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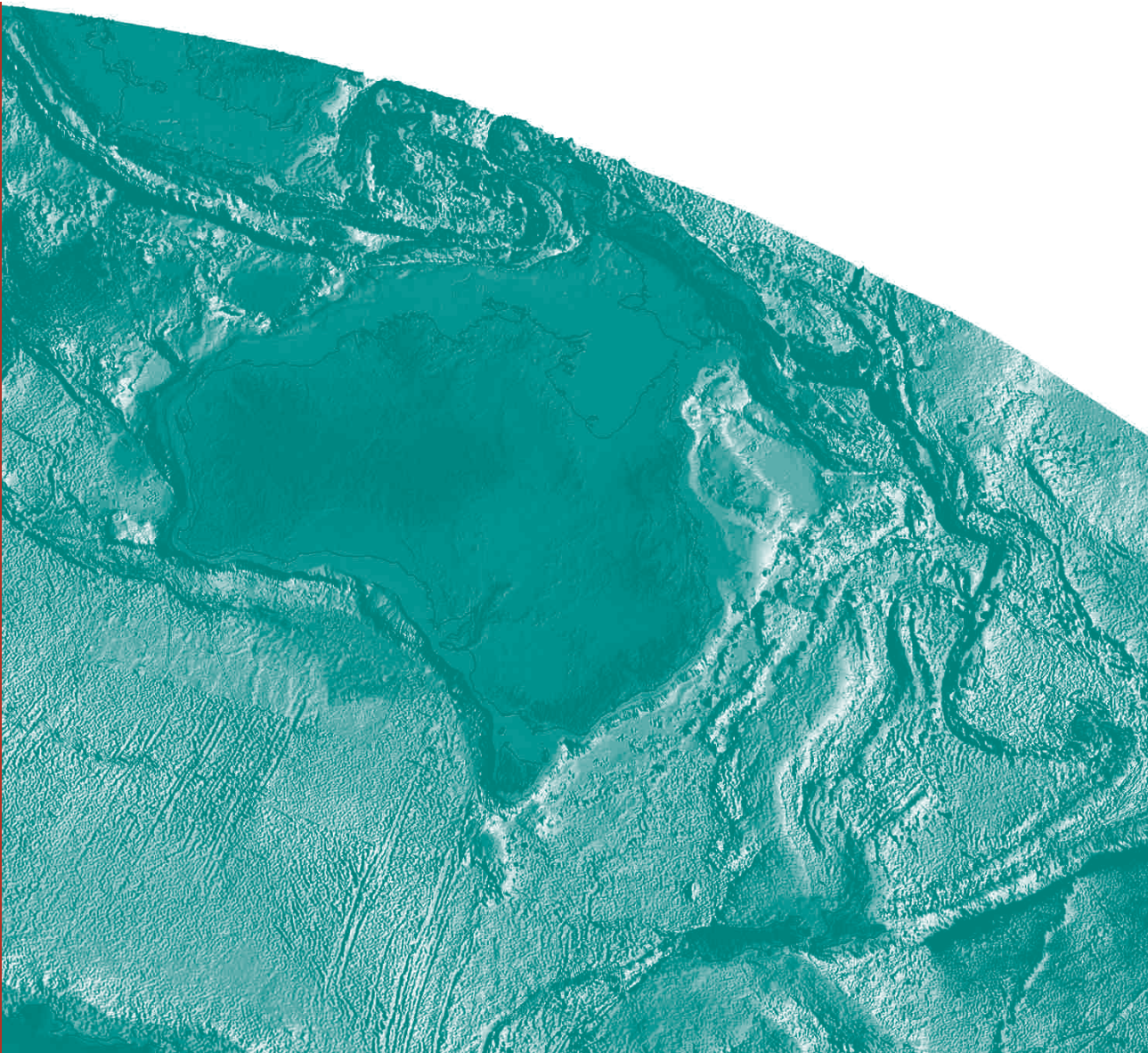
Geoscience Australia

Tectonic and Stratigraphic History of the Perth Basin

Norvick, M.S.

Record

2004/16



GEOSCIENCE AUSTRALIA
DEPARTMENT OF INDUSTRY, TOURISM & RESOURCES

Geoscience Australia Record 2004/16

**TECTONIC AND
STRATIGRAPHIC HISTORY
OF THE PERTH BASIN**

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CANBERRA 2004

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ISSN 1448-2177

ISBN 1 92087 11 X

Bibliographic reference: Norvick, M.S., 2003. Tectonic and Stratigraphic History of the Perth Basin. Geoscience Australia, Record 2004/16.

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Summary

The tectono-stratigraphic development of the southwestern corner of Australia is illustrated in a plate reconstructed setting with a series of palaeogeographic maps based on a newly compiled structural elements map and chronostratigraphic section for the Perth Basin.

The area is complicated by at least two periods of extensional faulting, one in the Late Carboniferous–Early Permian and a second in the Late Jurassic – Early Cretaceous, separated by sag basin development in the Late Permian to Middle Jurassic. Depositional centres migrated through time and appear to have suffered oblique extension, with the most structuring associated with the Late Jurassic – Early Cretaceous rifting episode. In addition, extensive volcanism leading up to breakup at about 132.5 Ma in the Valanginian has obscured the continent–ocean transition. The resulting basin structure comprises separate N–S to NNW–SSE oriented rifted sub-basins, which were rotated and shifted westwards through time. Barremian–Albian oceanic crust then grew in a northwesterly direction in the Perth Abyssal Plain and was followed after ~100 Ma by fast spreading in a NNW direction in the NE Indian Ocean. Strata deposited during the Barremian to Recent sag phase of the Perth Basin are relatively thin and unstructured.

Known or inferred source rocks in this complex basin include gas and minor oil-prone coals in the Lower Permian (Irwin River Formation), Upper Permian (Sue Group), Lower Jurassic (Cattamarra Coal Measures) and Upper Jurassic (Yarragadee Formation). Marine shales, which developed anoxia at flooding surfaces in the Lower Permian (?Carynginia Formation, ?Holmwood Shale) and basal Triassic (Kockatea Shale) became oil-prone source rocks. In addition, there is the possibility of a further speculative oil-prone source in the Bajocian (?Cadda Formation) in deep water areas.

Introduction

This report summarises a structural and stratigraphic compilation for the Perth Basin that was started in 2001, and revisited and revised in 2003. The project was initiated and supported by AGSO, now Geoscience Australia, as part of an ongoing series of studies aimed at predicting the stratigraphy and evolution of the undrilled outer continental margins of Australia (e.g., Norvick, 2000, 2001, 2002). The southwestern corner of Australia, including the Perth Basin, was considered sufficiently distinct to warrant a separate project. Oblique extension, the shifting loci of rift faulting and sedimentation, and extensive breakup volcanism make this area particularly complicated. Also, both the vintage of available seismic data, and intensive faulting, sometimes makes structural interpretation difficult. The final assessment of the tectono-stratigraphic history is therefore speculative and should be revised as new data becomes available.

As with previous studies on the continental margins of Australia, a structural elements map incorporating the latest structural interpretations of the area, at least to the continent–ocean boundary has been compiled. Then a composite cross section has been selected from published sources (discussed below), where possible based on seismic data, and a chronostratigraphic transect has been drawn to illustrate the evolution. The structural and stratigraphic history incorporates comments on known and hypothetical petroleum source systems, and is illustrated with a series of palaeogeographic sketch maps, which are largely based on Norvick & Smith (2001).

Geoscience Australia provided financial support and data under a Collaborative Research Project, and helped with the drafting. Heike Struckmeyer's (Geoscience Australia) encouragement was vital to the completion of the project. Of the large number of other people who helped with comments and suggestions, the following are particularly acknowledged:

- Barry Bradshaw (Geoscience Australia)
- Virginia Passmore (formerly Geoscience Australia)
- Irina Borissova (Geoscience Australia)
- Arthur Mory (Geological Survey Western Australia)
- Barry Kohn (Earth Sciences, University of Melbourne)
- Ursula Weber (Earth Sciences, University of Melbourne)

Structural Elements

MAPPING METHODOLOGY

The structural elements map for the Perth Basin ([Enclosure 1](#)) is based on gravity, magnetic and bathymetry/elevation displays extracted from the Geoscience Australia GIS database and a compilation of Geoscience Australia and Geological Survey of Western Australia (GSWA) structural element boundaries (documented in Bradshaw et al, 2003). Where possible, the Bradshaw et al (2003) boundaries have been used. However, in some cases, minor modification and new structural elements from published sources were used, based on the gravity and magnetic data.

The general elements and some of their names are taken from Jones (1976) and Hocking et al (1994). Northern onshore Perth Basin mapping is after Mory & Iasky (1994, 1996). In addition, Song & Cawood (1999, 2000, 2001) published detailed fault mapping in the northern Dandaragan Trough and Dongara Saddle. Southern onshore and offshore detailed mapping is based on Crostella & Backhouse (2000) and Bradshaw et al (2003), but with some of the elements extracted from Dentith et al (1994), Harris et al (1994) and Marshall et al (1989b, 1993).

