A New Kinematic Model for the Formation and Evolution of the West and Northwest Australian Margin.

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Abstract

Satellite altimetry has revolutionised our knowledge of the tectonic structure of the ocean floor and the continental shelves where ship data are sparse. We have used existing and new ship magnetic, bathymetric and seismic data with satellite derived gravity data to develop a revised model of Mesozoic continental breakup and sea-floor spreading in the Perth, Cuvier, Gascoyne and Argo abyssal plains. Based on this data set, we identified the boundary between continental and oceanic crust (COB), fracture zones, and traces of propagating rifts. In our model sea-floor spreading in the Gascoyne and Cuvier abyssal plains starts in the Lower Valanginian (136.2 Ma), 3.7 My earlier than previously interpreted. Combined with a model for the dispersal of Gondwanaland, our results imply that a shear zone between the southern and the northern part of Greater India is required to accommodate their relative motion between 136 and 99 Ma. A major plate tectonic event occurred at the Albian/Cenomanian boundary (~99 Ma), when the spreading direction between India and Australia changed from northwest-southeast to north-south. An event at about 61 Ma (magnetic anomaly 27) in the Early Paleocene is recorded in the Tasman Sea and in the southeast Indian and Pacific oceans as a change in spreading direction. Analysis of the tectonic history of 108 wells shows widespread anomalous subsidence or uplift on the North West Shelf at both times. The magnitude and location of the anomalous subsidence and uplift indicate that the 99 Ma event locally resulted in renewed lithospheric extension, whereas the 61 Ma event may reflect elastic buckling of the lithosphere. Both events may have originated from the stepwise subduction of the Neo-Tethyan Ridge, first north of India at 99 Ma and then north of Australia at 61 Ma. In the Miocene/Pliocene almost the entire North West Shelf from the Carnarvon Basin to the Timor Sea underwent accelerated subsidence, which started as early as 20 Ma in some areas, and reached magnitudes of more than 500 m up to 1000 km away from the Timor Trough. These observations cannot be explained by foreland basin loading, but are likely the result of a complex evolution of compressive intraplate stresses following the recent breakup of the Indo-Australian Plate into the Indian, Australian and Capricorn plates.

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Introduction

The breakup and early evolution of the dispersal of Gondwanaland is one of the remaining mysteries of plate tectonics. This is partly because no Mesozoic magnetic anomalies have been identified with confidence either offshore eastern India or in the Enderby Basin offshore from Antarctica. As a consequence, the breakup history between India and Antarctica can only be constrained indirectly. Further, that part of Greater India which was once adjacent to western Australia, is now either underthrusted or mixed into Eurasian lithosphere. Do the formation of the abyssal plains west of Australia reflect the breakup of an Antarctic-Australian Plate and a single Greater India Plate, or many separate pieces? Here, we utilise a combination of ship magnetic data and dense gravity anomalies derived from satellite altimetry to revisit this long-standing problem. We first present a revised, detailed model for the initial breakup and Cretaceous sea-floor spreading off western Australia, in the framework of the breakup of Gondwanaland. We then use this model jointly with other recently developed models for the history of sea-floor spreading east and south of Australia to review plate tectonic events around Australia and their impact on the tectonic evolution of the

North West Shelf. We show that, unlike most other passive margins, the North West Shelf has recorded several phases of anomalous tectonic subsidence or uplift since 100 Ma.

Previous Work

Regional Setting

The west and northwest margins of Australia are old, sediment-starved volcanic continental margins, which formed as a result of multistage rifting and sea-floor spreading during the late Palaeozoic and early Mesozoic (Baillie & Jacobson, 1995; Bradshaw et al., 1988; Veevers, 1988). They comprise the Argo, Gascoyne, Cuvier and Perth margins (Fig. 1). The Argo segment comprises the Argo Abyssal Plain, alongside the Browse and Roebuck (former offshore Canning Basin) basins. The Gascoyne segment comprises the Gascoyne Abyssal Plain, alongside the Exmouth Plateau and the Northern Carnarvon Basin. The Cuvier segment is delimited by the Cape Range Fracture Zone (CRFZ) and Wallaby-Zenith Fracture Zones (WZFZ), and includes the Southern Carnarvon Basin, the Exmouth Sub-basin, the Cuvier Abyssal Plain and the Wallaby and Zenith plateaus. The Perth segment extends from the WZFZ to the Naturaliste Plateau in the south, and includes the Perth Abyssal Plain, the Perth Basin and the Naturaliste Plateau.

Sea-floor Spreading

The sea-floor spreading history between Greater India and Australia has been investigated by a number of authors including Falvey and Mutter (1981), Fullerton et al. (1989), Johnson et al. (1976; 1980), Larson (1977), Larson et al. (1979), Powell et al. (1988), and Sager et al. (1992). In these models, breakup and spreading starting in the Early Cretaceous circa 125 Ma (magnetic anomaly M10) created the Gascoyne, Cuvier and Perth abyssal plains. A comprehensive review of Early Cretaceous sea-floor spreading led to the isolation of a distinct magnetic anomaly interpreted by Veevers et al. (1985a) as the boundary between continental and oceanic crust (COB). Larson (1975) and Heirtzler et al. (1978) postulated the presence of an unknown plate northeast of Greater India which would have separated from Australia in the Mid-Jurassic (c. 155 Ma), creating the Argo Abyssal Plain (Veevers, 1988). The magnetic lineations in the Argo Abyssal Plain have been reviewed by Fullerton et al. (1989) and Sager et al. (1992) based on new aeromagnetic data and results from the Ocean Drilling Program (ODP) Leg 123. They concluded that sea-floor spreading started immediately prior to anomaly M26 (c. 155 Ma).

Tectonic Events

The western and northwestern Australian passive margins have been subjected to substantial tectonic reactivation. Major tectonic events and following changes in intra-plate stresses in the Mesozoic and Tertiary on the Australian plate were described by Etheridge et al. (1991). They pointed out that all oil and gas fields in the Carnarvon, Bonaparte, Gippsland and Eromanga basins, and many of those in the Cooper, Canning and Surat basins, are associated with tectonic reactivation. Veevers et al. (1991) recognised three major tectonic events off the western and southeastern margins of Australia, (1) the divergence of Argo Land from Australia (~160 Ma), (2) the southward penetration of the Indian Ocean ridge separating India from Australia-Antarctica (c. 132.5 Ma), and (3) the mid-Cretaceous (~96 Ma) eastward penetration of the southeast Indian Ocean ridge separating Australia from Antarctica. The mid-Cretaceous event is contemporaneous with the breakup unconformity in the Otway Basin reviewed by Veevers (1984), the slightly younger onset of seafloor spreading in the southern Tasman Sea at 95 Ma (Gaina et al., 1998), inversion in the Bass Basin (Hill et al., 1995) and a major subsidence event in the Eromanga Basin at about 100 Ma (Gallagher et al., 1994; Gallagher & Lambeck, 1989). Another tectonic event in the Early Paleocene (~61 Ma) is expressed in changes in spreading direction in the Tasman Sea (Gaina et al., 1998) and the Southern Ocean (Tikku & Cande, 1998). In this paper, we re-analyse the timing of major events, and investigate the relationship between tectonic and reactivation events on the North West Shelf, by combining detailed plate reconstructions with tectonic subsidence analyses of wells on the North West Shelf.

Time Scale

Previous studies of the oceanic crust adjacent to the Australian margin largely used the geomagnetic time scale of Harland et al. (1982). For the present study, we used the Gradstein et al. (1994) and Cande and Kent (1995) time scales for Mesozoic and Cenozoic magnetic anomaly identifications, and the AGSO time scale (Young & Laurie, 1996) for the stratigraphy and tectonic subsidence analysis of well data. Table 1 summarises the differences between these two time scales for tectonic events discussed here.

