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# Western Otway Basin 1992 Aeromagnetic Dataset: Images and Interpretation

*by*

*C V Reeves, G W O'Brien, D M Finlayson, P R Milligan, M P Morse, R C Brodie & J B Willcox*

## RECORD 1993/14



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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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**Australian Geological Survey Organisation**

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## *SUMMARY*

Late in 1992 the Australian Geological Survey Organisation carried out a 14 200 km high resolution aeromagnetic survey in the western onshore and offshore Otway Basin, south-eastern Australia. The located profile data released for this survey have been gridded, image-processed and interpreted - in conjunction with gravity, geological and other data - to provide new insights into the tectonic evolution of the western Otway Basin.

The principal findings are:

❑ The aeromagnetic data have proven effective in imaging the structural fabric of the onshore and offshore western Otway Basin. Three principal structural directions are present within the data: NS, NE-ENE and NW-WNW.

  - ❑❑ The **NS direction** is believed to reflect the basement geology.
  - ❑❑ The **NE-ENE direction** is believed to originate from the earliest phase of extensional faulting within the western Otway Basin.
  - ❑❑ The **NW-WNW direction** defines the 'traditional' or 'break-up' normal fault direction within the Otway Basin.

❑ The above structural fabric suggests that the rifting history of the basin may have taken place in two distinct stages, rather than within the simple rift-to-drift framework that has been proposed previously. The initial stage, from, 150 to ~120 Ma, took place within a stress regime dominated by NW-SE extensional transport (similar to that of the basins of the Great Australian Bight). E-ENE-striking extensional rift segments, such as the Crayfish Platform-Robe Trough, developed during this period, contemporaneous with the deposition of thick sediments of the Crayfish Group. Other parts of the basin, such as the Penola Trough, developed within a strongly trans-tensional (left-lateral strike-slip) environment. After a period

of uplift and block faulting at ~120 Ma, rifting probably recommenced with an extensional transport direction oriented NNE-SSW, contemporaneous with the deposition of the Eumeralla Group. This later rift episode produced the 'traditional' normal fault orientation within the Otway Basin. Differences between the onshore (and often older) parts of the basin - where the major faults typically dip landward - and the offshore - which is dominated by seaward-dipping faults - can be explained by the different stress regimes which operated during these two periods. Oblique extension from 150 to 120 Ma over a SW-dipping master detachment produced landward-dipping faults blocks, whereas simple (pure) extension from 120-96 Ma over the same detachment produced seaward-dipping faults.

- At least three and possibly four NW-trending sets of volcanic/magnetic rocks have been identified, which may define the position of major basement or rift-related fault sets. The south-westernmost of these sets was previously unknown, and is located along the present-day shelf break, outboard of most of the exploration wells drilled in the region (with the exception of Morum 1). These volcanic rocks may have had a significant effect (at least locally) on the thermal history of the Otway Basin and have potentially charged many adjacent reservoirs with $CO_2$.

- There is no obvious spatial or causal relationship between the major/minor basin-forming structures or lineaments defined during the present study and the location of the known hydrocarbon discoveries in the western Otway Basin. The Katnook and Ladbroke Grove fields in the Penola Trough are, however, bracketed by NE-trending features which may represent either basement faults or Early Cretaceous (but post-Neocomian) accommodation zones.

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# CONTENTS



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# IMAGES IN FOLIO

Folio images are missing from the original hardcopy of Record 1993/14.

# INTRODUCTION

The Otway Basin, located on the south-eastern Australian margin, has been an area of active hydrocarbon exploration since the late 1950's. In fact, the western onshore Otway Basin was the site of Australia's first oil well, which was drilled at Alfred Flat, near the Coorong, South Australia, in 1866 (Sprigg, 1986).

In spite of this activity, success within the basin has been relatively limited. In the onshore Otway Basin, sub-commercial gas was encountered in the Port Campbell 1 well (Victoria) in 1959, while in 1967 a small commercial carbon dioxide ($CO_2$) discovery was made in South Australia at Caroline 1 (Mulready, 1977). More recently, exploration resulted in the discovery of commercial gas accumulations at North Paaratte (1979), Katnook (1987) and Ludbrook Grove (1989; see Parker, 1992), and Iona (1988; see Miyazaki *et al.*, 1990).

In the offshore part of the basin, the only significant hydrocarbon show recorded between 1967 and 1993 was in the Pecten 1A well, in the eastern offshore part of the basin, which flowed at approximately 90 000 cubic feet of gas per day. However, a recent upsurge in exploration activity in the offshore area has been rewarded by two large gas discoveries in early 1993, the Minerva and La Bella accumulations off Port Campbell in western Victoria.

These recent discoveries, as well as previous finds in the onshore part of the basin, have established the Otway Basin as a potential major gas province and have ensured the continuance of high levels of exploration activity.

In order both to assist the on-going exploration effort in the western Otway Basin, and fill in a gap in the national aeromagnetic coverage, the Australian Geological Survey Organisation (AGSO) acquired 14 200 km of high resolution aeromagnetic data in November and December 1992. These data were collected within the South Australian part of the Otway Basin, and principally covered the onshore Penola 1:250 000 Sheet area, extending offshore to approximately the 500 m isobath.

In this Record we present the preliminary results of this acquisition program, and include aeromagnetic data as processed images and a geophysical interpretation map.

In Part 1 of the Record, following a brief introduction to the current state of knowledge of the tectonic, structural and stratigraphic setting of the Otway Basin (Section 1.1), the report presents the results of the processing, image-processing and interpretation of the airborne magnetic and other geophysical data (Section 1.2). Section 1.3 provides a preliminary evaluation of the implications of the magnetic data to petroleum exploration in the onshore and offshore Otway Basin.

Part 2 provides a review of the regional tectonic setting of the Otway Basin, with reference to recent ideas on the intiation of continental rifting in the broader context for the Antarctic/southern Australia margins.

The text of this report is accompanied by a folio containing 1:250 000 scale images of the processed magnetic and gamma-radiometric data, a transparent interpretation overlay for the images, and several gravity and bathymetric images at more regional scales.

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# ACKNOWLEDGMENTS

The authors wish to acknowledge the many colleagues who have contributed to the compilation of the data sets interpreted in this Record. The work of the AGSO airborne crew and all those who have contributed to the National Gravity Database over the years, including members of the South Australia Department of Mines and Energy and the Victorian Geological Survey, is particularly appreciated. Staff in the AGSO Geophysical Mapping Section are thanked for their willing systems and administrative support during the preparation of this Record, often at short notice.

Dr Chris Tarlowski compiled the aeromagnetic data from the surrounding areas into the Magnetic Anomaly Map of Australia - to be published in June 1993 - that provided new insight into the study area. Ann Felton (formerly AGSO) is thanked for allowing the use of unpublished material on the lithofacies of the Otway Group sequences from her PhD thesis. Kathy Hill, Monash University, is thanked for access to unpublished seismic transects across the western Otway Basin. The help and assistance of Dr David Sandwell is acknowledged in the preparation and transfer of public domain Geosat data from the Scripps Institute of Oceanography, La Jolla, U.S.A. These data have been incorporated into the data package at no extra cost to those buying the AGSO aeromagnetic images and their interpretation.

We thank all those who reviewed parts of the manuscript during its somewhat erratic evolution.

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# PART 1

# *SECTION 1.1*

# PREVIOUS WORK

## Study Area, Tectono-Stratigraphic Evolution

### Study Area

The Otway Basin, located in south-eastern Australia (Fig. 1.1), trends northwest-southeast, and straddles the Victorian and South Australian coastlines for 500 km between the Mornington Peninsula in Victoria and Cape Jaffa in South Australia. The basin covers approximately 150 000 square km, of which only about 35% is onshore.

The area covered by AGSO's aeromagnetic survey is located within the South Australian part of the Otway Basin and extends between 37°S, 139°10'E and 37°S, 141°E, south to about the 500 m isobath offshore (see Fig. 1.2). Three commercial gas accumulations are located within the survey area:- the Katnook and Ludbrook Grove gas discoveries (Parker, 1992) and the Caroline $CO_2$ field. All of these are located onshore; to date only scattered hydrocarbon shows have been recorded from the offshore wells in this region. The recent offshore discoveries at Minerva and La Bella lie some 200 km east of the eastern margin of the present study area.

### Tectono-Stratigraphic Evolution

The Otway Basin initially developed along Australia's southern margin in the Late Jurassic to Early Cretaceous as part of the Bassian rift system that formed in response to rifting between Australia and Antarctica, and continued eastwards into the Bass and Gippsland Basins.

The exact nature of the tectonic processes that formed this rift system are still problematic (this Record, Part 2). Etheridge *et al.* (1985, 1987) have proposed that the Bassian rift was produced by NNE-SSW lithospheric extension, largely during the Early Cretaceous. This extension led to the development of a linked array of WNW-ESE-oriented, shallow-dipping, normal extensional faults and orthogonal, steeply-dipping, transfer or accommodation faults. In this scenario, the tectonic evolution proceeded smoothly from rift initiation, to active rifting, to sea-floor spreading and associated post-rift subsidence. In Etheridge *et al*'s model, this basic architecture was reactivated during the Tertiary by compressive stresses.

More recently, Willcox & Stagg (1990) have discussed the evolution of the Great Australian Bight basins. Whilst their study did not deal directly with the Otway Basin *per se*, it has potentially profound implications for understanding its tectonic development.

In the Great Australian Bight basins, Willcox & Stagg (1990) proposed that the initial rifting between Australia and Antarctica, which led to the formation of the Bassian Rift system, was significantly more complex than proposed by Etheridge *et al.* (1985, 1987).

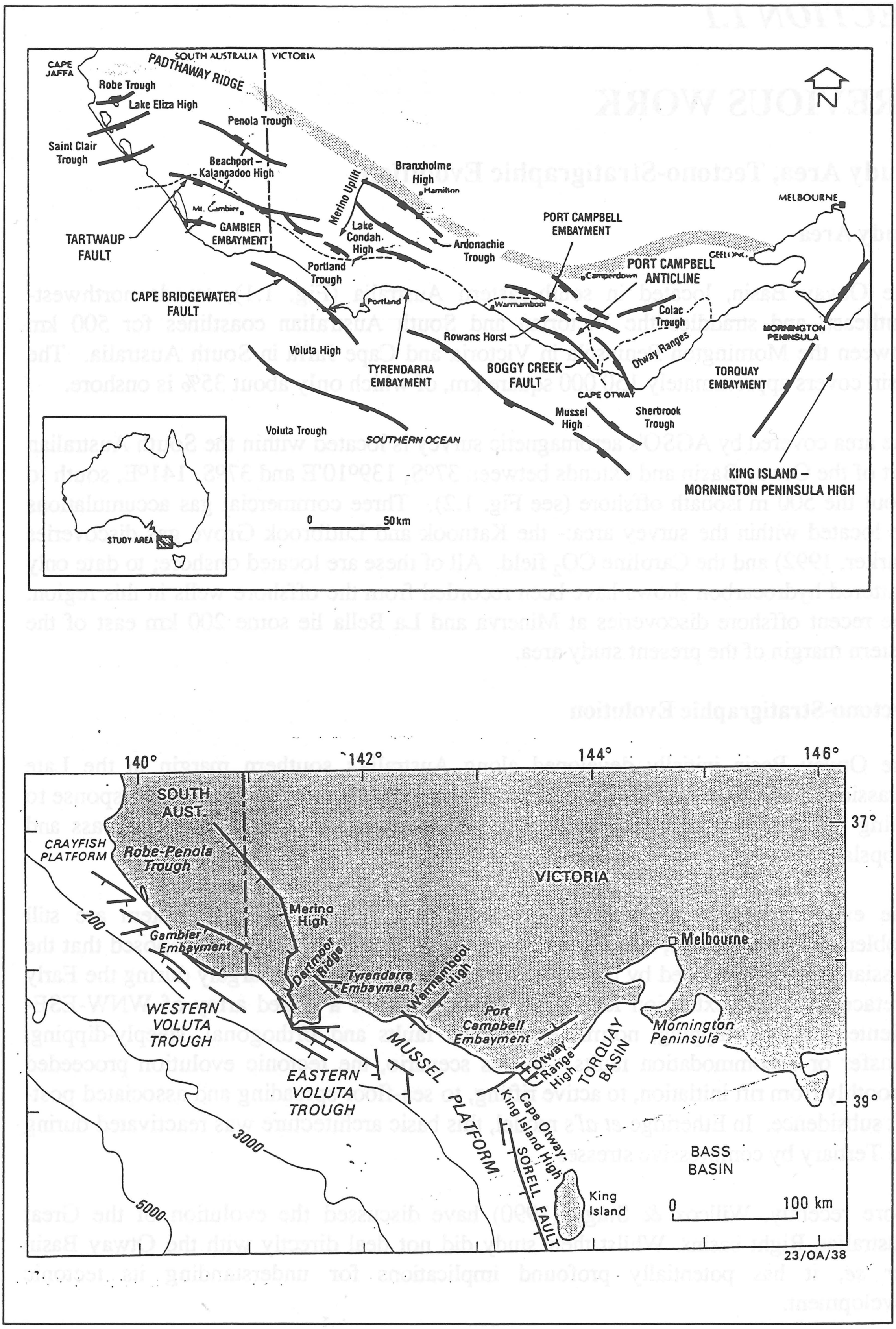


**Figure 1.1** Location map and structural elements of the Otway Basin, south-eastern Australia. From Williamson *et al.*, 1987/Liang *et al* (1989).

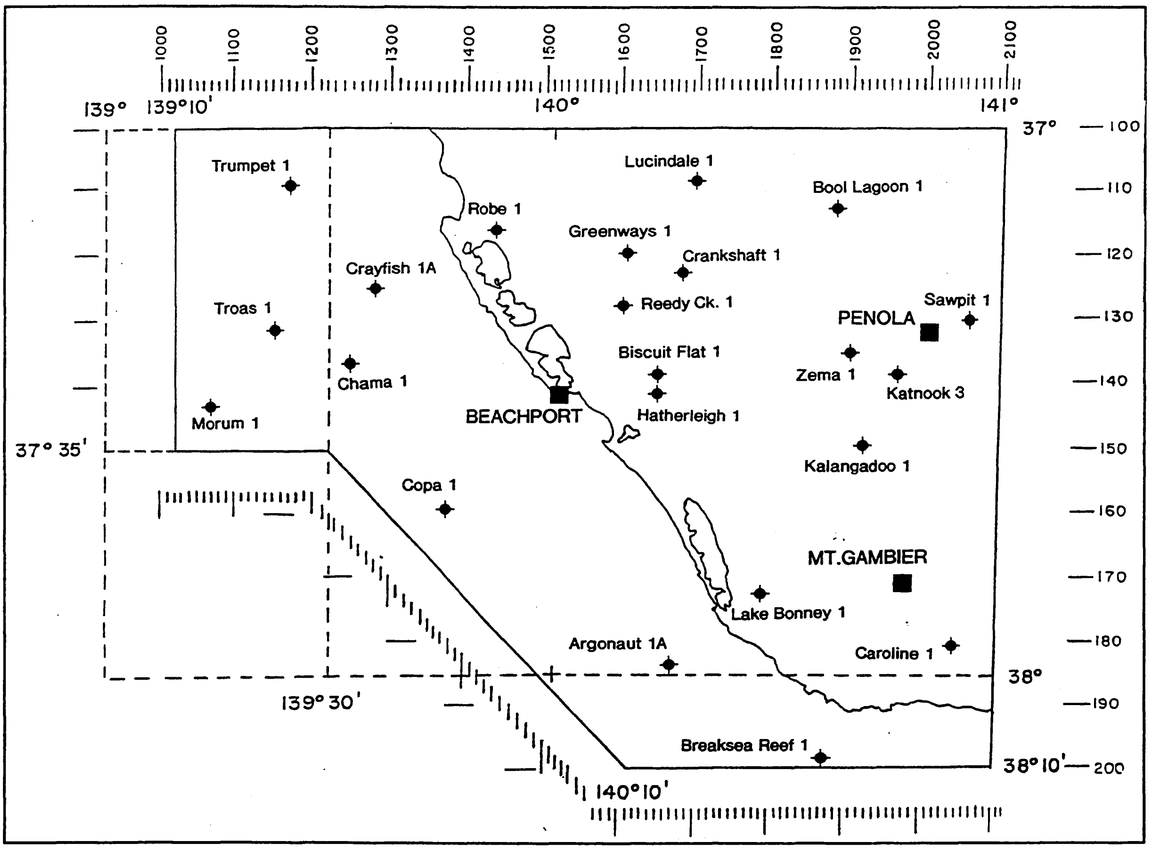


**Figure 1.2** Outline of AGSO's aeromagnetic survey area in the western Otway Basin, south-eastern Australia, with significant exploration wells shown. The numbers of the (north-south) flight-line numbers are shown along the northern margin and control-line numbers along the east. Towns are shown as solid squares and drill-hole locations as solid circles with four tick-marks.

Willcox & Stagg (1990) have in fact suggested that the development of the rift system in the Bight took place in two distinct stages.

During the first stage, which spanned from the Late Jurassic to Early Cretaceous (from ~153-122 Ma), the margin was extended by about 300 km; the extensional transport direction was oriented NW-SE (see Fig. 1.3), significantly oblique to the ENE-SSW orientation proposed by Etheridge *et al* (1985, 1987). Extrapolation of this stress regime to the south-eastern Australian margin suggests *that the Otway Basin was located within a significant left-lateral strike-slip stress regime throughout this period, and thus extension through this interval may have been significantly oblique.* The proposal for a NW-SE extensional transport direction during this period in the Bight basins has been independently supported by Etheridge *et al* (1989).

A second stage may have spanned through the Early Cretaceous from 122 Ma until about 100 Ma, and would have consisted of only 120 km of extension which was oriented along a NNE-SSW azimuth, identical to that proposed by Etheridge *et al.* (1985, 1987), and consistent with the normal fault directions which now dominate the Otway Basin (WNW-ESE). In this model the second extension event in the Otway Basin

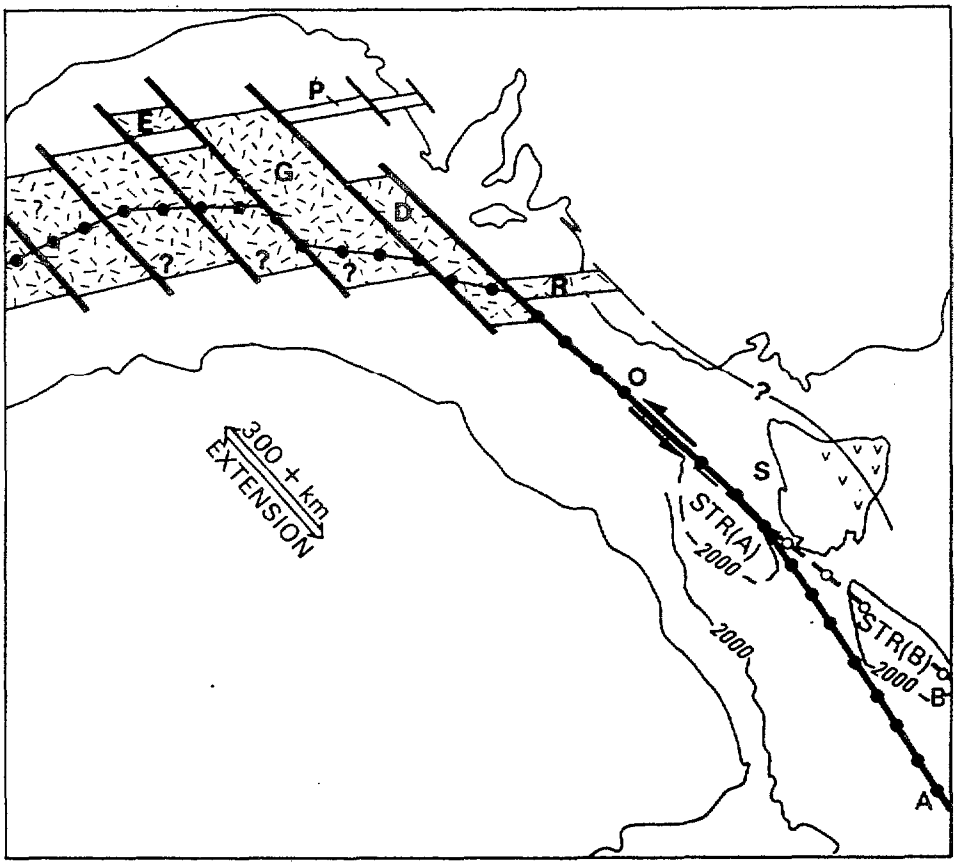


**Figure 1.3** Plate reconstruction from pre-Late Jurassic (>153 Ma-120 Ma (Neocomian) for the southern Australian margin. NW-SE extensional transport direction in the Great Australian Bight basins produces sinistral strike-slip movement through the proto-Otway Basin region. Redrawn from Willcox & Stagg, 1990.

was significantly oblique to the earlier event which would have led to major reactivation of structures formed between ~153 and 122 Ma.

However, most recently, Willcox *et al* (1992) interpreted deep seismic data from the Gippsland Basin. They suggest that this basin is probably also of similar age to the Great Australian Bight basins (that is, at least Late Jurassic-Early Cretaceous) and that it formed over a deep detachment by left-lateral NW-SE oblique extension. It would thus now appear that a linked system of basins was developed along Australia's southern margin and Bass Strait. All were products of NW-SE extensional transport which began during the Late Jurassic.

Irrespective of the uncertainties surrounding the early rift tectonics, it appears that continental break-up (i.e. the initiation of seafloor spreading) took place off the Otway Basin at about 96 Ma (Veevers *et al*, 1991).

The morpho-tectonics and stratigraphic distribution in the Otway Basin reflect the rift-to-drift transition discussed above. Onshore, the basin is composed of a series of predominantly SE-trending Early Cretaceous troughs or half-grabens separated by basement highs. In the western Otway Basin, significant features present within AGSO's

1992 aeromagnetic survey area include the Penola Trough, the Beachport-Kalangadoo High, the Padthaway ridge, and the ENE-trending Robe Trough, Lake Eliza High and Saint Clair Trough (Fig. 1.1).

Offshore, the basin can be loosely subdivided into three distinct structural provinces, namely the Crayfish Platform in the west, the Voluta Trough (western and eastern), and the Mussel Platform in the east (Fig.1.1). These three structural provinces have existed since at least the beginning of the Late Cretaceous, and have closely controlled the types of sedimentary facies developed throughout the basin.

The oldest sediments known from the Otway Basin belong to the Casterton Group (Knopsen & Scholefield, 1990), a latest Jurassic/Early Cretaceous (Tithonian/Berriasian) sequence of interbedded non-marine siltstones, mudstones, minor coals and volcanics (Wopfner *et al*, 1971; Dettmann & Douglas, 1976). Lacustrine sediments with good source rock potential have also been reported from this unit (Knopsen & Scholefield, 1990). To date, the Casterton Group is only known from the onshore part of the basin.

Overlying the Casterton Group is the Early Cretaceous Crayfish Group which consists principally of high energy fluviatile sands. The Crayfish Group appears to be particularly thick in the western Otway Basin; over 1500m were drilled in the Crayfish 1A well on the Crayfish Platform, with up to 4700 m present within the onshore Robe Trough (Knopsen & Scholefield, 1990). Crayfish Group deposition appears to have terminated at about 120 Ma., and was followed by a brief period of block faulting and erosion. The top Crayfish Group horizon became highly structured at this time, particularly on the Crayfish Platform (Williamson *et al*, 1990). It may be that deposition of the Crayfish Group was largely controlled by the initially oblique separation of Australia and Antarctica, as described earlier. The structuring event at ~120 Ma on the Crayfish Platform *may be related to the change in extensional transport direction from NW-SE to NNE-SSW in the basins of the Great Australian Bight*, as described by Willcox & Stagg (1990).

Deposition of the Eumeralla Group commenced at approximately 117 Ma, and largely blanketed the underlying Crayfish Group. Dominant lithologies were shales and claystones, with minor coals, argillaceous sands and sandstones. A significant amount of volcanogenic detritus has been described in the Eumeralla Group offshore.

Early Cretaceous sedimentation was terminated by a mid-Cretaceous period of block faulting, differential uplift, and erosion between 100-95 Ma, which was probably related to continental breakup and the initiation of seafloor spreading. Offshore, the basin became subdivided into a series of slowly subsiding platforms (Crayfish and Mussel Platforms) and rapidly subsiding troughs (western and eastern Voluta Trough). Subsequently, deposition of the Late Cretaceous Sherbrook Group commenced in the Cenomanian. The margin continued to subside throughout the Tertiary, eventually `leading to widespread carbonate deposition.

Volcanic rocks, which can provide a significant source of magnetic anomalies, are present in two distinct horizons in the Otway Basin (Megalla, 1986). The *Older Volcanics* were erupted in the Paleocene whereas, in the Neogene, extensive volcanic eruptions of basalts in central and western Victoria constituted the *Newer Volcanics*.

Thicknesses of up to 200 m have been observed for the Newer Volvanics in the area of the present study.

