Mesozoic/Cenozoic Tectonic Events Around Australia

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We use an absolute and relative plate motion model for the plates around Australia to identify major plate tectonic events, evaluate their causes, and investigate their effects on anomalous intraplate subsidence or uplift and on the history of oceanic crustal accretion. An event at ~136 Ma is marked by the onset of sea floor spreading between Greater India and Australia. At about this time long-lived subduction east of Australia ceased, probably due to subduction of the Phoenix-Pacific spreading ridge, changing this plate boundary to a transform margin. Between 130 and 80 Ma, Australia and East Antarctica moved eastward in the Atlantic-Indian mantle hotspot reference frame. This can be plausibly linked to ridge push from the NW-SE oriented spreading center NW of Australia and to the inferred geometry and continued subduction of the Phoenix plate beneath the West Antarctic margin. A drastic change in spreading direction between the Indian and Australian plates from NE-SW to N-S occurred at about 99 Ma, possibly caused by a change in absolute motion of the Pacific Plate. Chron 27 (~61 Ma) marks the onset of relative motion between East and West Antarctica, and a change in the relative motion between Australia and Antarctica. It may be linked to the subduction of a segment of the Neo-Tethyan Ridge. Both events caused anomalous subsidence on the Northwest Shelf of Australia. The almost stationary position of Australia w.r.t. the mantle from ~80 Ma to ~40 Ma may reflect the progressive subduction of the Pacific-Phoenix ridge to the east of New Zealand preceding 80 Ma, resulting in a diminished trench suction force east of Australia. Preliminary reconstructions to close the Pacific-Australian plate circuit based on recently collected geophysical data indicate that a tectonic event at 43 Ma may mark the onset of renewed subduction east of Australia. At the same time spreading in the Wharton Basin between India and Australia ceased, and tectonic reactivation is recorded in the Bass Strait. Excess late Tertiary subsidence on the northwest shelf of >500 m matches the anomalous depth of the

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The History and Dynamics of Global Plate Motions
Geophysical Monograph 121

Argo abyssal plain ocean floor. This anomalous subsidence may express large-scale intraplate deformation in the Indian Ocean. Asymmetries in oceanic crustal accretion around Australia are caused mainly by hotspot-ridge and coldspot-ridge interaction.

1. INTRODUCTION

The Australian and Indian plates are unique in that their absolute plate motion rates have been much higher than those of any other plates which include a large continent. Changes in plate boundary configurations and plate driving forces have clearly caused considerable fluctuations in paleo-intraplate stresses, as all major plate tectonic events are accompanied by intraplate tectonic reactivation. However, cause and effect are not well understood.

Recently, our models of the tectonic history of Australia and its neighboring plates have improved considerably for a number of reasons. Satellite altimetry has revolutionized our knowledge of the tectonic structure of the ocean floor where ship data are sparse. Additional magnetic and seismic data have recently been collected off Antarctica [*Ishihara et al.*, 1996; *Mizukoshi et al.*, 1986; *Saki et al.*, 1987; *Tsumuraya et al.*, 1985], around the Macquarie Triple Junction and in the Tasman Sea [*Cande et al.*, 1998] in the Tasman Sea and off West Australia [*Symonds et al.*, 1996]. These data are being used to construct more detailed plate tectonic models. We have combined some recently published work [*Cande et al.*, in press; *Cande et al.*, 1998; *Gaina et al.*, 1998a; *Gaina et al.*, 1999; *Gaina et al.*, 1998b; *Mihut and Müller*, 1998; *Müller et al.*, 1998a; *Müller et al.*, 1998b; *Müller et al.*, 1997; *Tikku*, 1998; *Tikku and Cande*, 1999] with other work in progress to present digital grids of the age of the ocean floor (Figure 1), spreading rates (Figure 2), asymmetries in crustal accretion (Figure 3) and plate tectonic reconstructions to identify major plate tectonic events, evaluate their cause, and investigate their effect on anomalous intraplate subsidence or uplift and on the history of oceanic crustal accretion.

Of particular interest is the relationship between anomalous intraplate subsidence or uplift and either mantle convection or lithospheric processes. The importance of intraplate stresses for the tectonic history and of sedimentary basins and fault reactivation has been recognised only recently. One of the main paradigms of plate tectonics was thought to be that there is a limited number of large tectonic plates that behave rigidly through long geological time intervals. Instead recent analyses of diffuse plate boundaries [*Gordon*, 1998; *Gordon et al.*, 1998] intra-plate earthquakes [*Crone et al.*, 1997; *Denham et al.*, 1979] and borehole breakouts [*Hillis*, 1991; *Hillis et al.*, 1997] on the Australian plate and elsewhere have shown clearly that forces applied at plate boundaries propagate into large plates, and produce substantial intraplate deformation. A spectacular example of oceanic intraplate deformation, resulting in an oceanic fold and thrust belt, can be found in the central Indian Ocean [*Royer and Gordon*, 1997]. Many tentative links between plate tectonic events and tectonic reactivation on the Australian plate have been proposed [*Cloetingh et al.*, 1992; *Etheridge et al.*, 1991]. *Etheridge et al.* [1991] pointed out that in many Australian sedimentary basins nearly all oil and gas fields are associated with tectonic reactivation, highlighting the need to understand changing plate driving forces through time and their impact on intraplate stresses from an exploration point of view.

2. TIMESCALE

For the work presented here, we used the *Gradstein et al.* [1994] and *Cande and Kent* [1995] time scales for Mesozoic and Cenozoic magnetic anomaly identifications, and the AGSO timescale [*Young and Laurie*, 1996] for the stratigraphy and tectonic subsidence analysis of well data from the northwest shelf of Australia. The AGSO timescale was chosen for this purpose, because the regional biostratigraphy is tied to it. Table 1 summarizes the differences between the former two timescales and the AGSO timescale for the times of some major tectonic events. The difference between the timescales is largest for chron M0, and negligible in the Cenozoic.

3. HISTORY OF OCEANIC CRUSTAL ACCRETION AROUND AUSTRALIA

We have used the isochrons by *Gaina et al.* [1998a] and *Gaina et al.* [1999] in the Tasman and Coral seas, respectively, from *Mihut* [1997] west of Australia, and from *Müller et al.* [1997] to construct grids of the age of the ocean floor, half-spreading rates, and asymmetries in crustal accretion (Figures 1-3). The isochrons are based on magnetic anomaly identifications and fracture zone picks (Figures 4a-d), which were used jointly to derive finite rotations describing relative plate motions around Australia (Table 2). We plot reconstructed magnetic anomaly and fracture zone picks, as well as selected small circles computed from stage rotation poles for each isochron time, keeping one plate fixed. Then best-fit continuous isochrons are constructed, connected by transforms, in the framework of one fixed plate (see also *Müller et al.*