Breakup and Sea-floor Spreading History

Data

Closely spaced (~6 km) satellite altimeter profiles collected during the Geosat Geodetic Mission (Geosat/GM), and the ERS-1 Geodetic Phase (8 km) have

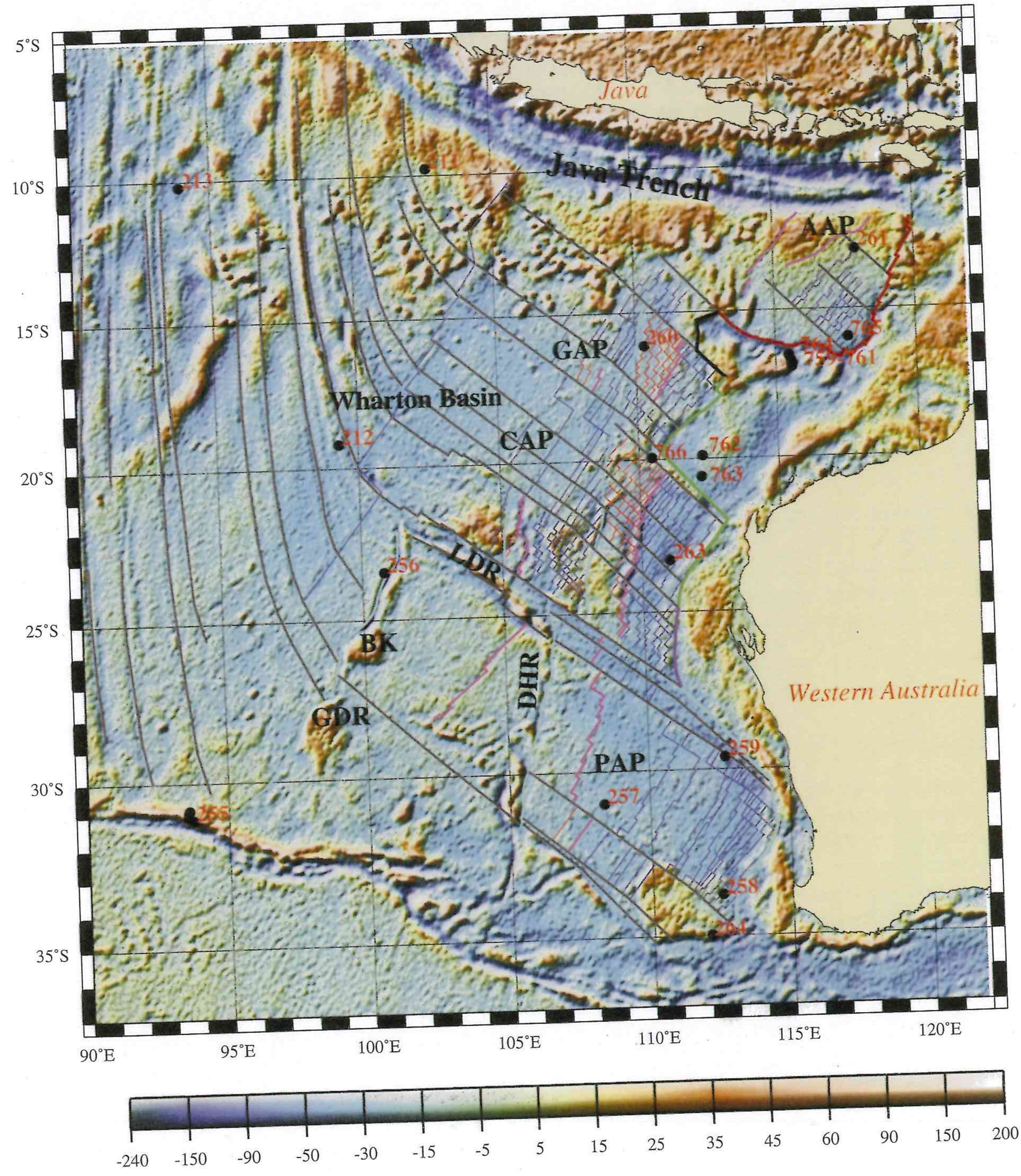

Figure 1: Isochrons (blue for Australian Plate and red for Indian Plate isochrons), COB (bold red – ~155-158 Ma, bold dark – ~138-140 Ma, bold green – ~ 130-135 Ma, bold lilac – ~136 Ma, bold cyan– ~130-131 Ma), fracture zones (grey), extinct ridges (magenta), and pseudofaults (cyan) superimposed on the gravity anomaly grid from Sandwell and Smith (1997). DSDP and ODP sites are numbered (red). AAP, GAP, CAP and PAP: Argo, Gascoyne, Cuvier and Perth abyssal plains; GDK and BK: Gulden Draak and Batavia knolls; DHR and LDR: Dirk Hartog and Lost Dutchman ridges.

yielded a dense gravity anomaly grid (Fig. 1) with an accuracy of 4–7 mGal (Sandwell & Smith, 1997). This marine gravity anomaly grid was used jointly with available magnetic data to interpret magnetic anomaly sequences in a structural framework of fracture zones and traces of ridge propagators/extinct ridges. The fabric of these tectonic features was not mapped before the construction of a detailed marine gravity grid from satellite altimetry. In particular, the new gravity data show that the abyssal hill fabric in the Argo Abyssal Plain does

Magnetic anomaly	Ages from Gradstein et al. (1994)[1], Cande and Kent (1995)[2]	Ages from Young and Laurie (1996)
M27	156.0[1]	153.0
M14	135.9[1]	133.9
M0	120.4[1]	114.9
	99.0[1]	96.4
C34	83.5[1]	83.0
C27	61.2[2]	61.1
C5	9.9[2]	10.0
C3	5.0[2]	5.0

Table 1: Ages for key times discussed in this paper from Gradstein et al. (1994), Cande & Kent (1995), and Young & Laurie (1996). Our magnetic anomaly identifications and models are based on the former two time-scales, whereas the ages of well data were determined using the biostratigraphy from Young & Laurie (1996).

does not match previous magnetic anomaly interpretations (Mihut & Müller, 1998a). We located the boundary between continental and oceanic crust (COB) based on the new gravity anomaly data, our magnetic anomaly interpretation, and seismic data.

Interpretation and Model

Argo Abyssal Plain

Our revised model for the formation of the Argo Abyssal Plain is presented in Mihut & Müller (1998a). Its major implication is that the Exmouth Plateau is not a Jurassic passive margin, as previously thought, but an oblique strike-slip margin. Our model also implies that the direction of the Jurassic opening between Argo Land and Australia was identical to that of the Cretaceous sea-floor spreading in the Gascoyne, Cuvier and Perth abyssal plains. This indicates that the breakup between Argo Land and Australia was merely the first step of a propagating rift, which separated Greater India from Australia in several steps.

Gascoyne Abyssal Plain

The Gascoyne Abyssal Plain (Fig. 2) is separated from the Argo Abyssal Plain to the north by the Roo and Joey rises, and bounded to the east by the Platypus Spur and the Exmouth Plateau. Fullerton et al. (1989) recognised M10 as the oldest anomaly found in all spreading compartments in both the Gascoyne and Cuvier abyssal plains, and suggested a nearly simultaneous breakup time along the western Australian margin. We interpreted three major fracture zones which divide the plain into three sectors, as well as two rift propagation events (Fig. 2). In the central part of the basin anomalies M0 (120.4 Ma) - M11 (132.5 Ma) were interpreted. This sector includes conjugate Indian anomalies M11-M7, whereas the southern sector includes conjugate anomalies M2-M3 (Fig. 2). In the northern part of the basin magnetic anomalies M10N-M12A were interpreted. Based on the satellite-derived gravity anomaly trends, two different sea-floor spreading directions were interpreted: a N45°E (different from the direction of N22°–26°E interpreted by Fullerton et al. (1989) for anomalies older than M5), and a N35°E trend, slightly different from the previous N33°E, for anomalies younger than M5.

Cuvier Abyssal Plain

The Cuvier Abyssal Plain (Fig. 2) is separated from the Exmouth Plateau by the Cape Range Fault Zone (CRFZ) and from the Perth Abyssal Plain by the Wallaby-Zenith Fracture Zone (WZFZ) and the Lost Dutchman Ridge (LDR). In the northern sector of the Cuvier Abyssal Plain east and west of the Sonne Ridge, conjugate anomaly sequences offset by local fracture zones were interpreted, which become progressively younger towards an interpreted extinct spreading ridge (Mihut & Müller, 1998a) (Fig. 2). The sequence identified on the eastern part of the Wallaby Plateau is represented by anomalies M11 to M14, offset by four local fracture zones. Conjugate anomalies (M2-M3) symmetric about a staircase shaped failed rift, followed to its eastern part by anomalies M4 to M10N are present in the Wallaby-Zenith Basin area (Fig. 2). In the northern compartments, M11A is the oldest anomaly interpreted. The distance between anomaly M11A and the interpreted COB is variable; therefore the breakup age is slightly asynchronous along this margin. This variability may be the result of differential stretching which occurred prior to continental breakup. In the southern compartment, the oldest anomaly is M14, which is older than the oldest anomaly in any other western compartment.

