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Plate Tectonic Reconstructions of Australia's Southern Margins

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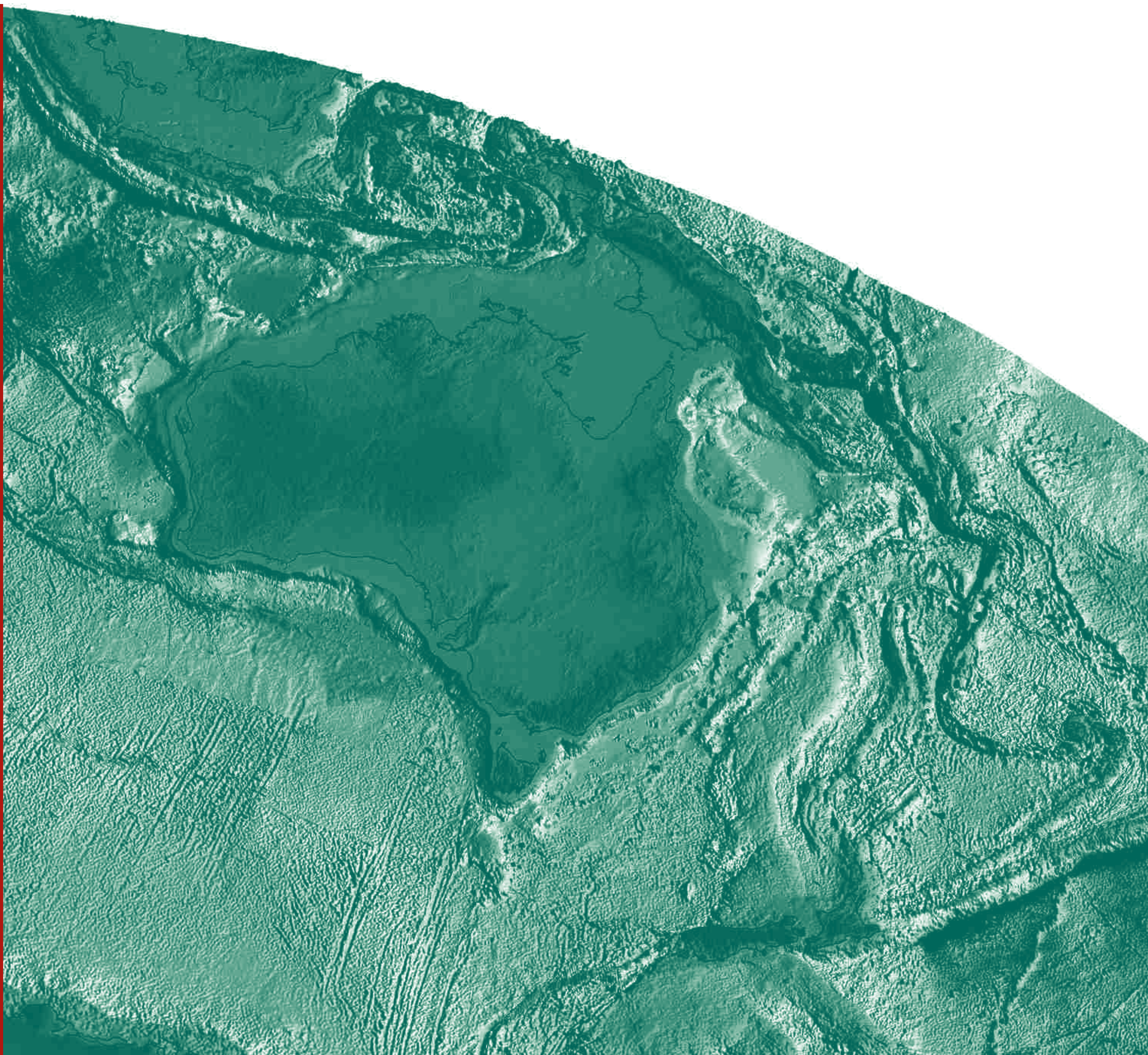

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PLATE TECTONIC RECONSTRUCTIONS OF AUSTRALIA'S SOUTHERN MARGINS

FINAL REPORT

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Summary

A set of 18 plate reconstruction maps is presented for the southern margins of Australia from the Late Jurassic to the present day. These maps were prepared on paper, and further work is needed to convert them to rigorous plate kinematics.

The rifting history of the southern margins of Australia can be divided into at least three phases, reflecting changing stress regimes and distinct spreading events. Stratigraphic signals from rift and drift events are apparent in many of the sedimentary basins, and the strength of the signal decreases with distance from the event locations. Structural variations have resulted in the Bight, Otway and Gippsland Basins having dramatically different late rift-early drift characteristics.

The first rifting phase began in the Callovian-Oxfordian and affected the Recherche, Bremer and Eyre Subbasins. These structures represent the right hand branch of a triple-junction rift complex, the other two arms being the Perth Basin and the India-Antarctica margin. In the Tithonian, rifting extended eastwards into the Duntroon, Otway and Gippsland Basins.

By the Valanginian, first ocean crust had formed between India and Antarctica-Western Australia. Structural style in the Recherche and Eyre Subbasins changed to thermal subsidence. However, non-marine fluvial and lacustrine sedimentation continued in active half grabens in the Duntroon, Otway and Gippsland Basins, at least until the Barremian when these basins also changed to thermal subsidence. During the early Barremian, massive amounts of dacitic volcanoclastic debris began to flood the eastern basins and indeed much of eastern Australia, presumably from volcanic centres in the Lord Howe Rise region. This style of volcanogenic fluvial sedimentation continued through the Aptian and Albian.

The second phase began during the Cenomanian when there was widespread uplift and denudation in eastern Australia, probably caused by cessation of subduction to the east. A complete reorganisation of stress directions and a divergence of individual basin development accompanied this event.

Around Tasmania, sedimentation recommenced in the Turonian in a new set of rift basins that were arranged in an approximate X-shape. The Otway, Sorell and Great South Basin in New Zealand formed in a transtensional strike-slip regime and may have received part of their sediment input from Antarctica. The rift basins underlying the Ross Sea and Lord Howe Rise have not been dated but may represent the other two branches of the X.

Uplift of the eastern Australian highlands and the Eromanga Basin resulted in the initiation of a major river system that drained into the Ceduna Subbasin where a large delta developed in the Late Albian-Cenomanian. Rapid sedimentation rates caused syn-sedimentary listric faulting and toe-thrusting riding on Albian marine shale. The delta system abruptly stopped near the end of the Cretaceous. New spreading events along the Diamantina Fracture Zone and disruption of the onshore river system may have been responsible.

During the Middle and Late Santonian, first ocean crust was generated around southern Australia, probably beginning in the southern Tasman Sea at about 85 Ma. As a result of slow extension, there was extreme attenuation of continental crust in the Bight and Otway Basins accompanied by subsidence into deeper water. New ocean crust probably started to form south of the Bight Basin by the end of the Santonian (c. 80 Ma) and also began to extend up the eastern coast of Australia and between the Campbell Plateau and Antarctica.

Extension between Australia and Antarctica was so slow that not all continental connection was lost. Marine to deltaic sediments in the outer Otway and Sorell Basins (eg Sherbrook Group) continued to accumulate in a rift setting until near the end of the Cretaceous. Sedimentation styles then changed to more locally derived marine progradational wedges (eg Wangerrip Group). Further fragmentation of proto-New Zealand caused new rift basin complexes to form in the Late Campanian (Pakawau) and Eocene (Challenger rifts).

The third stage in stratigraphic development was caused by Middle Eocene changes to fast spreading in the Southern Ocean, the final separation of Australia and Antarctica, and cessation of spreading in the Tasman Sea. These events caused a collapse of most of the outer continental margins into deepwater environments and widespread marine transgression.

Introduction

This report documents a study into the Late Jurassic to Recent breakup and drift history of southern Australia, Antarctica and New Zealand (Fig. 1), and the relationship between these tectonic events and the stratigraphy and drainage history of these areas. The study was conducted between March 1999 and August 2000. Many of the goals have been achieved, but the plate reconstructions still need to be put into a proper geo-referenced kinematic framework. The purpose behind the study was to lay the framework for understanding the palaeogeography, lithofacies, tectonics and geomorphology of these areas in a reconstructed palinspastic setting; something that had not been accomplished before.

The methodology has been to first of all compile structural elements maps for the southern Australian and conjugate Antarctic margins. An updated ocean age map was also prepared as a basis for a first-pass reconstruction. Then the stratigraphy was summarised for three representative cross sections in the Great Australian Bight, Otway and Gippsland Basins, and these were displayed as detailed chronostratigraphic sections in order to demonstrate the stratigraphic responses to the breakup history. One of the vital predictive conclusions was to try and understand the structure and stratigraphy under the lower continental margins; the prime tools for this part of the study were deep-penetration seismic lines shot by AGSO under the Law of the Sea and Continental Margins programs. Finally, a set of 18 plate reconstruction maps were compiled for the period from the Oxfordian to the Present Day, with elements of the tectonics and stratigraphy plotted on them.

Because of time constraints and the inability to work the appropriate plate kinematic software, the reconstructions presented here were prepared with scissors and tape from the ocean age map and hence must be regarded as indicative cartoons of the plate positions. This situation is obviously not ideal but is considered justified by the need to understand the geological relationships between the various terrains before going to a rigorous kinematic reconstruction.

Geoscience Australia (formally AGSO) supported this study as a Collaborative Research Project, providing both data and support with expenses. In addition, this work has been shown at various stages to a large number of people, all of whom helped by making comments and suggestions, and their contributions are gratefully acknowledged. Some of those involved were:-

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Structural Elements

The structural elements map of southeastern Australia (Fig. 2, Encl. 1) is a compilation based on the Geological Map of Australia (BMR, 1976) with additions and updates taken from recent products by the AGCRC and published and yet to be published AGSO mapping. The aim is to distinguish basins of differing age, overlain on pre-Jurassic structural elements. Encl. 2 is an amalgam of pre-Cretaceous structural elements, basin elements and ocean floor ages for Antarctica, southern Australia, the Southern Ocean and the Tasman Sea. Spreading centres and oceanic fracture zones were interpreted from the AGSO detailed bathymetry image. Sea floor magnetic anomalies and interpreted ages were compiled from the literature, largely Gaina et al (1998), Tikku & Cande (1998) and Veevers et al (1991). The UNESCO atlas (UNESCO, 1976) was used as the fall-back.

Basement trends in the Lachlan Fold Belt are taken from abstracts and field trip notes from the 1999 SGTSG meeting, Halls Gap. The western edge of the fold belt is drawn at the Moyston Fault, which can be followed on aeromagnetic images under the Murray Tertiary depocentre, where it curves to the NE and links to the Neckarboo Ridge. Many of the Palaeozoic faults in the Lachlan Fold Belt were reactivated in the Cretaceous and Cainozoic; the most obvious are the Rowsley and Selwyn Faults, which are active today, and the Combienbar Fault, which may have been exploited by Gippsland inversion anticlines.

The relationship between Tasmania and the Lachlan Fold Belt, especially the Melbourne Zone, is currently controversial. In this report, the concepts of Cayley & Taylor (1999), Cayley et al (in press) and David Moore (pers. comm.) are followed in showing Upper Proterozoic northern Tasmanian terrains running under the Bass Basin and continuing beneath the Melbourne Zone. Evidence comes from the clear aeromagnetic anomalies crossing the Bass Basin and also the presence at Cape Liptrap of Ordovician limestones resting unconformably on Cambrian volcanics. Transfer zones in the Bass Basin may also be following these NE-trending Upper Proterozoic lineaments. For example, the transfer zone marking the northwestern limit of the Durroon Subbasin appears to be an extension of the Arthur Lineament.

Relationships between eastern Australian basement terrains and those of Lord Howe Rise and New Zealand are derived from Harrington's poster at the SGTSG Halls Gap meeting (Harrington, 1998, 1999) and require additional investigation. The implications are that the New England Orogen originally extended southwards offshore of the South Coast of NSW and then almost as far as North Island New Zealand, and that its northern boundary was at or close to the bathymetric lineaments in the central Lord Howe Rise. The Upper Carboniferous to Triassic Sydney and Bowen Basins are a back-arc basin complex to the New England Orogen. Similar basins occupy central Tasmania and may also occur at depth under Gippsland (David Moore, pers. comm.).

Basement trends in Antarctica and their relationship with those in Tasmania and southern Australia also need clarification. Most of the coast opposite southern Australia contains older Pre-Cambrian metamorphics, which appear to be correlates of the Gawler and Yilgarn Cratons. Parts of the George V Coast and Oates Coast contain elements of the Ross Orogen, which include Upper Pre-Cambrian and Lower Palaeozoic metasedimentary rocks intruded by Cambro-Ordovician felsic intrusives (?Delamerian); these terrains seem to be a continuation of the Glenelg Zone and western Tasmania. However, the western limit of these rocks in Antarctica is unclear. Northern Victoria Land contains similar ?Delamerian metamorphics and also Lower Palaeozoic sediments deformed in the Middle Devonian. In other words, correlates of both the Glenelg-West Tasmania and Lachlan Terrains may be represented. There are also Permo-Triassic sediments and Jurassic dolerites in the Rennick Graben and at Horn Bluff, which can be correlated with the Tasmania Basin. It is hard to see any evidence for significant Cretaceous to Recent lateral movement of Tasmania relative to mainland Australia – the so-called Gabo lineament.

The direct continuation of Archaean to Middle Proterozoic high grade metamorphic terrains across the future Southern Ocean is disrupted by a number of later terrains. Examples are the Albany-Fraser Zone (c. 1100 Ma) and the Kanmantoo and Adelaide Fold Belts (Upper Cambrian), which seem to swing around parallel to the coast. It is possible that these later Pre-Cambrian-Cambrian sutures became the lines of weakness exploited by later Mesozoic rifting.

The Duntroon, Gippsland and onshore Otway Basins were initially formed in a distinct Early Cretaceous rifting phase, which later developed into NW-SE oblique extension and was abandoned in the Cenomanian. The main basin complex ran east-west with half graben depocentres aligned NE-SW. There were possible minor branches to the southeast (Bass, King Island). The existence of this Lower Cretaceous basin complex under later rocks in offshore Otway and Sorell is uncertain. One possible interpretation is that these two latter basins are largely Upper Cretaceous features.

Gippsland and onshore Otway may once have been continuous through the Melbourne area and perhaps were only separated by uplift and erosion in the Cenomanian and Late Tertiary in the vicinity of the Mornington Peninsula and Port Phillip Bay.

The Eyre and possibly the Bremer Basin contain an earlier rift fill that was initiated in the Late Jurassic; ie prior to the age of initiation in the eastern basins. Orientation was also distinct and they may represent a westward exploitation of the Pre-Cambrian – Permian Polda Trough.

The undrilled Recherche Subbasin allegedly contains Upper Jurassic – Lower Cretaceous rift fill and a thick, passive, post-rift fill of Lower Cretaceous to Tertiary. There is no obvious sediment input point for this basin. Adjacent palaeo-drainage on the Yilgarn craton appears to be directed northwards and then eastwards towards the Eucla Basin, although these old channels may have had their drainage reversed after faulting and rift shoulder uplift following breakup.

The extent of Lower Cretaceous rocks in Antarctica is complicated by glacial erosion. The only in-situ occurrence is of Aptian sediment in a gravity core off George V Coast. There may have once been basins elsewhere along the coast but glacial gouging may well have exploited these softer rocks and removed all evidence. Veevers (1984, 1987) shows the Aurora and Wilkes sub-ice basins as possible Cretaceous sags but they may equally well be merely ice-filled.

In the Late Cretaceous, the original Otway-Gippsland-Duntroon rift system was abandoned. A second Otway-Sorell rift system started up, limited at its inshore edge by the Tartwaup and Sorell faults. There are quite clearly no Upper Cretaceous to Lower Eocene magnetic anomalies from Kangaroo Island to the southern South Tasman Rise. During this period, the Otway-Sorell Basin filled as a strike-slip basin with a southwestern margin in George V Land. The fault geometries in these basins need re-examination in the light of this new concept.

The Upper Cretaceous in Gippsland was tectono-stratigraphically different and accumulated in a rift basin preceding the Tasman Sea opening in the Santonian (Emperor and Golden Beach Subgroups). Both this rift phase and the Santonian to Lower Tertiary post-rift (Latrobe Group) basin geometry were more or less coincident and controlled by north-south extension.

The Upper Cretaceous Bass Basin may have been in a similar type of tectonic setting to Gippsland, ie it had a rift phase that later became a sag over the same depocentre. However, unlike Gippsland, the Lower and Upper Cretaceous rift phases had more or less coincident orientations, although they were not in exactly the same place. There are abundant Middle and Upper Cretaceous volcanics in the Bass Basin.

The post-rift section in the Ceduna and Duntroon Subbasins was largely Late Cretaceous in age; there appears to be relatively little Tertiary cover. The Ceduna and Duntroon Upper Cretaceous comprises as much as 10,000m of sediment that accumulated as a prograding and growth-fault controlled depocentre, probably a delta., that was up to 500 kms in strike-length. There is evidence on the seismic data that listric faulting bottomed in a decollement in Albian shale and that a toe-thrust fold belt developed at the bottom of the delta slope, as in the Mississippi, Niger and Baram deltas. The location of the Ceduna trunk river is uncertain but may have debouched through the Polda Trough. The magnetic anomalies indicate that the ocean to the south was only a few hundred kilometres wide and lay at high latitudes. The Ceduna delta lasted from the Late Albian to approximately the end of the Cretaceous and sediment supply was then abruptly switched off. The present 1000-2000m of bathymetry probably did not develop until thermal subsidence began at the onset of fast spreading in the Middle Eocene.

Recent AGSO seismic has clarified the structure of some very unusual features on the continental rise adjacent to the Otway and Bight Basins. In the Bight, the area beyond the toe of the Ceduna delta contains basement highs where continental crust is thin or absent underneath thin rifted sediment (Sayers et al, in press). These basement highs appear to be lower crustal or mantle "core complexes", or in some cases mantle diapirs. They lie inboard of the line of onlap of rifted sediment onto basement (ie the continent-ocean boundary). The zone of "core complexes" occupies magnetic anomaly 34, and the COB is at anomaly 33. This implies that first ocean crust must be Early Campanian age (c.80 Ma), not Cenomanian (95 Ma) or Neocomian (120 Ma) as previously thought. In the deep water Otway Basin, lower crustal "core complexes" are interpreted to form the Outer Margin High. The Moho is only about 10kms beneath top basement and the highs appear to represent footwall uplift on low angle detachment faults. The faults and the highs were emplaced during the Turonian-Santonian, after which Campanian-Maastrichtian sediment onlapped these structures. Both the Otway and Bight Basin outer margin highs are aligned NW-SE and are offset en echelon to each other. Implications are therefore that they were formed by extreme extension and low angle mantle-linked faulting of the outer continental margin (beta factors >4; see Fig. 3) during the Turonian-Santonian. Similar structures have been described on the northwest Iberia continental margin by Reston et al (1995) and Boillet et al (1995).

The Broken Ridge and Kerguelen Plateau are both assumed to be largely oceanic volcanic plateaus, although there is evidence from lava chemistry and minor quartzose sand in sediment cores that small amounts of continental crust may also be present. The volcanics were extruded in the Barremian-Aptian (120-110 Ma). The two plateaus were originally joined. Satellite gravity images show that there is a perfect match between them along the Diamantina Fracture Zone. This fracture zone is assumed to be an intra-oceanic break-up boundary. It appears to die out eastwards in oceanic crust of latest Maastrichtian to Early Paleocene age, which may date the time of break-up. The Diamantina Fracture Zone is made up of segments that are concave northwards, which suggests that the failure in oceanic crust may have dipped in this direction.

The youngest basins are the Cainozoic basins in the Australian interior, which began forming in the Late Paleocene. They occur discontinuously from the Eucla Basin almost to the South Coast of NSW and, at least in the case of the Eucla and Murray Basins, have the form of circular or sub-circular intra-cratonic sags. They are all very thin (<500m total sediment) and the subsidence mechanism is unclear.

In conclusion, an overall pattern of different rift basin trends can be identified on the eastern Australian structural elements map (Fig. 2, Encl. 1). Thus, the first group of basins formed in the west, where Upper Jurassic rifts ran from the Recherche and Bremer Basins eastward to the Eyre Subbasin and the Polda Trough. In the Tithonian to Early Cretaceous, a second set of ESE-trending rifts formed in the east; the Duntroon, Otway and Gippsland Basins. Then, in the Mid-Cretaceous, a third set of Turonian-Santonian rifts formed along the Otway and west Tasmania coasts, with branches in the Bass and Gippsland Basins. A huge delta of slightly different Albian-Late Cretaceous age formed in the Ceduna Subbasin. Finally, several thin circular or sub-circular sag basins developed on the Australian craton starting near the end of the Paleocene; eg the Murray and Eucla Basins.

Chronostratigraphic Sections

BIGHT BASIN COMPLEX

Cross section

The representative section (Encl. 3) runs southeast from Potoroo-1 across the Ceduna Subbasin and, although partly oblique to dip, samples most of the structural elements in the Ceduna, Eyre and Duntroon Subbasins. The stratigraphy of the Eucla Basin and Polda Trough has also been projected onto the line (Encl. 4).

Principal unresolved issues concern the exact correlation of rock units from the Ceduna Terrace (where they are reasonably tied to the Potoroo-1 well) over the Upper Cretaceous shelf break into the toe-thrust zone. In this interpretation, the whole of the Tertiary is assumed to downlap into condensed sequences on the Ceduna Terrace. The Eyre half grabens are shown as Upper Jurassic to Barremian, although recent seismic mapping (Totterdell et al, 2000) indicates that the main phase of fault growth finished in the Valanginian. In the Ceduna Subbasin, the decollement horizon is in Lower-Middle Albian marine shale (Blue Whale/Ceduna sequence) that accumulated in a separate basin to the Eyre. The main growth fault sequence is Cenomanian (White Pointer/Platypus sequence)(assuming that Cenomanian A. distocarinatus zone is present – disputed by Alan Partridge). Implications are that the main post-rift delta phase is entirely Cenomanian to Maastrichtian and this period of loading caused the toe-thrusting in the Cenomanian and again in the Maastrichtian.

There are two post-thrusting sequences of uncertain age at the base of slope. AGSO's preliminary interpretations differs in showing the toe-thrusts being in place prior to the onset of Turonian progradation and the two base of slope sequences as Maastrichtian and Maastrichtian-Paleocene respectively, with most of the Turonian-Campanian missing at an unconformity at the base of slope. One source of these differences may be that the interpretation used here is based on correlations from the top of the section downwards, while those of AGSO may have started from the bottom of the succession. One of the undated base of slope sequences presumably pre-dated the Lower Tertiary downlap and hence is assumed to be latest Maastrichtian in age. The younger one appears to be thickest (>2 secs TWT) adjacent to the Duntroon Subbasin (ie not coincident with the main Ceduna depocentre). Jacques Sayers (pers. comm.) thinks that this second base of slope sequence correlates with the Paleocene-Middle Eocene. This sequence is interpreted here as a Paleocene-Eocene turbidite prism, derived from the Spencer Gulf.

Uncertainty also surrounds the structure of the continent-ocean boundary. Its location, as picked by AGSO, usually coincides with the transition from tilted or otherwise structured sedimentary sequences, to the zone where sediment fill is composed of completely unstructured passive infill. Latest AGSO mapping of the COB (Sayers et al, in press) indicates that onlap of the rifted sequences and first true oceanic crust corresponds to Anomaly 33. Thus, the oldest ocean crust is likely to be of Early Campanian age (c. 80 Ma), not Cenomanian or Neocomian as previously postulated (Veevers, 1986; Stagg & Willcox, 1992). North of the COB, there is a set of basement highs where the Moho approaches or even subcrops rifted sediment. These basement highs have been interpreted as mantle diapirs or areas of footwall uplift on low angle detachment faults. Orientation and the en-echelon arrangement of the basement highs suggest that extension directions were NE-SW.

Stratigraphic interpretation

Basement is probably Archaean to Middle Proterozoic high-grade metamorphics and granites (Encl. 4). However, there may also be Upper Proterozoic salt-bearing sediments underneath the Eyre Subbasin. Some of the seismic lines, for instance in the Recherche and Duntroon Subbasins, show sediment packages whose style of disruption is reminiscent of salt tectonics. It is possible that the Recherche and Eyre initially formed as Upper Jurassic grabens whose location was controlled by east-west striking, salt-bearing basins that terminated in the Polda Trough.

The first Mesozoic basins were these Upper Jurassic western half grabens, which started forming in the Callovian-Kimmeridgian (M. florida pollen zone) and had a second phase of growth in the Tithonian to Valanginian. It is suspected but by no means certain that the Callovian-Kimmeridgian phase occurred in the Bremer, Recherche and Eyre Subbasins but not in the Duntroon. Individual half grabens seem to be orientated NE-SW in an overall east-west basin complex, suggesting left-lateral transtension. The only penetrations are in Jerboa-1 and Potoroo-1, where they are probably in marginal facies adjacent to bounding faults. More typical (but undrilled) environments may be freshwater lacustrine.

Tithonian to Barremian half grabens appear to form the initial basin phase in the Duntroon, where they have an ENE-WSW trend that may be a continuation of the Gippsland-Otway rift system. Deep lacustrine sedimentation is well represented in this unit in Echidna-1. In the Eucla Basin, a thin section has been dated as equivalent to the upper part of this sequence, including the type Loongana Formation (Neocomian-Aptian incised valley fills, not Upper Jurassic as in the offshore).

The rift system altered and appeared to have broadened into a sag basin in the Aptian-Albian. A seaway appears to have opened, presumably from the west, and shallow marine shales were deposited, which later became the easy-slip horizon for decollement. According to AGSO, the decollement horizon is Middle Albian (Ceduna/Blue Whale). In other words, this is slightly older than the Upper Albian Toolebuc maximum transgression in the Eromanga Basin. However, the globally best developed eustatic sea level maxima occur in the Early Albian and Early Aptian.

In the Late Albian-Cenomanian (White Pointer/Platypus), the Ceduna Terrace became a large delta that filled rapidly with a generally regressive sequence, laid down in an unstable area riven with listric growth faults. It is assumed that this clastic pulse marked the onset of the river system that carried the erosion products from the Eromanga Basin and the rising eastern Australian highlands (~95 Ma, according to fission track dates). The exact route of this river system through the Gawler Craton is uncertain. However, the position of the apex of the Ceduna deltaic depocentre suggests that the river may have debouched through the Polda Trough.

The top of the growth-faulted section is marked by an obvious rift to post-rift unconformity and downlap surface at approximately the end of the Cenomanian (92-93 Ma; base Tiger sequence). However, there is no clear local plate breakup event that correlates with this sequence boundary.

The downlap surface is followed by three overall regressive deltaic cycles; of Turonian to Early Santonian (Tiger), Late Santonian to Campanian (Lower Hammerhead) and Maastrichtian age (Upper Hammerhead), separated by flooding or downlap surfaces. The middle sequence is a distinctive prograding unit, possibly represented by thick sands in the most basinward well, Greenly-1. The other two are much thicker and largely aggrading. In general, the delta that layed down these sediments was a continuation of the Albian-Cenomanian one and occupied roughly the same location.

Most of the post-Cenomanian delta was fairly unstructured and occupied the area of the present day Ceduna Terrace, which is clearly an Upper Cretaceous continental shelf that foundered in the Early Tertiary. However, the outer quarter of the palaeo-shelf became unstable during the latter part of the Maastrichtian (upper Hammerhead, Maastrichtian-1 on Encl. 4) and shows listric growth faulting. Some of the growth faulting appears to have linked to the Albian decollement while other faults may have become lost in incipient mud diapirs. There is considerable uncertainty how to correlate over the collapsing Maastrichtian continental slope and there may well be more slumped section than shown. However, the formation of the 4-8 rows of toe-thrusts is believed to have been completed in the Middle or Late Maastrichtian, with involvement of Turonian to Maastrichtian distal facies in the anticlines.

Two undrilled but quite distinctive post-folding megasequences occur on the palaeo-slope and at its base (see above). The older one, Maastrichtian-2, appears to truncate the eroded toe-thrusts, folds and most of the Maastrichtian-1 growth faults. The younger one, whose age is most likely to be Paleocene-Middle Eocene, forms a tilted, base of slope pillow or lens, which has the geometry of a large basin floor turbidite fan. This lens is best developed in the east and may have been caused by a shift in the principal exit point or canyon that fed eroding sediment over the palaeo-shelf edge; ie away from Ceduna and towards the Duntroon Basin. The implication is that this turbidite prism is the detached equivalent of the thin shelfal Wobbegong sequence; the intervening slope area is presumably a sediment bypass zone.

Two Tertiary megasequences are recognised, of which the Paleocene to Middle Eocene (Wobbegong) is thin in all wells and is assumed to be represented largely by a condensed downlap surface on the Ceduna Terrace and slope. The youngest megasequence is Middle Eocene to Recent and is characterised by at least two carbonate progradations. The megasequence boundary at the base was coincident with the onset of fast spreading (Lutetian, 44 Ma, lower N. asperus zone or magnetic zone C20). The Eucla Basin records two maximum transgressions; one in the Upper Eocene (Wilson Bluff Limestone, Princess Royal Spongelite) and the other in the Middle Miocene (Nullarbor Limestone).

OTWAY BASIN

Cross sections

Interpretation of the Otway Basin is based on three AGSO deep-water seismic lines (Stagg & Moore, 1998; Moore et al, 2000). The seismic lines run offshore from Port Campbell, Portland and Robe and each demonstrates a different structural style. The Robe line shows what looks like extensive growth faults and a thick Upper Cretaceous offshore fill and is poorly tied to wells. The Portland line was interpreted by Stagg & Moore (1998) as a basement platform or saddle. However, it is also possible that the apparent shallow basement is either intra-basin volcanics or multiples from near surface volcanics; there are traces of poorly imaged deeper reflectors, which may represent thick Upper Cretaceous sediments. The Port Campbell line shows the best reflection quality and can be tied both to onshore AGSO deep crustal seismic lines (described in Finlayson et al, 1996) and to a range of inshore wells in the Minerva area (Luxton et al, 1995; Arditto, 1995). For these reasons the Port Campbell line has been used as the representative for the Otway Basin (Enc. 3, 5), although it is recognised that the structure and possibly the stratigraphy may be different in the west across the SA state border. Indeed, for the inshore and onshore parts of the basin, there are separate stratigraphic schemes set up by the geological surveys of Victoria and South Australia (GSV, 1995; Dept Mines & Energy, SA, 1995). The Port Campbell line is also characteristic of at least the northern part of offshore west Tasmania.

Evolution of the Otway Basin was different to that of either the Bight or Gippsland Basins because there was no ocean crust adjacent to Otway until the Middle Eocene, and also because, for much of its Late Cretaceous history, the plate tectonic regime was left-lateral strike-slip and extension. This meant that the basin formed in a continental setting and the other margin was in George V Land or Oates Coast in Antarctica or on the western South Tasman Rise. In the chronostratigraphic section (Encl. 5), a second sediment source has been assumed.

As mentioned above, the onshore and offshore Otway Basins appear to be quite different structures, with the onshore basin dominated by Lower Cretaceous rifts and the offshore being largely an Upper Cretaceous depocentre. The boundary between the two is the Upper Cretaceous Tartwaup and Sorell faults, close to the coast, which swing around south of Cape Otway to follow the proximal edge of the Sorell Basin. The extent of Lower Cretaceous rifts underneath the Upper Cretaceous is still unclear but the interpretation used here is that these early rifts were small and short-lived outboard of La Bella.

The Port Campbell line shows an apparently typical Atlantic margin structure, dominated by seaward-dipping listric normal faults in about 3-4 secs twt of Upper Cretaceous (Encl. 3). The Tertiary is relatively thin and comprises two unfaulted, prograding megasequences. The progrades effectively downlap not far beyond the modern shelf break and the reflection packages of thick Lower Tertiary sediment basinward of this point are presumably either turbidite fans or are derived from Antarctica or from along strike to the south. Identity of this Lower Tertiary sag package is dependent on a difficult seismic tie to the La Bella-1 well and is by no means certain (Moore et al, 2000). If we assume that the basin did not collapse into abyssal water depths until the onset of fast spreading and the formation of first local ocean crust in the Middle Eocene, the implications are:-

The deep reflectors at 10-12 secs twt, where the listric faults appear to flatten out, may represent Moho. However, the continental crust must be highly attenuated in this area.
The outer part of the thinned continental crust is a topographic high, which was then onlapped by the Campanian-Maastrichtian partly faulted megasequence. The high seems to have the form of footwall uplift associated with the highly rotated faults that have their roots in the mantle. In other words, the outer margin highs are similar to core complexes.
The general form of the Upper Cretaceous basin would be shown more accurately by flattening the section to Middle Eocene. An approximation for flattening has been achieved by rotating the relevant part of the seismic section clockwise by about 30 degrees.
If we flatten to Middle Eocene, the Upper Cretaceous becomes a broad rift structure showing substantial growth into half grabens with multi-phase normal faulting (Encl. 3). This rift was presumably a trans-tensional structure.

The interpreted age of onlap of the various sedimentary packages against the outer margin high trend allows us to develop a timing for the main tectonic events under the continental slope:-

Half grabens were formed in the Turonian-Santonian (Waarre and Shipwreck Group).
At the same time, low angle faults caused crustal attenuation and formed the outer margin highs; the 'core complexes'.
A broader graben developed in the Campanian-Maastrichtian (Sherbrook Group), which became a sag in the Paleocene-Middle Eocene. All of this section onlapped the outer margin highs.

Rapid collapse of the margin occurred with ocean crust formation in the Middle Eocene and formed the prominent downlap surface seen on seismic.

Stratigraphic interpretation

Basement is Lachlan turbidites and granites in the east and Delamerian metasediments and granites in the west. The Moyston terrain boundary may have been reactivated as transfer faults at the western end of the Elingamite and Ferguson's Hill Troughs, as well as in approximately north-south faults offshore.

The first stage of half graben formation began in the Tithonian (R. watherooensis zone) and the bottoms of the localised basins were filled with basalts and lacustrine sediments (Casterton Beds). A short time break and rift rearrangement is assumed prior to resumption of lacustrine sedimentation in the Berriasian to Barremian (Crayfish Group). Geochemical biomarkers of oils from these two groups suggest derivation from a range of environments, including saline lacustrine, freshwater lacustrine, fluvio-lacustrine and even marginal marine (Edwards et al, 1999).

There may be two different ages of Neocomian half grabens with different orientations (Mark Smith, pers. comm.). Those in the west are aligned E-W or WSW-ENE and are possibly the oldest. Those in the east are strongly aligned NE-SW and may not have started assuming this orientation until the Barremian. Subtle differences in orientation of isopach thicks between the Crayfish Group and Eumeralla Formation provide hints that maximum north-south extension slowly changed to sinistral transtension during the Barremian (Perincek et al, 1994). These differences were presumably due to rotation of stress directions during evolution of the oblique rift system.

In the Barremian, faulting slowed and eventually stopped and the basins widened out into coalescing sags. Environments changed to a westerly flowing fluvial regime and there was a sudden marked increase of dacitic tuffs in the sediment composition (Eumeralla Formation). The rift-drift transition was not apparently accompanied by any identifiable oceanic breakup event; the entire process appears to have been intra-continental.

Significant basin reorganisation occurred in the Cenomanian. The onshore-inshore Otway rift system was abandoned, and an unconformity and a time gap accompanied this change. Alan Partridge (pers. comm.) maintains that the A. distocarinatus zone is missing throughout the Otway and Gippsland Basins. After the reorganisation, sedimentation resumed in a new NW-SE transtensional rift system south and west of the Tartwaup and Sorell faults.

The first two sediment packages in the new rifts were the Lower and Upper Shipwreck Groups, possibly separated by a small unconformity. Both show strong evidence of thickening into half grabens and downlap or condensation of the section towards the dip slope. The Lower Shipwreck is largely fluvial in the Minerva area (Luxton et al, 1995) but may also include the shallow marine Waarre Formation. The Upper Shipwreck is marine to deltaic and generally regressive upwards.

Towards the end of the Santonian (T. apoxyexinus zone), half graben formation ceased. There was a short time gap and a different set of growth faults became active. When sedimentation resumed in the Campanian, it was as another marine to deltaic upward-regressive megasequence, the Sherbrook Group.

