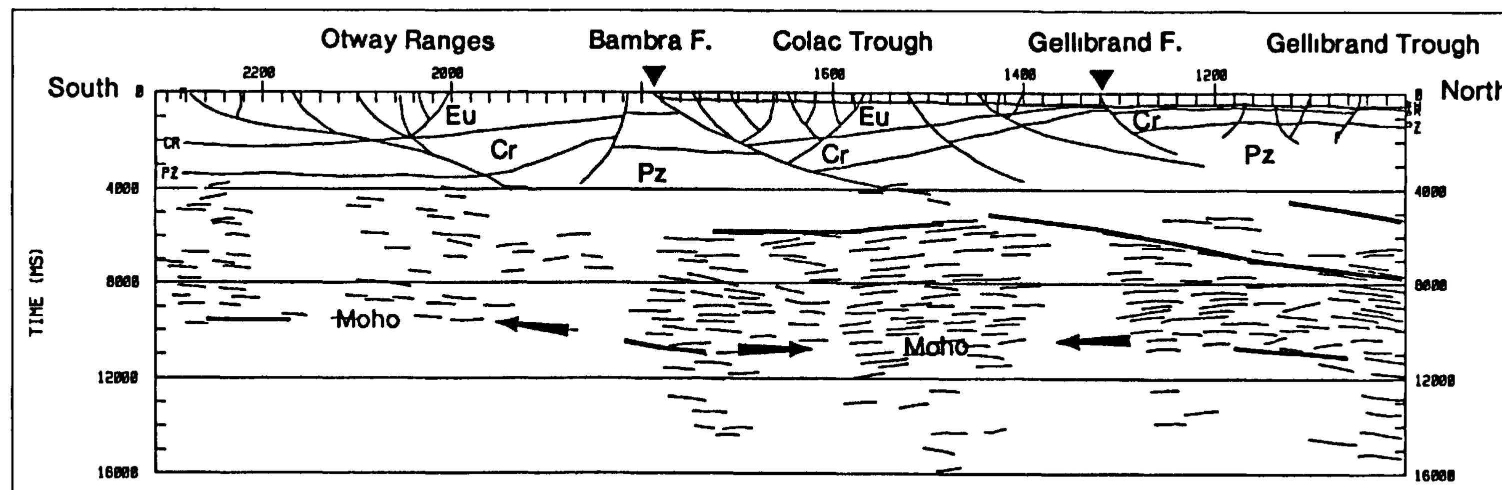


Line 1

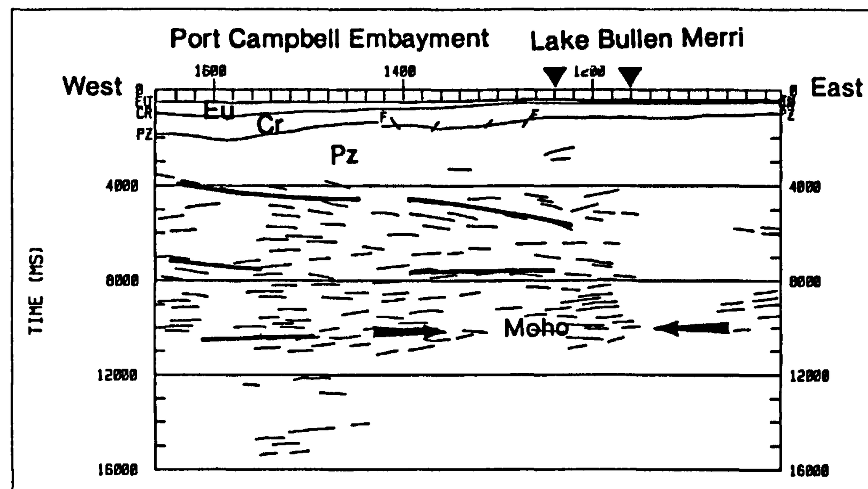
Australian Geological Survey Organisation	
Seismic Line :	BMR92OT1
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.

Interpretation of deep seismic profiles

D. M. Finlayson
Australian Geological Survey Organisation

As part of the National Geoscience Mapping Accord (NGMA) program in the Otway Basin, AGSO acquired deep seismic data (20 s two-way time, TWT) along seven profiles. These data enable major crustal features controlling basin development to be imaged. The 16 s TWT line-diagrams presented in this poster are derived from interpretation of the significant reflection events identified on full-scale seismic sections.

The basin sequences interpreted from shallow seismic data are shown in the upper part of the profiles (0-5 s TWT). Significant reflection horizons can be identified within basement at middle-to-lower crustal levels (5-9 s TWT) and at the crust-mantle boundary (the Moho, 9-12 s TWT). These are highlighted. Shallowing of the Moho and major through-going crustal features are evident on some profiles. A crustal velocity profile and the likely geology based on analysis of crustal and upper mantle xenoliths from the Lake Bullen Merri region (AGSO Line 2) are also shown.



Line 2

Australian Geological Survey Organisation	
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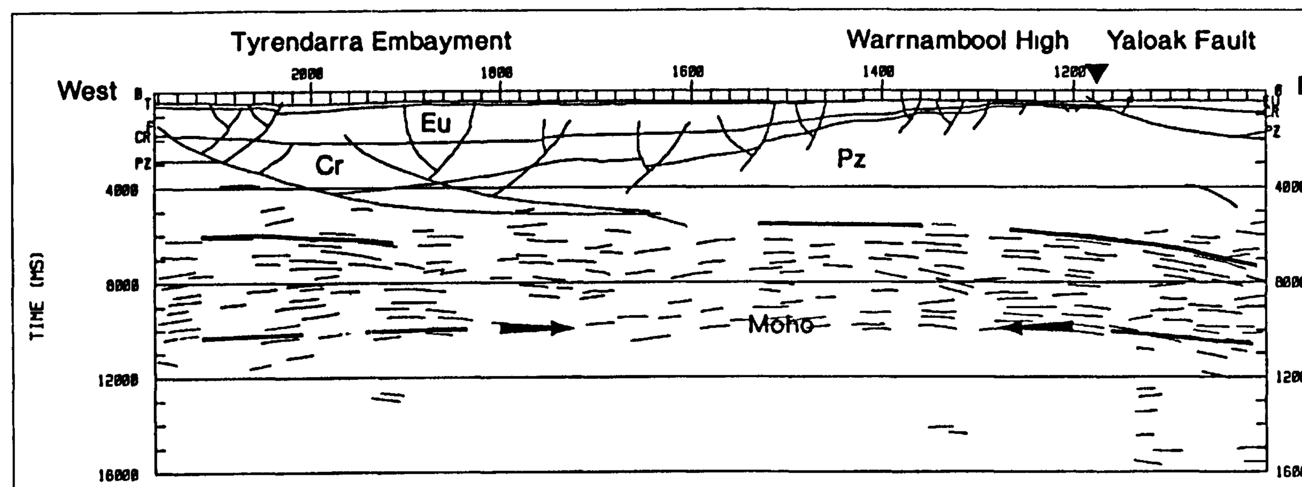

Line 3

Australian Geological Survey Organisation	
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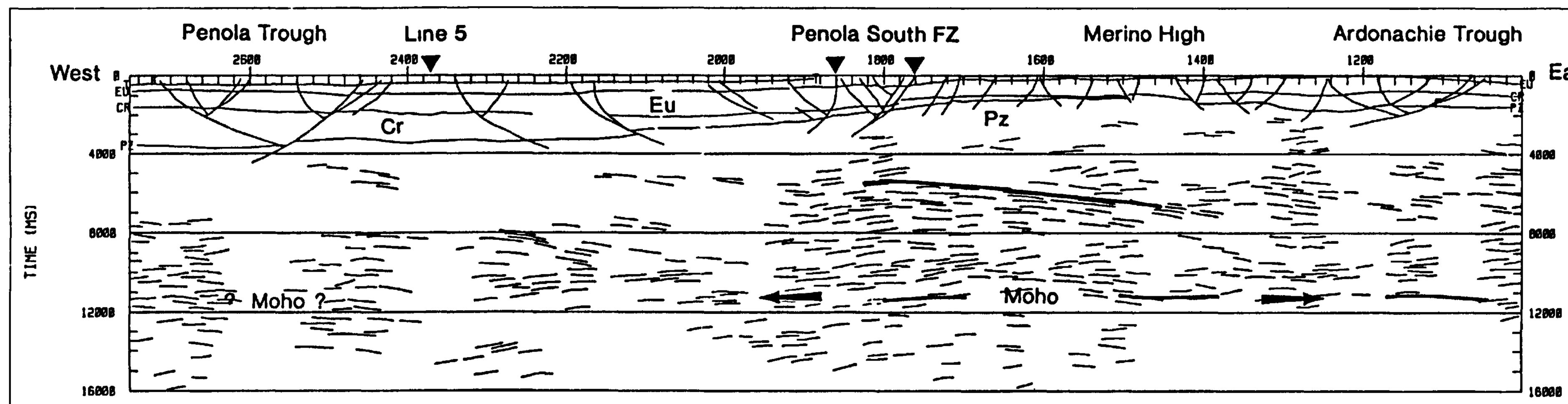
Vertical Scale :	1 cm = 2 sec



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Australian Geological Survey Organisation	
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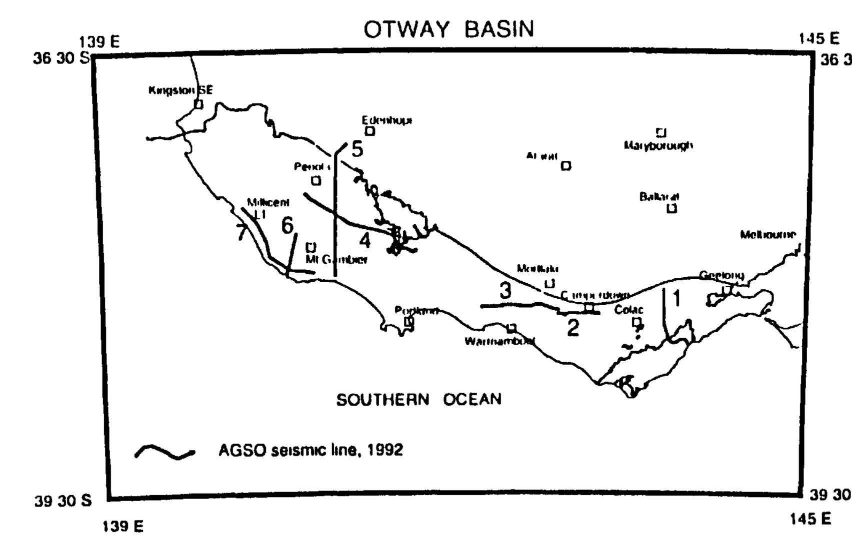
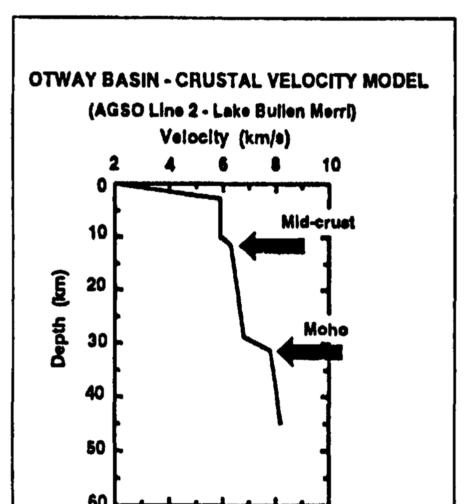
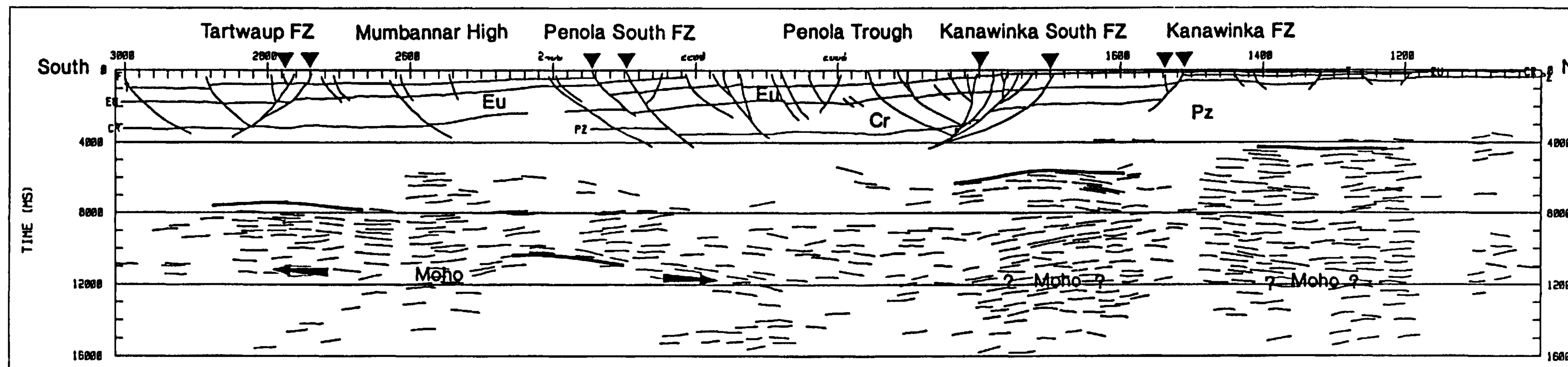