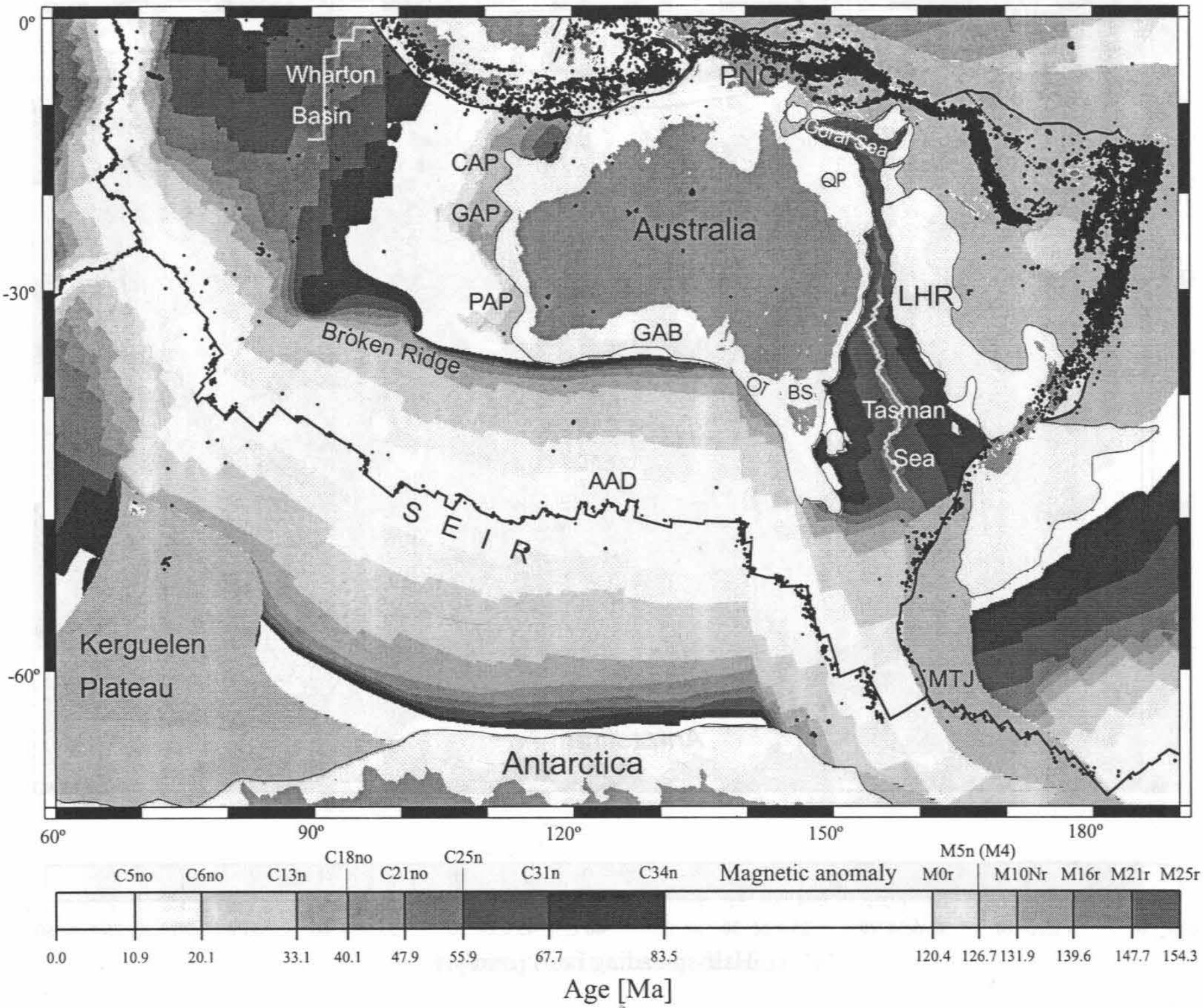

Figure 1. Age of the ocean crust, earthquake epicenters and plate boundaries around Australia. Continental crust below sea level is shown in light gray; oceanic crust of unknown age is medium gray. CAP, Cuvier Abyssal Plain; GAP, Gascoyne Abyssal Plain; PAP, Perth Abyssal Plain; GAB, Great Australian Bight; OT, Otway Basin; BS, Bass Basin; QP, Queensland Plateau; LHR, Lord Howe Rise; MTJ, Macquarie Triple Junction. Magnetic anomalies correspond to the young end of periods with normal polarity (labelled "n") for chrons younger than the Cretaceous Normal Superchron (from 120.4 to 83.5 Ma) or reversed polarity (labelled "r") for M-sequence anomalies, with the exception of anomaly M4, which actually corresponds to the young end of anomaly M5n. An "o" label indicates that the old end, rather than the young end of a period of normal polarity was chosen for magnetic anomaly identification.

[1991]). A complete set of isochrons for all conjugate plate pairs was derived by rotation of every isochron to their present day position.

Grids for crustal age, half-spreading rates and relative crustal accretion (expressing spreading asymmetry) were constructed by rotating adjacent pairs of isochrons on a given plate into a coordinate system in which the stage pole of motion between the two isochrons is the geographic north pole. For each pair of adjacent isochrons we determine the percentage of crustal accretion by dividing the angular distance between two isochrons by the half-stage pole angle assuming spreading symmetry. We create intermediate isochrons between adjacent isochron pairs by interpolating crustal ages linearly along small

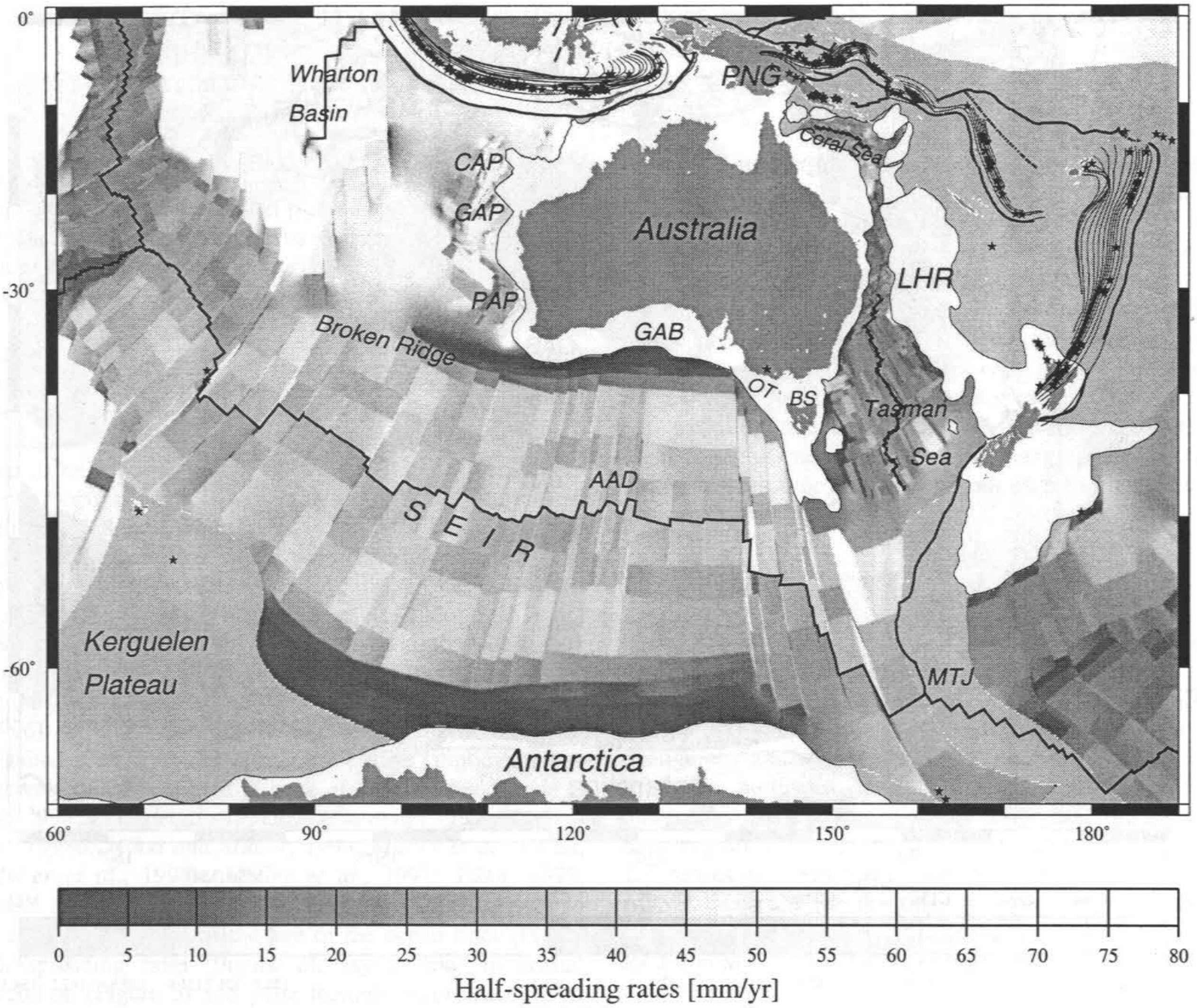

Figure 2. Half-spreading rates, contours of subducted slabs [*Gudmundsson and Sambridge*, 1998], active volcanoes (stars) and plate boundaries around Australia.

circles. Half-spreading rates on a particular ridge flank are based on the distance between two adjacent isochrons divided by their age difference. We rotate the complete set of isochron data for each stage back into the present-day geographic reference frame. To interpolate the data onto regular grids, we assume that the isochrons are continuous, which is implemented by densely interpolating between observation points along each isochron and gridding the resulting values onto a regular grid at a resolution of 0.1 degrees using continuous curvature splines in tension [*Smith*, 1990] with a tension factor of 0.7. The resulting grids are shown on Figures 1, 2 and 3, respectively, together with earthquake epicenters (Figure 1), contours of subducted slabs [*Gudmundsson and Sambridge*, 1998] and locations of volcanoes (Figure 2), as well as major hotspots (Figure 3).

The grids provide insights in crustal accretion processes which cannot be obtained by investigating active ridges alone. The largest asymmetries in crustal accretion are observed west of the Perth abyssal plain west of Australia. Here two major ridge propagation events during the Cretaceous Normal Superchon (KNS) accreted large segments of the Indian Plate to the Australian Plate [*Mihut*, 1997; *Müller et al.*, 1998a]. Virtually all crust created during the KNS in the spreading corridor west of the Perth Abyssal Plain between India and Australia was left on the Australian Plate. The most likely cause for these large asymmetries are consecutive ridge propagation events