There was strong basement-involved block rotation at the Outer Margin High at the end of the Santonian. In fact, the Outer Margin High probably formed at this time by footwall uplift as a set of incipient 'core complexes'. The Sherbrook Group appears to partly onlap the eroded and rotated fault blocks at the inner edge of the Outer Margin High. These relationships are quite difficult to confirm because seismic reflection quality is not the best and because of the absence of nearby well ties. However, if true, this event helps to constrain the plate tectonic history. If half graben formation and block rotation was the result of strike-slip movement between Antarctica and the Otway margin, it is possible to argue that the bulk of the movement, and also the attenuation of continental crust, occurred during the Turonian to Santonian.

Derivation of all three Lower Shipwreck, Upper Shipwreck and Sherbrook megasequences is assumed to have been from both Australia and Antarctica. The immediately adjacent part of Antarctica may have been a micro-continental sliver that subsequently became the western part of the South Tasman Rise (Royer & Rollet, 1997). However, the bulk of the sediment transport in this Upper Cretaceous rift system may have been axial, ie from the southeast.

Under the lower part of the slope and Outer Margin High, there is a sag megasequence that post-dates all of the Sherbrook faulting and onlaps the basement blocks. Moore et al (2000) show this sequence as Paleocene to Lower Eocene and Hill et al (1997) show it thickening southwards and perhaps prograding northwestwards from offshore West Tasmania. Lithological content is assumed to be outer shelf mudstones and slope turbidites.

End-Cretaceous changes include a resumption of Australia-derived sedimentation in an essentially unfaulted setting as the fluvial to marine Wangerrip Group. This sediment package shows progradation on seismic lines (Arditto, 1995). Facies belts have been mapped more or less parallel to the edge of the Port Campbell Embayment and they obviously extended much further inland than the Upper Cretaceous. The Deep Leads in parts of the Victorian Goldfields may have provided some of the feeder channels. Offshore, the height of the progrades is assumed to represent the marine water depths. Other end-Cretaceous events include early formation of inversions in the Otway Ranges and local basaltic volcanicity.

In the Middle Eocene, first ocean crust formed next to the Otway Basin, the margin tilted and collapsed, and there was a rapid marine transgression. The Middle Eocene to Lower Oligocene Nirranda sediment package that followed these events comprises a deltaic set of lithofacies onshore (Upper Eastern View Coal Measures, Demon's Bluff Formation), passing up into shelf and slope calcareous sands and marls near the present coast (Narrawaturk Marl and Browns Creek Clay). The whole megasequence was thus broadly transgressive.

Calcareous sedimentation became dominant in the Late Oligocene and lasted until the Late Miocene (Heytesbury Group).

The final events were at least two periods of inversion and folding from the Otway Ranges eastwards in the Pliocene and Pleistocene, followed by flood basalt vulcanism in the last 2-3 Ma.

GIPPSLAND BASIN

Cross section

The stratigraphy set out here (Encl. 6) is based on a composite cross section (Encl. 3) modified from the onshore east-west line shown in Holdgate & McNicoll (1992), and the axial offshore deep seismic lines 90/02 and 68/14 shown in Willcox et al (1992). Only slight modification has been done on the structure and seismic picks. The stratigraphy was projected into this cross section from published descriptions, augmented by diagrams included in the Victorian State Government's gas brochures and VIMP reports (Woollands, 1999; Smith, 1999; Smith et al, 2000).

The main problem with this interpretation is the poor correlation across the present day coastline. There appear to have been substantial facies changes from coal swamp to more marine deltaic environments roughly coinciding with this boundary. There may even be a large buried fault under the coastline. Also, stratigraphic nomenclature has obviously been set up independently onshore and offshore, both for different purposes (brown coal versus hydrocarbon extraction) and by different organisations (see: Barton et al, 1992, and Holdgate & McNicholl, 1992, for the onshore; and Rahmanian et al, 1990, and Partridge, 1976, for the offshore).

The other problem is that, while the Gippsland depocentre has remained in roughly the same place through its history, the orientation and controlling faults have rotated more than once. Consequently, it is impossible to fully demonstrate the tectono-stratigraphy with a single cross section. The solution has been to alter the orientation of the section for the Santonian-Campanian part of the history and this should be kept in mind when viewing Enclosure 6.

Stratigraphic interpretation

For most of the basin, the underlying basement terrains are various sections of the Lachlan Fold Belt. However, the implications of Harrington's (1999) reconstruction of the terrains under the Lord Howe Rise are that the New England Orogen may have originally extended southwards into the deep water part of the Gippsland Basin. If it exists, the Lachlan-New England terrain boundary, presumably an equivalent of the Hunter-Mookie Thrust, may be coincident with the Cape Everard or Gippsland margin transforms of Megallaa (1993), or with the COB.

Uppermost Jurassic to Lower Cretaceous rift sediments are quite similar to those in the Otway Basin and may once have been part of a continuous basin complex. The main difference is that in Gippsland, the cross sections suggest that the sedimentation was not restricted to half grabens, and that the NE-SW master faults played a much smaller part in controlling facies.

The initial rift phase was again Tithonian and included shale, siltstone and minor coal. Large amounts of gypsum suggest aridity or saline influences. There is a vitrinite step between the Tithonian and Neocomian (Holdgate & McNicholl, 1992), supporting a tectonic break between these two megasequences.

Lower Cretaceous rocks are all placed in the Strzelecki Group but there is a poorly defined internal unconformity between lower and upper divisions, which is assumed to correlate with the megasequence boundary between the Crayfish Group and the Eumeralla Formation. The overall section is very thick, more than 5 secs twt in the offshore, and has been interpreted by Willcox et al (1992) to be controlled by a low angle basal normal fault linked to a lower crustal detachment. An alternative interpretation, shown on the cross section included here, is that some of the Strzelecki of Willcox et al (1992) is in fact Emperor and Golden Beach Subgroups.

The Lower Strzelecki Group is made up of lower quartzose fluvial units with minor coal measures (Tyers Conglomerate and Rintoul's Creek Sandstone; Holdgate & McNicholl, 1992; Toscolini et al, 1999). This is followed by a marked compositional change to volcanogenic fluvial sandstones and coal measures in the Barremian (the "normal Strzelecki"). The Upper

Strzelecki (Aptian-Albian) is volcanogenic throughout and was derived from the east. Outcrops of Aptian-aged sediments on the coast near Cape Patterson include ice-rafted boulders and cryogenic soil structures (Constantine et al, 1998).

A time gap and a rearrangement of structural elements again occurred in the Cenomanian. Subsequent, ?uppermost Cenomanian-Turonian to Lower Campanian sediments accumulated in a rift setting under offshore Gippsland and can be subdivided into two subtly different megasequences, the Emperor and Golden Beach Subgroups (Woollands, 1999; Smith, 1999). Neither of these Mid-Cretaceous megasequences appears to be represented onshore.

The Emperor Subgroup (?uppermost Cenomanian-Turonian to Lower Santonian) was largely lacustrine and the rift valley was deepest in the north. Fault orientations were NNW-SSE in the south and ENE-WSW in the north. Coaly facies where extensive, especially along the southern side of the basin.

Within the Santonian (base T. apoxyexinus zone), localised oceanic crust began to form in southern areas of the Tasman Sea (magnetic zone C34). Following this early breakup event, there was a minor marine transgression at the bottom of the Golden Beach Subgroup. The northern fault system appears to have become inactive and the palaeo-topographic depocentre shifted southwards into the centre of the basin. Coaly facies became concentrated on the northern basin flank.

In the Middle Campanian, oceanic breakup in the Tasman Sea spread north as far as Gippsland (upper N. senectus zone or magnetic zone C33) and this event was recorded in the offshore stratigraphy as a rift to post-rift transition at the bottom of the Latrobe Group. The stratigraphic change was accompanied by volcanicity, especially along the northern basin flank, the Kipper Volcanics. The sag was located over the two Emperor and Golden Beach rifts but faulting became much less common.

A long period of post-rift sedimentation formed the Latrobe Group, which was marked by a complex interplay of deltaic, coastal and offshore facies belts and the construction of a third order sequence architecture that changed with sediment supply rates and subsidence (Rahmanian et al, 1990). This phase lasted from the Middle Campanian to the end-Eocene offshore, and perhaps the Middle Oligocene onshore. Best reservoir rocks in the offshore fields are in shoreface sands, the so-called 'coarse clastics'. However, it is interesting to speculate whether there might be lowstand fans developed in the deeper water areas during periods of maximum progradation or canyon cutting.

Initial Latrobe Group sedimentation was restricted to the offshore and was strongly prograding until more or less the end of the Cretaceous. There was no apparent tectonic break at the Cretaceous-Paleocene boundary.

The sequence stacking patterns were aggrading through the Paleocene. Maximum progradation was roughly in the middle of the Paleocene (intra-L. balmei zone). Also in the Paleocene, sedimentation spread to the onshore. If we believe the correlations, the Yarram Formation comprises Upper Paleocene incised valley fills capped by Lower Eocene Carrajung basalts (55-57 Ma).

At about the end of the Paleocene, gentle compressional folding began in the offshore along NE-SW anticlinal axes. Folding continued until approximately the end of the Eocene, keeping pace with sedimentation. The Barracouta, Veilfin and Kingfish-Halibut structures were formed at this time. This lengthy compressional event was the prime hydrocarbon trap-forming event in the basin, but at the moment, there is no satisfactory regional tectonic explanation for it.

Late in the Early Eocene (base M. diversus zone), strong retrogradation began in the offshore. Slightly before this event (upper L. balmei zone), there was apparently a widespread unconformity onshore and the onset of inversion folding offshore mentioned above. The cessation of active spreading in the Tasman Sea was at around this time (magnetic zone C24). Retrogradation lasted until the end of the Middle Eocene offshore and possibly the middle of the Oligocene onshore. There was also a Middle Oligocene unconformity onshore. Coals in the lower part of the Latrobe Valley Coal Measures (Traralgon Formation, N. asperus-lower P. tuberculatus, Middle Eocene-Lower Oligocene) dominated the onshore facies.

Major channels were cut in the offshore basin at least twice during the retrogradational phase of Latrobe Group sedimentation, namely towards the end of the Early Eocene (Tuna-Flounder channel) and towards the end of the Middle Eocene (Marlin channel). These canyons are suspected to have been the result of uplift events in the Eastern Highlands, but they could alternatively have been driven by eustatic sea level falls. Speculative lowstand fans are shown at the terminus of the canyons under the continental rise.

Carbonate sedimentation began in the middle of the Oligocene, as in the Otway Basin. Maximum flooding of the onshore was at the beginning of the Miocene. Non-marine onshore time equivalents were the upper part of the Latrobe Valley Coal Measures (Morwell and Yallourn Formations), that were separated from the limestones in the offshore by the Balook coastal barrier sand. There were volcanic episodes onshore at the end of the Oligocene and within the Early Miocene.

A further set of channelling events occurred in the Middle Miocene (foraminiferal zone E1 or approximately 16.5 Ma). Unlike the earlier channelling events, these canyons lacked siliciclastic fill and were probably not caused by hinterland uplift. Their fill is largely carbonate under the shelf and slope and a submarine turbidite origin seems unlikely as a cutting agent. Sinking by cold bottom currents, which were initiated by changes in oceanic circulation patterns, is one of the present hypotheses for their origin (Steve Gallagher, Guy Holdgate, pers. comm; Holdgate et al, 2000). The canyons were then rapidly infilled with thick Middle and Upper Miocene cool water carbonates (Gippsland Limestone).

The final events were the inversions that mainly affected the onshore areas. The most intense inversions were in the Late Miocene and these resulted in reversal of the Strzelecki basin controlling faults and the uplift of the Strzelecki Ranges and other blocks as far west as the Mornington Peninsula, as well as the formation of monoclines in the Latrobe Valley. This early inversion appears to have pre-dated the cessation of carbonate sedimentation, which occurred during a second phase of fault reactivation in the Pliocene.

The origin of the 4 km deep Bass Canyon (Hill et al, 1998) remains uncertain. Present channels contain siliciclastic material but may merely be late cuts in a much older depression. Possibilities include Middle Miocene current-induced channelling or Eocene turbidite canyoning. A further possibility is that the canyon was an original empty basin formed by Mid-Cretaceous oblique-slip rifting (a 'rhombochasm') that never became filled up with sediment. Perhaps Tertiary submarine currents of various origins helped to keep it largely swept of sediment.

OTHER BASINS

A north-south stratigraphic basin comparison from the Eromanga to the Ross Sea, Antarctica, is shown in Enclosure 7. The correlateable events, and also those that do not carry over from basin to basin, are both instructive.

Eromanga and Lake Eyre Basins

The Eromanga Basin has few stratigraphic events that are correlateable into the southern margin basins. Most of the Mesozoic can be placed in a long-lived post-rift or foreland basin megasequence that started with the formation of a large lake in the Early Jurassic and has an eroded top where the youngest preserved sediments are Upper Albian. First marine incursions were in the Valanginian and the first open marine transgression was Barremian. There are thus two significant maximum flooding surfaces; one in the Aptian Bulldog Shale and the other in the Upper Albian Toolebuc kerogenous limestone (basal P. pannosus zone). The reason why none of these marine incursions can be recognised in the southern margin is probably because they flooded from the north. After the Albian, the Eromanga Basin became uplifted and an unknown amount of sediment was removed. It is likely that this basin, and the Eastern Highlands, became the sediment source area for the major river system feeding the Ceduna delta during the Cenomanian to Maastrichtian, but no record has remained in the drainage basin.

The Lake Eyre Basin and other surrounding thin Tertiary basins (eg the Billa Kalina and Torrens Basins; see Drexel et al, 1993; Alley et al, 1999) were probably also part of the drainage system into the Southern Ocean from the Late Paleocene onwards. By the Early to Middle Eocene, extensive but sparsely dated fluvial sands (Eyre Formation) may have been part of the drainage route and they pass southwards into marine sands and limestones in the coastal basins such as the St Vincent Basin (James & Bone, 2000). There was a widespread disconformity and duricrust surface (the Cordillo surface) in the Oligocene. Apatite fission track data also suggest Oligocene-Miocene denudation along the northern edge of the Gawler Craton (Paul O'Sullivan, pers. comm). Then, there was further fluvial sedimentation in the Miocene (Etadunna Formation and its equivalents), followed by further silcrete/ferricrete development. The final events were the emplacement of Pliocene fluvial sands and Pleistocene aeolian sand sheets. Reconstruction of the Eocene and Miocene channel systems through the Gawler Craton or into the Spencer Gulf may be possible but will need further detailed compilation and correlation.

Murray Basin

The Murray Basin has an incomplete Eromanga post-rift megasequence, with only the Aptian and Albian preserved. A marine incursion occurred in the Late Aptian, presumably from the north. Volcanic detritus flooded the basin in the Early Albian; ie later than in the Otway Basin.

The Tertiary record starts with incised valley fills in the Upper Paleocene and continued with delta top/fluvial sedimentation throughout the Eocene. First marine incursions occurred near the end of the Eocene (base of the Buccleuch Beds). There was a short hiatus in the Early Oligocene. This was followed by a major marine transgression which resulted in carbonate deposition in the western half of the basin (Murray Group), held behind shoals along the Padthaway Ridge, which continued through the rest of the Oligocene to the Middle Miocene.

The maximum flooding surface was within the Middle Miocene (c. 13 Ma). A Late Miocene regression and erosive event was followed by another major transgression at about 6 Ma, followed by a regression that layed down rows of Pliocene beach ridges (Loxton-Parilla Sands). Final events were Pleistocene erosion and a fluvial clastic pulse.

Thus, the importance of the Murray Basin record is not that it was a drainage basin feeding the southern margin. It subsided very slowly and most of the published accounts suggest that it always had its exit to the sea via its present position (eg Brown & Stephenson, 1991). Of greater importance is that the Murray Basin provides a well-documented succession of stratigraphic signals recording the uplift history of the southeastern Australian highlands. For instance, a detailed sequence architecture is emerging in the Oligo-Miocene carbonates (Lukasyk & James, 1998), which we may be able to follow 'upstream'.

Western Offshore Tasmania

West Tasmania and the South Tasman Rise suffer from a sparsity of drilling and lack of stratigraphically deep well penetrations. Cape Sorell-1, in the Strahan Subbasin has the deepest penetration - to the Maastrichtian. There are also problems with correlation and seismic event identification relative to the Otway Basin (referred to earlier). There are probably Lower Cretaceous syn-rift grabens, but they may not be as deep or extensive as shown by Hill et al (1997). If the model shown here is correct for the Late Cretaceous age of initiation of the Sorell Basin, most of the graben fill will be Upper Cretaceous and perhaps Lower Tertiary. Clastic prograding packages are shown in the Paleocene, Lower to Middle Eocene and Upper Eocene to Lower Oligocene. Rifting died out during the first or possibly the second of these sequences.

There was a Middle Oligocene unconformity, followed by Upper Oligocene to end-Miocene carbonate deposition, as there is elsewhere.

Antarctica

Finally, the Ross Sea is used here as a representative section for the stratigraphic history of the conjugate margin of Antarctica. This choice is largely governed by data availability. Seismic data and an onshore borehole (Ciros-1) provide incomplete stratigraphic coverage (Encl. 8). The only other areas where seismic data give at least some idea of the stratigraphic relationships are in Prydz Bay (opposite eastern India in the pre-rift position) and Adelie Land (opposite Ceduna). However, the lack of well ties in these two areas makes it almost impossible to currently build a stratigraphic column that is more than speculation. In Prydz Bay, the most recent ODP results from Site 1166 suggest that Turonian clastics are represented at TD (Phil O'Brien, AGC, Sydney, July 2000). In addition, AGSO is preparing to conduct new seismic surveys along the Antarctic margin. Thus in future years, these new data may facilitate a much better appreciation of the Antarctic geological history.

In the southern Ross Sea, seismic lines show a late rift and possibly an early rift system, which are assumed to be ?Paleocene-Eocene and Lower or Mid-Cretaceous respectively. Content is unknown, but the ?Mid- Cretaceous rift may include rocks similar to the Aptian siltstone recovered from a drop core offshore George V Coast. This latter occurrence is the only documented Lower Cretaceous rock sample known in this sector of Antarctica. Other Lower to Mid-Cretaceous basins may be present but are either buried or they have been preferentially gouged out by glacial action.

The arguments for a Paleocene-Lower Eocene (55-50 Ma) rift event in the Ross Sea area are somewhat circular. Fitzgerald (1992, 1994) and Fitzgerald & Gleadow (1989) have documented a sharp denudation and uplift event from apatite fission track analyses in the Trans-Antarctic Mountains at around 55-50 Ma. Their explanation is that massive rift shoulder uplift has occurred on a regional normal fault with upto 6 kms of throw. This implies a very deep-seated rift running adjacent to the length of the Trans-Antarctic Mountains under the edge of the Ross Ice Shelf and Ross Sea. The only seismic data supporting this concept is in the Ross Sea, where Brancolini et al (1995) and Davey & Brancolini (1995) show a possible rift phase of unproven age on poor-quality data. Subsequently, several plate tectonic models have indicated that the has been up to 200 kms of Paleocene-Lower Eocene separation between Marie Byrd Land and East Antarctica (Cande et al, 2000; Storey et al, 1999). There is clearly no oceanic crust beneath either the Ross Sea or the Ross Ice Shelf, so a well-developed Paleocene-Lower Eocene rift has been suggested of this age on the basis of these tenuous arguments.
Above the syn-rift packages in the Ross Sea is an unknown post-rift section, probably Eocene, overlain by the Upper Eocene to Miocene post-rift sediments penetrated by Ciros-1. Sea level glaciation appears to have begun in the Late Eocene and is recorded by the first glacial dropstones. The first evidence of substantial sea level glaciation is in the Lower Oligocene section, which contains thin horizons of both dropstones and diamictite. However, a major increase in glaciation was in the Middle Oligocene, and from then onwards, conglomerates dominate the section.

Seismic lines, both in the Ross Sea and elsewhere along the Antarctic margin (Encl.8), show that the Oligocene to Quaternary forms a major prograding shelf package, linked to turbidites on the continental rise. These geometries are noticeably absent on the Australian margin, which did not, of course, receive any large glacially derived sediment pulses. The final events in the Ross Sea are the onset of intra-plate plume volcanism (including the McMurdo volcano) in the Middle Miocene (c. 18 Ma), and large scale glacial scouring in the Quaternary. Scouring has left bathymetric holes up to 500m deep on the shelf.

CORRELATEABLE EVENTS BETWEEN BASINS

Thus in summary, the lessons learned from the basin comparison are that both Lower and separate Mid-Cretaceous rifts are a common theme from the Otway Basin southwards, but are not represented in the inland basins. The Mid- Cretaceous rifts may have extended into the Paleocene and perhaps even the Eocene in West Tasmania and the Ross Sea, but these later dates are possibly artefacts due to correlation problems. Within the Mesozoic, there is apparently little detailed correlation possible between the inland sag basins and the southern margin rifts. Marine incursions in the Eromanga were apparently derived from the north, not the south. The earliest clear stratigraphic record of past drainage systems appears to have been in the Late Paleocene- Early Eocene, when fragments of fluvial section in the inland basins may have been linked to parts of the under-filled southern prograding packages.

The principal plate tectonic events that are recorded across more than one basin are as follows:-
Early rift phases started in the Callovian in the Bight area and in the Tithonian from the Duntroon eastwards.
The early rift phase usually changed to post-rift sagging in the Aptian-Albian, perhaps due to rearrangement and relaxation of stresses. There was no obvious formation of oceanic crust at this time. The plate tectonic cause and precise date of the marine shale transgression in the Bight Basin complex are still unresolved.

A major reorganisation of rifting accompanied by regional unconformities occurred in the Cenomanian (the "distocarinatus gap"). Afterwards, a new set of basins evolved, post-rift in the

Bight area and transtensional rifts in the east and south. First ocean crust was probably in the Mid-Santonian (c. 83-85 Ma) in the southern part of the Tasman Sea.

Unconformities and slowing of fault movement are common in the Late Santonian and Middle Campanian. These events may have been driven by episodic formation of ocean crust in the Tasman Sea at these times. The only true rift-drift transition is the one in the Gippsland Basin in the Middle Campanian (base Latrobe Group, upper N. senectus zone, c. 80 Ma).

The trans-tensional rifts changed to post-rift sags at various times from the Mid-Santonian to near the end of the Maastrichtian (or perhaps locally in the Eocene). Plate tectonic causes are not obvious but may have been associated with switches in the location of first ocean crust between different micro-continental fragments and along different parts of the margin.

The Paleocene to Middle Eocene was usually a period of post-rift clastic progradation. Along the southern margin, this was terminated by a rapid transgression in the Lutetian (P. asperopolus zone), which was driven by the collapse of the margin at the onset of fast southern ocean spreading at about 44 Ma. First oceanic crust began to form off Otway and West Tasmania sequentially from about 47 to 40 Ma, ie during the Middle Eocene (lower to middle N. asperus zone).

In Gippsland, the transgression, or the onset of retrogradational sequence stacking, was slightly earlier; within the Ypresian at c. 53 Ma (base M. diversus zone). This event was caused by cessation of spreading in the Tasman Sea.

Carbonate sedimentation became suddenly common in most southern margin basins in the Middle Oligocene. This event is usually attributed to clearance of Antarctica from the South Tasman Rise, establishment of circum-Antarctic currents and the drift of southern Australia far enough into lower latitudes to allow cool water carbonate productivity. The Middle Oligocene disconformity was probably due to a eustatic sea level fall caused by a major increase in Antarctic ice volumes.

The final events are local inversions and periods of fold growth in the Late Miocene and again in the Pliocene. A reason that is often given is the initiation of collision on the northern margin of Australia. However, actual inversion ages seem to differ slightly from basin to basin and may well have local causes.

Plate Reconstructions

PLATE RECONSTRUCTION METHODOLOGY

This stage of the project has been directed towards the production of preliminary plate reconstructions. The objective has been to develop an outline view of plate and microplate positions, crustal state, basin tectonostratigraphy, drainage and denudation (including uplift) events.

At present, all of the restorations have been prepared on paper with scissors and tape. The resulting maps are obviously only indicative cartoons but they help to understand the approximate positions of the plates and the geological issues. The next Stage will be more rigorous plate kinematics on a globe.

The starting point has been the ocean age map for Australia at Lambert conformable conic projection (Encl. 2). Oligocene to Recent reconstructions were prepared by cutting out and discarding the relevant pieces of oceanic crust. However, prior to the Oligocene, the strike length of the Antarctic margin is too long to fit into the Great Australian Bight. From the Oligocene to the Jurassic, a map of Antarctica at south polar stereographic projection was used, based on Tingey (1991a, b), reduced to 93%. This methodology works quite well back into the Campanian, although it is recognised that there will be artefacts introduced by mixing more than one projection. Prior to the Campanian, however, there are further problems associated with overlap of continent boundaries.

Another concept introduced here is that continental plates have suffered considerable deformation. Prior to plate breakup, there will have been extension, sometimes extreme extension, of the lower continental margins (Fig. 3). An attempt has therefore been made to show areas of continental crust that have been extended by beta factors of more than 1.5, and also to attempt to restore these areas in a rough sense to their pre-rifting position. As a rule of thumb, all major rift basins are assumed to have extended by about 1.5 and deep water plateaus by about 2.0-4.0. Extension will, of course, be cumulative. Areas of thickened crust (New Zealand –New Caledonia) are shown separately.

There are significant problems associated with the full restoration of the southern Tasman Sea prior to the Campanian. This is partly because of impingement of the Campbell Plateau into Mary Byrd Land and also because of residual gaps left after the simple restoration of the large plates (Campbell Plateau, Antarctica, Lord Howe Rise, Challenger Plateau). Many of the recent restoration attempts produced by IGNS, NZ (eg Sutherland, 1999a, b) have assumed oceanic spreading under the Ross Sea. However, most of the Ross Sea and Ross Ice Shelf would have to be composed of oceanic crust in order to accommodate the spatial problems. The solution in the present study has been to split the Campbell Plateau along the so-called Campbell Fracture Zone (Kamp, 1986a, b) and to fill the residual oceanic gaps with detached and rotated microplates (East Tasman Plateau, Gilbert seamount, central and eastern South Tasman Rise, Iselin Bank, northern and southern Campbell Plateau, Chatham Rise). Also, the whole complex of Tasman Sea microplates and continental plateaus has been squeezed to close all the gaps and to restore crustal extension (see Fig. 4). One introduced problem is that the pre-Jurassic terrain correlations have been distorted, particularly the Brook Street terrain and its equivalents (Fig. 5). This issue may again be an artefact of mixing projections and restoring on paper, rather than with solid geometry.

Overall, the reconstructions presented should therefore be viewed as 'work in progress' and subject to improvement with rigorous plate kinematics. Even with this caveat, a large number of geological events have begun to make sense tectonically, and this preliminary geological history is summarised below.

PRE-UPPER JURASSIC TERRAIN RECONSTRUCTION

The pre-Jurassic terrain reconstruction (Fig. 5) helps to provide a check on the validity of the reconstruction method.

Most of the western part of Australia plus the adjacent parts of India and East Antarctica are underlain by high grade Archaean to Middle Proterozoic metamorphics. Upper Proterozoic-Lower Palaeozoic basins, including the Officer Basin and elements of the Adelaide Fold Belt overlie these cratons. In Greater India, at least three Upper Carboniferous to Permian Gondwana grabens occur roughly parallel to each other. The central one, the Mahanadi Graben, probably crosses the future Southern Ocean into the Permian graben under the Amery ice shelf adjacent to Prydz Bay. Further Gondwana sags and grabens occur in Australia and were sub-parallel to those in India in the pre-rift reconstruction; namely, the Perth Basin, Merlinleigh Basin, Fitzroy Trough, Bonaparte Basin and Goulburn Graben.

Upper Proterozoic metamorphics in the Albany-Fraser zone swing around parallel to the WA coast but does not appear to cross over to Antarctica. This parallelism with the future breakup line is mirrored by the Kanmantoo zone west of Kangaroo Island. It is possible that Cretaceous breakup in fact followed east-west lines of weakness that were set up late in the Pre-Cambrian.

East of the high grade metamorphic terrains, the Delamerian represents a Cambrian-Ordovician low grade metamorphic and magmatic zone that can be followed from the Kanmantoo zone in South Australia, across western Tasmania into the Ross Orogen in Antarctica. A set of Cambrian-aged mixed volcanic/sedimentary grabens occurs on its eastern side (Mt Read Volcanics in Tasmania, Bowers Terrain in North Victoria Land).

The Lachlan Fold Belt occupies a large portion of eastern Australia and is also represented in the western province of South Island New Zealand, the Challenger and southern Campbell Plateaus, North Victoria Land (Robertson Bay Terrain) and Marie Byrd Land. There is still controversy about the correlation of Upper Proterozoic crust from Tasmania under the Melbourne Zone, but so far, no-one has attempted to identify this sub-terrain in Antarctica.

The New England Orogen is shown extending southwards, past the Gippsland Basin, into the West Norfolk Ridge, where it terminates (Harrington, 1999). South of Newcastle, the suture between the Lachlan and New England Orogens may have been exploited by Cretaceous breakup. The Sydney-Bowen Basin, Tasmania Basin and a speculative Permian basin beneath Gippsland are assumed to be back-arc basins to the New England Orogen.

Permian volcanics can be followed from the Brook Street Terrain in New Zealand to the Highbury Volcanics in southeast Queensland (Harrington, 1998, 1999), although their location in the intervening marine areas is speculative. With similar reservations, the Murihiku and Matai Terrains are correlated with western New Caledonia and the Gympie Terrain in southeast Queensland.

Finally, the suspect terrains that make up the Torlesse in New Zealand are assumed to have formed as accretion prisms derived from rivers flowing out of Queensland and the New England Orogen during the Permian to Early Jurassic. They then moved from north to south along strike-slip faults during the Triassic to Jurassic. The Balimbu Greywacke in the PNG Highlands may be a similar suspect terrane. This theory (by Adams et al, 1998a, b) is based on

U/Pb isotope signatures in zircons from the Torlesse matched to those in Permian granites in the Queensland hinterland. An alternative reconstruction by Rozer & Korsch (1999) using bulk rock geochemistry suggests little or no strike-slip displacement.

MIDDLE OXFORDIAN RECONSTRUCTION – 155 MA

NE-SW rifting began in the MacRobertson Shelf (Truswell et al, 1999), ?Bremer, Recherche and Eyre Subbasins (Sea Lion sequence; Totterdell et al, 2000) and Polda Trough. This phase (Encl. 9, Fig. 6) may be as old as Callovian but can only be dated to within the broad M. florida pollen zone (Callovian-Kimmeridgian). The rift complex represented the right branch of a triple junction, the other two arms being the Perth Basin and the India-Antarctica margin.

In New Zealand, the Torlesse and Waipapa accretion prisms are shown growing into a subduction zone and progressively moving southwards along dextral transcurrent faults, as in Adams et al (1998a, b).

The Eromanga and Surat Basins were occupied by a large, long-lived lake and continued to be so until marine incursions began in the Valanginian (Bradshaw & Yeung, 1992; Beynon et al, in prep).

EARLY TITHONIAN RECONSTRUCTION – 145 MA

During this time-slice (Encl. 10, Fig. 7), there was continued NE-SW rifting along MacRobertson Shelf, Perth, ?Bremer, Recherche, Eyre (Minke sequence) and Polda Basins. However, at the same time, east-west rifting started in new half grabens under the Duntroon, Gippsland and Otway Basins. The stresses leading to this new basin complex are assumed to be minor rearrangement of extension directions between Antarctica and eastern Australia but the eastward continuation of the rift valley complex under the Lord Howe Rise cannot yet be mapped. Most of the rift infill comprised non-marine clastics, but basalts and gypsum accumulated in at least Otway (Casterton Beds) and Gippsland.

Further growth and southward dextral movement is shown in New Zealand and new Caledonia in the Torlesse, Waipapa, and New Caledonia accretion prisms.

HAUTERIVIAN/VALANGINIAN BOUNDARY RECONSTRUCTION – 135 MA

First ocean crust formed in the Valanginian (132.5 Ma according to Veevers et al, 1991) between Assam and the Perth Basin (Enc. 11, Fig. 8). It is assumed that the rest of India also broke away from East Antarctica at the same time. However, there are no confirmatory magnetic lineaments available for this southern arm of the triple junction. The alternative is that the southern breakup may have started just south of the Naturaliste Plateau and propagated southwards.

Major north-south directed extension and east-west orientated half grabens continued to form along the Gippsland-onshore Otway Basin trend, which were possibly joined in the Melbourne area. This led to the accumulation of quartzose to arkosic fluvio-lacustrine clastics in the lower Strzelecki and Crayfish Groups. Half grabens with deeper water, fine grained lacustrine sedimentation also continued forming in the Duntroon Basin as far west as Potoroo-1 (Southern Right/Bronze Whaler sequences). However, there was a change to a thermal sag phase in the

Bremer, Recherche and Eyre Subbasins, probably caused by the formation of first ocean crust in the nearby Indian Ocean.

The Torlesse phase of subduction and dextral movement was completed along the New Caledonia–New Zealand margin. Subduction patterns then changed, resulting in the initiation of a thermal event during Rangitata folding and metamorphism.

MIDDLE BARREMIAN RECONSTRUCTION – 120 MA

Voluminous dacitic tuff deposition started in the Gippsland-Otway, Bass, Eromanga, Surat and Clarence-Morton Basins and probably also in New Guinea (Encl. 12, Fig. 9). This vulcanism was coeval with the Whitsundays Volcanics in Queensland. Bryan et al (1998) have indicated that the geochemistry, petrology and volcanic stratigraphy are typical of ignimbritic volcanoes formed by back-arc extension, not calc-alkaline Andean volcanism, as others have suggested. The volcanoes were probably located in the Lord Howe Rise. However, subduction may have been continuing under New Zealand at this time (see later).

It is uncertain whether this volcanic province also extended south of Tasmania because there are no outcrops to control mapping. However, volcanics of this age have been recorded from Marie Byrd Land, which may have been a continuation of the same magmatic belt.

Faulting slowed in Gippsland, onshore Otway and Duntroon Basins. There was a gradual change to thermal sagging in a slightly trans-tensional setting. This sinistral strike-slip couple resulted in the formation of the NE-SW depocentres in the Otway and Strzelecki Ranges for example. Realignment occurred of depocentres in the western onshore Otway Basin with NW-SE basement trends. Paludal to coaly sedimentation occurred in onshore Otway.

Anoxic deep lacustrine sedimentation, without significant volcanic debris, was widespread in the Duntroon Basin. Thermal sag sedimentation continued in the Recherche Subbasin.

In New Zealand and New Caledonia, Rangitata folding and metamorphism was completed by 120 Ma.

LATE APTIAN RECONSTRUCTION – 110 MA

During the Aptian (Enc. 13, Fig. 10), there was continued volcanogenic sedimentation in a thermal sag setting in the Gippsland, onshore Otway and Bass Basins. Environments changed to mainly fluvial braided facies, fairly close to the palaeo-pole. Cryogenic structures are known in Gippsland. By the Aptian, sedimentation had spread out beyond the rift boundaries. Aptian siltstone in a gravity core off the George V Coast suggests that sedimentation may also have extended over into Antarctica.

A final fluvio-lacustrine sag or late syn-rift fill occurred in the Duntroon Basin (Bronze Whaler) and thermal subsidence continued in the Recherche Subbasin. Minor volcanogenic detritus finally reached the Duntroon Basin. For reasons that are still unclear, this phase was followed during the Aptian-Early Albian by uplift and erosion throughout Bight Basin complex.

An extensive marine transgression occurred in the Eromanga (Bulldog Shale), Surat (Wallumbilla Formation) and Berri Subbasin beneath the Murray Basin (Merreti Member of the

Monash Formation). This transgression, which caused the maximum Mesozoic flooding of the Australian continent, probably came from the north. The southern margin basins were the only ones still in a non-marine facies at this time.

The New Zealand margin entered an extensional phase as soon as subduction and Rangitata metamorphism ceased at about 120 Ma. The development of core complexes, such as the Paparoa core complex (Spell, et al, 2000) and an Aptian marine transgression (Korangan) in the East Coast Basin (Field et al, 1997) were part of this extensional event. Meanwhile further north, subduction probably continued east of New Caledonia.