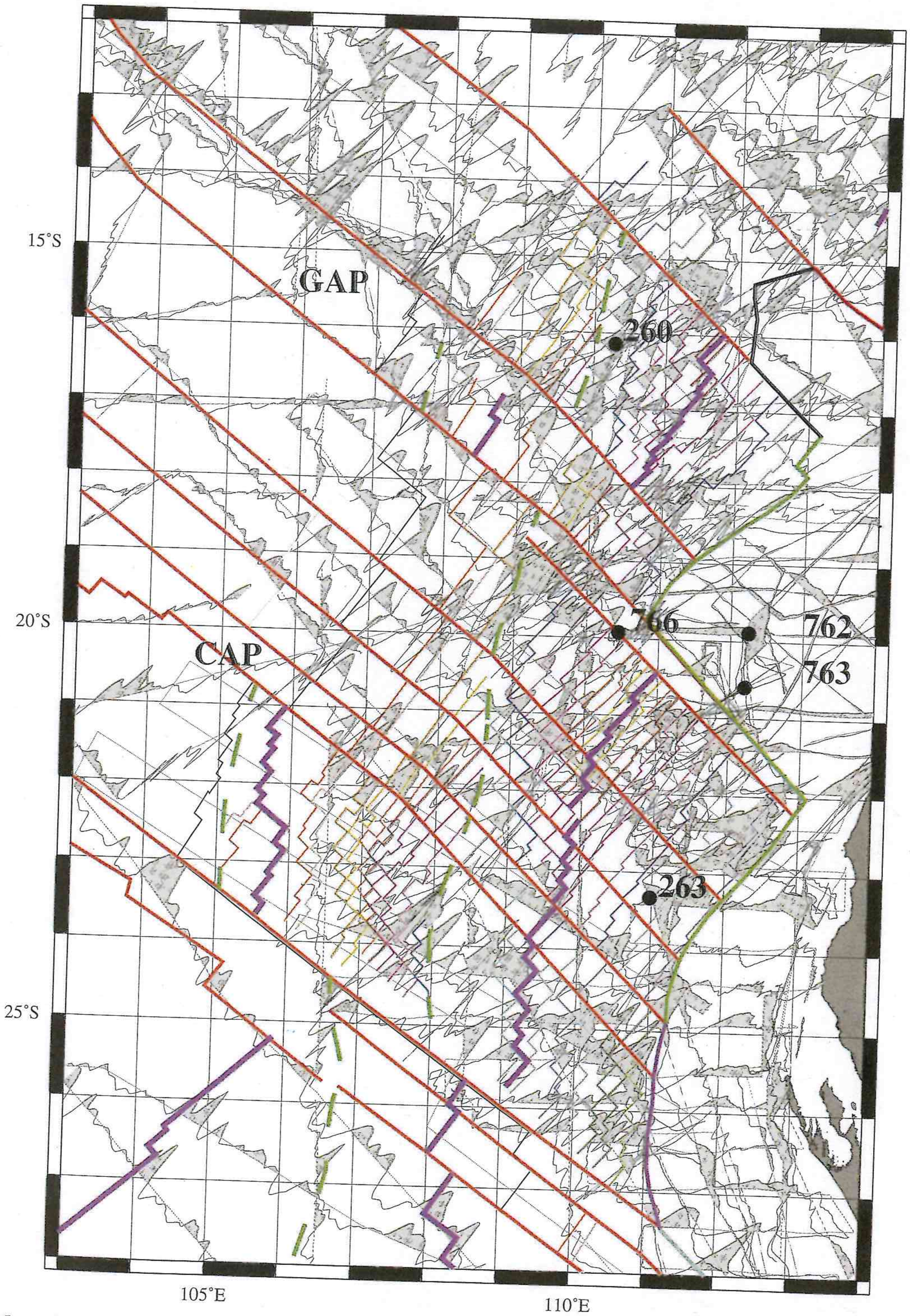

Figure 2: Magnetic anomalies along-track with positive anomalies plotted at 45° azimuth in the Gascoyne (GAP) and Cuvier (CAP) abyssal plains. Isochrons are colour coded as follows: M11 (132.1 Ma) — cyan, M10N (130.9 Ma) — dark blue, M10 (130.2 Ma) — pink, M9 (129.5 Ma) — magenta, M7 (128.4 Ma) — red, M6 (128.2 Ma) — light red, M5 (127.7 Ma) — yellow, M4 (126.7 Ma) — orange, M3 (124.7 Ma) — light pink, M2 (124.0 Ma) — brown, M1r (115 Ma) — light pink, M0 (120.4 Ma) — red. Extinct spreading ridges are coloured magenta, pseudofaults are dashed green, fracture zones red and the COB is bold black, green and lilac (see Fig. 1 for details). Both extinct ridges and pseudofaults are formed by migration of offsets in a mid-ocean ridge. In the Cuvier and Gascoyne abyssal plains, two rift propagation events have accreted segments of the Indian Plate to the Australian Plate between magnetic anomalies M10N and M4 and between M3 and M0. These segmants are bounded by extinct ridges to the east and by pseudofaults (separating older from younger crust) to the west.

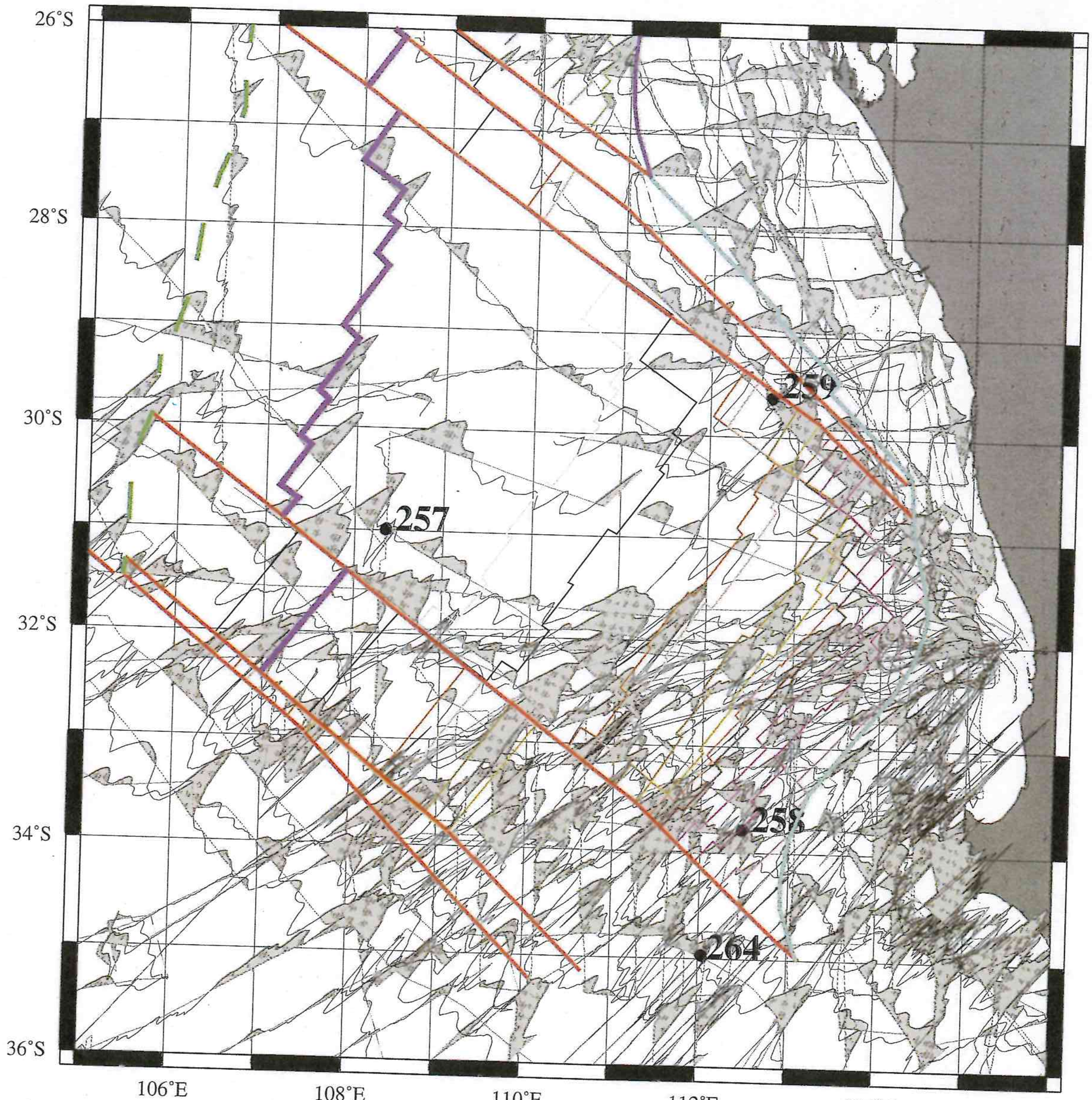

Figure 3: **Magnetic anomalies along-track with positive anomalies plotted at 45° azimuth in the Perth Abyssal Plain. Isochrons and other tectonic features are coloured as in Fig. 2.**

Perth Abyssal Plain

The Perth Abyssal Plain is bounded to the north and south by two fracture zones, the WZFZ and the Naturaliste Fracture Zone (NFZ), to the east by the Perth Basin and to the west by the Wharton Basin (Fig. 3). Our magnetic interpretation in the Perth Abyssal Plain resembles that of Veevers et al. (1985b). Gravity anomalies show several local fracture zones with similar trends to those interpreted in the Argo, Gascoyne and Cuvier abyssal plains. The centre of the basin is defined by a set of parallel anomalies that range from M1r to M10 (Fig. 3). An extinct ridge and pseudofault were identified west of the interpreted anomaly M1r (Fig. 3). The pseudofault is expressed in gravity anomalies by undulating, continuous linear highs (the Dirk Hartog Ridge) paralleling the failed ridge. These features were formed by a propagating rift between about 110 and 108 Ma (Fig. 3).