*SECTION 1.2*

# AEROMAGNETIC AND GRAVITY DATA, PRESENTATION METHODS AND INTERPRETATION

## Geophysical Data

As part of its ongoing program of reconnaissance aeromagnetic mapping of the Australian continent, the Australian Geological Survey Organisation (AGSO) used its geophysical survey aircraft to carry out a modern, high-sensitivity aeromagnetic survey over much of the western Otway Basin late in 1992. The immediate goal of this survey was to replace older, 'sub-standard' airborne data for the Penola 1:250 000 Sheet area (and extensions of the Penola Sheet to the south and west). A further goal of the survey was to demonstrate the usefulness of high resolution aeromagnetic data to both petroleum exploration and basin analysis in general. Most of the airborne survey data acquired over petroleum provinces in Australia date from an earlier generation of acquisition when both magnetometer sensitivity and positional accuracy were often poor. It is hoped that the Penola Survey will be the fore-runner of further AGSO surveys in petroleum provinces.

The 1992 survey is described by Brodie (1993) and the results form the main body of new data imaged and interpreted in the present study. Survey details are provided in Table 1. These new data are supported by other data from a number of sources, including principally the data-bases of regional geophysical data held by AGSO.

About 14 200 line kilometres of airborne survey were carried out over the area of the western Otway Basin shown in Fig. 1.2. Lines were flown north-south at a nominal spacing of 1.5 km, at a flying height of 80 m above terrain, and extended offshore to approximately the 500 m bathymetric contour. The magnetic field was sampled at intervals of 0.1 seconds with a noise envelope of about 0.1 nanoteslas (nT). A gamma-ray spectrometer with 33 litres of sodium iodide crystal was used to detect gamma-radiation during the airborne survey. Position-fixing to an accuracy of about 5 m was achieved using Global Positioning System (GPS) satellites in differential mode.

These instrument specifications correspond to the current standard for airborne geophysical surveys in Australia, differing from those used in more detailed mapping programs (such as in geological mapping of 1:250 000 Sheet areas in hard-rock areas for the National Geoscience Mapping Accord) only in the spacing of flight-lines and tie-lines. In a petroleum province, such as the western Otway Basin, the principal magnetic sources are not expected to be at, or near, the ground surface, but rather they will lie within the igneous and metamorphic basement with the possibility of some sources

## Table 1: Survey details of the 1992 Penola Survey, western Otway Basin, south-eastern Australia.

PENOLA SA 1992
AIRBORNE GEOPHYSICAL SURVEY

**AREA DESCRIPTION**

| | | |
|---|---|---|
| Survey Base | Mt Gambier, SA | |
| Sheet Area | Included most of the standard 1:250000 map series sheet of PENOLA + an extension to the south and west. Both on and offshore (ie map attached). | |

**SURVEY PARAMETERS**

| | | |
|---|---|---|
| Altitude | 80 m agl/asl | |
| Flight line direction | North - South | |
| Tie line direction | East - West | |
| Flight line spacing | 1500m | |
| Tie line spacing | 15,000m | |
| Survey Distance | LINES | 12626 km |
| | TIES | 1534 km |
| | TOTAL | 14160 km |

**FLYING DATES**

| | |
|---|---|
| Compensation (Test Flights) | 27, 28 November 1992 |
| Survey | 28 November - 14 December 1992 |

**SURVEY EQUIPMENT**

Major Equipment:

| | |
|---|---|
| Magnetometer | Geometrics G833 Helium vapour magnetometer |
| Compensator | RMS Instruments Automatic Aeromagnetic Digital Compensator |
| Gamma-ray Spectrometer | Geometrics spectrometer with two DET1024 Crystal detectors (331) |
| Altimeter | Collins ALT-50 radar altimeter |
| Barometer | AGSO digital - Setra sensor |
| Thermometer | AGSO digital - RS sensor |
| Navigation | Ashtec XII "Ranger" GPS receivers and Ashtec "Ranger" differential processing software |
| Doppler | Racal (Decca) doppler antenna (80561 CAD) Sperry C 14 D compass |
| Video | National colour video camera (WV CL 302E) National VCR (NV 180) National LCD TV (TCL 3A) National Time Date Generator (WJ810) |
| VLF | Data recorded (not available) |

**Table 1 *continued:* Survey details of the 1992 Penola Survey, western Otway Basin, south-eastern Australia.**

MAGNETIC SPECIFICATIONS

| | | |
|---|---|---|
| Sampling interval | 0.1 seconds | |
| Compensation | Real time compensation by RMS Instruments automatic aeromagnetic digital compensator. | |
| Resolution | 0.01 nT | |
| Base Station diurnal | recorded with a Geometrics G866 Base Station Magnetometer at 20 sec intervals. | |

RADIOMETRIC SPECIFICATIONS

| | | |
|---|---|---|
| Sampling interval | Total Count Window 1s | |
| | Potassium Window 1s | |
| | Uranium Window 1s | |
| | Thorium Window 1s | |
| | 256 Channel Spectrum 100s | |
| Windows | Total Cound | 0.4 - 3.0 MeV |
| | Potassium | 1.35 - 1.57 MeV |
| | Uranium | 1.63 - 1.89 MeV |
| | Thorium | 2.42 - 2.82 MeV |
| Crystal Volume | 33.6 litres | |

within the sedimentary section giving anomalies detectable with sensitive equipment. Consequently, the close line spacings typically used in mineral-oriented airborne surveys are not usually justified since most of the expected anomalies will be comparatively broad and can be mapped adequately using more widely-spaced lines.

In addition, the on-going program of digitising older aeromagnetic data has recently produced a digital version of the aeromagnetic survey of the Bass Strait and Encounter Bay area which was flown by Aero-Service (for Haematite Explorations Pty Ltd) in 1960-61 (BMR, 1965). The western extremity of this survey extends somewhat further to the west of, and further offshore than, the Penola Survey, albeit with more widely-spaced lines and with a magnetometer of much lower resolution (Fig. 1.4). In the limited areas of overlap, the quality of the older survey is seen to be good, even though it lacks the capacity to map with accuracy the low amplitude, short wavelength anomalies (from presumed intra-sedimentary sources) which are a feature of modern airborne surveys over sedimentary basins. The digitising was carried out in 1992-3 by Geoterrex Pty Ltd under contract to the Geological Survey of Victoria, in collaboration with AGSO, the Geological Survey of Tasmania and the South Australia Department of Mines and Energy. These digital data were publicly released in March, 1993.

The setting of the Penola 1:250 000 Sheet area with respect to magnetic anomaly patterns for the whole of onshore Australia may be determined from the 1:5 000 000

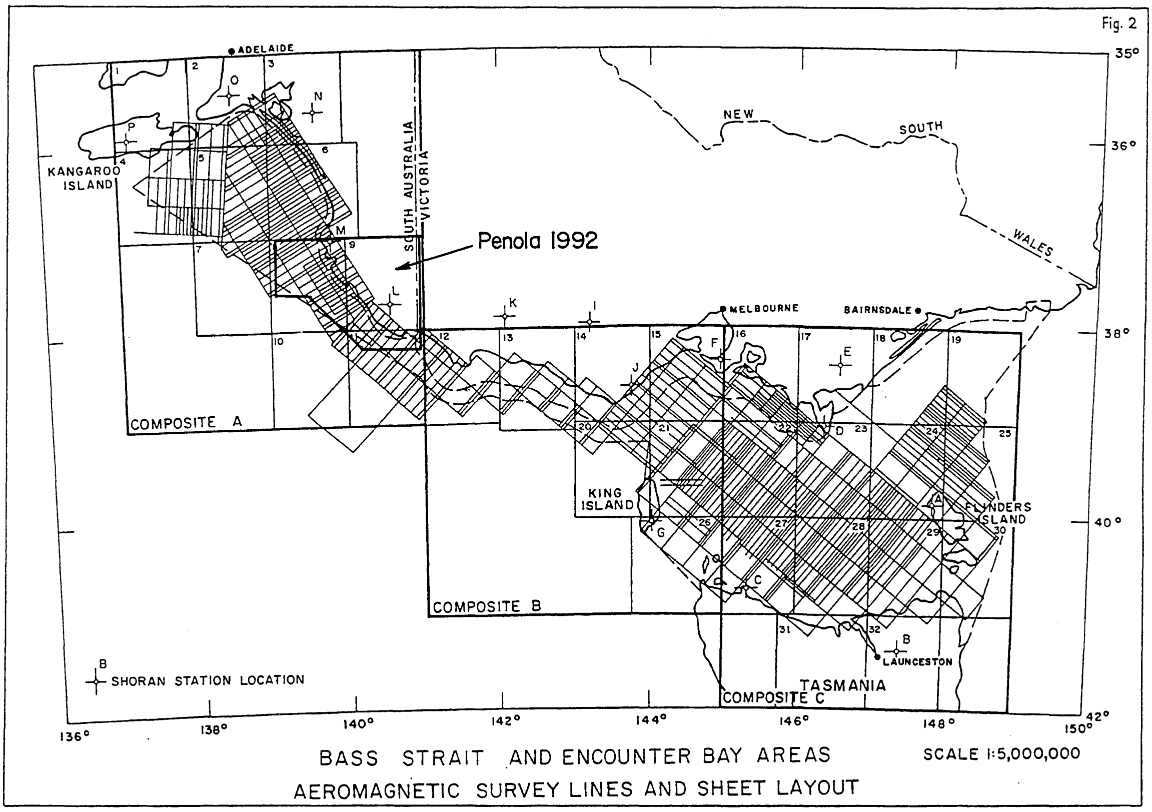


Figure 1.4 The location of the Penola 1992 survey (heavy outline) in relation to flight-lines of the Bass Strait/Encounter Bay survey of 1962.

scale Magnetic Anomaly Map of Australia, which will be published by AGSO in 1993 (Tarlowski, 1993).

Gravity data for the study area are available from the national gravity data-base for Australia held by AGSO. Bouguer anomaly maps reproduced here have been specifically generated from these point-data sets and from the Gravity Anomaly Map of Australia (Morse, 1992).

An additional source of gravity data is the recently released Geosat satellite gravity data-set for the Southern Ocean, which is held by the Scripps Institute of Oceanography (Sandwell, 1992). These data, which have been image-processed by AGSO and linked to the onshore gravity data during the course of the present study, provide important new controls on the interpretation of the geological evolution of Australia's southern margin.

## Data Processing And Interpretation Methods

The reduction and presentation of the airborne geophysical data acquired in late 1992 followed the standard procedures adopted by AGSO in routine aeromagnetic survey work and are reported in detail by Brodie (1993). The data were released to the public in April 1993, together with the associated suite of standard profile and contour maps at 1:250 000 scale.

Further processing of these data and their presentation as images was carried out to assist the interpretation of the magnetic data reported here. A variety of proprietary software suites available within (and outside) AGSO was employed for this and included:

- the ARGUS airborne data-processing system of AGSO;
- GIPSI software (Paterson Grant and Watson [Toronto]) for contour presentation, spectral analysis and Fourier domain processing;
- ER-Mapper and $I^2S$ software for image enhancement, presentation and hard-copy production;
- ACRES facilities for image-writing and production of final positives.

Inversion of individual magnetic anomalies was carried out using Geosoft's MAGMOD modelling system. Gravity anomalies were studied using other forward modelling and inversion programs in the possession of AGSO.

The results of the interpretation and integration of the magnetic, gravity and other data were plotted progressively on an overlay which was subsequently refined into an interpretation map at 1:250 000 scale (see folio, **Image 20**). The tectonic features interpreted from this study are described in the following sub-sections which should be used in conjunction with figure 1.5 as a guide to the interpretation overlay .

## Gravity Anomalies

The geological map of the Penola Sheet area reveals that 'basement' formations do not outcrop. The low topography of the onshore area is made up mostly from recent dunes and some volcanic edifices, such as those at Mt. Gambier, overlying uplifted Neogene limestones. Interpretation of the sedimentary successions and the underlying igneous and metamorphic geology is therefore principally reliant on geophysical interpretations and limited drilling results.

Examination of the gravity map of Australia shows that a major gravity gradient commences SW of a line crossing the SW corner of the Penola Sheet on a strike of N $120^{o}$ E (A, Fig. 1.5). Such gradients are typical of the gravity expression of continent-ocean margins as the Bouguer anomaly rises from the negative values typical of continental areas (and attributable to the mass deficiency of sialic 'roots' below continental land-masses) to the highly positive values typical over oceanic crust.

Gravity data over the Southern Ocean derived from the recently released Geosat data show a distinct N-S gravity feature, probably associated with a transform/transfer fault zone, coming ashore near longitude $139^{o}$ 45' E, approximately co-linear with the lower reaches of the Murray River (see folio, **Image 3**).

From contour maps of the study area generated from the Australian National Gravity Database, the most prominent gravity features within the remainder of the survey area are negative anomalies associated with the Robe and Penola Troughs respectively .

The Robe Trough (B, Fig. 1.5) trends N 70° E and extends from the western sheet margin through the settlement of Robe, to about longitude 140° 15'. It has a negative anomaly of amplitude of about 15 mGal, which suggests an increased thickness of sediment within the trough (relative to the flanks) of about 2 km, for an assumed density contrast of -0.25 $t/m^3$.

The Penola Trough (C, Fig. 1.5) trends N 125° E and extends from longitude 140° 15'E, south of the town of Penola, to beyond the eastern sheet margin. With an amplitude of about -25 mGal, an extra thickness of 3 km of sediment (of density contrast -0.25 $t/m^3$) would be required to produce such an anomaly within the trough.

Both troughs are 20-25 km wide and neither are delineated by sharp gravity gradients, as would be the case if they were true, strongly fault-controlled grabens. Both appear to be axes of structural 'sagging'; this subsidence is probably represented in the near-surface rocks by repeated faulting in directions parallel to the trough axes. However, in both cases the crystalline basement, even on the up-thrown flanks, is probably buried by several kilometres of sediment which similarly contribute to the smooth appearance of the gravity anomalies.

Two distinct positive gravity anomalies, both circular in appearance, are evident centred respectively at Beachport (the Beachport High; D, Fig. 1.5) and at the intersection of the Robe and Penola Troughs (the Lucinda High; E, Fig. 1.5). Only the former has any significant coincident expression in the magnetic anomaly map. Both gravity anomalies have been modelled to help establish their depth of burial and geometry.

For the Lucinda High, a plug-like circular body, of radius ~ 3500 m, and having vertical sides extending to great depth, could account for the observed anomaly, providing that the top of the plug was about 1000 m below ground surface and the density contrast with the surrounding rocks was +0.12 $t/m^3$. The best interpretation is that the Lucinda High represents a mafic intrusive body that contains little or no magnetite.

A similar gravity model for the Beachport High gave a body of radius 5500 m, with its top at a depth of ~ 2400 m below the surface (for a density contrast of +0.25 $t/m^3$). The Beachport High has a clearly expressed coincident magnetic anomaly, however.

Between the Robe and Penola Troughs and the continent-ocean margin gradient in the SW corner of the Penola Sheet area, the gravity anomaly map shows only a few subtle, low amplitude anomalies. The implication is that strata through this area are generally horizontal; there appear to be few offsets of the strata with significant density contrast. It is perhaps notable that the usual rise of Bouguer anomaly values towards the

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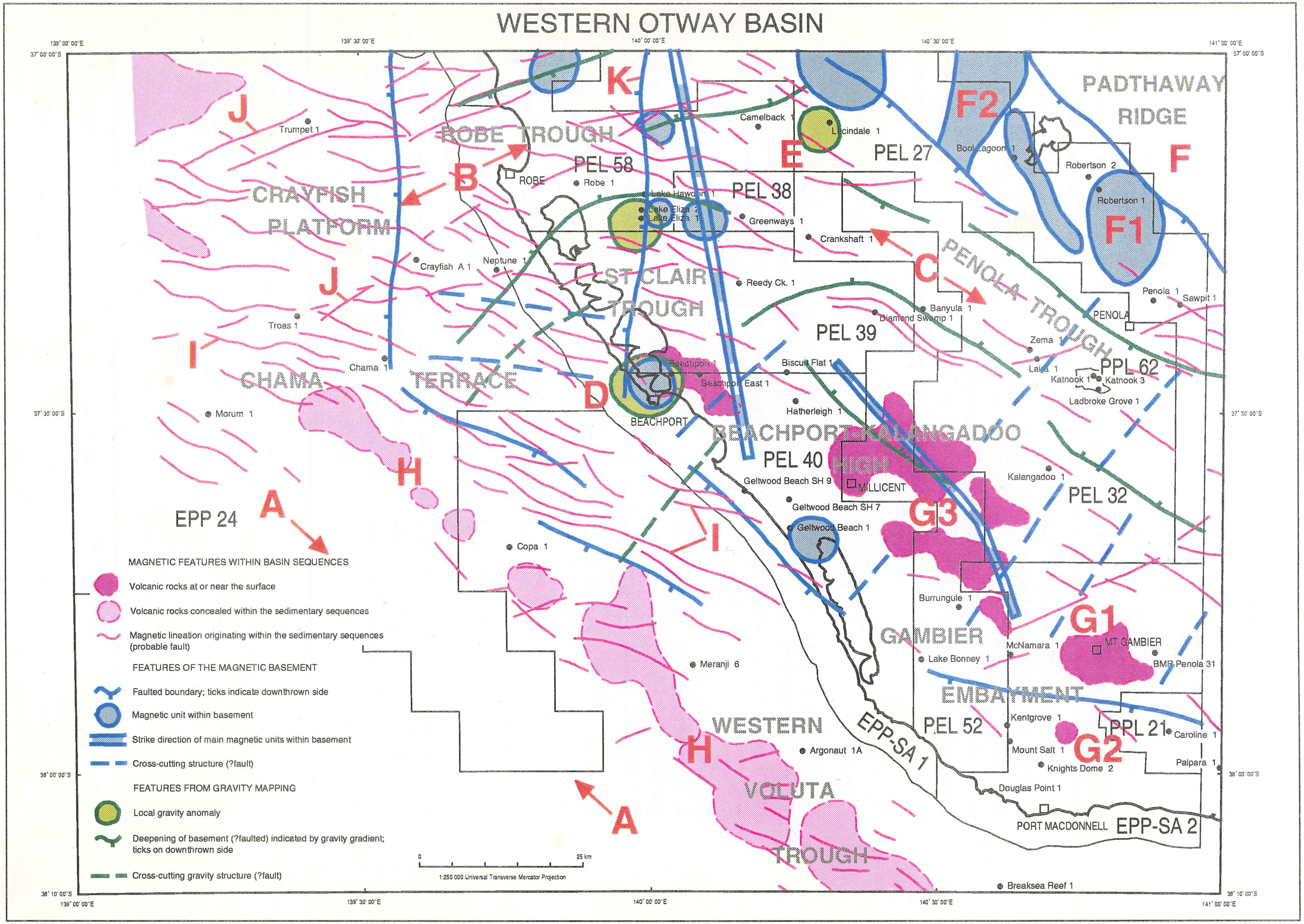
**Figure 1.5 (facing page).** Interpretation map reduced from Image 20 as a key to gravity and magnetic features described in the text.



WESTERN OTWAY BASIN
139° 00' 00"E
139° 30' 00"E
140° 00' 00"E
140° 30' 00"E
141° 00' 00"E
37° 00' 00"S
37° 30' 00"S
38° 00' 00"S
38° 10' 00"S
PADTHAWAY RIDGE
ROBE TROUGH
CRAYFISH PLATFORM
ST CLAIR TROUGH
CHAMA TERRACE
PENOLA TROUGH
BEACHPORT-KALANGADOO HIGH
GAMBIER EMBAYMENT
WESTERN VOLUTA TROUGH
PEL 58
PEL 38
PEL 27
PEL 39
PEL 40
PEL 32
PEL 52
PPL 62
PPL 21
EPP 24
EPP-SA 1
EPP-SA 2
A
B
C
D
E
F
F1
F2
G1
G2
G3
H
I
J
K
Trumpet 1
Camelback 1
Lucindale 1
Bool Lagoon 1
Robertson 2
Robertson 1
ROBE
Robe 1
Lake Hawdon 1
Lake Eliza 2
Lake Eliza 1
Greenways 1
Crankshaft 1
Crayfish A 1
Neptune 1
Reedy Ck. 1
Banyula 1
Diamond Swamp 1
Penola 1
Sawpit 1
PENOLA
Troas 1
Zema 1
Laira 1
Katnook 1
Katnook 3
Ladbroke Grove 1
Chama 1
Beachport 1
Beachport East 1
Biscuit Flat 1
Hatherleigh 1
Morum 1
BEACHPORT
Geltwood Beach SH 9
MILLICENT
Geltwood Beach SH 7
Geltwood Beach 1
Kalangadoo 1
Copa 1
Burrungule 1
McNamara 1
MT GAMBIER
Lake Bonney 1
BMR Penola 31
Meranji 6
Kentgrove 1
Caroline 1
Mount Salt 1
Knights Dome 2
Palpara 1
Argonaut 1A
Douglas Point 1
PORT MACDONNELL
Breaksea Reef 1
MAGNETIC FEATURES WITHIN BASIN SEQUENCES
Volcanic rocks at or near the surface
Volcanic rocks concealed within the sedimentary sequences
Magnetic lineation originating within the sedimentary sequences (probable fault)
FEATURES OF THE MAGNETIC BASEMENT
Faulted boundary; ticks indicate downthrown side
Magnetic unit within basement
Strike direction of main magnetic units within basement
Cross-cutting structure (?fault)
FEATURES FROM GRAVITY MAPPING
Local gravity anomaly
Deepening of basement (?faulted) indicated by gravity gradient; ticks on downthrown side
Cross-cutting gravity structure (?fault)
0
25 km
1:250 000 Universal Transverse Mercator Projection

continental margin does not commence until the continent-ocean margin is almost reached. It is suspected that this rise does exist, but is more-or-less negated by the negative gravity effect of a wedge of sediments increasing in thickness towards the continental margin. Isostatic compensation of highly attenuated crust in this region could also play a part.

High and complexly varying gravity features are evident in the NE corner of the survey area over the Padthaway Ridge (F, Fig. 1.5). Taken together with the magnetic anomaly evidence, it seems likely that the cover of sedimentary rocks here is minimal, and igneous and metamorphic rocks occur within a few hundred metres of the surface. Variations in the physical properties of these rocks give rise to the observed gravity and magnetic anomalies. At least two granite plutons (F1, F2, Fig. 1.5) are likely to be present here. These are characterised by oval outlines which are coincident with local gravity lows and have a distinct magnetic expression in one of the two cases.

## Magnetic Anomalies

Anomalies displaying a wide range of wavelengths - which implies a similarly wide range of source depths - are evident on the magnetic profile data, in the contour maps and in the images. Several distinct groups or populations of magnetic sources may be inferred:

**Group 1: Cultural**
There are a number of very local magnetic anomalies which can be attributed directly to man-made (cultural) objects at the ground surface. Typical examples may be seen along the road from Mt. Gambier to Penola, at coastal settlements such as Robe, and over two offshore oil exploration platforms west of Robe. These are not shown on the interpretation map.

**Group 2: Volcanic extrusions of recent geological age**
The high-amplitude, short wavelength anomalies in this category are typified by those seen in the vicinity of Mt. Gambier itself (G1, Fig. 1.5) and at Mt. Schank(G2). More extensive occurrences are easily identified around the volcanic centres in the region north-west of Mt. Gambier (G3), as shown on the 1:5 000 000 geological map of South Australia. A further occurrence, perhaps slightly buried, is evident near Beachport. These have been delineated on the interpretation map (folio, **Image 20**) from their expressions in the original profile data and their distinctive amplitudes of hundreds of nT.

**Group 3: Buried volcanic extrusions**
A second family of magnetic expressions, generally similar to Group 2, but associated with sources at greater depth and having a much lower amplitude, can be identified along a line trending NW-SE near the southern limit of the aeromagnetic survey area (H, Fig.1.5). These are thought to arise from volcanic accumulations slightly deeper in the sedimentary succession, following a line some 50 km SW of the more recent volcanic activity. Estimates of source depths made from typical magnetic anomalies in this group fall mostly in the range 200 to 800 m below sea level. In most cases where the source

areas mapped magnetically are crossed by traverses of marine gravity, ill-defined coincident local gravity anomalies are found, indicating a density contrast (probably positive) with respect to the average for the sediments within which the volcanic rocks are located.

**Group 4: Intra-sedimentary sources following probable fault lines**
These are generally low amplitude anomalies (a few nT or less) which, because of their low amplitude, would probably have been missed in aeromagnetic surveys of all but the most recent vintage. The most prominent of them form curvi-linear features which extend for distances of 30-40 km and generally strike in a similar orientation to faults mapped by seismic methods in the area (I, Fig. 1.5). They become quite obvious after the application of image enhancement techniques, and can be mapped with a confidence which varies from certain to doubtful, according to the magnetic setting in which they occur. They have several possible origins of which the most likely include:

- normal faults offsetting magnetic horizons (?pyroclastic rocks) within the sedimentary section.

- intrusions following fault planes.

The former explanation appears the more likely, given that the features tend to die out in areas where the magnetic anomaly field is particularly quiet, presumably because the magnetic horizon pinches out totally - or perhaps drops to greater depth of burial - in the 'quiet' areas.

Basic intrusions in fault planes usually produce magnetic anomalies which are several orders of magnitude higher in amplitude than those observed in the present case. Magnetic forward-modelling has been used to demonstrate that an horizon of quite low magnetic susceptibility (0.005 e.m.u.), about 50 m thick, and at a depth of 500 m, could produce anomalies of 5 nT amplitude when offset by faulting a distance of 100 m (Fig. 1.6). The typical amplitude of the observed features recorded is only a few nanoteslas. It is worth noting that theory predicts the resulting anomaly (for the magnetic inclination of Penola) would be positive over a fault down-thrown to the north, and negative over an offset down-thrown to the south. In the presence of such markers, the aeromagnetic method employed at the most recent specifications becomes a very efficient method of mapping faults.