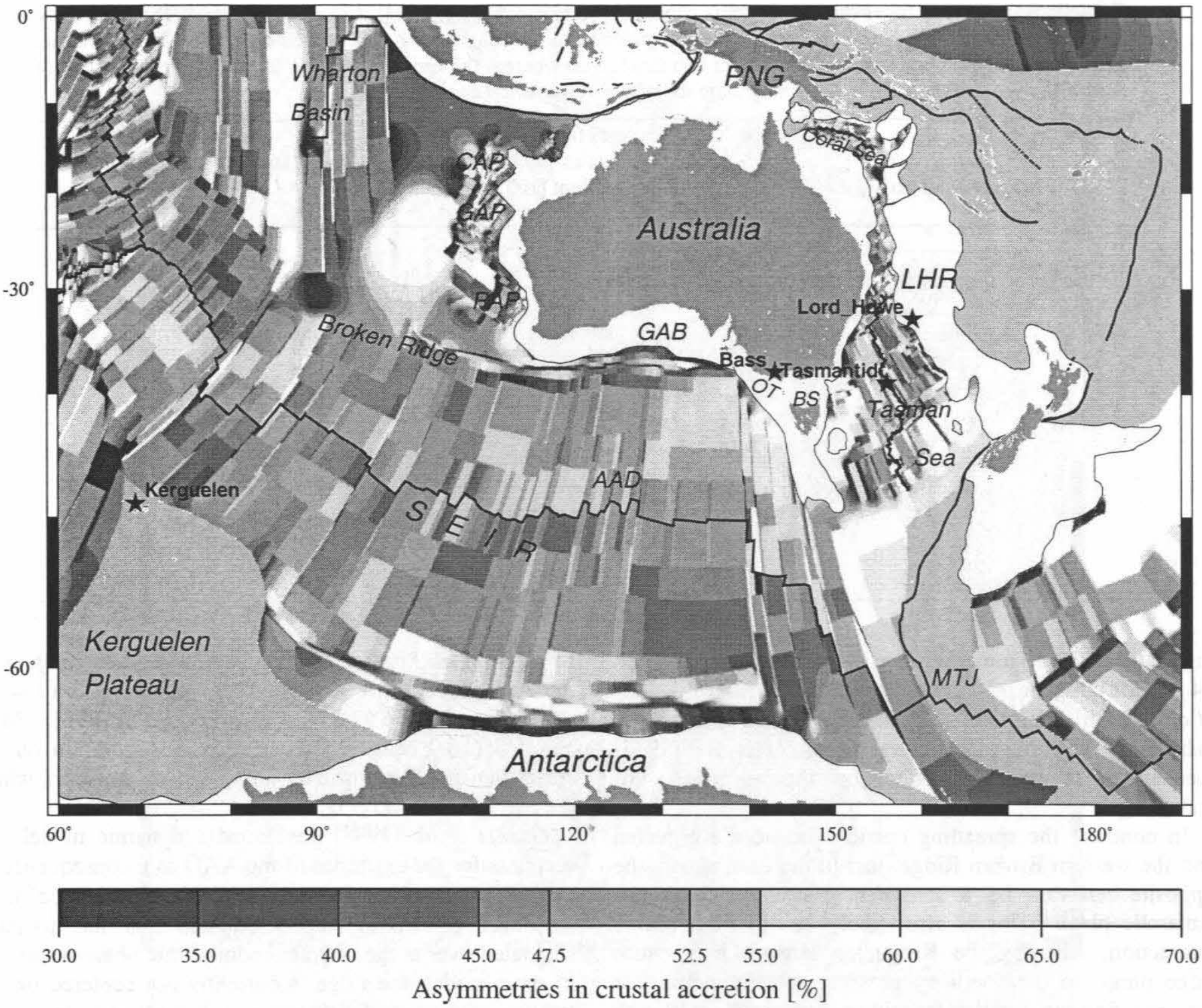

Figure 3. Asymmetries in oceanic crustal accretion and major hotspots around Australia. Asymmetry is expressed as the percentage of crustal area on one plate relative to the total area of crust formed for a given time range and length along the ridge axis between conjugate plates. Symmetric spreading results in values of 50% on both plates, whereas extreme asymmetry results in 100% on one plate and 0% on the conjugate plate.

towards the Kerguelen hotspot, which would have been located between the Elan Bank and India at 99 Ma (Figure 5a), assuming that it is now situated at Kerguelen Island (Figure 3). *Müller et al.* [1998b] found that most observed long-term asymmetries in spreading are likely caused by ridge-hotspot interaction, rather than by the migration of the spreading ridge over a fixed or slowly moving mantle [*Stein et al.*, 1977]. *Stein et al.'s* [1977] model suggests that trailing flanks of mid-ocean ridges, i.e. ridge flanks on plates that move more slowly relative to the mantle than their counterparts, should always show excess accretion. Their argument is based on minimizing energy dissipation. However, the extreme asymmetries in crustal accretion observed in the Perth Abyssal Plain are not accompanied by asymmetries of similar magnitude further north in the Gascoyne and Cuvier abyssal plains, which would be expected if they were caused by absolute ridge migration.

Along the central Indian Ridge, pronounced asymmetries in spreading are recorded in the westernmost segment on Figure 3, i.e. the segment that has recorded relative motion between India and Antarctica, west of Kerguelen. This segment shows consistent excess accretion on the trailing Antarctic ridge flank, in accord with *Stein et al.'s* [1977] model. This ridge also moved at

Table 1. Ages for key times discussed in this paper from *Gradstein et al.* [1994], *Cande and Kent* [1995], and *Young and Laurie* [1996]. Our magnetic anomaly identifications and models, and the ages of well data from the Queensland and Marion plateaus are based on the former two timescales, whereas the ages of well data from the northwest shelf of Australia were determined using the biostratigraphy from *Young and Laurie* [1996].

Magnetic anomaly	Ages from Gradstein et al. [1994][1], Cande and Kent [1995][2]	Ages from Young and Laurie [*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

high rates of 30-80 mm/y relative to the mantle since chron 34 (83 Ma), higher than any other spreading ridge. *Müller et al.* [1998b] interpreted this as suggestive of a minimum "absolute" ridge migration speed for *Stein et al's* [1977] mechanism to have an effect on the asymmetry of spreading.

In contrast, the spreading corridor between Kerguelen and the western Broken Ridge, just to the east, shows the opposite behavior, i.e. a consistent crustal deficit on the Antarctic plate. This is most likely due to ridge-plume interaction, whereby the Kerguelen hotspot may cause ridge jumps to the south by pressure release melting of material flowing toward the ridge, causing excess dike intrusion on the ridge flank proximal to the hotspot [*Müller et al.*, 1998b]. Together with the large spreading asymmetries found in the Perth Abyssal Plain, these observations document a history of interaction between the Kerguelen hotspot and adjacent spreading ridges which can be traced back to about 110 Ma. This is the time at which the first major ridge propagation event occured in the Perth Abyssal Plain, accompanied by an increase in roughness of the oceanic basement (Figure 4a). A causal connection between this ridge propagation event and the arrival of the Kerguelen plume head is plausible, as the oldest basalts recovered from the Kerguelen Plateau have been dated as about 110 m.y. [*Pringle et al.*, 1997; *Storey*, 1995].

Seafloor further east, between the eastern Broken Ridge and the Australian Antarctic Discordant Zone (AAD), shows no consistent long-term asymmetries, presumably because it is not influenced by a plume, and neither has the ridge migrated fast enough to produce the effect suggested by *Stein et al.* [1977]. The spreading segments adjoining the AAD show little asymmetry in accretion, until some time after chron 6 (19 Ma) [*Marks et al.*, 1999]. After chron 5 (10.9 Ma), we observe excess accretion on the Australian flank in virtually all spreading corridors which are part of the AAD (Figure 3).

Gurnis et al. [1998] developed a dynamic model that accounts for the existence of the AAD as a consequence of the spreading ridge drawing up cold mantle material from an old N-S striking subducted slab that has partially stagnated over at the 660 km endothermic phase transition. In their model, the ridge is currently not centered on the volume of drawn up slab material, but offset to the north. This is because the ridge has continually migrated north while pulling up old slab material. This model prediction is confirmed by *Marks et al.* [1999], who showed that the residual depth anomaly is also offset to the south of the ridge. In this context, considering that the AAD has become more pronounced through time if *Gurnis et al.'s* [1998] model is correct, the observed spreading asymmetries, starting some time after 19 Ma, may be interpreted as ridge jumps towards the center of the dynamic topography low while it increased in amplitude. However, the process driving ridge jumps towards a "cold spot" is unclear.

Further east, between the AAD and the George V Fracture Zone, we find the opposite pattern, i.e. excess accretion on the "leading" Australian Plate before 11 Ma, but symmetric spreading thereafter. Firstly, this indicates that ridge migration over the mantle cannot account for these asymmetries, as it would result in excess accretion on