Wharton Basin

The Wharton Basin is delimited to the northeast by the Java Trench and Argo Abyssal Plain: to the east, by the Gascoyne, Cuvier and Perth abyssal plains, to the south, by Broken Ridge, and to the west, by Ninetyeast Ridge (Fig. 1). Following the magnetic anomaly identifications in the Wharton Basin by Sclater and Fisher (1974) and Liu et al. (1983), Krishna et al. (1995) identified a complete series of anomalies C33 to C20. Spreading stopped in the eastern Wharton Basin shortly after anomaly C20 (46.2

Ma) (Liu et al., 1983), possibly as a direct result of the collision between Greater India and Eurasia.

Early Cretaceous magnetic anomalies identified in the Gascoyne and Cuvier abyssal plains (Figs 1 & 2) display northeast-southwest orientations normal to the fracture zones recognised in the eastern Christmas Island area. The pattern of spreading in the Early Cretaceous persisted until about 99 Ma in the Cretaceous Magnetic Quiet Zone, when a drastic clockwise change in spreading direction from northwest–southeast to north–south occurred, resulting in roughly north-south oriented spreading in the Wharton Basin. This event is expressed by a major bend in many fracture zones and some unusual linear troughs, ridges and knolls visible in the gravity anomaly grid southeast of the Wharton Basin, including the Batavia and Golden Draak knolls (Fig. 1).

It is important to determine the timing of this event, because it resulted in major tectonic reactivation on the North West Shelf, as will be discussed later. Powell et al. (1988) proposed an age of 96 Ma for the event, based on extrapolation of spreading rates and directions. A ridge north of Batavia Knoll, 150 km southeast of the major bend in fracture zones (Fig. 1) was sampled at Deep Sea Drilling Project Site 256, and microfossils yielded a minimum age of 102 Ma (Luyendyk and Davies, 1974). The Albian-Cenomanian boundary is placed at 100 Ma in the time scale used by Luyendyk and Davies (1974), whereas this boundary is dated as 98.9 Ma by Gradstein et al. (1994), reducing Luyendyk and Davies' (1974) basement age estimate at Site 256 to a minimum of about 101 Ma. Our modelled half-spreading rate between Greater India and Australia after magnetic anomaly M0 time is 36 mm/y. Combining the DSDP minimum age of 101 Ma of the ridge north of Batavia Knoll with our estimated spreading rate yields a minimum age of 97 Ma for the fracture zone bend, located 150 km northwest of the dated ridge.

The breakup unconformity on the southern margin of Australia straddles the Albian–Cenomanian boundary (98.9 Ma, Gradstein et al., 1984) between the volcanogenic Otway Group and the quartzose Sherbrook Group, dated by means of the *Phimopollenites pannosus* palynological zone (Veevers, 1984). Veevers (1984) argues that the southern margin breakup and the major tectonic reorganisation between India and Australia are contemporaneous and mark the onset of the Poteroo tectonic regime. The difference between this age and the minimum age of 97 Ma derived above for the plate reorganisation between Greater India and Australia is within the combined errors of these age estimates. Therefore, we conclude that the two events can be regarded as identical in age, and we assign the Albian-Cenomanian boundary age of ~99 Ma to the major fracture zone bend south of the Wharton Basin (Fig. 1). In the AGSO time scale (Young & Laurie ,1996), this age corresponds to 96.4 Ma (Table 1), as their age assigned to magnetic anomaly M0 is 5.5 million years younger than Gradstein et al.'s (1994) age (Table 1). We follow the latter timescale, as their M0 age is well constrained by a radiometric tiepoint of anomaly M1r (123.5 ± 0.5 Ma) at ODP Site 878 on MIT guyot in the Pacific Ocean. The varying distance between the 99 Ma isochron and the M0 isochron west of Australia (Fig. 1) suggests that west of the Perth Abyssal Plain a major ridge propagation event accreted a segment of the Indian Plate about 500 by 500 km large to the Australian Plate.

Ocean Floor Isochrons

Stage rotations were computed from the time of opening of the Argo Abyssal Plain (~156 Ma) to anomaly C34 (83.5 Ma). We derived two stage poles that describe the motion of the Indian Plate relative to the Australian Plate for the period from 156 Ma to 127 Ma (Barremian–Hauterivian boundary, magnetic anomaly M5), and 127–99 Ma. We computed finite rotation poles that describe the relative motion between the Australian Plate and Greater India by adding stage rotations to the finite rotation for India relative to Australia for magnetic anomaly 34 (83.5 Ma from Royer & Sandwell, 1989).

Based on our plate model and the identified magnetic lineations and fracture zones we constructed continuous isochrons for the Perth (Fig. 3), Cuvier, Gascoyne (Fig. 2) and Argo (Fig. 1) abyssal plains, including isochrons on the Indian plate which are now subducted (Fig. 4). In the plate reconstructions shown in Figure 4, the isochrons aid in illustrating the evolution of the propagating rift which gradually separated Greater India from Antarctica, the development of transform margins as well as the history of rift propagators which accreted large portions of the Indian plate onto the Australian plate.

Breakup and Dispersal of Gondwanaland

In order to test our revised model for the breakup between Greater India and Australia in the context of Gondwanaland breakup, we combined it with a model for relative plate motions between Africa and Antarctica and between Madagascar and Africa (Müller et al., 1997; Royer and Sandwell, 1989) and the model by Müller et al. (1993) for post-130 Ma plate motions relative to the Indian–Atlantic ocean hotspots. For times older than 130 Ma, for which no continuous hotspot tracks are available, the present model assumes that Africa was fixed relative to the mantle.

Reconstruction

Our reconstructed fit of Africa, India and Antarctica is largely constrained by the fit of the COB's interpreted from Sandwell & Smith's (1997) marine gravity anomalies. The fit between Madagascar and India is

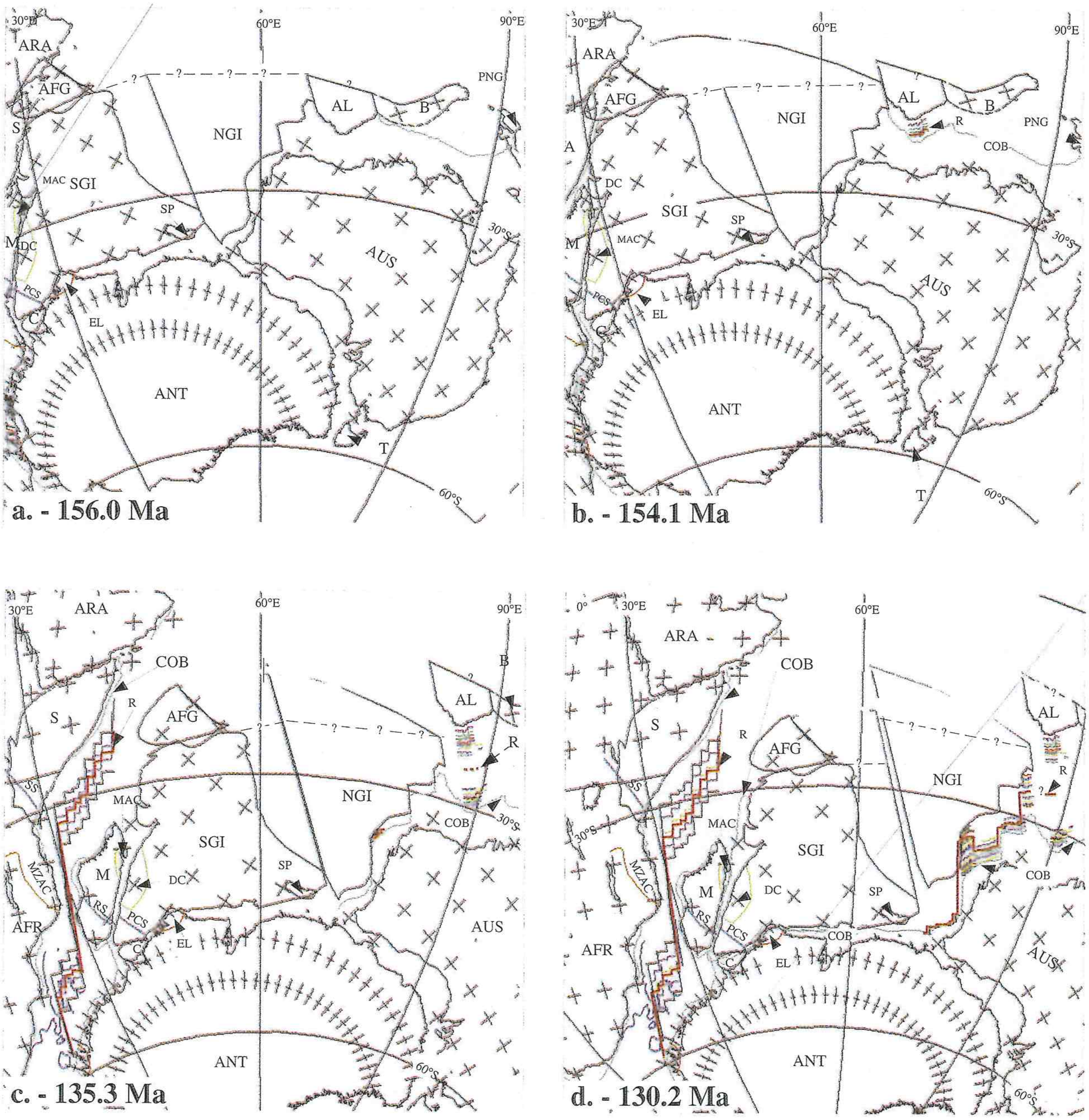

Figure 4: **Plate kinematic model for the breakup and dispersion of eastern Gondwanaland. Isochrons are colour coded as follows: M5, M11A, M23, M26 green, M4, M11, M22A, M24, M25A red, M2, M9, M13, M25 magenta, M0, M8, M10N, M12A, M24B blue, M1r, M3, M6, M7, M10, M12, M14, M24A black. AUS Australia, AFR Antarctica, ARA Arabia, AFG Afghanistan, M Madagascar, T Tasmania, B Burma, PNG Papua New Guinea,**