From - Finlayson & Collins, 1993



Line 5

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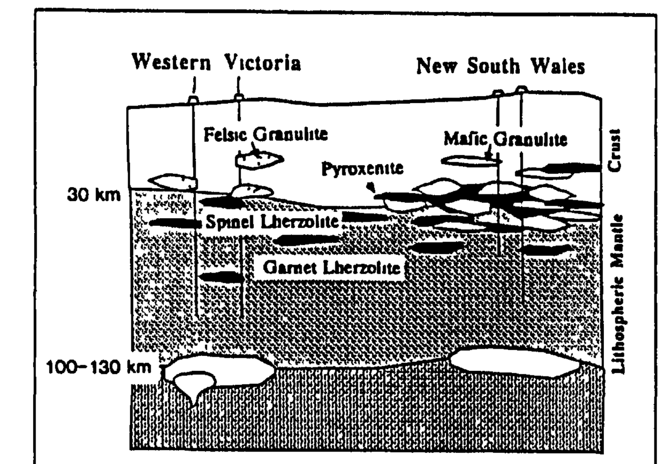
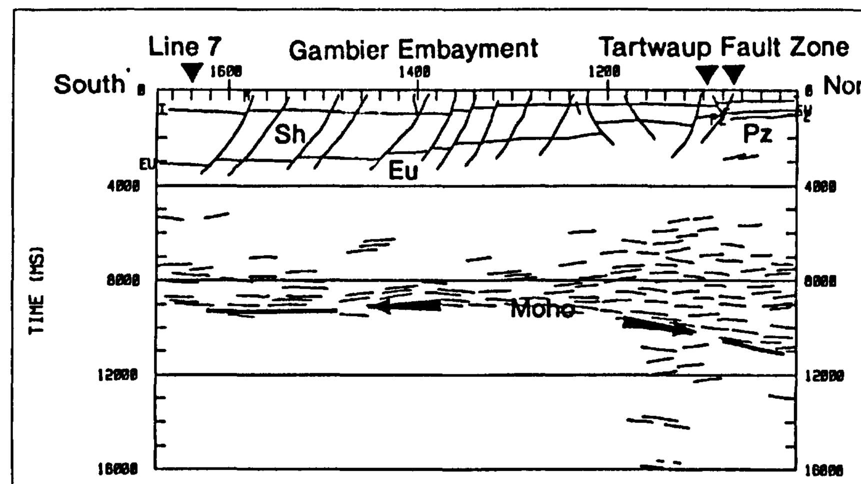
Vertical Scale :	1 cm = 2 sec



Adapted from - McDonough, Rudnick & McCulloch, 1991



Line 6

Australian Geological Survey Organisation	
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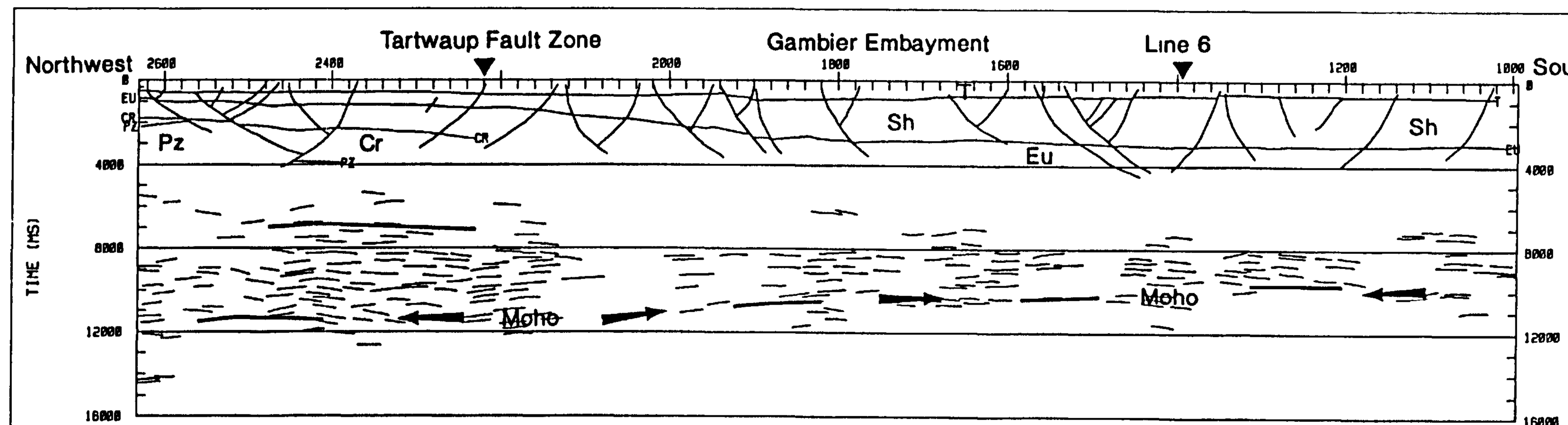
Vertical Scale :	1 cm = 2 sec.



Line 7

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT7
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec

Figure 3 - (Finlayson, Johnstone, Owen & Wake-Dyster) Crustal profiles along 1992 AGSO deep seismic lines 1 to 7 across onshore areas of the Otway Basin. Note on scales: this poster is a 75% reduction from the original.

NGMA OTWAY BASIN PROJECT - CRUSTAL PROFILES

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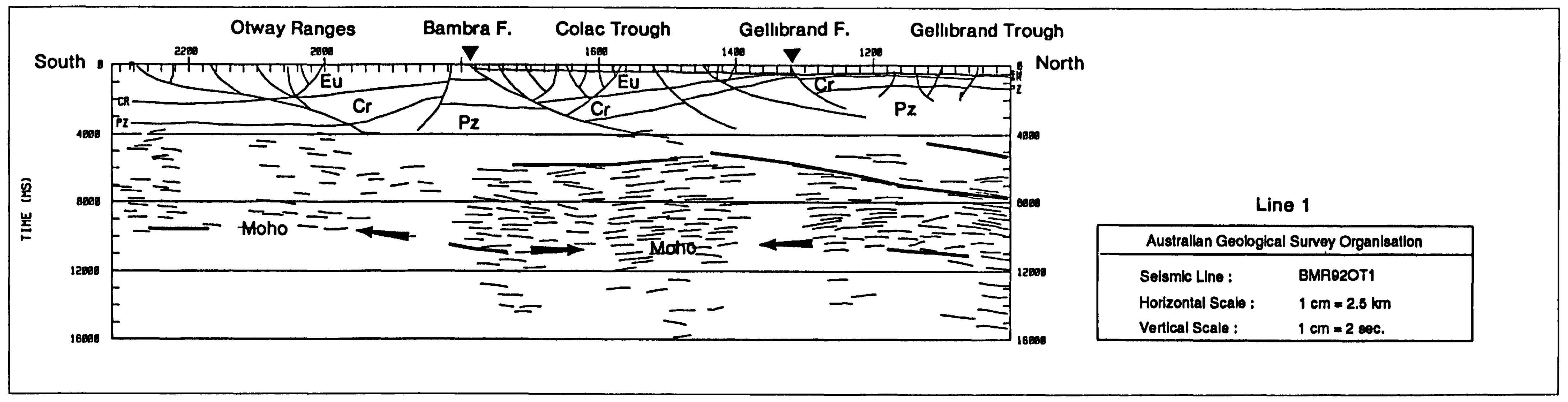

Interpretation of deep seismic profiles

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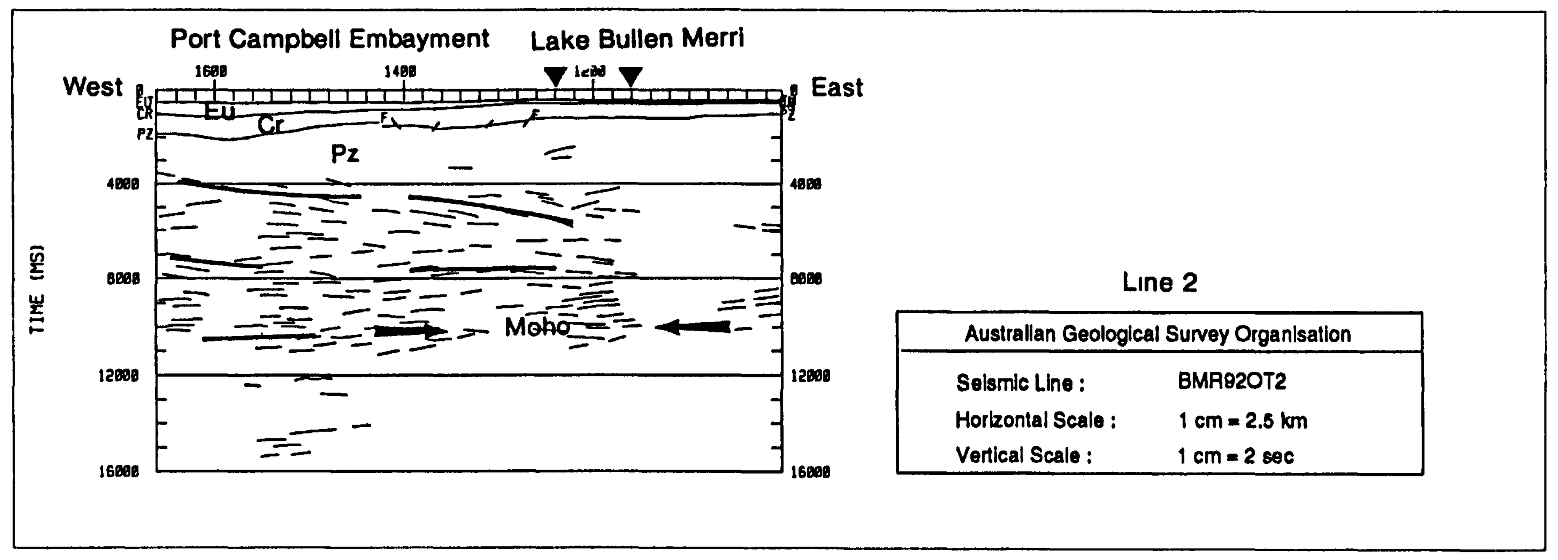