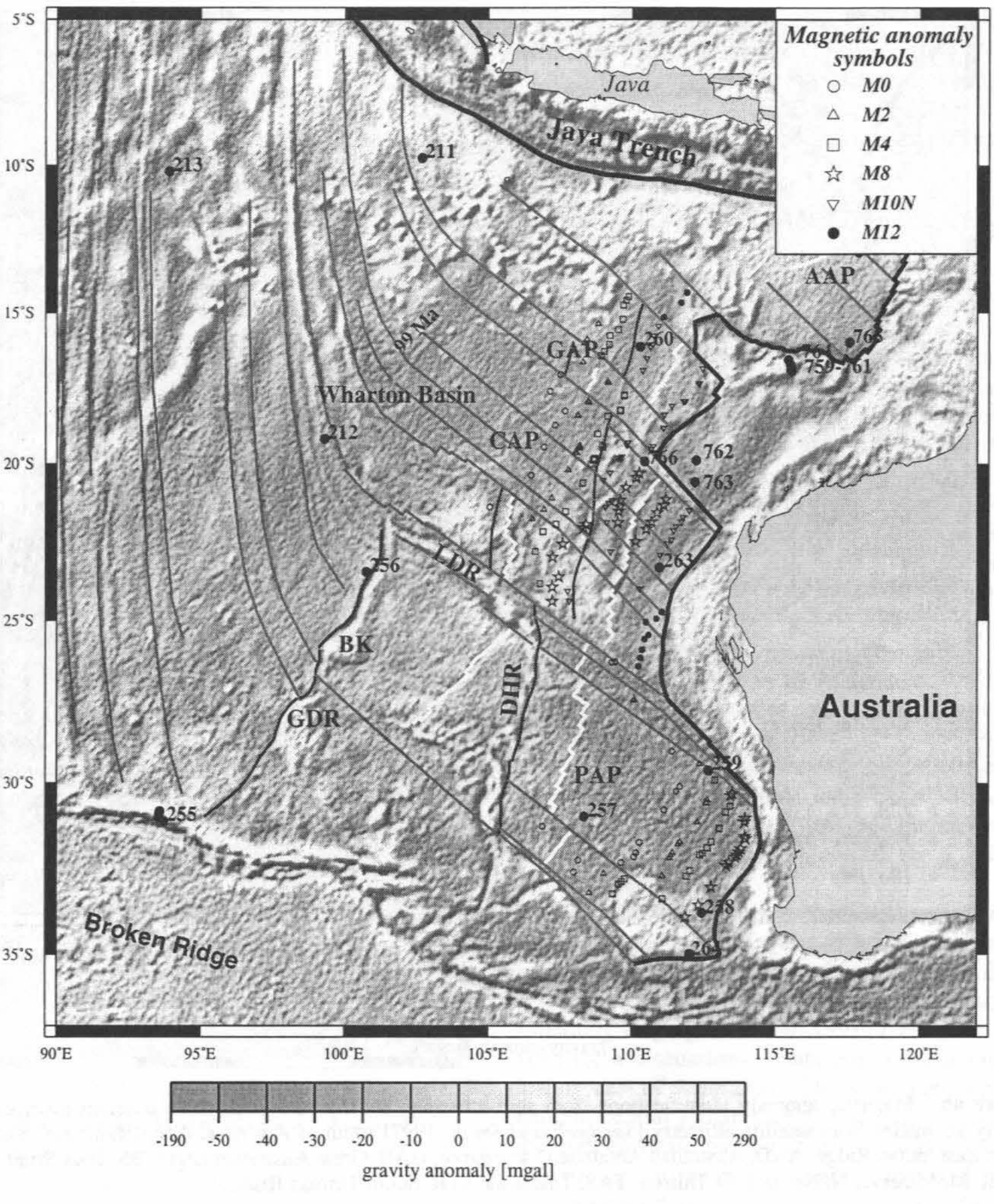

Figure 4a. Magnetic anomaly identifications from ship crossings and fracture zone picks overlain on marine gravity anomalies from satellite altimetry [*Sandwell and Smith*, 1997] west of Australia. Extinct ridges are shown as white staircase patterns, and pseudofaults are bold black lines. Well locations are shown as bold black dots; DSDP and ODP sites are numbered. Abbreviations are: AAP, Argo abyssal plain; GAP, Gascoyne abyssal plain; CAP, Cuvier abyssal plain; PAP, Perth abyssal plain; GDK, Gulden Draak Knoll; BK, Batavia Knoll; DHR, Dirk Hartog Ridge; LDR, Lost Dutchman Ridge.

the trailing Antarctic Plate. Secondly, this observation suggests that the V-shaped patterns visible in gridded gravity anomalies east of the AAD (Figure 4b) are not caused by ridge propagators, as suggested by *Phipps-Morgan and Sandwell* [1994]. They interpreted the V-shaped limbs north of the ridge as the wakes of extinct rifts and the conjugate traces on the Antarctic Plate as pseudofaults, consistent with the present-day transform offsets of the mid-ocean ridge. However, this scenario would result in excess accretion on the Antarctic Plate. In

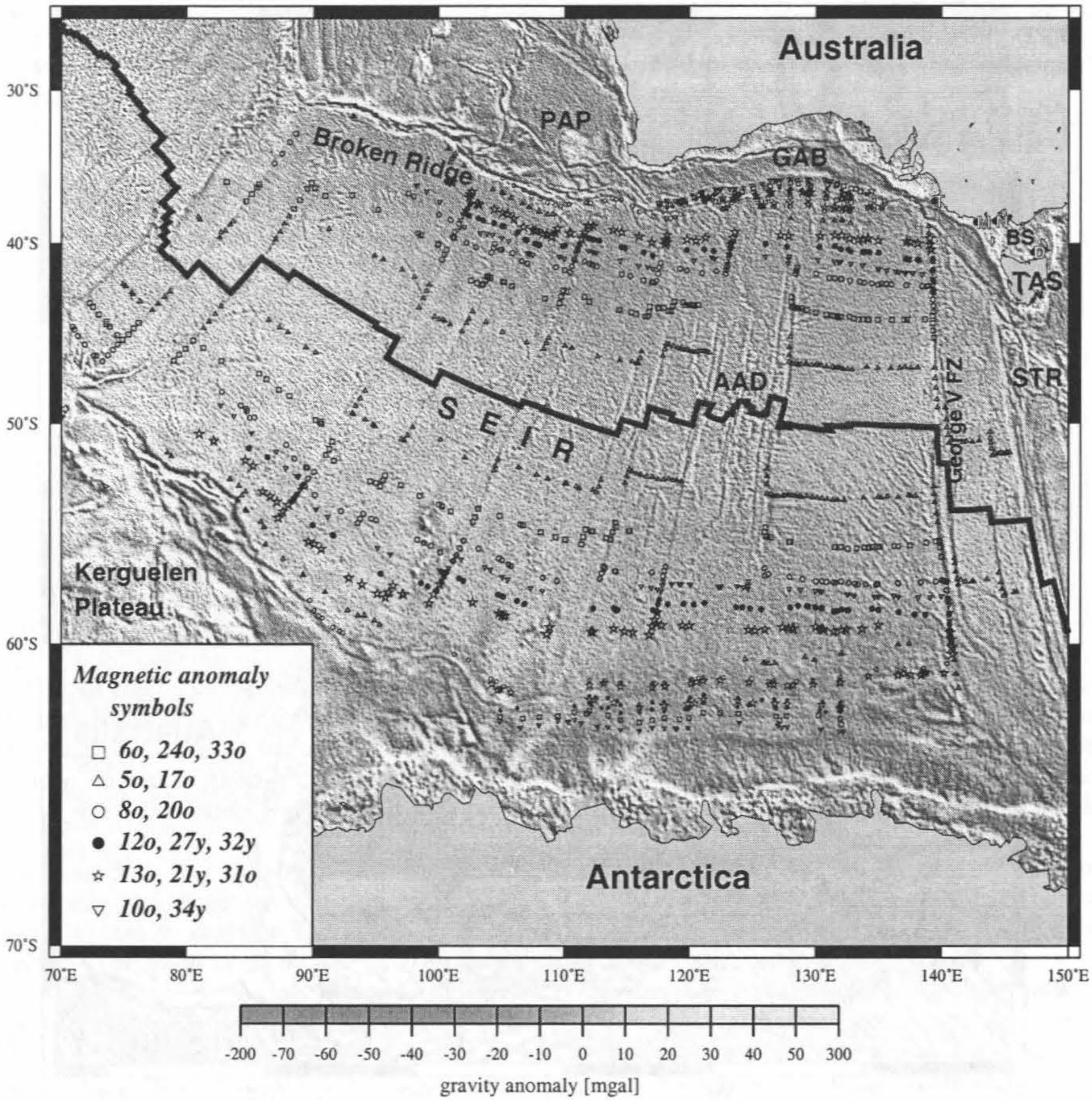

Figure 4b. Magnetic anomaly identifications from ship crossings and fracture zone picks overlain on marine gravity anomalies from satellite altimetry [*Sandwell and Smith*, 1997] south of Australia. Annotations are: SEIR, South East Indian Ridge; AAD, Australian Antarctic Discordance; GAB, Great Australian Bight; BS, Bass Strait; T, Troast; M, Minerva; N, Nerita 1; D, Durroo; TAS, Tasmania; STR, South Tasman Rise.

contrast, we find the opposite before 11 Ma, and spreading symmetry after 11 Ma. Therefore it is more likely that the V-shaped traces observed in the gravity field are due to the migration of the ridge over small-offset volcanic spreading centers, as described by *Schouten et al.* [1987]. However, the eastward component of ridge migration east of the AAD is not large enough to account for the steep angle of the observed V-shaped traces. The V-shapes could be created by a combination of eastward ridge migration and westward flow of the asthenosphere. The required westward flow of Pacific asthenosphere may rather be an expression of an evolving spreading ridge over a shallow wedge of Indian mantle material, dipping to the west (see Figure 9 of *Gaina et al.*, this vol.). This wedge may have been created by lateral viscous drag of Indian asthenosphere over Pacific mantle to the east by the Late Cretaceous eastward motion of Australia and Antarctica [*Gurnis et al.*, this vol.]. The early Southeast Indian Ridge in this area would have first sampled Indian mantle from a thin westward dipping wedge, which was progressively replaced by Pacific mantle from underneath this wedge. This would explain both the apparent westward migration