constrained by the geometry of the space available between India, Antarctica and Africa, as well as by a prominent tectonic lineament on Madagascar and India, the Ranotsara Shear Zone (Katz, 1976) on Madagascar and the Palghat-Cauvery Shear Zone (Kröner, 1991) on southern India (Fig. 4a). Our Australia-Antarctica fit is based on best-fitting the conjugate gravity anomalies in the Great Australian Bight and off Antarctica that define the landward extent of the magneticly quiet zone in this area. This interpretation implies that the quiet-zone largely represents oceanic crust, rather than thinned continental crust, but a detailed discussion of this problem is beyond the scope of this paper.

Formation of the Argo Abyssal Plain

Figure 4a shows the initial outline of the east

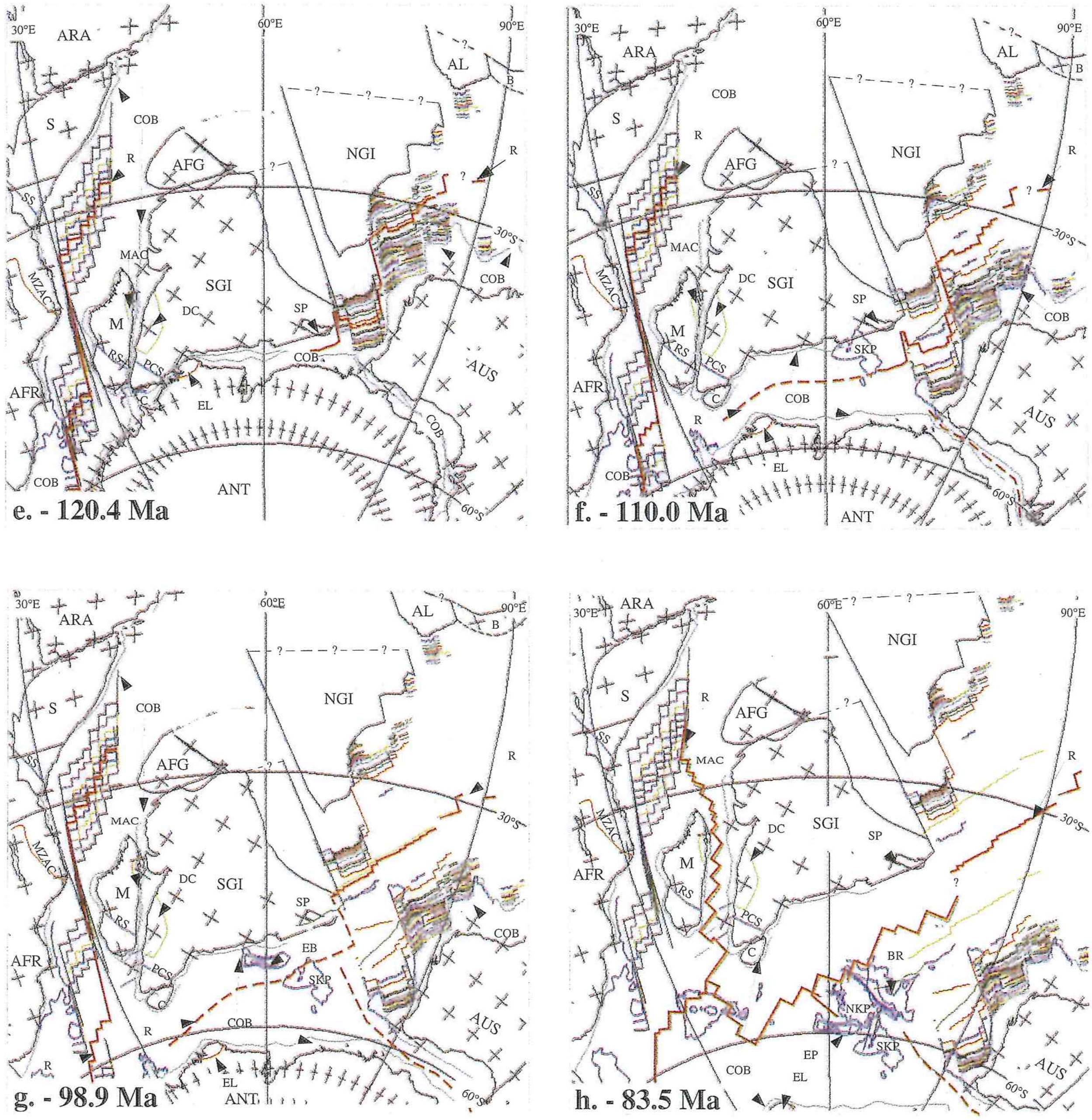

Figure 4 (continued): **EB Elan Bank, SP Shillong Plateau, RS Ranotsara Shear Zone, SS Surma Shear Zone, D Dhawar Craton, MAC Madagascar Archean Craton, PCS Palghat-Cauvery Shear Zone, Somalia, SKP South Kerguelen Plateau, NKP North Kerguelen Plateau, EL Enderby Land, Ceylon, AL Argo Land, NGI, SGI North and South Greater India. Bathymetric contours plateaus are shown in magenta.**

Gondwanaland province of Pangea by reconstructing the fit of Greater India, Antarctica and Australia at the onset of plate divergence in the Argo Abyssal Plain at about 156 Ma, the extrapolated age for the COB in the central part of the Argo Abyssal Plain. Argo Land and Burma were separated from Greater India along a transform fault. The northeastern Exmouth Plateau margin formed as a stepped transform margin along this fault. After the onset of sea-floor spreading Argo Land started to move northwest relative to Australia at a high average spreading rate about 160 mm/y (Mihut & Müller, 1998a) (Fig. 4b). Th hypothesis of a hotspot associated with volcanism in th Joey Rise region (Cook et al., 1978), along the enti northern sector of the Argo Abyssal Plain, and activ during breakup, is one explanation for the fast spreadin rate between Australia and Argo Land. A stage pole 35°S and 10°W in an Australian reference frame be models the spreading pattern at that time. Sea-flo spreading between Africa and East Antarctica started soon after about 148 Ma (Royer et al., 1992).

Breakup and Sea-floor spreading from the Gascoyne to the Perth Abyssal Plains

Between M22A (the youngest magnetic anomaly interpreted in the Argo Abyssal Plain) and this time, it is likely that Argo Land became attached to the main part of Greater India as transform motion stopped. Figure 4c shows the incipient spreading system west of Australia at 135.3 Ma (Lower Valanginian, chron M13), which had started at about 136.2 Ma (chron M14). By this time, about 600 km of sea floor had formed in the Mozambique and Somalian basins between Africa and Madagascar-Antarctica. The main unresolved question regarding the opening between India, Australia and Antarctica is whether sea-floor spreading between India and Antarctica commenced contemporaneously with the formation of the Gascoyne and Cuvier abyssal plains, as depicted in Veevers (1984). If it did, then Greater India and Australia would have constituted a two-plate system, and we should find Mesozoic M-sequence magnetic anomalies in the Enderby basins off Antarctica west of Kerguelen and off the east coast of India. However, the Enderby Basin is extremely poorly mapped, with no M-sequence anomalies identified to date, while low-amplitude magnetic anomalies off eastern India have recently been interpreted as reflecting the magnetically quiet Cretaceous Normal Superchron (CNS) (Gopala Rao et al., 1997).

Powell et al. (1988) suggested that Greater India may have separated from Australia/Antarctica in the early Cretaceous around a stage rotation pole located not far west off the southern tip of India. If this scenario were correct, then small circles about this stage pole should follow the fracture zones in the Perth, Cuvier and Gascoyne abyssal plains. However, we find a large discrepancy between small circle and fracture azimuths, implying that this model does not agree with the tectonic fabric of the ocean floor formed during this time. Further, the counter-clockwise rotation of India required by this scenario would have given rise to transpression between India and Madagascar, and for this there is no evidence.