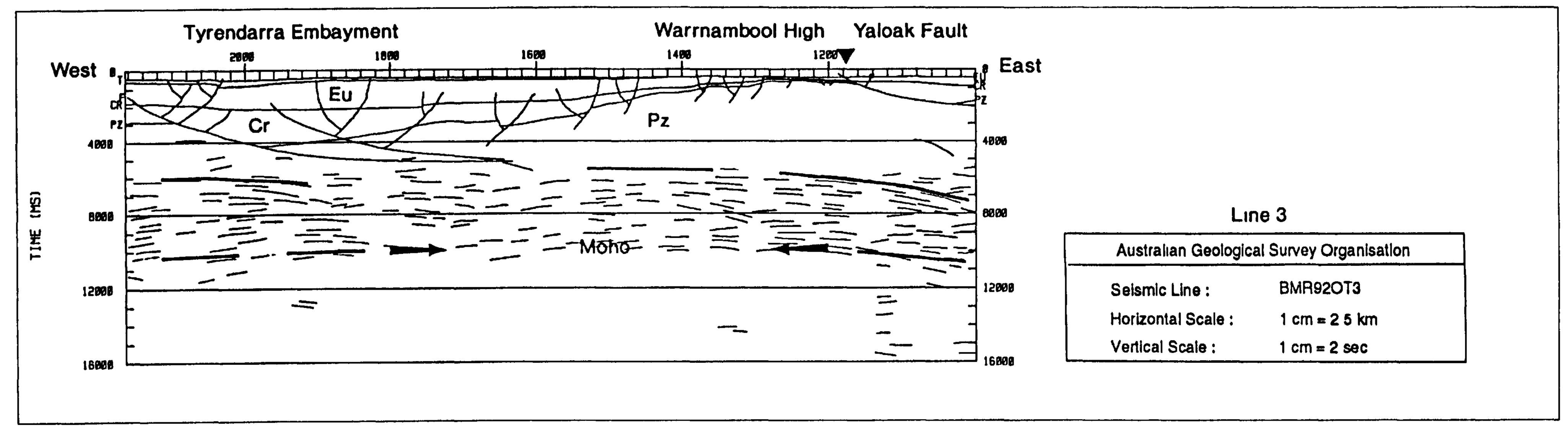

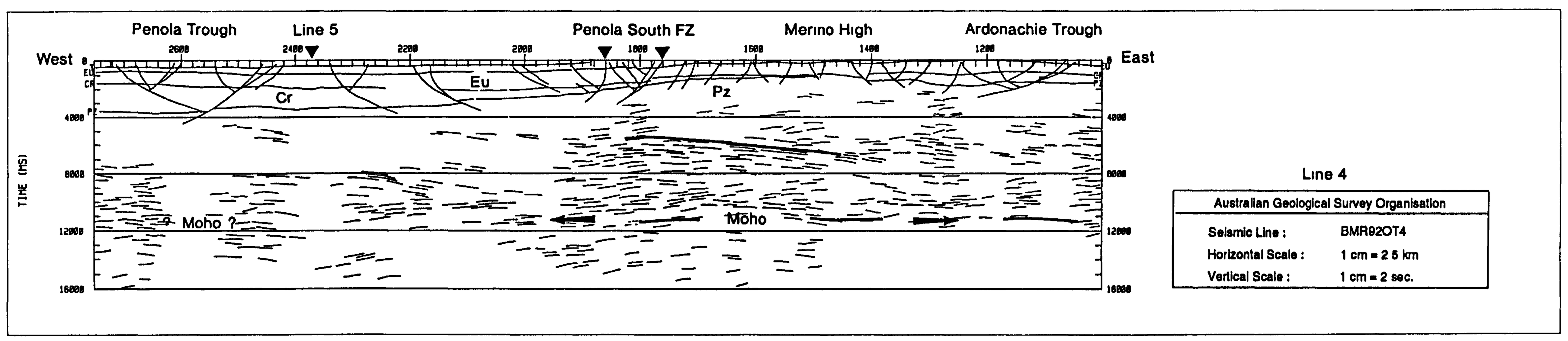

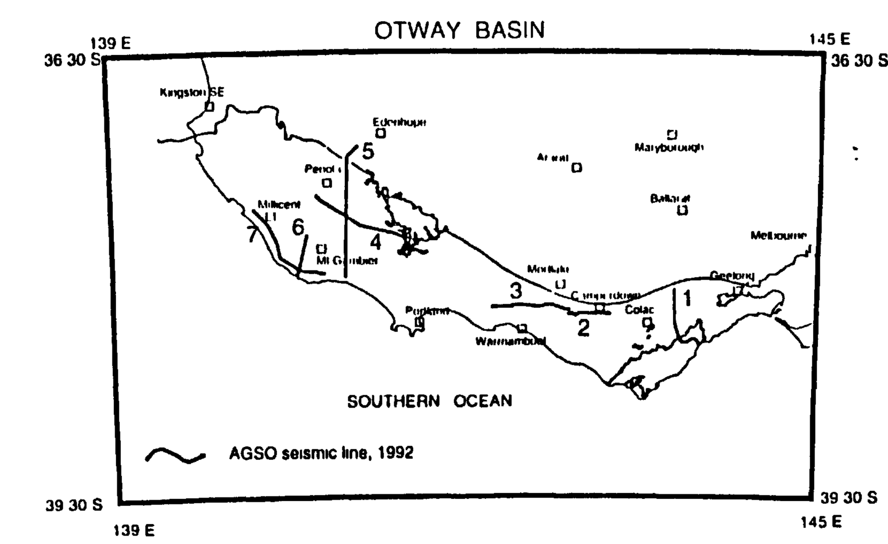

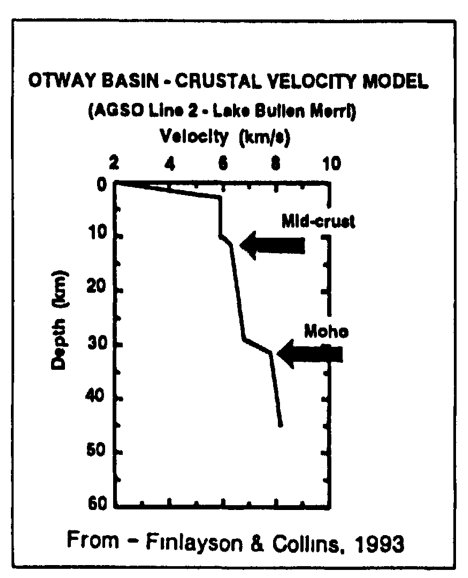

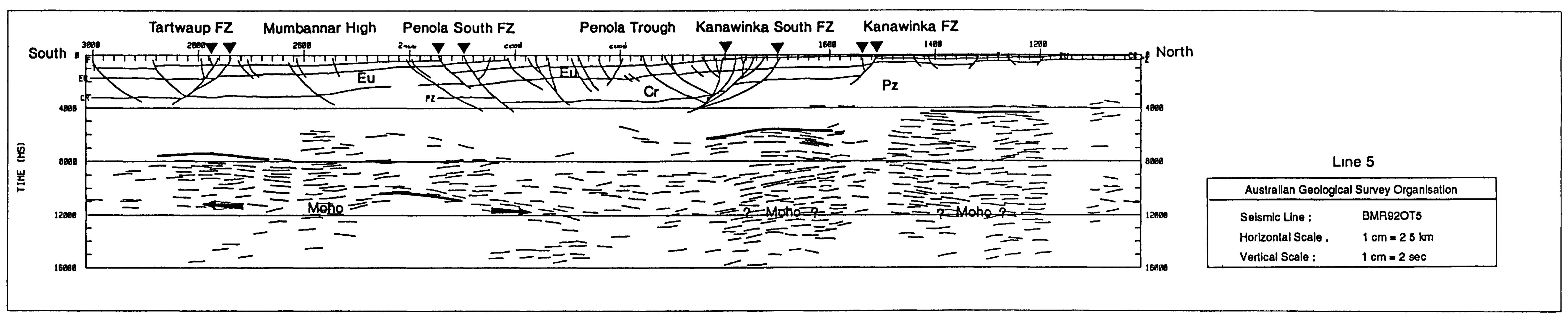

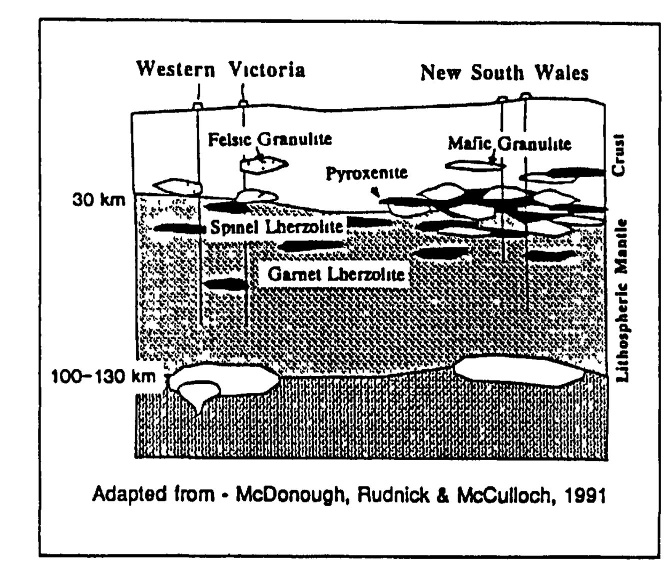

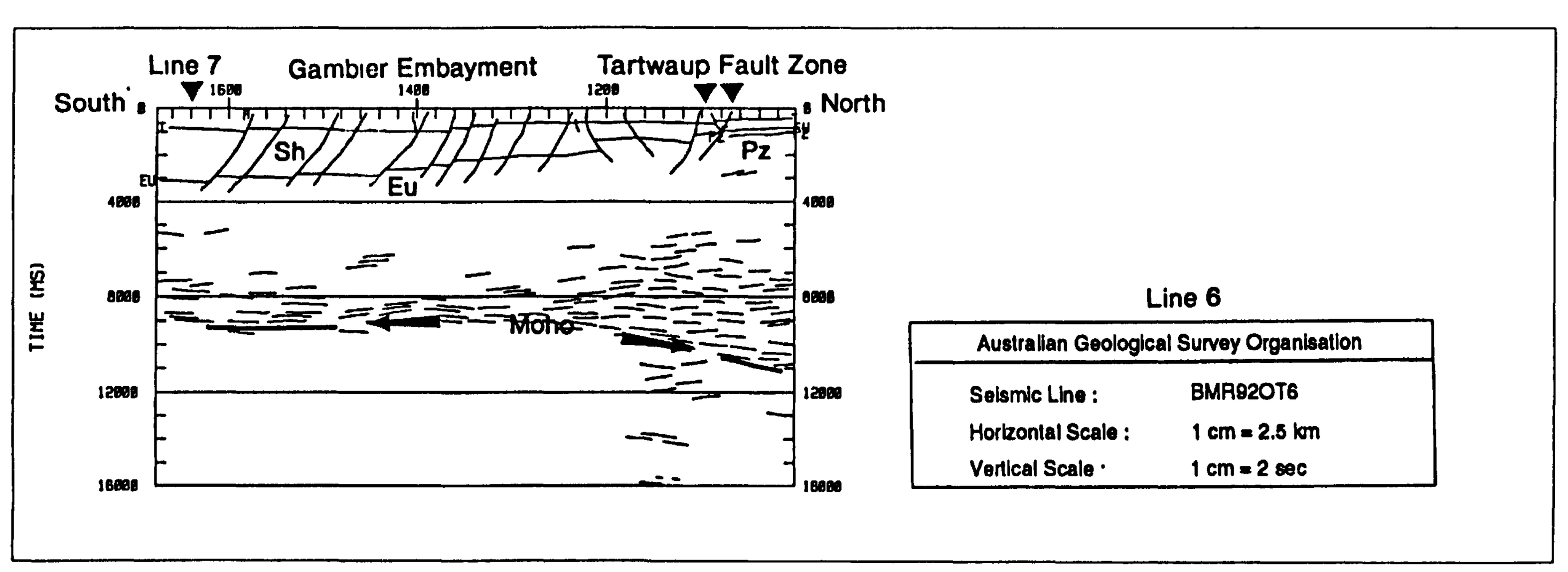

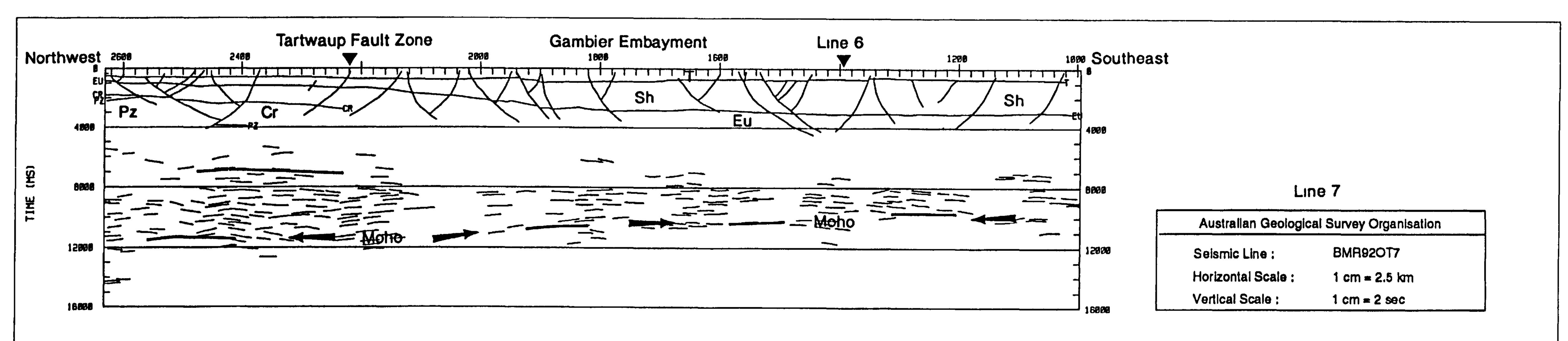

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NGMA OTWAY BASIN PROJECT - CRUSTAL PROFILES

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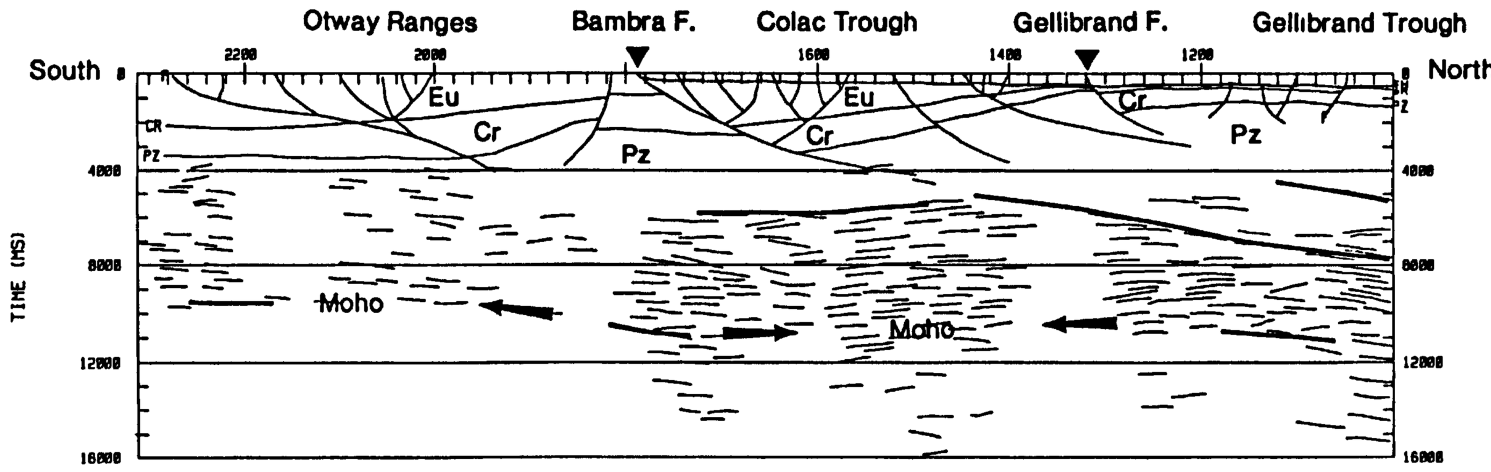

Line 1

Australian Geological Survey Organisation	
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Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.