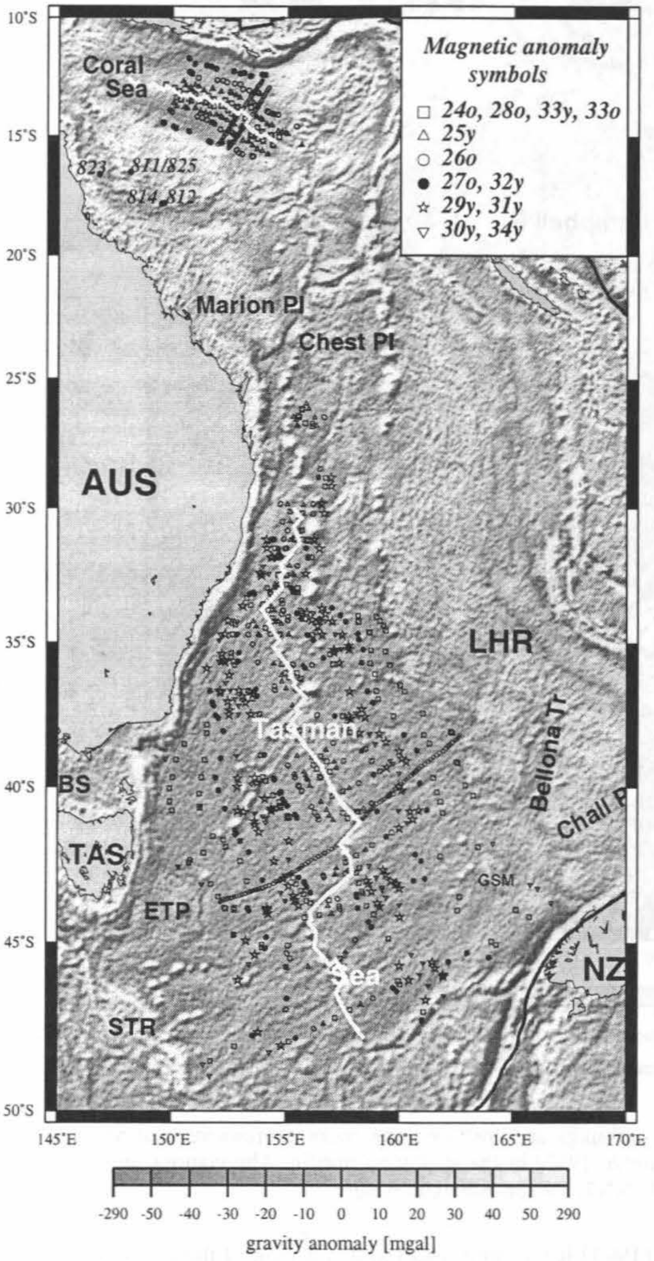

Figure 4c. Magnetic anomaly identifications from ship crossings and fracture zone picks overlain on marine gravity anomalies from satellite altimetry [*Sandwell and Smith*, 1997] east of Australia. Abbreviations are: Chest Pl, Chesterfield Plateau; LHR, Lord Howe Rise; Chall Pl, Challenger Plateau; ETP, East Tasman Plateau; NZ, New Zealand; GSM, Gilbert Seamount.

of Pacific mantle, and, together with an eastward component of ridge migration in the Tertiary [*Gurnis et al.*, 1998] the observed V-shapes in the gravity field, if small-scale convection under the ridge resulted in a series of small volcanic centers. Isochrons east of the George V Fracture Zone (Figure 4b) are currently not well constrained, and the asymmetries shown on Figure 3 have to be interpreted with caution. The prominent asymmetries in accretion visible in the Tasman Sea (Figures 4c, 4d) are discussed in a separate paper [*Gaina et al.*, this vol.].

4. RELATIVE AND ABSOLUTE PLATE MOTIONS

Relative and absolute plate motions for the plates around Australia since the Early Cretaceous are based on the rotations summarized in Table 2. The oldest magnetic anomaly found in the Perth, Gascoyne and Cuvier abyssal plains west of Australia that can be interpreted with confidence is M10N (~132 Ma) ((Figure 4). *Mihut* [1997] interpreted anomalies as old as M14 east of the Wallaby Plateau in the Cuvier abyssal Plain. However, the relationship between these oldest magnetic lineations and seaward dipping reflectors based on new multichannel deep seismic data collected by the Australian Geological Survey Organization (AGSO) (*P. Symonds, pers. com.*) is still under investigation. Figures 5 and 6 show the positions of the plates in an Atlantic-Indian hotspot frame starting at 132 Ma, rather than a paleomagnetic reference frame. *Van Fossen and Kent* [1992] showed that a 12° latitudinal difference between the two reference frames my have existed in the Atlantic from 122 to 88 Ma, implying that the actual latitude of Australia might have been 12° farther south at 130 Ma compared to the position shown in Figures 5 and 6.

It is interesting to note that the breakup age between Greater India and Australia roughly corresponds to the time when subduction stopped east of Australia at around 130 Ma, probably due to subduction of the Phoenix-Pacific spreading ridge [*Bradshaw*, 1991] (see *Gurnis et al.* [this vol.] for a discussion of data constraining the subduction history east of Australia). The subsequent opening of the nascent central Indian Ocean was partly accomplished by the joint eastward motion of Australia and Antarctica in an Atlantic ocean mantle reference frame and partly by the northwestward motion of India (Figures 5a, 5b, and 6). However, these observations are at odds with *Duncan and Clague's* [1985] model for westward Pacific absolute plate motion from 150 to 100 Ma, as it would require convergence between the Australian and Pacific plates from 130 to 100 Ma, if all hotspot have been fixed relative to each other. This discrepancy highlights the possibility of large-scale differential mantle motion as suggested by *Tarduno and Gee* [1995] and *DiVenere and Kent* [1999], rather than true polar wander, to account for *Van Fossen and Kent's* [1992] observations and for the lack of evidence for Australian-Pacific convergence from 130-100 Ma.

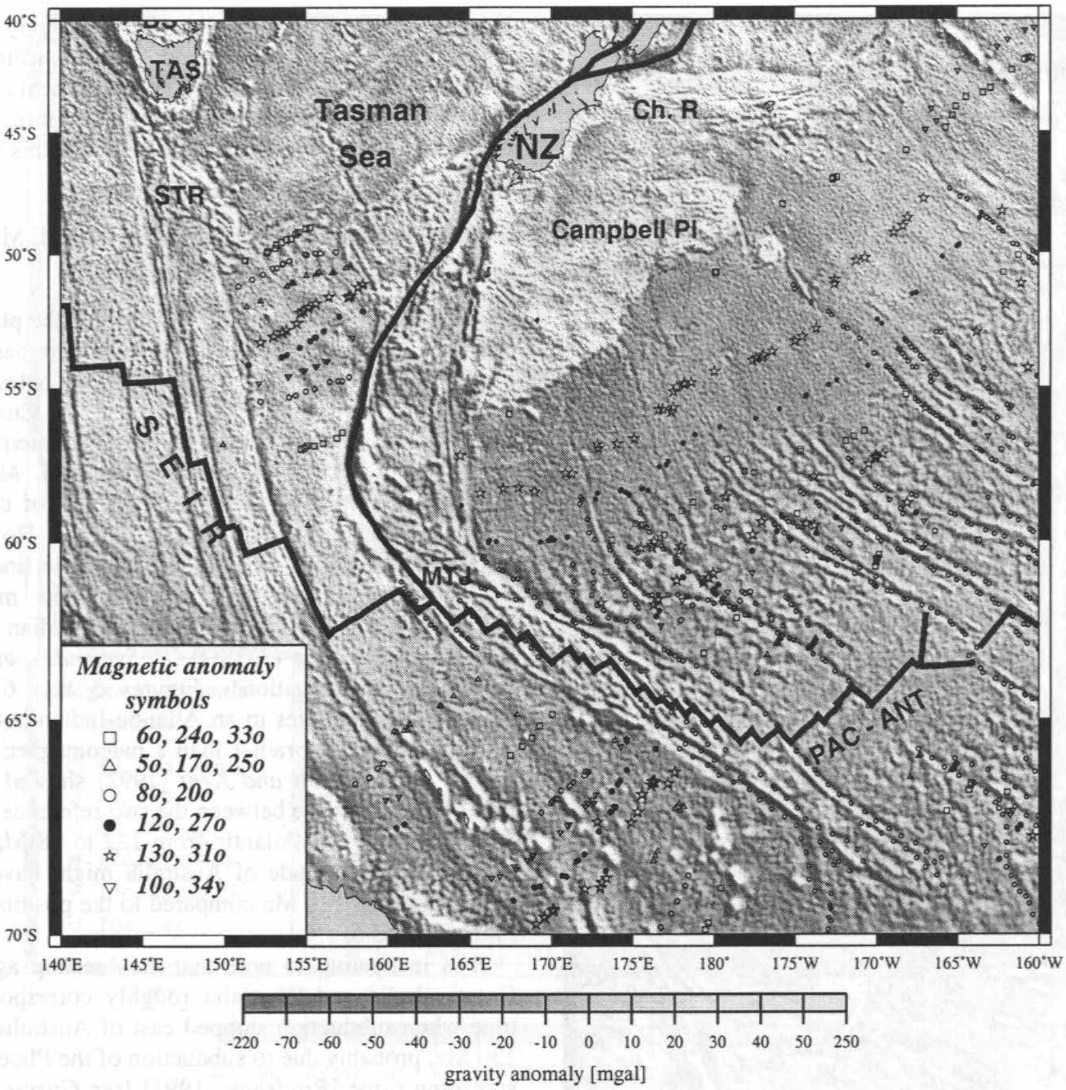

Figure 4d. Magnetic anomaly identifications from ship crossings and fracture zone picks overlain on marine gravity anomalies from satellite altimetry [*Sandwell and Smith*, 1997] in the southwest pacific. Abreviations are: MTJ, Macquarie Triple Junction; Ch. R, Chatham Rise; PAC-ANT, Pacific-Antarctic Ridge.