Instead, the fracture zones west of Australia indicate that Greater India separated from Australia/Antarctica about a stage rotation pole at roughly 35°S and 10°W in an Australia reference frame. If Greater India represented one single plate, the associated northward motion of India would have resulted in about 1000 km of left-lateral strike-slip between India and Madagascar from 136 Ma to 99 Ma. This may seem conceivable, except that India's pre-breakup position with respect to Madagascar is fairly well constrained by conjugate fracture zones visible in the marine gravity anomaly grid. This pre-breakup position requires India to be located slightly further south relative to Madagascar than shown in the fit reconstruction (Fig. 4a). Consequently, the left-lateral strike-slip between India and Madagascar required to model sea-floor spreading between Greater India and Australia as a two-plate system would have to be succeeded by an even greater amount of right-lateral strike-slip before breakup between India and Madagascar. This model also results in compression between India and Arabia from 136 to 120 Ma, for which there is no evidence. Consequently, we consider this model as highly unlikely.

The most plausible, internally consistent model for the breakup of eastern Gondwanaland involves a large transform fault which would have formed in the Lower Valanginian, when sea-floor spreading started west of Australia, while rifting between India and Antarctica remained slow until breakup in the Aptian at about 120 Ma (Figs 4c-e). The transform fault separated northern Greater India (NGI) from southern Greater India (SGI) until motion between the two plates stopped at about 120 Ma. The triple junction between NGI, SGI and Antarctica would have been located southwest of the Naturaliste Plateau. This model implies that the ocean floor west of the Naturaliste Plateau, southwest of the southernmost isochrons constructed in the Perth Abyssal Plain (Figs 1 & 3) would reflect post-120 Ma Greater India-Antarctica spreading. Support for this scenario is found in the juxtaposition of the relatively smooth gravity field of the Perth Abyssal Plain with the rough gravity anomalies south of the Perth Abyssal Plain isochrons (Fig. 1) and by the relative smoothness of the magnetic anomalies in the southwestern corner of Figure 3, suggesting that they were formed during a magnetically quiet period. Cretaceous excess volcanism on the Naturaliste Plateau may also be linked to its proximity to a triple junction.

At 110 Ma (Fig. 4f) sea-floor spreading between Antarctica and India had created sufficient space for the southern Kerguelen Plateau (SKP) to form. Our model requires the plateau to have formed initially on the Indian Plate. At 99 Ma (Fig. 4g) SKP has been transferred to the Antarctic Plate, and the Elan Bank formed on the Indian plate. Between 110 and 99 Ma about 200 km of right-lateral strike-slip between India and Madagascar brought Madagascar to its pre-breakup position. This position is marked by three pairs of conjugate fracture zones digitised from their marine gravity anomalies, shown as three fracture zone segments in Figure 4g (magenta for Madagascar and light blue for India). This opening model for Madagascar and India is similar to that proposed by Royer et al. (1992) who suggested a comparable amount of right-lateral strike-slip to have occurred between 119 and 91 Ma in order to bring Madagascar into its pre-breakup position relative to India. A drastic change in spreading direction occurred at about 99 Ma (Figs 4g & h), possibly triggering rifting between Madagascar and India. Relative motion between NGI and SGI ceased at this time (Fig. 4g).

The reconstruction at 83.5 Ma (Fig. 4h) largely corresponds to the reconstruction by Royer & Sandwell (1989), except for the addition of our modelled isochrons off western Australia, and the tying of all relative plate motions to Müller et al.'s (1993) absolute plate motion model. This reconstruction demonstrates that cumulative sea-floor spreading between India and Antarctica has been quite asymmetric, especially in the Kerguelen Plateau area, where about two thirds of the ocean floor created up to this time has been left on the Antarctic Plate, resulting in successive accretion of parts of the Kerguelen Plateau from the Indian to the Antarctic Plate.

Our reconstructions also demonstrate how a succession of ridge propagation events west of Australia have accreted large segments of the Indian Plate onto the Australian Plate. Figure 1 shows the accreted oceanic crustal segments that are bounded by extinct ridges (magenta) and pseudofaults (light blue). Two ridge propagators in the Cuvier Abyssal Plain increased the offset of the Wallaby-Zenith Fracture Zone (WZFZ) to about 830 km. As a consequence, the ridge-transform intersection bounding the Cuvier Abyssal Plain to the south abutted Indian continental crust until about chron M0 (120.4 Ma) (Mihut & Müller, 1998b). If the volcanism recorded on the Cuvier margin and the Wallaby and Zenith plateaus has been caused by small-scale convection, resulting from the juxtaposition of cold cratonic crust with hot young ocean crust, then ridge propagators have played a major role in affecting the volcanic and thermal history of the Cuvier margin.

Tectonic Events on the North West Shelf

Backstripping of Well Data

Passive margins are expected to exhibit thermal, exponential subsidence after rifting ceases. Instead, tectonic subsidence curves on the North West Shelf of Australia show many deviations from exponential subsidence. Here we investigate regional anomalous subsidence and uplift on the North West Shelf postdating the onset of sea-floor spreading and examine how these tectonic events may be related to the plate tectonic history around Australia. To map anomalies in tectonic subsidence, we have compiled open-file data from 108 wells on the North West Shelf. Stratigraphic ages are based on the AGSO time scale (Young & Laurie, 1996). Lithology and water depth ranges were determined from micropalaeontological and lithological data from well completion reports. Water-loaded tectonic subsidence curves were constructed for all wells by applying the backstripping technique of Sclater and Christie (1980).

Many wells show drastic departures from exponential thermal subsidence at different times after rifting ceased, as shown on Figure 5. To identify at which times anomalous subsidence or uplift was most widespread, we created histograms which show the number of wells which exhibit either anomalous subsidence (Fig. 6a) or uplift (Fig. 6b) for 10 my time periods since 130 Ma. The subsidence histogram shows three distinct peaks for the periods 100-90 Ma, 70-60 Ma and 10 Ma to present, whereas the uplift histogram shows widespread anomalous uplift from 90 to 60 Ma.

Gridding Tectonic Subsidence

Contours of tectonic subsidence and uplift for 10 my time slices centred on 95, 65 and 5 Ma are shown on Figures 7a-c. The individual observations were first block averaged using a median filter and then gridded using a natural spline with a grid interval of 0.1 degrees. Especially during the time brackets centred on 65 and 5 Ma, the magnitude of subsidence resulting from thermal cooling is so small that it is negligible compared with the anomalous subsidence we record (up to 700 m within a few million years). The smooth spatial distribution of tectonic subsidence and uplift as shown in Figure 7 gives a qualitative, regional image of tectonic reactivation, as it does not include error estimates. Also, fault bounded tectonic blocks are not properly represented, as we have not yet integrated the well data with seismic data. However, we argue that these images are meaningful because (1) they are based on a large number of wells, and (2) the anomalous vertical motions seen in this area are up to an order of magnitude larger than the expected thermal subsidence for the same time period.

Anomalous Tectonic Subsidence through Time

100–90 Ma

The event between 100 and 90 Ma (Fig. 7a) resulted in tectonic subsidence not exceeding 550 m in the Malita Graben-Sahul Trough, extending south to the Londonderry High, and moderate anomalous tectonic subsidence (not exceeding 200 m) in the Browse Basin. This event is clearly related to the plate reorganisation between India and Australia that we date at about 99 Ma. Many other roughly contemporaneous tectonic events all around Australia have been identified. The cause for this event is unclear, but may be related to subduction of part of the Neo-Tethyan ridge north of India and resultant changes in intra-plate stresses due to a diminished ridge-push force north of India. Most of the tectonic subsidence recorded at this time has been permanent. This indicates that the change in intra-plate stresses triggered by the 99 Ma event resulted in renewed rifting and lithospheric thinning of parts of the North West Shelf.

70–60 Ma

This time period is characterised by accelerated tectonic subsidence of the Sahul and Ashmore platforms and the Londonderry High, while the intervening grabens

(Malita, Vulcan) show either slight uplift or no anomalous subsidence (Fig. 7b). The magnitudes of subsidence at this time are smaller than at 100-90 Ma, ranging from up to 100 m of uplift to 100-200 m of subsidence (Figs 5e-h). The amplitude and spatial distribution of anomalous subsidence and uplift between 70 and 60 Ma may reflect elastic plate bending caused by extensional in-plane stresses, in that platforms exhibit subsidence, whereas rifted grabens show uplift or no subsidence anomalies. This event correlates with a change in spreading direction at 61 Ma (chron 27) both in the Tasman Sea (Gaina et al., 1998) and the Southern Ocean (Tikku & Cande, 1998), which established the subsequent north-south oriented spreading direction, followed by Australia's rapid northward drift. Both the extensional elastic plate deformation on the North West Shelf as well as changes in plate kinematics suggest a decrease in southward oriented ridge push force north of Australia, pointing to the subduction of some segments of the Neo-Tethyan spreading ridge north of Australia. This event also appears to be associated with the charging of some traps on the North West Shelf (Symonds et al., 1994).