The majority of fault features seem to be of the type illustrated in Figure 1.6 (i.e. normal faulting, downthrown to the south) and are oriented on a strike of N 120$^{o}$ E, consistent with down-to-the-basin faulting (i.e. towards the proto-continental margin). Some positive anomalies are also evident and some features show a tendency to change from positive to negative when traced along strike, again consistent with fault offsetting, rather than igneous emplacement. A smaller number of fault features with similar magnetic expression may be identified following a ENE strike direction, parallel to the Robe Trough (J, Fig. 1.5). Some quite prominent members of this group are evident west of Robe on images enhanced with a north-westerly illumination (see folio images).

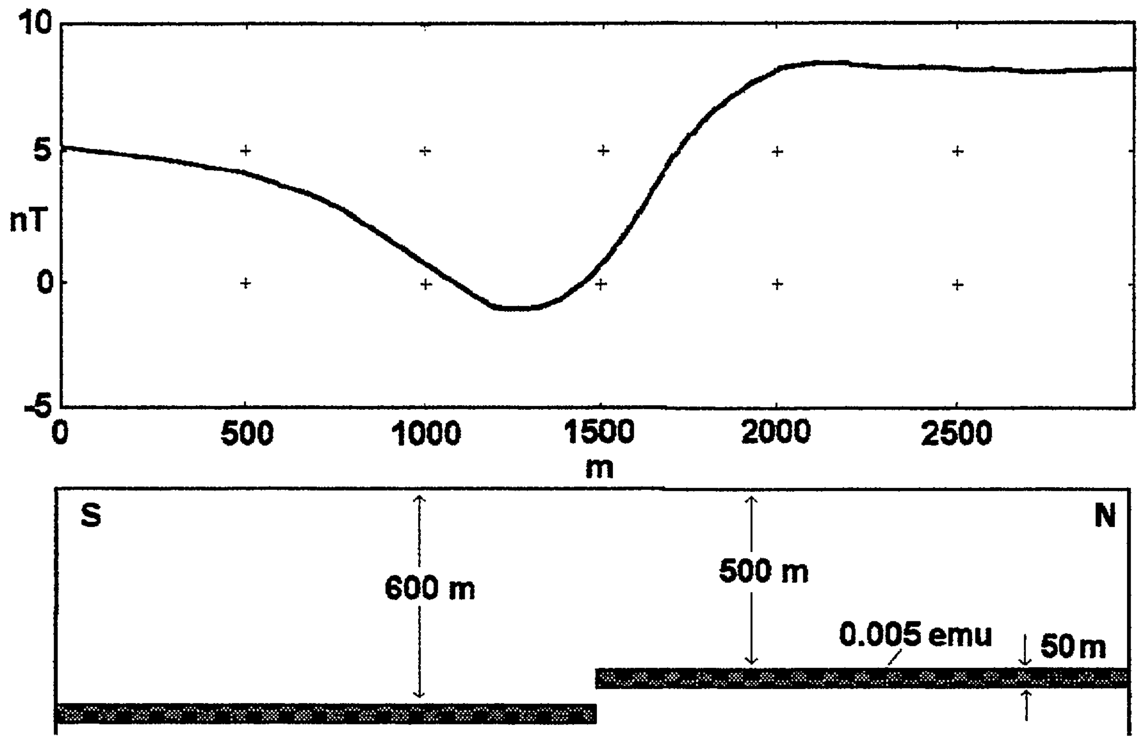



**Figure 1.6** Forward model of the magnetic anomaly to be expected over a thin magnetic horizon, vertically offset by faulting. In the case shown, the downthrow is to the south and produces a predominantly negative magnetic anomaly. Total field intensity: 61000nT, inclination: -70 degrees, declination: 8 degrees E.

**Group 5: Features associated with the 'magnetic basement'**

The larger amplitude, long wavelength anomalies, which form the bulk of the information portrayed in the magnetic contour map, are almost certainly attributable to the igneous and metamorphic rocks which underlie the sediments, at least within the onshore parts of the survey area. The main strike direction for these anomalies is north-south (K, Fig. 1.5) and their origin can be attributed with some confidence to the southerly extension (below sedimentary cover) of the Palaeozoic Delamerian/Lachlan rocks east of the Adelaide Fold Belt. The expression of these rocks is clear on the magnetic map of Australia (Tarlowski *et al.*, 1993) and, from the abrupt increase in wavelength, they evidently deepen below an increasing sedimentary cover along an approximately east-west line lying a little north of the present study area.

## Spectral Analysis

Spectral analysis of the 400 m grid generated for the entire survey reveals most of the features described above as separate populations of sources in the radially-averaged spectrum. The spectrum obtained is shown in Fig. 1.7.

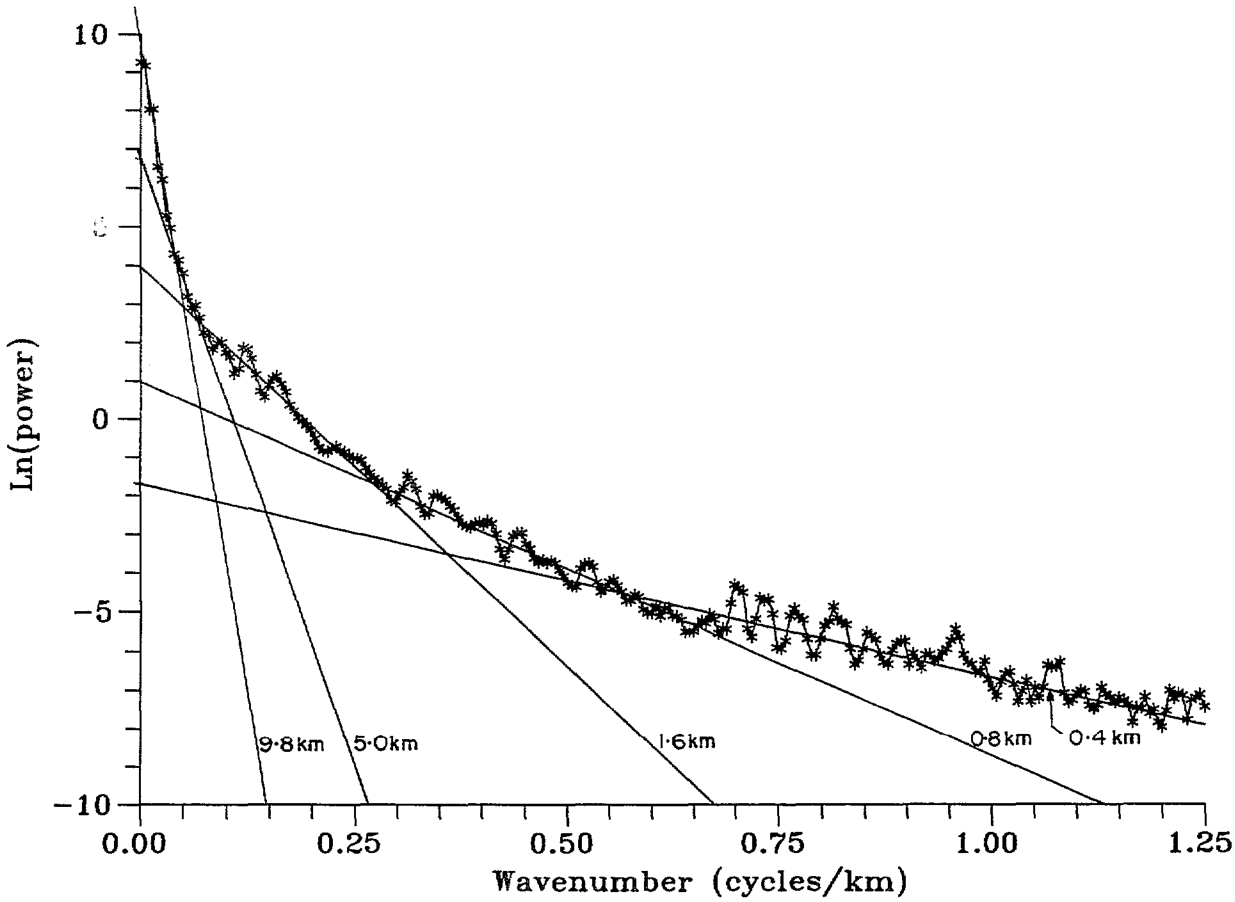



**Figure 1.7** Radially-averaged wavenumber spectrum for the magnetic anomaly field over the whole of the survey area. Straight-line branches are indicated, corresponding to populations of sources at depths of 9.8, 5.0, 1.6, 0.8 and 0.4 km.

By fitting straight-line segments to the power spectrum, according to the principles established by Spector and Grant (1970), the depth to a statistical population of sources can be derived from the relationship:

$$\textbf{Depth} = -\textbf{Slope}/4\pi$$

The deepest sources appear to lie at a depth of 9-10 km on this analysis, with shallower populations at 1.6 km, 0.75 km and 0.38 km. The shallowest (surficial) sources will already be aliased in a 400 m grid and will appear only in this last population. These population depths agree quite well with the more detailed analyses of selected individual anomalies, both within and below the sedimentary succession (see later).

In view of the distinct difference in magnetic character between the northeast (largely onshore) and western (offshore) parts of the survey area, separate spectral analyses were carried out on two grid sub-areas of equal size, one covering most of the presumed deep-basement area in the west of the sheet and the other located centrally on the 'shelf' area in the northeast.

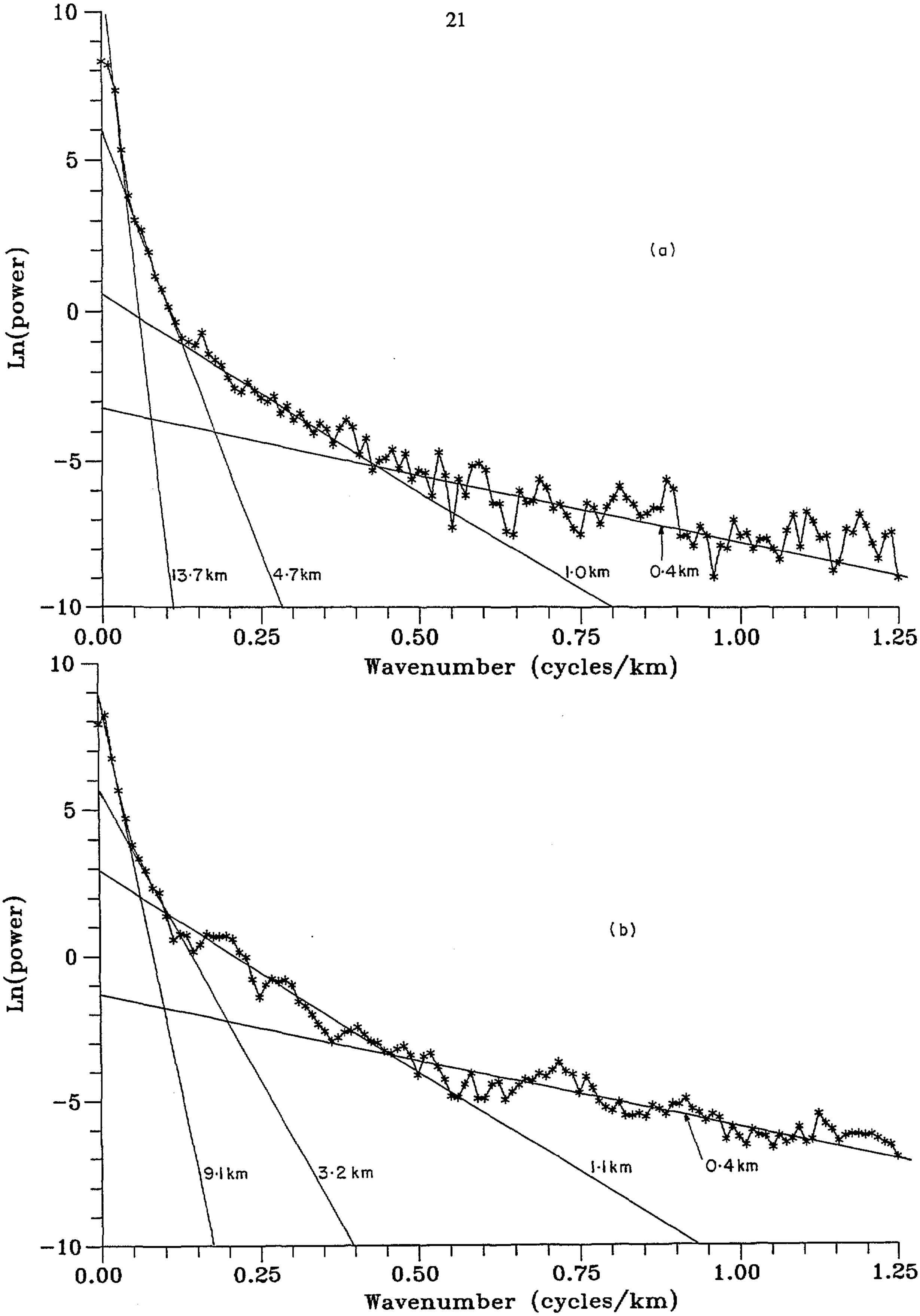



**Figure 1.8** Radially-averaged wavenumber spectra for the magnetic anomaly field over selected parts of the survey area. (a) Western part - straight-line branches are indicated, corresponding to populations of sources at depths of 13.7, 4.7, 1.0 and 0.4 km. (b) North-eastern part - straight-line branches are indicated, corresponding to populations of sources at depths of 9.1, 3.2, 1.1 and 0.4 km. Note the higher energy levels for sources of intermediate depth in the case of curve (b).

Both spectra showed populations of sources at depths corresponding to 8-10 km, 3-4.5 km, 1.0-1.5 km and 0.4 km, though with considerably less energy in the second, third and fourth branches in the west compared with the northeast. (Fig. 1.8).

## Determination Of Depth To Magnetic Basement

A selection of representative anomalies were identified from the original profile data and screened with reference to the contour map to ensure that profiles were representative of (for example) the two-dimensional nature of many features. The profile sections covering these anomalies were fitted with theoretical profiles generated from simple geometrical source-models by the iterative Marquardt method employed by the Geosoft MAGMOD software (Marquardt, 1963). In many cases, several different source models were used in the attempt to achieve a source-configuration that was geologically reasonable. Over fifty anomalies were modelled in this way, divided approximately equally between anomalies attributable to the magnetic basement and those attributable to the intra-sedimentary markers described under Group 4 above. As usual, the choice of profiles was limited by the paucity of anomalies that are relatively free from the interference of neighbouring sources which significantly degrades the validity of modelling. As a result, the total number of depth estimates falls short of optimal, but some scope remains for a more exhaustive analysis from the original profile data. An example of the type of fit achieved by the software is shown in Fig. 1.9.

In the vicinity of the central part of the Penola Sheet, depth estimates on magnetic anomalies, which are presumed to arise from the underlying magnetic basement, give a consistent set of values in the range 3.5 to 4.5 km below surface. Basement depths almost twice this value were found west of Beachport, where modelling of anomalies suggests that the magnetic basement steps down in two stages across north-south trending fault lines which follow longitudes 140° 0' and 139° 35' E respectively. Depth estimates for the magnetic basement in the most westerly region of the survey are about 10 km below sea level.

Shallower magnetic anomalies, presumably sourced from within basement, are encountered along the Padthaway Ridge in the NE corner of the survey area, where magnetic basement rocks appear to lie at depths of only a few hundred metres below the surface. The basement steps down to the SW in several stages to the Penola Trough by way of faults which strike N 120° E. Between the first and second of these faults, the basement, which is quite shallow at the northern margin of the survey area, appears to plunge to greater depth towards the SE.

Apart from the sedimentary depressions representing the Penola and Robe Troughs, the remainder of the onshore areas that are covered by the survey seem to have magnetic basement at a depth of ~4.0 km. As determined from gravity modelling, the additional depths of sediment within the troughs are estimated to be about 3 km and 2 km respectively. Certain magnetic anomalies, and the Lucinda gravity high, suggest some emplacement of intrusives into this sedimentary sequence.

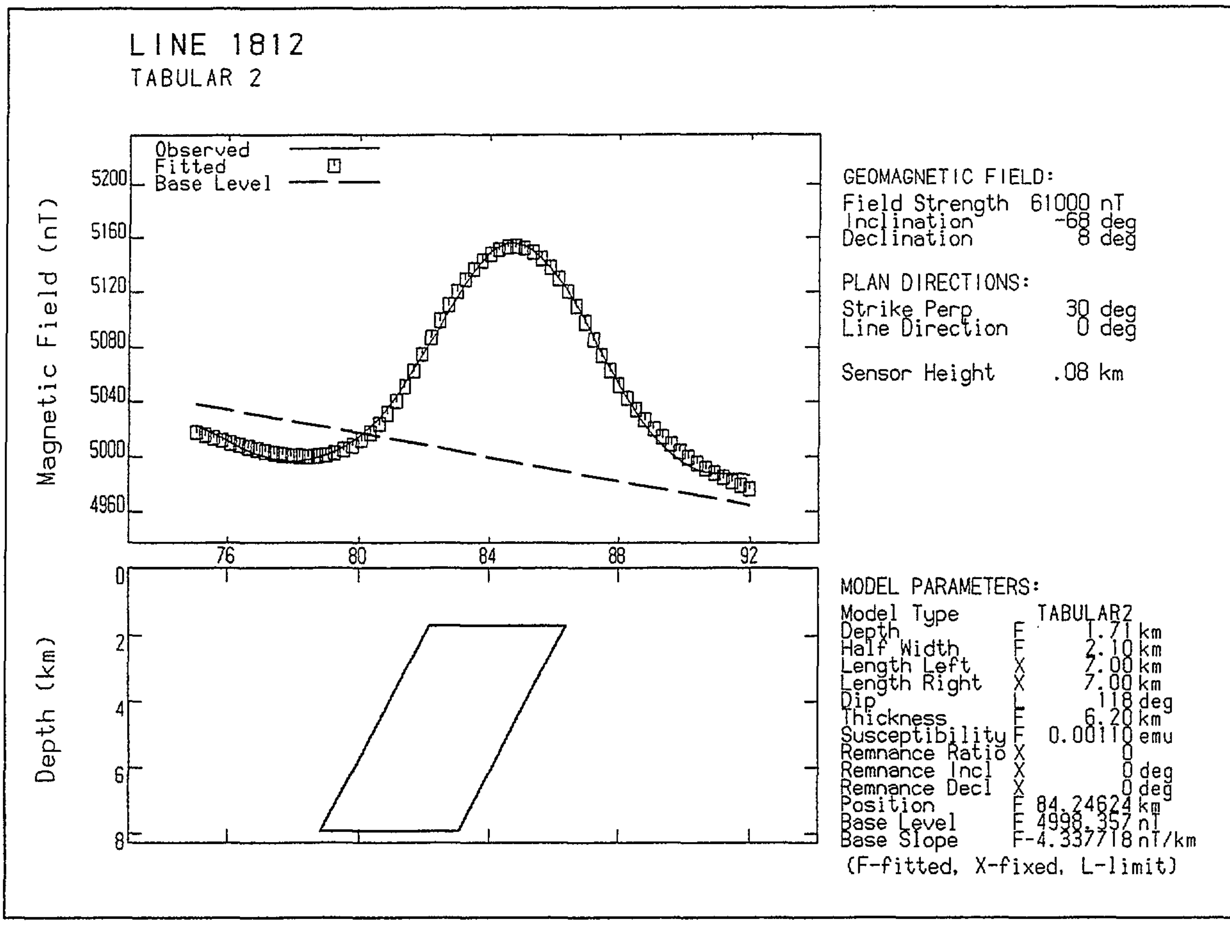



**Figure 1.9** An example of the fit between observed and theoretical profiles obtained using Geosoft's MAGMOD program for a given model of the subsurface (shown in section) with geomagnetic and model parameters at the right of the diagram.

An attempt was made to synthesise the depth information for the magnetic basement in the form of a basement depth-contour map. Such an exercise can only be carried out with some circumspection, but does serve to summarise the interpreter's perception of the basement topography from the limited number of estimates available from magnetic modelling. The result is shown in Fig. 1.10. Some comparisons of depths obtained in this way with estimates obtained from seismic sections will be made later.

## Depth Of Intra-Sedimentary Magnetic Sources

Anomalies attributable to the intra-sedimentary magnetic markers described earlier were often only about 5nT in amplitude, but were seen to be well-defined and smooth in suitable profile presentation. They could be modelled as steps in a magnetic horizon, as ribbons of finite thickness, or as tabular bodies of weak magnetisation. Depths, in general, were found to lie in a range between about 300 m and 1000 m, regardless of model type. (One anomaly, thought to be due to an exploration drilling platform, modelled as being very close to the sea bed). Since water depths of up to 500 m are encountered in the SW part of the survey area, it is concluded that these magnetic sources must occur very close to the top of the sedimentary succession, probably within the top 500 m. Given the fact that the sources are likely to be of only very limited depth

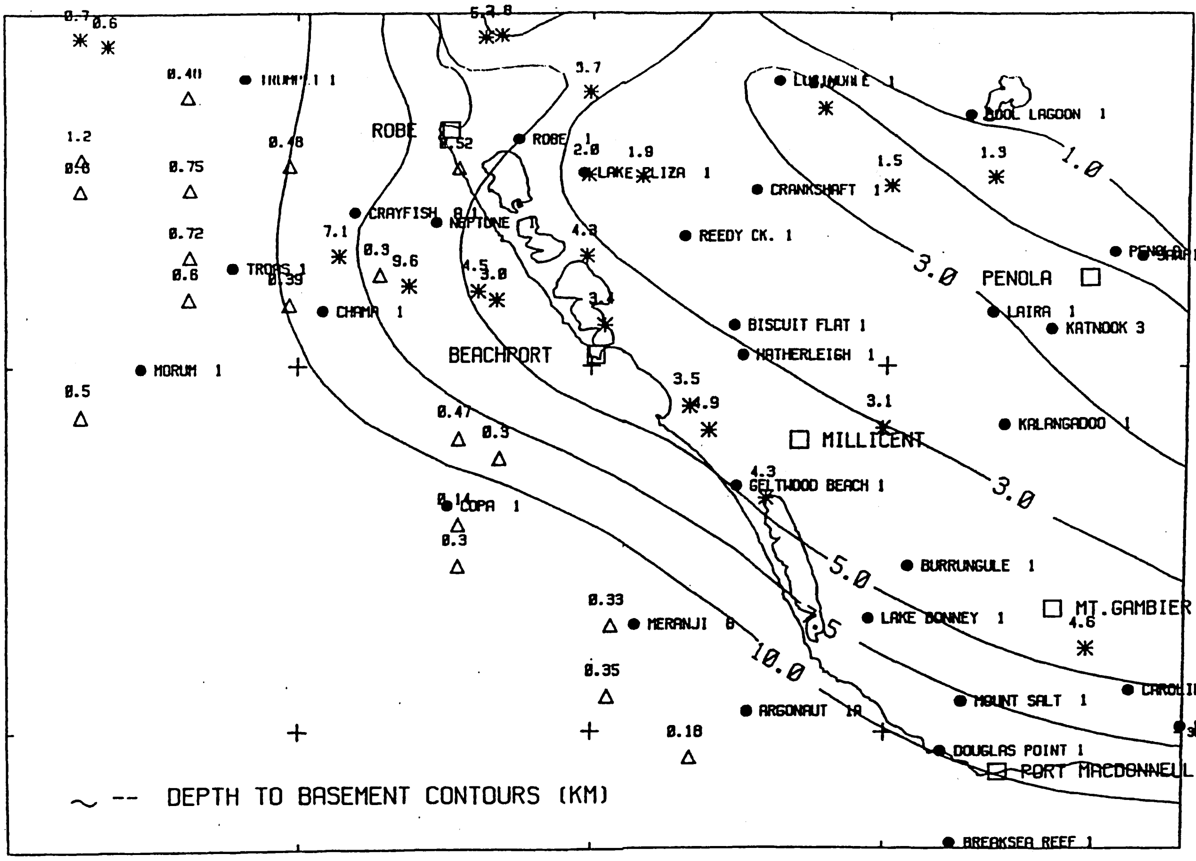



**Figure 1.10.** Magnetic anomaly depth estimates (in kilometres) for the western Otway Basin. Triangles are anomaly depths within the Tertiary sedimentary sequences; stars are anomaly depths within the Otway Group sequences or within Palaeozoic basement.

extent (i.e. thin, flat-lying bodies), it is to be expected that their anomalies will decay quickly with increasing distance between source and magnetometer. As they produce only weak anomalies at shallow depths, it seems probable that any similar sources at depths greater than about 1000 m will simply go undetected, even with the most sensitive modern magnetometer equipment.

In order to enhance the appearance of these shallow magnetic markers in image form, the depth range determined from modelling was employed to design band-pass filters. These were applied to the profile data (Fig. 1.11) which were subsequently gridded and imaged. Again, the result emphasised the N 120$^{o}$ E trend of most of the intra-sedimentary magnetic features, presumably showing that faulting in this direction has been active during and/or after the deposition of the uppermost parts of the sedimentary column. The strike direction is also parallel to the trends of volcanic activity, both onshore and offshore, and to that ascribed to the Tartwaup Fault Zone in the south-eastern part of the survey area. This direction is also interpreted as that across which the magnetic basement abruptly deepens or terminates. Presumably all these features have a common origin in the extension and attenuation.of sialic crust along the continental margin.