BASEMENT TERRAINS

Precambrian terrain boundaries, and basement lineaments adjacent to the Perth Basin, have been discussed by Dentith et al (1994). Archaean crust underlies the Yilgarn Craton and is made up of several separate terrains. Of these, the boundary between the Lake Grace and Boddington terrains, which is coincident with the Yandanooka-Cape Riche gravity lineament, appears to have been reactivated as the Turtle Dove transfer zone (discussed below). South of the Yilgarn Craton, the Albany Fraser Zone is a later Proterozoic orogen (~1.4 – 1.1 Ga). The Darling Fault marks the eastern margin of the Perth Basin and is probably a Phanerozoic reactivation of a much older end-Archaean terrain boundary (Blight et al., 1981; Dentith et al., 1993). Thus, the older Proterozoic Pinjarra Orogen (~2.1 – 2.0 Ga in the Mullingarra, Northampton and Leeuwin inliers, which was reactivated ~1.5 – 1.1 Ga in the Leeuwin Block) probably underlies most of the Perth Basin, although dating of basement intersections in wells (Peers & Trendall, 1968) requires re-evaluation.

PALAEOZOIC SOUTH CARNARVON BASIN

Palaeozoic onshore basin trends in the southern Carnarvon Basin are taken from gravity images, and GSWA and AGSO reports. Mory et al (1998) mapped the Coolcalalaya Sub-basin. Iasky and Mory (1999), Iasky et al (1998, 2003) and Gorter et al (1994) have examined the structure of the Gascoyne Platform and surrounding areas. The Ordovician to Devonian basin was perhaps originally a saucer shaped depression and contained thick basal clastics

(Tumblagooda Sandstone) and a mixed carbonate–clastic association higher in the succession. Peculiar features in this province include a small area of Lower Silurian salt, which falls in part within the Devonian Woodleigh impact structure (Iasky et al., 2001). The Woodleigh structure is ~120 kms in diameter and has been dated at close to the Frasnian-Famennian boundary, based on illitic clays from the central shock-metamorphosed granitoid basement and reworked material from the base of Jurassic lacustrine fill (Mory et al, 2000; Mory, GSWA, pers. comm.).

The Gascoyne Platform shows strong NE–SW orientated gravity trends that are interpreted as faults. These are somewhat at variance with the published lineaments shown in Iasky et al (1998b). In the western part of the Gascoyne Platform, the Bernier Ridge is a large fault-bounded area with Cretaceous resting directly on basement over its crest. The Giralia Fault just enters the northern border of the map area. This lineament marks the southwesternmost limit of Carnarvon Basin trends and it intersects NW–SE orientated faults characteristic of the northern offshore Perth Basin.

In the latest published structural elements maps (Bradshaw et al, 2003), the inshore ‘Edel Terrace’ has been abandoned as a separate named element. There is apparently no evidence from seismic or gravity data for any separation from the onshore Gascoyne Platform, which is now interpreted to continue offshore as far as the edge of the Abrolhos Sub-basin.

CARBONIFEROUS–PERMIAN BASINS

Large half grabens of Late Carboniferous to Early Permian age occur both under the Mesozoic basins (eg Dandaragan Trough, Abrolhos Sub-basin) and also well away from later depocentres (eg Coolcalalaya, Merlinleigh and Byro Sub-basins, and the Collie outlier). In many cases, but not exclusively, the original rift phase was aligned north–south. There appears to have been a change to post-rift sagging within the Early Permian but it is unclear whether this transition was synchronous across the region. Structural elements for the Coolcalalaya Sub-basin are from Mory et al (1998), the Merlinleigh Sub-basin is based on Iasky et al (1998) and Crostella (1995), and the Collie outlier on Le Blanc Smith (1993).

TRIASSIC–CRETACEOUS BASINS

After the Early Permian, the overall picture of basin development has been one of intermittent sagging and oblique rifting until the Valanginian, followed by margin subsidence during a passive spreading phase in the Valanginian to Recent. A complicating aspect is that the successive Permian to Lower Cretaceous depocentres sometimes had slightly different locations. Also, the extension direction appears to have rotated through time. For instance, in the northern Perth Basin (Dongara area), the Lower Permian rifts (Irwin Terrace, Dandaragan Trough) are close to north–south but the Triassic to Middle Jurassic basins (Abrolhos Sub-basin) tend to be aligned NNW–SSE, and the Upper Jurassic to Valanginian depocentres (Houtman Sub-basin) are more NW–SE. Many of the earlier faulted depocentres became inverted in the next youngest phase, either by deformation on listric normal faults (eg Dandaragan Trough; Song & Cawood, 2000) or by fault reversal (Turtle Dove Ridge, rollovers in the proximal Houtman Sub-basin).

A further complication is that there has been significant segmentation of the basin by approximately NW–SE orientated transfer faults. From south to north, the major transfers are the Perth Fracture Zone south of the continent, the Harvey transfer within the Vlaming Sub-basin, the Turtle Dove and Cervantes transfers on either side of the Turtle Dove Ridge, and the Abrolhos transfer leading into the Wallaby–Zenith Fracture Zone. Dentith et al (1994) demonstrated that Precambrian terrain boundaries and other ancient shears played a significant part in forming these transfer zones. Some of the transfers appear to have turned into strike-slip faults and led to inversions of previous half grabens at certain times of basin reorganisation. For instance, on the Turtle Dove Ridge, Permian half grabens seem to have suffered inversion prior to the Triassic (see sections in Quaife et al, 1994).

Northern offshore Perth Basin mapping is based on Quaife et al (1994) and Smith & Cowley (1987), with additional studies by Marshall et al (1989a, b), Crostella (2001) and Bradshaw et al (2003). However, published maps and interpretations are of little help in the deeper water parts of the Houtman Sub-basin and north of Wittecarra-1. In these frontier areas, the mapping is based on gravity, magnetics and Shell Petrel seismic lines N305–308. There are also 1986 BMR seismic lines over these areas (Marshall et al, 1989b) but their published display quality did not allow significant reinterpretation. The relationships between the northern Houtman Sub-basin and Bernier Platform, and the area north towards the Carnarvon Terrace, are also poorly constrained on [Enclosure 1](#). It is assumed that depocentres in this area are equivalent to those in the Houtman Sub-basin and infilled with Upper Jurassic – Lower Cretaceous strata. However, it is possible that the rift fill sediment packages seen on seismic sections may be Permian rather than younger. Two of the Shell Petrel seismic lines (N305 and N306) also show broad inversions of ?Late Cretaceous – Tertiary age. These inverted structures seem similar to others farther north on the Carnarvon Terrace and southern Exmouth Sub-basin (see Tindale et al, 1998; Muller et al, 2002), and perhaps were also caused by stresses set up at the northwestern corner of the Australian continent in the Late Cretaceous and Tertiary.

Bradshaw et al (2003) name a new deep-water structural element, the Zeewyck Sub-basin, which they suggest may contain stratigraphic elements of both the Houtman and Vlaming Sub-basins. In [Enclosure 1](#), the southern half of the Zeewyck Sub-basin has been changed from Bradshaw et al (2003), and is shown here as volcanic margin crust because the reflections on the seismic lines look more like seaward dipping reflectors (SDRS) than sedimentary rocks.

The Vlaming has been drilled but little has been published apart from Marshall et al (1993), Spring & Newell (1993), and Crostella & Backhouse (2000). The structural elements are based on Crostella & Backhouse (2000) and Bradshaw et al (2003). It contains localised thick Upper Jurassic – Lower Cretaceous depocentres and sub-commercial oil accumulations. It is still difficult to find published reviews about geology of the western Vlaming Sub-basin, the deep water Mentelle Basin and the Naturaliste Plateau. The stratigraphy and structure of the undrilled Mentelle Basin are speculative. Interpretation of seismic lines by Bradshaw et al (2003) suggests that only a thin section of Upper Jurassic and Lower Cretaceous is present. Naturaliste Plateau structural elements are based on Borissova (2002a, b), Bradshaw et al (2003) and a new interpretation of the gravity images. The plateau appears to be thinned continental crust, which is connected to the mainland via extensional zones below the Mentelle Basin.

The relationship between the Perth Basin and Australia's southern margin is also difficult to determine. North–south Permian and Triassic faults appear to be abruptly truncated south of the Bunbury Trough. Southern margin basins are assumed to be Callovian–Kimmeridgian to Early Cretaceous in age and include the faulted Denmark Trough and Bremer Sub-basin (but not the onshore Tertiary feathered edge of the Bremer, east of the map area). East–west faults mark the inner edges of these depocentres and the Recherche Sub-basin, the western limit of which is marked by the Perth Fracture Zone. Further west other sub-parallel NW–SE fracture zones occur in oceanic crust. The GSWA distinguishes the western half of the Recherche as the Albany and Mondrain Sub-basins (Hocking et al, 1994) but this subdivision is not followed by Bradshaw et al (2003).