The Keguelen-Broken Ridge volcanic plateaus, which were joined until the end of the Cretaceous, was emplaced by an Icelandic-type plume between 120 and 110 Ma.

LATE ALBIAN RECONSTRUCTION – 100 MA

Accentuated intra-cratonic thermal sagging began in the Middle Albian in the Ceduna Subbasin, possibly driven by dextral trans-tensional rifting or by significant lower crustal extension or both (Encl. 14, Fig. 11).

An extensive Middle-Late Albian marine transgression occurred in Ceduna, resulting in the deposition of thick marine shales (Blue Whale sequence). This transgression was followed by initiation of a major, rapidly deposited delta, fed by a river system originating in the Eromanga Basin. Listric faulting began, with decollement on the Middle Albian marine shales.

A major marine transgression of slightly later, Late Albian age also entered the Eromanga and Surat Basins from the north (Toolebuc Limestone) but without apparently reaching the southern margin basins.

There was continued volcanogenic fluvial sedimentation in a thermal sag setting in the Gippsland, onshore Otway and Bass Basins, which probably spread to its maximum extent in this period over the inter-basin highs. The burial of much of eastern Australia, suggested by apatite fission track data, may have occurred during the Albian, although the extent and amount of burial are contentious.

Subduction probably continued east of New Caledonia, but not east of New Zealand. Half grabens began forming in a number of places in New Zealand and filled with fluviatile clastics (Hawks Crag Breccia in the Westland Basin) and in some cases marine shales (East Coast Basin).

MID-CENOMANIAN RECONSTRUCTION – 95 MA

There was a complete reorganisation of the basin framework over much of eastern Australia (Encl. 15, Fig. 12), that may have been caused by cessation of subduction east of New Caledonia. According to Korsch (1999) and Waschbusch et al (1999), cessation of subduction would have resulted in the end of viscous corner convection in the mantle under the edge of eastern Australia, and this change in turn caused widespread rebound and uplift of the margin. Mitrovica et al (1989) described a general model for such events. A further effect was that volcanogenic sedimentation ceased throughout eastern Australia as soon as subduction stopped.

Broad uplift and denudation occurred along the Australian Eastern Highlands, Tasmania and possibly in North Victoria Land. This event is interpreted from apatite fission track analyses

(O'Sulluivan et al, 1995, 1997, 1999, 2000). The exact location of uplifted areas is still imprecisely mapped, and it is possible that some areas were not uplifted to the same level (eg the Sydney Basin).

Folding and uplift occurred in the onshore Otway, Gippsland and Bass Basins. There was uplift and erosion over the whole basin complex, but it was concentrated in rhombic areas, some of them having been previous depocentres (Duddy, 1999). The three basins became separated by inversions in the vicinity of the Mornington Peninsula and Melbourne. This may have been the time when overturned folds and thrusts were formed in the Otway Ranges (eg Skene's Creek anticline), although it is also recognised that these folds had substantial later growth in the Late Miocene and Pliocene.

Continued intra-cratonic subsidence and rapid fluvio-deltaic sedimentation continued in the Ceduna depocentre (White Pointer). Unstable listric faulting and decollement resulted in toe-thrusting at its southern edge. The river system feeding this delta was probably formed when the uplift of the Eastern Highlands initiated erosion through the Eromanga Basin. However, there may be a small unresolved overlap with depositional ages in the Eromanga Basin (eg Upper Albian age for the top of the Winton Formation).

There are several recorded igneous events allegedly of this age, although uncertainties in the precise dating may mean that they are partly Albian, which would fit better with the current tectonic model. These occurrences include the Mount Dromedary acid intrusion, minor basalts at Poowong in West Gippsland (Johnson, 1989) and some small alkaline intrusions near Cygnet in Tasmania (David Moore, pers. comm.).

Finally, a change occurred to rapid spreading about a new rotation pole in the Indian Ocean.

TURONIAN RECONSTRUCTION – 90 MA

A completely new complex of rift basins developed around the eastern margins of Australia, New Zealand and Antarctica (Encl. 16, Fig. 13). Some of them have been drilled and dated (offshore Otway Basin (Shipwreck Group), Bass Basin, Gippsland Basin (Emperor Subgroup) and the Great South Basin of New Zealand (Hoiho Group; Beggs, 1993; NZ IGNS, in press)). Others are imaged on seismic but have not yet been confirmed by drilling. This second group includes the Sorell Basin, the South Tasman Rise, other basins on the Campbell Plateau and parts of the Lord Howe Rise (eg the Fairway Basin). A third group is more speculative (Terror Rift in the Ross Sea, Bounty Trough and poorly known parts of the Lord Howe Rise). However, the existence of this third group is suspected on the basis that they adjoin future breakup sutures.

The distribution of rifts is quite confusing, but it is possible to view their arrangement as an X pattern (Fig. 14). The northwestern branch is in the offshore Otway and Sorell Basins, where the Tartwaup and Sorell Faults form the northeastern edge. The southeastern branch lies on the Campbell Plateau and Bounty Trough. A northeast branch is in the Lord Howe Rise and a more speculative southwest arm underlies the Ross Sea. The northwestern and southeastern branches may have been associated with a sinistral intra-cratonic transcurrent fault that developed along the boundary between Antarctica and Tasmania-North Island New Zealand. A possible southeastern dextral fault splay was the speculative Campbell fault zone of Kamp (1986a, b). These fault movements imply that the X-shaped rift pattern was a conjugate set with maximum extension in an east-west direction

Sedimentation styles in these new rift basins were largely non-marine initially, but in some areas marine transgressions and deltaic sedimentation occurred at later stages. In offshore Otway, sediment fill is fluvial to deltaic clastics. The Outer Margin High began to form at this time, due to extreme extension of the outer continental crust. In offshore Gippsland, the Emperor Subgroup comprises fluvial to lacustrine clastics and coaly sedimentation. In the Great South Basin, the Hoiho Group includes non-marine sediment that accumulated in a major active graben. The East Coast Basin also has possible syn-rift sediments, although these tend to be more marine.

Accelerated subsidence in Ceduna resulted in slowing of syn-depositional faulting, rapid transgression, downlap and the deposition of a new aggradational marine to deltaic cycle (Tiger sequence). Implications are that significant marine bathymetry was formed at this time.

MID-SANTONIAN RECONSTRUCTION – 85 MA

First ocean crust began to form at around 85 Ma in a number of places on the eastern seaboard, including the southernmost Tasman Sea and between Campbell Plateau and Antarctica (Encl. 17, Fig. 15). The plate reconstruction shown here accomplishes closure of most of the oceanic areas but requires movement by several of the smaller microplates in order to fill the gaps (East Tasman Rise, eastern South Tasman Rise, Gilbert Seamount, Iselin Bank). Movement on the speculative Campbell Fault is also required to prevent overlap of Antarctica and Campbell Plateau, although this may be an artefact of projections.

Along the southern Australian margin (Ceduna and deepwater Otway), there was extreme low angle crustal fault extension, block rotation and the formation of outer margin highs that became onlapped by post-Santonian sediments. There was probably also similar extreme crustal extension in the microcontinents along the eastern side of Australia. On the map, this extension is accounted for mainly in the Lord Howe Rise, Dampier Ridge and New Caledonia Basin.

In Ceduna, there was continued deposition of slope mudstones (upper Tiger sequence, T. apoxyexinus zone). The trunk river system feeding this delta from the eroding Eromanga was still in place.

In offshore Otway, block rotation, an unconformity and rift relocation marked the boundary from Shipwreck to Sherbrook deltaic megasequences.

A minor unconformity, marine transgression and subtle changes in fault activity in offshore Gippsland occurred at the Emperor-Golden Beach Subgroup boundary. This event was effectively the first breakup unconformity.

Continued syn-rift, non-marine sedimentation occurred in basins on the Campbell Plateau (eg Great South Basin; Hoiho Group).

A syn-rift to post-rift transition and a marked unconformity occurred in a number of basins on the New Zealand east coast. For instance, this unconformity marked the base of the Tinui Group in the East Coast Basin and the base of the Seymour Group in Marlborough (Field, et al, 1997).

EARLY CAMPANIAN RECONSTRUCTION – 80 MA

First ocean crust began to form in the Great Australian Bight at about 83 Ma (anomaly 33)(Encl.18, Fig. 16). The pattern of closely spaced Upper Cretaceous to Lower Eocene magnetic anomalies in the eastern Bight is not represented further west. It is therefore possible that spreading started south of Ceduna and slowly propagated westwards during the Campanian-Maastrichtian. This model implies that the proto-Southern Ocean was an enclosed and restricted seaway.

In the Ceduna Subbasin, there was a major sequence boundary at the base of the strongly prograding deltaic Hammerhead sequence (approximately the N. senectus/T. apoxyexinus boundary). This stratigraphic change equates to the 80 Ma breakup event.

In the offshore Otway and Sorell Basins, Sherbrook deltaic to marine aggradational sequences accumulated in a trans-tensional rift.

Tasman seafloor spreading extended to just north of Gippsland. The megasequence boundary between the Golden Beach Subgroup and the Latrobe Group is probably the rift-drift transition associated with the local opening of Tasman Sea oceanic crust. This stratigraphic change is followed by the transgression of a marine shale and then by the progradation towards the east of lowest Latrobe Group deltaic sequences.

Apatite fission track data (O'Sullivan et al, 1995; Duddy, 1999) suggests that a coastal uplift began at about 80 Ma adjacent to the tip of new oceanic crust in southernmost NSW and moved slowly northwards following this spreading tip.

New ocean crust began to form between Dampier Ridge and Lord Howe Rise (Middleton Basin). Meanwhile, extreme stretching of continental crust between the Lord Howe Rise and Norfolk Ridge-New Caledonia resulted in the main period of subsidence into deep water of the New Caledonia Basin. In these reconstructions, the New Caledonia Basin is floored by highly extended continental crust. At the same time, a passive margin with siliciclastic sedimentation became established over New Caledonia.

The Campbell Plateau finally separated from Antarctica. On the Campbell Plateau, the rift/post-rift transition occurred in the Great South Basin at approximately 80 Ma, top Hoiho Group (R. Sutherland, pers. comm.). The Bounty Trough opened as a short-lived seafloor-spreading event, released by the speculative Campbell fault zone.

LATE CAMPANIAN RECONSTRUCTION – 75 MA

Slow spreading continued south of Australia (Encl. 19, Fig. 17) and may have begun to propagate westwards towards the Labuan Basin.

There was a marine transgression, followed by aggradational regression in the Ceduna deltaic depocentre (upper Hammerhead).

The trans-tensional trough filling with the Sherbrook Group continued to form in offshore Otway, but faulting gradually ceased and sediments began to onlap the rotated Santonian fault blocks on the outer margin highs.

Tasman Sea spreading reached as far north as Merimbula and was replaced by sinistral strike-slip movement north of this point. The coastal uplift reached Sydney.

Completion of spreading occurred in the Middleton oceanic basin. At the same time, extreme stretching was completed in the continental crust under the New Caledonia Basin. Also at about this time, there was a change from rift to post-rift sedimentation in basins on the Lord Howe Rise.

Half graben formation and fluvial to coal measure deposition, the Pakawau Group, began in the Taranaki and West Coast Basins along the west side of New Zealand. Meanwhile, post-rift marine sedimentation continued in Great South Basin.

The geometry is uncertain and currently difficult to resolve, but spreading may have begun in the area between the South Tasman Rise, Iselin Bank and Challenger Plateau. A Palaeogene east-west orientated spreading ridge, the Adare Trough, has been modelled by Cande et al (2000). However, the space problems set up in the present reconstruction, perhaps partly due to projection artefacts, suggest that the Adare Trough also had a Late Cretaceous history.

CRETACEOUS/TERTIARY BOUNDARY RECONSTRUCTION – 65 MA

A new slow spreading centre was initiated between Broken Ridge and the Kerguelen Plateau along the Diamantina Fracture Zone (Encl. 20, Fig. 18). Precise timing is uncertain but this event was approximately end-Cretaceous.

Ceduna delta building finished with a thick and unstable Maastrichtian aggradational package (upper Hammerhead sequence). This delta loading resulted in the final stage of toe-thrusting being completed. The sediment-input point possibly switched from the Polda Trough to the Spencer Gulf and a new base of slope turbidite fan depocentre is thought to have evolved in deep water adjacent to the Duntroon Basin. The shelf and slope were apparently a sediment bypass zone. Timing is again uncertain but this event was approximately Late Maastrichtian-Early Paleocene.

In offshore Otway, the marine to deltaic Sherbrook faulted trough gradually changed to sag geometries, but sediment was probably still derived from both Antarctica and Australia. Minor faulting, broad uplift and local volcanic activity occurred near the end of the Cretaceous in the Otway Ranges area. There was a further change to Wangerrip progradation from the Port Campbell Embayment, over a slope bypass zone and into a turbidite depocentre in the deep-water Otway Basin. All of these events may be Early Paleocene and precise dating is uncertain.

Tasman Sea spreading extended at least as far north as Newcastle, with strike-slip movement to the north. The coastal uplift reached Port Macquarie.

In the offshore Gippsland Basin, Latrobe Group delta aggradation continued across the Cretaceous/Tertiary boundary without obvious interruptions.

In New Zealand, there was continued non-marine syn-rift deposition in the Taranaki and West Coast Basins, the Pakewau Group.

Finally, the deposition on the New Caledonia passive margin gradually changed from siliciclastic sedimentation to deepwater marls and cherts, indicating accelerated thermal subsidence.

PALEOCENE/EOCENE BOUNDARY RECONSTRUCTION – 55 MA

Spreading finished in the Tasman Sea (52-54 Ma), but slow spreading continued in the Southern Ocean (Encl. 21, Fig. 19).

The interpreted base of slope fan continued to grow in the deepwater Duntroon Basin, presumably fed by a river system along the Spencer Gulf. The shelfal equivalent further west was the condensed Wobbegong sequence.

Wangerrip progradation continued in the Otway Basin. Meanwhile, a syn-rift/post-rift transition has been interpreted in the Sorell Basin.

The western South Tasman Rise became detached from Antarctica and was welded with the rest of the South Tasman Rise (?Late Paleocene-Early Eocene according to Royer & Rollet, 1997).

Thin fluvial sedimentation started in a large number of inland Australian basins, but the driving mechanism is uncertain. Apatite fission track cooling events between 65 and 50 Ma have been recorded in several areas and an explanation is that there was a great deal of drainage reorganisation at this time over large areas of low relief in the interior of the continent. Thus, poorly defined denudation events have been suggested in the Eastern Highlands, Darling Basin-Canobolas divide area and Murray Basin at about 60 Ma (65-55 Ma) (P.O'Sullivan, pers comm) and also in the Adelaide Hills (Gibson & Stuwe, 2000). Inland areas that began to receive incised valley fill in the Late Paleocene-Early Eocene include the Murray Basin and Lake Eyre Basin. The incised valleys in the Murray Basin may have been linked to development of some of the Deep Leads in western Victoria. Drainage may have started from north to south, perhaps debouching into the Otway Basin (eg the Dilwyn depocentre, G. Holdgate, pers comm). However, this interpretation is contentious and other interpretations (eg Stephenson & Brown, 1989: Brown & Stephenson, 1991) suggest that the Murray Basin always debouched through the Padthaway Ridge.

Incised valley fill also occurred in onshore Gippsland, followed by hiatus (?uplift) and volcanics (55-57 Ma). Rapid retrogradation began, together with marine transgressions and folding in offshore Gippsland (54 Ma). The tectonic reasons for the initiation of folding is difficult to determine, but far-field ridge push from the New Zealand area is one of the possibilities.

According to Cande et al (2000), the main phase of spreading occurred in the Adare Trough, linked to the initiation of major crustal extension and rift basin formation under the Ross Sea and Ross Ice Shelf. The associated footwall or rift shoulder uplift in the adjacent Trans-Antarctic Mountains has been dated by apatite fission track analyses (Fitzgerald, 1992, 1994; Fitzgerald & Gleadow, 1989).

In New Zealand, the Pakawau rifts were abandoned and a new set of Challenger rifts initiated. Some were marine and some had non-marine/deltaic fill (eg the Kapuni Group in the Taranaki Basin). The Challenger rifts were the first stage of crustal extension leading to the evolution of the Emerald oceanic basin (Kamp, 1986b).

There was widespread anoxic marine shale deposited at the end of the Paleocene in New Zealand, associated with a sea level high and a global warming event (Waipawa hot shale).

MID-EOCENE (LUTETIAN) RECONSTRUCTION – 45 MA

Fast spreading began in the Southern Ocean about a more distant pole at approximately 44 Ma (anomaly 20 or lower N. asperus pollen zone) (Encl. 22, Fig. 20). This event led to rapid thermal subsidence and marine transgression on many areas of Australia's continental margins. In the Bight Basin, the shelf area subsided to 1000-2000m water depths (the Ceduna Terrace) and sedimentation effectively switched off. The sediment source into the deepwater Duntroon Basin also ceased and the base of slope fan complex suddenly stopped forming. Carbonate sedimentation began in the Eucla Basin (Wilsons Bluff Limestone). At the same time, parts of the older river channel systems on the Yilgarn Craton (Lefroy and Cowan drainage channels) received marine transgressions and carbonate or spongolite sedimentation (Plantaganet Group).

Further east, first ocean crust formed off the Otway Basin, propagating southwards offshore west Tasmania. Marine transgression occurred in both basins (eg Narrawaturk Marl).

There was major canyon cutting in offshore Gippsland (Tuna-Flounder channel c. 52 Ma; Marlin channel c. 45 Ma). Meanwhile in onshore Gippsland, non-marine sedimentation spread towards the Latrobe Valley.

Intra-plate basaltic plume vulcanism started in the Eastern Highlands at Monaro, Barrington Tops, Walcha and Flinders.

Folding and ophiolite obduction took place in New Caledonia, carried by slab roll-back in the Loyalty subduction system.

Completion occurred of the second phase of seafloor spreading in the Adare Basin and of rifting in the Ross Sea and Ross Ice Shelf. New oceanic crust began to form southwest of New Zealand between the Resolution Ridge and the western Campbell Plateau in the Emerald Basin. These events resulted in the expansion of the non-marine to marine Challenger rift system in the Taranaki Basin.

LATEST EOCENE (PRIABONIAN) RECONSTRUCTION – 35 MA

Breakthrough of oceanic crust occurred between Antarctica and the South Tasman Rise (Encl. 23, Fig. 21).

Antarctic glaciation was initiated, possibly in the mountains at the head of the Lambert Glacier (P. Quilty, AGC, Sydney, July 2000). Evidence of the first sea-level ice (glacial dropstones) appeared in the offshore sedimentary record and was followed by the start of prograding glacio-marine sediments on the shelf.

Marine incursions occurred into the Murray Basin (Buccleuch Beds) and sedimentation expanded over much of the basin.

Erosion, weathering and ferricrete and silcrete formation started in many parts of interior Australia (the Canaway profile and Cordillo surface).

Folding finished in offshore Gippsland. Marine transgression continued in both the Gippsland and Otway Basins.

Active subsidence started in the New Zealand Challenger rift system. There was a change to carbonate sedimentation in these basins (Tikorangi Limestone).

Rapid spreading occurred in the Emerald Basin accompanied by active prolongation of the spreading tip towards the Balleny Trough.

Unroofing of the metamorphic zones began in New Caledonia, accompanied by further thrusting (?migrating southwards).

Spreading was initiated at the South Fiji triple junction.

LATEST OLIGOCENE (CHATTIAN) RECONSTRUCTION – 25 MA

Circum-Antarctic currents became established in the Mid-Oligocene (Encl. 24, Fig. 22).

There were major increases in Antarctic sea level glaciation in the Mid-Oligocene accompanied by sediment progradation on the shelf.

Widespread cool temperate carbonate sedimentation began in the Bight and Eucla Basins (Nullabor Limestone), Otway Basin (Heytesbury group), Murray Basin (Murray Group), Sorell Basin and Gippsland Basin (Seaspray Group) in the Mid-Oligocene (c. 30 Ma). In onshore Gippsland, maximum marine transgression occurred at c.25-27 ma and was followed by a volcanic episode.

There was widespread cutting of Deep Leads river valleys in the Australian Alps at about 30 Ma (eg Kiandra, Owen, 1988). This was followed by initiation at around 25 Ma of uplift of a southeast-dipping block between Melbourne and Canberra (but with the highest areas between Mt Buffalo and the Brindabella Mountains and centred on the Kosciuszko region). This uplift event is based only on geomorphological interpretation (M. Orr, pers. comm) and, if correct, it may have marked the final formation of elevated topography in the Eastern Highlands.

Intra-plate basaltic vulcanicity occurred in many areas of eastern Australia at this time (Liverpool, Central, Bogong High Plains, Kiandra). Volcanoes generated by mantle plumes also started forming in the northern parts of the Tasman Sea and Middleton Basin and began migrating southwards.

Initiation began of the Vening Meinesz and Van Der Linden transcurrent faults and subduction occurred north of New Zealand. There was back-arc spreading in the Norfolk Basin, leading to formation of the Three Kings Rise as a volcanic arc (starting 26 Ma). The South Fiji triple junction stoped spreading at c.24 Ma. Emplacement of the Northland and Raukumara allochthonous units occurred at about 25 Ma.

Movement started on the New Zealand Alpine Fault (slightly later at 24 Ma). The Challenger rift shoulders expanded (eg into North Wanganui Basin).

LATE MIOCENE (TORTONIAN) RECONSTRUCTION – 10 MA

Desiccation began of inland Australia at about 10 Ma (Encl. 25, Fig. 23), together with the shrinkage of most river systems. There was also widespread erosion, weathering and duricrust formation in interior Australia.

Early inversion folding started in Otway, Gippsland and interior Australia.

Major channelling events occurred in offshore Gippsland (14 or 16.5 Ma) followed by accelerated limestone deposition (Gippsland Limestone).

A major regression and erosion ended carbonate deposition in the Murray Basin (c.10 Ma). This was followed by marine transgression and the emplacement of Pliocene chenier ridges (the Loxton-Parilla sands).

Intra-plate vulcanism occurred in the Australian Eastern Highlands (eg Tweed volcano, 20-24 Ma; Warrumbungles, 14-17 Ma; Brisbane Main Range, 23-27 Ma; Nandewar, 17-21 Ma; Ebor, 18-19 Ma). There was also plume vulcanism on two separate north to south tracks in the Tasman Sea and Middleton Basin, which were more or less completed during this time slice (27 – 11 Ma).

In New Zealand, continued movement on the Alpine Fault caused many basins to enter a convergent phase. Uplift and erosion in the highlands probably did not begin until a little later (5 Ma according to Batt et al, 1999). Active subduction started in the Hikurangi and Kermadec Trenches.

PRESENT DAY – 0 MA

There was further desiccation of inland Australia and the emplacement of an aeolian sand sheet during the Pleistocene (2-0.5 Ma)(Encl. 26, Fig. 24).

Montane glaciation occurred in Tasmania and the Eastern Highlands.

A new intra-plate mantle plume led to the eruption of widespread flood basalts in western Victoria and southeastern South Australia (2-0 Ma), and also in north Queensland.

The main phase of uplift started in the New Zealand Alps at about 5 Ma, caused by locking and contraction on the Alpine transcurrent fault. This led to erosion products forming massive progrades in the adjacent basins (eg the Giant Foresets). Subduction on the Hikurangi Trench became linked with back-arc spreading and vulcanicity in the Taupo volcanic zone.

There were one or more phases of inversion in many folded areas of the Gippsland and Otway Basins. These events were then followed by the deposition of fluvial sand sheets. Neotectonic movement occurred on many older faults in the Eastern Highlands (eg Towonga, Lake George, Long Plain, Shoalhaven faults), the Flinders Ranges (Adelaide Hills) and in west Gippsland (Strzelecki Hills, Selwyn fault) and Otway (Rowsley fault). These movements are continuing and may have resulted in upto 1000m of cumulative displacement, mainly as reverse or more rarely strike-slip movement.

The Next Phase

Significant achievements have been made in this past phase of study in understanding the tectonostratigraphy and evolution of the southern and southeastern margins of the Australian plate (Fig. 25). Specific advances include the identification of a quite complex three-phase rifting history and the realisation that the stratigraphic responses to multiple rifting and breakup have been fairly muted, possibly because continental separation was relatively slow. Also, there has been such extensive stretching of the lower continental slopes around southern Australia that reconstruction mapping needs to allow for significant increases in area prior to oceanic spreading. In other words, matching of continent-ocean boundaries fails to give a true picture of the palinspastic relationship between conjugate margins, especially prior to the Cainozoic.

The work to date has provided a firm basis for basin studies in the region but there is now a need to add detail to the plate reconstruction mapping and to improve the useability of the interpretations. It has therefore been proposed that a new two year phase of study is initiated to address the following subjects:-

All of the reconstructions have so far been constructed on paper with scissors and tape, and need to be tested with rigorous plate kinematics on a globe. There are several software packages available (Atlas, PaleoGIS, Platyplus) and we need to investigate which one to use and whether a collaborative effort would be preferable with an existing study group, such as R.D. Muller's group at U. Sydney.

More detailed mapping of the lithofacies and palaeo-tectonics needs to be incorporated with the reconstruction maps. Elements should include palaeo-coastlines, depositional facies, denudation events derived from apatite fission track data, volcanicity and active faulting. Also, further maps are needed in order to split up the Tertiary restorations with additional time-slices. If possible, displays for 30, 20, 15 and 5 Ma should be added to the map set. In this somewhat unusual case, it is the Tertiary time-slices that are more difficult to compile than the older ones, perhaps because of the poorer dating of events in inland, non-marine environments.

Additional stratigraphic compilation is required. Chronostratigraphic sections are needed for Antarctica (previously delayed because of poor data quality), the Perth Basin, the Great South Basin (New Zealand) and the Lord Howe Rise. The stratigraphic database for other basins also needs formalising.

A more detailed examination is proposed, centred on SE Australia, of the relationship between basin stratigraphy, tectonics, denudation events, landscape development, drainage evolution and plate tectonic events. The intention would be to compile the Tertiary stratigraphic successions for all the thin inland basins and then to plot the elements listed above on expanded versions of the reconstruction maps for the area between Sydney, the Gawler Craton and the South Tasman Rise. This area has the greatest data density in the region and could be an ideal laboratory for establishing the links between dynamic geomorphology and stratigraphy.

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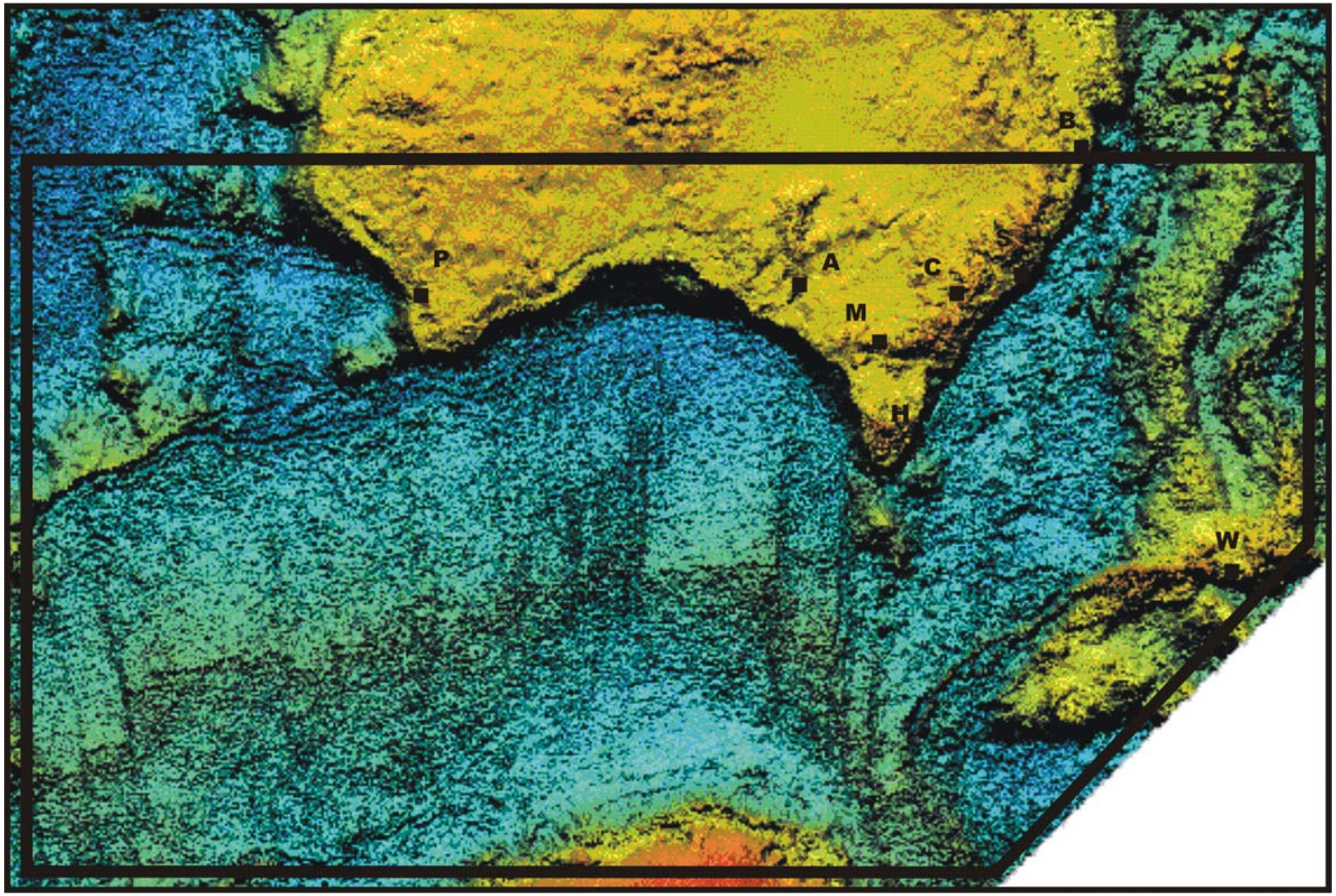