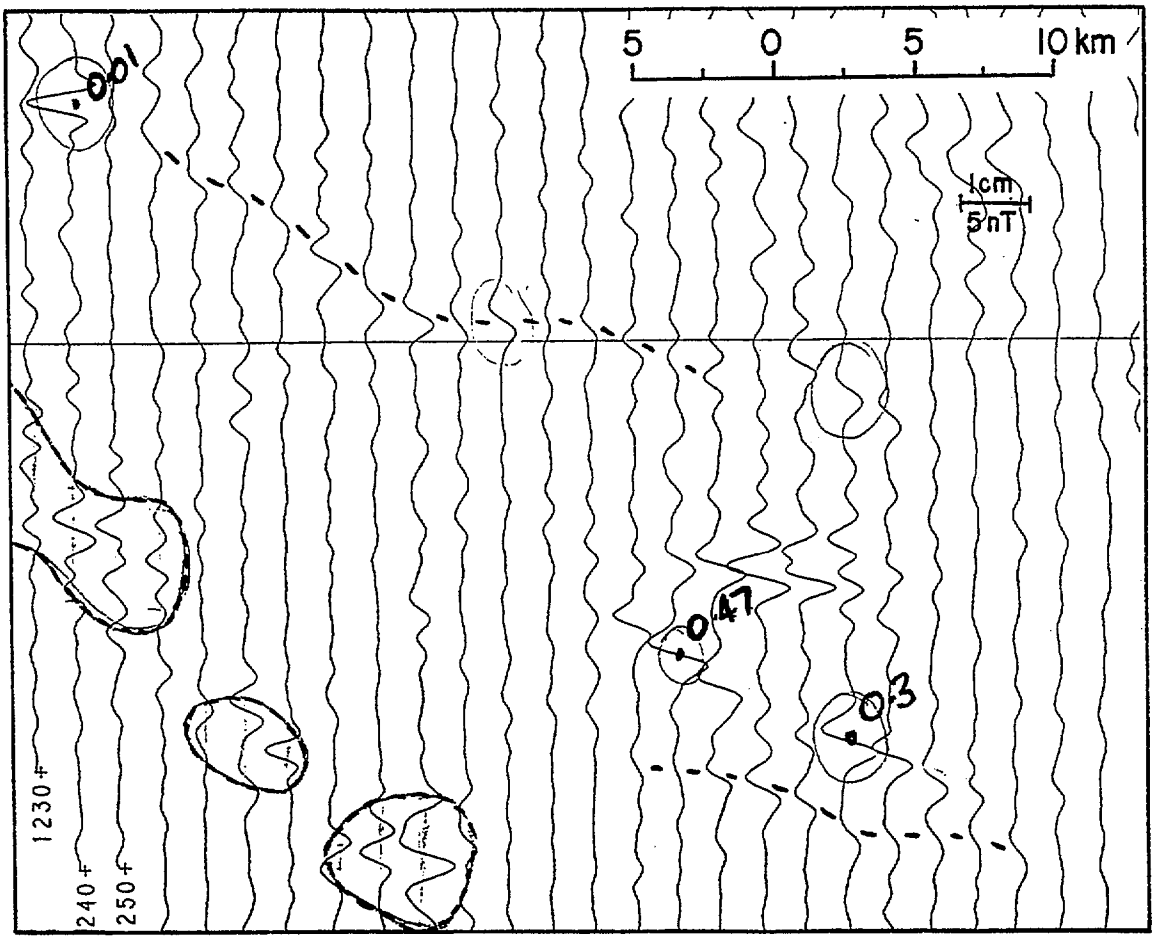



**Figure 1.11** Sample area of profile map showing band-pass filtered magnetic anomaly profiles. The continuity of low amplitude anomalies attributable to faulted magnetic layers in the sedimentary section (Figure 1.6) is clear. Map scale 1:250,000. Magnetic intensity scale: 1 cm = 5 nT. Areas of buried volcanic rocks outlined. Depth estimates to selected anomalies in km. The anomaly due to an offshore structure is seen in the NW corner.

It cannot be reasonably expected that simplistic methods of depth estimation employed in the interpretation of magnetic (and gravity) data will give a detailed and faithful representation of the disposition of the igneous and metamorphic rocks underlying the sediments in the area, particularly since the basement itself is certainly far from simple in structure. However, the magnetic method does offer an inexpensive uniformity of cover that is not available from the siesmic data. Within the scope of the present project, however, it has not been possible to attempt a detailed analysis of the various generations of seismic data that have been shot over the survey area.

In an attempt to demonstrate the strengths and weaknesses of the analysis carried out in the present study, a small number of depth estimates from magnetic anomalies are plotted on interpreted seismic sections in Figs. 1.12 and 1.13. In Fig. 1.12a, basement depth estimates in the region of the Lake Eliza High are seen to be in good agreement with estimates from seismic data for the top of the Paleozoic basement. Figure 1.12b shows the sources of 'intra-sedimentary' magnetic anomalies to be situated within the

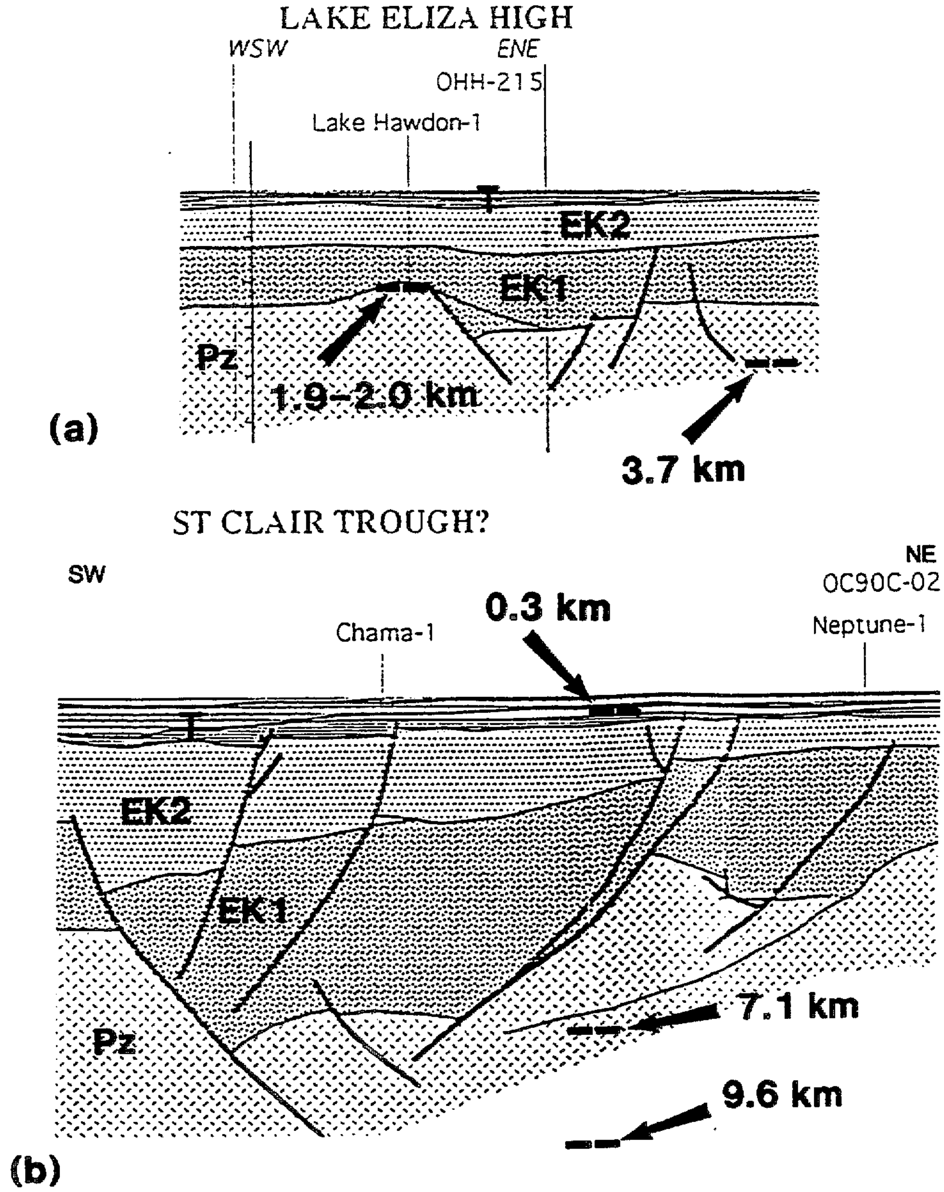



**Figure 1.12** Estimated depths to magnetic anomalies in the vicinity of (a) the Lake Eliza High and (b) the Chama Terrace in relation to seismic line interpretations by Hill & Durrand (1993). Pz = Palaeozoic basement; EK1 = Crayfish Group; EK2 = Eumeralla Group; T = Tertiary sequences.

Tertiary section, while basement depths at 7.1 and 9.6 km somewhat overestimate the depth of the basement interpreted from the seismic data in the area between the Chama 1 and Neptune 1 wells in the offshore western Otway Basin. In Fig. 1.13a, a basement depth of 4.6 km underestimates the seismically-determined depth below the Tartwaup Fault Zone, falling within the Eumeralla Group sediments. Figure 1.13b indicates less serious under-estimates of 3.5 and 4.9 km for the depth of the Palaeozoic basement SW of the Hatherleigh High.

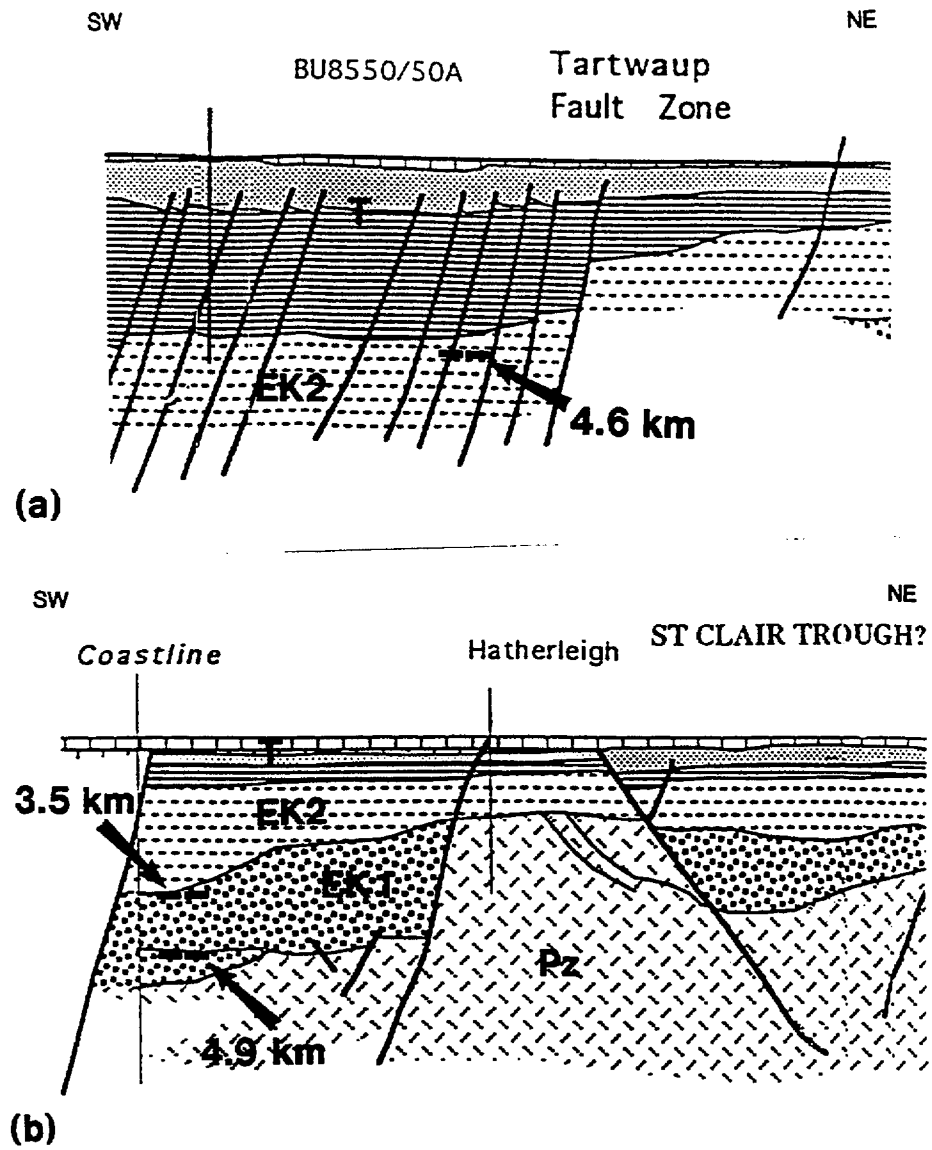



**Figure 1.13** Estimated depths to magnetic anomalies in the vicinity of (a) the Tartwaup Fault Zone and (b) Gambier Embayment in relation to seismic line interpretations by Hill & Durrand (1993). Pz = Palaeozoic basement; EK1 = Crayfish Group; EK2 = Eumeralla Group; T = Tertiary sequences.

The seismic sections also illustrate the complexity of basement structures, however, and since it is unlikely that all parts of the Palaeozoic sequence will be equally magnetic, it is clearly unrealistic to expect a magnetic survey to reveal the level of detail that is apparent on seismic profiles. Despite these liomitations, the aeromagnetic data and images do:

- provide an overview of the present gross topography of the surface of the pre-rift geological formations, and

- constrain both the location and the orientation of faults within the more recent parts of the sedimentary succession.

## Rationale For Image Preparation

Two objectives were identified in preparing images to emphasise and support the geological features recognised and interpreted from the aeromagnetic survey data. The first was to make as clear as possible the expression of the intra-sedimentary magnetic markers. The second was to emphasise the structure of the magnetic basement. The resulting images are contained in the folio accompanying this Record.

**Image 7**
In order to achieve both these objectives in one image, the original total field data were imaged using a conventional red-green-blue colour presentation. This was then modulated in saturation and intensity using the output of a shaded-relief operator (illumination from the SW) applied to a high band-pass filtered version of the TMI (Milligan *et al.*, 1992) to emphasise the shallower sources .

The first objective was achieved by band-pass filtering the magnetic profile data in the wavelength range 750 m to 2.25 km. This band-pass is centred on the wavelength of 1.5 km, which is likely to be typical of sources with a depth of about one-quarter of this value, i.e. 350-400 m. It will preserve anomalies from sources in the depth-range 400 m to 1100 m - the range encountered from the detailed modelling of individual sources. It was found to be important to suppress as far as possible the magnetic effects of the surface sources (shallow volcanic extrusives/intrusives and cultural features) which were of such high amplitude that serious 'leakage' could occur along profiles over considerable distance as a result of filtering. The filtered profiles were plotted as a profile map which was invaluable in tracing the continuity of the shallow magnetic features (Fig.1.11). The profile data were gridded and displayed as an image. The approach proved very successful, with the exception of the incomplete removal of the surface sources.

**Images 8 & 9.**
Shaded relief enhancement is normally used in image presentation where enhancement of local, short-wavelength features is desired. The illusion of illumination from the SW emphasised the intra-sedimentary features striking NW to SE (Image 8), while a south-easterly illumination direction was used to emphasise the minority of shallow features striking sub-parallel to the Robe Trough (Image 9).

**Image 10** is a colour representation of the same band-pass filtered total magnetic intensity values, without the enhancement of directional illumination.

**Image 11**
Reduction to the magnetic pole is a standard process which is designed to transform the essentially dipolar anomalies (i.e. anomalies having both positive and negative lobes),

which are evident at most inclinations of the inducing geomagnetic field, into the purely positive anomalies situated above the causative bodies predicted by theory when the magnetic inclination is vertical (i.e. at one of the magnetic poles). This process was applied to the data-set as presented in Image 11. While there is some considerable reduction in the magnitude of the negative anomaly lying to the south of the main area of shallow magnetic basement, this negative has not been entirely eliminated. The origin of the negative is probably the southern termination of the magnetic rocks of the basement. Its incomplete elimination through pole migration probably indicates that the termination is not vertical, but takes place along a plane dipping to the south, again supporting the concept of basement deepening and/or attentuating along the line of the Tartwaup Fault Zone. The presence of remanent magnetisation contributing to the same effect cannot be totally ruled out, however.

In order to improve the resolution of the structures and lithologies of the magnetic basement, several images were produced from longer wavelength components of the total magnetic intensity.

**Image 12**

A regional component magnetic map was computed by operating an optimum Wiener filter on the wavenumber domain spectrum to eliminate all sources other than those originating from the basement. The regional field was then downward-continued to 4 km below sea level, the depth at which modelling indicated that the basement sources were located. This should "focus" the image on the anomalies arising from the basement and delineate the location of deep-seated faults and lithologies more closely. The result is shown in Image 12.

**Images 13 & 14**

Two bandpass images were also generated using a cosine non-directional filter. These were for wavelengths from 6 000 m to 12 000 m and for wavelengths from 12 000 m and 24 000 m (Images 13 & 14). Such bandpass images are sometimes referred to as "depth-slicing", using the assumption that different wavelengths of anomalies represent different source depths. If this is true, then these images represent depth of sources centred on 2.25 km and 4.5 km respectively. These images both clearly show an arcuate feature, convex to the north, spanning from west to east across the northern part of the survey area, immediately north of the Robe Trough. It separates higher residual magnetic values to the north from lower values to the south, although there is no associated wavelength change.

The final images derived from the total magnetic intensity were for the first and second vertical derivatives in pseudocolour and grey scale.

**Images 15 to 18**

Vertical derivatives are computed using operators derived from potential field theory, and are used to enhance shallow source anomalies present in total magnetic intensity data. Tne computed frist vertical derivatives are shown in colour and grey-scale in images 15 and 16 respectively. The second vertical derivative images (Images 17 & 18) again show clearly the shallow elongate features already discussed in connection with

Images 7 to 11. Both the first and second vertical derivatives delineate the very shallow basement sources in the NE corner of the survey area from the deeper sources elsewhere.

**Image 19**

Image 19 displays the gamma-ray spectrometric data as a colour composite with potassium (red), thorium (green) and uranium (blue). It should be noted that there is no gamma-ray signature obtained over free-standing bodies of water and the signal also markedly degrades as the amount of surface water increases. There are four main units of mapped surficial geology (Sprigg, 1951) which may be correlated with the gamma-ray expression in Image 19:

- Tg - lower Tertiary fossiliferous Gambier Limestone. This is blue/white on the image and occurs in the south and the north-east.

- Qpv - Pleistocene ash, lapilla and volcanic basalts in isolated occurrences. It is relatively high in the three radio-elements and maps as white on Image 19.

- Qpb/Qpe - Pleistocene consolidated beach sands, sea beach and sea floor depositis with included travertinous horizons. These are stranded sand-dunes from previous high sea-level stands, characteristically low in all three radio-elements and map as nearly black. the exception is the unit near the coats, just east of Mt Gambier, that is of more recent origin and relatively high in potassium and thorium. It appears with more red on the image. this unit has probably undergone less weathering than the more inland dunes and has retained radio-active elements.

- Qrp/Qrl - Recent deep flat-lying sands and sand sheets, meadow podsols, swamps and marshes. These are generally rather high in poatassium, uranium and thorium except for some areas where there is virtually no signal at all, perhaps due to water-logging of the surface.

**Image 20**

The interpretation map presented in the folio as Image 20 - presented as a transparent overlay - may be used, with reference to Figure 1.5, to relate the known and interpreted geological features of the area to their expression in the processed images.

## Tectonic Setting From Magnetic And Gravity Data

The survey area lies near a continental margin trending N 120° E. Furthermore, it is close to an important fracture zone or transform/transfer fault zone which is interpreted, from the satellite gravity data, to pass onshore through the western third of the survey area. An expression of this zone is evident in the Haematite (1962) aeromagnetic survey (BMR, 1965) where a north-south striking trough, which appears as a 30 km wide strip of low magnetic relief, is observed to cross Encounter Bay and is co-linear with the lower reaches of the Murray River (Fig. 1.14). To the west of this trough lies an area of high magnetic relief and evident shallow magnetic sources extending below Encounter

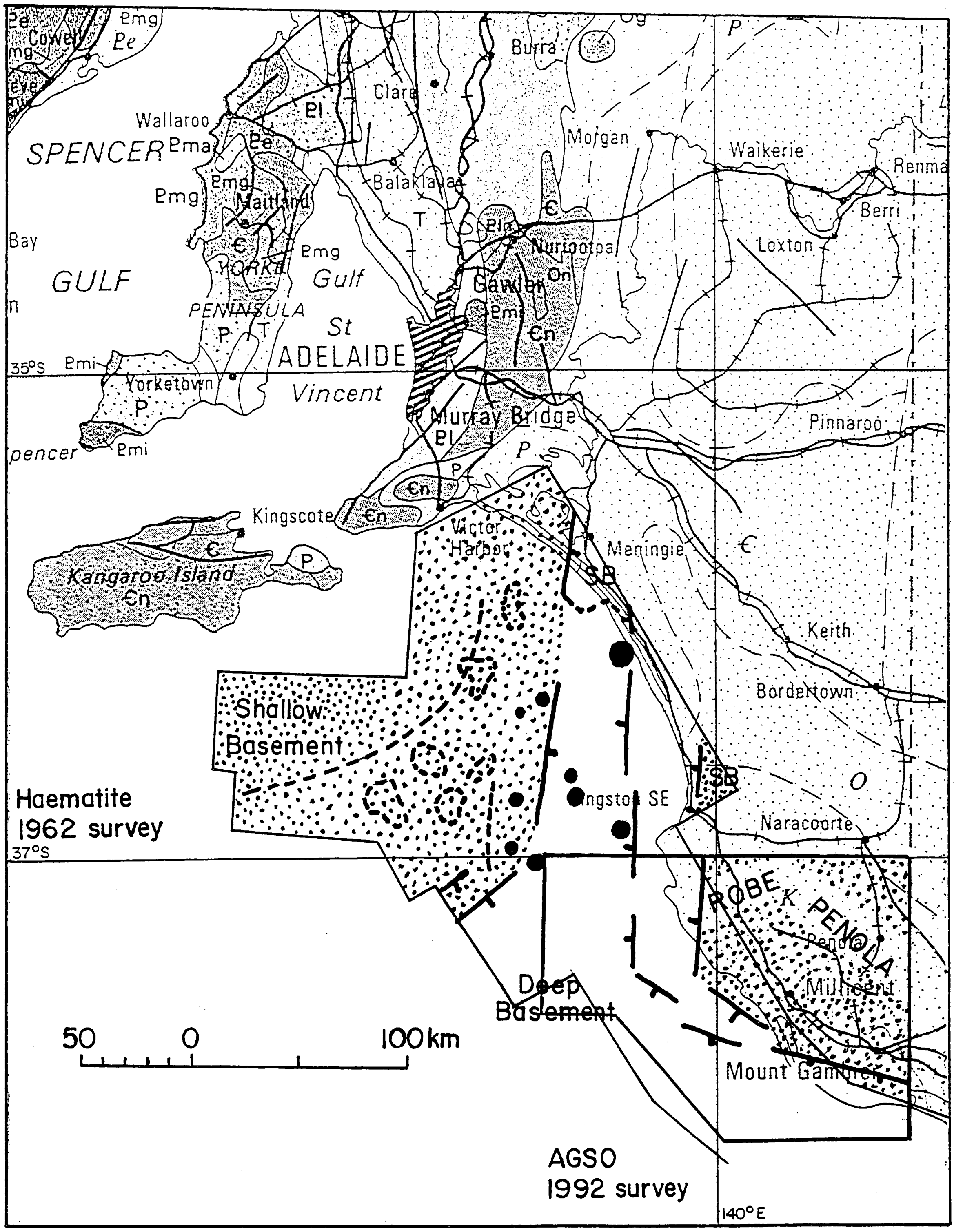



**Figure 1.14** Outline interpretation of aeromagnetic anomalies in the western portion of the Bass Strait/Encounter Bay magnetic survey of 1962 and the AGSO 1992 survey in relation to the geology of southern South Australia (from the Geological Map of Australia, 1982). Fault directions interpreted from the two surveys are shown by heavy lines. Note the relationship of the approximately north-south faulting to the direction of the lower reaches of the Murray River. Intrusions interpreted from the magnetic data are shown as solid circles and areas of shallow magnetic basement by stipple.

Bay up to, and including, Kangaroo Island. The SE margin of this area of shallow basement appears to be delimited by faults striking at about N 60° E, parallel to, but not co-linear with, the strike of the Robe Trough.

The three strike directions recognised regionally, North, N 60° E, and N 120° E, are echoed repeatedly in the structural fabric recorded in the magnetic anomaly patterns of the Penola Sheet. The following observations can be made about these directions:

**WNW-ESE (N120°E) - Continental margin trend**
This direction is expressed by the direction of the Penola Trough, and also the faulting which increases the depth of the magnetic basement, approximately coincident with the coastline, south and west of Mt. Gambier (the Tartwaup Fault Zone). It is also the direction of axes of volcanic eruptions in the Late Tertiary (the *Newer Volcanics*) in the onshore areas and, in the less recent past (?Paleocene), in the offshore areas. Furthermore, it is the direction of strike of most of the intra-sedimentary magnetic markers which are presumed to reflect normal faulting, downthrown to the SW, in the youngest part of the sedimentary sequence.