The pattern of spreading in the Early Cretaceous west of Australia persisted until about 99 Ma in the Cretaceous Magnetic Quiet Zone, when a drastic clockwise change in spreading direction from NW-SE to N-S occurred, resulting in the roughly north-south oriented spreading in the Wharton Basin (Figure 1). This event is expressed by a major bend in many fracture zones and some unusual linear troughs, ridges and knolls visible in *Sandwell and Smith's* [1997] gravity anomaly grid southeast of the Wharton Basin (Figure 4a). Preceding the 99 Ma event, a number of ridge propagators accreted large portions of the Indian Plate onto the Australian Plate, propagating northward (see also *Mihut and Müller* [1998] and *Mihut* [1997] for a more detailed discussion of these events). The timing of the bend in the fracture zones that documents this major change in spreading direction can only be constrained indirectly. *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 SE of the major bend in fracture zones 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 & Davies'*

Table 2. Finite Rotations for Different Plates around Australia

Age, Ma	*Latitude* +°N	*Longitude* +°E	*Angle,* deg
*North Lord Howe Rise Relative to Australia (90-84 Ma)**			
84.0	3.51	– 43.6	12.27
North Lord Howe Rise Relative to Middle Lord Howe Rise(84-64 Ma)			
84.0	8.10	-35.62	-2.72
Middle Lord Howe Rise Relative to Australia			
53.3	14.19	130.41	-0.723
55.8	15.93	133.47	-2.112
57.9	16.93	136.23	-3.792
61.2	4.65	131.51	-4.432
62.5	4.71	132.68	-5.168
64.0	0.19	130.37	-5.461
65.6	3.99	131.80	-6.735
67.7	9.04	134.46	-8.83
71.1	14.72	139.04	-13.08
73.6	9.53	137.20	-12.94
79.0	0.37	133.82	-13.00
83.0	1.57	133.42	-13.04
84.0	4.50	– 42.26	14.96
86.0	4.06	– 42.35	15.51
90.0	3.27	– 42.59	16.61
Challenger Plateau Relative to Middle Lord Howe Rise (90-77 Ma)			
86.0	60.83	63.50	-1.00
90.0	72.27	63.13	-1.39
*North Dampier Ridge Relative to Australia (90-71.4 Ma) **			
71.4	11.84	– 44.20	11.20
Middle 1 Dampier Ridge Relative to Australia (90-72.4 Ma)			
72.4	13.05	– 41.52	12.49
Middle 2 Dampier Ridge Relative to Australia (90-74.2 Ma)			
74.2	7.25	– 44.15	11.46
South Dampier Ridge Relative to Australia(90-79 Ma)			
79.0	5.28	– 43.88	11.87
Gilbert Seamount Complex Relative to East South Tasman Rise (90-79 Ma)			
79.0	0.52	131.47	-13.10
90.0	7.5	-50.4	14.87

Table 2 (continued)

Age, Ma	*Latitude* +°N	*Longitude* +°E	*Angle,* deg
Chesterfield Plateau Relative to Australia (90-71.6 Ma)			
71.6	7.57	112.18	– 5.03
Chesterfield Plateau Relative to North Lord Howe Rise (71.6-64 Ma)			
71.6	22.48	-24.74	-8.83
East Tasman Plateau Relative to Australia (90-84 Ma)			
84.0	60.20	-38.13	-2.70
East South Tasman Rise Relative to Antarctica (90-60 Ma)			
60.0	10.00	36.42	-25.50
West South Tasman Rise Relative to Antarctica(90-40.1Ma)			
40.1	26.19	22.65	-30.63
Tasmania Relative to Australia (120-95 Ma)			
95.0	90.0	0	0
120.0	28.43	177.10	-1.15
Small Plate Between Middle Lord Howe Rise and Challenger Plateau Relative to Challenger Plateau (90-86 Ma)			
90.0	56.51	64.76	0.59
Small Plate Between Middle Lord Howe Rise and Challenger Plateau Relative to middle Lord Howe Rise (86-77 Ma)			
86.0	65.08	108.98	-0.83
Louisiade Plateau Relative to Australia (61.3-53.3 Ma)			
53.35	-7.746	144.566	-2.085
55.89	7.155	124.346	-1.895
57.91	1.144	132.092	-4.630
61.28	-3.001	137.843	-10.650
Finite rotations for different tectonic elements in the Tasman Sea and Coral Sea are from Gaina et al. [1998] and Gaina et al. [1999]			
*North India Relative to Australia (131-99) **			
99.0	6.89	0.33	-44.68
120.4	5.26	-176.95	53.96
124.0	6.56	-176.61	55.28
126.7	7.79	-176.29	56.60
129.0	8.64	-176.14	57.82
130.9	9.43	-176.06	59.20

* *Mihut, [1997]*

Table 2 (continued)

Age, Ma	*Latitude* +°N	*Longitude* +°E	*Angle,* deg
*Pacific relative to Marie Bird Land (West Antarctica) (86-0 Ma)**			
0.78	64.25	-79.06	0.68
2.58	67.03	-73.72	2.42
5.89	67.91	-77.93	5.42
8.86	69.68	-77.60	7.95
12.29	71.75	-73.77	10.92
17.47	73.68	-69.85	15.17
24.06	74.72	-67.28	19.55
28.28	74.55	-67.38	22.95
*Pacific relative to Marie Bird Land (West Antarctica) (86-0 Ma)**			
33.54	74.38	-54.74	27.34
42.54	74.90	-51.31	34.54
47.91	74.52	-50.19	37.64
53.35	73.62	-52.50	40.03
61.1	71.38	-55.57	44.90
67.7	69.33	-53.44	51.50
86.0	65.77	-47.44	67.10
** Cande et al. [1995]*			
*Pacific relative to the mantle (150-86 Ma) **			
86.0	63.50	-50.30	58.99
100.0	44.80	-77.0	63.45
150.0	54.80	91.50	81.36
** Duncan and Clague [1985]*			
*East Antarctica Relative to West Antarctica (61.2-33.5) **			
33.54	-18.15	-17.85	0.696
43.08	-18.15	-17.85	1.7
** Cande et al. (in prep)*			
East Antarctica Relative to Australia (135-0)			
* 10.95	11.74	38.16	5.80
** 43.80	15.07	31.78	24.55
46.30	14.00	33.34	24.70
52.70	10.39	35.59	25.15
60.9	9.95	36.52	25.55
*** 79.1	5.12	39.80	25.57

Table 2 (continued)

Age, Ma	*Latitude* +°N	*Longitude* +°E	*Angle,* deg
83.0	2.05	40.79	27.12
**** 95.0	1.4	40.5	27.35
135.0	0.55	39.77	28.13

* *Cande et al. [in prep]*
** *Tikku [in prep]*
*** *Tikku and Cande [1999]*
**** *this study*

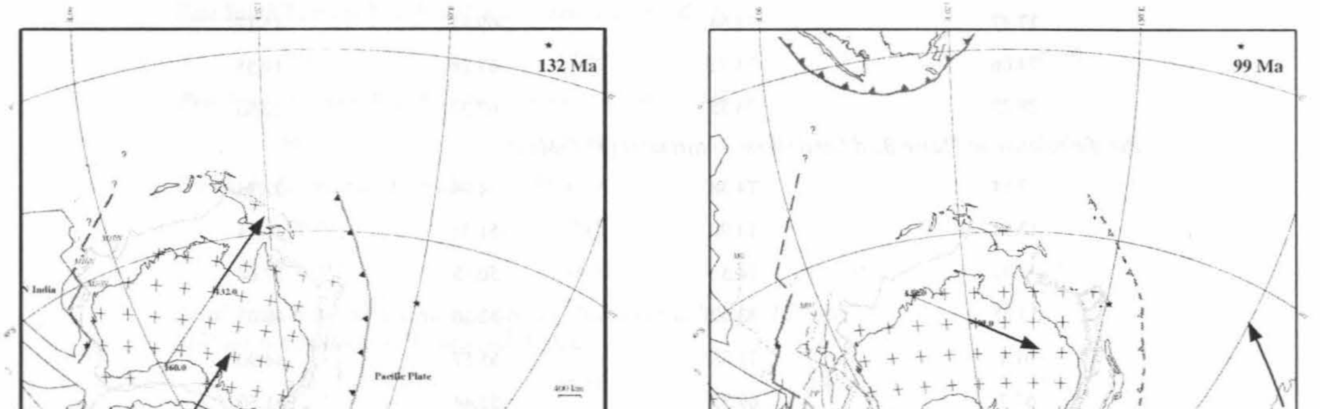

Figure 5a. Plate reconstructions in the Atlantic-Indian hotspot frame from *Müller et al.* [1993]. Pacific Plate absolute motion at 132 and 99 Ma is shown in the Pacific hotspot reference frame, as the closure of the plate circuit between the Pacific Plate and Atlantic-Indian hotspots is impossible to due the absence of Pacific passive margins at these times. Black stars represent hotspot locations. Arrows indicate the absolute plate motion of Australian, Antarctic and Pacific plates. Abbreviations are: PF, pseudofault; ER, extinct ridge, F, fault; BR, Broken Ridge; WB, Wharton Basin; NR, Ninetyeast Ridge; BA, Banda Arc; OP, Ontong-Java Plateau; DR, Dampier Ridge; CP, Campbell Plateau; CR, Chatham Rise; MTJ, Macquarie Triple Junction; TK, Tonga-Kermadec.