Figure 1: Location Map

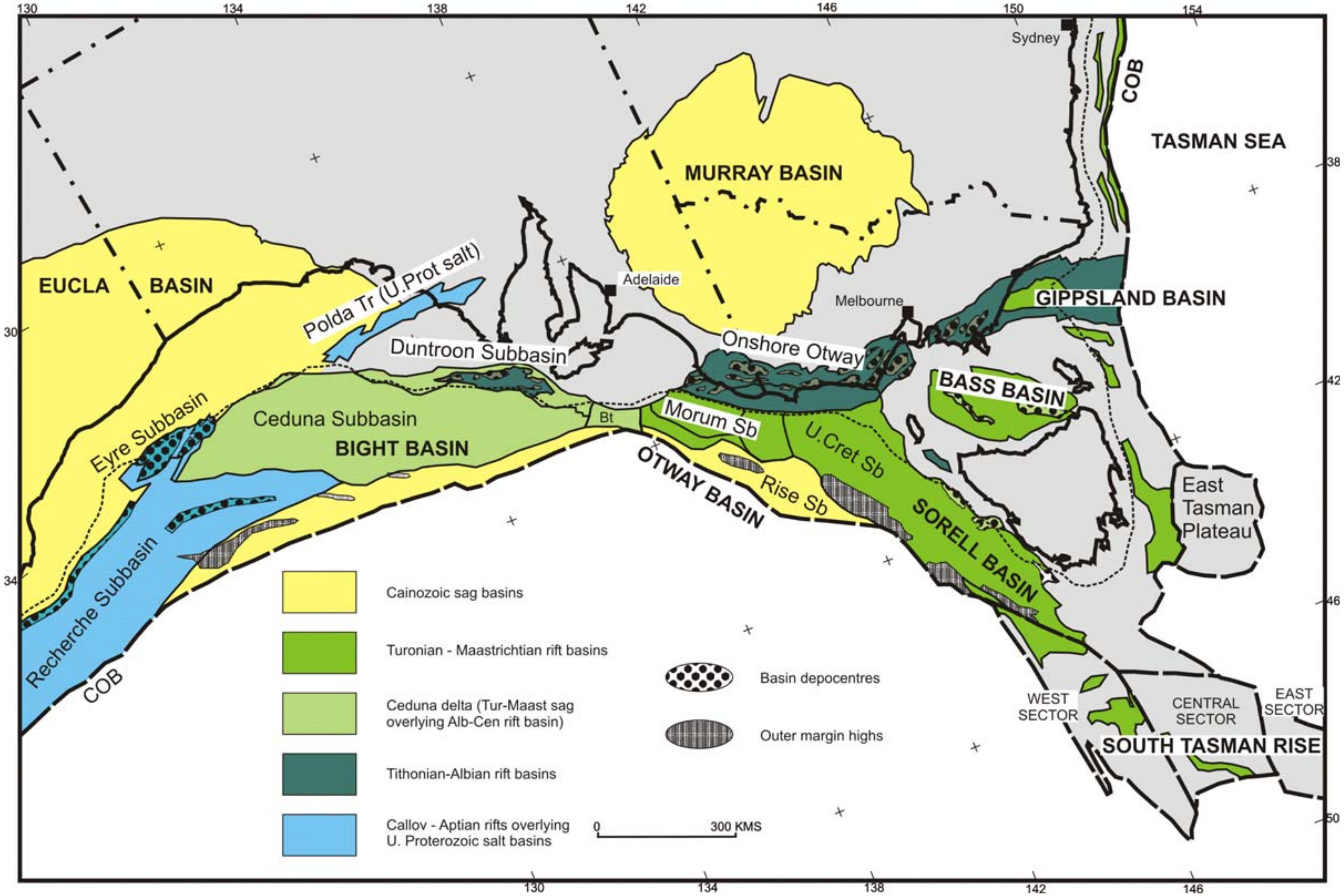

Figure 2: Structural Elements

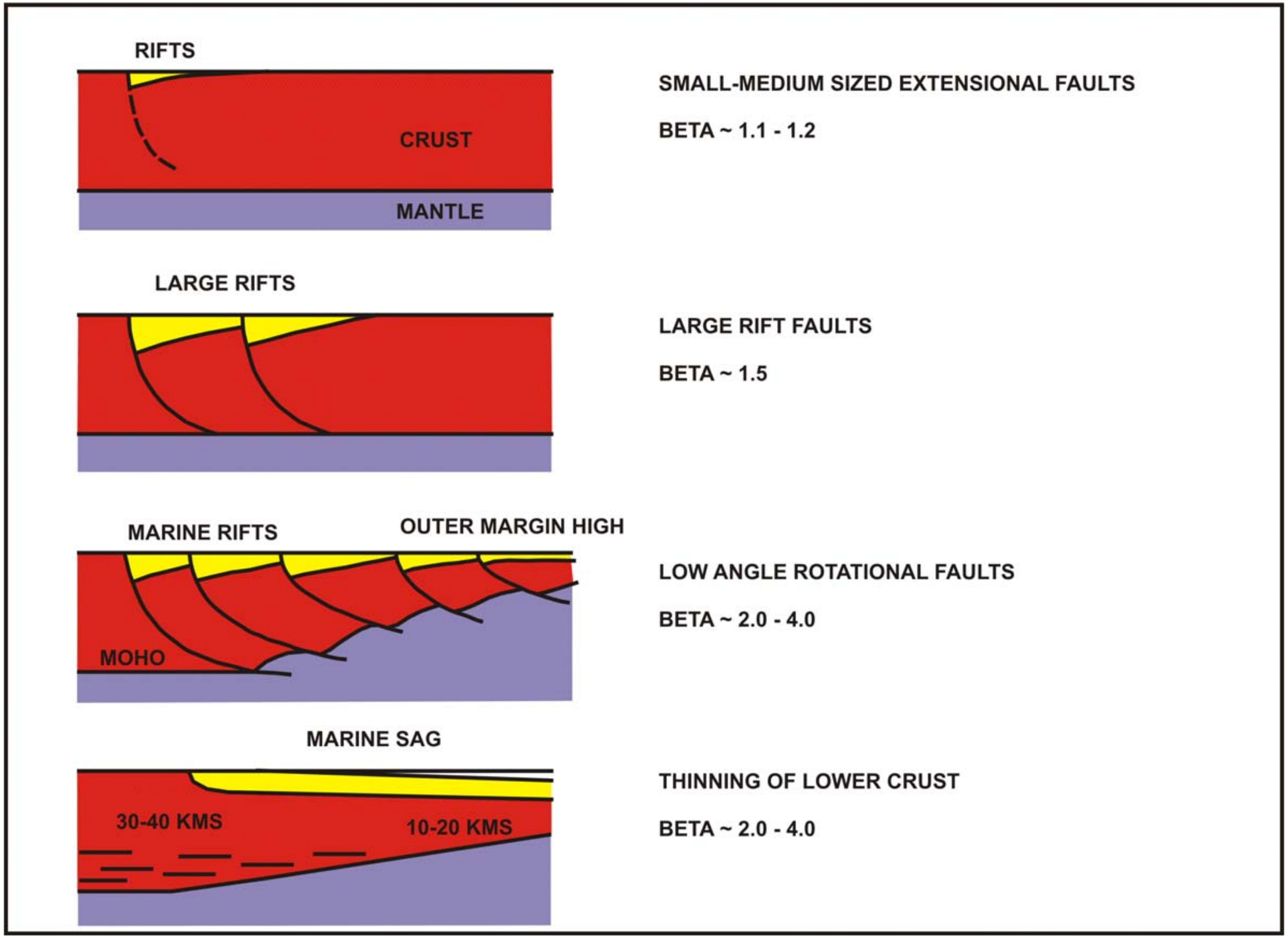

Figure 3: Thinning mechanisms for continental crust

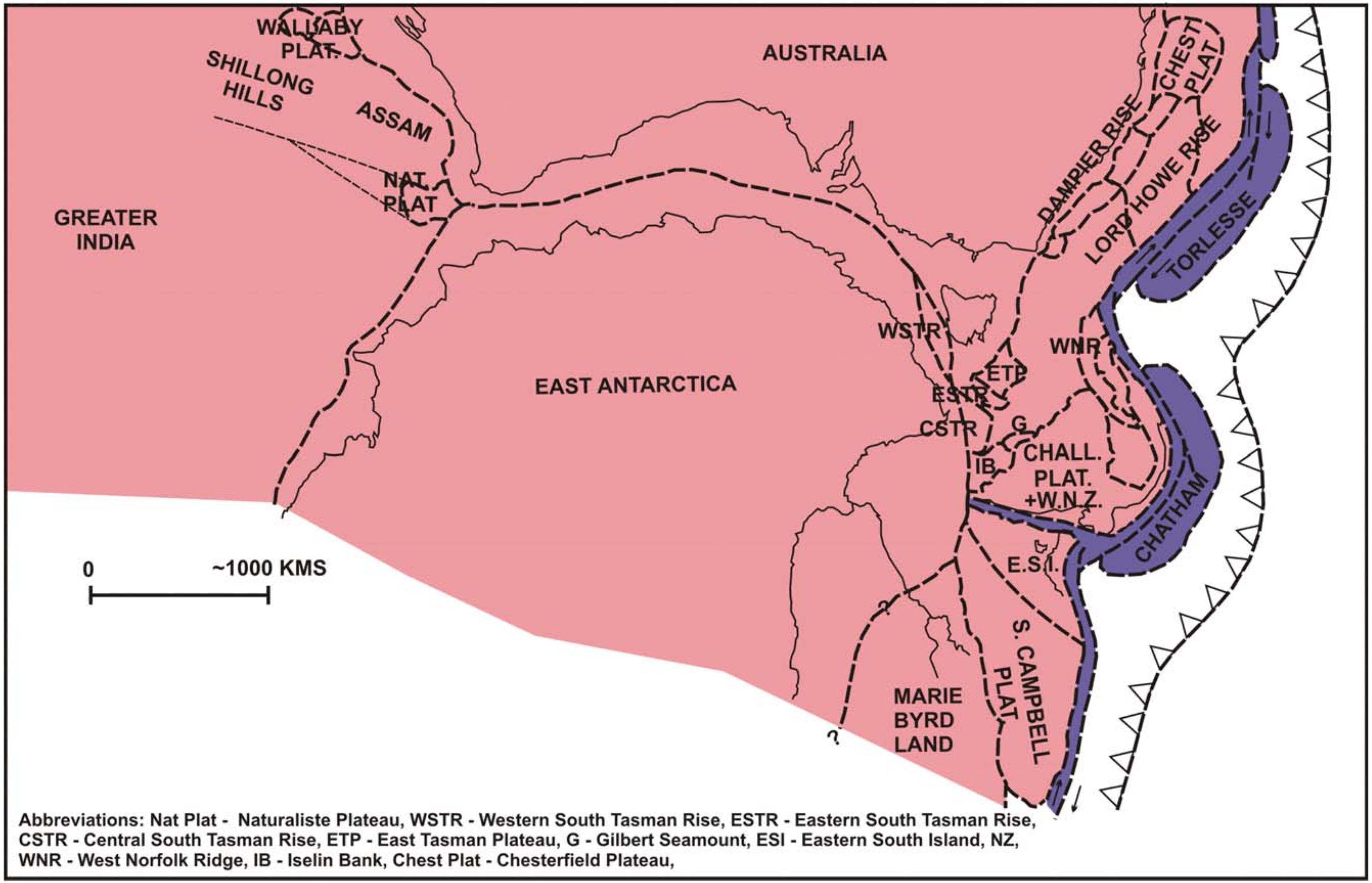

Figure 4: Plate outline in the Late Jurassic

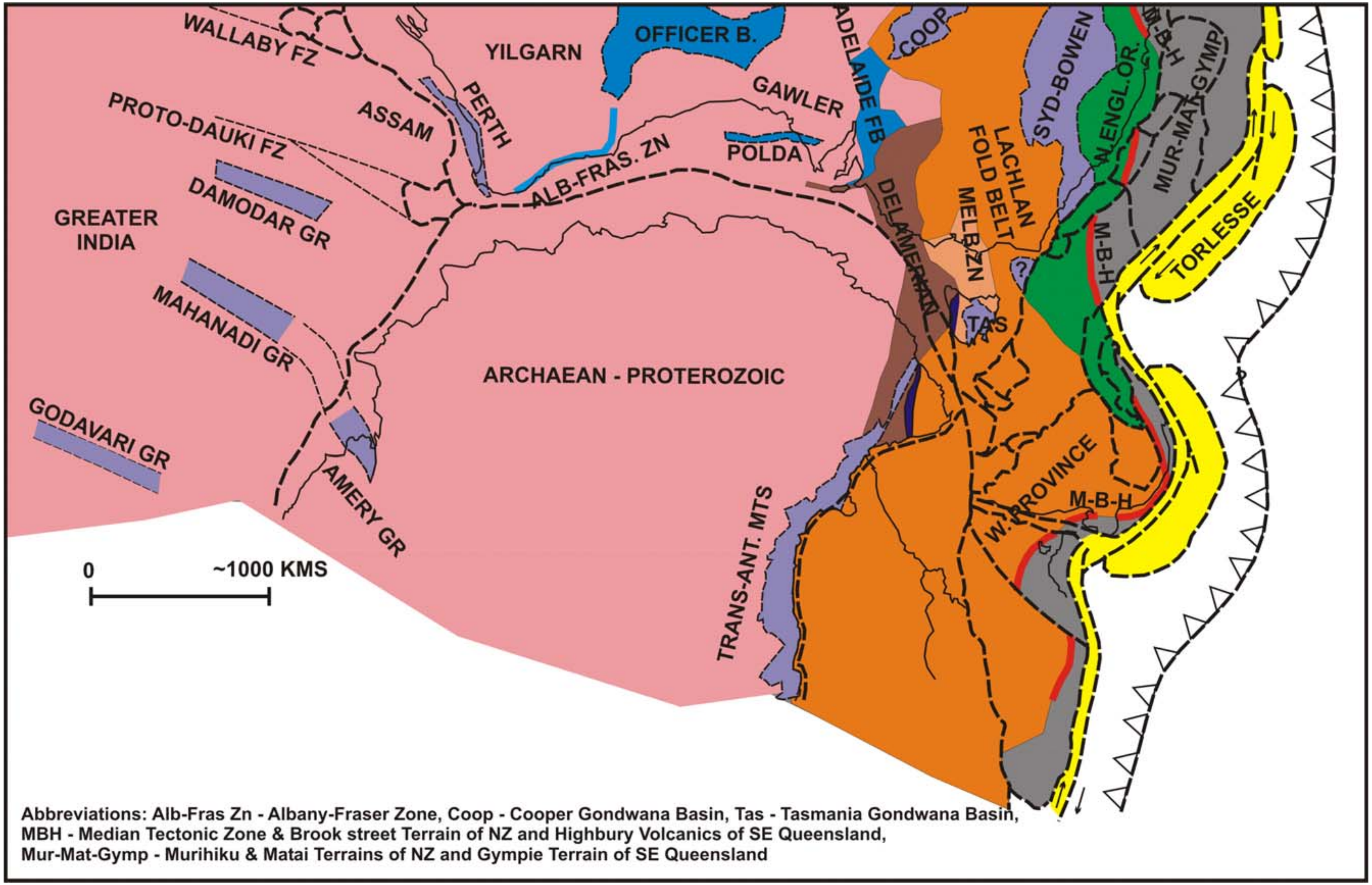

Figure 5: Pre-Jurassic terrain reconstruction

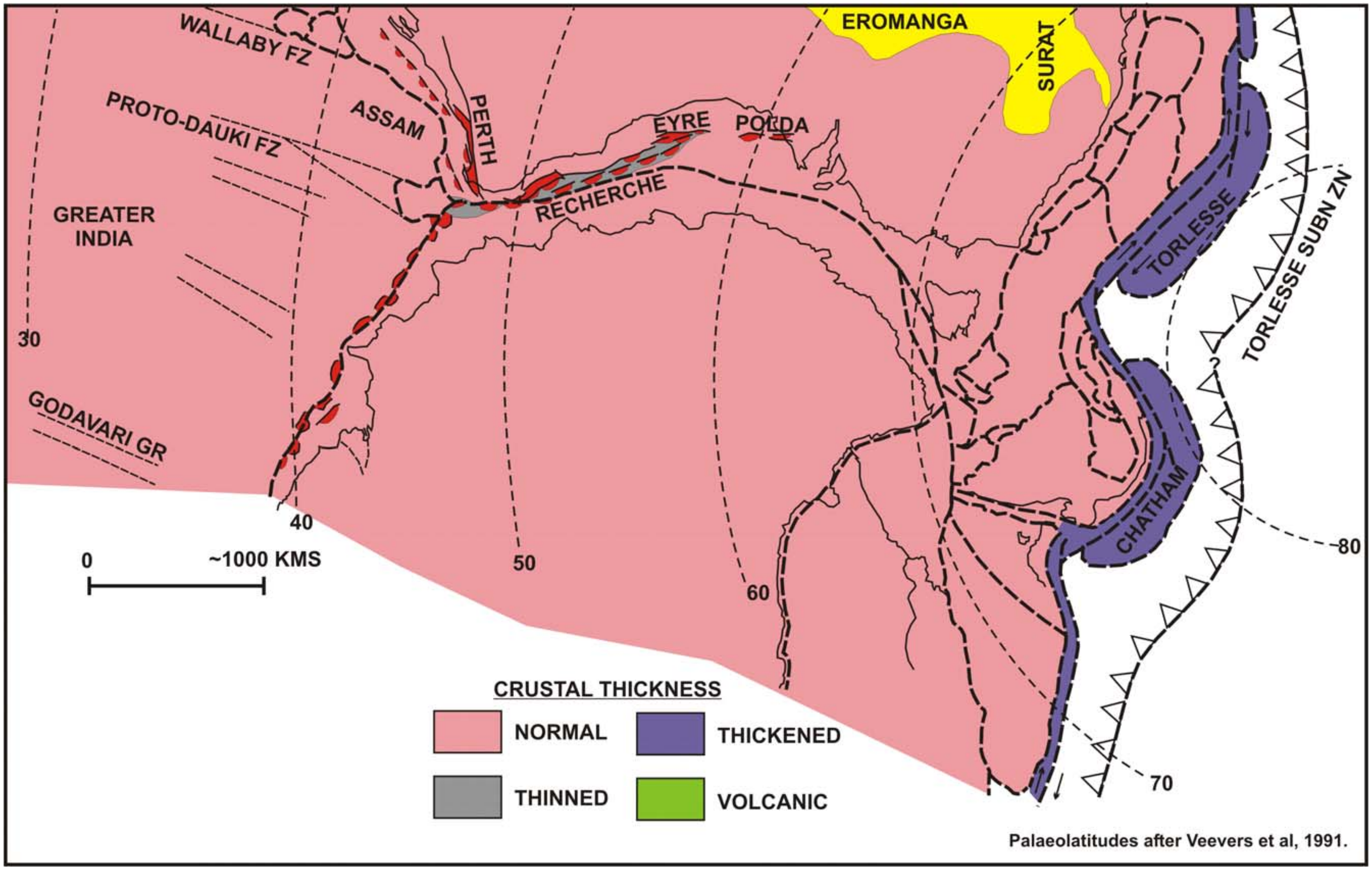

Figure 6: Middle Oxfordian 155 Ma

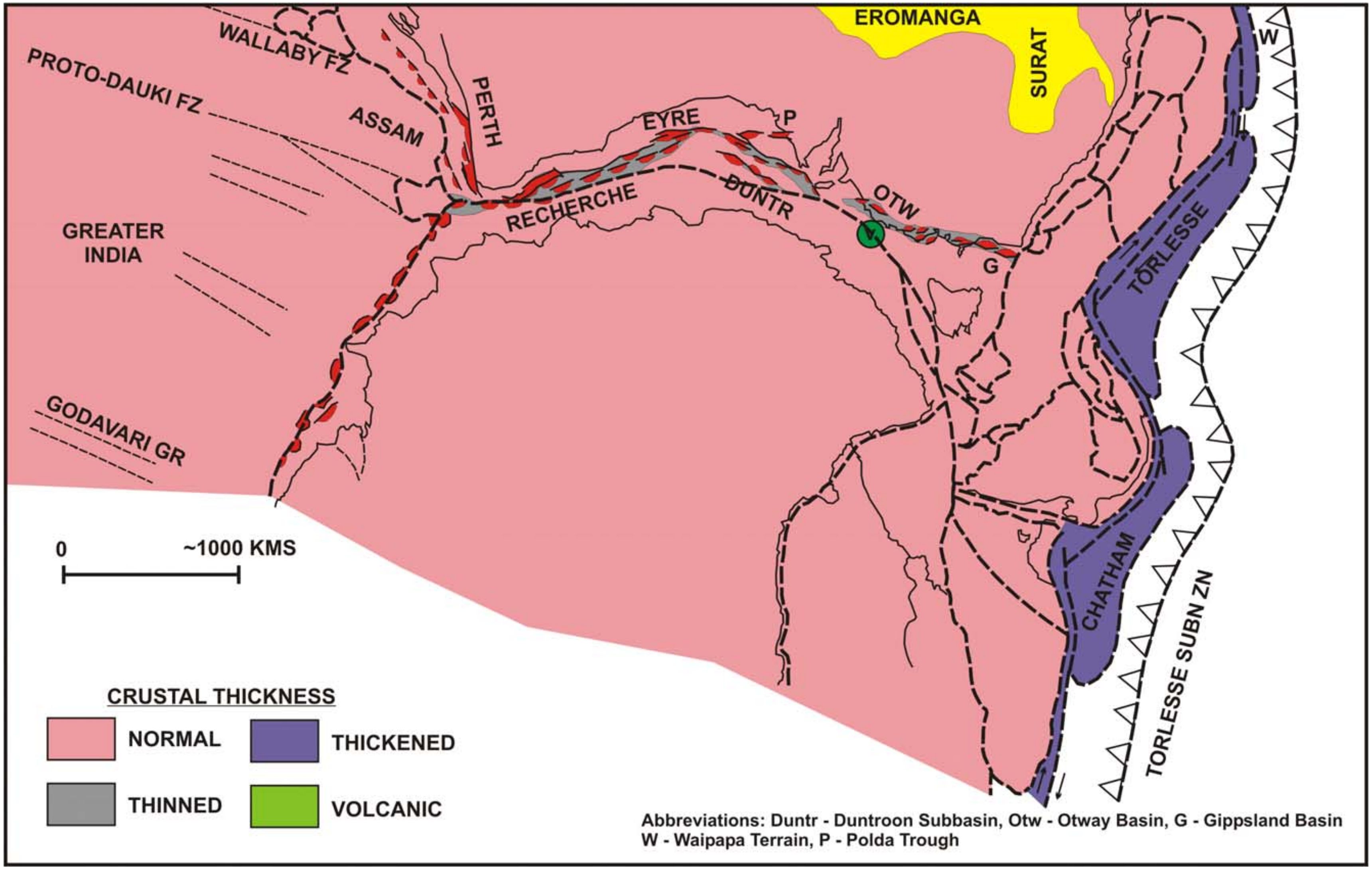

Figure 7: Early Tithonian 145 Ma

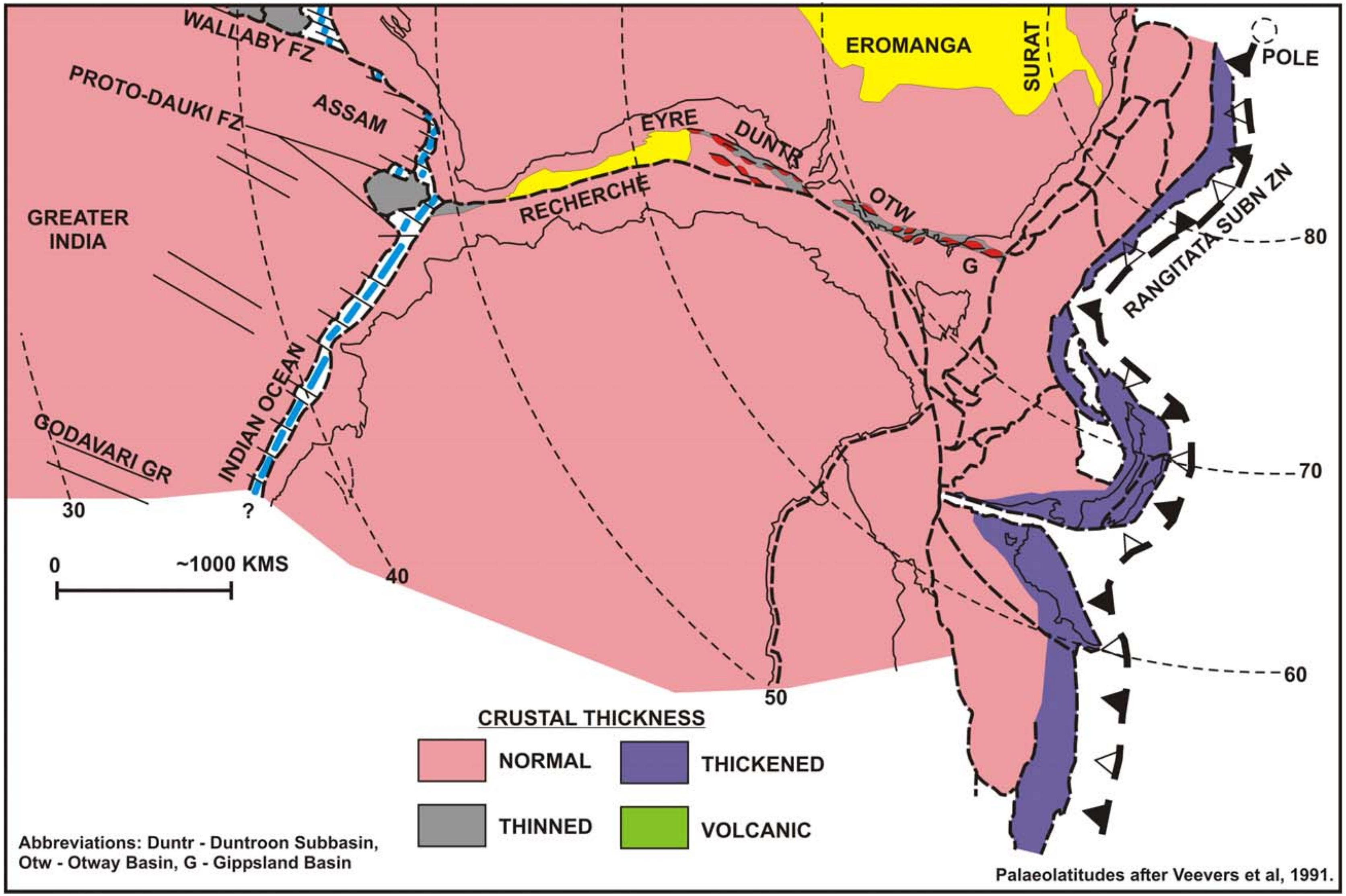

Figure 8: Valanginian/Hauterivian boundary 135 Ma

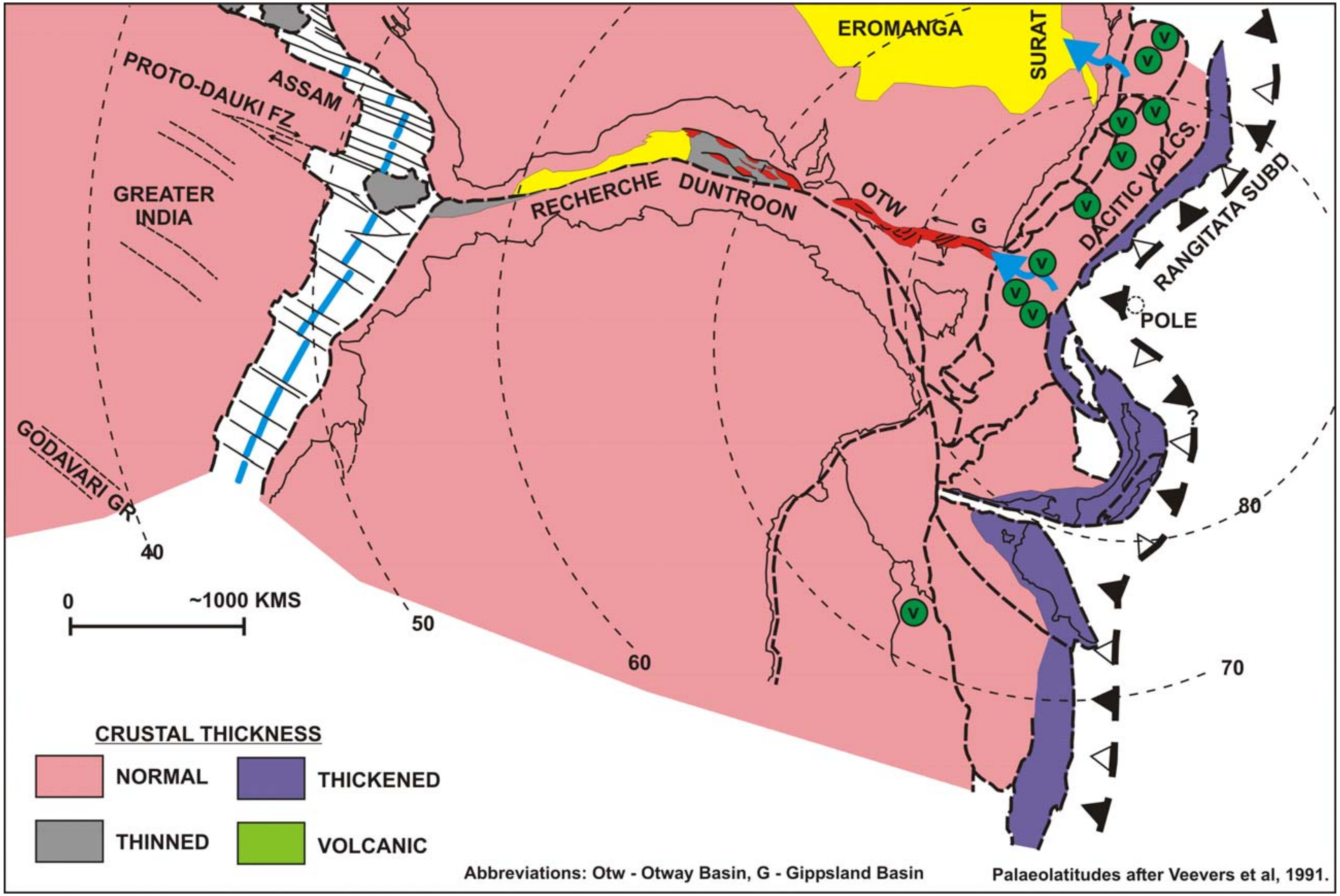

Figure 9: Middle Barremian 120 Ma

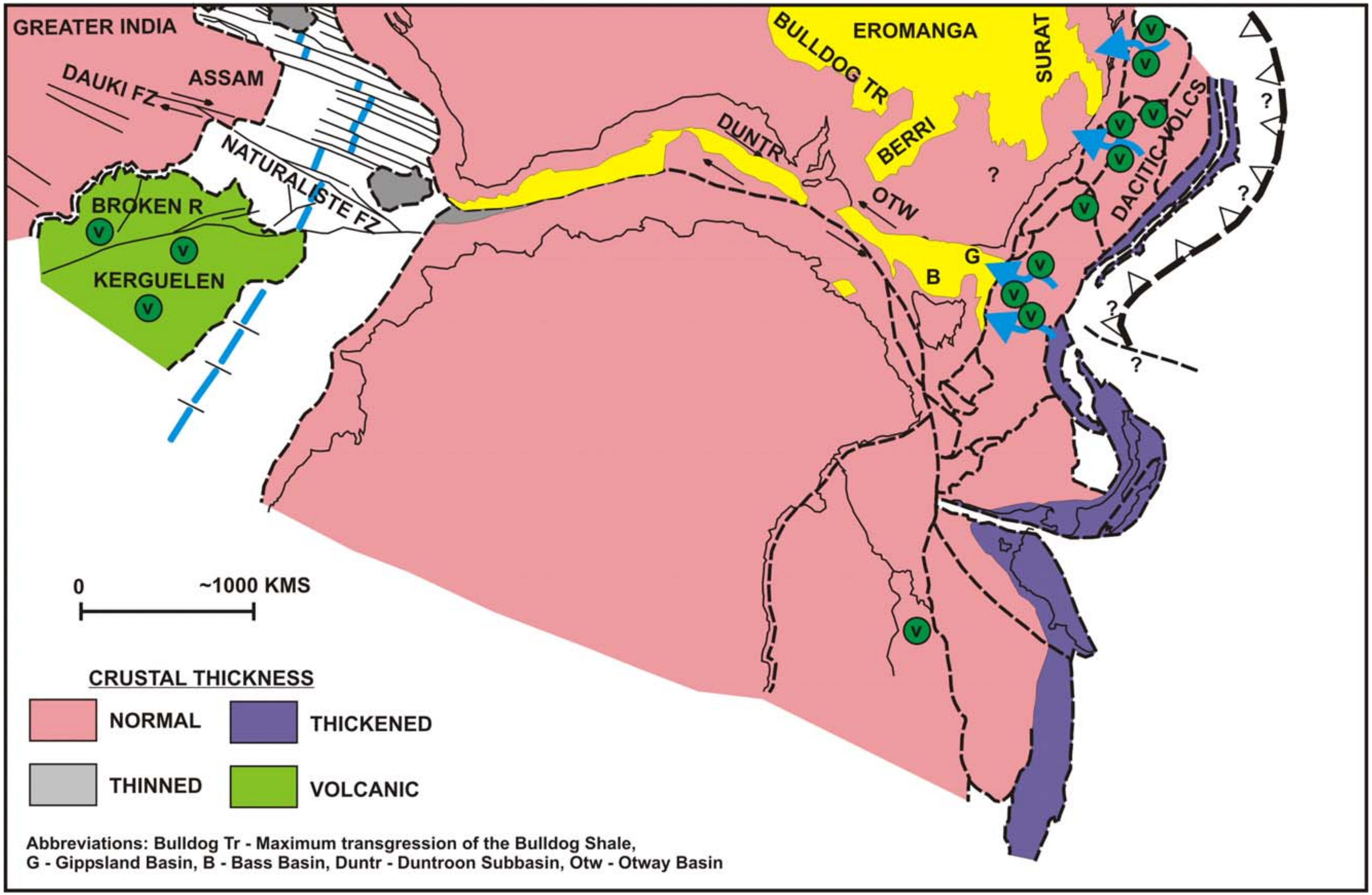

Figure 10: Late Aptian 110 Ma

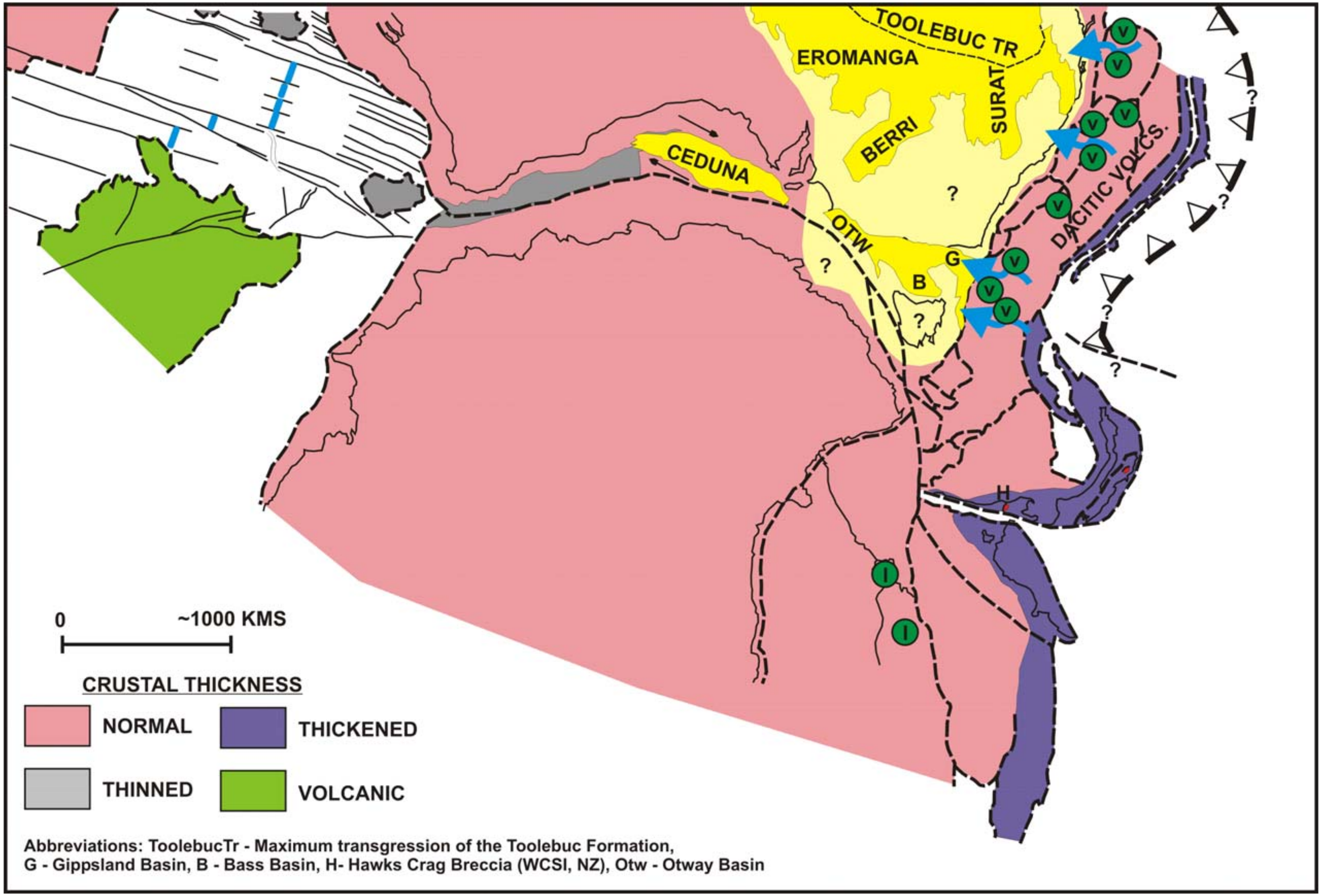

Figure 11: Late Albian 100 Ma

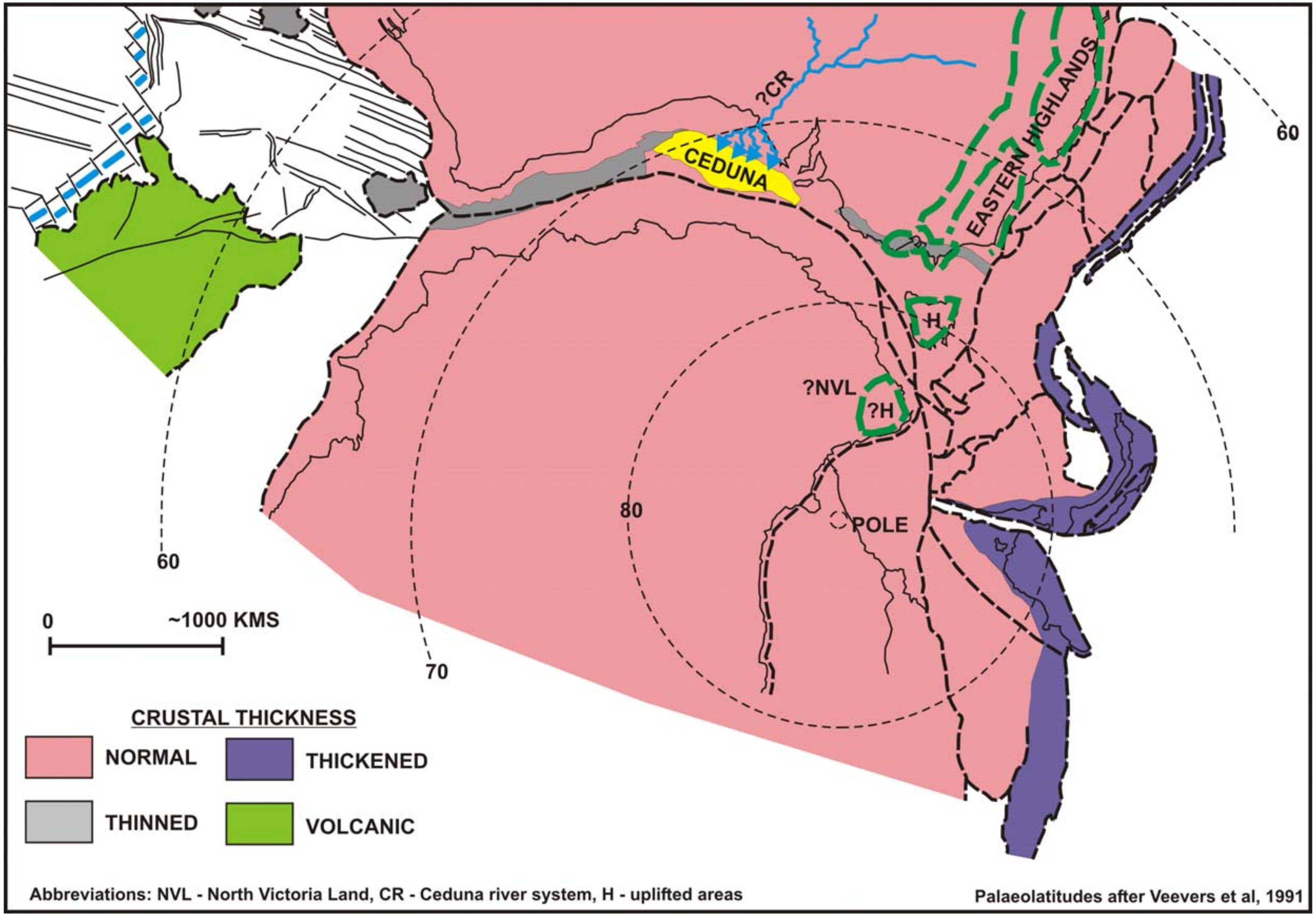

Figure 12: Middle Cenomanian 95 Ma

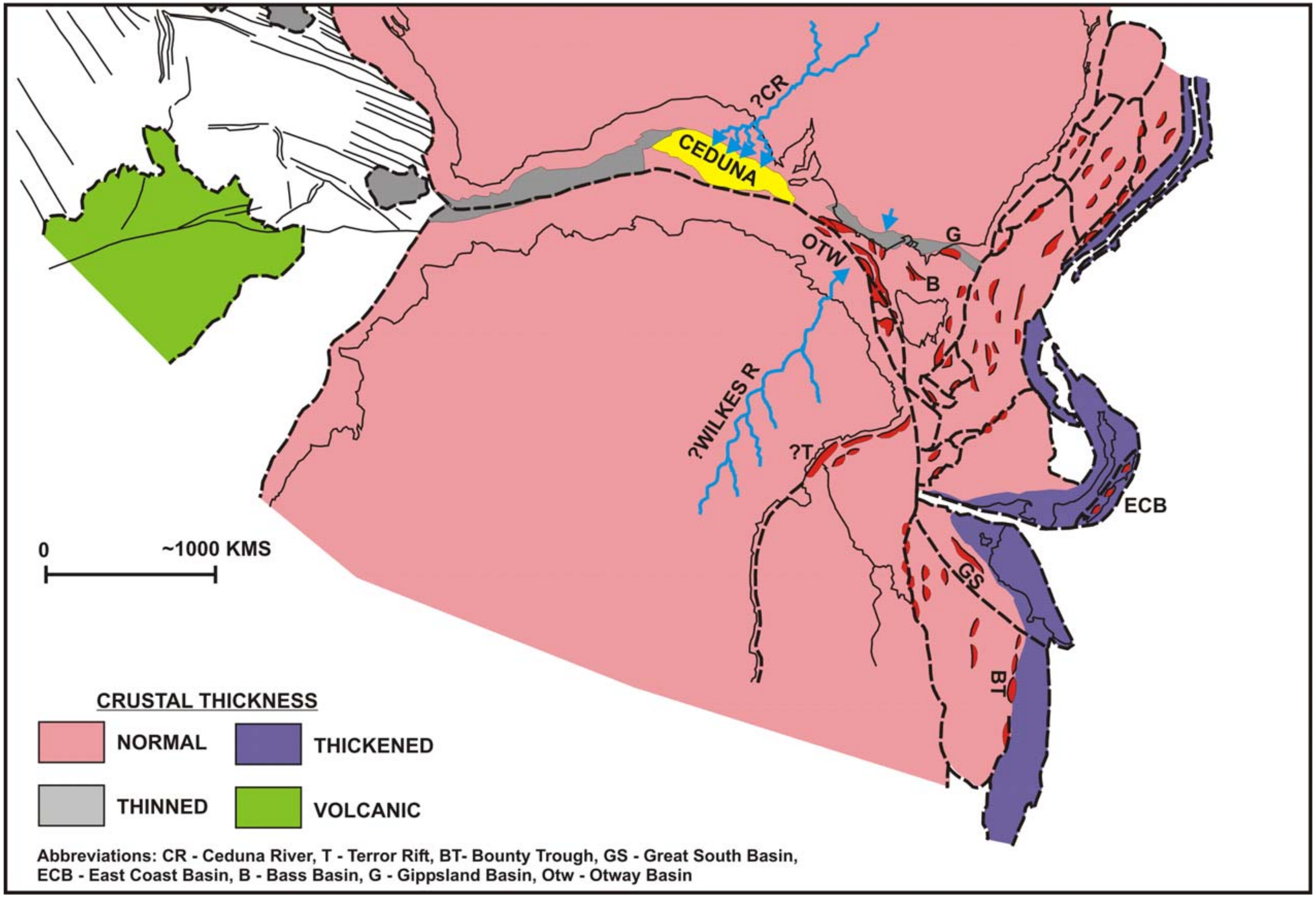

Figure 13: Turonian 90 Ma

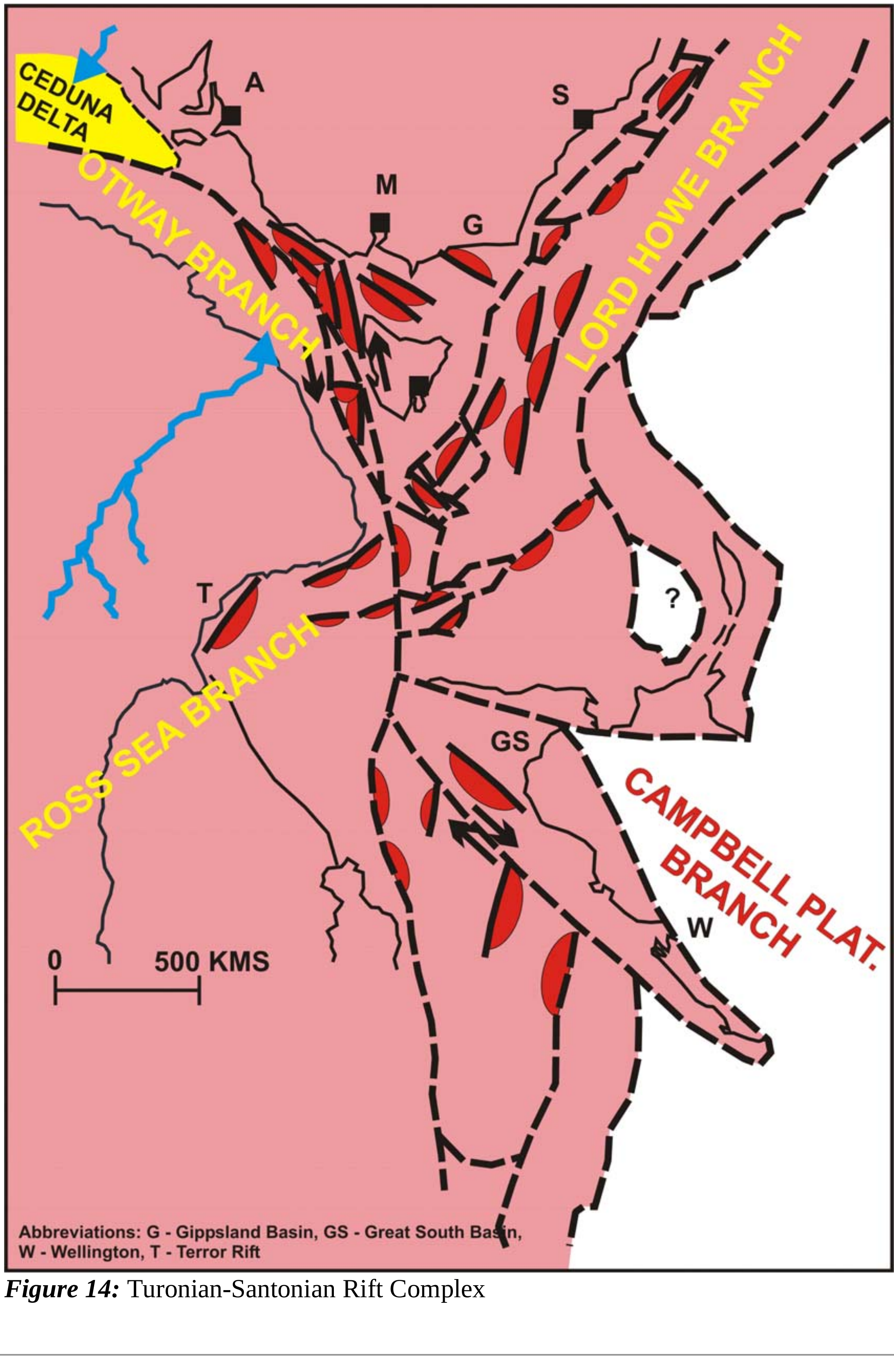

Figure 14: Turonian-Santonian Rift Complex

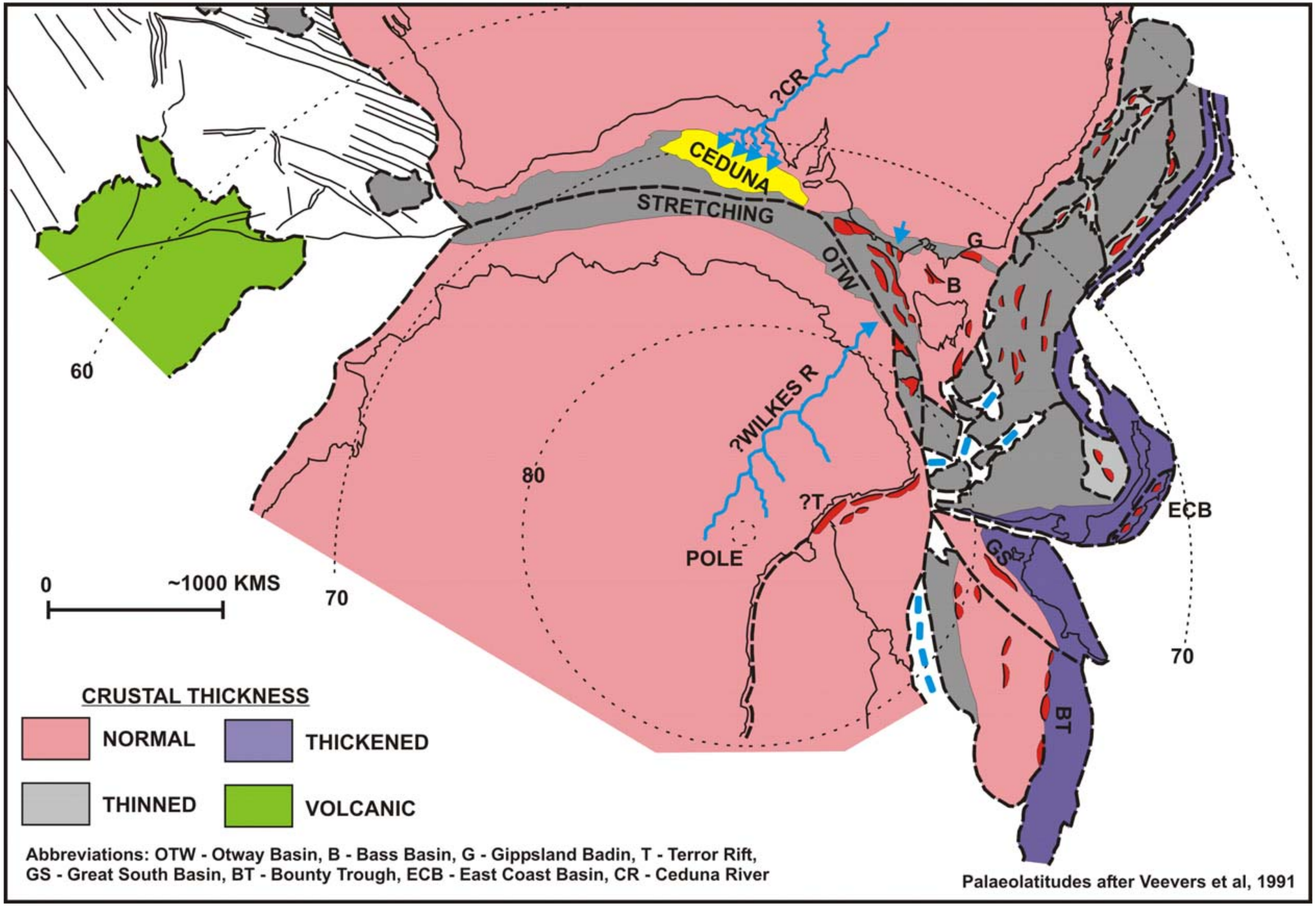

Figure 15: Middle Santonian 85 Ma

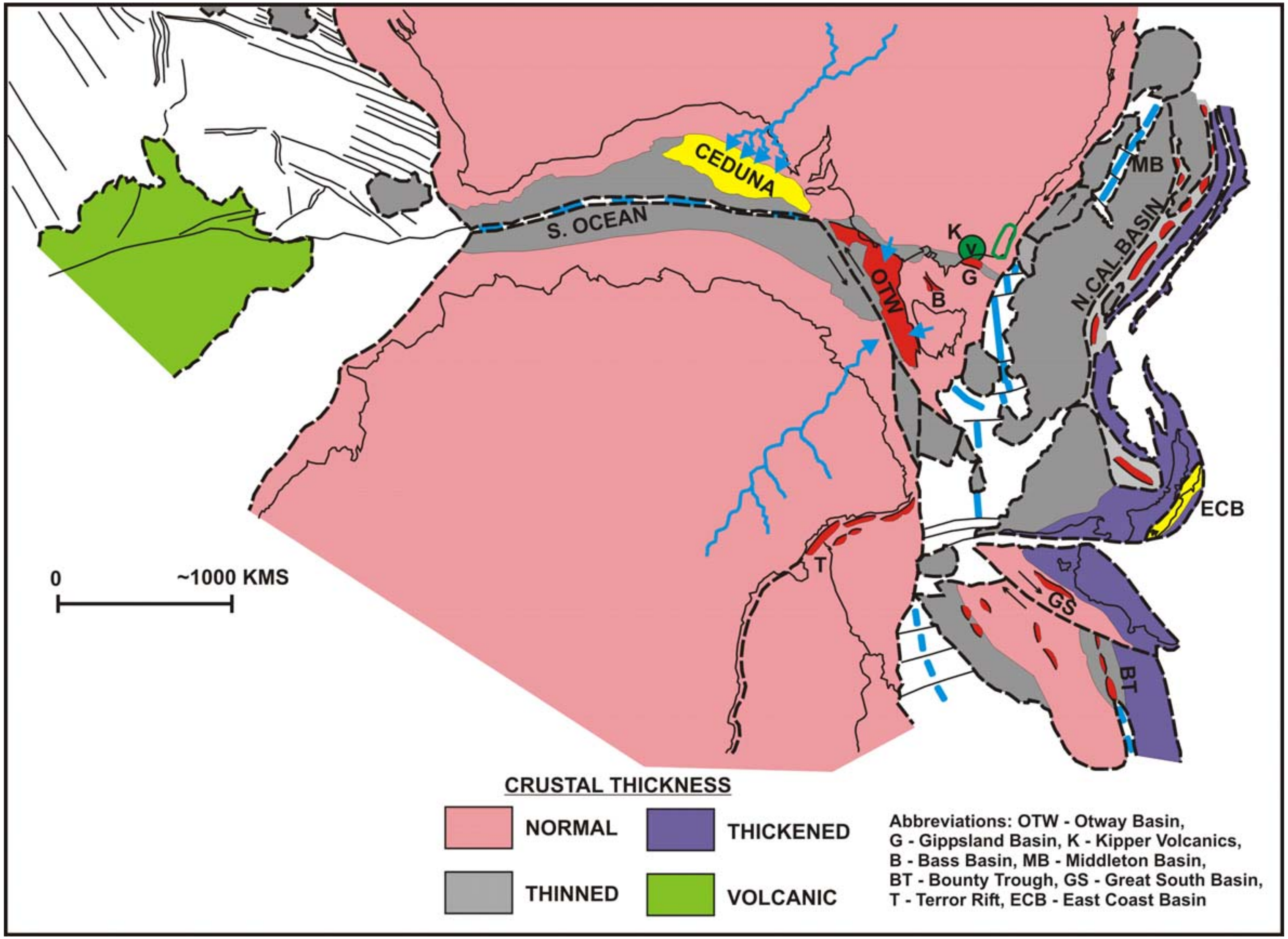

Figure 16: Early Campanian 80 Ma

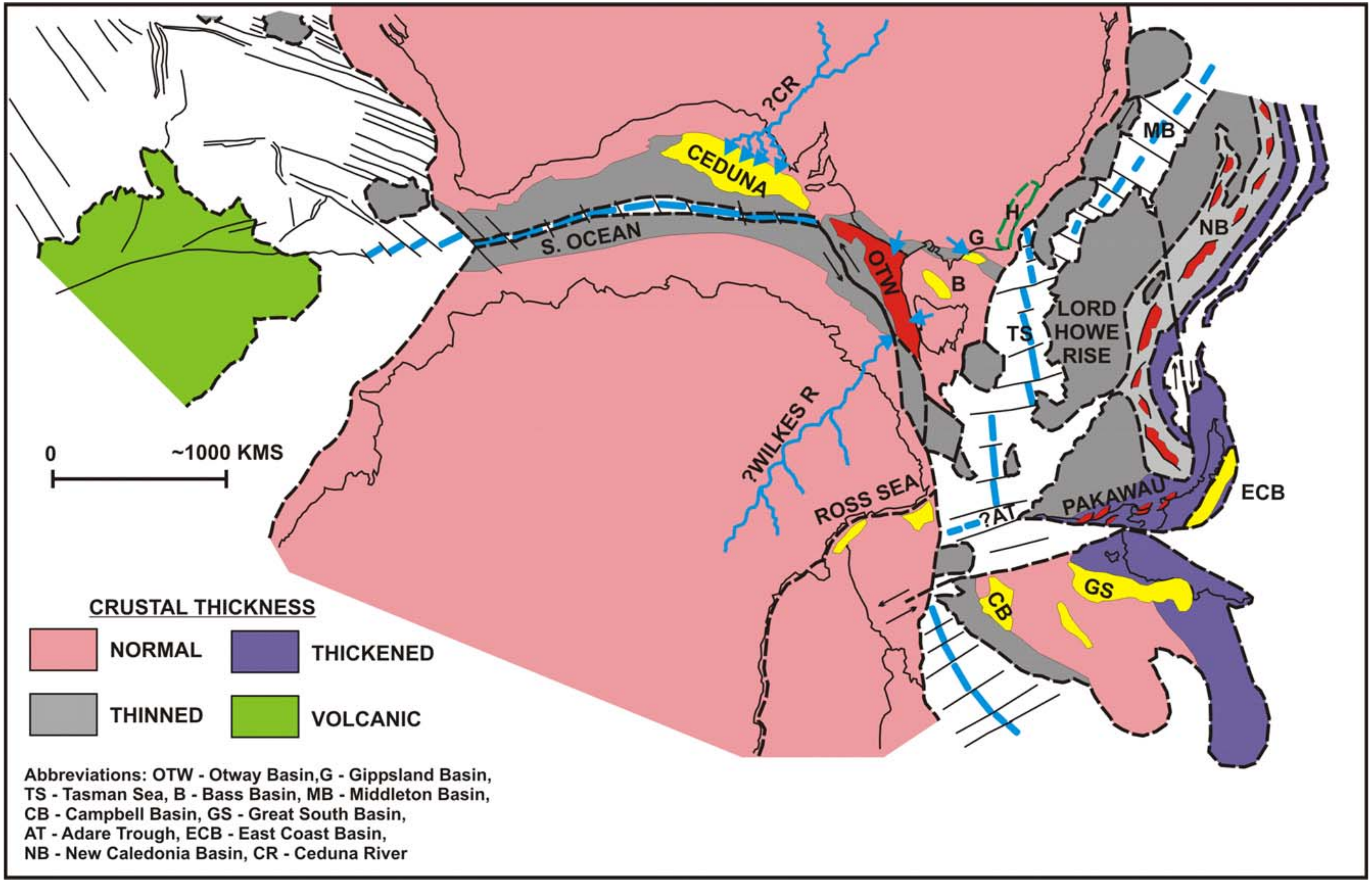

Figure 17: Late Campanian 75 Ma

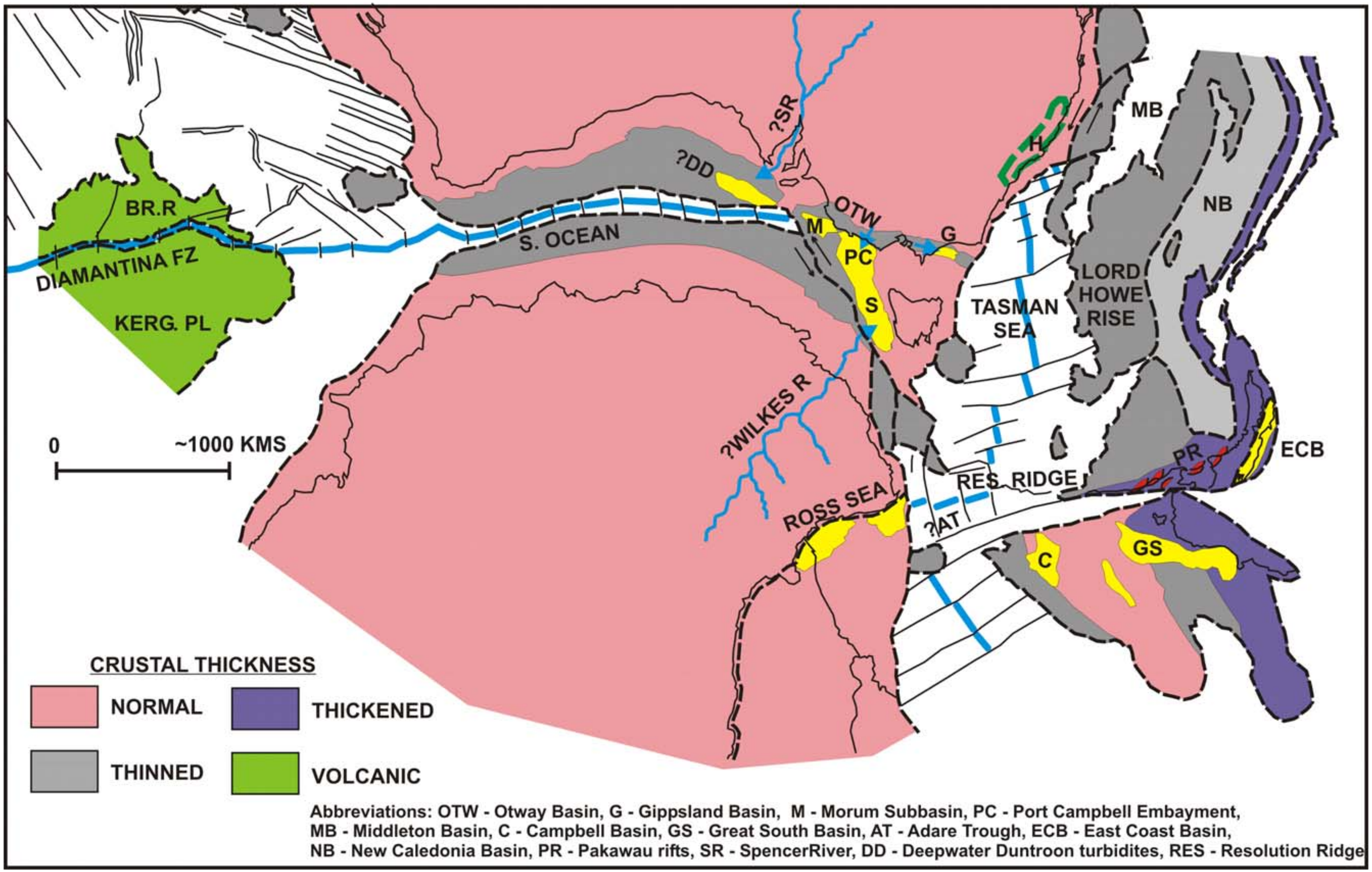

Figure 18: Cretaceous-Tertiary Boundary 65 Ma

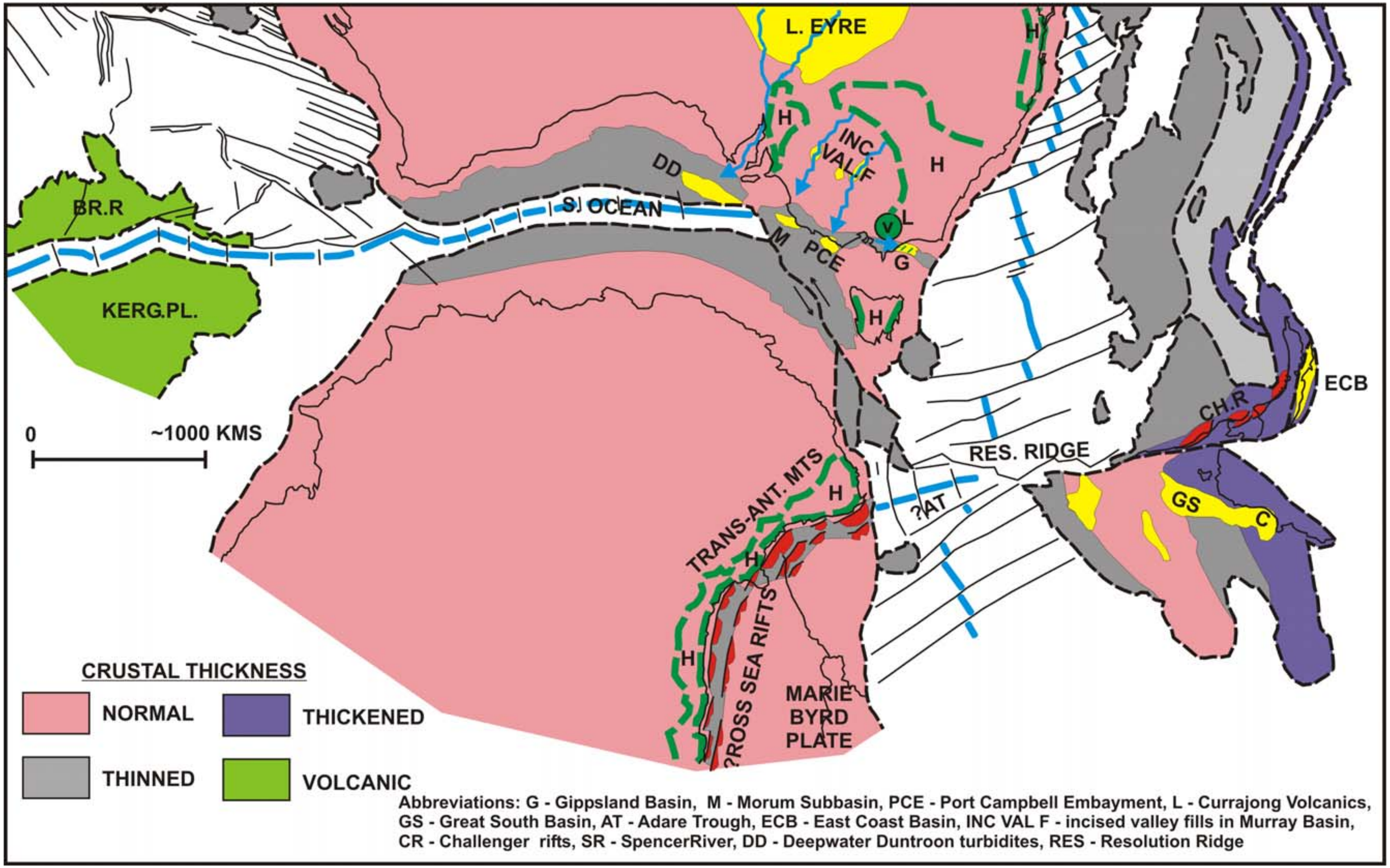

Figure 19: Palaeocene-Eocene Boundary 55 Ma

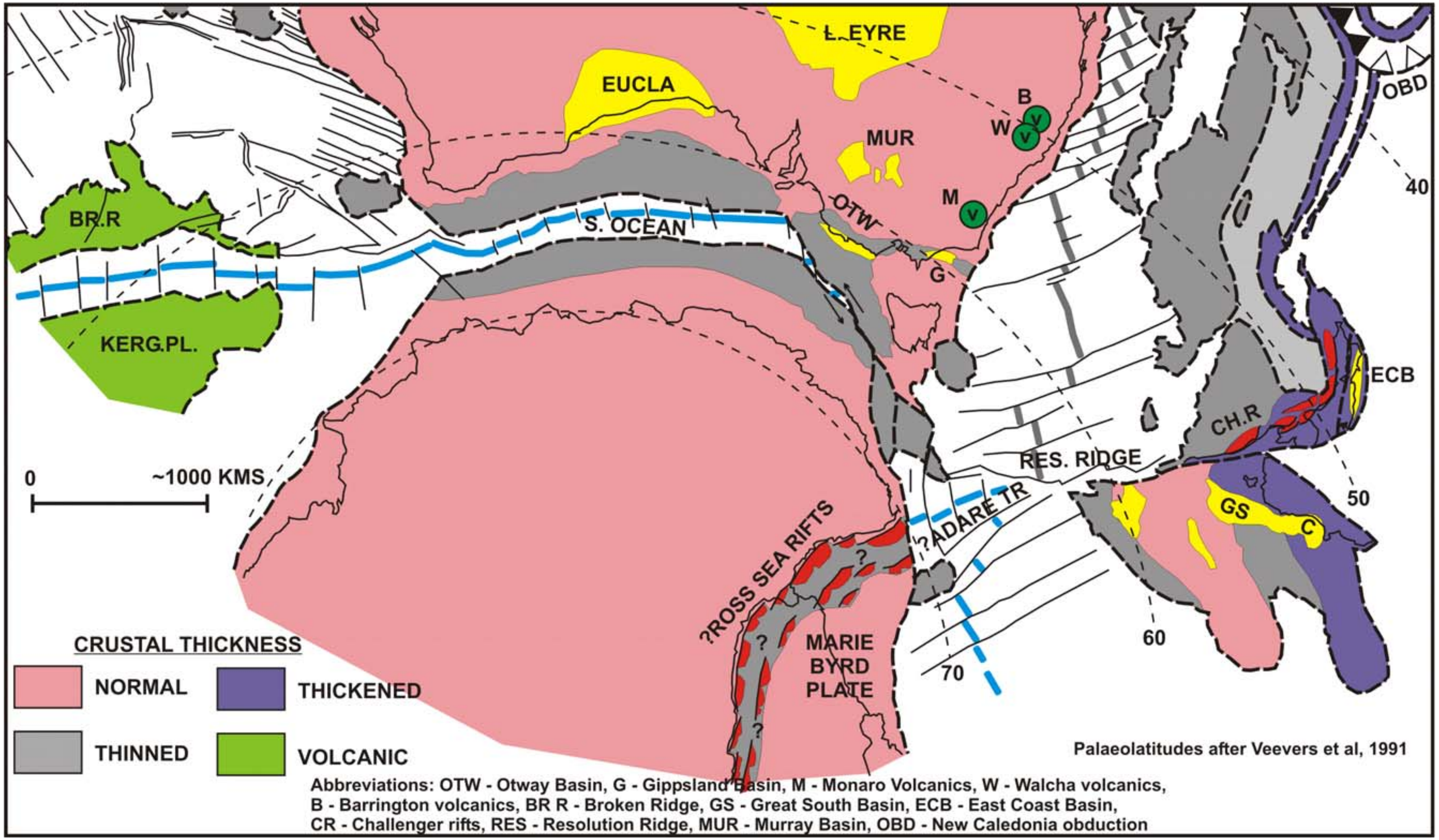

Figure 20: Middle Eocene 45 Ma

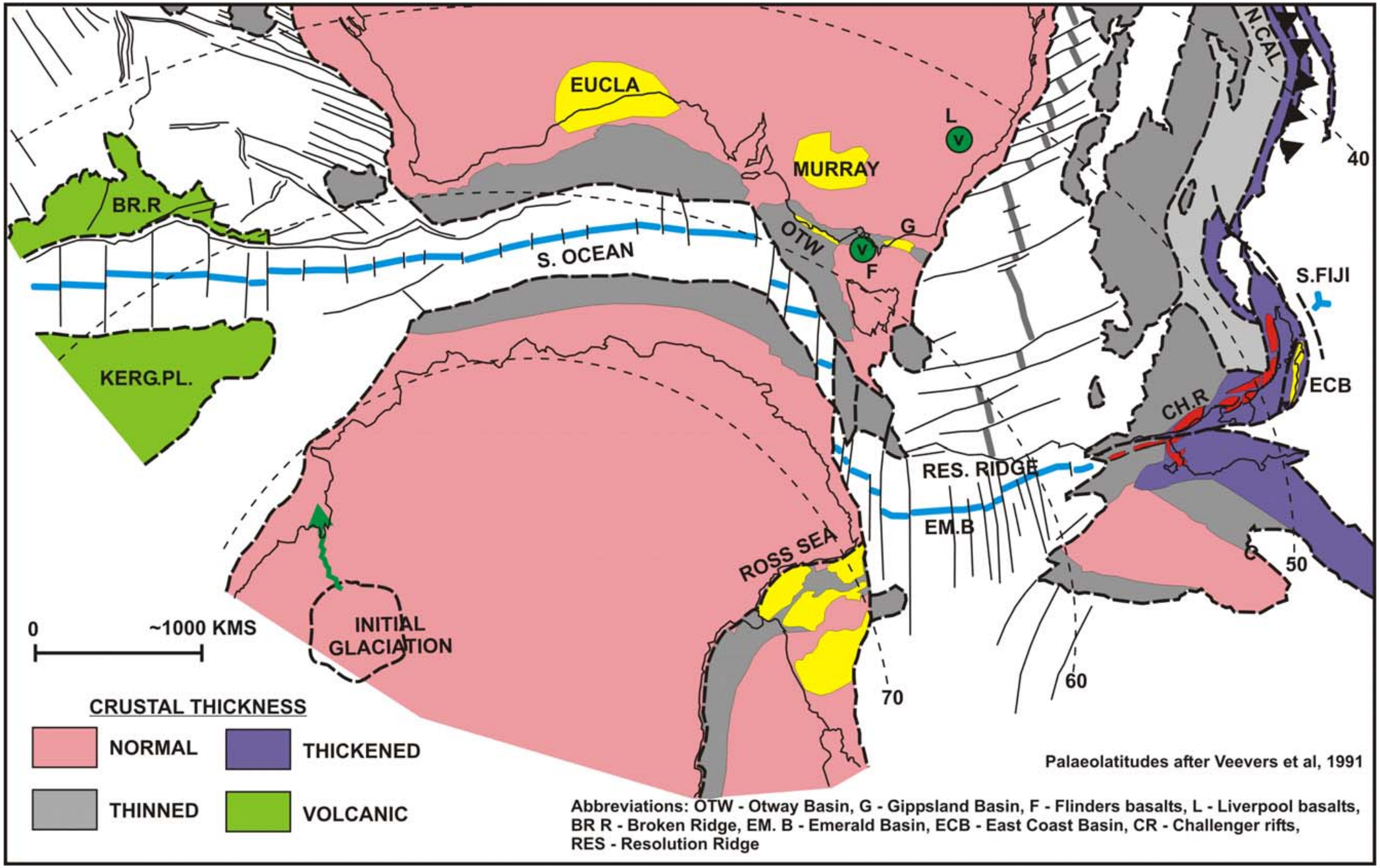

Figure 21: Uppermost Eocene 35 Ma

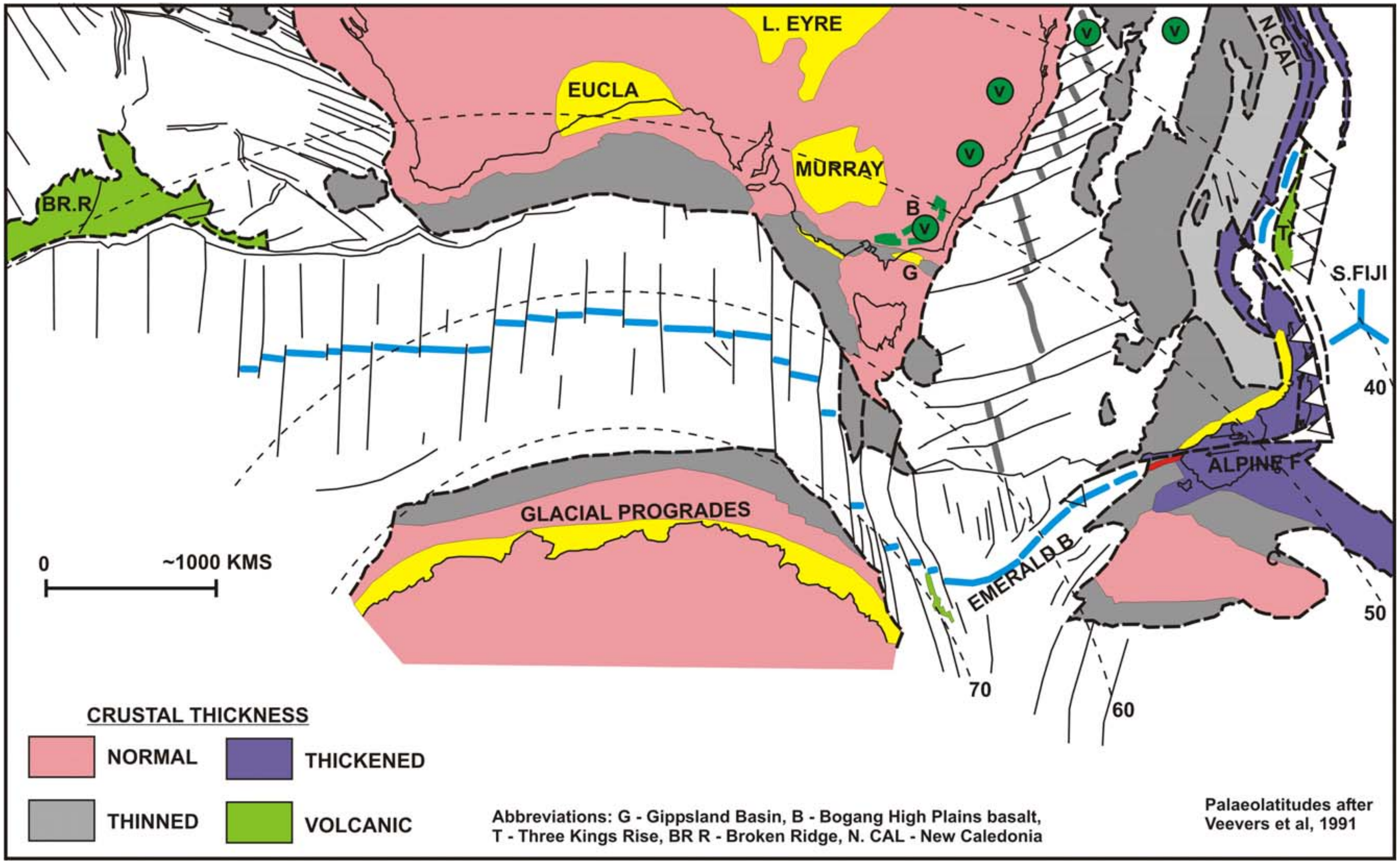

Figure 22: Uppermost Oligocene 25 Ma

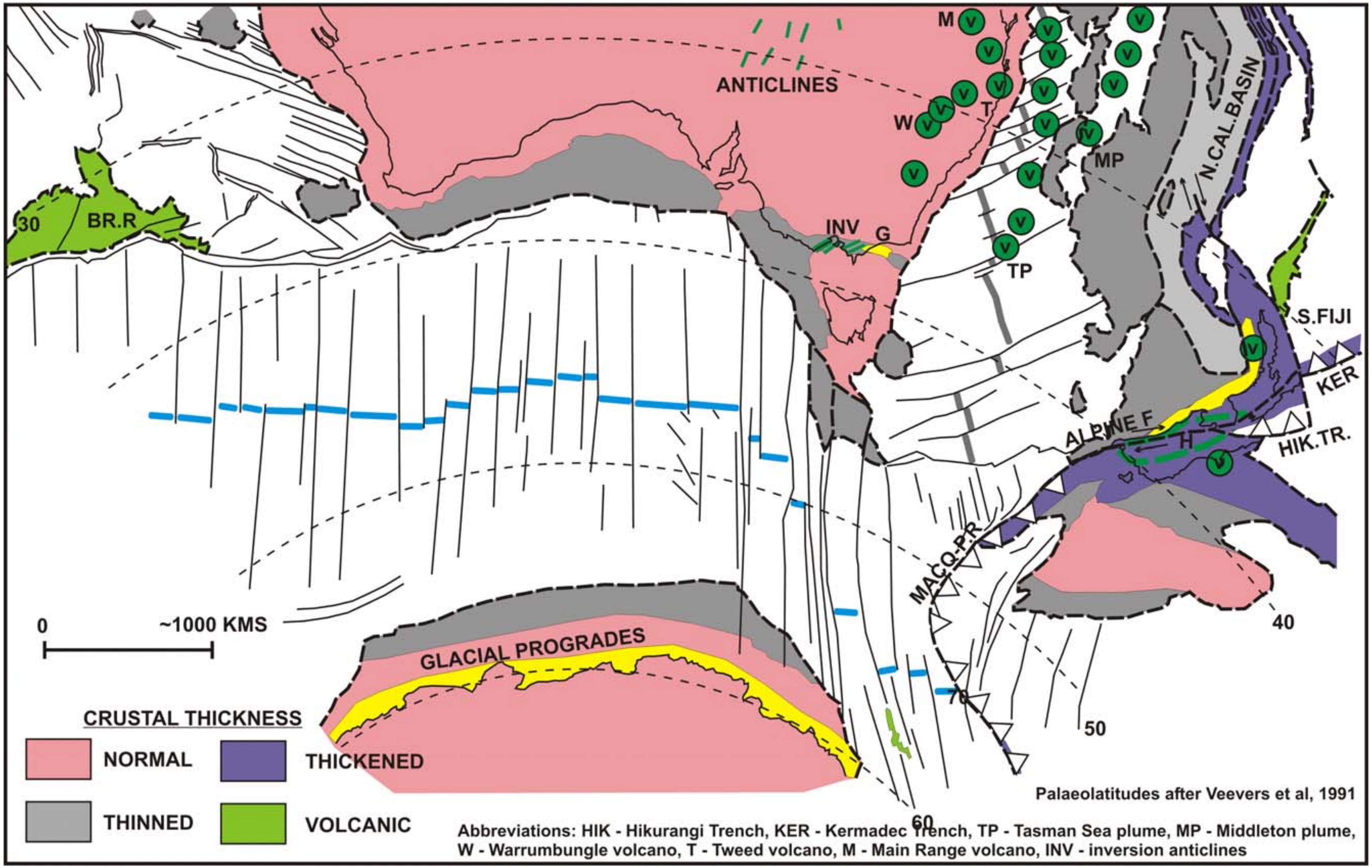

Figure 23: Late Miocene 10 Ma

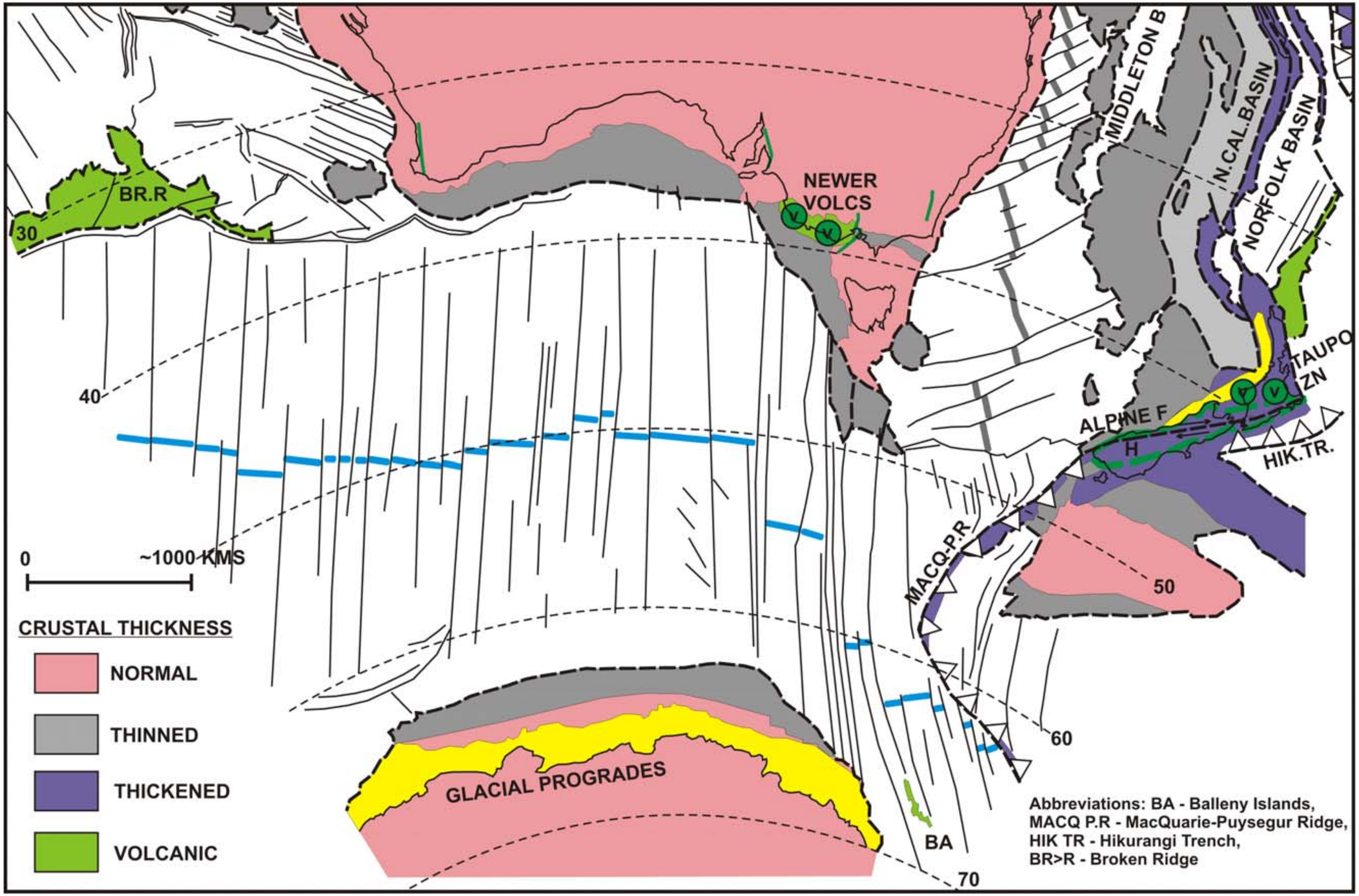

Figure 24: Present Day 0 Ma

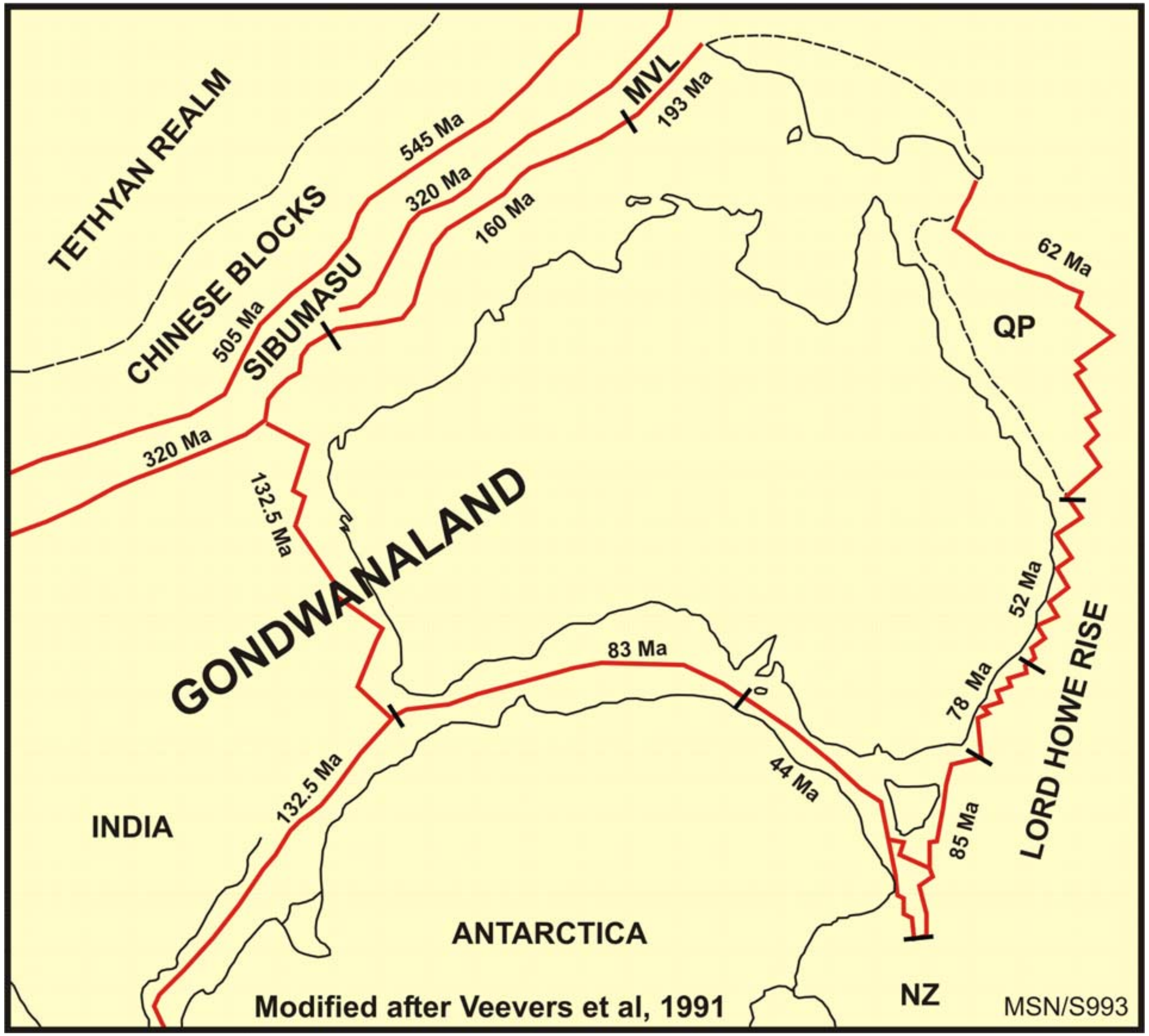

Figure 25: Australia's Breakup History


ENCLOSURE 1
STRUCTURAL ELEMENTS MAP OF THE SOUTHERN AUSTRALIAN MARGIN
Geoscience Australia
Chief Executive Officer: Dr Neil Williams
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This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.
Australian Government
Geoscience Australia
MUSGRAVE BLOCK
OFFICER BASIN
EUCLA BASIN
GAWLER CRATON
YILGARN CRATON
CEDUNA SUB BASIN
BIGHT BASIN
RECHERCHE SUB-BASIN
BREMER BASIN
DUNTROON SUB-BASIN
OTWAY BASIN
MURRAY BASIN
DARLING BASIN
SYDNEY BASIN
GIPPSLAND BASIN
BASS BASIN
SORELL BASIN
EAST TASMAN PLATEAU
SOUTH TASMAN RISE
LEGEND:-
THIN THICK