Interpretation of deep seismic profiles

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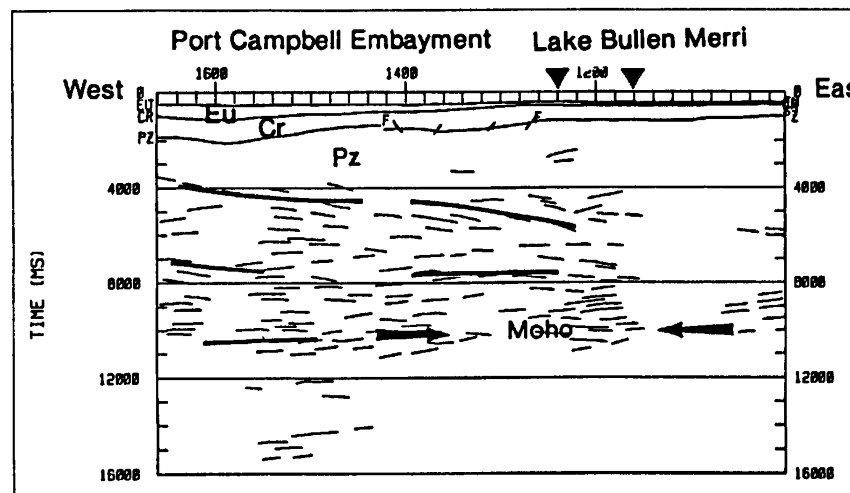

Line 2

Australian Geological Survey Organisation	
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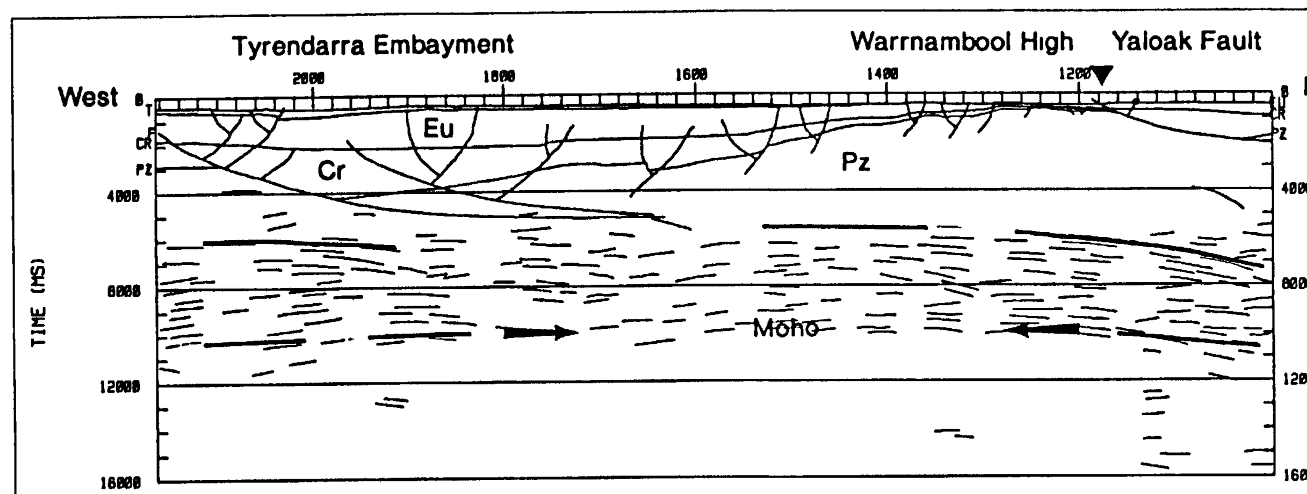
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



Line 3

Australian Geological Survey Organisation	
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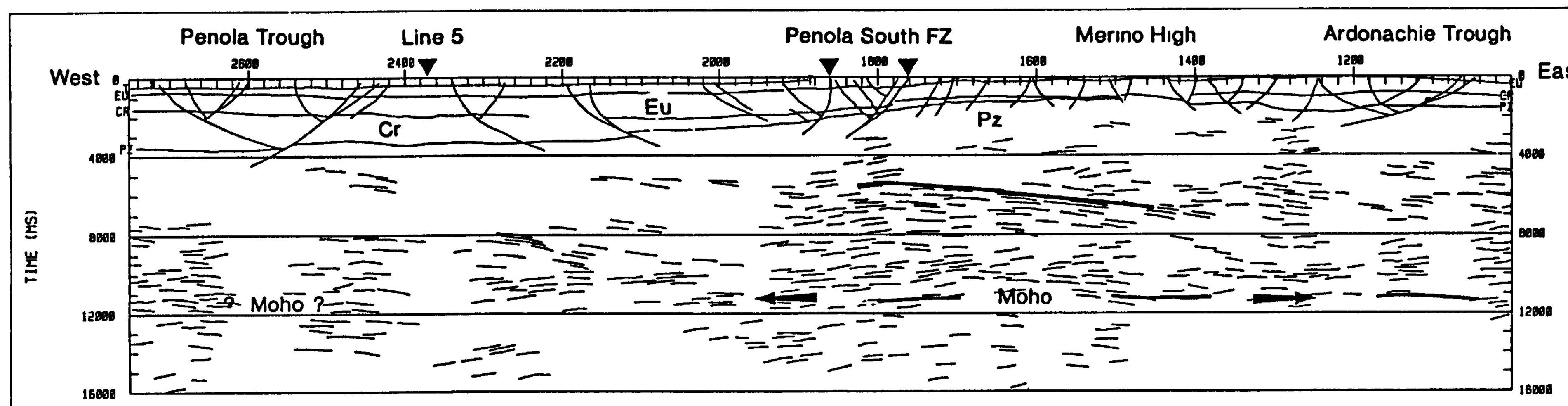
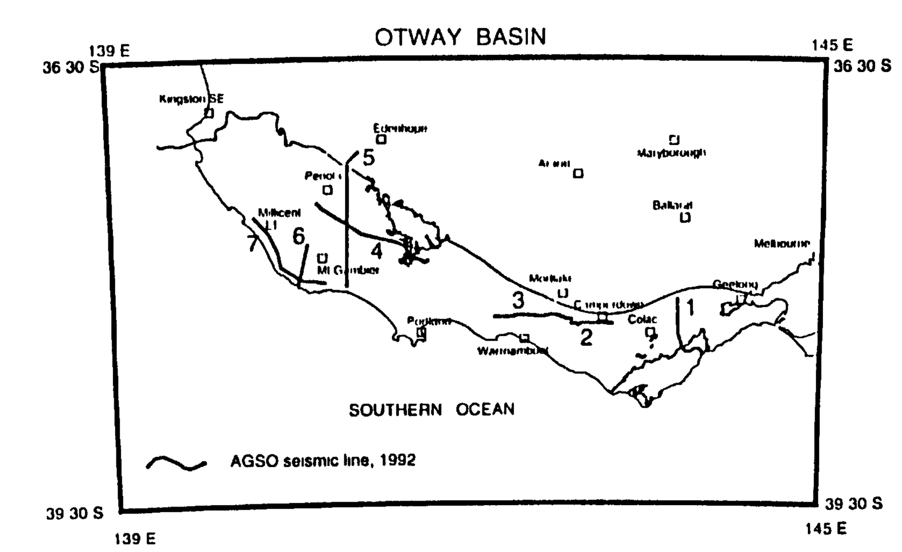
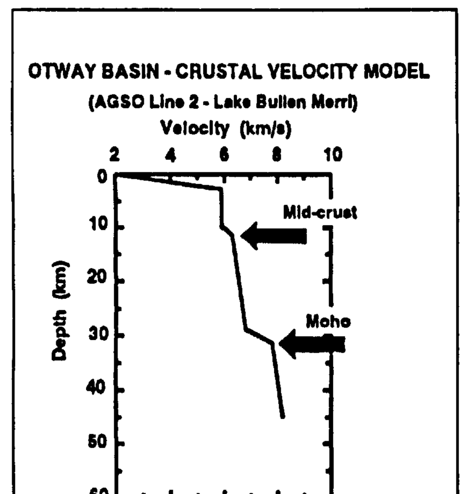
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec



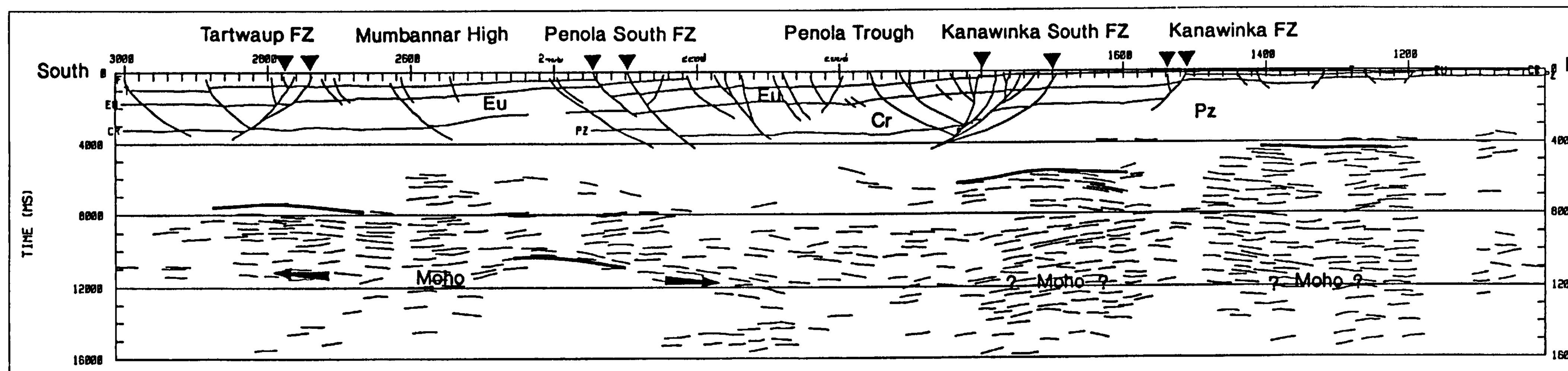
Line 4

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT4
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec



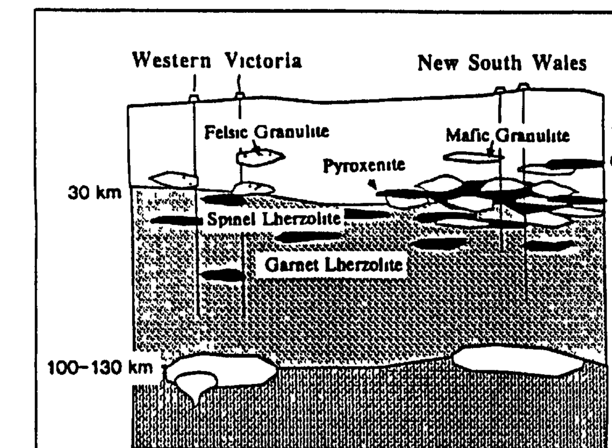


From - Finlayson & Collins, 1993

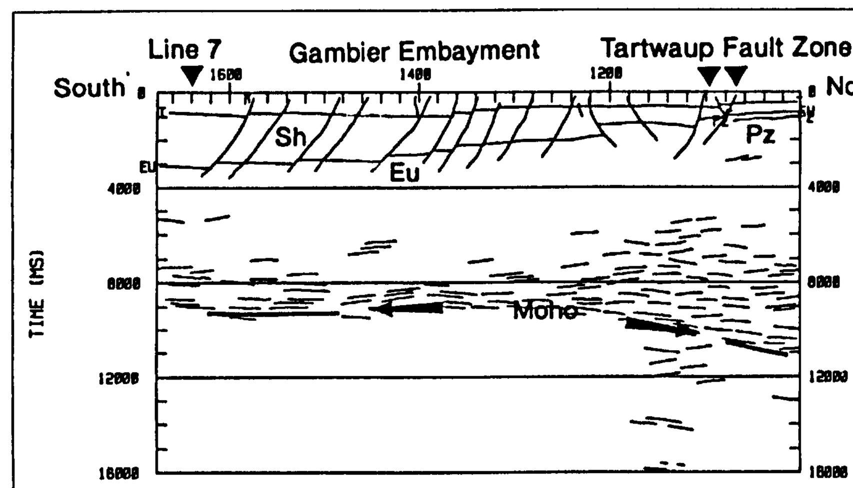


Line 5

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT5
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec

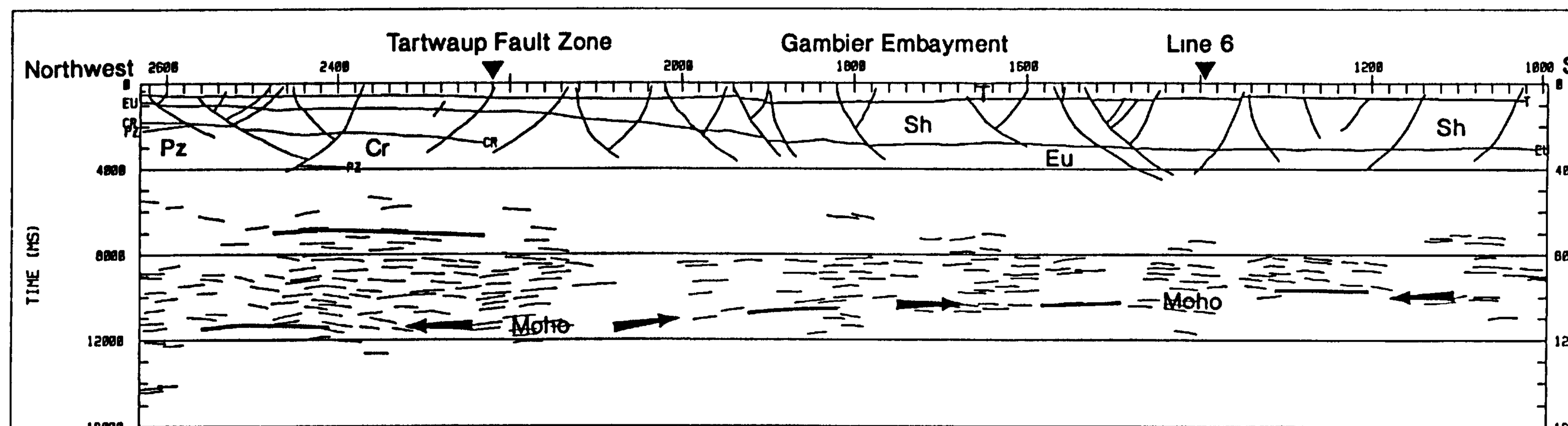


Adapted from - McDonough, Rudnick & McCulloch, 1991



Line 6

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT6
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



Line 7

Australian Geological Survey Organisation	
Seismic Line .	BMR92OT7
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec

Figure 3 - (Finlayson, Johnstone, Owen & Wake-Dyster) Crustal profiles along 1992 AGSO deep seismic lines 1 to 7 across onshore areas of the Otway Basin. Note on scales: this poster is a 75% reduction from the original.

NGMA OTWAY BASIN PROJECT - CRUSTAL PROFILES

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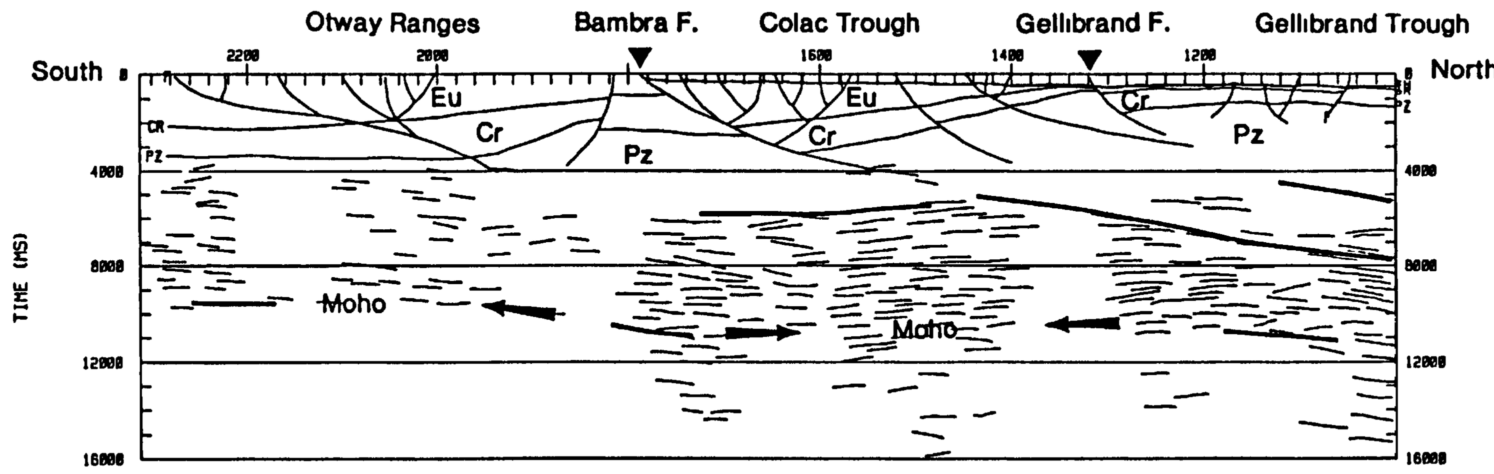

Line 1

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT1
Horizontal Scale :	1 cm = 2.5 km
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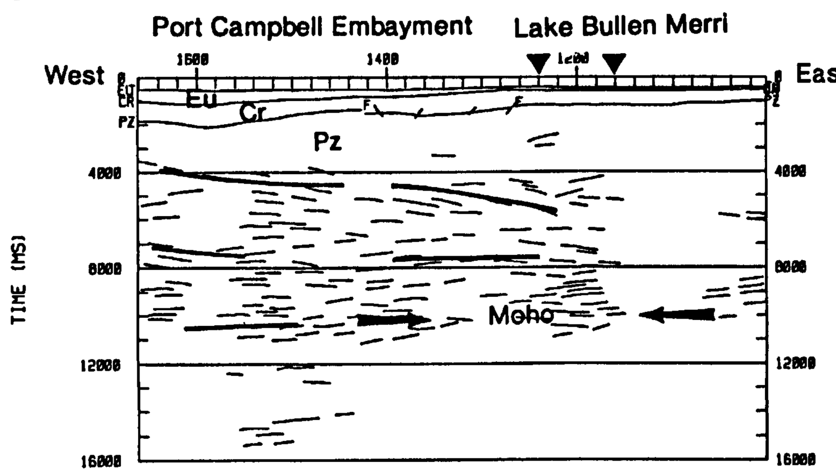
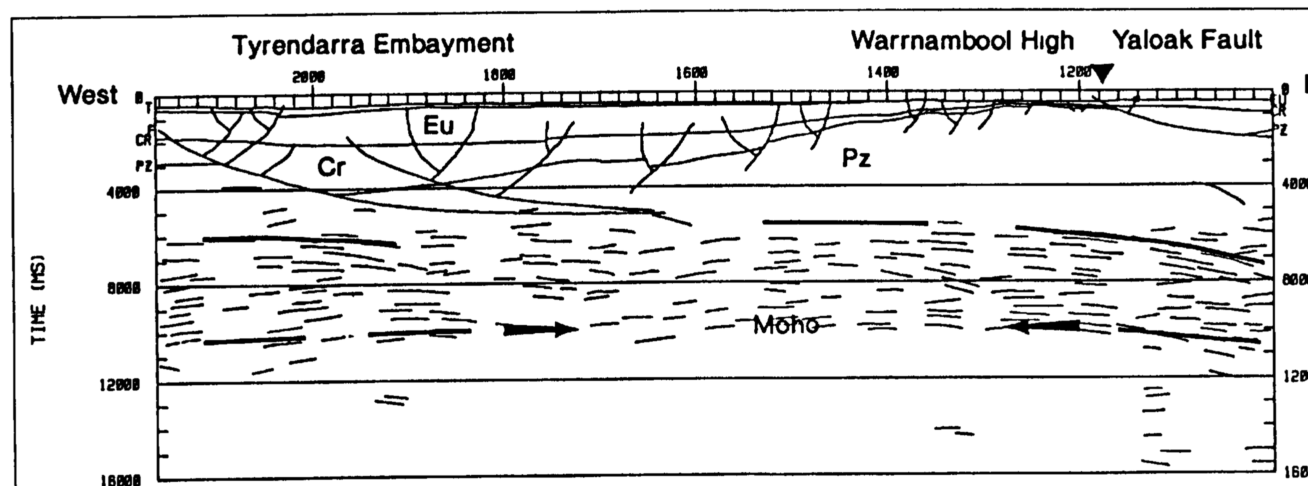


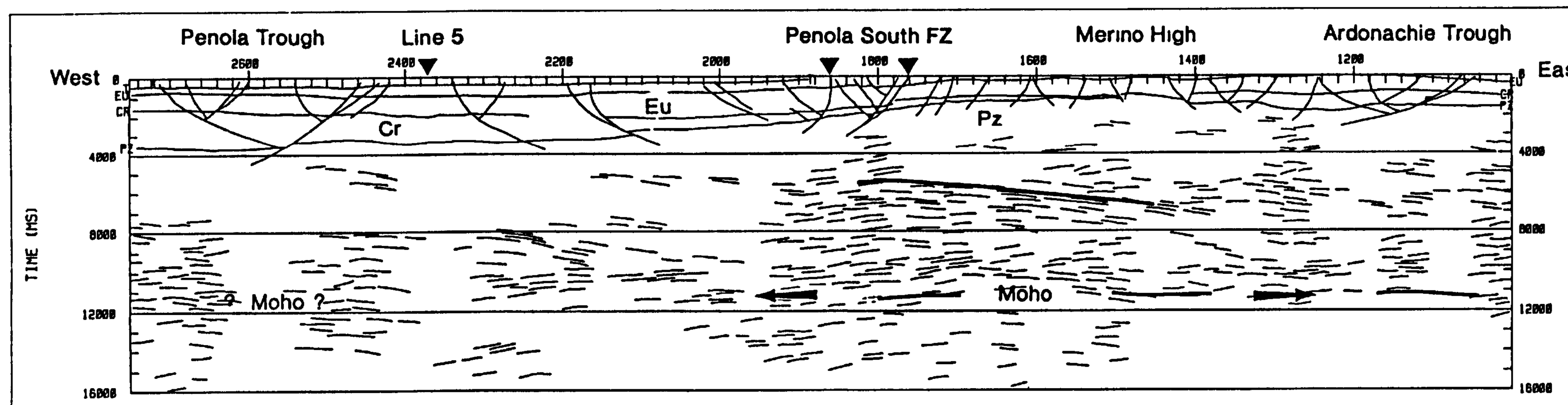
Line 2

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT2
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec



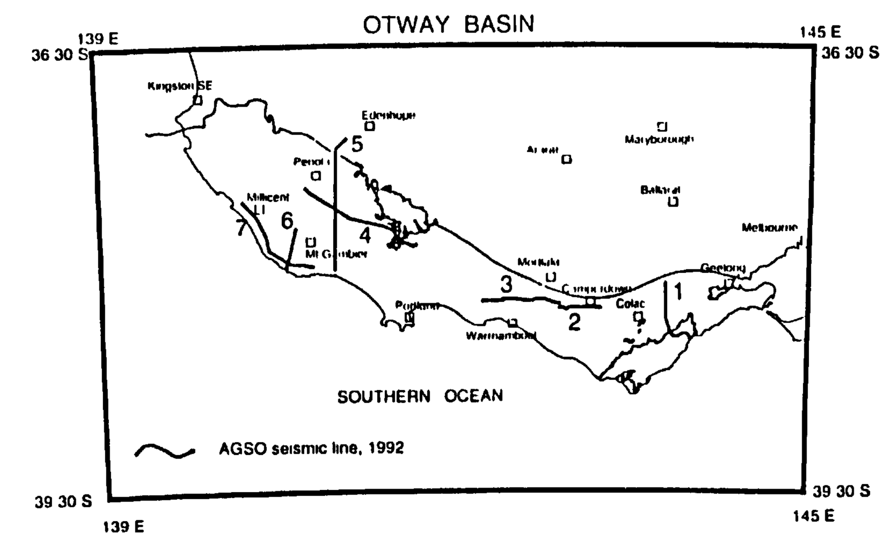
Line 3

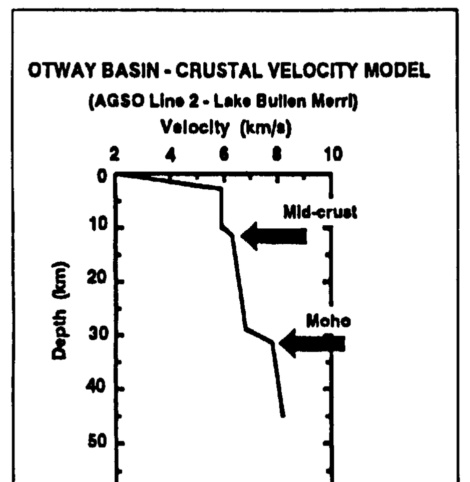
Australian Geological Survey Organisation	
Seismic Line :	BMR92OT3
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec



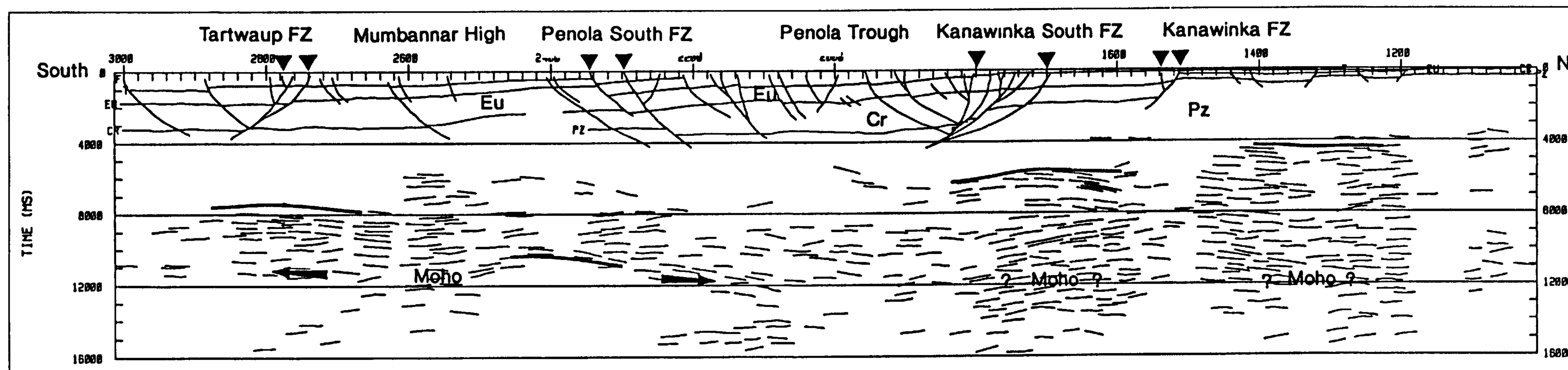
Line 4

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT4
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec



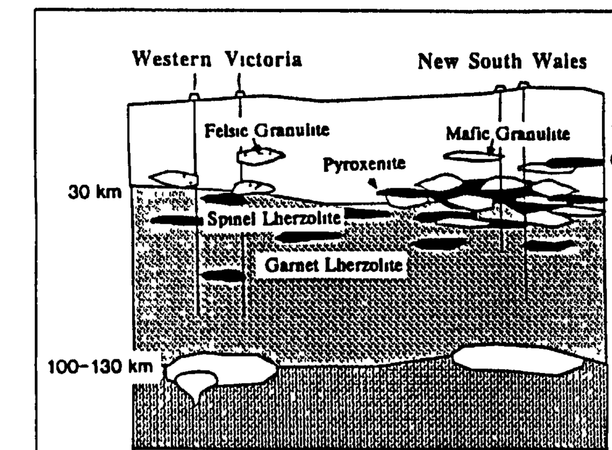


From - Finlayson & Collins, 1993

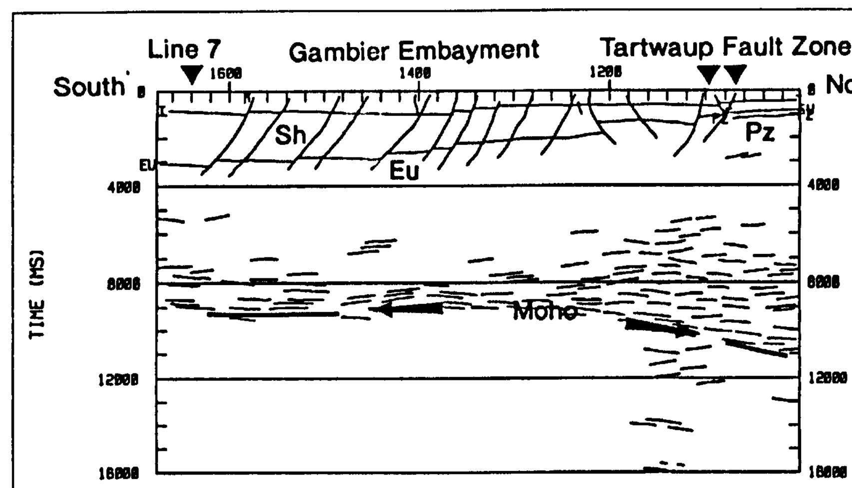


Line 5

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT5
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec

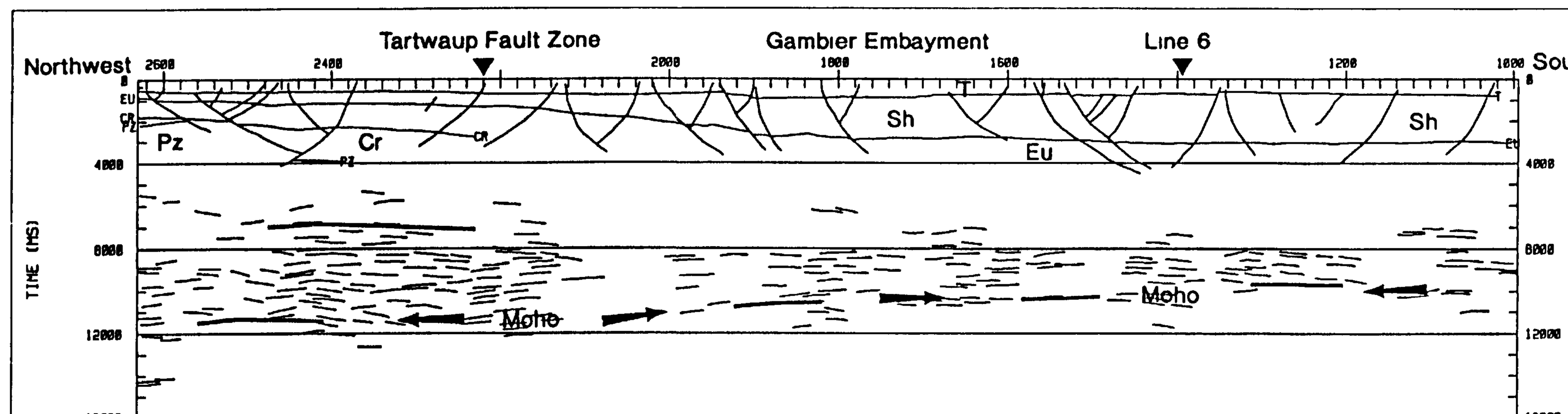


Adapted from - McDonough, Rudnick & McCulloch, 1991



Line 6

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT6
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec



Line 7

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT7
Horizontal Scale .	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec.

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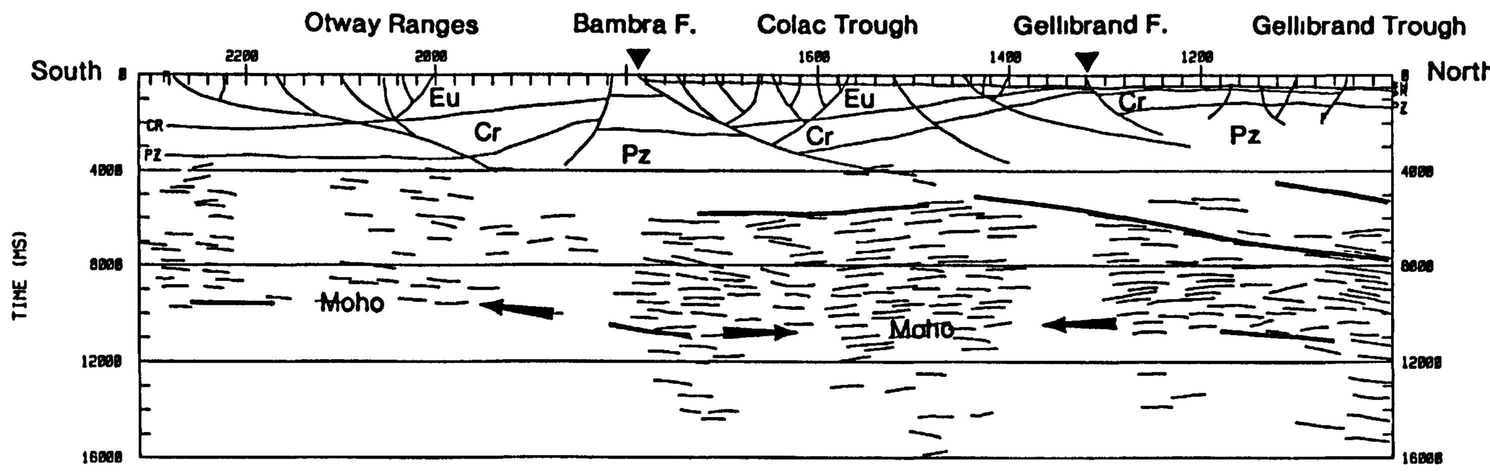

Line 1

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT1
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec

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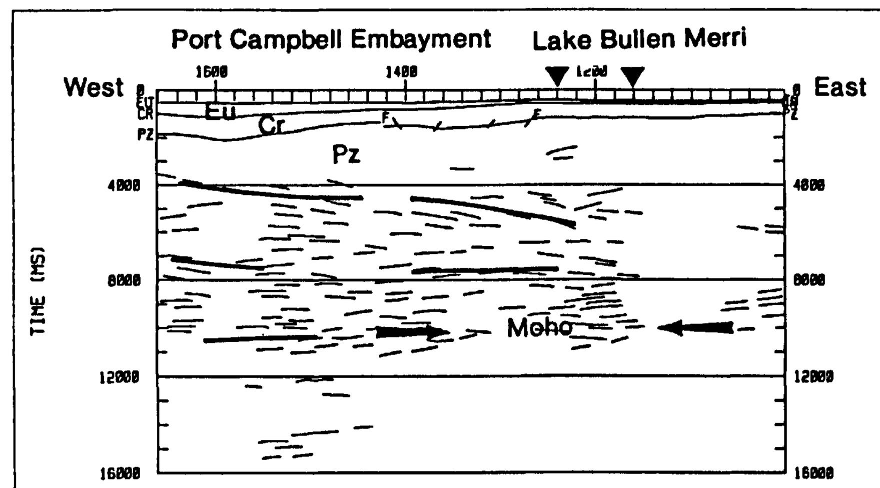
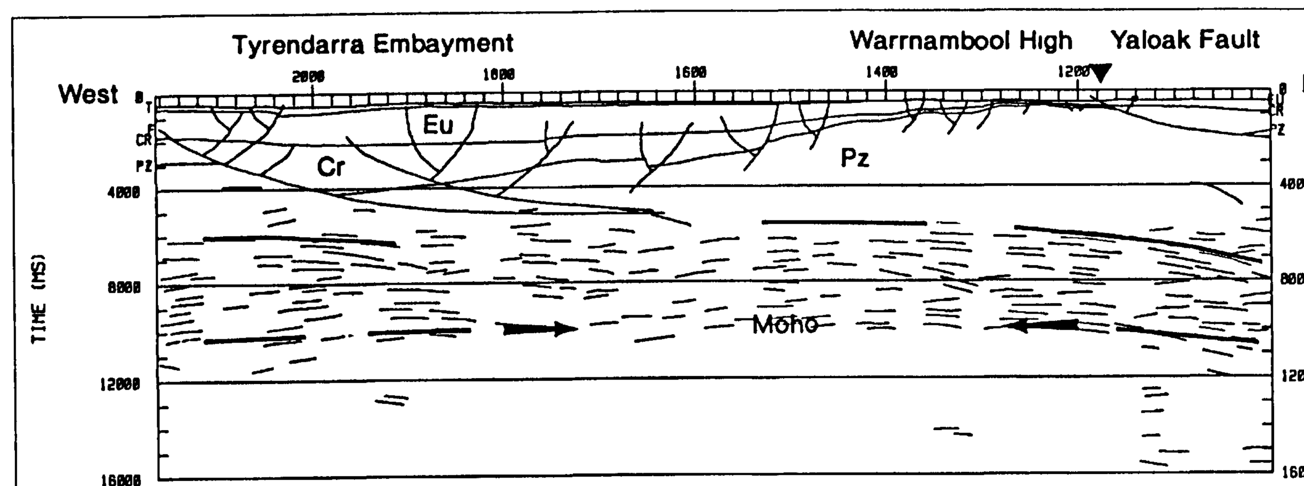


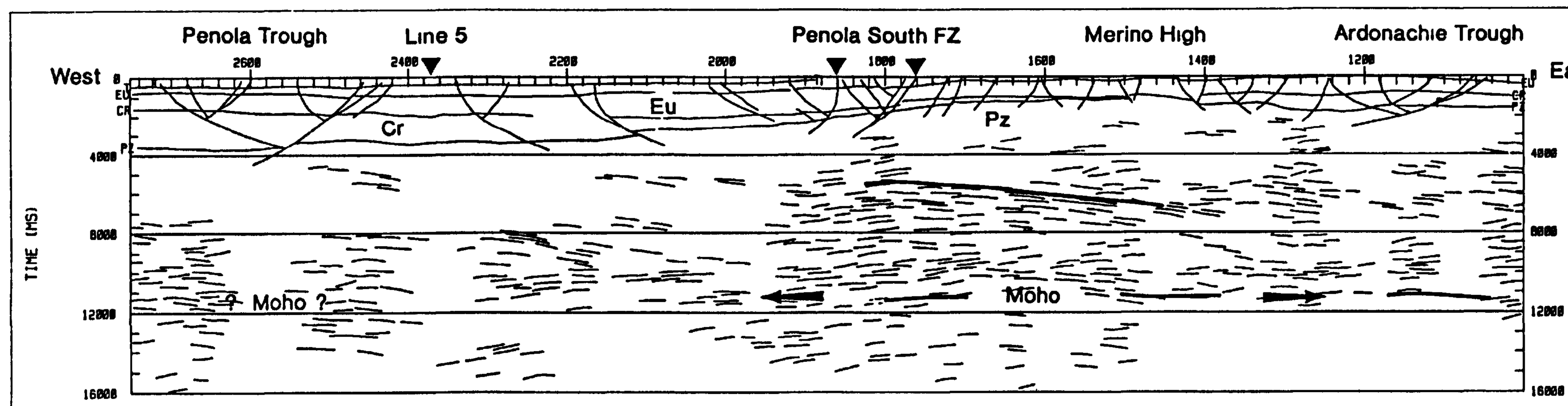
Line 2

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT2
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