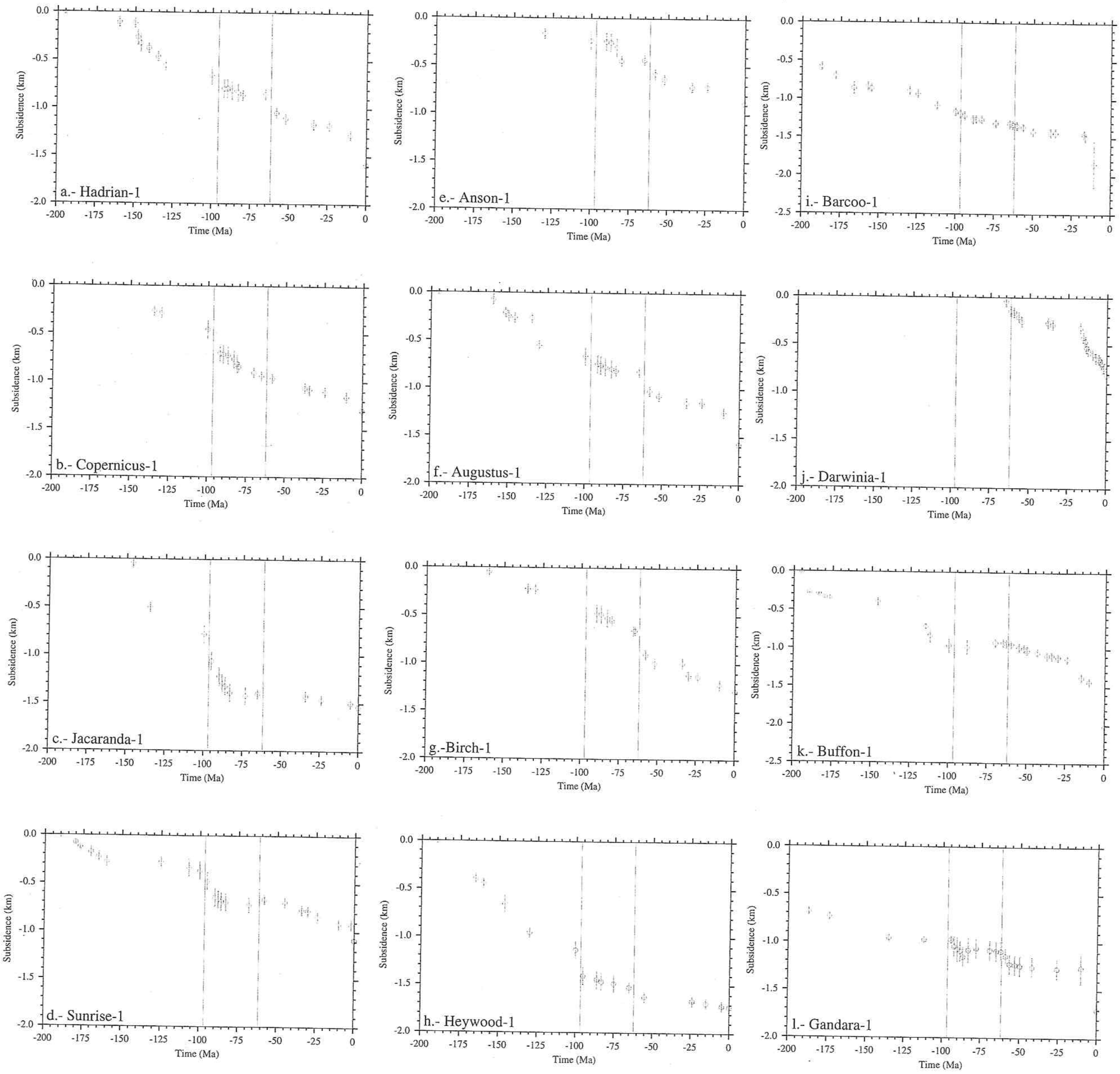

Figure 5: Selected backstripped wells from the North West Shelf. Well locations are shown on Fig. 7c. Water depth uncertainties are shown by vertical error bars. Note deviations from exponential subsidence at about 96 Ma (99 Ma in Gradstein et al.'s (1994) time scale) and 61 Ma (thin black vertical lines), and 10 Ma – present.

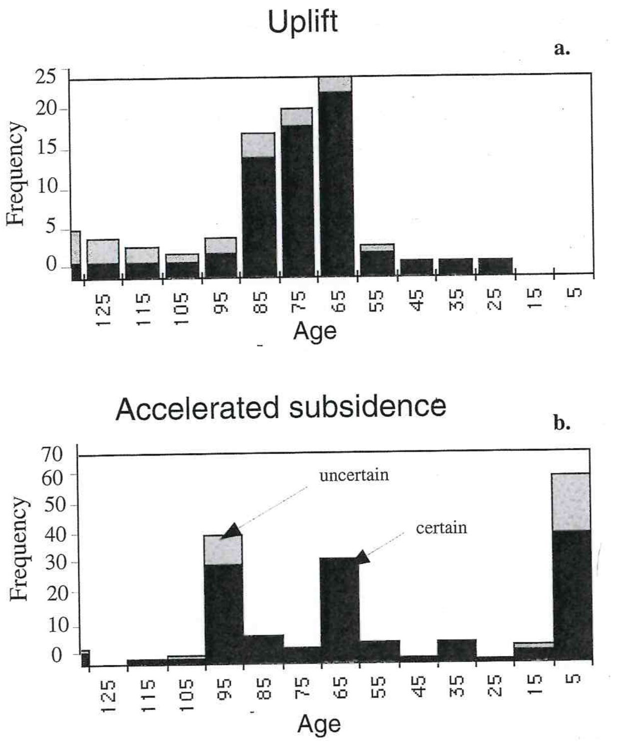

Figure 6: Histogram showing frequency of accelerated subsidence or uplift events on the North West Shelf. Note tectonic subsidence events at 100–90 Ma, 70–60 Ma and 10 Ma – present and uplift events at 70–60 Ma.

10 Ma to Present

Widespread tectonic reactivation occurred on the North West Shelf in the Late Miocene-Pliocene. Our regional subsidence map (Fig. 7c) shows widespread accelerated post 10 Ma subsidence of the outer North West Shelf area, stretching from the Vulcan Graben to the Northern Carnarvon Basin. Wells in the Roebuck Basin and the northern Carnarvon Basin show accelerated subsidence commencing as early as 20 Ma (e.g. Barcoo 1, Darwinia 1, 5i & j). Anomalous subsidence and/or uplift has been linked to wrench and inversion tectonics and foreland basin formation (Etheridge et al., 1991; Lorenzo et al., 1998; Shuster et al., 1998). In accordance with Shuster et al. (1998), our map also shows recent tectonic subsidence of the Malita Graben, which is likely due to pull-apart basin formation. Miocene to Recent anomalous subsidence in the Cartier Trough and the Malita Graben has likely been caused by reactivation of rift structures by sinistral shear, as a consequence of oblique collision north of Australia (Shuster et al., 1998). Other structures in the Timor Sea have been inverted by left-lateral shear at confining bends of faults (Shuster et al., 1998).

Collision along the Banda Orogen has created a foreland basin including the Timor Trough and the outer North West Shelf (Lorenzo et al., 1998). Sea floor faulting due to foreland basin formation occurs within a 300 km radius south of the axis of the Timor Trough and modelled values of the elastic plate thickness suggest that plate flexure due to thrust loading should not affect the North West Shelf south of latitude ~14-15°S. Therefore it is unexpected to find up to 500 m of Late Miocene-Pliocene subsidence west of the Rankin Trend, in the western Roebuck Basin, the western Browse Basin, and the Vulcan Graben (Fig. 7c). Regional accelerated subsidence, which started between 20 and 10 Ma, cannot be accounted for by simple foreland basin modelling, as the wavelength of the elastic deformation caused by thrust loading along the Banda Arc does not exceed a few 100 km (Lorenzo et al., 1998). Nor can it be explained by dynamic topography (Gurnis et al., 1998), as plate reconstructions do not suggest that this area has recently overridden a subducted slab.

Accelerated subsidence from 25-20 Ma to the present has also been observed on the western Indian margin, where the rate of subsidence increased both on the continental shelf and seaward of the shelf edge, resulting in up to one km of tectonic subsidence in 20 million years (Agraval & Rogers, 1988). This event correlates with the break-up of the Indo-Australian plate into two plates (Royer & Chang, 1991). Further, Royer and Gordon (1997) showed that at least since 11 Ma a third plate, named the Capricorn Plate, has formed by further fragmentation of the Australian Plate. This process has created an intra-plate deformation zone extending from the central Indian Ocean to the Northwest shelf (Royer & Gordon, 1997). The large area affected by Miocene-Pliocene accelerated subsidence on the North West Shelf, together with contemporaneous accelerated subsidence off western India, suggests both are related to the complex breakup of the Indo-Australian Plate into the Indian, Australian and Capricorn plates, rather than foreland and pull-apart basin formation alone.