Mainly Tertiary Sedimentary Basins
Mainly Upper Cretaceous Sedimentary Basins
Mainly Lower Cretaceous Sedimentary Basins
Mainly Upper Jurassic Sedimentary Basins
Major normal fault
Reverse and thrust faults
Hingelines and monoclinal flexures
Anticline and high areas
Continent - Ocean boundary
Half grabens and other basin depocentres (age of fill shown)
Depositional axis
Palaeo - drainage system
Submarine canyon
Volcanic seamount
Oceanic magnetic anomaly
PRINCIPAL AGE OF BASIN FILL:-
UP Є - Late Proterozoic
LPz - Early Palaeozoic
SD - Silurian - Early Devonian
DC - Late Devonian - Early Carboniferous
UPz - Late Carboniferous, Permian and Triassic
UJ - LK - Uppermost Jurassic - Cretaceous
LK1 - Neocomian (Crayfish Gp and Eq)
LK2 - Aptian - Albian (Otway Gp and Eq)
UK - Late Cretaceous
Cz - Cainozoic
SOURCE OF MAPPING:-
- ONSHORE Pz (Plus Base Map) - BMR Geology Map of Australia, 1:2.5 M, 1976
- OFFSHORE S NSW - Colwell et al, 1993
- GIPPSLAND BASIN - Willcox et al, 1992, Barton et al, 1992, Gilbert and Hill, 1994, Hill et al, 1998
- SOUTH TASMAN RISE - Exon et al, 1997a
- EAST TASMAN PLATEAU - Exon et al, 1997b
- WEST TASMANIA - Moore et al, 1992, Hill et al, 1997
- BASS BASIN - Gunn et al, 1996, Setiawan, 1998
- ONSHORE OTWAY - Perincek and Cockshell, 1995, Hill et al, 1995, Lavin, 1997
- OFFSHORE OTWAY - Trupp et al, 1994, Cooper, 1995, Luxton et al, 1995, BMR Otway Folio, 1988, Moore et al, 2000
- MURRAY BASIN - Brown, 1989, Brown and Stephenson, 1991
- DARLING BASIN - NSW Dept Min Res, 1995, Alder et al, 1998
- DUNTROON BASIN - BMR Great Australian Bight Folio, 1990, Smith and Donaldson, 1995, Totterdell et al, 2000
- CEDUNA SUB-BASIN - AGSO Southern Margin Frontiers Project, Pers Comm., 1999, Willcox and Stagg, 1990, BMR Great Australian Bight Folio, 1990, Willcox, 1990, Stagg and Willcox, 1992, Totterdell et al, 2000
- POLDA TROUGH - Stagg et al, 1992, BMR Great Australian Bight Folio, 1990
- EYRE SUB-BASIN - Totterdell et al, 2000
- BREMER BASIN, RECHERCHE SUB-BASINS - BMR Great Australian Bight Folio, 1990
- EAST AUSTRALIAN PALAEOZOIC - Wilson STGST Field Guide, 1999 Murray et al, 1998 (Tectonic Map of South Tasman Fold Belt)
- OCEANIC AREAS - Veevers, 1988, 1987, Veevers et al, 1990, Royer and Rollet, 1997, Murray et al, 1997 (Gravity Map of Australia), Borissova and Symonds, 1997 (Basins of Australia)
SCALE 1:2 500 000
0 100 200 KILOMETRES
SIMPLE CONIC PROJECTION WITH TWO STANDARD PARALLELS AT 18° S AND 36° S, CENTRAL MERIDIAN 136° E
AUSTRALIAN GEODETIC DATUM 1966, AUSTRALIAN NATIONAL SPHEROID