**N-S (N0°E) - Fracture zone/ transform trend**
This direction is evident in the magnetic lithology of the basement rocks which gives rise to the main north-south striking magnetic anomaly falling near the central meridian of the Penola Sheet. The direction recurs as the strike of normal faulting which drops the magnetic basement down to the west along two well-defined fault lines west of Beachport. Some evidence of igneous intrusion is evident along this direction, including the Beachport gravity high and intrusive features revealed within the Encounter Bay 'quiet trough' by the Haematite aeromagnetic survey (Figure 1.14). This direction is clearly an ancient one, being the strike direction of late Precambrian and early Paleozoic structures and lithology. However, it is still an active direction as revealed by maps of recent seismicity in Australia. Probably the transform here found a path of least resistance during the initiation of rifting.

**NE/ENE- SW/WSW (N60°E).- Robe Trough/Crayfish Platform**
Within the survey area, this direction is most evident in the gravity expression of the Crayfish Platform and the Robe Trough, but also in the southeasterly termination of the shallow magnetic basement which underlies much of Encounter Bay. Like the transform direction, it is here located approximately tangential to the outer margin of the Gawler Craton. In the area of relatively shallow igneous/metamorphic basement which underlies much of the onshore areas of the Penola Sheet, this direction recurs repeatedly, being typically expressed as rather subtle offsets in both the magnetic and gravity anomaly patterns

## *SECTION 1.3*

# IMPLICATIONS FOR BASIN DEVELOPMENT

In this section, a limited comparison is made between the interpretation of the magnetic and gravity data, as shown on folio **Image 20**, and the geology of the western Otway Basin. Many of the concepts presented below must be considered speculative at this stage, but they can be tested with more detailed work.

The following observations are made:

- A brief comparison between the intra-sedimentary magnetic lineations (shown as thin red lines on **Image 20**) and both offshore and onshore seismic data shows that these lineations are often (but by no means exclusively) due to seismically-mappable faults. Consequently, at least in the western Otway Basin, high resolution aeromagnetic data can successfully establish the gross basin architecture both quickly and cheaply, as well as providing information which is directly relevant to petroleum exploration.

- The strike direction of the basement geology underlying the area, as revealed by magnetic survey, strikes clearly N-S.

- Three prominent fault orientations are visible in the aeromagnetic data:

  - **ENE:** These are principally expressed in the north-west corner of the survey area, and are present through the Crayfish Platform, then continue onshore through the Robe and St Clair Troughs. Similar orientations can be seen in the south-eastern part of the survey area, immediately north of Mt Gambier, and also just south of the township of Penola. A further manifestation of this direction is evident in older aeromagnetic data for the marine areas of Encounter Bay.

  - **ESE-SE:** This is the dominant fault orientation in the basin, corresponding to the tradition 'normal' or 'breakup' fault suite.

  - **NE:** These are cross-cutting faults which are oriented approximately normal to the ESE-SE fault set and sub-parallel to the ENE fault set.

- It may be significant that the three fault directions and the N-S basement strike direction are separated from each other by approximately 120$^{o}$. Where these directions are reflected in the pre-rift structure, pre-existing structural grain can be expected to have influenced the initial surface manifestations of rift development.

- The orientation of these fault sets provides potentially critical information on the early rifting history of the western Otway Basin. The magnetic data indicate that the E-ENE-trending Crayfish Platform and the Robe Trough comprise part of the one tectonic unit, and indeed, there are some indications that the inshore part of the Chama Terrace and the St Clair Trough might also be contiguous. Traditionally, rifting and breakup along the Otway margin is considered to have taken place with a NE-SW extensional transport direction (see Gravestock *et al.*, 1986; Etheridge *et al.*, 1985, 1987), although Willlcox & Stagg (1990) inferred a left-lateral strike-slip to 'trans-tensional' origin for the proto-Otway Basin.. However, the orientation of both the Crayfish Platform and the Robe Trough is identical to that of the early (153-120 Ma) extensional basins in the Great Australian Bight, but oblique to the dominant structural grain of the Otway Basin. Moreover, both the Crayfish Platform and the Robe Trough contain very thick sediments of the Crayfish Group (Gravestock *et al.*, 1986) that are contemporaneous with the early rifting phase in the Bight, as documented by Etheridge *et al.* (1989) and Willcox & Stagg (1990).

- Recently, Williamson *et al.* (1990) noted that the Crayfish Platform appeared to represent a 'fossil' rift system, which extended from the latest Jurassic until about 120-115 Ma. This rift had extensional faults striking EW to ENE, again identical to that of the early rift phase in the Bight. Williamson *et al.* (1990) concluded that this rift event terminated at the end of Crayfish Group deposition. Subsequently, the extensional transport direction switched to NE-SW, contemporaneous with the beginning of the deposition of the Early Cretaceous Eumeralla Group. Significant changes in fault trend and style, subsidence rate and sedimentary facies accompanied this change from the "Crayfish Rift" to the "Eumeralla Rift", according to Williamson *et al.* (1990).

Putting the above observations together, a plausible tectonic history for the western Otway Basin is as follows:

## Tectonic History

### 153-120 Ma

During the period from about 150 Ma until the end of Crayfish Group deposition at about 120 Ma, rifting in the Otway Basin took place in rift segments oriented EW-ENE. The extensional transport direction was NNW-SSE, identical to that in the basins of the Great Australian Bight. During this period, high energy, fluviatile sands of the Crayfish Group were deposited in rapidly subsiding grabens. The Crayfish Platform-Robe Trough, and perhaps the inshore Chama Terrace-St Clair Trough developed in an almost purely extensional stress regime (with perhaps some minor transtensional (left-lateral) movement). By analogy with the Bight Basins, most of the crustal extension would have occurred during this interval, and one would expect, therefore, that the Crayfish Group would be both the thickest but also the most areally restricted and tectonically-controlled, of the Early Cretaceous sequences, i.e. a syn-rift deposit. In this scenario, the NW-trending Penola Trough, which also contains a thick Crayfish Group, would have been under a strongly trans-tensional (left-lateral) stress regime, with the bounding faults having significant strike-slip components, as shown by Willcox *et al* (1992, fig. 14B) and Colwell & Willcox (1993).

In their model the Crayfish Platform-Robe Trough effectively comprised part of the head-wall of the extensional fault system, with the Penola Trough representing a trans-tensional arm of the Crayfish-Robe rift segment. A diagram which crudely represents a possible configuration for the Penola Trough is shown in Figure 1.15. Whilst we believe that it is likely that the Penola Trough and the Crayfish Platform-Robe Trough *actually comprised part of one extensional/trans-tensional tectonic unit*, Figure 1.15, for the sake of simplicity, only shows a representation of the 'Penola Trough'. In the model in Figure 1.15, left-lateral strike slip, diverging (to the south-east) faults are located over a SW-dipping detachment surface. In the model, the trough widens to the south-east, and prominent, rotated fault blocks are associated with NE-dipping faults along the SW margin. This is consistent with the Penola Trough, which also widens to the south-east and has been interpreted as a simple half-graben which thickens into the south-western faulted margin (Hill & Durrand, 1993). Structural features such as the Beachport-Kalangadoo High would correspond to the leading edge of one of the rotated fault blocks on the south-western margin of Figure 1.15. Interestingly, if the Penola Trough was interpreted as a simple extensional half-graben (see Hill & Durrand, 1993), rather than as a trans-tensional feature (as in this study), then *the fault and fault block geometries on the south-western margin of the trough suggest that the master detachment dips landward (i.e. NE), rather than south-west.*

Support for the proposal for an ENE-oriented extensional rift system comes from a recent study of the Katnook and Ludbrook Grove discoveries in the onshore Penola Trough (Parker, 1992). Even though the overall trend of the Penola Trough is NW-SE, detailed seismic mapping (Parker, 1992) of the 'Top Crayfish Group' (i.e. Top Pretty Hill Sandstone Horizon) shows *that the principal faults at this level generally trend E-ENE, coincident with the early extensional direction from the Great Australian Bight* (Willcox & Stagg, 1990) and also the Crayfish Platform (Williamson et al., 1990). Moreover, Pettifer *et al.* (1991) recently carried out a lineament study in Victoria, and have identified a major suite of lineaments trending ENE within the onshore part of the Otway Basin. Whilst Pettifer *et al.* (1991) did not propose an origin for them, we would suggest that they are the result of the earlier extensional event that produced the Crayfish-Robe rift segment.

**120-96 Ma**

At about 120 Ma, the stress regime changed and the Crayfish Group was uplifted and eroded. By about 115 Ma, a NE-SW extensional transport direction appears to have been established, which over-printed the earlier EW-ENE trending, 'Crayfish-Robe' rift segments. Deposition of the more low-energy, widespread Eumeralla Group commenced contemporaneously and was controlled by ESE-SE faults resulting from normal extension directed SSW-SW. This later 'rift' geometry largely controlled the post-rift subsidence and thermal sag throughout the Late Cretaceous and Tertiary, thereby largely obscuring the underlying ENE-trending rift segments of the true rift. An exception was on the inboard part of

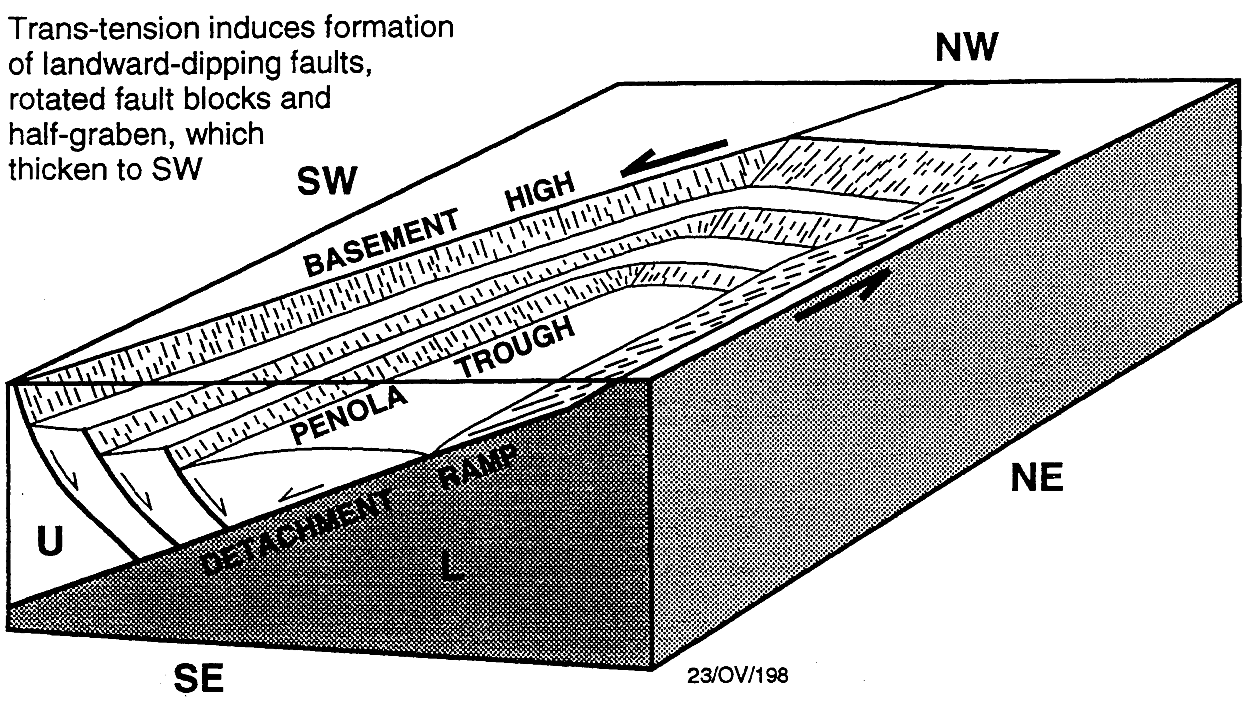



**Figure 1.15** Highly schematic block diagram showing how the Penola Trough may have developed from 150 to ~120 Ma within a strongly left-lateral strke-slip (trans-tensional) environment. Modified from Gibbs (1987).

the Crayfish Platform and also in the onshore Otway Basin, where the first-generation rift was at least in part preserved.

## Master Detachments

Examination of regional seismic lines across the onshore and offshore Otway Basin, as published by Hill & Durrand (1993), shows that a fundamental 'break' takes place on either side of the WNW-trending Beachport-Kalangadoo/Diamond Swamp Highs. To the NE of these highs, the faults are principally landward-dipping, whereas south of this zone, they are seaward-dipping. According to Hill & Durrand (1993), both the prominent unconformity at the top of the Crayfish Group, and the change in the fault styles on either side of the highs, are related to a switch at about 120 Ma from a northward-dipping, to a southward-dipping, master detachment. This switch changes the rotation of the fault blocks from landward (north-dipping detachment) to seaward (south-dipping detachment). Our model, in contrast, does not require a switching in the dip of the master detachment. Rather, within the Penola Trough, landward-dipping fault blocks develop *as a result of oblique extension* over a SW-dipping detachment from 153 until about 120 Ma. As a consequence of a change in the orientation of the stress field, uplift and erosion resulted in the Top Crayfish Group unconformity. The new rift axis developed slightly outboard of the earlier rift (i.e. south-west of the Beachport-Kalangadoo/Diamond Swamp Highs), with simple (~pure) extension proceeding (with a NE-SW extensional transport direction) over a SW-dipping master detachment.

**Accommodation Or 'Transfer' Zones**

If the general rift history outlined above is correct, then accommodation or 'transfer' zones should be present within the western Otway Basin. In the earlier rift phase (the Crayfish-Robe Rift), these would trend NW-NNW, whereas in the later phase, they would be more NE. Unfortunately, the NW-NNW direction is very close to the orientation of the traditional 'normal' fault direction in the western Otway Basin, and thus the transfer zones are not readily identifiable. In contrast, several NE trends cut the basin, with one set bracketing the Katnook and Ludbrook Grove fields. If these orthogonal trends are in fact accommodation zones, then they could either facilitate or impede hydrocarbon migration, as well as affecting both the distribution of sedimentary facies and the reactivation history of particular structures.

Examination of regional seismic lines through several of the NE-trending structures within PEL 32 and PPL 62 in the eastern part of the survey area has revealed that the dip and/or sequence character commonly changes across these zones, with structural reactivation above them often extending into the Tertiary. On the seismic sections, there is generally no evidence of a discrete transfer or other fault zone which extends through the Eumeralla Group and younger sequences, perhaps indicating that these features are related to structures within either the Crayfish Group or basement.

Even if the above rifting history is not correct, the recent results from the Bight Basins and the Crayfish Platform indicate that the western Otway Basin was under a strongly trans-tensional stress regime from the Late Jurassic until about 120 Ma. Left-lateral strike-slip faulting would have dominated; it would seem unlikely that features like the Penola Trough could have formed by simple extensional processes in such a stress regime.

- The distribution of the faults in the offshore part of the survey area, as indicated by the magnetic data, is quite interesting. The faults are most abundant on the Crayfish Platform and the Chama Terrace then, south of the Geltwood Beach wells in the central part of the survey area, they die out quite suddenly along strike. This is actually at variance with the geology of the area. On the Crayfish Platform, the Otway Supergroup (i.e. the Crayfish and Eumeralla Groups) are relatively shallow, and the faults are typically broadly-spaced and not strongly reactivated through the Late Cretaceous and Tertiary section (see Fig. 1.16). In contrast, the western Voluta Trough contains a much thicker Late Cretaceous section, and the faulting is very intense, closely-spaced and is often reactivated all the way through the Tertiary sequence (Fig. 1.17).

  If the magnetic anomalies were simply imaging diagenetic minerals which have precipitated along shallow fault planes, it would be expected that the faulting would actually be more obvious on the magnetics in the western Voluta Trough. As the reverse is true, three possible geological explanations present themselves:

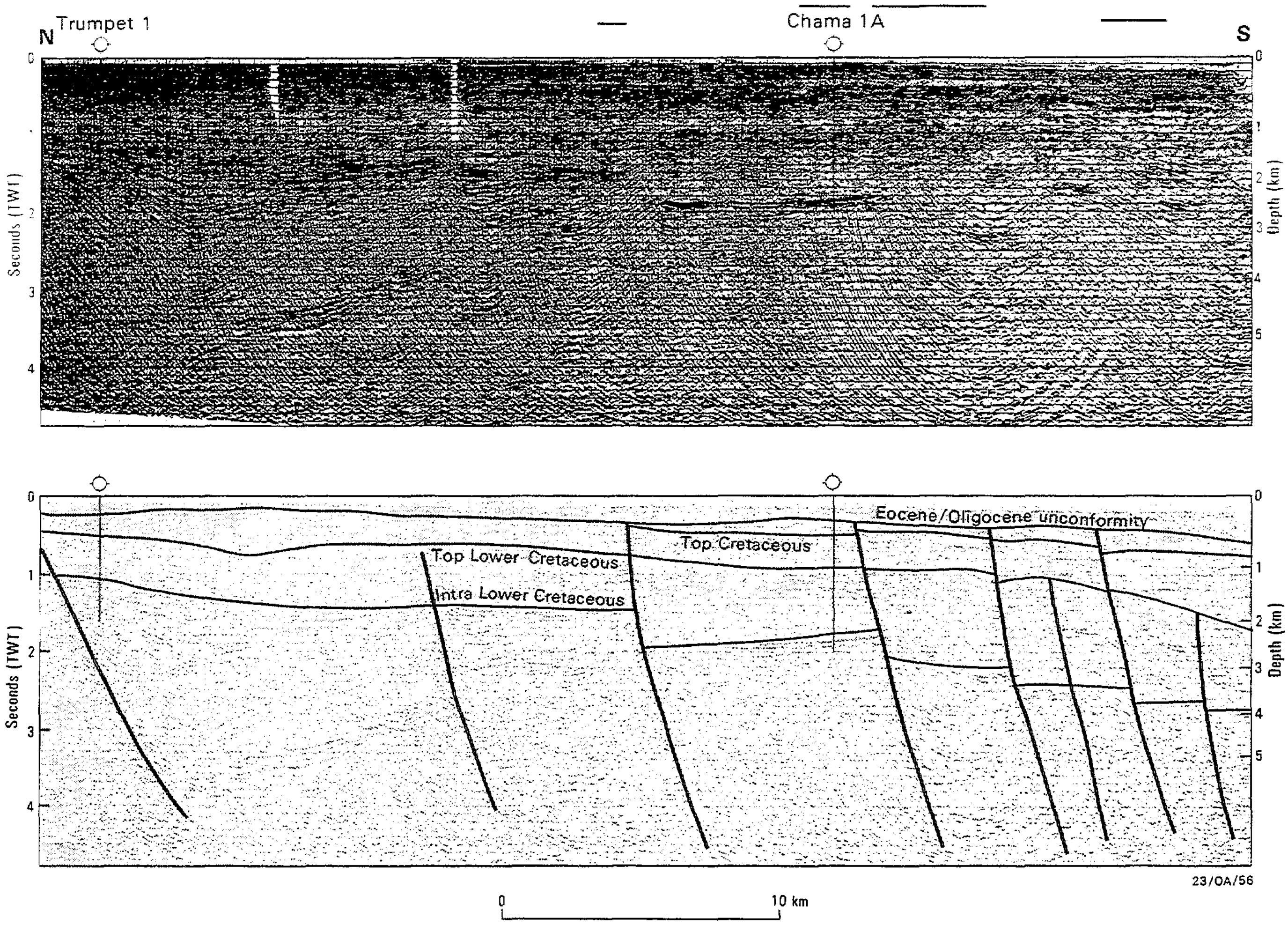



**Figure 1.16** AGSO seismic line 48/37, which trends NNW-SSE across the Crayfish Platform, western Otway Basin. From Williamson *et al.* (1987).

- The magnetic horizon which allows the magnetic survey to image the faults is in the Early Cretaceous, perhaps within volcanogenic intervals in the Eumeralla Group. This could be relatively shallow on the Crayfish Platform but then, with the rapidly increasing thickness of the Late Cretaceous into the western Voluta Trough, this horizon is buried too deeply to have a measurable magnetic expression.

- The horizon responsible for the magnetic expression is truncated by some orthogonal structural feature. The region where the imaged faults die out is cut by two NE-trending features (possible accommodation zones), which trend both north and south of the Geltwood Beach wells. The northern of these two features appears to offset the trend of the volcanic rocks (see later) in the offshore part of the survey area. In addition, a very strong N-NNW trending basement feature extends down through the region where the fault traces are terminated.

- ❑❑ A combination of both the above possibilities, where orthogonal/oblique structures actually result in the magnetic horizon being buried too deeply to be imaged (i.e. an oblique structure actually controlled the development of the Voluta Trough).

- ❑ The magnetic data have delineated several sub-parallel sets of volcanic/magnetic rocks in the sub-surface. All trend approximately north-west. The first set (Set 1) is located on a terrace which flanks the northern margin of the Penola Trough. This set consists of a series of circular-to-oblong magnetic units within basement. The next set (Set 2) consists of a well-defined suite of volcanics which are located at, or near, the surface and presumably correspond to the distribution of the *Newer Volcanics*. This set trends north-west from Mt Gambier towards the Biscuit Flat 1 well. A prominent basement lineament is also co-linear with this trend. This set appears to be on-trend with similar volcanics in Victoria. The next set (Set 3) is rather poorly defined, but may be expressed by scattered magnetic basement units, intrusive units and possibly shallow volcanics between Geltwood Beach 1 well and the town of Beachport. If the shallow volcanics shown near Beachport actually belong to Set 2, then Set 2 actually strikes more WNW than NW. The final set (Set 4) consists of buried volcanics that trend NW along the entire western margin of the Otway Basin, quite close to the shelf break. This set is located outboard of most of the wells in this area, with the exception of Morum 1. Set 4 has previously not been identified on any published studies of the Otway Basin, whilst Set 3, though previously known, has been much better delineated by the magnetic data.

  The position of these sets, particularly Sets 1, 2 and 4, appear to loosely correspond with major hinge or fault zones, with the thickness of the Cretaceous and Tertiary sequences thickening significantly to the south of them (see Williamson *et al.*, 1987; Laing *et al.*, 1989). Their identification has potentially important implications for petroleum exploration. The emplacement/extrusion of volcanic rocks in Sets 2 and 4 may have had a profound effect on the local heat-flow, in particular, and, depending on their age, the volcanics of Set 4 may also have affected reservoir quality in the offshore areas. More importantly, *perhaps, is the possibility that the volcanics might have introduced $CO_2$ into hydrocarbon reservoirs, and, perhaps, have even flushed the hydrocarbons from the structures*. If that is true, then the distribution of the volcanics, as defined by the magnetics, at least provide a predictive tool for determining which structures or areas are most likely to have experienced $CO_2$ charging. Pettifer *et al.* (1991) have suggested that the WNW-NW direction represents major zones of weakness within the basement in onshore Victoria. By analogy, this may indicate that the volcanics that we have identified in the western offshore Otway Basin may have been intruded along basement fault zones which have been reactivated in the Mesozoic and Tertiary.