Conclusions

Our revised model for the formation and evolution of the west and northwest Australian margins, based on combining gravity data from satellite altimetry with ship-borne surveys, has several major differences with existing models. Fracture zones in the Jurassic Argo Abyssal Plain follow the same small circles as those in the Gascoyne, Cuvier and Perth abyssal plains. This indicates that the breakup between Argo Land and Australia was merely the first phase of a southward propagating rift, rather than a tectonic event unrelated to subsequent breakup between Australia and Greater India. Our model dates the oldest ocean crust in the Gascoyne and Cuvier abyssal plains as 136.2 Ma. We show that propagating rifts have played a

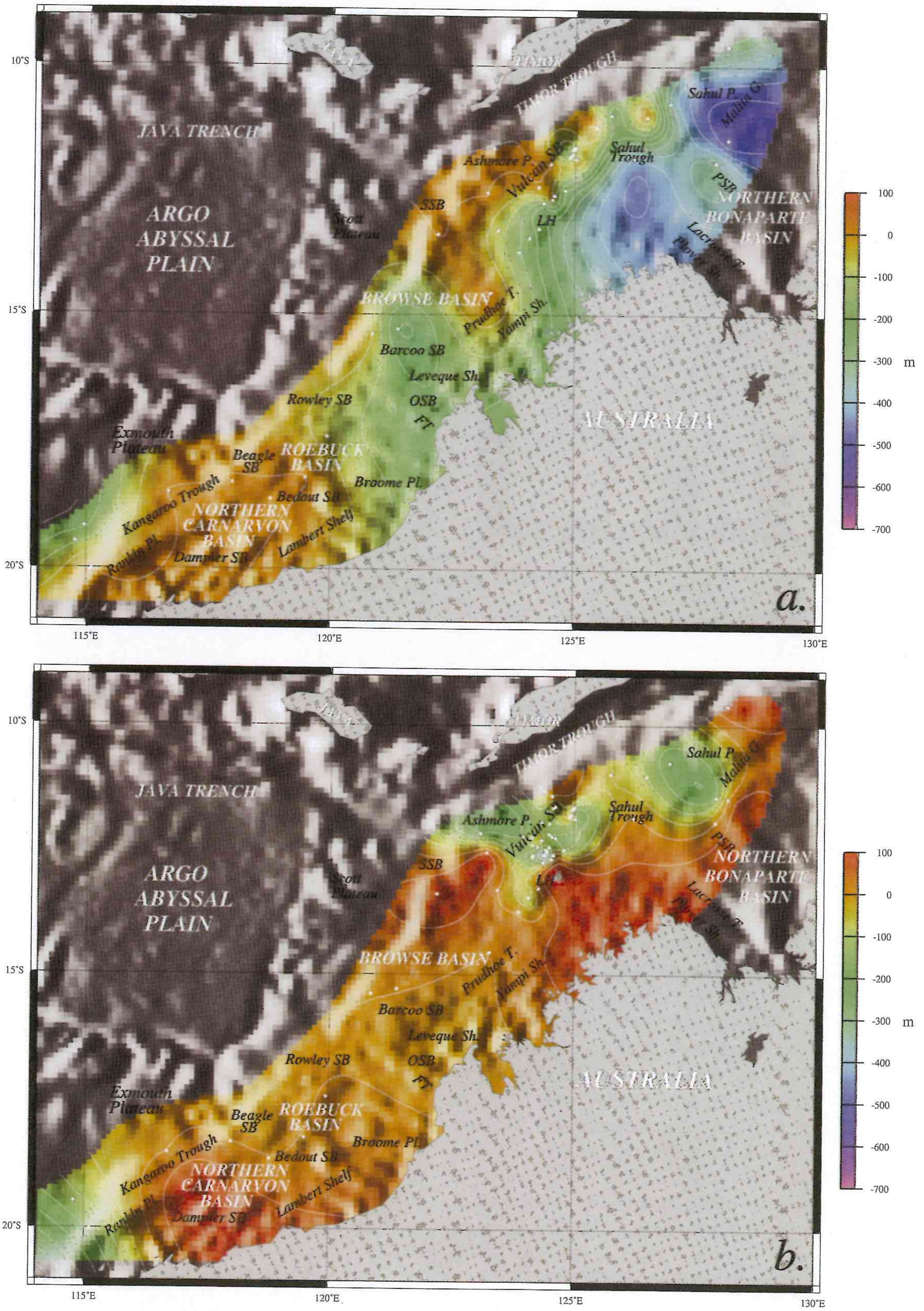

Figure 7: Gridded tectonic subsidence on the North West Shelf at 100-90 Ma (a), 70-60 Ma (b). Positive values indicate uplift, whereas negative values represent subsidence. White dots represent well locations and red letters denote wells shown on Fig. 5. SB: Sub Basin; T: Terrace; Sh: Shelf; G: Graben; P: Platform; FT: Fitzroy Trough; PSB, SSB, OSB: Petrel, Seringapatam and Oobagooma sub-basins; subdivision of North West Shelf after Hocking et al. (1994).

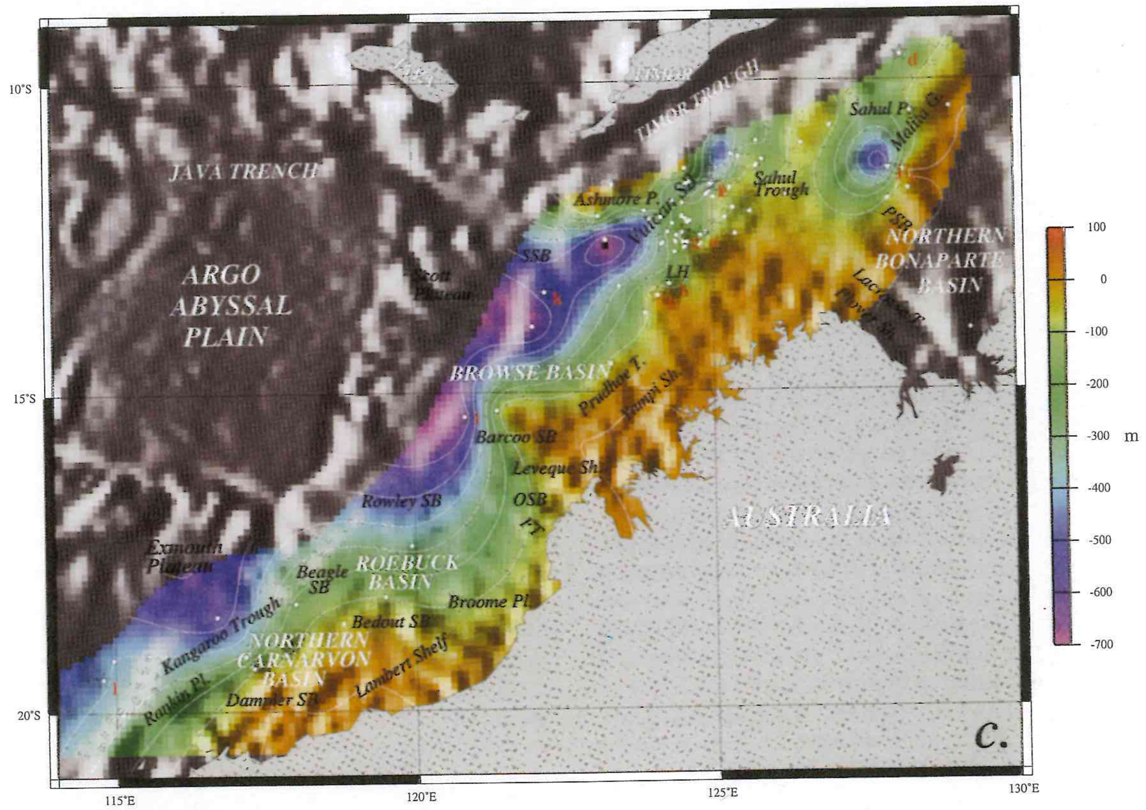

Figure 7: 10 Ma–present (c).

major role in accreting large segments of Indian crust onto Australia and extending the offset of the Wallaby-Zenith Fracture Zone to over 800 km, thereby maintaining an active continental-oceanic transform margin for over 15 million years south of the Bernier Platform. This may have contributed to the long-lived volcanism at this margin which is expressed on the Wallaby and Zenith plateaus (Mihut & Müller, 1998b). Our model also suggests that northern Greater India was likely separated by a large transform fault from southern Greater India from 136 to 99 Ma.

The North West Shelf has undergone at least three phases of tectonic reactivation after breakup, spanning 100-90 Ma, 70-60 Ma, and 10 Ma to present. Accelerated subsidence during the most recent phase started as early as 20 Ma in the Roebuck and the Northern Carnarvon basins. A correlation with plate tectonic events around Australia suggests that the first of these events was caused by a major plate reorganisation between India and Australia at 99 Ma, whereas the second event is contemporaneous with changes in spreading direction at 61 Ma south and east of Australia. Both events may have been caused by the stepwise subduction of the Neo-Tethyan spreading ridge, first north of India, and later north of Australia. Miocene-Pliocene accelerated subsidence is recorded from the Timor Sea to the Carnarvon Basin. It occurred contemporaneously with accelerated subsidence on the western Indian margin, and the breakup of the Indo-Australian Plate.

Elucidating this regional anomalous subsidence and Miocene reactivation on the North West Shelf and the Indian Plate will require modelling the breakup of a large plate with laterally varying yield-stress envelope, and its effect on basin reactivation. Understanding the link between palaeo-intraplate stresses and basin reactivation is more important for hydrocarbon exploration on the Australian tectonic plate than on most other plates, which have experienced much smaller fluctuations in plate driving forces in the Late Mesozoic/Cainozoic.

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