NATURE OF THE CONTINENT–OCEAN TRANSITION

In the Perth Basin, the location of the continent–ocean boundary (the COB) is difficult to pick because of extensive volcanics over the transition zone. Symonds et al (1998) have distinguished various volcanic features especially in the Wallaby Plateau and its vicinity, including SDRS, and submarine and subaerial volcanic highs. Wherever possible, the mapping of Symonds et al (1998) is followed on [Enclosure 1](#). It is possible that some of the volcanic areas, such as the Wallaby Saddle, are underlain by thinned continental crust. Further south, Borissova et al (2002a, b) mapped the area adjacent to the Perth Basin (south of Geraldton to

the north side of the Naturaliste Plateau) as volcanic margin crust. Borissova et al also indicated a lack of clear oceanic magnetic anomalies in the area south from the Naturaliste Plateau to the Diamantina Fracture Zone and in the Gonneville Triangle. The Gonneville Triangle may be oceanic crust, but the area north of the Diamantina Fracture Zone is strongly faulted, and may include thinned continental crust as well as oceanic crust.

The COB is marked on [Enclosure 1](#) where the bathymetry and gravity signature indicates the outer edge of rifted continental crust and the beginning of volcanic edifices and ‘normal’ oceanic crust. The age of oceanic crust generally follows Muller et al (1998). However, the gravity displays show poorly defined oceanic lineaments that run slightly oblique to obvious major fracture zones (such as the Abrolhos FZ). It is therefore possible that there has been more than one direction of Early Cretaceous spreading. Perhaps spreading started parallel to the indistinct fracture zones running in a NW–SE direction, and then rotated to the clear WNW–ESE fractures by the Aptian–Albian.

Stratigraphic Compilation

CROSS SECTION

Because of the shifting nature of sedimentary depocentres and their fragmentation through time, it is impossible to choose a single representative dip-directed cross section to represent the structure and stratigraphy of the Perth Basin. Instead, a doglegged section was compiled from several sources. This composite section also demonstrates lateral changes in the chronostratigraphy ([Encl. 2](#)).

The onshore Perth Basin is represented using a section across the Irwin Terrace, Dandaragan Trough and Dongara Saddle from Song and Cawood (2000, fig. 5), even though the stratigraphy along this section differs from that in the southern onshore Perth Basin. The Dandaragan Trough shows clear syn-sedimentary fault growth in the Lower Permian and Upper Jurassic, with more laterally continuous sag sedimentary packages in between. The Collie coalfield (Le Blanc Smith, 1993) is tied onto the Dandaragan Trough via a dogleg. On the chronostratigraphic section, the stratigraphy of the palaeo-drainages in the Norseman area (Clarke, 1994; Clarke et al, 2003) is also projected into the section line to represent the featheredge of the Eucla Basin. For completeness, the stratigraphy of the Bunbury Trough, offshore Vlaming Sub-basin and the onshore area around Perth have also been projected onto the chronostratigraphic section, based on Spring & Newell (1993), Crostella & Backhouse (2000) and Davidson (1995).

Offshore sections of Quaife et al (1994, figs 4 and 5) through the Abrolhos Sub-basin are tied onto the adjacent Dandaragan onshore line. Once again, there is clear half graben formation in the Lower Permian, followed by relatively thin Upper Permian sags. Quaife et al show the sag sequence extending to the Upper Triassic. However, some of the seismic lines suggest that there was fault-controlled thickening into the same Lower Permian faults during the Early to Middle Triassic, for example just east of Geelvinck-1. Also, Quaife et al, and Song & Cawood (2000), indicate that renewed rifting occurred in the Late Triassic or Early Jurassic, during the deposition of the Eneabba Formation, although this is hard to see on the available seismic lines. Most of the evidence for this second rifting event appears to come from regional mapping of formation thicknesses. The final phase of rifting in the Late Jurassic to Valanginian is more obvious, although it does not appear to involve thickening into faults in the Abrolhos Sub-basin, when most of the faults were active.

The Houtman Sub-basin is represented by the southwestern end of Quaife et al’s (1994) figure 4, tied via a dogleg onto BMR line 57-09. The latter shows poor reflection quality and is difficult to interpret. On neither of these lines is there enough lateral variation in reflector

geometry to predict facies changes, nor is there useful seismic penetration beyond the top of the Middle Jurassic (top Cadda reflector). In this study, the interpretation of Stagg et al (1999) (similar to that of Marshall et al, 1989b) is used for line 57-09 with a little modification. One of the two wells in the Houtman Sub-basin, Houtman-1 penetrated only slightly deeper than the base Cadda horizon.

Quaife et al (1994) show the Houtman hinge and the transition to the Houtman Sub-basin via a collapsed rollover anticline. The principal change over this hinge zone is the thickening of the Upper Jurassic Yarragadee Formation, although it is uncertain whether the thickening was caused by expansion of the section over faults or erosion on the landward side. The former interpretation is favoured. The BMR line shows a second collapsed rollover anticline in deep water. Farther out again, there is a clear set of seaward-dipping reflectors, which are assumed to be basic volcanic flows of approximately Berriasian–Valanginian age, implying equivalence to the Bunbury Basalt. The COB in this area is not visible on the seismic section but is expected to be a strike slip fault. There are a few indistinct seaward-dipping reflectors outboard of the COB, which raises the possibility of a more transitional margin.

The geology of the Collie Coalfield (Le Blanc Smith, 1993) raises some interesting issues about missing section in areas peripheral to the Perth Basin. In the Collie Coalfield, most of the Permian biozones except the uppermost ones are present, although the section is relatively thin (1400 m) compared with the Dandaragan Trough (up to 6500m) and Bunbury Trough (up to 2000m). Also, the orientation of the faults is at odds with that in most of the Perth Basin depocentres, in that the controlling faults are aligned NW–SE, ie parallel to the Harvey Ridge and other offshore transfer zones, and oceanic fracture systems. Vitrinite reflectance (Ro) measurements average 0.43% in the Upper Permian and 0.60% in the Lower Permian of the Collie Sub-basin. These maturities clearly indicate past burial and the removal of at least some overburden, although it is difficult to reach the 4000–6500 m of eroded section calculated by Le Blanc Smith. Given that Ro at surface before burial will have been about 0.20%, a more realistic estimate of missing section would be ~1000–2000m.

In the Irwin Terrace the Lower Permian Irwin River Coal Measures (Le Blanc Smith & Mory, 1995) has a similar maturity to that at Collie. About 1700m of Permian section is present and the coal measures are ~550m below the top of the preserved section. A thickness of ~1500 m of Mesozoic can therefore be deduced as once covering the existing section.

If the stratigraphy was similar to that in the Dandaragan Trough, the implication is that Triassic and Lower – Middle Jurassic section once extended over the Collie and Irwin River Coalfields and perhaps over other parts of the Yilgarn Craton, prior to footwall uplift and erosion during Upper Jurassic rifting.

Recent work on U/Pb dating of zircons (Cawood & Nemchin, 2000) provides additional support for this rather radical hypothesis. Zircons from the Upper and Lower Permian in the northern Dandaragan Trough indicate mixed derivation from a wide range of Archaean and Palaeo- to Neoproterozoic terrains. However, Lower Triassic Kockatea Shale samples completely lack Archaean zircons and in fact have a Late Palaeoproterozoic to Mesoproterozoic age spectrum quite similar to that in the Northampton Block, which may underlie much of the onshore Perth Basin. Cawood and Nemchin explain the absence of Archaean zircons in the Triassic to the initiation of northward flowing river systems derived from Antarctica, which completely bypassed the local Yilgarn sediment source. Perhaps an equally believable explanation is that the Yilgarn Craton was quarantined from providing sediment during the Triassic because it was covered by ~1–2 km of overburden, and the zircon spectrum was largely derived from India or Antarctica. Additional zircon dating from the Upper Triassic and Lower Jurassic are needed to confirm this hypothesis.

Implications from the hypotheses set out above are that the Triassic – Lower Jurassic Perth Basin had a very different palaeogeography and cross section than we see today. The basin may have spread out far beyond the Darling Fault and been much more of an intra-cratonic sag.

Given the faulting patterns and breakup history that we see offshore, it seems likely that the main period of faulting in the Bathonian to Early Valanginian was responsible for fragmentation of this Triassic – Lower Jurassic sag basin and erosion of section on the footwall of the major faults. Thus the Darling Fault for instance may have been active mainly during the Early Permian and again in the Bathonian – early Valanginian. However, the Urella Fault was also active throughout the Triassic and Jurassic, because the Triassic–Middle Jurassic to the west of that fault is ~4000 m thick (Mory & Iasky, 1996).

CHRONOSTRATIGRAPHIC SECTION

Basement terrains beneath the Perth Basin are expected to be Palaeo-, Meso- and some Neoproterozoic equivalents of the Northampton and Leeuwin Blocks. The Darling Fault may have been an ancient terrain boundary with the Archaean Yilgarn Craton to the east. At the western edge of the present continental slope, there may have been attenuation of the lower crust during the earliest Cretaceous. Outcrops in the Shillong and Mikir Hills, Assam, India, may represent the adjacent basement terrain. Hutchison (1989) describes an older series of high-grade metamorphics in Assam, unconformably overlain by younger metasediments up to garnet grade and intruded by granites dated 795–765 Ma.