- ❑ Basement rocks of the Otway Basin are comprised of generally north-south trending Late Proterozoic to Palaeozoic rocks of the Lachlan and Delamerian Orogens (Gatehouse *et al.*, 1992; Glen *et al.*, 1992, Ferguson & Glen, 1992). These older trends may have influenced, at least to some extent, the development of the

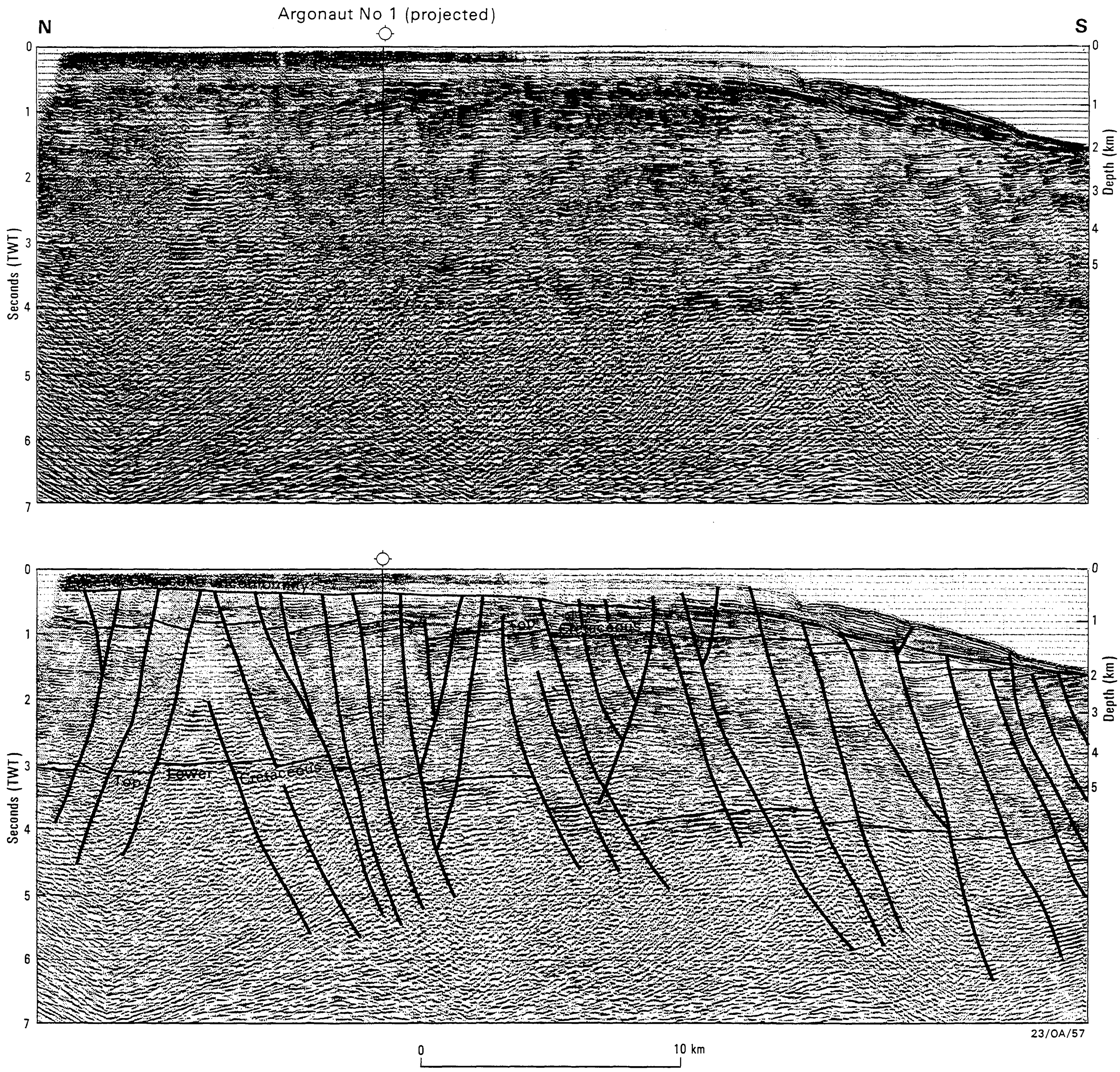



**Figure 1.17** AGSO seismic line 48/43, which trends NNE across the western Voluta Trough, Otway Basin. From Williamson *et al.* (1987).

Mesozoic rift system through the western Otway Basin. To the west of the Woorndoo-Sorrel trend, for example, there are major NW-SE structural trends but these are segmented by significant N-S trending basement features, such as the basement ridges separating the Port Campbell and Tyrendarra Embayment, and the Dartmouth-Merino high separating the Penola Trough-Gambier Embayment from the Ardonachie Trough-Tyrendarra Embayment.

- Offshore, the influence of Delamerian/Lachlan structures is more difficult to demonstrate. The fact that the major linear NW-SE gravity trend at the edge of the continent off South Australian and western Victorian changes to a N-S trend across the Woorndoo-Sorrel trend of Foster & Gleadow (1991, 1993) provides circumstantial evidence that the Woorndoo-Sorrel trend is a controlling lineament affecting basin structure.

- In general, there is little agreement between the distribution of lineaments mapped during the present study and the position of those published by Gravestock *et al.* (1986; see their Figure 3).

- There is no obvious spatial or causal relationship between the major/minor basin-forming structures or lineaments and the location of the known hydrocarbon discoveries in the western Otway Basin. The Katnook and Ladbrook Grove structures lie within the NW-trending Penola Trough and are bracketed on either side by two cross-cutting, NE-trending features (probably faults) which perhaps represent either accommodation zones or basement features. These cross-cutting trends may be potentially important as either facilitators or inhibitors of hydrocarbon migration. The Caroline-1 $CO_2$ accumulation appears to be largely independent of the magnetic and gravity features outlined on **Image 20**, though it is, as would be expected, on trend with the shallow volcanics of Set 2.

- One enigmatic feature is the absence of a clear gravity expression of the north-south direction within the Penola Sheet where, at least, the westward down-faulting of the magnetic basement west of Beachport would be expected to have a clear coincident gravity expression. Without reference to other geological and geophysical data, it can be postulated that the older sediments deposited in this area are of high density, comparable to the density of the magnetic basement below the onshore area of the Penola Sheet. Dense sedimentary accumulations are commonly equated with carbonate rocks. Other possible explanations include the gravity effects of deep-seated bodies compensating near-surface features isostatically.

- It may be worth noting that the Eumeralla Group is typically widely distributed, is of relatively even thickness over much of the western Otway Basin, and often shows onlap relationships to the Crayfish Group and basement highs (see Williamson *et al.*, 1987). In view of the strongly fault-controlled nature of the Crayfish Group, *it could be speculated that breakup was of Neocomian (120 Ma),* rather than the traditional mid-Cretaceous, age. This is consistent with the proposed Neocomian breakup which Stagg & Willcox (1992) interpreted in the region of the wstern Bight. In this scenario, the Eumeralla Group would comprise part of the early post-rift package, with the seafloor spreading (breakup) azimuth being quite oblique to the Crayfish Group rifting azimuth.

## *SECTION 1.4*

# CONCLUSIONS

An aeromagnetic survey carried out to present-day specifications has proved to be of value not only in the traditional role of mapping basement lithology and structure but also in (a) detecting the distribution of volcanic rocks within sedimentary basins and (b) in mapping very subtle magnetic expressions arising from faults disrupting sedimenatry sequences. These advantages come from the abilitiy to provide a unformity of regional coverage seldom possible with seismic surveys, even at vastly greater expense, both onshore and offshore with equal ease. Furthermore, a broad-brush picture of sediment depth over the study area has been possible through modelling magnetic anomalies thought to arise from magnetic sources within the rocks of the 'basement'. The simulataneous intepretation of the reegional gravity survey data for the area provides further controls on the geological interpretation of geophysical data.

The principal findings of this interpretation study in obtaining new geological information relevant to the western Otway Basin - and perhaps to south-eastern Australia as a whole - are as follows:

- ❒ It appears possible that the rifting history of the western Otway Basin was divided into two distinct stages. The initial stage, from, 150 to ~120 Ma, took place with an extensional transport direction oriented NW-SE, similar to that of the Great Australian Bight Basins. In parts of the basin, such as the Crayfish Platform and Robe Trough, purely extensional rift segments which struck E-ENE developed, contemporaneous with the deposition of thick Crayfish Group sediments. Other parts of the western Otway Basin, such as the Penola Trough, were probably under strongly trans-tensional stress throughout this period, with highly rotated, landward-dipping fault blocks developing over a SW-dipping master detachment. After a period of uplift and block faulting at ~120 Ma, rifting recommenced with an extensional transport direction oriented NNE-SSW, contemporaneous with the deposition of the Eumeralla Group. This rift axis was located outboard (SW) of the earlier rift, and because extension was simple rather than oblique, seaward (SW)-dipping fault blocks developed over a SW-dipping master detachment. This later rift episode produced the 'traditional' normal fault orientation within the Otway Basin.

- ❒ Several NW-trending, sub-parallel sets of volcanic/magnetic rocks have been identified in the sub-surface, which may define the position of major basement or rift-related fault sets. Determination of the location of these volcanic rocks may allow predictions to be made as to the likelihood of $CO_2$-rich reservoir or $CO_2$ flushing of reservoirs being encountered.

- ❒ There is no obvious spatial or causal relationship between the major/minor basin-forming structures or lineaments and the location of the known hydrocarbon discoveries in the western Otway Basin.

- ❒ The trends of basement depth provided by modelling magnetic sources in the basement provide an important new overview of basin structure.

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# PART 2

# SYNRIFT TECTONICS OF THE WESTERN OTWAY BASIN

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## Abstract

*The Otway Basin evolved in a ?sinistral trans-tensional environment along part of a rift system which developed between Australia and Antarctica during Mid-Jurassic -Early Cretaceous times. The basin is one of many within the Austral petroleum system extending from the Mesozoic part of the Perth Basin in the west to the Gippsland Basin in the east.*

*In the western Otway Basin region, early basin-forming episodes were influenced by Palaeozoic structures within basement. Major features bounding basin development in that region are 1) the Padthaway Ridge and hinge zones to the north, 2) a zone trending generally north-south through the Merino Uplift in the east, and 3) offshore, the structures of the Otway-Sorrel microplate defined by Geosat data.*

*Aeromagnetic data from the western Otway Basin contribute significantly to detailed knowledge of the Palaeozoic basement geology and improve analyses of basin-forming events. Earlier concepts of rifting within the western Otway Basin have to be modified. Extensional features and basin evolution within the Otway-Sorrel microplate were influenced by remnant Palaeozoic blocks and cross-cutting trends, producing rift segments and accommodation zones which did not evolve into a single basin until the latter part of the Early Cretaceous.*

## INTRODUCTION

Recent research work in the Otway Basin as part of the Australian National Geoscience Mapping Accord (NGMA) program has highlighted the need to achieve a better understanding of early basin history as a guide to determining how it has affected structures and processes leading to the formation, migration and entrapment of hydrocarbons. Many source rocks are thought to be early rift Otway Group sequences and it is generally acknowledged that the early basin structures were affected by underlying Palaeozoic geology. This review summarises some of the more recently published literature on basin-forming processes and how they may be applied to early events in the Otway Basin. The 1992 AGSO aeromagnetic coverage of the western Otway Basin provides timely information on basement and intra-basin structures and thus plays an important part in the assessment of basin-forming processes and how they affect the exploration for resources.

## SOUTHERN MARGIN RIFTING

The Otway Basin in western Victoria, southeastern South Australia, and the adjacent offshore areas is part of the southern margin of Australia and, with its conjugate margin

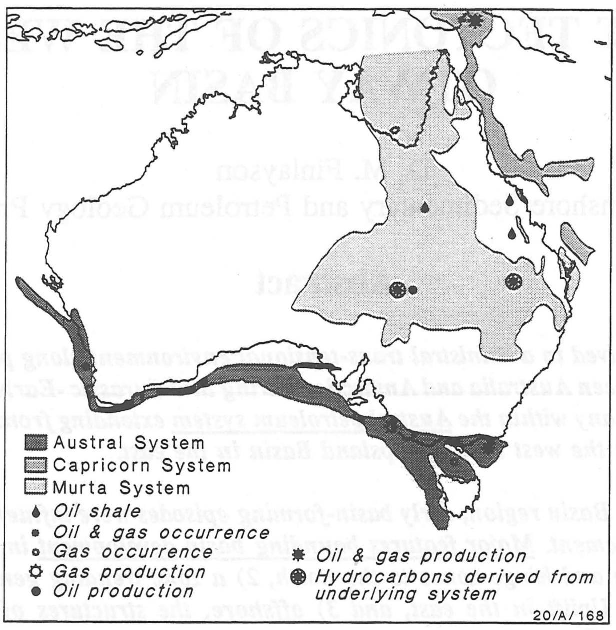



Fig. 2.1 Location of the Austral Petroleum System along Australia's southern margin (from Bradshaw, 1992).

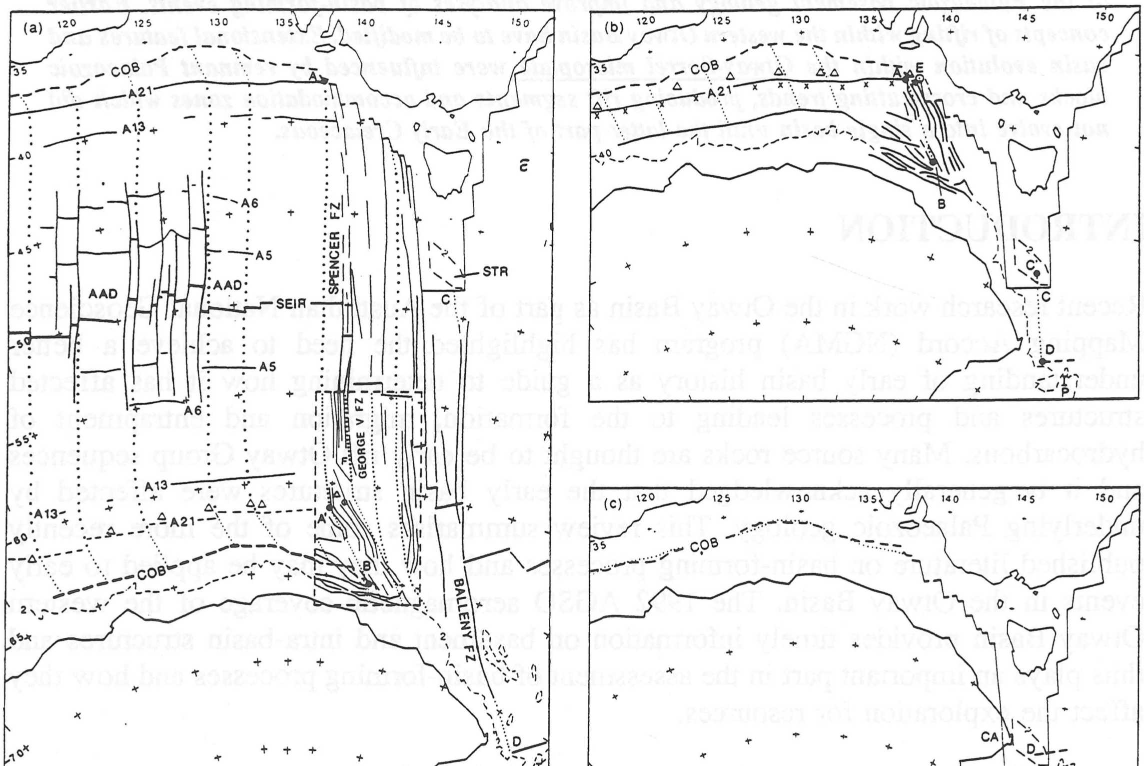



Fig. 2.2 Southern Ocean spreading history as described by Veevers (1990); (a) the present-day structural trends; A - A'- B defines the trends for fast and slow phases of spreading; (b) the Southern Ocean at 49 Ma when there was a change from slow to fast spreading; (c) inferred closure of the Southern Ocean along the continent-ocean boundary (COB) at 96 Ma (COB defined from magnetic and seismic data).

in Antarctica, formed part of a Mesozoic continental rift system. Analogues include the margins of the Atlantic Ocean and the current rifting system in eastern Africa. In mid-Jurassic to mid-Cretaceous times, lithospheric extension and rifting processes affected the Australian/Antarctic continental land mass and eventually formed the Austral petroleum system proposed by Bradshaw (1992) (Fig. 2.1). Mogoon & Dow (1991) define a petroleum system as encompassing "a hydrocarbon source rock and all generated oil and gas accumulations and includes all the elements that are essential for an oil and gas deposit to exist: source rock, overburden, reservior, seal, and trap. All these elements must be in place temporally and spatially such that the processes required to form a petroleum deposit can occur."

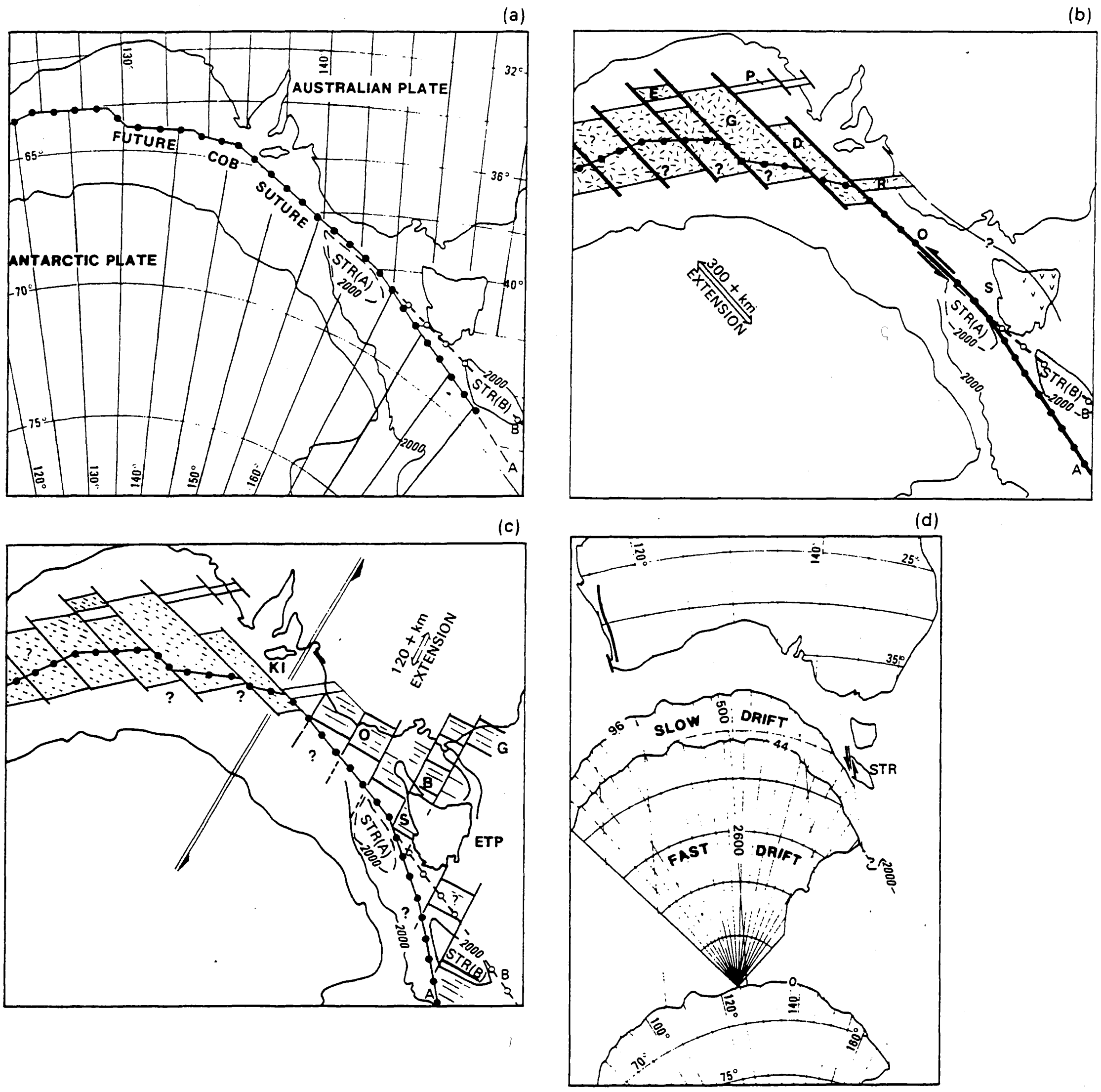



Fig. 2.3 Early (pre- 96 Ma) rifting episodes for Australia's southern margin interpreted by Willcox & Stagg (1990); (a) pre-rift (>153 Ma) modified from Veevers & Eittreim (1988); (b) NW-SE rifting in the period 153-120 Ma; (c) plate configuration in the period 120-96

Bradshaw (1992) included all the basins on Australia's southern margin in the Austral petroleum system, extending from the Mesozoic and younger parts of the Perth Basin in the west to the Gippsland Basin in the east. The facies within the system are generally early non-marine clastics, which were followed from the Late Cretaceous onwards by marine clastics and then carbonates. The timing of events along the whole margin suggests that the earliest breakup events occurred in the west and progressed eastward.
Veevers (1990) has reviewed the magnetic, bathymetric and satellite data on the conjugate margins and reconstructed the seafloor spreading stages affecting the Southern Ocean since breakup at 96 Ma. Figure 2.2 shows Veevers' (1990) closure of the Southern Ocean with two phases of spreading being recognised; the more recent phase of fast spreading at a rate of up to 27 mm/year took place from 49 Ma to the present, determined from magnetic reversal patterns and mapping of synchronous fracture zones within the Southern Ocean basin, e.g. Spencer and George V Fracture Zones (180° azimuth), and an earlier slow spreading rate of 4.5 mm/year from continental separation at 96 Ma to 49 Ma. The azimuth of this earlier slow-spreading phase is not as well constrained (about 150° azimuth) (Fig. 2.2).

Names have been attached to the various oceanic fracture systems which imply correlation with fault zones found on the Australian margin, e.g. Spencer, St. Vincent, and Gambier Fracture Zones. These correlations may need revision in the light of the data now available on the gravity map of Australia and the Geosat data from the Southern Ocean (Sandwell, 1992). Some of the previously proposed fracture zones may

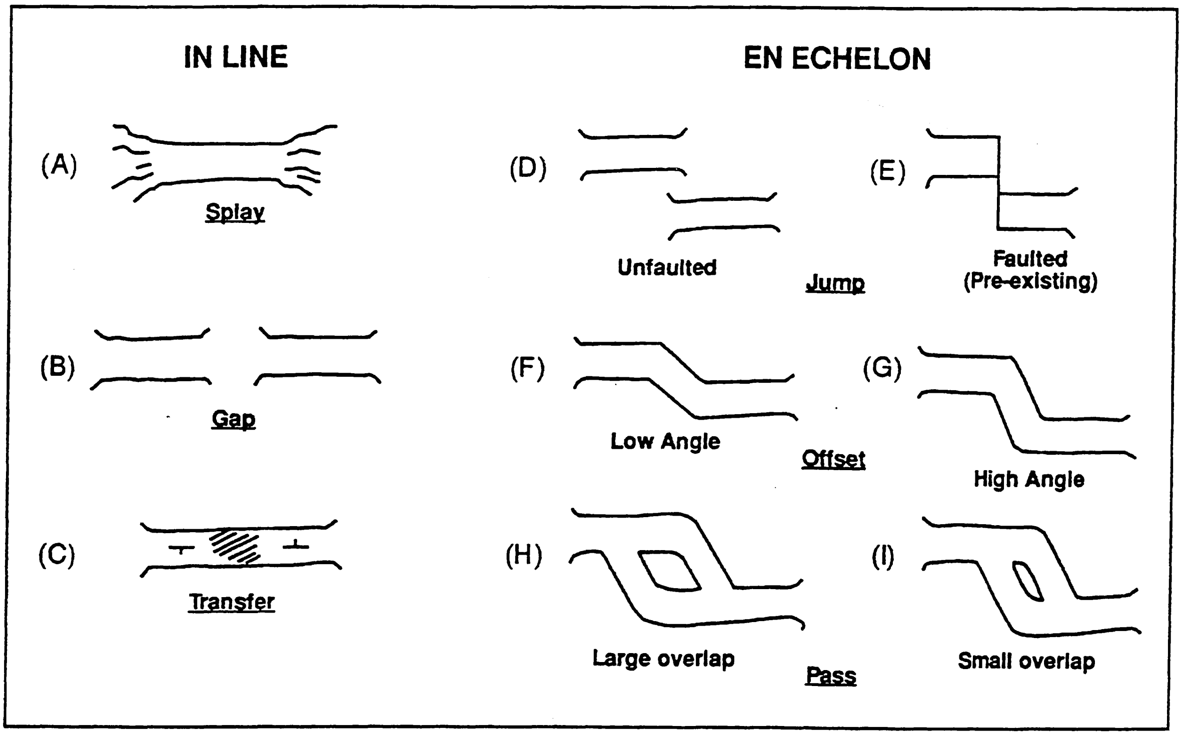



Fig. 2.4 The generic classification of rift segment interaction defined by Nelson et al. (1992).

not exit. The gravity-Geosat image of the southern Australian margin (Enclosure 3, accompanying map and image folio) strongly suggests the existence of, what I will call here, the Otway-Sorrel microplate, a triagular region of lithosphere defined by the northern onshore margins of the Otway Basin, the eastern limits of the Sorrel Basin off western Tasmania, and a prominent Geosat lineament (?fault zone) extending from the offshore Crayfish Platform to the southern tip of Tasmania. This microplate is the region of attenuated lithoshere which forms the substrait of Otway and Sorrel Basins. On the basis of the Geosat/Bouguer image, it seems quite probable that any major onshore-offshore correlations are with the fracture system running south from the western edge of the Murray Basin (what Murray et al. (1989) call their Scopes Range - Padthaway Gravity High) and extending south from the western apex of the Otway-Sorrel microplate (Enclosure 3, accompanying map and image folio).