ENCLOSURE 2

AUSTRALIA TO ANTARCTICA: AGE OF OCEANIC CRUST

This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.

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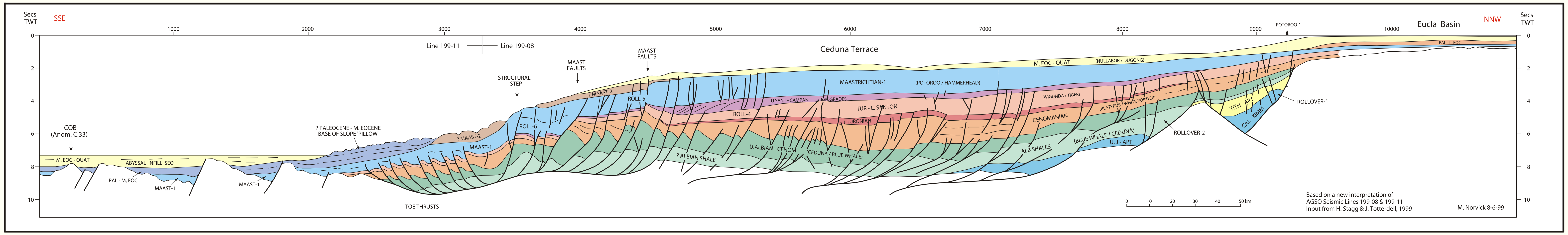
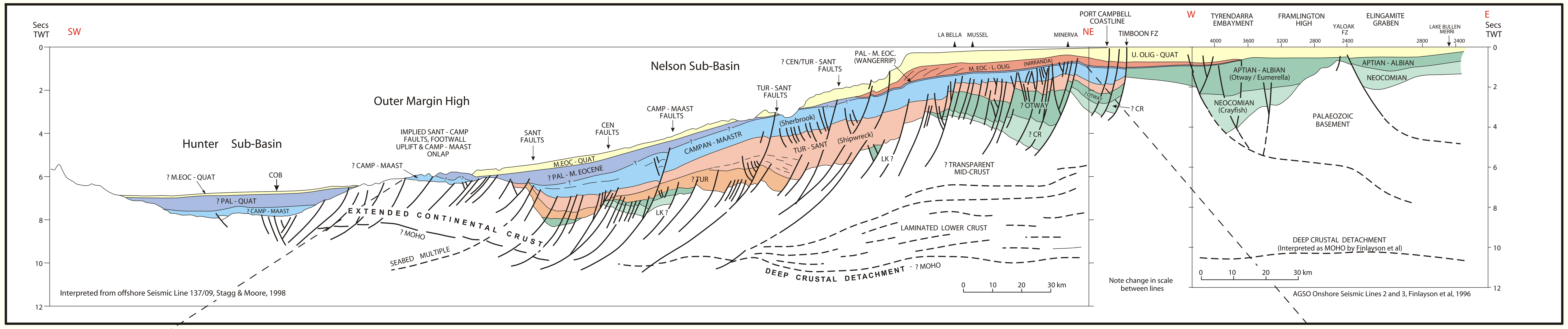
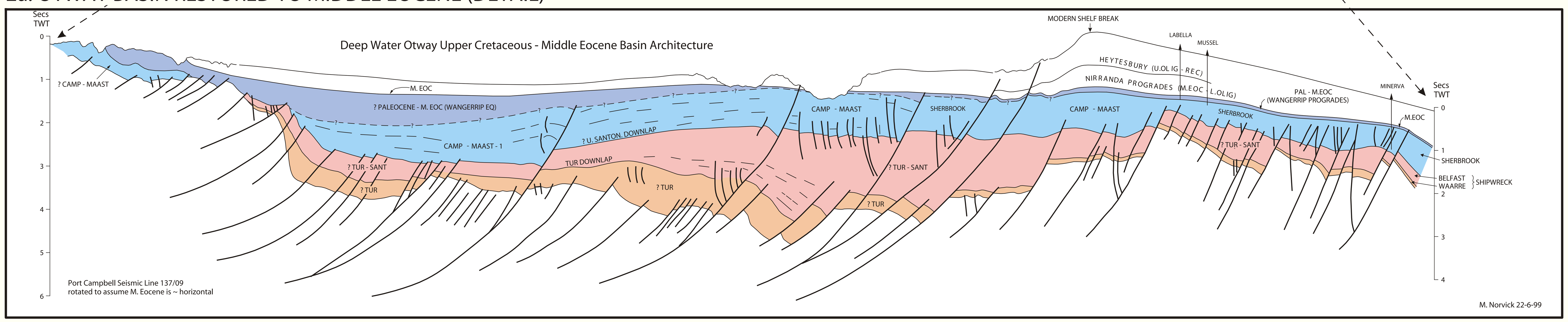
1. CEDUNA SUB-BASIN



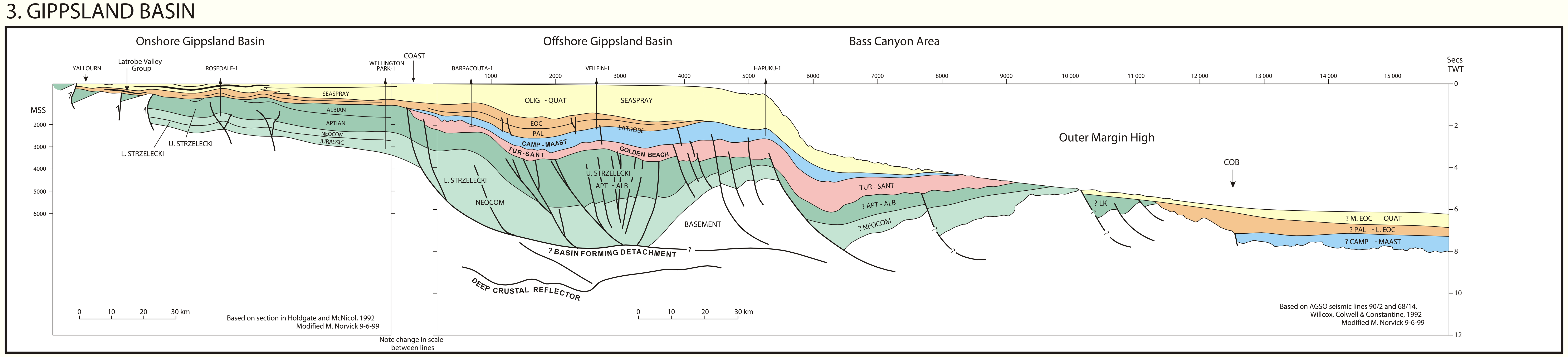
2. OTWAY BASIN

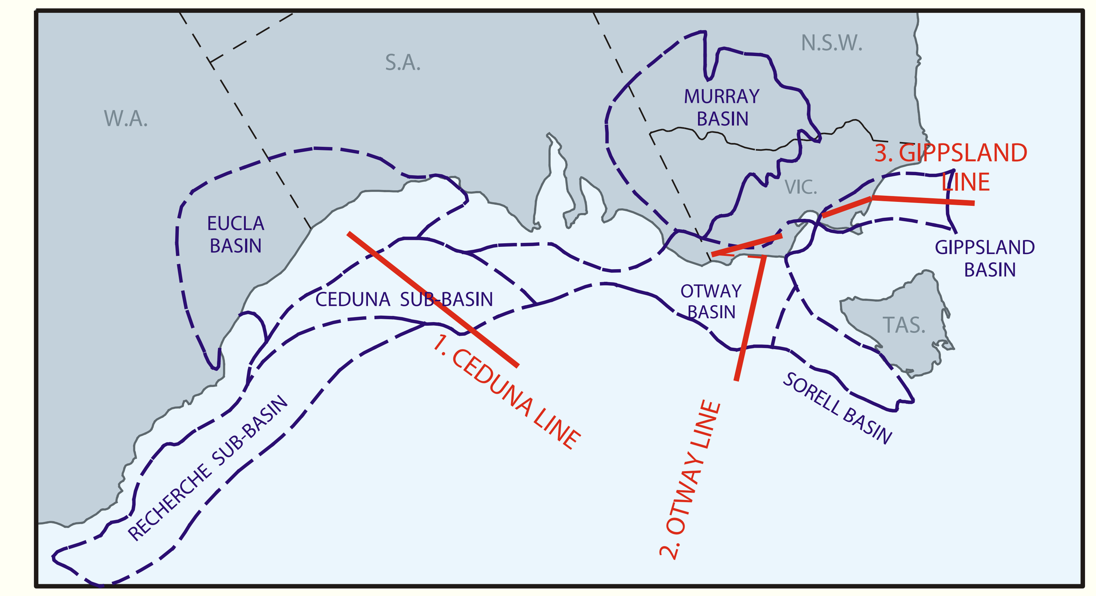


2a. OTWAY BASIN RESTORED TO MIDDLE EOCENE (DETAIL)



3. GIPPSLAND BASIN





LOCATION MAP

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This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.

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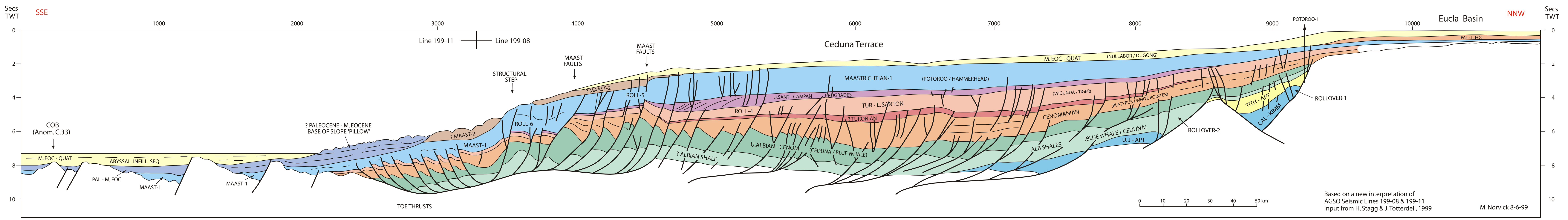
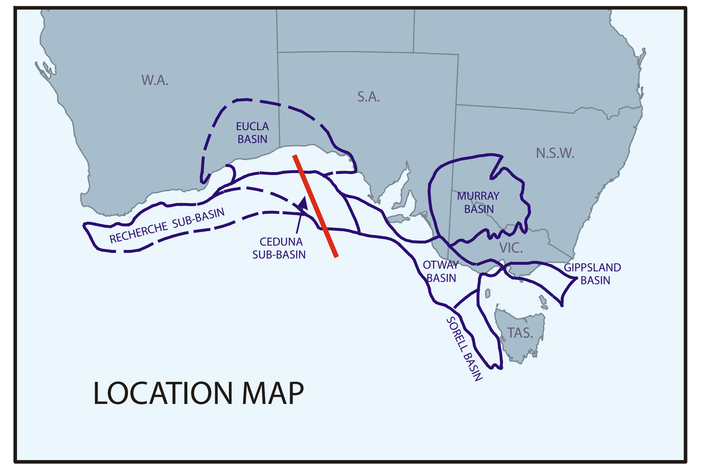
Enclosure 3

REPRESENTATIVE GEOSEISMIC CROSS SECTIONS

AUSTRALIA'S SOUTHERN MARGINS





LEGEND

- Shallow marine and deltaic sands
- Turbidite fans
- Non-marine sands
- Coal measures and lacustrine/delta plain muds
- Marine muds
- Shallow marine carbonates
- Deep water marls
- Condensed deep water deposits
- Volcanics and oceanic crust

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This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.

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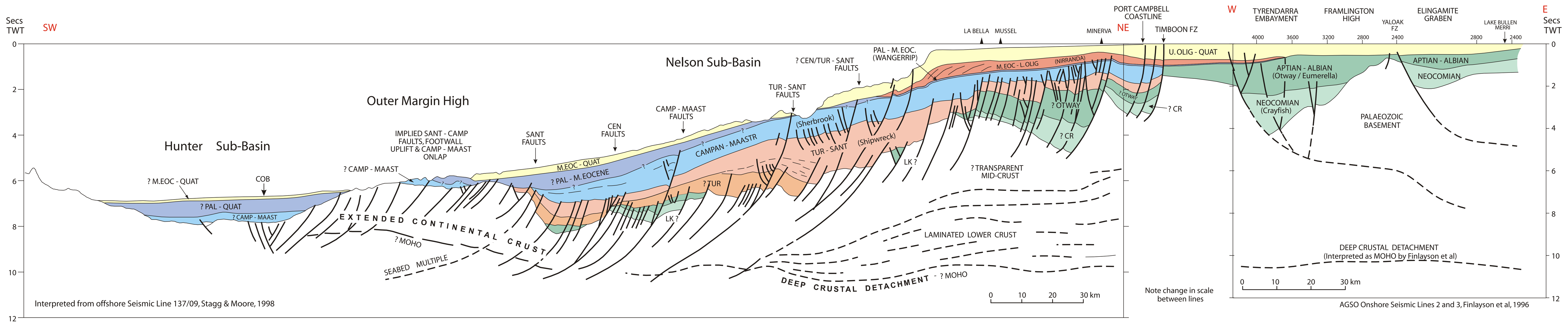
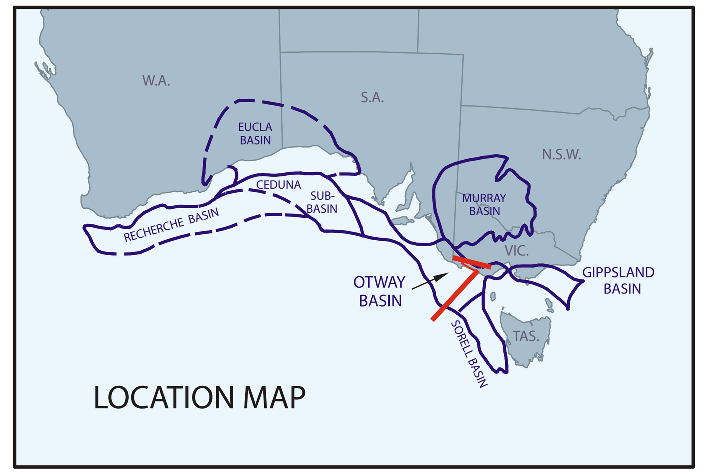
Enclosure 4

CEDUNA SUB-BASIN

(BIGHT BASIN)

CHRONOSTRATIGRAPHIC SECTION: POTOROO TO THE SOUTHEAST





LEGEND

- Shallow marine and deltaic sands
- Turbidite fans
- Non-marine sands
- Coal measures and lacustrine/delta plain muds
- Marine muds
- Shallow marine carbonates
- Deep water marls
- Condensed deep water deposits
- Volcanics and oceanic crust

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Geoscience Australia
Chief Executive Officer: Dr Neil Williams

This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.

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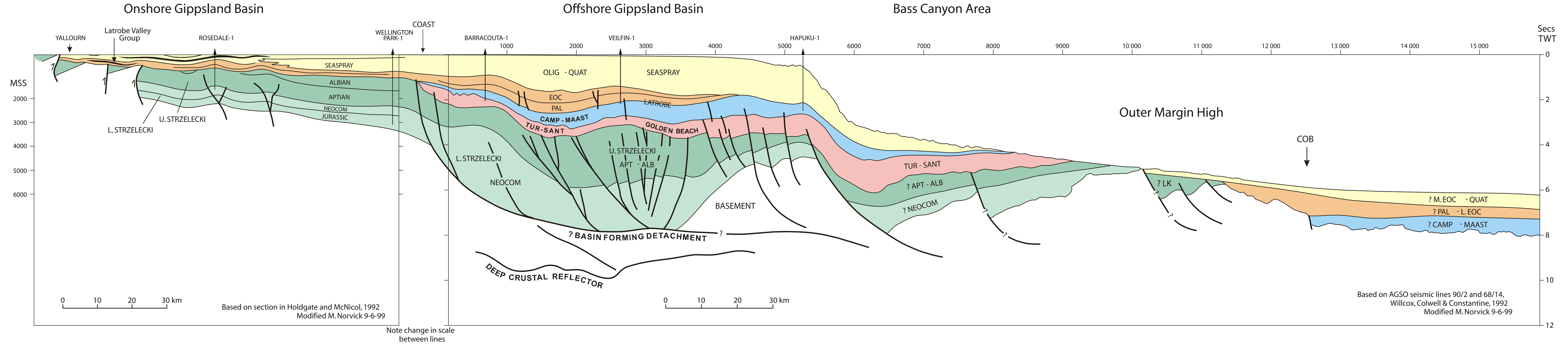
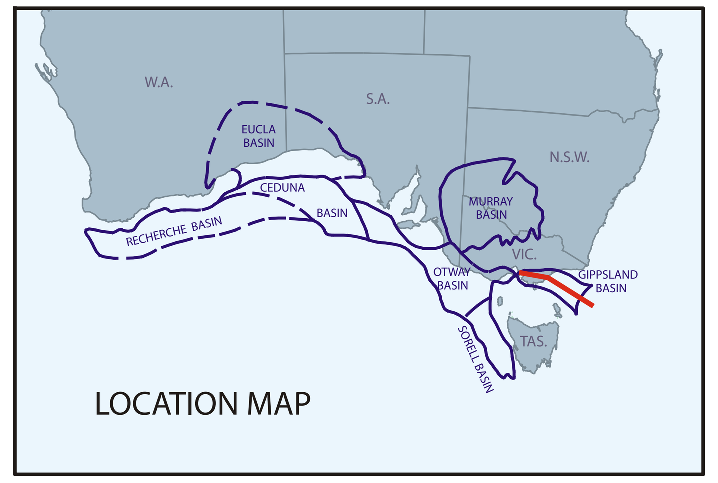
Enclosure 5

OTWAY BASIN

CHRONOSTRATIGRAPHIC SECTION: PORT CAMPBELL TO THE SOUTHWEST





LEGEND

- Shallow marine and deltaic sands
- Turbidite fans
- Non-marine sands
- Coal measures and lacustrine/delta plain muds
- Marine muds
- Shallow marine carbonates
- Deep water marls
- Condensed deep water deposits
- Volcanics and oceanic crust

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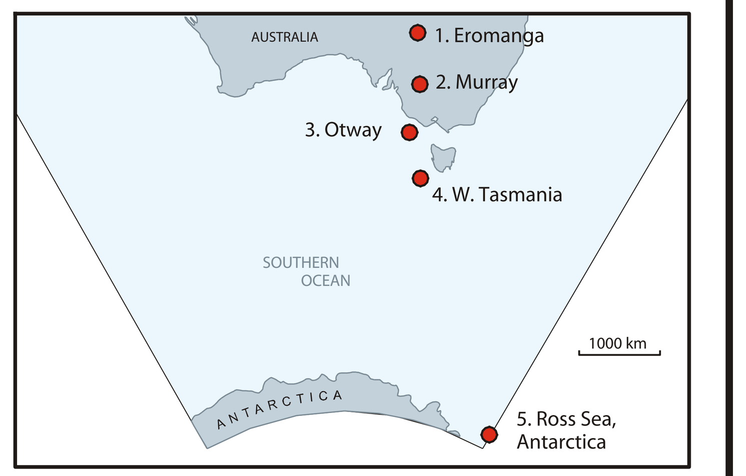
This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.