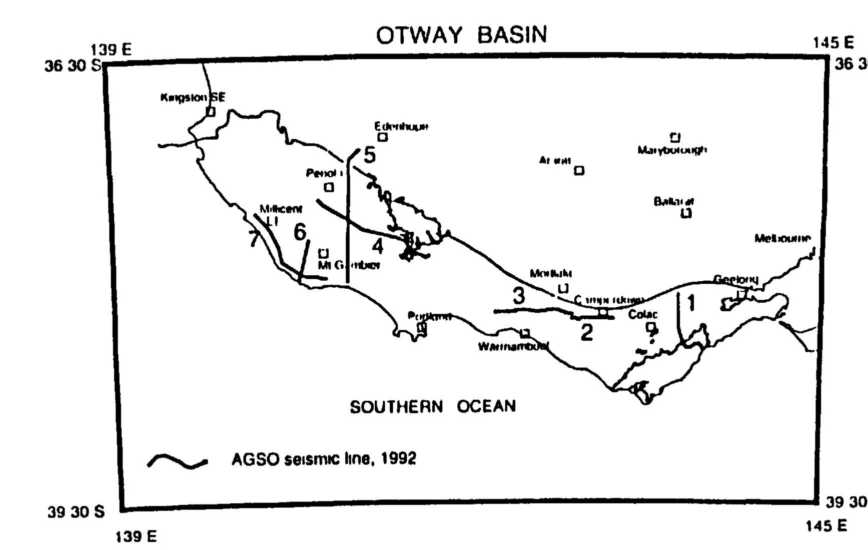
Line 3

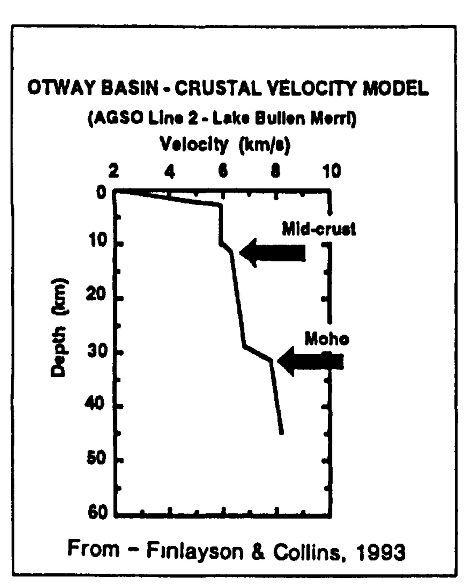
Australian Geological Survey Organisation	
Seismic Line :	BMR92OT3
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec

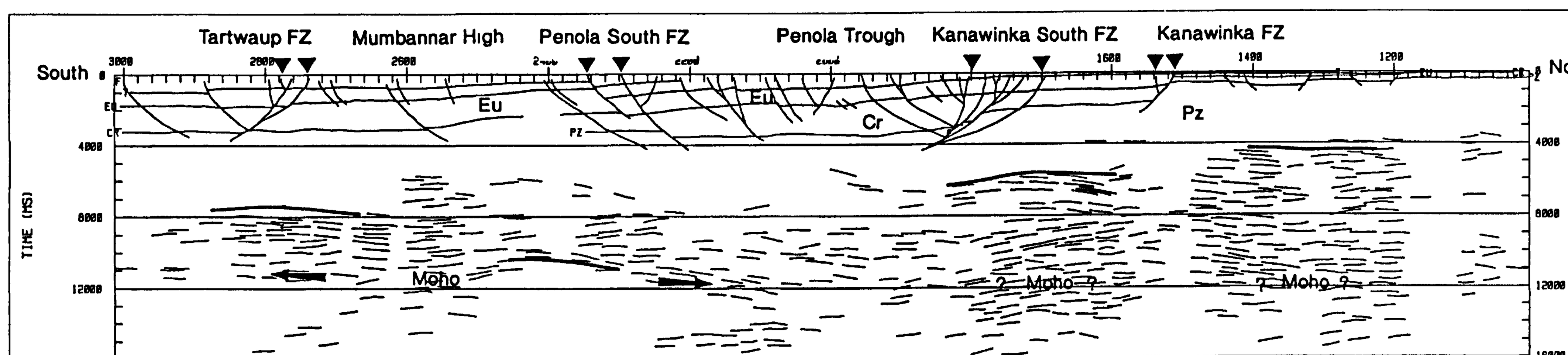


Line 4

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT4
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec.

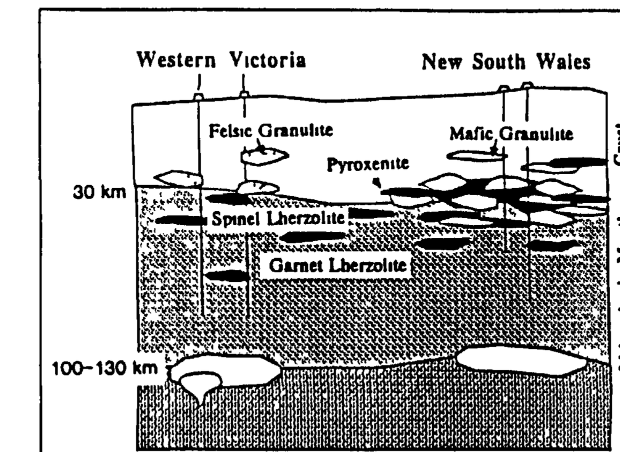






Line 5

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT5
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec



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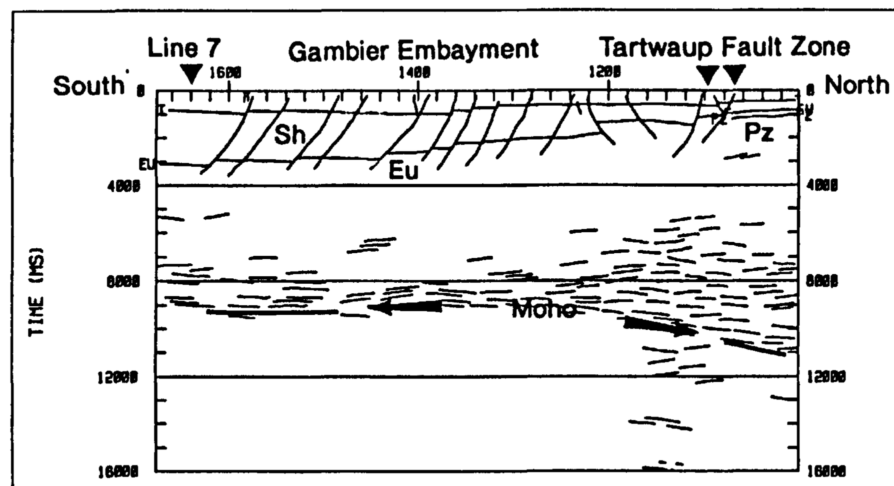
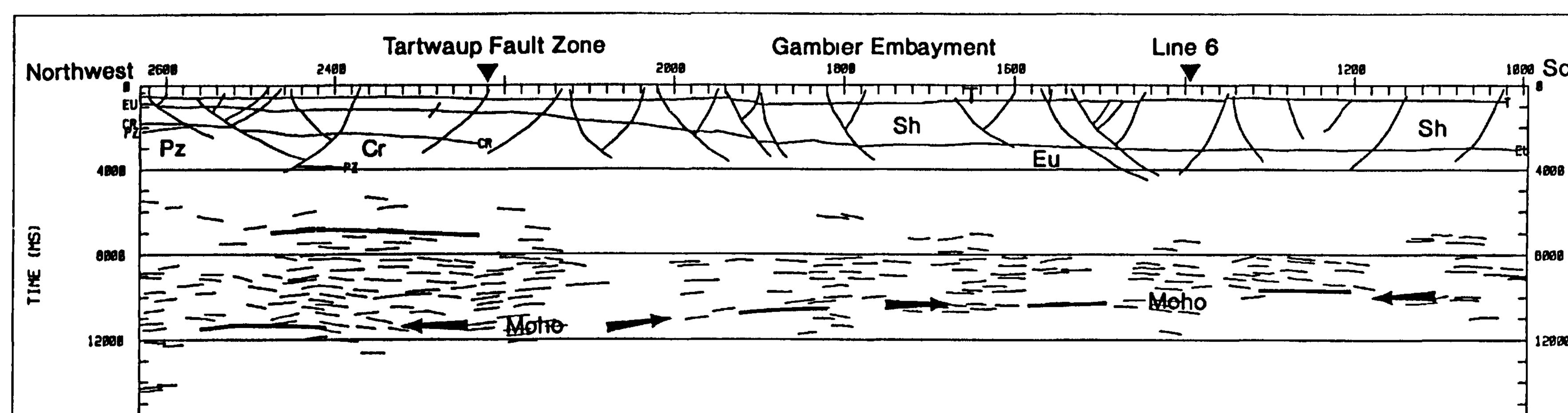


Line 6

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT6
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



Line 7

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT7
Horizontal Scale :	1 cm = 2 5 km
Vertical Scale :	1 cm = 2 sec

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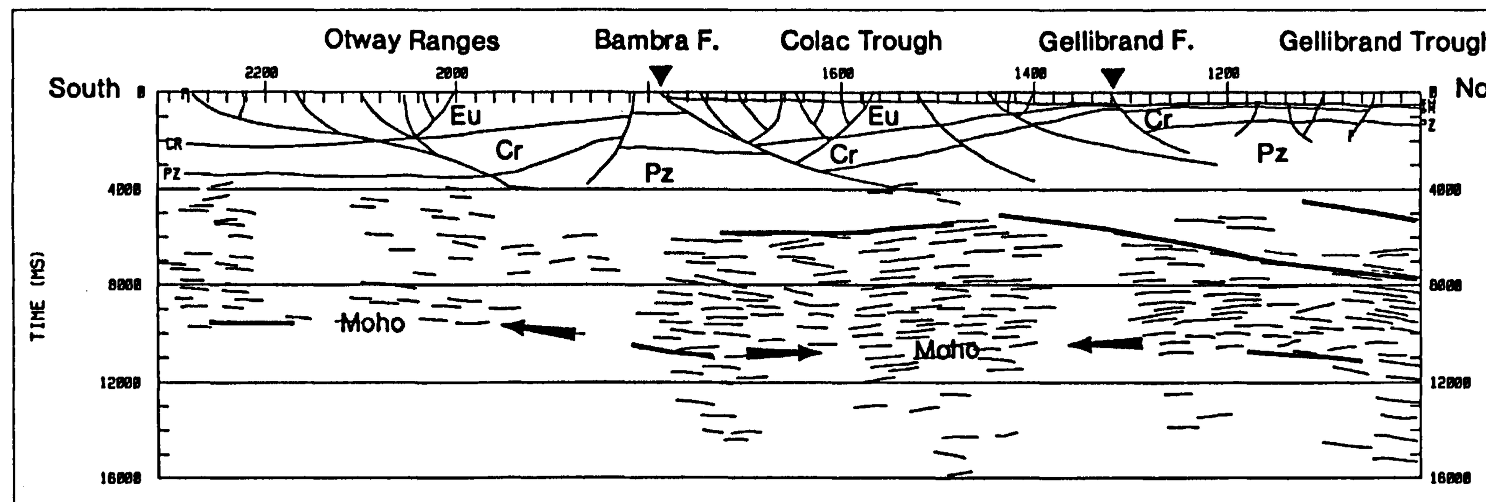