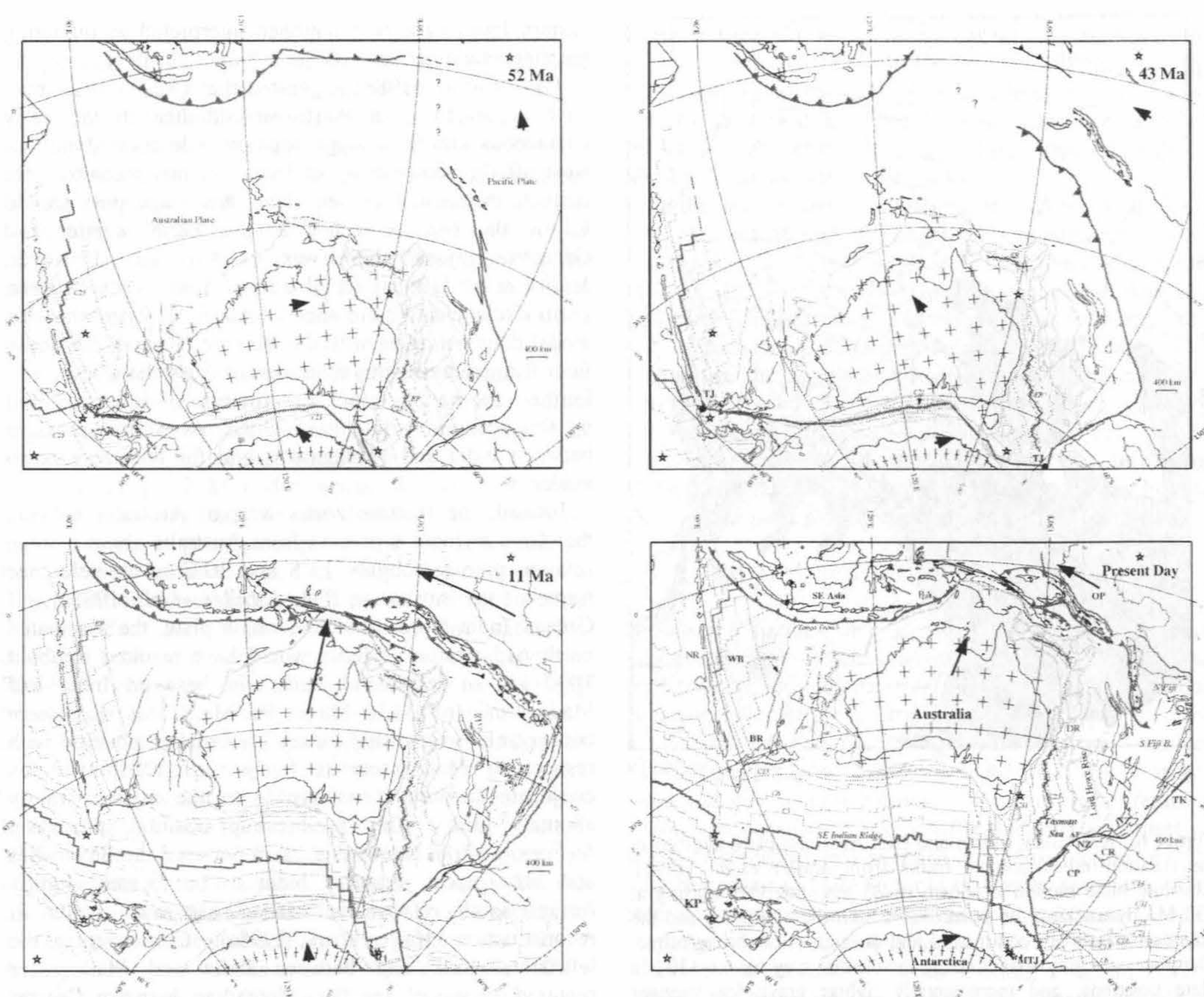

Figure 5b. Plate reconstructions in the Atlantic-Indian hotspot frame from *Müller et al.* [1993]. Abbreviations are: BR, Broken Ridge; WB, Wharton Basin; NR, Ninetyeast Ridge; BA, Banda Arc; OP, Ontong-Java Plateau; DR, Dampier Ridge; CP, Campbell Plateau; CR, Chatham Rise; MTJ, Macquarie Triple Junction; TK, Tonga-Kermadec.

[1974] basement age estimate at Site 256 to a minimum of about 101 Ma. Our modeled half-spreading rate between Greater India and Australia after chron M0 is 36 mm/yr. This spreading rate is not merely an extrapolation of M-sequence spreading rates, but based on a number of arguments outlined in *Müller et al.* [1998a] to create a self-consistent set of reconstructions between Australia, Antarctica, India, Africa and Madagascar. Combining the DSDP minimum age of 101 Ma of the ridge north of Batavia Knoll with this spreading rate yields a minimum age of 97 Ma for the fracture zone bend, located 150 km NW of the dated ridge.

A major unconformity on the southern margin of Australia , interpreted as the breakup unconformity by *Veevers* [1984], is well exposed and straddles the Albian-Cenomanian boundary (98.9 Ma, [*Gradstein et al.*, 1994]) between the volcanogenic Otway Group and the quartzose Sherbrook Group, dated by means of the *Phimopollenites pannosus* palynological zone [*Veevers*, 1984]. 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 argue that it is likely that the two events occurred contemporaneously, and assign the Albian-Cenomanian boundary age of ~99 Ma to the major fracture zone bend south of the Wharton Basin. Tectonic lineations expressed in gravity anomalies south of the Great Australian Bight (Figure 4b) indicate that the

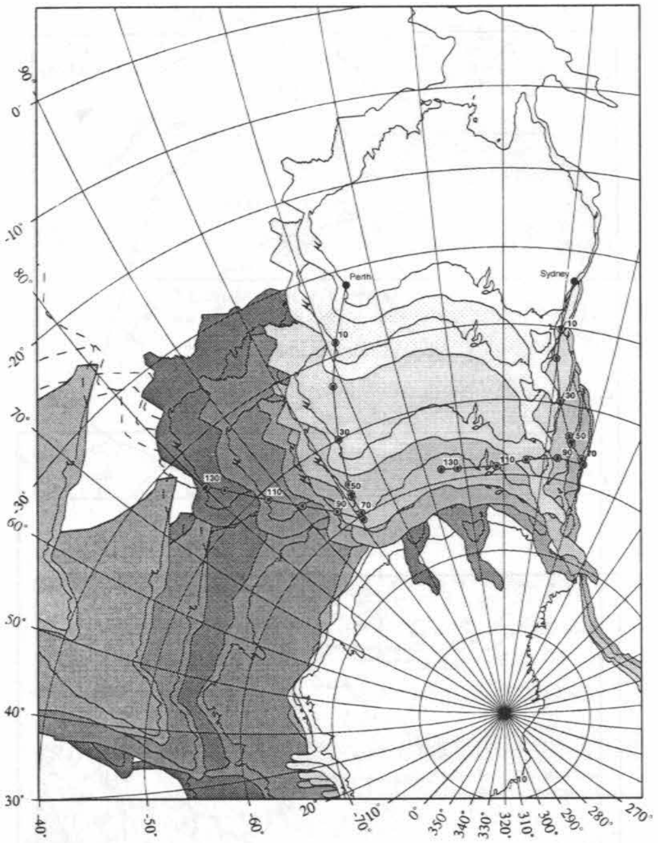

Figure 6. Australian, Indian and East Antarctic plate motions in the Atlantic-Indian hotspot frame from *Müller et al.* [1993]. Absolute plate motion is shown in 20 m.y. intervals starting at 130 Ma by tracking the positions of both the coastlines and the boundaries between continental and oceanic crust through time. The plates are gray-shaded using the darkest gray for the 130 Ma plate positions, and incrementally lighter grays for younger reconstruction times. In addition, we show the positions of Perth and Sydney through time in 10 m.y. intervals.

relative motion between the Australian and East Antarctic plates was oriented NW-SE initially, and changed to N-S roughly at chron 27 (61.2 Ma) [*Tikku*, 1998].

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 Basin 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 magnetic quiet zone [*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 west of Australia. However, *Müller et al.* [1998a] found a large discrepancy between small circle and fracture zone azimuths, implying that this model does not agree with the tectonic fabric of the ocean floor formed during this time west of Australia (Figure 4a). 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 about a stage rotation pole at roughly 17°S and 10°E in the reference frame of the Australian Plate [*Müller et al.*, 1998a]. 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, preceding formation of the Mascarene basin between the Seychelles and Madagascar, requires India to be located slightly further south relative to Madagascar than in its fit reconstruction [*Müller et al.*, 1998a]. 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 reject this model as unlikely.

The most plausible, internally consistent model for the breakup of eastern Gondwanaland involves a large transform fault between southern and northern Greater India, which would have formed in the Early 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 (Figure 5a). The transform fault would have 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 in the Perth Abyssal Plain (Figures 1, 4a) would reflect post-120 Ma Greater India-Antarctica spreading.