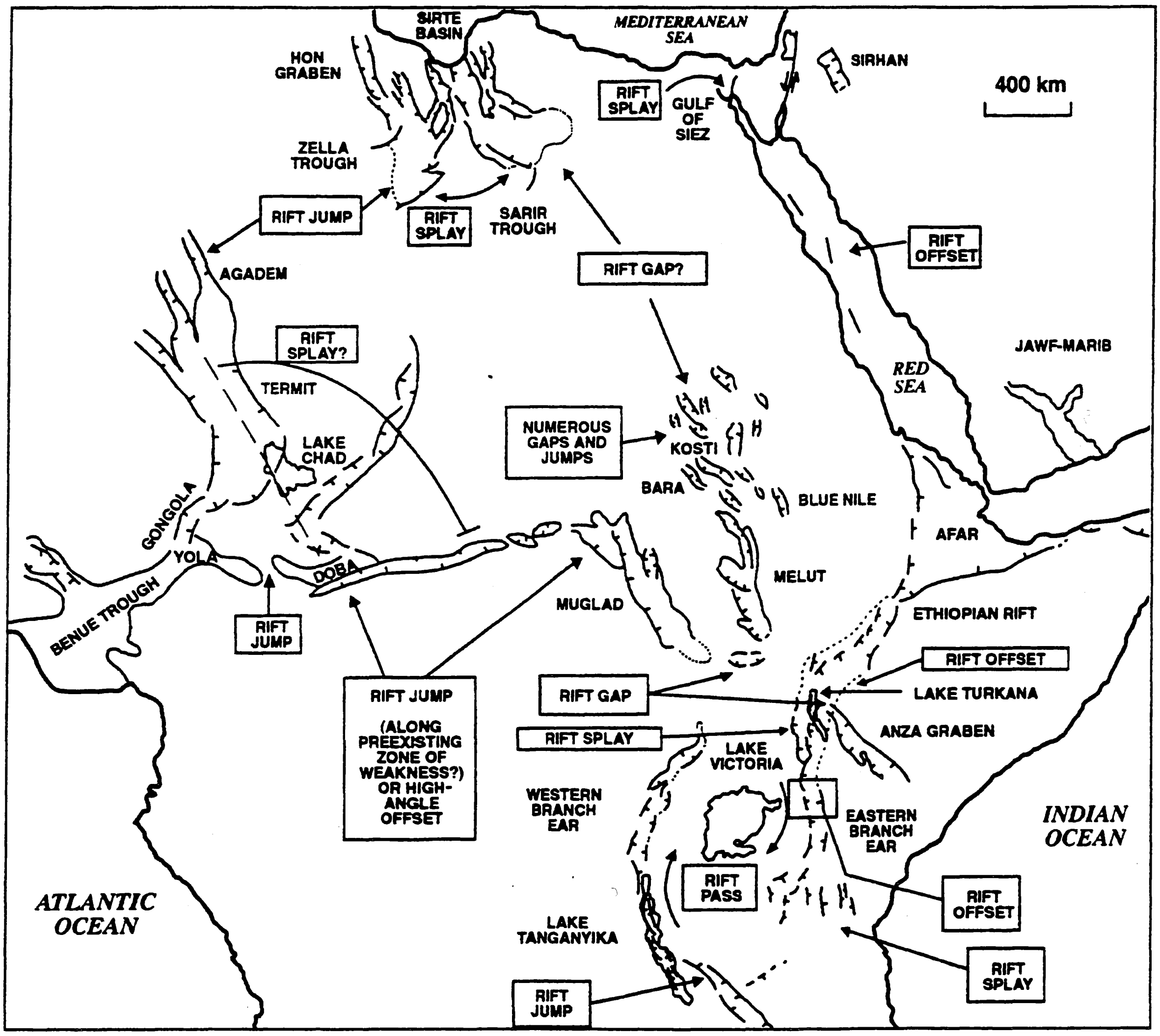



Fig. 2.5 Examples of rift segment interaction geometries in the African continent (from Nelson et al., 1992).

Willcox & Stagg (1990) argued that the evolution of the South Tasman Rise and the basins of the Great Australian Bight (GAB) could be best explained by oblique extension prior to 96 Ma (Fig. 2.3). In the GAB region they proposed an interpretation which included 300 km of oblique extension along a NW-SE azimuth during the period >153 Ma (Late Jurassic) until about 122 Ma (Early Cretaceous), followed by 120 km extension in a NNE-SSW azimuth in the period from 122 Ma until about 100 Ma. Such early basin-forming events provide an explantion of structures found in the Eucla Basin, Eyre Terrace, Polda Trough, and other parts of the GAB.

The sequence of NW-SE and NNE-SSW azimuths of extension has significant

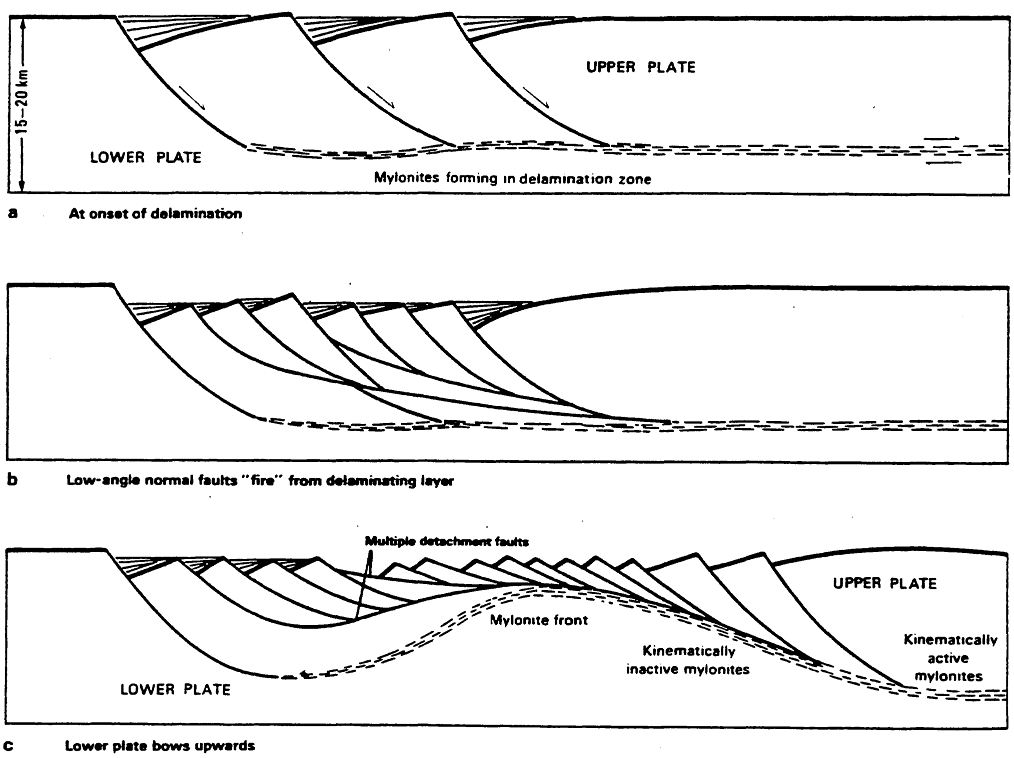



Fig. 2.6 Simple form of continental extension using the detachment model on a single, low-angle detachment fault/shear zone (from Etheridge et al., 1988).

implications for the structures to be expected in the western Otway Basin and how they might have been affected by pre-existing Palaeozoic structures. Willcox & Stagg (1990) consider that this rifting process took place prior to the slow and fast oceanic extension phases beginning at 96 Ma and described by Veevers (1990). Fission track analysis shows that 96.6±5.3 Ma was a time of major regional uplift and erosion at the end of deposition of Otway Group sediments (Duddy & Green, 1992).

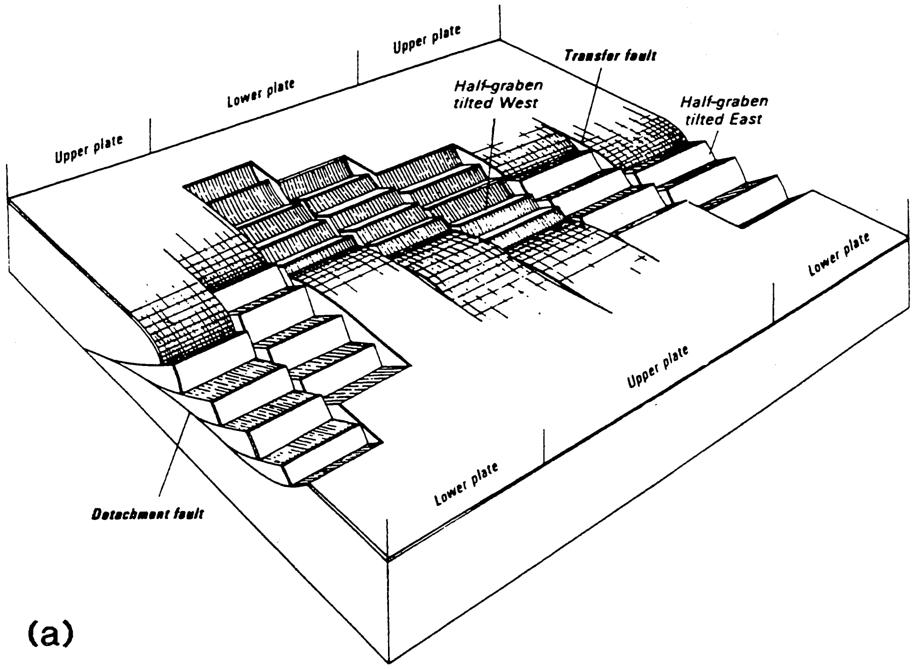
# RIFTING PROCESSES

Rifting processes in the continental lithosphere are still not fully understood but, increasingly, studies of rifts and passive continental margins around the world are showing that the early stages of rifting in Mesozoic and Cainozoic basins are controlled largely by the pre-existing geological structures. Dunbar & Sawer (1989) examined data from the Atlantic margins of North America, Africa, and Greenland and concluded that the style of continental extension is largely controlled by the orientation of the rift break relative to the pre-existing structural grain. Daly et al. (1989) reviewed many of the African basins and emphasizes that strike-slip fault zones produce pronounces mechanical anisotropy in the upper crust and exercise a kinematic constraint on rift geometry. Coward et al. (1989) interpreted many of the basin structures to the north of Scotland and concluded that Caledonian structures seen onshore developed a crustal anisotropy which was subsequently reworked to form extensional basins.

Much of the work on the initial rifting process was reviewed by Nelson et al. (1992) and they developed models of early rifting events. They proposed that the rifting process develops from early isolated pockets of continental extension which they term ***rift segments*** (Fig. 2.4). These pockets grow and interact as the rift system matures. Nelson et al (1992) pointed out that the same principle of crack growth can be seen in a brittle medium on just about any scale from laboratory models to continental-scale rifts. They indicated that during orthogonal extension the main bounding faults generally strike perpendicular to the regional extension direction, but that these faults may be oblique when following existing basement fabric.

Figure 2.4 shows Nelson et al.'s (1992) generic classification of rift segment interaction; inline segments may eventually link, and en-echelon segments may link but with original segments and edges preserved. Crustal inhomogeneities may lead to a number of consequent rift structures such as rift splays, rift gaps, rift jumps, and rift offsets. Rift offsets may introduce structural complexity and the possiblity of structural closure within the offset zones. The offset zones may well be structurally higher at the basement level than the normal segments, generating a regional structural saddle between adjoining rift segments (Nelson et al.; 1992). Examples of the diverse rifting geometries which can occur in continental-scale rifting can be seen in the present-day African continent (Fig. 2.5). Possible identification of rift segments in the Otway Basin is discussed later in this paper.

The approach taken by Nelson et al. (1992) to the description of rift systems is to apply mechanical principles to an essentially brittle upper crustal layer. However, this gives few clues to the processes that might be occurring at depth. In the scientific literature, however, there is now overwhelming evidence that processes on a lithosphere scale control basin-forming processes. The rheology of the deeper parts of the Earth's crust changes significantly as temperature increases, leading to large-scale shear and the formation of ***detachment surfaces*** within the middle-to-lower crust and at the crust-mantle boundary (CMB). The extensive scientific literature on this topic is only touched upon here. Significant papers on the subject include Bally (1981), Gibbs (1984),



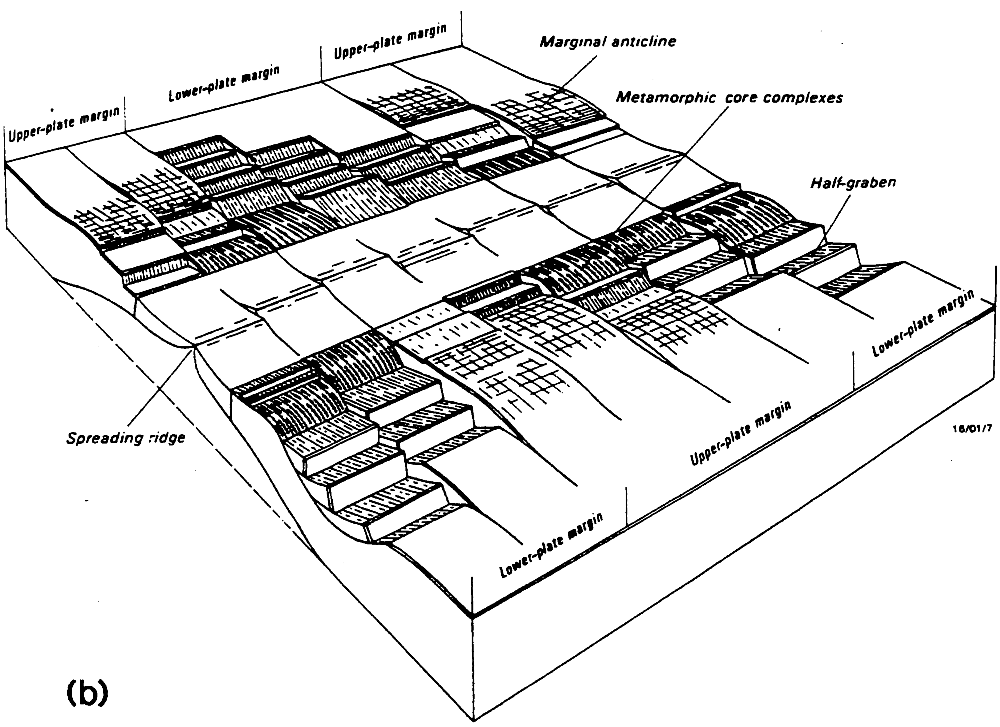




Fig. 2.7 Transfer faults can segment an extensional terrane at both (a) the continental rift stage, and (b) the passive margin stage. Complete reversal of dip direction of the detachment can occur on the same margin (from Etheridge et al., 1988)

Etheridge et al. (1988), Wernicke & Burchfiel (1982), Lister et al. (1986), and Ziegler (1982, 1992a,b,c), Scott et al., (1992), Rosendahl (1987), Rosendahl et al. (1992), and a volume edited by Beaumont & Tankard (1987).

Figures 2.6 and 2.7 show some of the conceptual models described by Etheridge et al. (1988). Figure 2.6 shows possible processes at depth within the crust and upper mantle, and Figure 2.7 shows the separation of rifting segments by ***transfer faults or transfer zones***, illustrating their importance in enabling offsets in the major depocentres and reversal of polarity. Etheridge et al. (1988) used the structures seen across the Eyre Terrace through Jerboa No. 1 well in the Great Australian Bight, together with data from the conjugate Antarctic margin to suggest that area of the Bight is a classical lower plate extensional margin and that the Antarctic margin is the complementary upper plate margin.

The simple concepts presented in Figures 2.6 and 2.7 are considerably complicated when there is a component of strike-slip associated with extension (Scott et al., 1992; Gibbs, 1987) and when there are multiple extension episodes on detachments at different levels. Rosendahl (1987) gives a comprehensive description of the architecture of the early rifting process in eastern Africa where ***accommodation zones*** connect rift segments and half graben with opposing polarity, rather than simple transfer zones. Between rift segments there may be low-relief and high-relief accommodation zones (LRAZ's and HRAZ's) depending on the amount of overlap between opposing rift segments, and there may be strike-slip between such rift segments.

Rosendahl (1987) indicates that the dimensions of discrete structural basins is 80-160 km and length-to-width ratios of 2-4 (the true "building blocks" of rifts). He also emphasizes the difficulties that may be experienced in matching conjugate rift margins, and the dangers in making correlations between oceanic and continental lineaments. He cites the case of what might be expected from an opening of the Tanganyika Rift Zone and shows that the correlations would not be obvious. He does, however, consider that high-relief accommodation zones (HRAZ's) probably present the most likely correlations with offshore oceanic transforms where they follow pre-existing structural grains of regional extent.

Tectonic reversal/thrust episodes, uplift and erosion also complicate the present-day image of basin structures seen on seismic sections. Hence, although we may be able to put forward ideas on the processes affecting basin formation, the number of parameters to be considered in any one region, together with the variations in pre-existing basement geology, lead inevitably to the conclusion that ***all basins are unique***. Although we can look for analogues of Otway Basin structures in other basins around the world, we must evaluate particular Otway structures on an individual basis and propose an evolutionary history consistent with, but not necessarily the same in detail as, that of other basins.

# OTWAY BASIN BASEMENT

Basement rocks of the Otway Basin comprise Late Proterozoic to Palaeozoic rocks of the Lachlan and Delamerian Orogens. There is still controversy regarding the tectonic events which formed the various basement terranes. Recent excursions and symposia have added further insights into the region but no concensus (Gatehouse et al., 1992; Glen et al., 1992, Ferguson & Glen, 1992).

Chappell et al. (1988) defined the basement terranes of the region using isotopic and geochemical analysis of granitic rocks which resolved marked differences between various terranes. They confirmed the early establishment of several terranes identified in outcrop to the north of the Otway Basin, namely the Glenelg Basement Terrane within the Delamerian Fold Belt, and the Grampian-Stavely, Stawell, and Melbourne

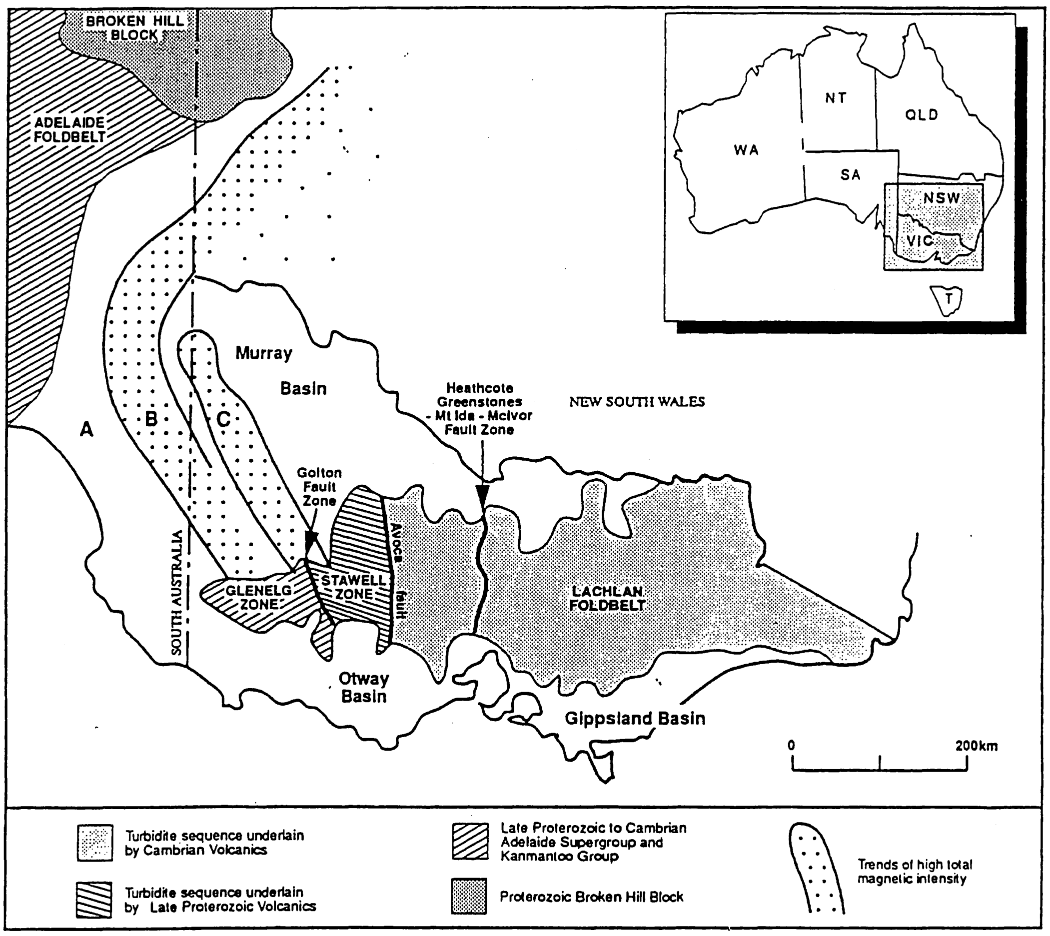



Fig. 2.8 Regional tectonic setting within the Delamerian/Lachlan Orogens according to Wilson et al. (1992). Also shown are the magnetic domains that underlie the Murray Basin (simplified from Brown et al., 1988). A = magnetic striped zone with intensive short wavelength anomalies: B = a broad magnetic smooth zone; C = magnetic high that corresponds with the Mt. Stavely Volcanic Belt.

Basement Terranes within the Lachlan Fold Belt; not all geologists agree on the existence and boundaries of terranes. Many of the generally accepted terrane boundaries trend approximately north-south near the northern margins of the Otway Basin.

Gibson (1992) supports Chappell et al.'s (1988) conclusion that the boundary between the westward verging Delamerian structures and eastward verging Lachlan structures lies along the north-south trending faulted eastern margin of the Glenelg River Complex. Various strike-slip and normal/reverse faulting episodes are interpreted along this boundary. Following Stump et al. (1986), Gibson (1992) correlates this faulted terrane boundary with the Lanterman Fault Zone in Antarctica.

There are, however, other authors who differ markedly with the above location of the Delamerian-Lachlan boundary. Wilson et al. (1992), using the field mapping of structures throughout the Stawell terrane argue persuasively that the whole of the Stawell and Glenelg zones lie on Late Proterozoic metavolcanics and that the north-south trending Avoca Fault at the eastern boundary of the Stawell Basement Terrane is the location of the Delamerian-Lachlan boundary (Fig. 2.8). Glen et al. (1992) also associate the Avoca Fault with the western limit of the Lachlan Orogen and indicate that the

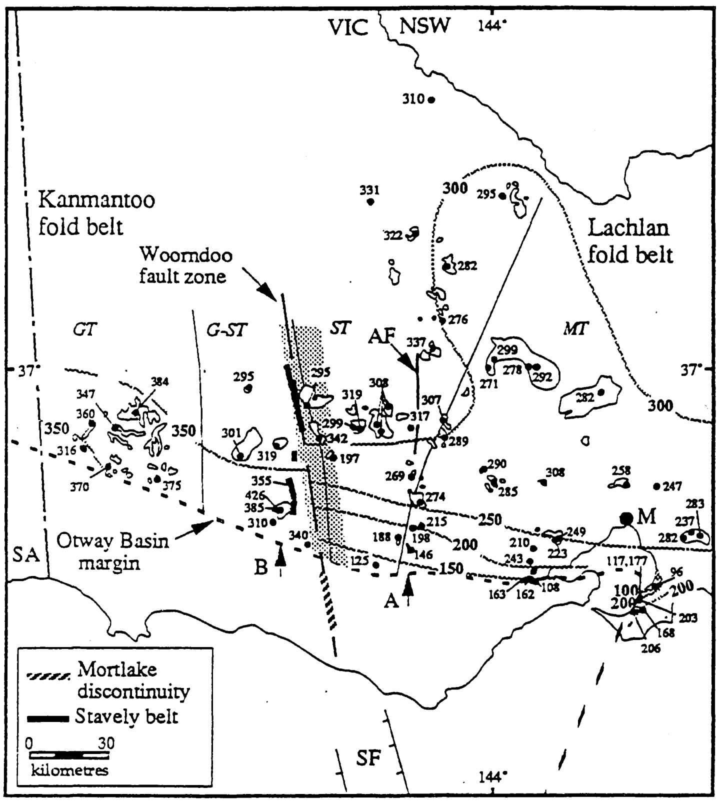



Fig. 2.9 Fission track ages for western Victoria from Forter and Gleadow (1992), and the location of the abrupt change in ages along the trend of the Woorndoo fault zone and the Sorrel Fault. AF = Avoca Fault; GT = Glenelg terrane; G-ST = Grampians-Stavely terrane; ST = Stawell terrane; MT = Melbourne terrane; SF = Sorrel Fault.

terrane to the east (the Melbourne-Mathinna terrane) is allochthonous over thinned Precambrian continental crust. Cayley (1992) also argues that the Avoca Fault at the eastern margin of the Stawell terrane is the Lachlan/Delamerian boundary.