Lower Palaeozoic sequences beneath the northern part of the Perth Basin (Gascoyne Platform and Edel Terrace) represent the southern margin of the Carnarvon Basin. These sequences were deposited within an intra-cratonic sag in a tropical carbonate-siliciclastic environment that lasted from the Ordovician to the Devonian. There was an interval of salt deposition at the end of the Early Silurian (Wenlockian Yaringa Formation) but no evidence has so far been seen on seismic lines of salt tectonism. A meteorite or bolide impact crater has been identified at Woodleigh, of probable Late Devonian age.

Deposition in the Perth Basin began in the Early Carboniferous in a series of active half grabens with either a north–south or NW–SE orientation. Sedimentation was initially glacio-marine (Nangetty Formation and Holmwood Shale) with deglaciation in the Sakmarian. This was followed by deposition of marine sands (High Cliff Sandstone), regression into delta-top coal measures (Irwin River) and transgression into Artinskian–Kungurian marine muds and sands (Carynginia Formation). According to Quaife et al (1994) and Song and Cawood (2000), the initial syn-rift phase ended with deposition of the Holmwood Shale when the Darling Fault became less active. However, a significant unconformity within the Upper Permian (?top Carynginia Formation), is more likely to represent the end of the syn-rift I megasequence. The Irwin River Coal Measures and shales within the Carynginia Formation provide two of the gas-prone source rocks in the basin.

The Upper Permian appears on offshore seismic lines as a thin sequence infilling the bottom of sags immediately after the cessation of active half grabens, indicating an early post-rift or transitional basin phase. Stratigraphically, this megasequence contains a range of laterally variable units, including the shallow marine Dongara Sandstone, fluvial Wagina Sandstone and mixed carbonate-siliciclastic marine units over the Beagle Ridge, collectively referred to as the Beekeeper Formation.

Quaife et al (1994) and Song and Cawood (2000) show the Upper Permian as being continuous into the Lower Triassic Kockatea Shale. However, there are frequently several end-Permian biozones missing, apparent thickening of the Kockatea Shale across selected faults and the presence of localised basal Triassic sands (Wittecarras Sandstone Member), all of which suggest a degree of fault reactivation at the beginning of the Triassic.

One of the more conspicuous regional stratigraphic events is the marine flooding surface and gamma ray log peak at the base of the Kockatea Shale that carries high TOC and represents a regional source rock with distinctive acritarch-based biomarkers. This horizon is followed in the offshore by a generally regressive marine to fluvial section up into the Woodada

Formation. A regional sequence boundary was mapped extensively at the top of the Woodada Formation by Quaife et al (1994), where there may be minor local erosion. However, other Middle and Upper Triassic sequence boundaries shown in Quaife et al are difficult to follow on the available seismic sections. The overlying Middle – Upper Triassic Lesueur Sandstone forms a thick and distinctive unit of amalgamated fluvial sands. This was probably laid down by one of the long-lived northward-flowing river systems. Quaife et al suggest that there are more marine seismic facies in the outer offshore areas, but these changes are not obvious on seismic lines seen in the present study.

The change across the Triassic–Jurassic boundary appears to be transitional and the intra-Upper Triassic sequence boundary from post-rift to syn-rift geometries is not obvious. The main change seems to be a gradual, and perhaps diachronous, transition from fluvial sands to multi-coloured playa lake deposits near the bottom of the Jurassic (Eneabba Formation). Song and Cawood (2000) record fault activity near the beginning and also near the end of Eneabba deposition. A top Eneabba seismic horizon is sometimes mapped offshore, which may also represent a sequence boundary. Above this horizon, there is a change to coal-bearing, delta top sandstones (Cattamarra Coal Measures), which locally have gas-prone source potential. This Lower to Middle Jurassic package represents a second major period of deposition by northward-flowing rivers.

There is a distinctive Middle Jurassic shallow marine interval, largely Bajocian in age, which represents the next regional marine flooding surface, the Cadda Formation. Source potential has never been demonstrated within this interval, but facies considerations suggest that more distal marine equivalents may be in the correct facies and sequence position to develop anoxia, perhaps in the north of the basin or in (present day) deep water areas to the west. This is the last Jurassic unit to be deposited in a passive subsidence phase, although Quaife et al (1994) show it as part of the rift megasequence, which is difficult to support here.

The third major northward-flowing fluvial package is the Bajocian–Tithonian Yarragadee Formation, laid down during a period of active normal faulting throughout the basin. In the Berriasian to Early Valanginian, a second unit, the Parmelia Group includes strata of fluvial origin onshore. More marine time equivalents to the Parmelia Group may be present in the Vlaming Sub-basin. The combined Yarragadee–Parmelia package reaches over 6000m in thickness adjacent to the Urella and Darling Faults in the southern Dandaragan Trough. Facies belts in the Yarragadee Formation and Parmelia Group are difficult to map on a regional scale, but a change from fluvial to deltaic or shallow marine sedimentation in the north of the Houtman Sub-basin is possible. The collapsed rollovers and final faulting phases may be coeval with its deposition. The Parmelia Group is assumed to be equivalent to the Bunbury Basalt onshore, and the volcanics implied by the seaward-dipping reflectors in deep water. It is also coeval with the offshore Barrow delta in the Northern Carnarvon Basin, implying a separate and possibly parallel river system debouching into the sea.

Continental breakup, and the associated formation of ocean crust, was in the Valanginian (132.5 Ma according to Veevers et al, 1991). Faulting and sedimentation then more or less stopped throughout most of the basin. However, in the Vlaming Sub-basin, up to 1500 m of Valanginian–Barremian clastics (Warnbro Group) accumulated starting with basinal turbidites and finished with deltaic and fluvial facies (Spring and Newell, 1993). This succession may represent an early post-rift megasequence. The stratigraphy of the Zeewyck Sub-basin is largely unknown but, given its position, a sequence similar to this area is probable, although facies are more likely to be entirely deep water.

BMR seismic lines suggest that the Cretaceous–Tertiary section reaches a maximum thickness (up to 1 second twt) in the outer continental shelf. Most of this long period of time, therefore, is represented by deepwater condensed sequences offshore, and by hiatuses and thin limestone and greensand onshore. Turbidite mounds have been recognised on seismic data in the offshore northern Perth Basin in the Upper Aptian or Lower Albian (Quaife et al, 1994). Carbonate sedimentation became more widespread in the Campanian–Maastrichtian with the deposition of

the Gingin Chalk. There are downlap or maximum flooding surfaces in the Aptian (112 Ma), Campanian (80 Ma), end-Early Eocene (49 Ma) and Mid-Eocene (44 Ma). Erosional sequence boundaries occur at the end-Cretaceous (65 Ma), Mid-Oligocene (30 Ma) and end-Miocene (6 Ma). Correlations into the Norseman area suggest that flooding events are difficult to follow between the two basins. In the Bremer Sub-basin and around Norseman, marine flooding surfaces occur at ~44–42 Ma and 38–35 Ma (Hou et al, 2003; Clarke, 1995; Clarke et al, 2003; Gammon et al, 2000). The final events in the Perth Basin are the formation of deep canyons along its outer continental margins, and the deposition of carbonate aeolian dunes along the coast, during the Pleistocene.

Palaeogeographic Evolution

METHODOLOGY AND PALAEOGEOGRAPHIC MODELS

Palaeogeographic maps for the Perth Basin have been constructed on palinspastic plate reconstructions in an attempt to piece together the depositional systems in the basin and the drainage that supplied sediment to them. The plate reconstructions of Veevers & Tewari (1995), Veevers (2000) and Norvick & Smith (2001) were used for the reconstructions. Isopach and palaeo-current directions published by Mory & Iasky (1996) and Veevers (2000) were used as a guide to predicting depositional facies and river directions.

Figure 3 shows a plate palaeogeographic map for the end-Carboniferous glacial episode based on Veevers & Tewari (1995) and Figure 4 shows Permian to Cretaceous palaeogeographies modified from Norvick (2000) and Norvick & Smith (2001). The two slightly different plate models for the end-Carboniferous and Early Permian (Figs. 3 and 4a) illustrate the uncertainties associated with the precise shape and position of the Perth Basin early in its history. Thus, the Veevers & Tewari model is similar to other configurations shown for instance by Muller et al (1998), and assumes rigid crust in NE India (the Shillong Plateau of Assam) and the eastern Himalayas. In the former model these areas abut the western side of the Naturaliste Plateau in the pre-rift position, and the area opposite the Perth Basin comprises thinned Greater Indian crust that is now hidden under the Tibet overthrust. On the other hand, Norvick & Smith (2001) assumed that NE Indian crust was significantly deformed, both by thinning prior to breakup and also by strike-slip faulting for instance along precursors of the Dauki Fault in northern Bangladesh. In this model, Assam and the Shillong and Mikir Hills occupy the conjugate margin adjacent to present day Perth, and the proto-Dauki Fault and its splays continued to the SE and linked with the Naturaliste and Perth Fracture Zones. In both cases, the Mahanadi Graben in India was the northern continuation of the Amery Permian basin in Antarctica, and this relationship provides the principal tie point to either reconstruction.