Australian Government
Geoscience Australia

Enclosure 6

GIPPSLAND BASIN

CHRONOSTRATIGRAPHIC SECTION: YALLOURN TO THE OFFSHORE



LOCATION MAP

LEGEND

- Shallow marine and deltaic sands
- Turbidite fans
- Non-marine sands
- Coal measures and lacustrine/delta plain muds
- Marine muds
- Shallow marine carbonates
- Deep water marls
- Condensed deep water deposits
- Volcanics and oceanic crust

BASED ON:-

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This work was undertaken as part of a collaborative research project between M.S. Norvick and Geoscience Australia.

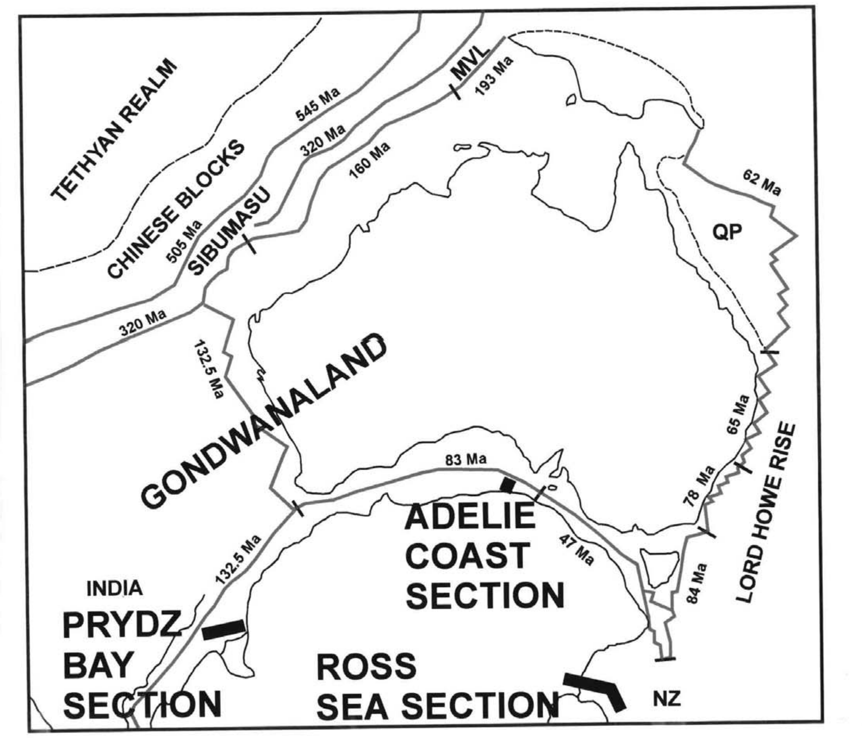
Australian Government
Geoscience Australia

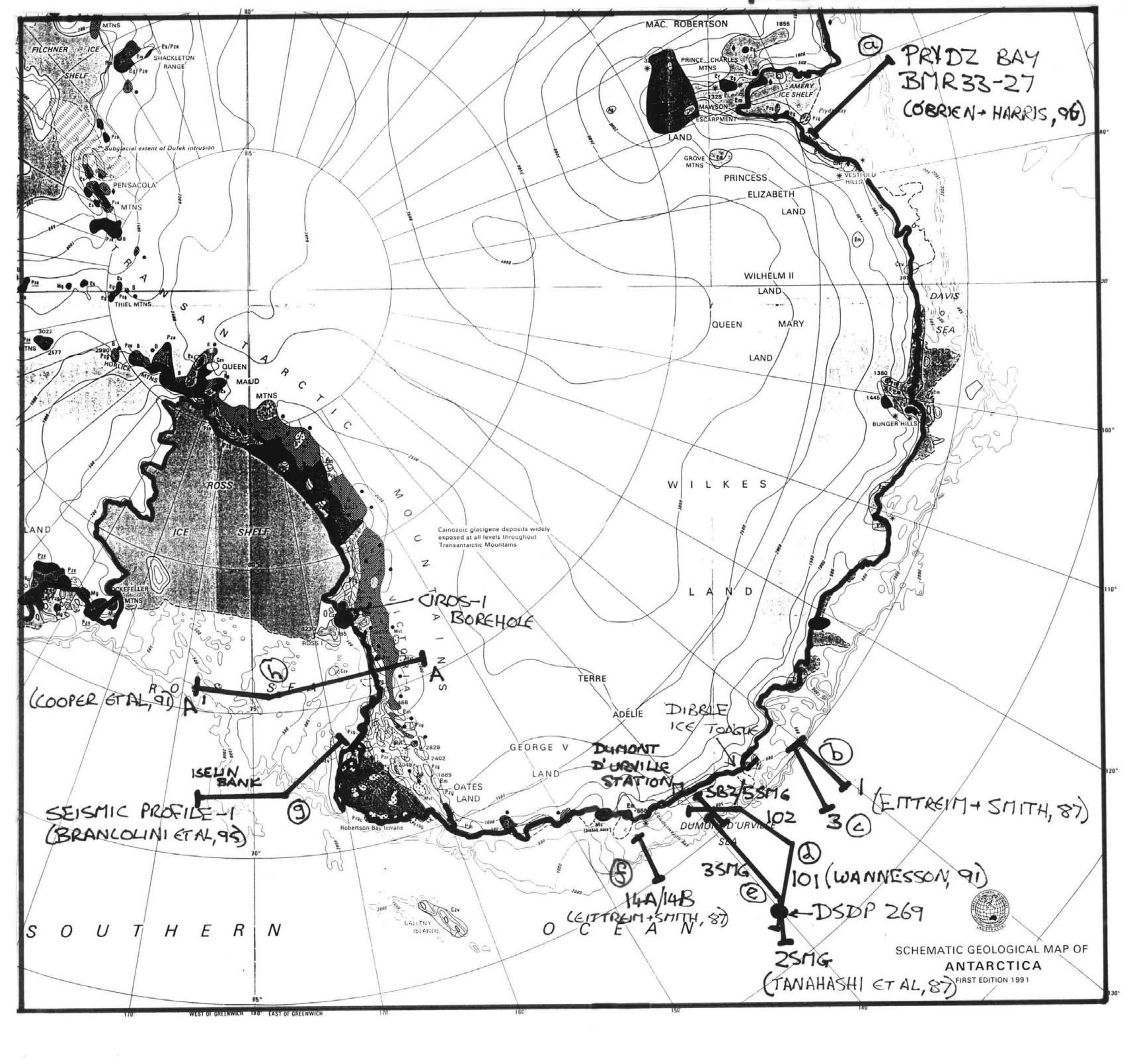
Enclosure 7

STRATIGRAPHIC COMPARISON:

EROMANGA TO ANTARCTICA

LOCATION MAPS





PRYDZ BAY SECTION

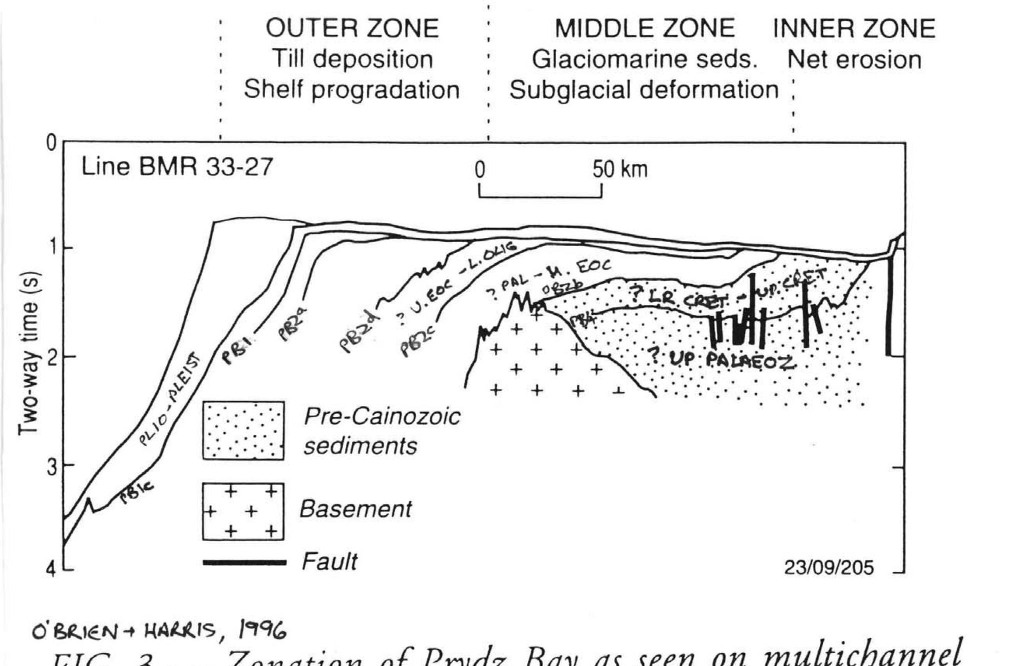
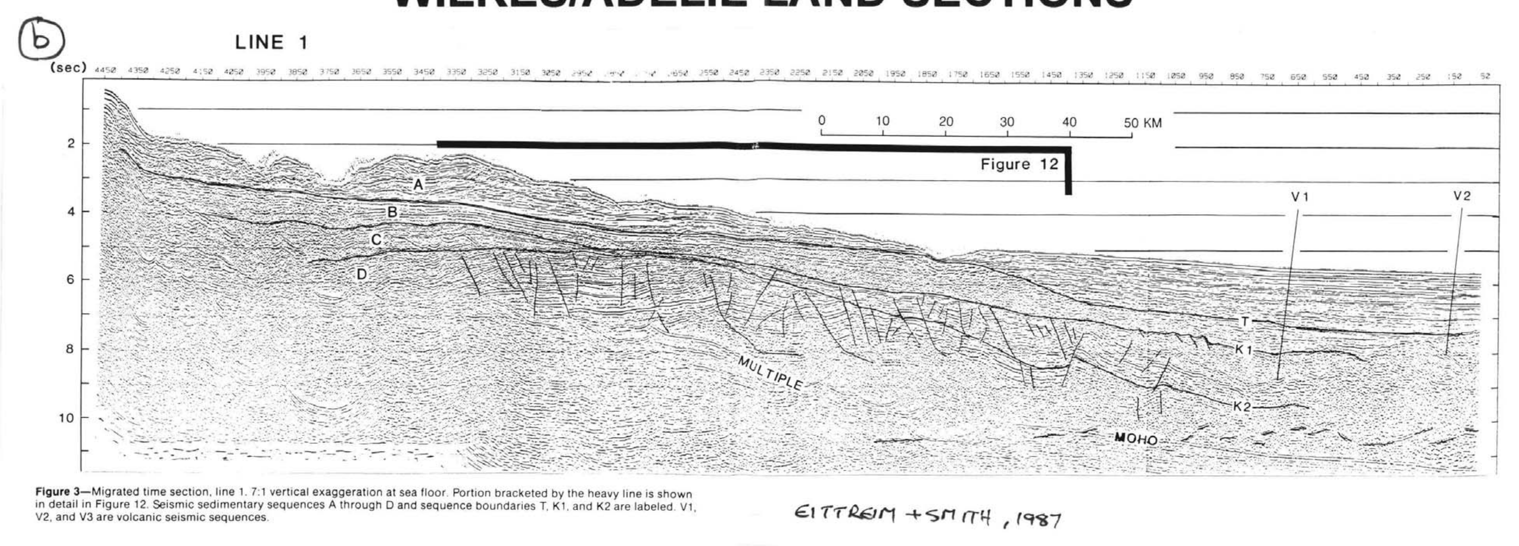
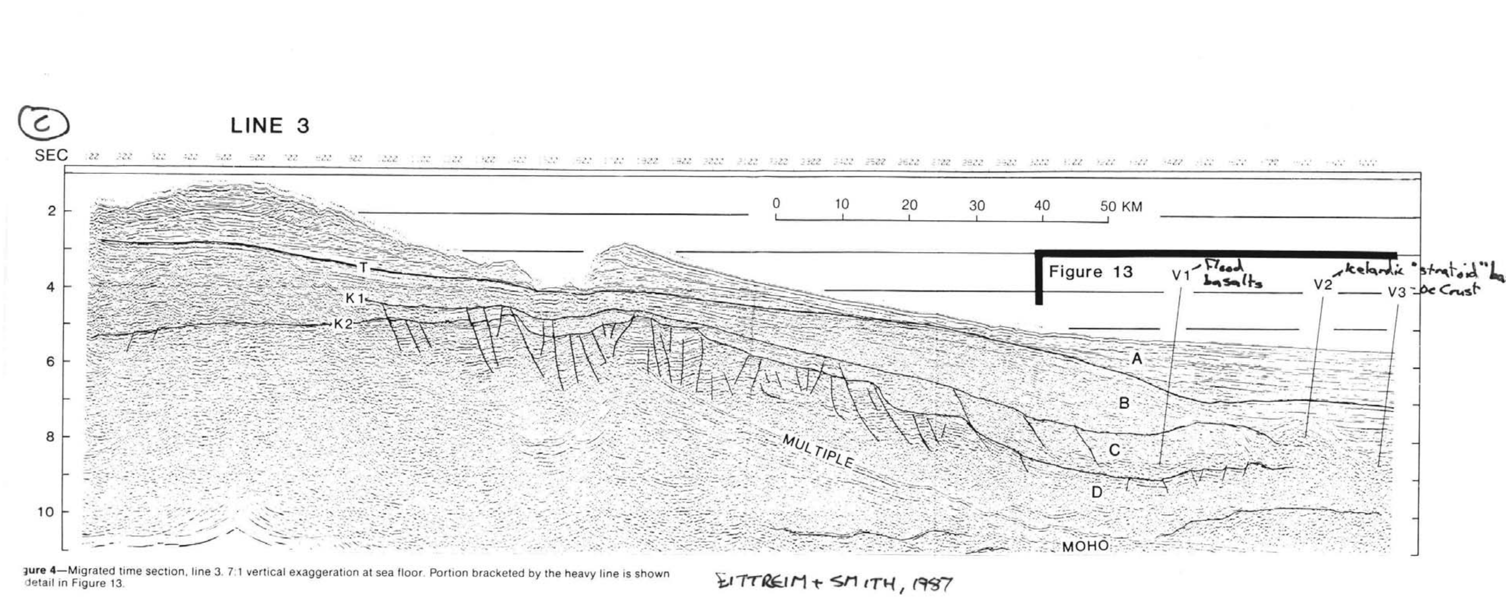


FIG. 3 — Zonation of Prydz Bay as seen on multichannel seismic line BMR33-27.

WESTERN OFFSHORE WILKES/ADELIE LAND SECTIONS





CENTRAL OFFSHORE WILKES/ADELIE LAND SECTIONS

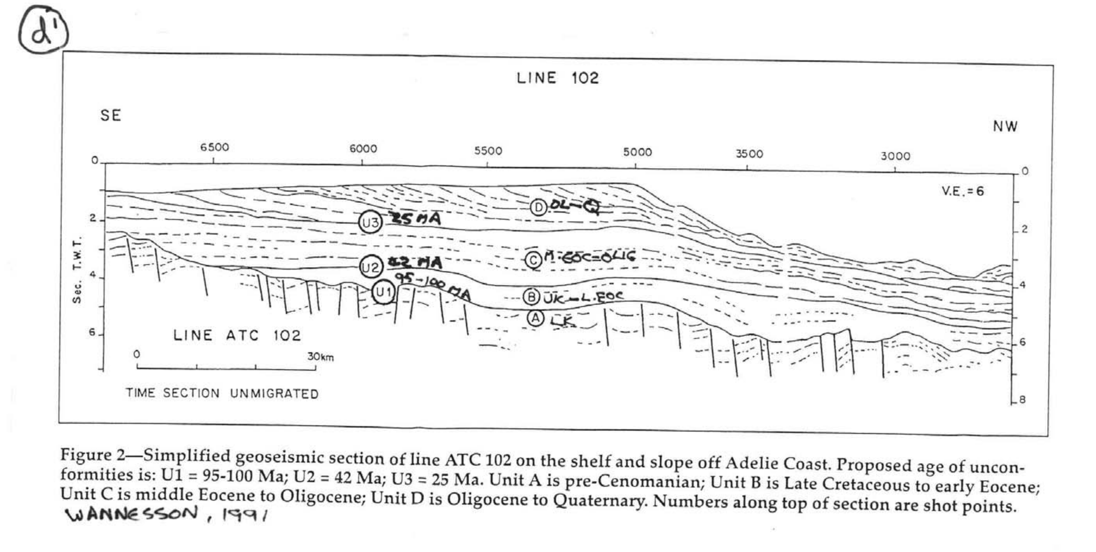


Figure 2—Simplified geoseismic section of line ATC 102 on the shelf and slope off Adelie Coast. Proposed age of unconformities is: U1 = 95-100 Ma; U2 = 42 Ma; U3 = 25 Ma. Unit A is pre-Cenomanian; Unit B is Late Cretaceous to early Eocene; Unit C is middle Eocene to Oligocene; Unit D is Oligocene to Quaternary. Numbers along top of section are shot points.

WANNESSON, 1991

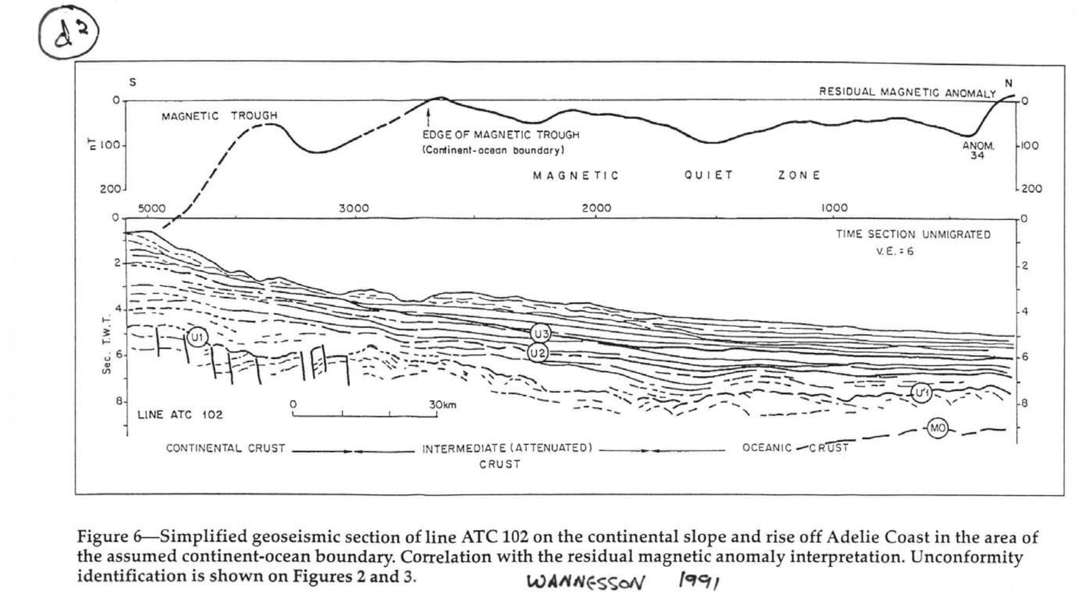
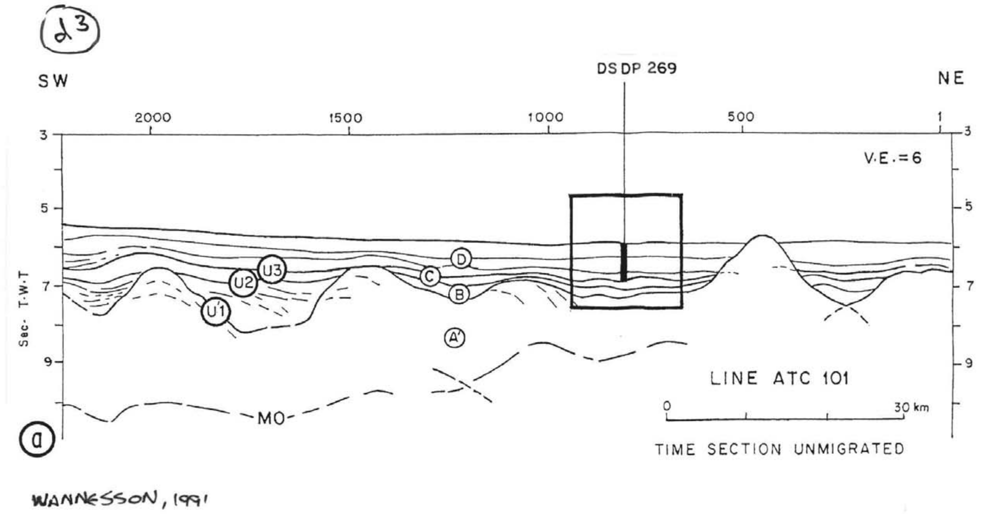


Figure 6—Simplified geoseismic section of line ATC 102 on the continental slope and rise off Adelie Coast in the area of the assumed continent-ocean boundary. Correlation with the residual magnetic anomaly interpretation. Unconformity identification is shown on Figures 2 and 3.

WANNESSON, 1991



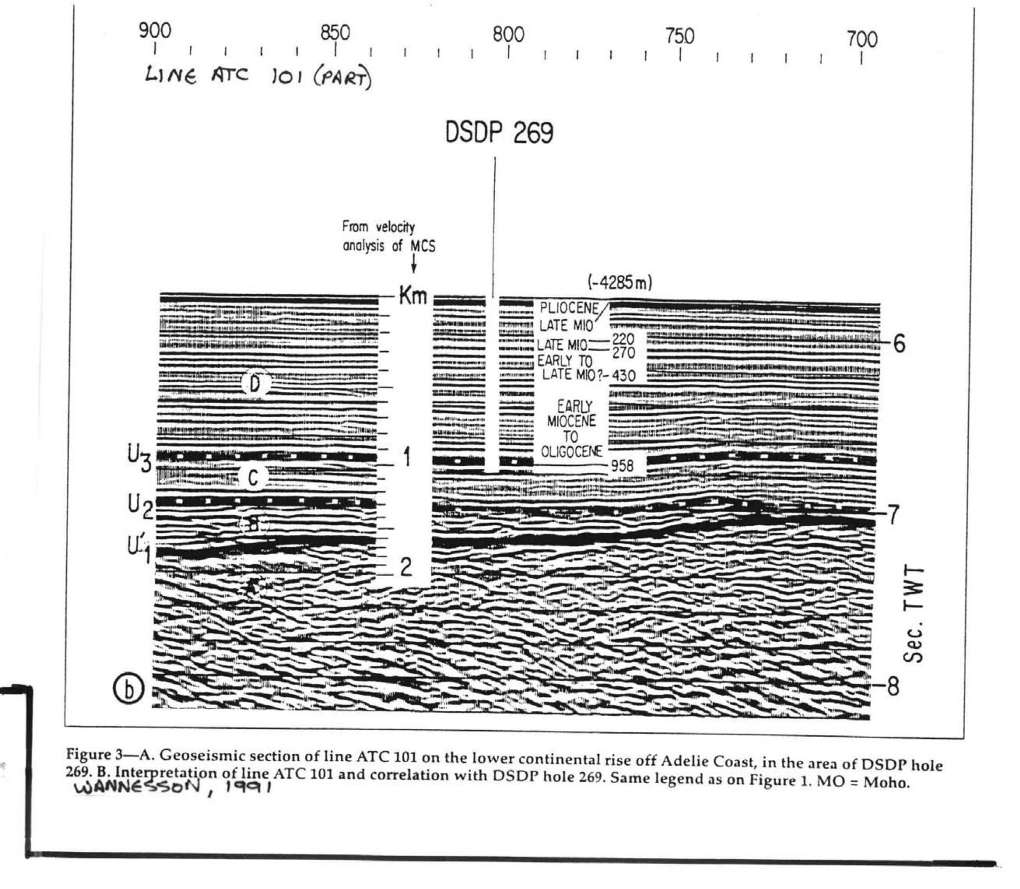
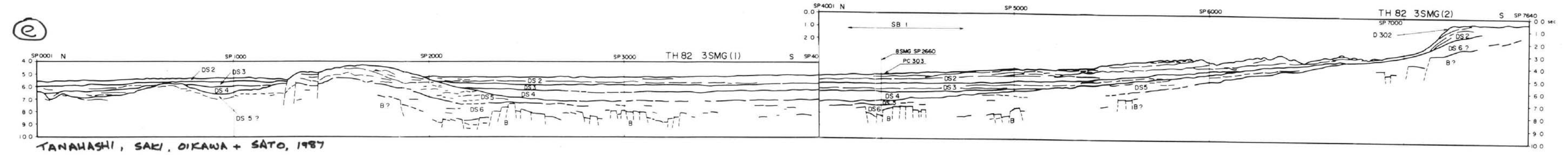


Figure 3—A. Geoseismic section of line ATC 101 on the lower continental rise off Adelie Coast, in the area of DSDP hole 269. B. Interpretation of line ATC 101 and correlation with DSDP hole 269. Same legend as on Figure 1. MO = Moho.

WANNESSON, 1991



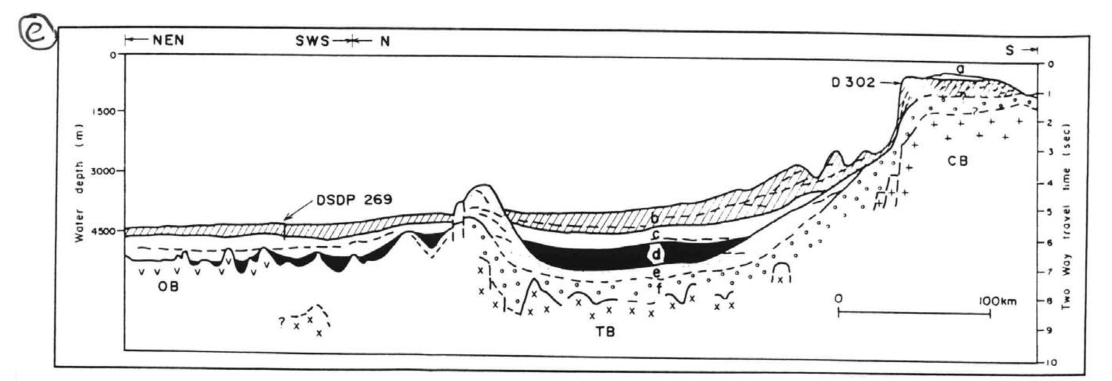
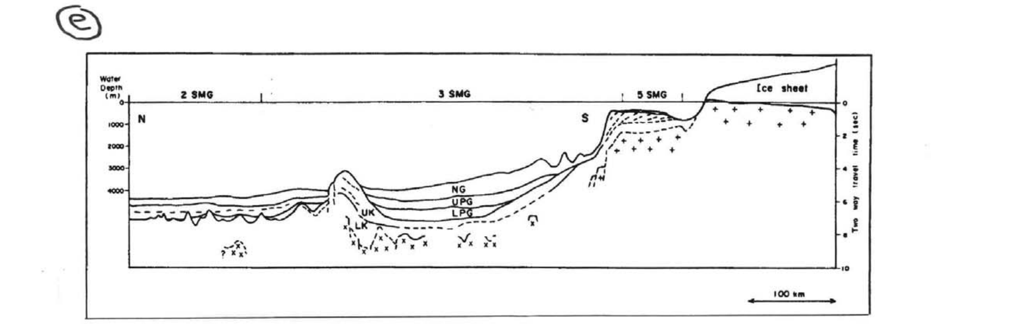
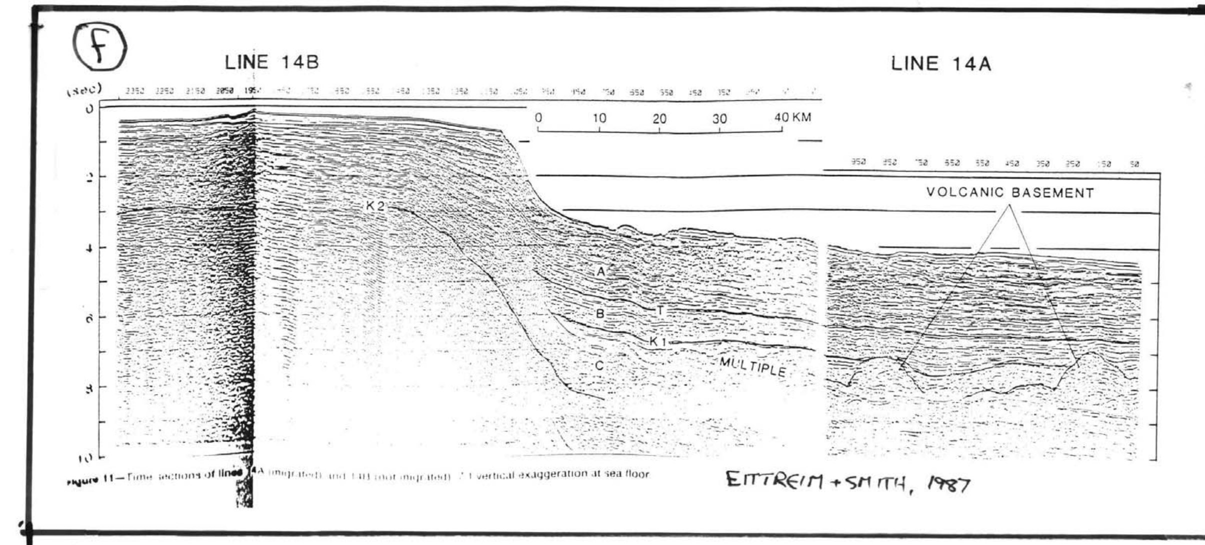


Figure 8—Simplified and estimated geologic section across the continental margin in the Dumont d'Urville Sea area. a, upper Neogene glacial and glacial marine sequence (seismic sequence DS-1); b, Neogene marine sequence in the continental rise, mainly Paleogene nonmarine to marine sequence in the shelf (DS2); c, upper Paleogene marine sequence (DS3); d, lower Paleogene marine and shallow-marine sequence (DS4); e, Upper Cretaceous mainly shallow-marine sequence (DS5); f, Lower Cretaceous continental sequence (DS6); CB, continental basement; TB, transitional basement; OB, oceanic basement.

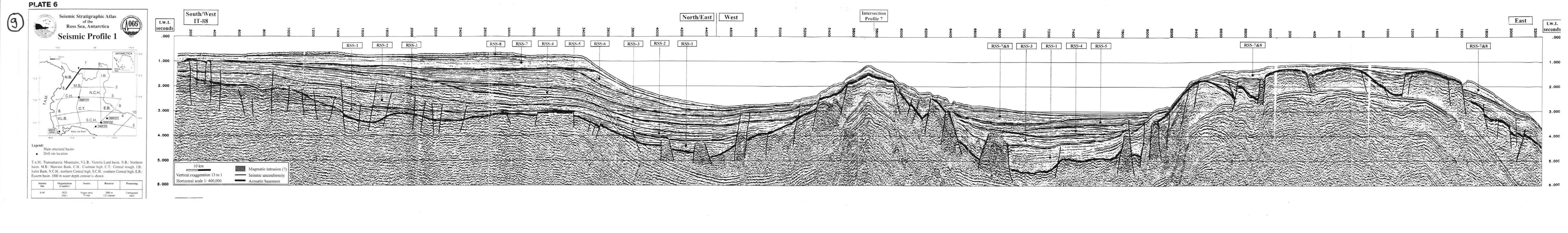
TAKAHASHI, SAKI, OIKAWA + SATO, 1987

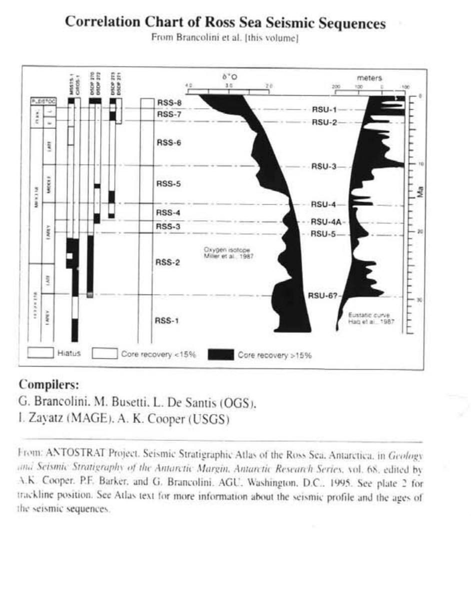


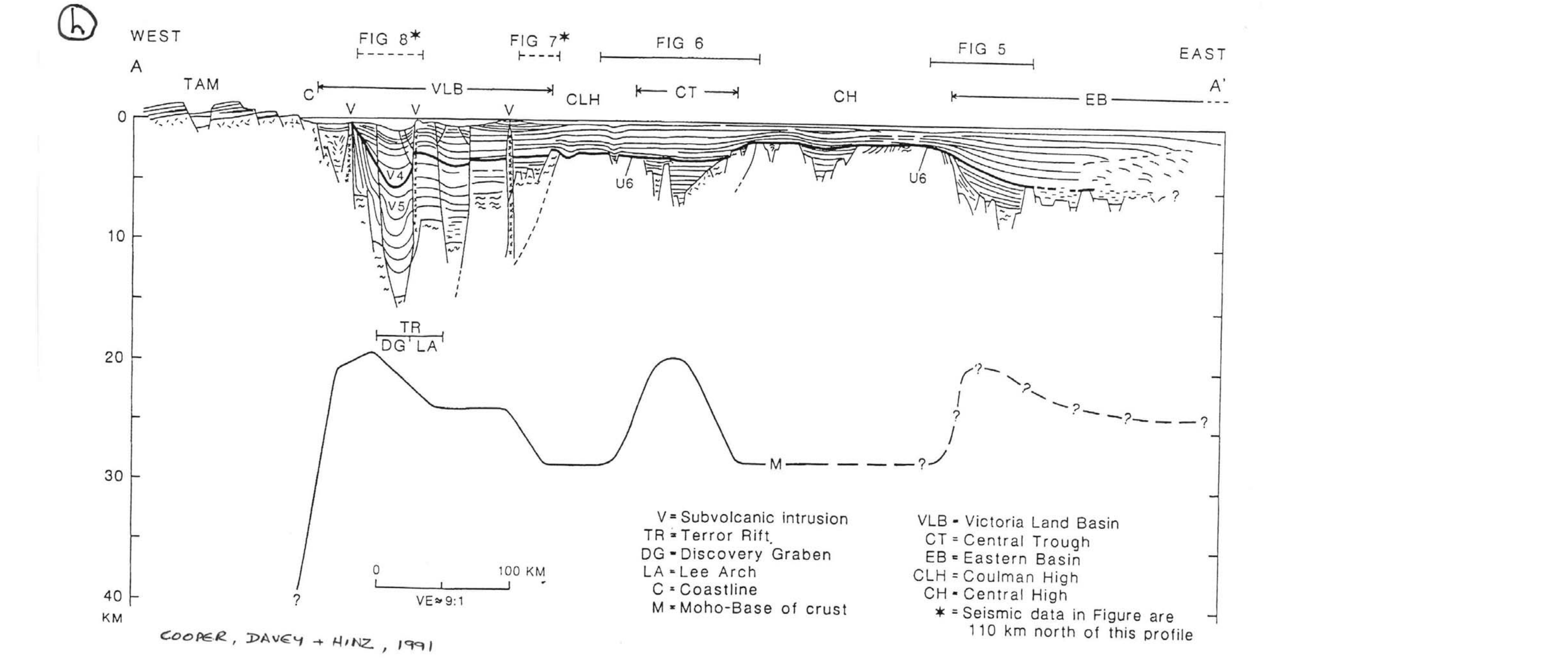


EASTERN OFFSHORE WILKES/ADELIE LAND SECTIONS

ROSS SEA SECTIONS







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ENCLOSURE 8

ANTARCTIC MARGIN

PUBLISHED SEISMIC SECTIONS

LEGEND

Relatively undeformed continental crust (ß= 0-1.5)	Active rift basin
Thinned continental crust (ß=1.5-6.0)	Active sag basin
Volcanic plateaus (small amounts of continental crust)	Active inversion anticline
Compressional orogens (thickened during Cret-Tert)	Broad uplift/denudation
Oceanic crust	Compression/thrusting
Oceanic spreading ridge	Subduction
Intra-plate volcanics (seamounts and onshore)	