What evidence is there for the Delamerian/Lachlan structural trends affecting the rifting history of the Otway Basin? That such control exists in other extensional margins is well demonstrated, e.g. eastern North America (Swanson, 1988), and the Atlantic margins (Tankard & Balkwill, 1989). In the eastern Otway Basin, Foster & Gleadow (1992) have shown from apatite fission track analysis that there is a marked difference in the thermal history from east and west of the Woorndoo fault zone (Fig. 2.9), suggesting that it has

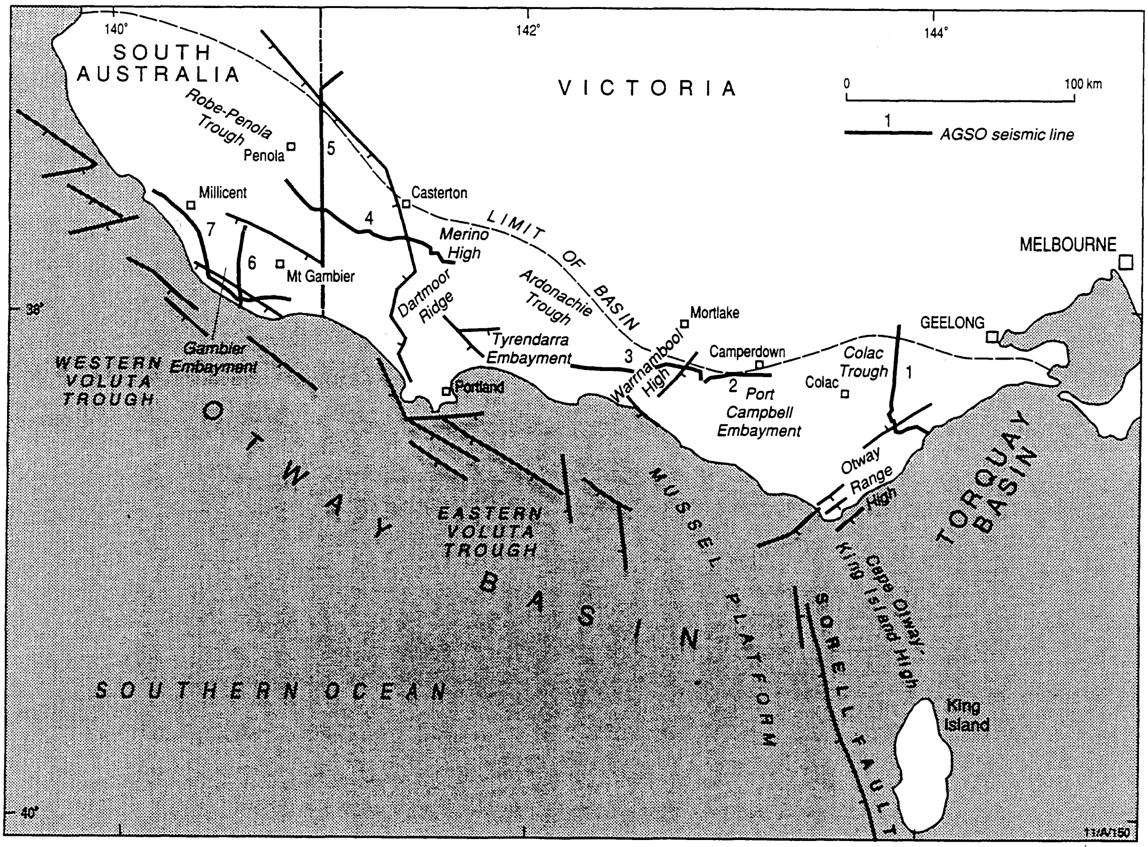



Fig. 2.10 Simplified structure of the Otway Basin and the location of 1992 AGSO region deep seismic profiles.

exercised an influence as a transfer fault on the segmentation of the basin during its formation. They associate the Woorndoo-Sorrel trend further south with the N-S trending Tasman Fracture Zone across the Southern Ocean (see Veevers et al., 1990).

To the east of the Woorndoo-Sorrel trend, the Colac Trough, Otway Ranges, and Torquay Embayment have NE-SW trends which are linked to the early rifting history of the Gippsland Basin (Enclosure 6, accompanying map and image folio). Constantine (1992) has indicated that initial Late Jurassic - early Neocomian synrift sediments were derived from Palaeozoic metasediments and granites exposed along the rift margins and deposited into asymmetric sub-basins and that the Otway and Strzelecki Groups were linked over their traditional boundary, the Mornington High. Cooper et al. (1993) have shown that there has been major uplift of the Otway Ranges (about 2.5 km) to the east of the Woorndoo-Sorrel trend (cooling at 90±5 Ma) which they link to minor crustal shortening, possibly as a consequence of N-NW movement of Tasmania, near the beginning of continental separation. Using fission track data, Dumitru et al. (1991) interpreted rapid cooling for the northern margin of the eastern Otway Basin at 95-100 Ma. Continuing apatite fission track and vitrinite reflectance studies (Mitchell et al., in prep) indicate that within the Otway Basin there were significant variations in cooling times and uplift, indicating local fault-controlled movements throughout the basin's history.

To the west of the Woorndoo-Sorrel trend, there are major NW-SE structural trends (Enclosure 6, accompanying map and image folio) but these are segmented by significant N-S trending basement features, such as the basement ridges separating the Port Campbell and Tyrendarra Embayment, and the Dartmouth-Merino high separating the Penola Trough - Gambier Embayment from the Ardonachie Trough - Tyrendarra Embayment (Fig. 2.10). Pettifer et al. (1991) have described many of the trends associated with gravity and magnetic data in western Victoria, including the Dartmoor and Warrnambool Gravity Highs. It is difficult not to associate the major basement highs with Delamerian - Lachlan Orogen features such as the Mt. Stavely Fault Zone (Vandenberg, 1988) and Gibson's (1992) proposed crustal boundary along the eastern margin of the Glenelg River Complex (Enclosure 6, accompanying map and image folio). Reeves et al. (this Record) discuss the possible influence of Palaeozoic structures on the western Otway Basin based on aeromagnetic and gravity data.

Offshore, the influence of Delamerian/Lachlan structures is more difficult to demonstrate. Seismic records are not always clear on the nature of basement faulting and in the deepest parts of the Voluta Trough it is inferred that there is little impedance contrast between the deepest basin sequences and Palaeozoic basement. The seismic data are inadequate to image the rift onset unconformity. However, what is readily apparent is the major linear NW-SE gravity trend at the edge of the continent off South Australian and western Victorian and its significant change to a N-S trend coincident with the Woorndoo-Sorrel trend of Foster & Gleadow (1992, 1993). As discussed above, there is at least circumstantial evidence that the Woorndoo-Sorrel trend is a controlling lineament affecting basin structure.

There is a basement high trending generally N-S from the Mt. Stavely - Golton fault zone (Fig. 2.8) and forming the eastern limit of Morenda Trough. Offshore from this feature, some of the structural trends on the Mussel Platform develop a significant N-S orientation and it is therefore seems quite likely that Palaeozoic basement trends are affecting offshore structures within that part of the basin. Offshore from the Dartmoor High changes in the basement structures strongly suggest that Palaeozoic structures are influencing the early depositional environment between the eastern and western Voluta Trough.

In the western Otway Basin discussed specifically in this Record, the major Palaeozoic controlling influences are:

1) In the west, the N-S trending gravity features associated with the Scopes Range-Padthaway Gravity High and its offshore correlation with Geosat features in the Southern Ocean

2) In the east, the the N-S trending Merino basement high associated with Gibson's (1992) (unnamed) fault through the Glenelg River Complex, and its possible offshore extension

and 3) In the north, the fault/hingeline at the northern edge of the Robe and Penola Troughs.

Offshore to the southeast the Palaeozoic basement terminates, by definition, at the continent-ocean boundary and includes the western part of the Otway-Sorrel microplate defined earlier in this paper. Within the western Otway Basin, a number of basement highs are identified with Palaeozoic blocks isolated during early rifting by extensional rift segments (see elsewhere in this Record).

## EARLY OTWAY BASIN EVOLUTION

There have been a number of reviews of the tectonics of the Otway Basin (Megallaa, 1986; Yu, 1988), and Carey (1986) gave an insight into some ideas on the evolution of the region as a whole. However, the recent extensive geophysical work in the Southern Ocean and the onshore areas of the basin has set the scene for a closer look at the processes likely to have formed the Otway Basin, taking into account that it is one of a series of basins within the Austral petroleum system along the whole of Australia's southern margin.

Essentially we are trying to define the events which led to the deposition in the western Otway Basin of what is here termed the Otway Group sequences, following Megallaa (1986), Moreton (1990), and Tickell & Arditto (1992), but which has been termed the Otway Supergroup by Kopsen & Scholefield (1990) (Fig. 2.11). One objective of the NGMA Otway Basin Project is to correlate some of the nomenclatures used and establish a standard scheme.

A lithofacies approach to correlation within the Otway Group has been applied by Felton (pers. comm.) using core and logs from twenty-five wells throughout the basin (onshore and offshore) that penetrated significant Otway Group sequences. She identifies seven lithofacies, two assigned to the Casterton Formation, one to the Pretty Hill Formation, and four to the Eumeralla Formation. On the basis of limited control, deposition of facies I and II (Casterton Formation) was seen as being areally restricted in one or more rifts at the northern margin of the Otway Basin. Lithofacies III (Pretty Hill Formation and equivalents) was formed by widespread fluvial deposition in more than one river systems (at least two river systems in the central and western Otway). The Robe and

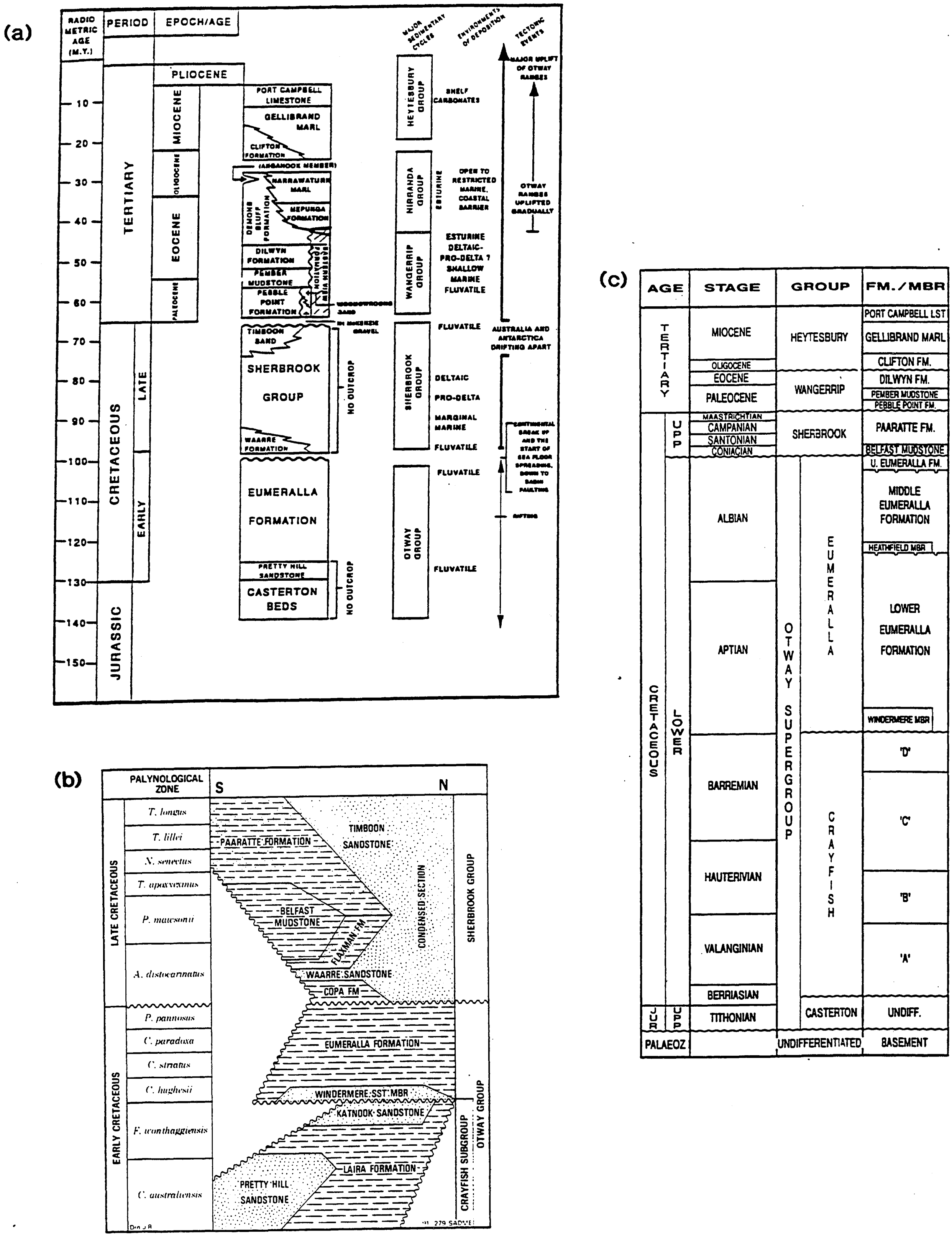



Fig. 2.11 Stratigraphic nomenclatures used for the Otway Group sequences - (a) Tickell & Arditto (1992); (b) Moreton (1990); (c) Kopsen & Scholefield (1990).

Penola Troughs were largely filled by these systems.

Lithofacies IV proposed by Felton (pers. comm.) occurred on a basin-wide scale and implies that by the early Aptian there was a high degree of connection between the depositional systems, and the character of distribution implies a major rearrangement of drainage patterns. There was local ponding of freshwater (lithofacies V). During the early Albian, the central and eastern parts of the basin were blanketed by thick volcaniclastic sands deposited by large active rivers (lithofacies VI). This was followed by increases in sand body thickness and frequency, but in the north and west of the basin, deposition consisted of thick siltstones with local coally facies (lithofacies VII).

Etheridge et al. (1987) made a significant contribution to tectonic modelling of the Gippsland, Bass, and Otway Basins when they proposed a model which incorporated the concepts of lithopheric extension along detachment surfaces and the idea of basin partition between transfer zones (Fig. 2.12). However their model was highly idealized and favoured a NE-SW spreading direction which took little account of extension in other parts of the Australian southern margin farther west.Marine work along the whole southern margin and more recent detailed structural analysis in the onshore parts of the eastern Otway and Gippsland Basins provide data for assessing a possible rifting history. Willcox et al. (1992) synthesised data from the Gippsland Basin and, in the process, placed constraints on events in the whole Bass Strait region. They proposed that the NW-SE extension direction which they interpreted for the basins of the Great Australian Bight region, probably applied to the southern Australian margin as a whole.

Willcox et al. (1992) indicated that at the western boundary of the Gippsland Basin, isolated pockets of Strzelecki Group sediments on the Mornington High, show that the Gippland and Otway Basins were connected during the Late Jurassic - Early Cretaceous. The oldest stage 1 faults in the Gippsland Basin are consistent with NNW-SSE lithospheric extension and the deposition of "lower" Strzelecki Group sediments which exhibit structurally controlled "synrift-type" geometries (?equivalents of the Crayfish sequences in the Otway Basin). "Upper" Strzelecki sequences were once very extensive and blanketed the region (?equivalents of the Otway Group Eumeralla Fm.). Willcox et al. (1992) concluded that the Gippsland Basin is an integral part of southern Australian margin and that the early stages of the Bass Strait basins were formed by sinistral trans-tension in an environment of NW-SE lithospheric extension (Fig. 2.13).

The main focus of the Willcox et al. (1992) analysis was the Gippsland Basin. Hence, in the western Otway Basin region Willcox et al. (1992) offer little information and their suggestion that the initial basin-forming events were the result of NW-SE extension in the Robe Trough and sinistral trans-tension in the Penola Trough region must be taken as tentative at this stage. Tectonic events are likely to be constrained in detail by the Palaeozoic structures in that part of the basin. Hence the importance of the recently acquired aeromagnetic and gravity data.

However, the broad concepts by Willcox & Stagg (1990) on the early evolution of the rifted southern margins of Australia (Fig. 2.3) are generally supported by the Geosat

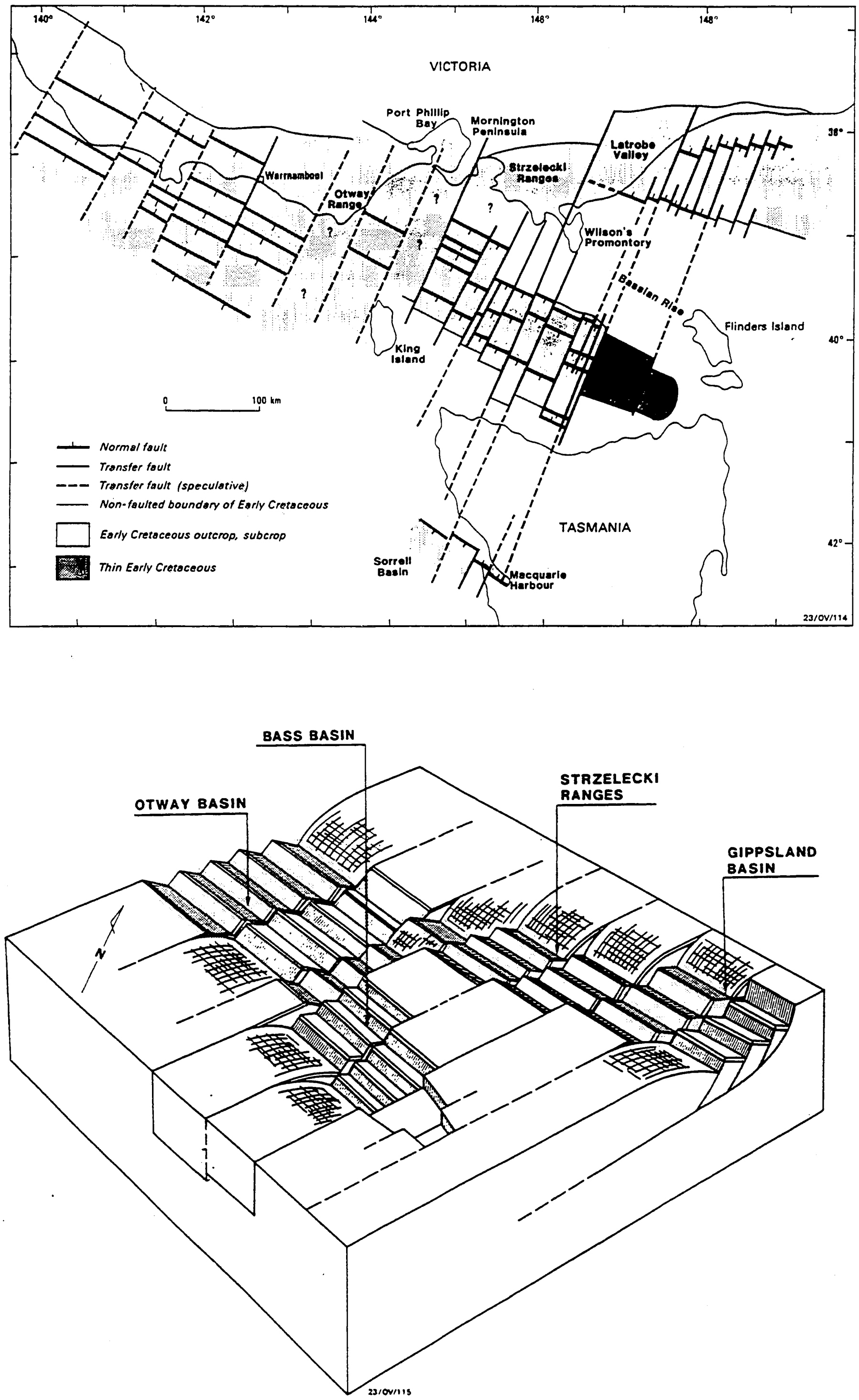



Fig. 2.12 Etheridge et al. (1987) models of rifting structures within the Bass Strait basins.

images of the Southern Ocean. Their proposal for strike-slip movement along a continent-ocean boundary extending northwest from the southern tip of Tasmania is a possible explanation of the Geosat lineament (?fault zone) along that azimuth (Enclosure 3, map and image folio). Their proposals for early (153-120 Ma) NW-SE extension in the Australian Bight region is also supported by the Geosat trends in that region. In addition, their suggestion of a later NE-SW extension episode (120-96 Ma) may be the mechanism for some of the Geosat trends seen across the Otway-Sorrel microplate, also corresponding to the extension direction suggested by Etheridge et al., 1987.

Hill & Durrand (1993) have analysed seismic profiles across the western Otway Basin and concluded that in the western Penola Trough area, late Jurassic to Early Cretaceous (EK1) rift sequences (Casterton - Crayfish - Pretty Hill) were deposited in asymmetric

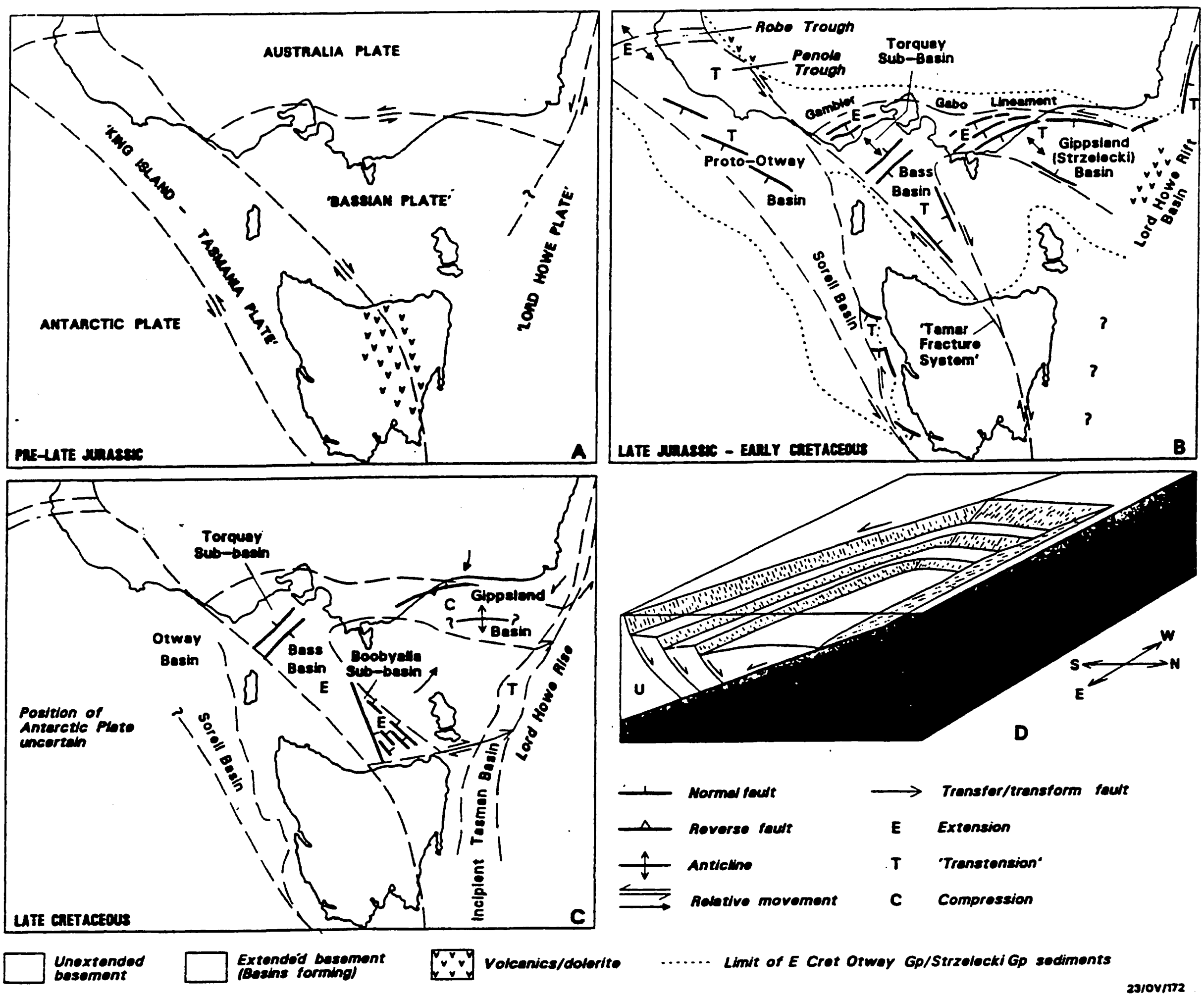



Fig. 2.13 Model for the Bass Strait basins as part of a linked, largely trans-tensional system (after Willcox et al., 1992; Fig. D from Gibbs, 1987).

half-graben formed above north-dipping extensional faults. In the eastern Penola Trough the main bounding faults are more difficult to identify. The Aptian - Albian (Eumeralla) sequences (EK2), however, were separated from the underlying sequences by a major unconformity and are less affected by major rifting. These EK2 sequences generally blanket the region and Hill and Durrand (1993) interpret a change in vergence from northwards to southwards.

The Hill & Durrand (1993) seismic profiles are mostly oriented NE-SW across the Penola Trough, and the authors admit that this possibly biases their interpretation on vergence, i.e. that their conclusions will only highlight tectonic movements in the NE-SW direction. Hence the E-W trending Robe Trough is not well represented in the analysis and the question of possible strike-slip movements and accommodation zones in the Penola Trough still remains open.

The new aeromagnetic, gravity, and Geosat data described elsewhere in this Record add a significantly new perspective to our detailed knowledge of the western Otway Basin. The gravity and aeromagnetic data give an indication of the onshore rift segments. These are commonly identified as the Robe and Penola Troughs from seismic data. If Rosendahl's (1987) general concept of discrete structural basins is used, then these troughs can be equated with the half-graben described by Hill & Durrand (1993) having identifiable bounding faults.

However, on more detailed inspection, this simple picture must be modified. The band-passed aeromagnetic data (low bandpass and downward continued image) clearly indicate that there is a significant NE-SW trending feature bisecting the Penola Trough in the region of the Katnook wells, most probably controlled by underlying Palaeozoic basement blocks. Hence the Penola Trough should probably be sub-divided into more than one rift segment with an intervening accommodation zone.

On the same image, features associated with the bounding faults of other rift segments, the St. Clair Trough and Gambier Embayment, can be identified. Offshore, the sinuous boundaries of inferred Palaeozoic basement blocks are identified on the Crayfish Platform. These can be correlated with features identified on seismic profiles, but detailed descriptions are beyond the scope of this paper. However, the significant conclusion resulting from the aeromagnetic data acquisition is that the published tectonic syntheses, although providing a broadscale picture of early basin evolution in the area, must be revised in the light of detailed work.

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