UPPER CARBONIFEROUS – PERMIAN RIFTS

The initial stage of development of the Perth Basin in the Carboniferous was the formation of a set of half grabens, linked by saddles and switches in the position of the master faults (Fig. 3). According to Eyles et al (2002), glaciation accompanied graben formation as early as late Viséan–early Namurian. By the end of the Carboniferous, the graben complex ran at least from the Merlinleigh Sub-basin in the north to the Bunbury Trough in the south and may also have continued into Antarctica, where ice cover and lack of outcrop prevents its identification. Other rifts also occurred further to the southwest in Damodar, the Mahanadi–Amery basin complex and the Krishna–Godavari Basin.

Initially, the basins were filled with glacial sediments derived from the ancestral Gamburtsev Mountains in central East Antarctica. One of these major glaciers crossed over into the Bunbury Trough (Mosswood and Nangetty Formations) and there may have been a separate one directed towards the northwest into the Collie Basin (Stockton Group). The glaciers opened

into shallow seaways in which glacio-marine sands and shales (eg Holmwood Shale and Highcliff Sandstone), alternating with deltaic sediments (eg Irwin River Coal Measures, [Fig. 4a](#)) were deposited in the Perth Basin.

Deglaciation started in the Sakmarian and the deltaic to marine rifts continued to fill from the south and became more marine towards the north. Active faulting slowed in the north from the Sakmarian onwards, and in the Kungurian–Ufimian, the Dandaragan Trough and other northern basins went into an early post-rift sag phase (Wagina and Dongara Sandstones, and Beekeeper Formation). It should be noted that this detailed timetable of glacial retreat and slowing of extensional faulting is not precisely dated, especially in areas reliant on seismic interpretation.

Upper Permian–lowermost Triassic volcanics and some intrusives are also known from the northern Perth Basin. Volcanics and lamprophyre dykes in Edel-1 are the best documented (see review in Gorter & Deighton, 2002). These igneous rocks may be associated with the final stages of extension in one of the failed arms of the Permian breakup event, but their ages are somewhat later than the Early Permian rift to post-rift transition mentioned above.

TRIASSIC – MIDDLE JURASSIC SAG BASINS

There was a subtle basin reorganisation at the beginning of the Triassic in which deposition spread out over a much larger area than in the Late Permian ([Fig. 4b](#)). At this time much of the Yilgarn Craton may have become covered with sediment (discussed above). An extensive marine transgression affected not only much of the Perth Basin (Kockatea Shale) but also the Carnarvon (Locker Shale), Canning (Blina Shale) and Bonaparte Basins (Mt Goodwyn Shale). The basal few metres of these units often comprise a radioactive shale with high organic carbon, and a very rapid regional transgression is indicated. In the Perth Basin, there may also have been minor erosion from high areas of former fault blocks causing the deposition of the localised Wittecarra Sandstone Member, although this sandy facies may be somewhat younger than the radioactive shale. The Kockatea Shale covered most of the basin but in the south there was a sandier facies (Sabina Sandstone in the Bunbury Trough), suggesting that the basin was closed and filling from this direction.

Towards the end of the Early Triassic, there was regression to fluvial facies (Woodada Formation). This was followed after a localised disconformity by further Early to end Triassic, long-lived fluvial systems (Lesueur Sandstone) ([Fig. 4c](#)). In this study, the Lesueur rivers are assumed to have flowed from the south or SW and covered both the Perth Basin and much of the Yilgarn Craton. Palaeo-current data in the northern Perth Basin support a SW to NE river direction in this area (Mory & Iasky, 1996) and the local isopachs suggest a degree of syn-depositional thickening into the Urella Fault.

Around the beginning of the Jurassic, there was a slightly diachronous change to non-marine red bed sedimentation (Eneabba Formation), including multi-coloured silts and clays, with some channel sands. These sediments may have been laid down in playa lakes and high sinuosity rivers. Minor extensional syn-depositional faulting is indicated in some parts of the northern Perth Basin at this time. This mild tectonism apparently ceased in the Pliensbachian at a localised disconformity, and was followed by deposition of delta-top swamp deposits, the Cattamarra Coal Measures ([Fig. 4d](#)). Overall, this Eneabba–Cattamarra succession suggests gradual slowing of sedimentation and/or growth of accommodation space, perhaps accompanied by slow transgression. Certainly, in the Early Jurassic marine sedimentation covered the Exmouth Sub-basin to the north (Sinemurian–Pliensbachian Murat Siltstone and Pliensbachian–Aalenian Athol Formation), suggesting that Eneabba–Cattamarra rivers debouched into a northern seaway.

An extensive but short-lived Bajocian marine transgression deposited thin marine silt and sand (Cadda Formation; [Fig. 4e](#)). The age of this transgression is unusual regionally on the Australian western margins, and the driving force is difficult to identify.

UPPER JURASSIC – LOWER CRETACEOUS RIFTS

During the Bathonian, there was an abrupt resumption of coarse fluvial sedimentation (Yarragadee Formation), which was probably accompanied by the onset of major extensional faulting that lasted to the end of the Jurassic. In the palaeogeographic reconstruction (Fig. 4f), the Perth Basin is shown as the left branch of a triple armed rift system. A southern arm probably ran along the future Antarctica–India boundary (although there is no direct information) and a western branch ran into the Recherche and Eyre Sub-basins. The Yarragadee fluvial systems apparently flowed from south to north, and the original rivers may have had their headwaters in the India–Antarctica rift (implied by the provenance study of Sircombe and Freeman, 1999). The northern end of the Yarragadee rift probably passed into more deltaic and finally marine environments, because the next basin to the north (Exmouth Sub-basin) was definitely marine by the Middle to Late Jurassic (non-marine to marine sands in the Learmonth Formation and marine shales in the Athol, Anchor and Dingo Formations).

The reactivation of the Darling Fault and footwall uplift of the adjacent Yilgarn (Fig 4f) is assumed to have resulted in the initiation of east-flowing drainage across the Yilgarn Craton and the dismemberment and erosion of Triassic cover there. However, the apatite fission track information from southwest Australia compiled by Kohn et al (2002) does not show any increase in apparent denudation in the Late Jurassic – Early Cretaceous. This tectonic reconstruction must therefore be regarded as hypothetical.

In the Tithonian to Berriasian, there was a poorly delineated change to red bed sedimentation in the Parmelia Group. This unit was probably also deposited in a syn-tectonic rift setting. The deeper water parts of the Houtman and Zeewyck Sub-basins may have received more deltaic or marine equivalents of the Parmelia Group at this time (Encl. 2) but there are so far no well penetrations to confirm this possibility.

The time equivalent of the Parmelia Group further north in the Exmouth and Barrow Sub-basins is the very thick Barrow Group delta. This major delta appears to have been fed from a relatively short-lived river system debouching from the depression underlain by the Merlinleigh Sub-basin but the position of its headwaters is unclear. It is possible that much of the erosion products of the Yarragadee and older units from the Perth Basin could have been funnelled into the Barrow delta. However, the route of a speculative river from the northern Houtman Sub-basin through the Carnarvon Terrace to the Barrow delta has been disrupted by Early Cretaceous inversion and is no longer identifiable. A river along the Merlinleigh Sub-basin appears the more likely sediment source for the Barrow delta.

VALANGINIAN BREAKUP

Early in the Valanginian, there was extensive basic volcanism along the southwest margin of Australia as a precursor to breakup and the formation of ocean crust (Fig. 4g) at around 132.5 Ma (Veevers et al, 1991). The volcanism was particularly voluminous on the Wallaby Plateau, where it formed both subaerial and submarine flows (Symonds et al, 1998). Other areas of volcanic activity are evident along the base of the continental slope adjacent to the Perth Basin as far south as the Naturaliste Plateau. Basalts were also extruded onshore in the Bunbury Trough and Gorter & Deighton (2002) review several other occurrences in the Houtman Sub-basin. The most recent aeromagnetic data over the Bunbury Trough clearly shows flows confined to palaeovalleys, and presumably coming off the Yilgarn (A. Mory, GSWA, pers. comm.). The flows appear to be heading south, at least in the onshore part of the trough and their source seems to be somewhere east of the Darling Fault.

The early stages of ocean crust formation are difficult to map because of masking by volcanism, but the most likely place that it started was on either side of the Naturaliste Plateau before it propagated both north towards the Wallaby–Zenith Fracture Zone, and south along the India–Antarctica margin. At the same time as breakup, the eastern rift branch into the

Recherche Sub-basin changed to post-rift sagging. On the map ([Fig. 4g](#)), uplift shown close to the south coast is presumed to have disrupted the palaeo-drainage, and redirected runoff to the north and east towards the Norseman area and the western Eucla Basin. Once again, this uplift event is speculative and is not supported by apatite fission track data.

Immediately following breakup, faulting in the Perth Basin virtually ceased, and localised sagging into deeper water became the dominant structural process. Valanginian to Barremian submarine sediments, including turbidites accumulated in these more basinal areas, of which the best known is the Gage Sandstone (Warnbro Group) in the Vlaming Sub-basin (Spring & Newell, 1993). There may have been similar sediment packages developed in the outer Houtman and Zeewyck Sub-basins, but they have not yet been drilled in these areas.