EVENTS – 155 MA

- Onset of NE-SW rifting in MacRobertson Shelf, ?Bremer, Recherche, Eyre (Sea Lion) and Polda grabens (?as early as Callovian)
- NZ Torlesse, Waipapa accretion prisms growing into subduction zone and ?progressively moving south along dextral transcurrent faults

ENCLOSURE 9

MIDDLE OXFORDIAN RECONSTRUCTION

155 MA
M. florida

Palaeolatitudes after Veevers et al, 1991

EVENTS – 145 MA

- Initiation of E-W rifting in Gippsland, Otway (Casterton), Duntroon half grabens. Accompanied by basaltic vulcanism in Otway
- Continued NE-SW rifting along MacRobertson Shelf, ?Bremer, Recherche, Eyre (Minke) and Polda grabens
- Further growth and ?southward dextral movement of NZ Torlesse, Waipapa, New Caledonia accretion prisms

ENCLOSURE 10

EARLY TITHONIAN RECONSTRUCTION
145 MA
Lr R. watherooensis
Anomaly M22

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

EVENTS – 135 MA

- First ocean crust (intra-Valanginian) between India and Perth margins. Possibly also between Antarctica and India (no data)
- Major E-W rifting along the continuous Gippsland-onshore Otway Basin (Crayfish) and Duntroon Basin as far west as Poteroo (Southern Right/Bronze Whaler)
- Change to thermal sag phase in Bremer, Recherche, Eyre depocentres
- Subduction and dextral movement completed along New Caledonia–NZ margin. Changed subduction patterns result in initiation of Rangitata folding and metamorphism

Palaeolatitude after Veevers et al. 1991

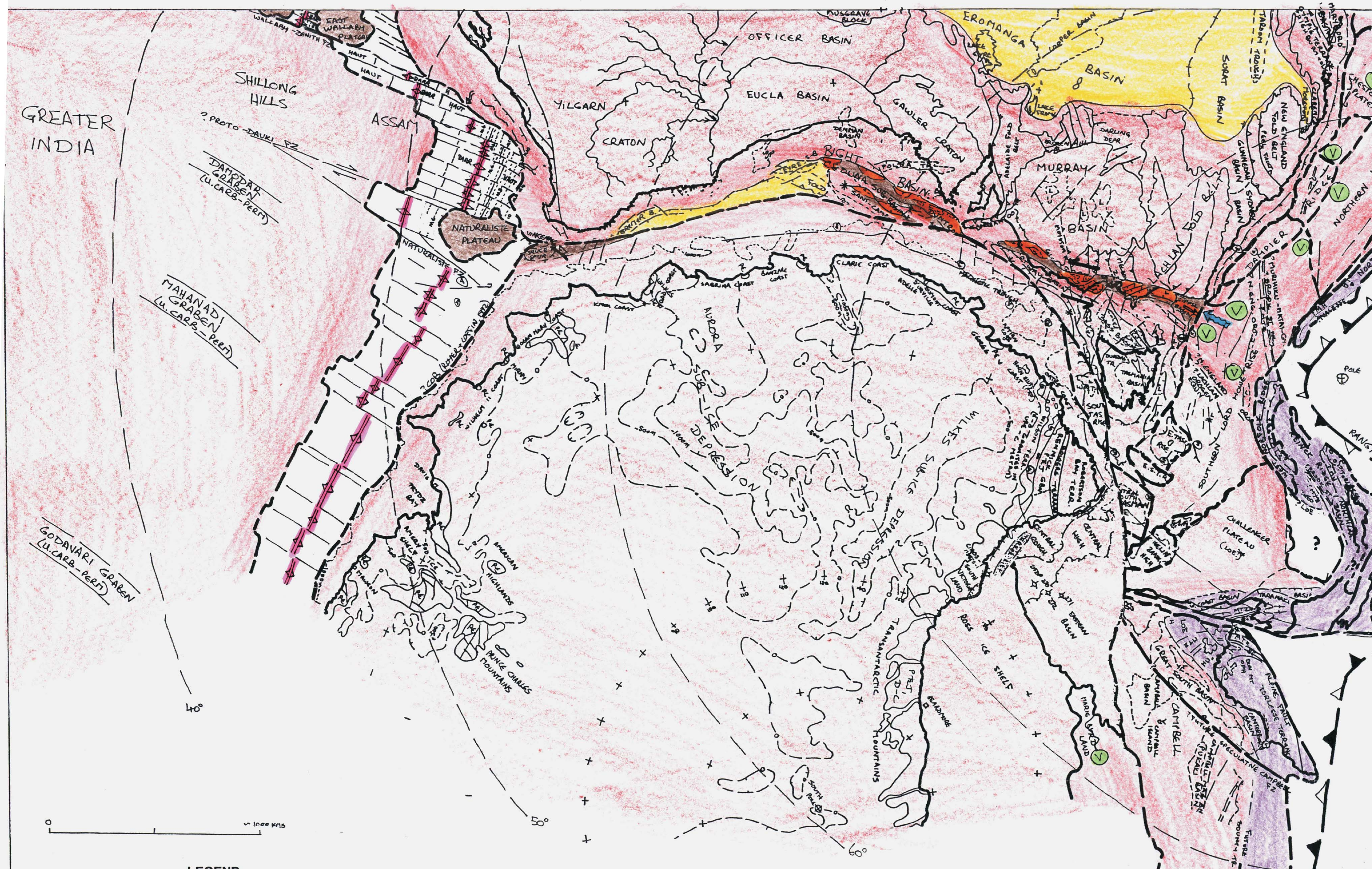
ENCLOSURE 11

HAUTERIV./VALANGIN. BOUNDARY RECONSTRUCTION

135 MA

F. wonthaggiensis

Anomaly M10n/M11



LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- H Broad uplift/denudation
- Compression/thrusting
- Subduction

EVENTS – 120 MA

- Voluminous dacitic tuff deposition starts in the Gippsland-Otway, Bass, Eromanga, Surat, Clarence-Morton Basins and ?in New Guinea. Coeval with Witsundays Volcanics. ?Caused by back-arc extension. However, an arc system is assumed to exist east of the back-arc extensional zone
- Faulting slows in Gippsland, onshore Otway, Bass, Duntroon Basins. Gradually changes to thermal sagging.
- Eastern Otway and Gippsland depocentres aligned NE-SW due to sinistral trans-tensional couple. Realignment of depocentres in western onshore Otway with NW-SE basement trends. Paludal to coaly sedimentation in onshore Otway
- Anoxic lacustrine sedimentation without significant volcanic debris in Duntroon Basin
- Continued thermal sag sedimentation in the Recherche Subbasin
- Rangitata folding and metamorphism completed in New Zealand and New Caledonia

Palaeolatitudes after Veevers et al, 1991

ENCLOSURE 12

MIDDLE BARREMIAN RECONSTRUCTION

120 MA

Lower C. hughesii

Anomaly M3

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

EVENTS – 110 MA

- Continued volcanogenic sedimentation in a thermal sag setting in the Gippsland, onshore Otway, Bass Basins. Change to mainly fluvial environments
- Final fluvio-lacustrine sag or late syn-rift fill in Duntroon (Bronze Whaler) and thermal subsidence in Recherche. Volcanogenic detritus finally reaches Duntroon. Followed by uplift and erosion throughout Bight Basin complex
- Maximum transgression in the Eromanga (Bulldog Shale), Surat Wallumbilla Fm) and Berri Basins (Merreti Mb of Monash Fm)
- Post-Rangitata extension and core complex formation in New Zealand, accompanied by widespread marine transgression
- Subduction along the New Caledonia margin (but not east of New Zealand)
- Emplacement is almost completed of the Keguelen-Broken Ridge volcanic plateau by an Icelandic-type plume

ENCLOSURE 13

LATE APTIAN RECONSTRUCTION
110 MA
Upper C. hughesii
Anomaly C34n

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

EVENTS – 100 MA

- Continued volcanogenic fluvial sedimentation in a thermal sag setting in Gippsland, onshore Otway, Bass Basins. Sedimentation reached its greatest extent over SE Australia, possibly even covering much of the southeastern highlands (based on apatite data)
- Accentuated intra-cratonic thermal sagging starts in Ceduna, possibly driven by dextral transtensional rifting and/or by significant lower crustal extension.
- Extensive Middle Albian marine transgression in Ceduna (Blue Whale) followed by initiation of a major, rapidly deposited delta, fed by a river system originating in the Eromanga Basin. Listric faulting linked with decollement on Middle Albian marine shales
- Major Late Albian marine transgression from the north into the Eromanga and Surat Basins (Toolebuc) but without apparently reaching southern margin basins
- Continued subduction east of New Caledonia (but not off New Zealand)

ENCLOSURE 14

LATE ALBIAN RECONSTRUCTION

100 MA

P. pannosus

Anomaly C34n

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

EVENTS – 95 MA

- Cessation of volcanogenic sedimentation throughout eastern Australia
- Broad uplift/denudation in the Australian eastern highlands, Tasmania and possibly in North Victoria Land. Uplift may be driven by rebound following the end of subduction east of the continent
- Basin reorganisation in onshore Otway, Gippsland and Bass. Uplift and erosion occurs over the whole basin complex but concentrated in rhombic areas, some being previous depocentres. Separation of the three basins in the vicinity of the Mornington Peninsula
- Continued intra-cratonic subsidence and rapid fluviodeltaic sedimentation in Ceduna depocentre (White Pointer). River system fed by erosion products from the Eromanga Basin. Unstable listric faulting and decollement results in toe-thrusting at its southern edge
- Change to rapid spreading on new rotation pole in the Indian Ocean

Palaeolatitudes after Veevers et al, 1991

ENCLOSURE 15

MID CENOMANIAN RECONSTRUCTION
95 MA
A. distocarinatus
Anomaly C34n

EVENTS – 90 MA

- A new complex of rift basins developed around the eastern margins of Australia and Antarctica. These were arranged in an X-pattern, with a NW branch in the offshore Otway (Shipwreck Gp) and Sorell Basins, a SE branch in the Campbell Plateau and Bounty Trough, a NE branch along the Lord Howe Rise and a speculative SW branch in the Ross Sea (Terror Rift; no dating).
- The NW and SE branches may have been associated with a sinistral intra-cratonic transcurrent fault developed along the boundary between Antarctica and eastern Australia-New Zealand. A possible SE dextral splay was the speculative Campbell fault zone. This implies that the X-shaped rift pattern was a conjugate set with maximum extension in an E-W direction
- In Otway, the northern edge of the new Shipwreck rift is the Tartwaup Fault. Sediment fill is fluvial to deltaic clastics. The outer margin high began to form at this time, due to extreme extension of the outer continental crust
- Other new rifts form in offshore Gippsland (Emperor Subgroup; fluvial to lacustrine and coaly sedimentation), the Bass Basin and possibly the Lord Howe Rise
- In the Great South Basin of New Zealand, the Hoiho Group includes non-marine sediment that accumulated in a major active graben. The East Coast Basin also has possible syn-rift sediments
- Accelerated subsidence in the Ceduna delta resulted in slowing of syn-depositional faulting, rapid transgression, downlap and the deposition of a new aggradational marine to deltaic cycle (Tiger). Implications are that significant marine bathymetry was formed at this time.

0 ~1000 kms

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

ENCLOSURE 16

TURONIAN RECONSTRUCTION
90 MA
Lower. P. mawsonii
Anomaly C33y

EVENTS – 85 MA

- Along the southern Australian margin (Ceduna and deepwater Otway), there was extreme low angle crustal fault extension, block rotation and the formation of outer margin highs (resembling core complexes) that became onlapped by post-Santonian sediments
- There was probably also similar extreme crustal extension in microcontinents along the east side of Australia. On the map, this extension is accounted for mainly in the Lord Howe Rise, Dampier Ridge and New Caledonia Basin
- First ocean crust formed at 87-85 ma in a number of places on the eastern seaboard, including the southernmost Tasman Sea and between Campbell Plateau and Antarctica
- The plate reconstruction shown accomplishes closure of most of the oceanic areas but requires movement by several of the smaller microplates in order to fill the gaps (East Tasman Rise, eastern South Tasman Rise, Gilbert Seamount, Iselin Bank). Movement on the speculative Campbell Fault is also required to prevent overlap of Antarctica and Campbell Plateau, although this may be an artefact of projections
- In Ceduna, there was a major sequence boundary associated with downlap and the beginning of progradation of a new Upper Santonian-Maastrichtian delta cycle (Hammerhead). The trunk river system feeding this delta from the eroding Eromanga was still in place
- In Otway, block rotation, an unconformity and rift relocation marked the boundary from Shipwreck to Sherbrook deltaic megasequences
- A minor unconformity, marine transgression and subtle changes in fault activity in offshore Gippsland occurred at the Emperor-Golden Beach boundary. This event was effectively the breakup unconformity
- Continued syn-rift non-marine sedimentation occurred in basins on the Campbell Plateau (eg Great South Basin; Hoiho Gp)
- A syn-rift to post-rift transition occurred in the NZ East Coast Basin

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

ENCLOSURE 17

MID SANTONIAN RECONSTRUCTION
85 MA
Base. T. apoxyexinus
Anomaly C34n

EVENTS – 80 MA

- First ocean crust began to form in the Great Australian Bight at 83 Ma.
- In Ceduna, progradation continued of Hammerhead deltaic sequences
- In the offshore Otway and Sorell Basins, Sherbrook deltaic to marine aggradational sequences accumulated in a transtensional rift
- Tasman seafloor spreading extended to just north of Gippsland. Coastal uplift, defined by apatite data, began in Cape Howe region adjacent to the tip of Tasman Sea spreading
- A marine transgression in the offshore Gippsland Basin (Angler Shale) was followed by progradation of the lowest Latrobe Group deltaic sequences towards the east
- New ocean crust began forming between Dampier Ridge and Lord Howe Rise (Middleton Basin)
- Stretching of continental crust between Lord Howe Rise and Norfolk Ridge-New Caledonia resulted in subsidence of New Caledonia Basin into deep water
- A passive margin with siliciclastic sedimentation became established over New Caledonia at approximately this time
- On the Campbell Plateau (eg Great South Basin), rifting and non-marine sedimentation (Hoiho Gp) changed at about this time to post-rift subsidence and the deposition of a transgressive marine sandstone (Kawau)
- A speculative early phase of rifting in Ross Sea (Terror Rift) may have also changed to post-rift subsidence (little data)
- The Bounty Trough opened as a short-lived seafloor spreading event released by the speculative Campbell fault zone
- Campbell Plateau finally separated from Antarctica

0 ~1000 KMS

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

ENCLOSURE 18

EARLY CAMPANIAN RECONSTRUCTION

80 MA

Mid-N. senectus

Anomaly C33o

EVENTS – 75 MA

- Continued slow spreading south of Australia extending westwards towards the Labuan Basin
- Marine transgression followed by aggradational regression in Ceduna deltaic depocentre (upper Hammerhead)
- Transtensional Sherbrook trough continues in offshore Otway but faulting gradually ceases and sediments onlap rotated Santonian fault blocks
- Tasman Sea spreading reaches as far as Merimbula and is replaced by sinistral strike slip north if this point. Coastal uplift extends northwards as far as Sydney, adjacent to the tip of Tasman Sea spreading
- Completion of spreading in Middleton Basin
- Extreme stretching completed of continental crust under the New Caledonia Basin, resulting in subsidence into deep water
- Uncertain first stages of spreading in the Adare Trough
- Half graben formation and fluvial-coal measure deposition (Pakawau) initiated in Taranaki and West Coast Basins, NZ
- Continued post-rift sedimentation in Great South Basin with marine incursions

0 ~1000KMS

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- (V) Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- (H) Broad uplift/denudation
- Compression/thrusting
- Subduction

ENCLOSURE 19

LATE CAMPANIAN RECONSTRUCTION

75 MA

Lower. T. lilliei

Anomaly C33y

EVENTS – 65 MA

- Initiation of new slow spreading centre between Broken Ridge and Kerguelen Plateau along Diamantina Fracture Zone. Precise timing uncertain but approximately end-Cretaceous
- Ceduna delta building and toe-thrusting are completed, sediment input point switches to Duntroon and a new base of slope fan depocentre evolves. Timing uncertain but is approximately Late Maastrichtian-Early Paleocene
- In offshore Otway, marine to deltaic Sherbrook faulted trough gradually changes to sag geometries, probably still derived from SE. Minor faulting, broad uplift and local volcanic activity. Further change occurs to Wangerrip progradation from Port Campbell Embayment, over a slope bypass zone and into a turbidite depocentre in the deepwater Otway. All of these events may be Early Paleocene; precise dating uncertain
- Tasman Sea spreading extends at least as far north as Newcastle, with strike slip movement to the north. Coastal uplift occurs adjacent to spreading tip
- Continued Latrobe delta aggradation in Gippsland, without obvious interruptions
- In New Zealand, post-rift subsidence continues in the Great South Basin. Further non-marine syn-rift deposition occurs in Taranaki and West Coast Basins (Pakewau)
- ?End of first phase of spreading in the Adare Trough
- New Caledonia passive margin sedimentation gradually changes from siliciclastic to deepwater marls and cherts, indicating accelerated thermal subsidence

0 ~1000KMS

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

ENCLOSURE 20

CRETACEOUS/TERTIARY BOUNDARY RECONSTRUCTION

65 MA

T. longus/Lr. L. balmei

Anomaly C29y

EVENTS – 55 MA

- End of spreading in the Tasman Sea (54 Ma)
- Slow spreading continues in Southern Ocean
- Base of slope fan continues to grow in deepwater Duntroon, presumably fed by river system along Spencer Gulf. Shelfal equivalent is a condensed bypass zone (Wobbegong)
- Syn-rift/post-rift transition in Sorell (uncertain age dating)
- Poorly understood cooling, denudation and ?uplift events recorded by apatite data in the SE Australian highlands, Canobolas Divide and ?Adelaide Fold Belt.
- Initiation of Murray basin with incised valley fills fed by southward flowing rivers (SW Highlands Deep Leads?). Continued Wangerrip progradation into two separate Otway depocentres, ?fed by these two rivers
- Initiation of fluvial sedimentation in Lake Eyre Basin
- Incised valley fill in onshore Gippsland, followed by hiatus (?uplift) and volcanics (55-57 Ma). Beginning of rapid retrogradation, marine transgressions. Folding starts in offshore Gippsland (54 Ma)
- Western South Tasman Rise detaches from Antarctica and welds with rest of South Tasman Rise (?Late Paleocene-Early Eocene)
- Onset of second phase of spreading in the Adare Trough and rifting in the Ross Sea/?Ross Ice Shelf. Associated footwall uplift of North Victoria Land and the Trans-Antarctic Mtns confirmed by apatite data. Implied c.200kms stretching of continental crust under the Ross Sea and ice shelf
- In New Zealand, Pakawau rifts are abandoned and a new set of Challenger rifts initiated, some marine and some with non-marine/deltaic fill (Kapuni). Challenger rifts are the first stage of crustal extension leading to evolution of the Neogene Emerald Basin
- Widespread anoxic marine shale in New Zealand associated with global warming event and sea level high (55 Ma)

LEGEND

- Relatively undeformed continental crust (ß= 0-1.5)
- Thinned continental crust (ß=1.5-6.0)
- Volcanic plateaus (small amounts of continental crust)
- Compressional orogens (thickened during Cret-Tert)
- Oceanic crust
- Oceanic spreading ridge
- Intra-plate volcanics (seamounts and onshore)
- Active rift basin
- Active sag basin
- Active inversion anticline
- Broad uplift/denudation
- Compression/thrusting
- Subduction

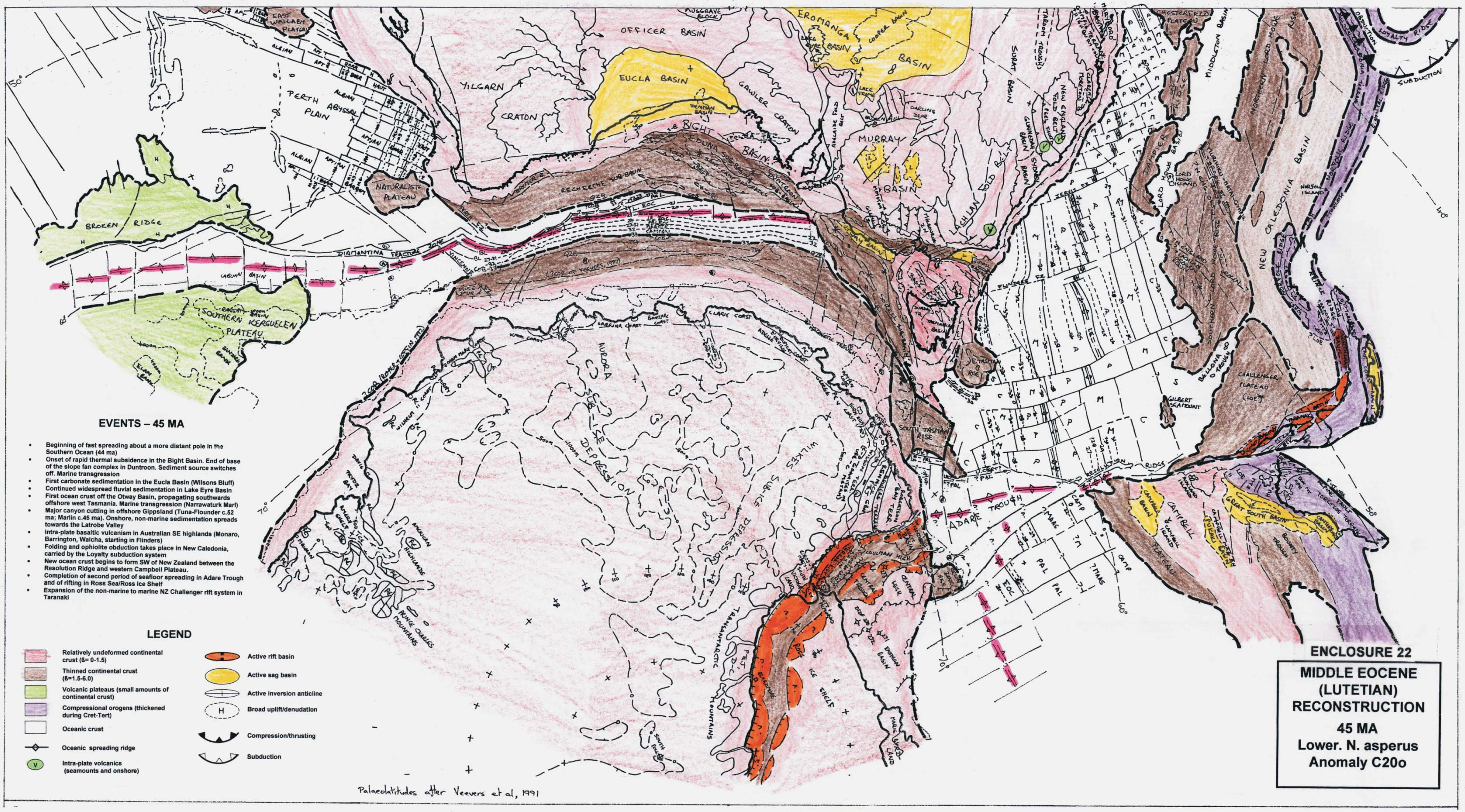
ENCLOSURE 21

PALEOCENE/EOCENE BOUNDARY RECONSTRUCTION

55 MA

Upper. L. balmei

Anomaly C24o



EVENTS – 45 MA
• Beginning of fast spreading about a more distant pole in the Southern Ocean (44 ma)
• Onset of rapid thermal subsidence in the Bight Basin. End of base of the slope fan complex in Duntroon. Sediment source switches off. Marine transgression
• First carbonate sedimentation in the Eucla Basin (Wilsons Bluff)
• Continued widespread fluvial sedimentation in Lake Eyre Basin
• First ocean crust off the Otway Basin, propagating southwards offshore west Tasmania. Marine transgression (Narrawaturk Marl)
• Major canyon cutting in offshore Gippsland (Tuna-Flounder c.52 ma; Marlin c.45 ma). Onshore, non-marine sedimentation spreads towards the Latrobe Valley
• Intra-plate basaltic vulcanism in Australian SE highlands (Monaro, Barrington, Walcha, starting in Flinders)
• Folding and ophiolite obduction takes place in New Caledonia, carried by the Loyalty subduction system
• New ocean crust begins to form SW of New Zealand between the Resolution Ridge and western Campbell Plateau.
• Completion of second period of seafloor spreading in Adare Trough and of rifting in Ross Sea/Ross Ice Shelf
• Expansion of the non-marine to marine NZ Challenger rift system in Taranaki
LEGEND
Relatively undeformed continental crust (ß= 0-1.5)
Thinned continental crust (ß=1.5-6.0)
Volcanic plateaus (small amounts of continental crust)
Compressional orogens (thickened during Cret-Tert)
Oceanic crust
Oceanic spreading ridge
Intra-plate volcanics (seamounts and onshore)
Active rift basin
Active sag basin
Active inversion anticline
Broad uplift/denudation
Compression/thrusting
Subduction
ENCLOSURE 22
MIDDLE EOCENE (LUTETIAN) RECONSTRUCTION
45 MA
Lower. N. asperus
Anomaly C20o
Palaeolatitudes after Veevers et al, 1991
OFFICER BASIN
EROMANGA BASIN
COOPER BASIN
EUCLA BASIN
YILGARN CRATON
GAWLER CRATON
PERTH ABYSSAL PLAIN
NATURALISTE PLATEAU
BIGHT BASIN
MURRAY BASIN
LACHLAN FOLD BELT
SURAT BASIN
BROKEN RIDGE
SOUTHERN KERGUELEN PLATEAU
DIAMANTINA FRACTURE ZONE
LABUAN BASIN
AURORA SUBGLACIAL DEPRESSION
WILKES SUBGLACIAL DEPRESSION
SOUTH TASMAN RISE
ADARE TROUGH
RESOLUTION RIDGE
CAMPBELL PLATEAU
GREAT SOUTH BASIN
BOUNTY TROUGH
CHALLENGER PLATEAU
GILBERT SEAMOUNT
NEW CALEDONIA BASIN
NORFOLK ISLAND
LORD HOWE ISLAND
DAMPIER RIDGE
MIDDLETON BASIN
CHESTERFIELD PLATEAU
LOYALTY RIDGE
SUBDUCTION
OBDUCTION
BELLONA TROUGH
TRANSANTARCTIC MOUNTAINS
ROSS ICE SHELF
AMERICAN HIGHLANDS
PRINCE CHARLES MOUNTAINS
SABRINA COAST
CLARIE COAST


EVENTS – 35 MA
• Breakthrough of oceanic crust between Antarctica and the South Tasman Rise
• Initiation of Antarctic glaciation at the head of the Lambert Glacier. First sea level ice in Antarctica. Beginning of prograding glacio-marine sediments on the shelf
• Marine incursions into the Murray Basin (Buccleuch Beds) and expansion of sedimentation
• Erosion, weathering, ferricrete and silcrete formation start in interior Australia (Canaway profile and Cordillo surface)
• Folding finishes in offshore Gippsland. Marine transgression continues in Gippsland and Otway
• Active subsidence starts in NZ Challenger rift system. Change to carbonate sedimentation (Tikorangi)
• Rapid spreading in the Emerald Basin accompanied by active prolongation of the spreading tip towards the Balleny Trough
• Unroofing begins in New Caledonia, accompanied by further thrusting (?migrating southwards)
• Initiation of spreading at the South Fiji triple junction
LEGEND
Relatively undeformed continental crust (ß= 0-1.5)
Thinned continental crust (ß=1.5-6.0)
Volcanic plateaus (small amounts of continental crust)
Compressional orogens (thickened during Cret-Tert)
Oceanic crust
Oceanic spreading ridge
Intra-plate volcanics (seamounts and onshore)
Active rift basin
Active sag basin
Active inversion anticline
Broad uplift/denudation
Compression/thrusting
Subduction
ENCLOSURE 23
LATEST EOCENE (PRIABONIAN) RECONSTRUCTION
35 MA
M. N. asperus/P15/Up.M
Anomaly C16
OFFICER BASIN
EROMANGA
BASIN
EUCLA BASIN
YILGARN
CRATON
GAWLER CRATON
PERTH ABYSSAL PLAIN
NATURALISTE PLATEAU
BROKEN RIDGE
SOUTHERN KERGUELEN PLATEAU
MURRAY BASIN
RECHERCHE SUB-BASIN
CEDUNA SUB-BASIN
DIAMANTINA FRACTURE ZONE
MIDDLE-UPPER EOCENE
EOC
SOUTH TASMAN RISE
LORD HOWE RISE
NEW CALEDONIA BASIN
CHALLENGER PLATEAU
SOLANDER TROUGH
GREAT SOUTH BASIN
BOUNTY TROUGH
CAMPBELL PLATEAU
AURORA SUBGLACIAL DEPRESSION
WILKES SUBGLACIAL DEPRESSION
TRANSANTARCTIC MOUNTAINS
ROSS ICE SHELF
MARIE BYRD LAND
PRINCE CHARLES MOUNTAINS
INITIAL ANTARCTIC GLACIATION
Palaeolatitudes after Veevers et al, 1991


EVENTS – 25 MA
Establishment of circum-Antarctic currents (Mid-Oligocene)
Major increases in Antarctic sea level glaciation in the Mid-Oligocene accompanied by progradation on the shelf
Beginning of widespread carbonate sedimentation in the Bight (Nullabor), Otway (Clifton), Murray (Gambier), Sorell and Gippsland in the Mid-Oligocene (c.30 ma)
In Gippsland, maximum marine transgression occurred at c.25-27 ma and was followed by a volcanic episode onshore
Resumption of fluvio-lacustrine sedimentation in Lake Eyre Basin (Etadunna Fm)
Rejuvenation of SE Australian highlands (Kosciuszko event; geomorphological evidence)
Intra-plate volcanics onshore Australia (Liverpool, Central, Bogong basalts)
Plume volcanics start in Tasman Sea and Middleton Basin
Initiation of Vening Meinesz and Van Der Linden transcurrent faults and subduction north of New Zealand. Growth of back-arc spreading in Norfolk Basin, leading to formation of the Three Kings Rise as a volcanic arc (starting 26 ma). South Fiji triple junction stops spreading at c.24 ma
Movement starts on the New Zealand Alpine Fault (24 ma). Challenger rift shoulders expand (eg into North Wanganui Basin)
Emplacement of the NZ Northland allochthon
LEGEND
Relatively undeformed continental crust (ß= 0-1.5)
Thinned continental crust (ß=1.5-6.0)
Volcanic plateaus (small amounts of continental crust)
Compressional orogens (thickened during Cret-Tert)
Oceanic crust
Oceanic spreading ridge
Intra-plate volcanics (seamounts and onshore)
Active rift basin
Active sag basin
Active inversion anticline
Broad uplift/denudation
Compression/thrusting
Subduction
ENCLOSURE 24
LATEST OLIGOCENE (CHATTIAN) RECONSTRUCTION
25 MA
M. P. tuberculatus/P22/Up.I
Anomaly C6Co-C7
Paleolatitudes after Veevers et al., 1991
OFFICER BASIN
EROMANGA
BASIN
EUCLA BASIN
YILGARN
CRATON
GAWLER CRATON
PERTH ABYSSAL PLAIN
NATURALISTE PLATEAU
BROKEN RIDGE
DIAMANTINA FRACTURE ZONE
RECHERCHE SUB-BASIN
MURRAY BASIN
SURAT BASIN
NEW ENGLAND FOLD BELT
LACHLAN FOLD BELT
MIDDLE - UPPER EOCENE
ABYSSAL PLAIN
SOUTH TASMAN RISE
LORD HOWE RISE
NEW CALEDONIA BASIN
NORTHERN LORD HOWE RISE
CHALLENGER PLATEAU
GILBERT SEAMOUNT
CAMPBELL PLATEAU
GREAT SOUTH BASIN
BOUNTY TROUGH
CHATHAM RISE
BRUCE SPUR
WILKES
KNOX COAST
SABRINA COAST
BANZARE COAST
CLARK COAST
ADÉLIE COAST
GEORGE V COAST
QUEEN MARY COAST
DUMONT D'URVILLE
MAGNETIC TROUGH
EMERALD BASIN
S. FIJI BASIN
TRIPLE JUNCT DIES


ENCLOSURE 25
LATE MIOCENE
(TORTONIAN)
RECONSTRUCTION
10 MA
Up. T. bellus/ N16/ Lr B2
Anomaly C5y
EVENTS – 10 MA
Desiccation begins of inland Australia
Early inversion folding starts in Otway, Gippsland and interior Australia.
Widespread erosion, weathering and silcrete formation in interior Australia
Major channelling event in offshore Gippsland (14 ma) followed by accelerated limestone deposition
Major regression and erosion ended carbonate deposition in the Murray Basin (c.10 ma). Followed by marine transgression and the emplacement of Pliocene chenier ridges (Loxton-Parilla sands)
Intra-plate vulcanism in eastern Australia (eg Tweed volcano, c.20 ma). Completion of plume volcanoes in the Tasman Sea and Middleton Basin
In New Zealand, continued movement on the Alpine Fault causes many basins to enter a convergent phase. Uplift and erosion in the highlands results in erosion products prograding northwards along Taranaki
Active subduction starts in the Hikurangi and Kermadec trenches
LEGEND
Relatively undeformed continental crust (ß= 0-1.5)
Thinned continental crust (ß=1.5-6.0)
Volcanic plateaus (small amounts of continental crust)
Compressional orogens (thickened during Cret-Tert)
Oceanic crust
Oceanic spreading ridge
Intra-plate volcanics (seamounts and onshore)
Active rift basin
Active sag basin
Active inversion anticline
Broad uplift/denudation
Compression/thrusting
Subduction
Palaeolatitudes from Veevers et al, 1991
OFFICER BASIN
EROMANGA
BASIN
YILGARN
CRATON
EUCLA BASIN
GAWLER CRATON
MURRAY BASIN
PERTH ABYSSAL PLAIN
NATURALISTE PLATEAU
BROKEN RIDGE
RECHERCHE SUB-BASIN
CEDUNA SUB-BASIN
DIAMANTINA FRACTURE ZONE
MIDDLE-UPPER EOCENE
KERGUELEN ABYSSAL PLAIN
SOUTH TASMAN RISE
LORD HOWE RISE
NEW CALEDONIA BASIN
NORFOLK BASIN
CHALLENGER PLATEAU
CAMPBELL PLATEAU
CHATHAM RISE
HIKURANGI TRENCH
BOUNTY TROUGH
GREAT SOUTH BASIN
MACQUARIE RIDGE
WILKES
KNOX COAST
SABRINA COAST
BANZARE COAST
CLARK COAST
ADELIE COAST
GEORGE V COAST
MIDDLETON BASIN
DAMPIER


EVENTS – 0 MA
Further desiccation of inland Australia. Emplacement of aeolian sand sheets (2-0.5 ma).
Glaciation in Tasmania and SE Australian Highlands
Flood basalts in W. Victoria and SE SA (2-0 ma)
Neotectonic fault movement in Adelaide Hills and SE Australia
LEGEND
Relatively undeformed continental crust (ß= 0-1.5)
Thinned continental crust (ß=1.5-6.0)
Volcanic plateaus (small amounts of continental crust)
Compressional orogens (thickened during Cret-Tert)
Oceanic crust
Oceanic spreading ridge
Intra-plate volcanics (seamounts and onshore)
Active rift basin
Active sag basin
Active inversion anticline
Broad uplift/denudation
Compression/thrusting
Subduction
ENCLOSURE 26
PRESENT DAY
0 MA
OFFICER BASIN
EROMANGA
BASIN
YILGARN
CRATON
EUCLA BASIN
GAWLER CRATON
MURRAY
BASIN
PERTH ABYSSAL PLAIN
NATURALISTE PLATEAU
BROKEN RIDGE
BIGHT
BASIN
MIDDLE - UPPER EOCENE
DIAMANTINA FRACTURE ZONE
NEW CALEDONIA BASIN
NORFOLK
CHALLENGER PLATEAU
SOUTH TASMAN RISE
CAMPBELL
PLATEAU
KERGUELEN PLAIN ABYSSAL
MIDDLE - UPPER EOCENE
WILKES
KNOX COAST
SABRINA COAST
BANZARE COAST
CLARIE COAST
ADELIE COAST
GEORGE V COAST
0
1000 KMS