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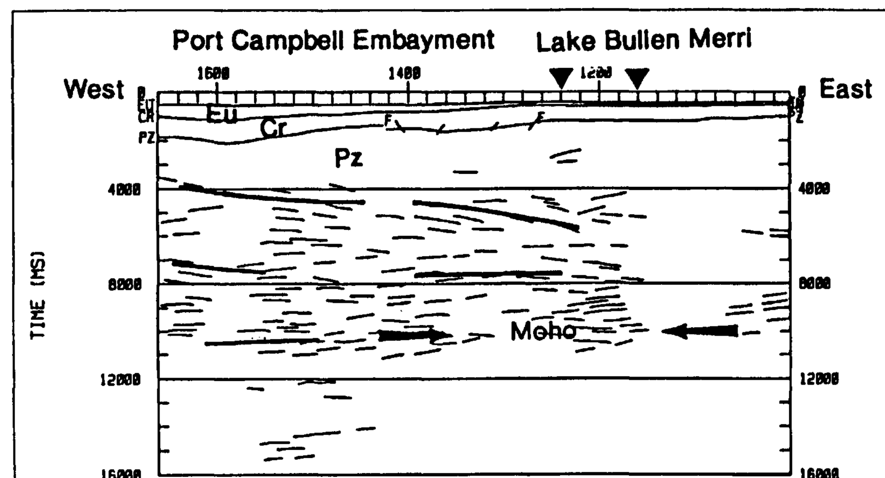
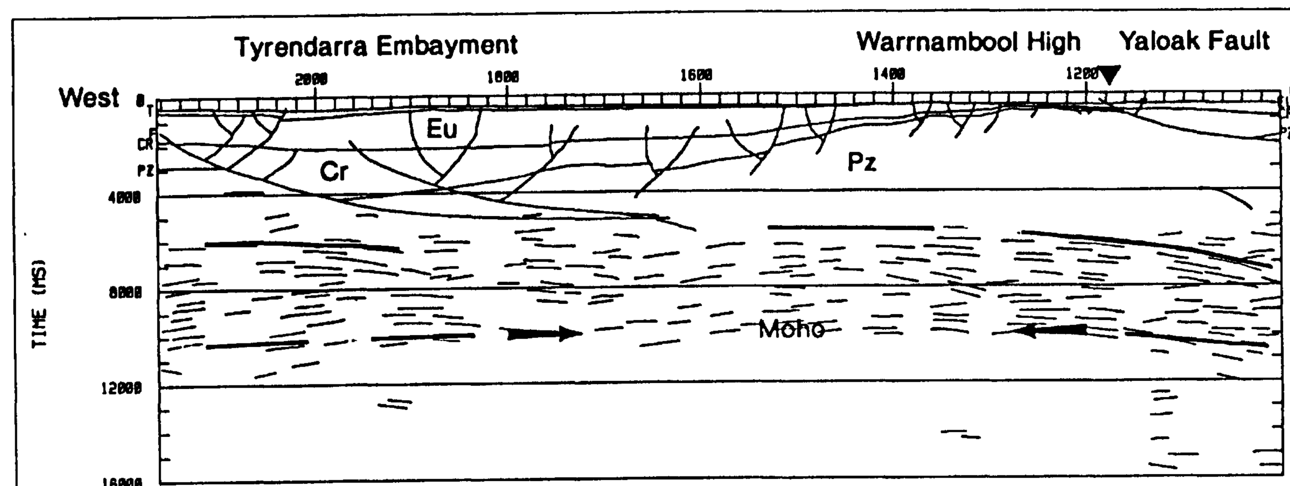


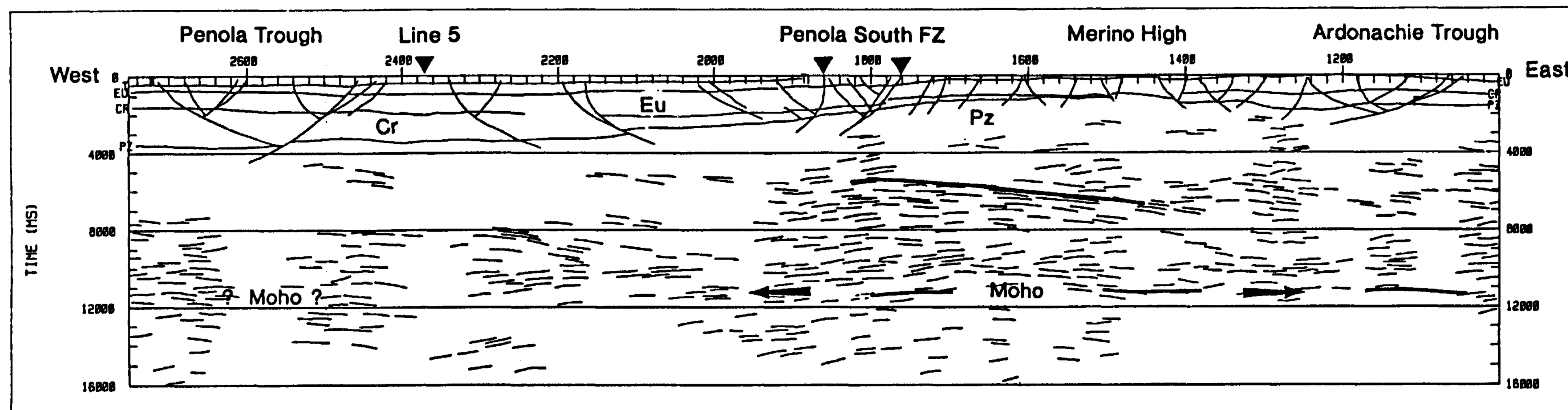
Line 2

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT2
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



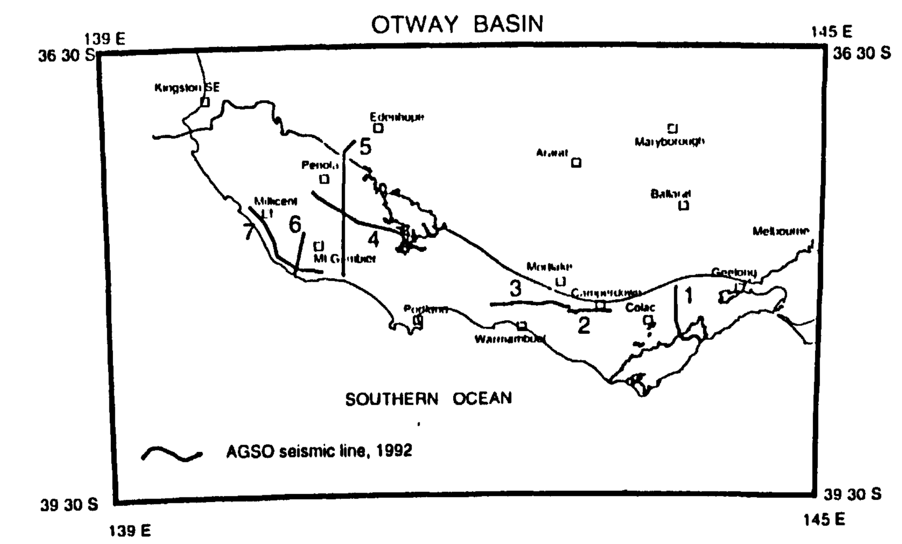
Line 3

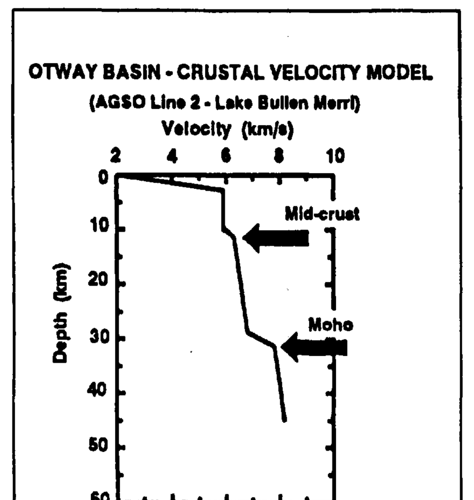
Australian Geological Survey Organisation	
Seismic Line :	BMR92OT3
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



Line 4

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT4
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.





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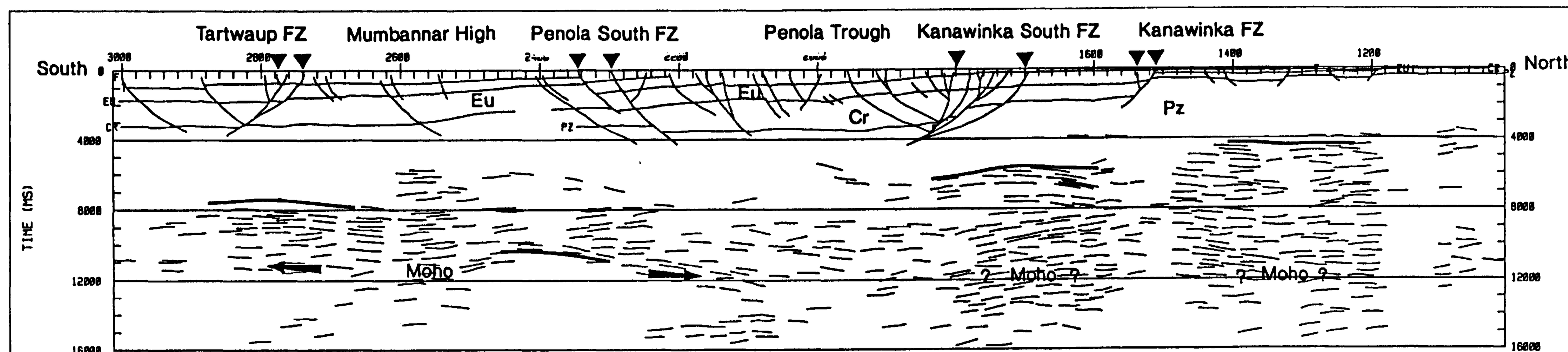
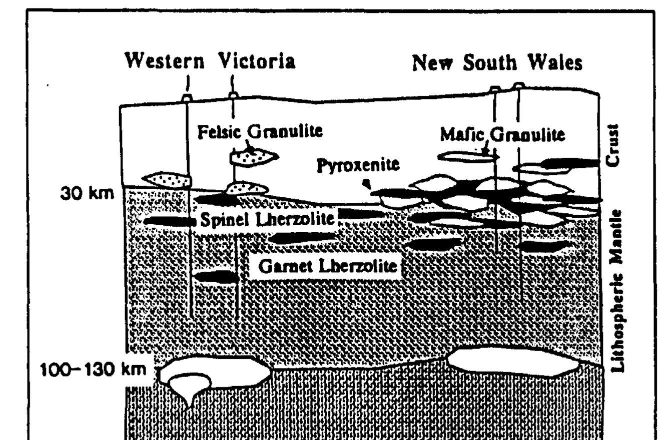


Line 5

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT5
Horizontal Scale :	1 cm = 2.5 km
Vertical Scale :	1 cm = 2 sec.



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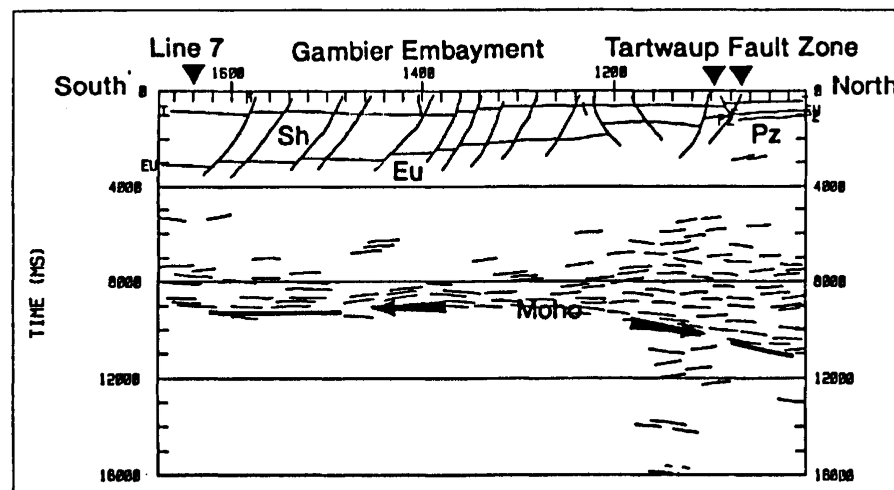

Line 6

Australian Geological Survey Organisation	
Seismic Line :	BMR92OT6
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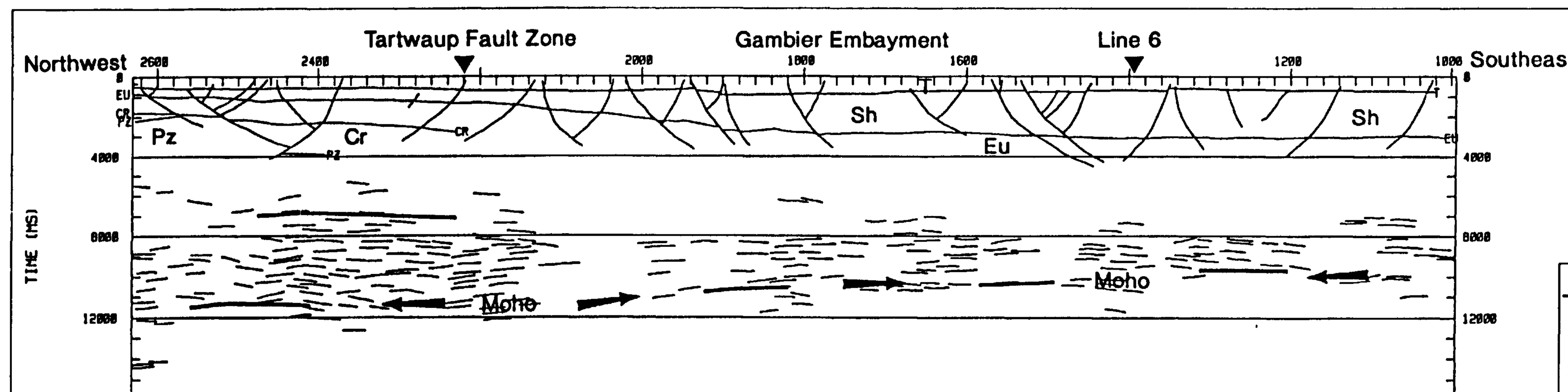
Vertical Scale :	1 cm = 2 sec.



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Australian Geological Survey Organisation	
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