EARLY CRETACEOUS TO RECENT SAG PHASES

From the Barremian onwards, the southwestern margins of Australia became tectonically quiescent and relatively little sediment was laid down. The palaeogeographic map for the Aptian ([Fig. 4h](#)) shows a widening ocean basin between Australia and India. A very large igneous province began to form adjacent to the coast of India, which later became the Broken Ridge and Kerguelen Plateau, but this had no apparent influence on SW Australia. Sedimentation in the Perth Basin consisted of thin coastal clastics, chalks and marls in the Upper Cretaceous and thin coastal limestones and marls in the Tertiary.

Petroleum Systems

The known petroleum systems in the Perth Basin (also summarised on [Encl. 2](#)) include the following source rocks and reservoirs –

- Gas and oil in the north Perth Basin, sourced from the Kockatea Shale and Irwin River Coal Measures, is reservoirised in a variety of levels in the Permian and Lower Triassic. Accumulations include Dongara gas field, Mt Horner oil field and probably the newly discovered offshore Cliff Head oil field. Other fields include Mondara (now depleted), Yardarino, Beharra Springs, Beharra Springs North, Woodada, Jingemina, and Hovea. Coal measures and marine deglaciation-driven marine shales in the Permian are two obvious source systems. In addition, the basal Triassic Kockatea Shale is a classic high-TOC ‘hot’ shale produced by a regional flooding surface and has been tied to some of the oils with distinctive dinoflagellate-related biomarkers. Elsewhere in the world such a source could be expected to be highly productive. However, in spite of several fields being full to their spill points, the experience of drilling in the Perth Basin suggests that the Kockatea has apparently only generated moderate amounts of oil.
- Some of the gas in the north Perth Basin is sourced from the Cattamarra Coal Measures and coals in the Yarragadee Formation and reservoirised at several levels in the Cattamarra Coal Measures (eg Gingin, Mt Horner, Walyering, N. Yardarino).
- Gas occurs in tight sands in the Sue Group of the Bunbury Trough, which is probably sourced from coal measures in the same unit (eg. Whicher Range).
- Oil and gas in the Gage Roads area of the Vlaming Sub-basin is reservoirised in the Parmelia Group. The source is not entirely certain but is probably from the oil and gas-prone coals in the Upper Jurassic Yarragadee Formation.

In addition to these known or inferred source rocks, it is also possible that the Cadda Formation could include source potential. No source quality analyses are available but the unit was deposited at a maximum flooding surface at a tectono-stratigraphic position where marine anoxia could be expected. This unit may be in a better location under the more marine parts of the deep water Houtman Sub-basin to develop anoxia and here it may provide another, albeit speculative source rock.

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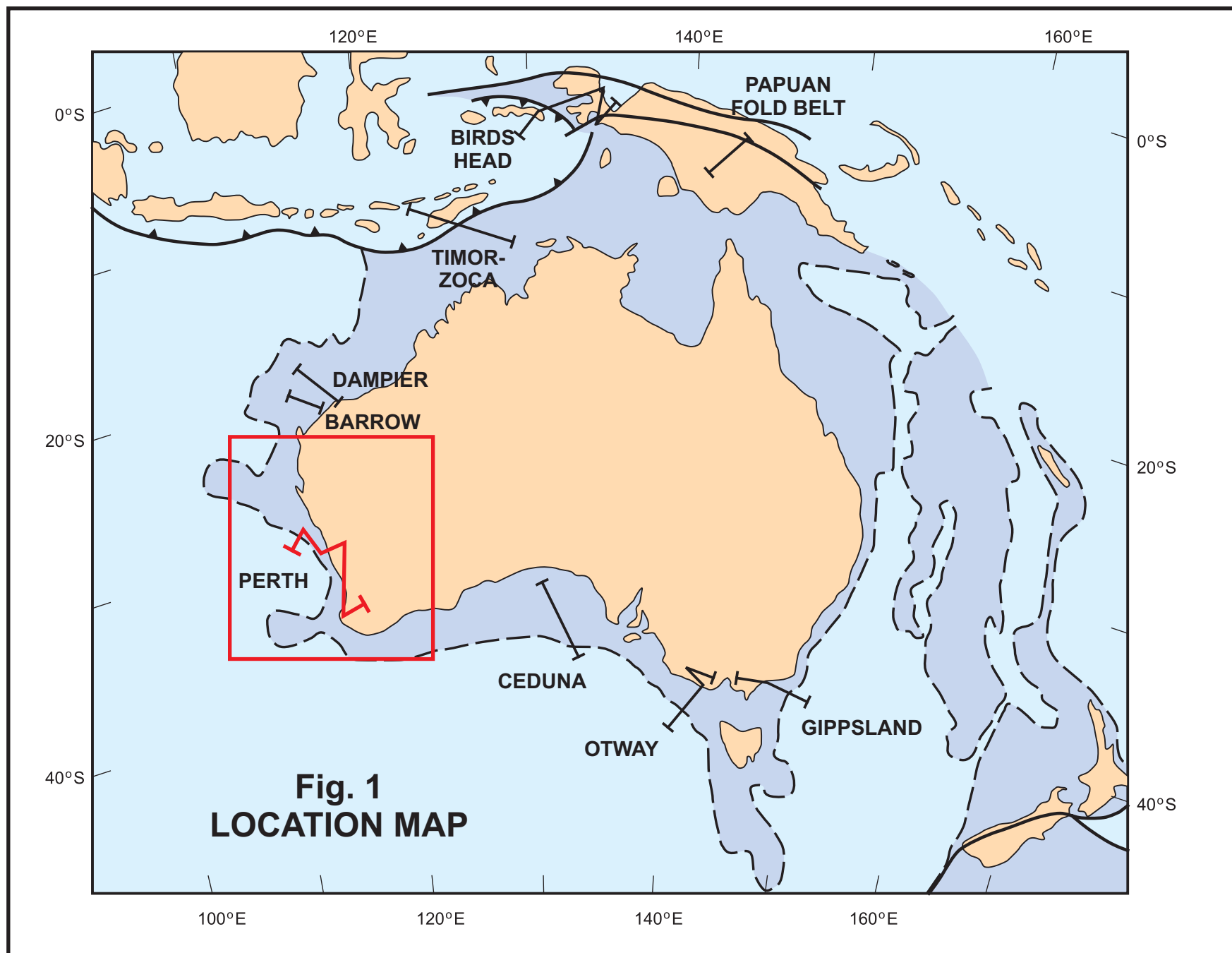
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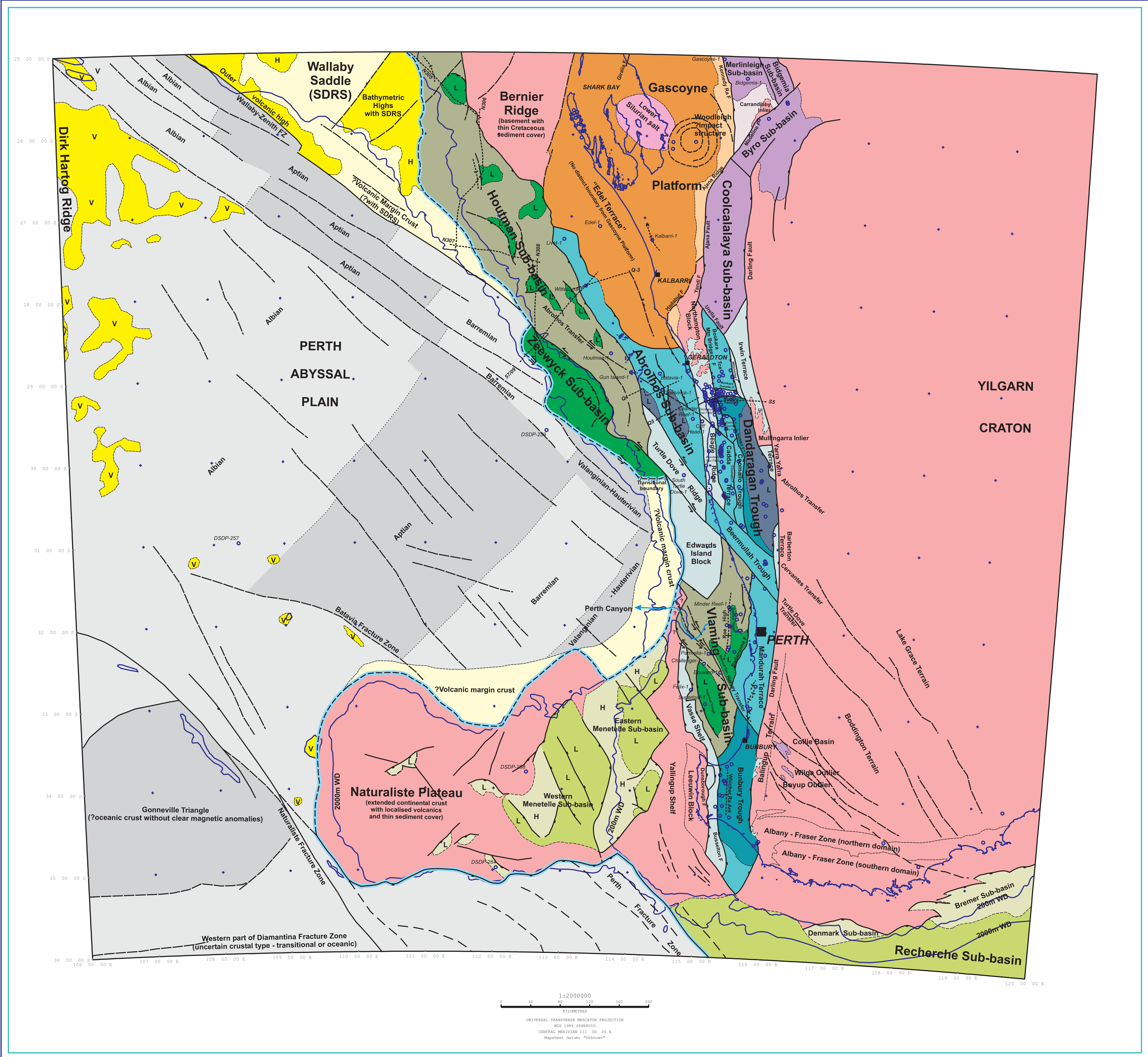


Fig. 2. STRUCTURAL ELEMENTS MAP

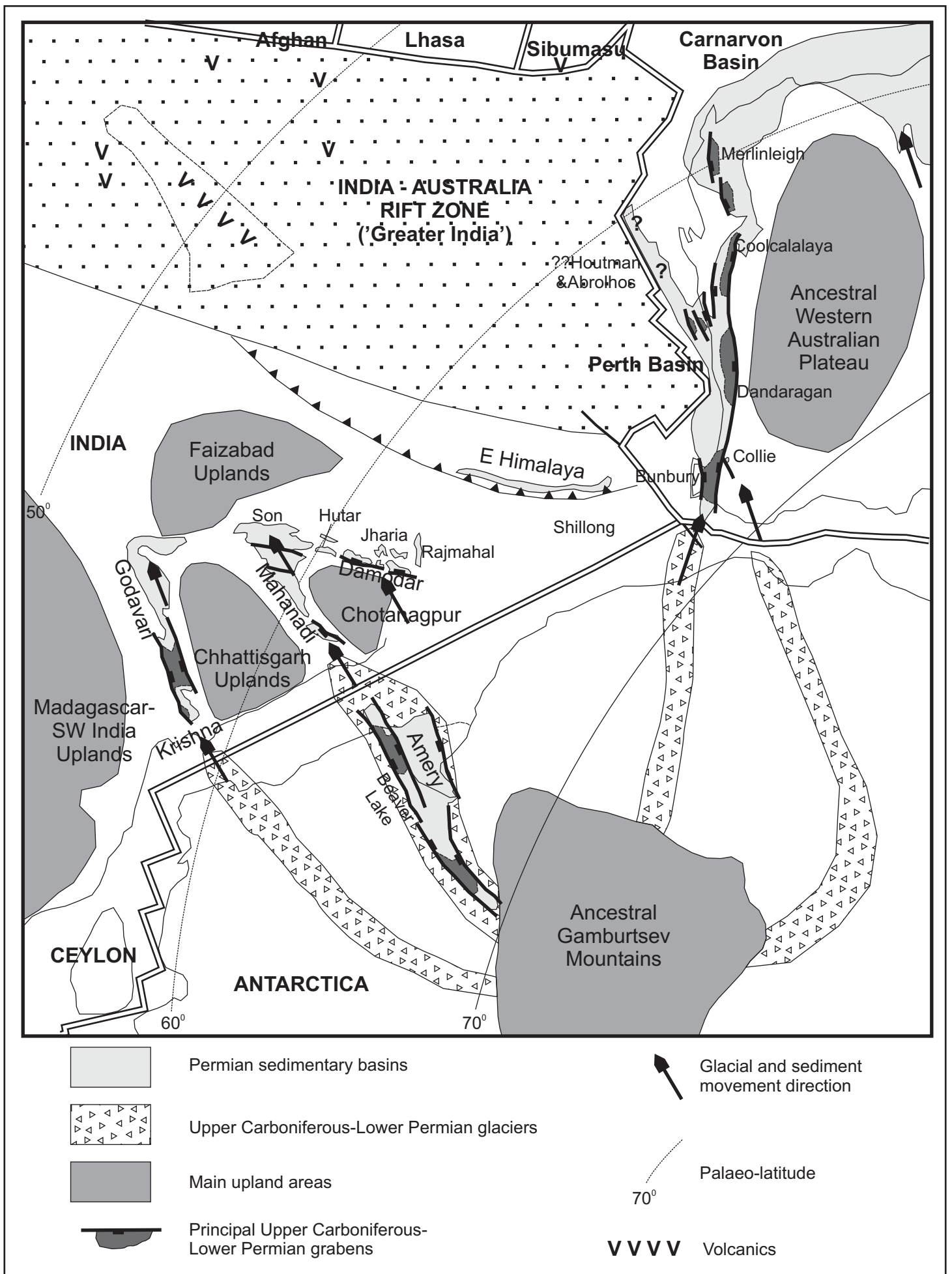
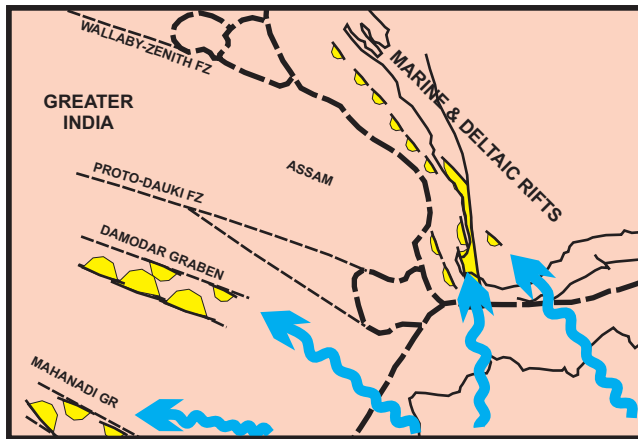
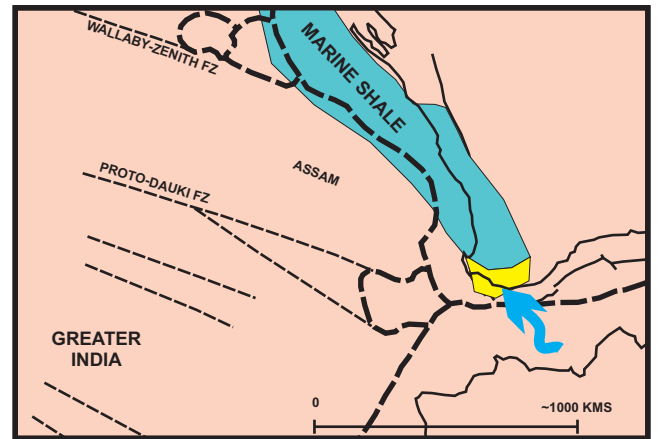


Fig. 3. Regional tectonic framework of Western Australia, India and Antarctica at about the Carboniferous-Permian boundary (~300-290 ma). Based on Veevers & Tewari (1995), figs 33 and 43.

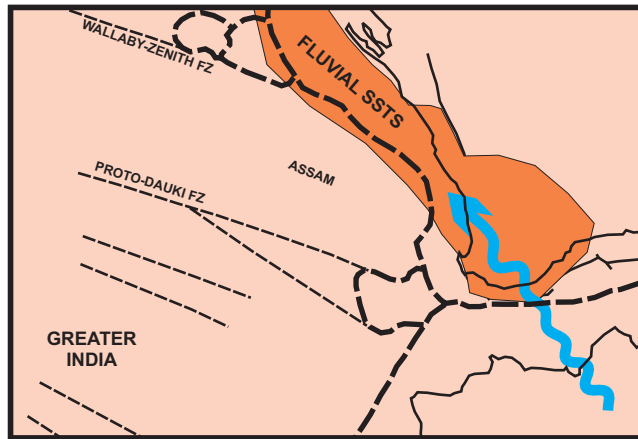
**a. EARLY PERMIAN, ARTINSKIAN (280MA)
IRWIN RIVER COAL MEASURES**



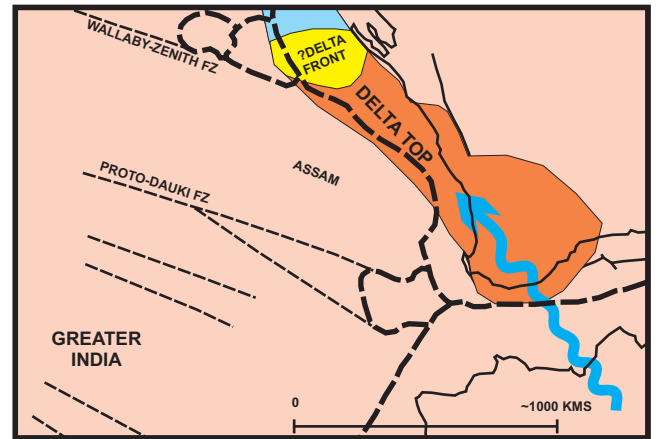
**b. EARLY TRIASSIC (250 MA)
KOCKATEA SHALE**



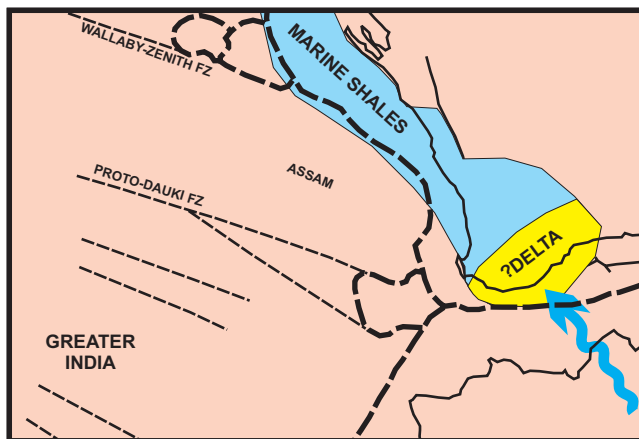
**c. LATE TRIASSIC, CARNIAN-NORIAN (220 MA)
LESUEUR SANDSTONE**



**d. EARLY JURASSIC, PLIENSCHACHIAN-TOARCIC (190 MA)
ENAEBA-CATTAMARRA COAL MEASURES**



**e. MID-JURASSIC, BAJOCIAN (175 MA)
CADDA FORMATION**



**f. LATE JURASSIC, MID-OXFORDIAN (155 MA)
YARRAGADEE FORMATION**

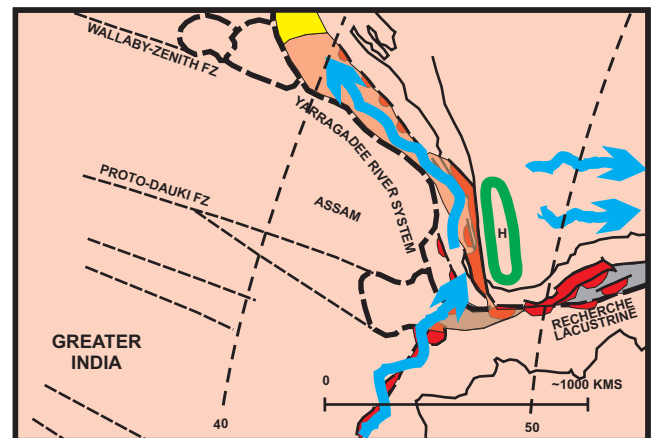
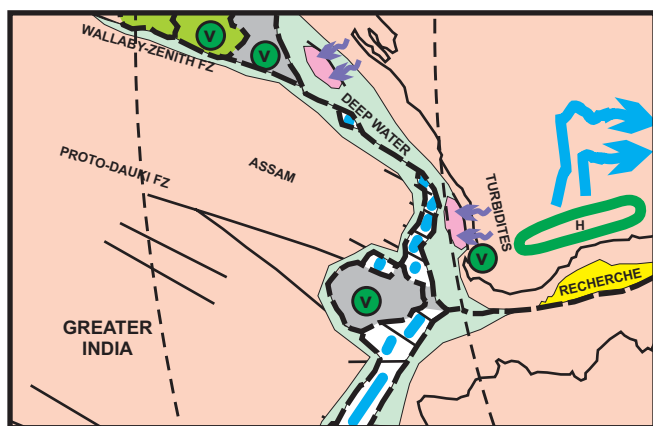
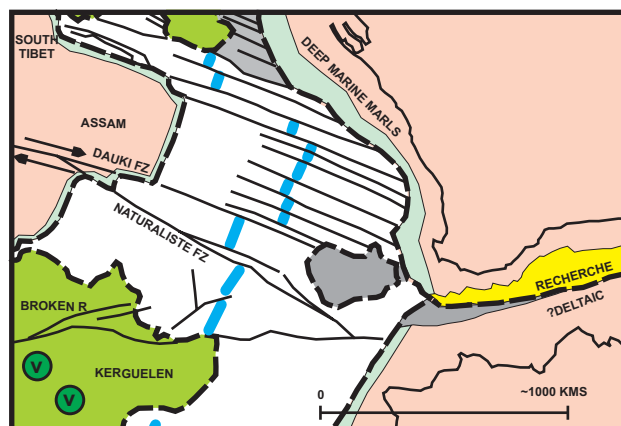


Fig. 4. Palaeogeographic sketch maps of the Perth region

g. EARLY CRETACEOUS, VALANGINIAN-HAUTERIVIAN (135 MA)
WARNBRO GROUP



h. EARLY CRETACEOUS, APTIAN (110 MA)



Legend

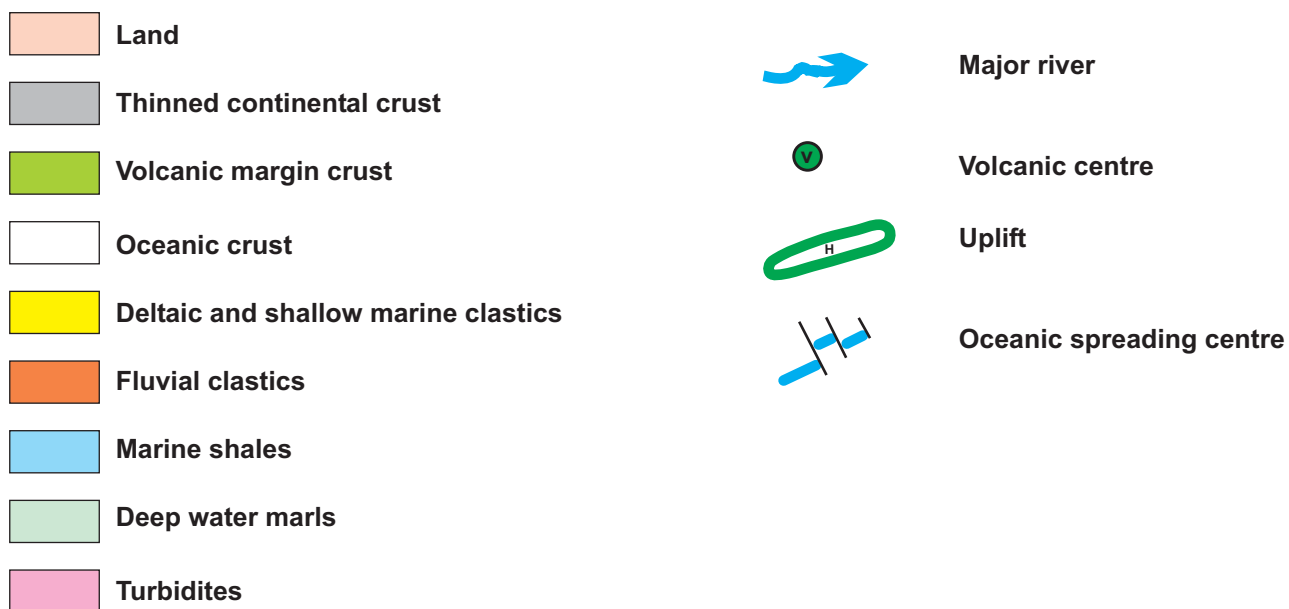
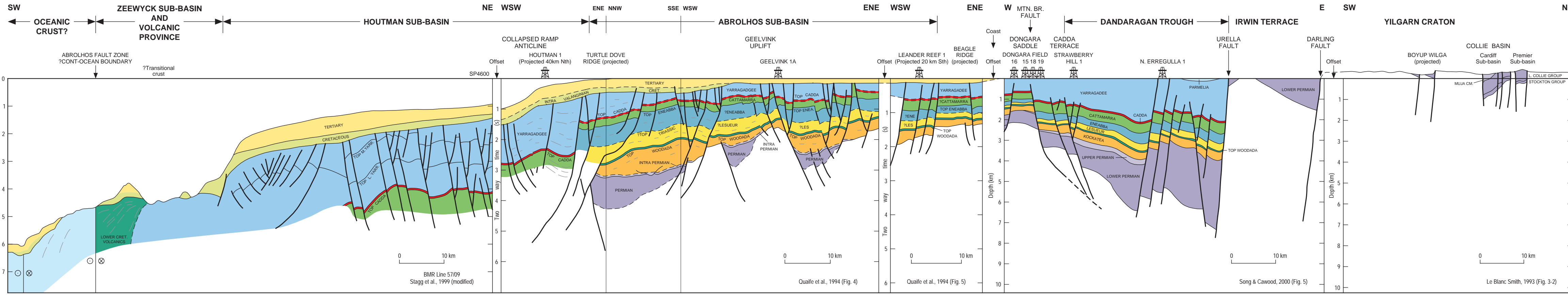
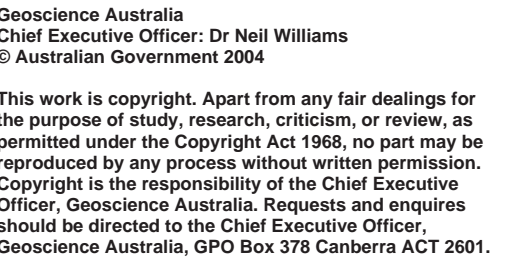


Fig. 4 (continued). Palaeogeographic sketch maps of the Perth region



REFEREN



Enclosure 2
PERTH BASIN
**CHRONOSTRATIGRAPHIC
SECTION**