Breakup between India and Antarctica after rather than before 120 Ma is also supported by seismic data and the biostratigraphy of sediments from the Mac. Robertsen shelf, northwest of Prydz Bay, East Antarctica [*Truswell et al.*, 1999], which is conjugate to the northeastern Indian margin. They found evidence for half-graben formation on the Antarctic margin until at least until the early Aptian, which started at 121 Ma [*Gradstein et al.*, 1994]. Truswell et al. [1999] dated the onset of marine conditions in this area to Aptian-Paleocene, i.e. the age of the oldest offlapping, marine sediments on the outer shelf, in accordance with our tectonic model.

Chron 27 (61.2 Ma) also marks the onset of faster seafloor spreading east of the Balleny Fracture Zone [*Cande et al.*, in press], compared with the remainder of the Southeast Indian Ocean, indicating the formation of a triple junction which accommodated the incipient motion between East and West Antarctica. The spreading direction between Australia and Antarctica changed from NW-SW to N-S, accompanied by the initiation of rifting between Broken Ridge and the Kerguelen Plateau as well as a magmatic pulse creating conjugate volcanic ridges on both plates [*Tikku*, 1998]. Another tectonic event, the joining of the Bellinghausen plate to West Antarctica, was recorded at this time in the Pacific Ocean [*Cande et al.*, 1998]. The 61 Ma event also affected the Tasman Sea basin resulting in a counterclockwise change in the spreading direction, which initiated a period of transform motion along the central and northern parts of the eastern Australian margins [*Gaina et al.*, 1998b]. *Klepeis* [1999] showed that at about 60 Ma dextral transpression was initiated in Fiordland, New Zealand, as a result of a change in the plate boundary geometry. The Coral Sea started opening off northeast Australia at the same time [*Gaina et al.*, 1999] (Figure 5a). Chron 24 young (52 Ma, Figure 5b) marks the cessation of seafloor spreading along the entire eastern and northeastern Australian margin [*Gaina*, 1998; *Gaina et al.*, 1998a] and the onset of a compressional event in the Papua-Rennell-New Caledonia region [*Kroenke*, 1984].

The almost stationary position of Australia w.r.t. the mantle from ~80 Ma to ~40 Ma (Figures 5a, 5b) may reflect the progressive subduction of the Pacific-Phoenix ridge to the east of New Zealand preceding 80 Ma, resulting in a diminished trench suction force east of Australia. However, we stress that the timing of the apparent bend in the absolute plate motion path of Australia (Figure 6) is not well constrained. It essentially reflects the bend between the New England seamount chain and the Corner seamounts at roughly 80 Ma in the central North Atlantic [*Müller et al.*, 1993], since the Walvis Ridge as the only other constraint for pre-80 Ma hotspot track models in the Atlantic-Indian oceans is too broad to be useful for constraining rapid changes in absolute plate motion directions.

In the late Tertiary Australia has moved north rapidly at rates between 40 and 60 mm/yr. It is important to realize that the absolute motion of Australia relative to the mantle is quite different from the relative motion of Australia away from Antarctica, as expressed in magnetic lineations and fracture zones along the Southeast Indian Ridge. This is because the absolute motion of both Antarctica and Australia since about 40 Ma has had an eastward component (Figure 6), while Australia has moved northward relative to Antarctica. Therefore, fracture zones of the Southeast Indian Ridge reflect only relative, but not the absolute plate motion of Australia.

5. ANOMALOUS SUBSIDENCE AND UPLIFT

Passive margins are expected to exhibit thermal, exponential subsidence after rifting ceases [*Jarvis and McKenzie*, 1980; *McKenzie*, 1978]. Instead, tectonic subsidence curves on Australia's continental shelves show many large, unexpected deviations from thermal subsidence, many of which occurred at times of major plate tectonic reorganizations. We investigate regional anomalous subsidence and uplift postdating the onset of sea floor spreading and examine how these tectonic events may be related to plate tectonic or mantle processes. The tectonic subsidence analysis is based on 108 industry wells on the northwest shelf of Australia, 4 wells on Australia's southern margin, and 5 Ocean Drilling Program (ODP) Sites on the northeast shelf of Australia. The magnitude of subsidence or uplift in a region depends on the net contributions from sediment and water loading/unloading and vertical tectonic movements. We have isolated the tectonic component of subsidence/uplift by removing the isostatic component caused by sediment and water loading, using a standard backstripping methodoloy [*Sclater and Christie*, 1980], based on the age, thickness and lithology of each stratigraphic unit, the present depth below sea-level of each unit, a porosity-depth relationship for each lithology, and an estimated range for the palaeo water depth at the time of deposition of each unit.

To identify at which times anomalous subsidence or uplift was most widespread on the Northwest shelf, we created histograms which show the number of wells which exhibit either anomalous subsidence or uplift (Figure 7) 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, also clearly visible

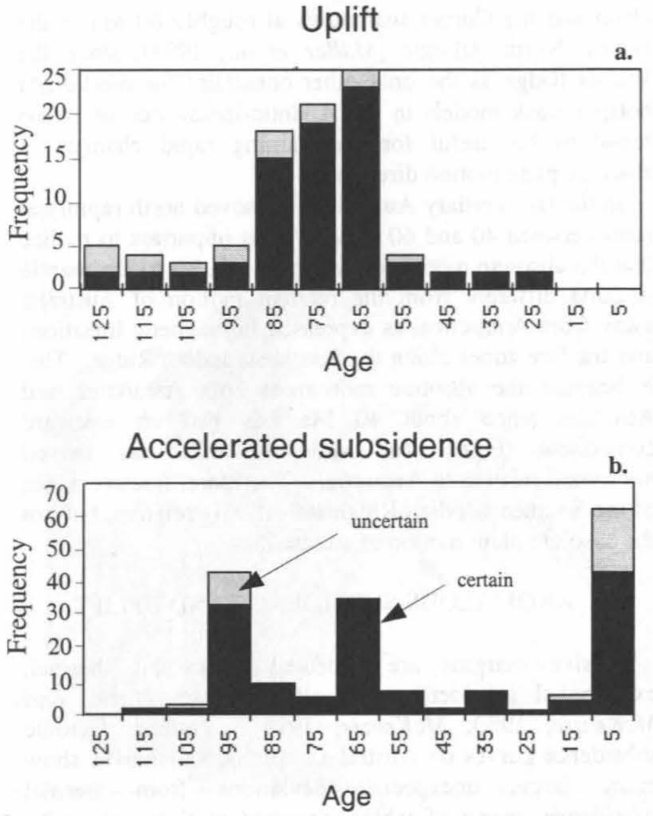

Figure 7. Histogram showing frequency of accelerated subsidence or uplift events on the North West Shelf. Note tectonic subsidence events at 100-90 Ma, 70-60 Ma and 10 Ma - present and uplift events at 70-60 Ma.

in many of the subsidence curves shown in Figure 8, whereas the uplift histogram shows widespread anomalous uplift from 90 to 60 Ma (Figure 7).

The anomalously high subsidence (or uplift) for the three time intervals from 100-90 Ma, 70-60 Ma and 10 Ma to present were then block averaged using a median filter and gridded using a natural spline with a grid interval of 0.1 degrees. The smoothed spatial distribution of tectonic subsidence and uplift as shown in the contour plots in Figure 9 gives a qualitative, regional "low-pass filtered" image of tectonic reactivation. The results are meaningful despite the shortcomings of this simple method, as (1) it is based on a large number of wells, and (2) the anomalous vertical motions observed (up to 700 m within a few million years, Figure 9) are up to an order of magnitude larger than the expected thermal subsidence for the same time period. We also show the tectonic subsidence for four wells with a relatively high-resolution stratigraphy covering the period from 130 Ma to present from the Otway and Bass basins, southeastern margin of Australia (Figure 10).

Available ODP data from the Queensland and Marion Plateau off northeast Australia only cover the last 20 million years. *Müller et al.* [1999] integrated geophysical logs, biostratigraphic and lithological information and seismic reflection data to correlate the pattern of Miocene hardgrounds to 3rd order eustatic sea-level lowstands at ODP Sties 812 and 814 to better estimate ages where biostratigraphic information is poor. They backstripped the sediment sequence to compute tectonic subsidence histories for five sites on the Queensland and Marion plateaus and in the Queensland Trough (Figure 11).

6. TECTONIC EVENTS

6.1. 99 MA

A tectonic event between 100 and 90 Ma (Figure 9a) resulted in tectonic subsidence up to 550 m on the Northwest shelf of Australia 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. At the same time, inversion in the Bass Basin north of Tasmania occurred [*Hill et al.*, 1995]. These events are clearly related to the plate reorganisation between India and Australia that we date at about 99 Ma. 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 local lithospheric thinning. In contrast, this time marks the cessation of rifting in many wells along the southern margin of Australia (Troas-1, Durroon-1, Figure 10, see also *Hegarty et al.* [1988]), and likely corresponds to the breakup-unconformity in the Otway Basin [*Veevers*, 1984]. These observations are consistent with an approach of the Neo-Tethyan ridge north of India towards the trench as a cause for this event. As the subducted plate becomes smaller and younger in age, the ridge push force decreases, and vanishes when the ridge is subducted.

6.2. 61 MA

The time period from 70-60 Ma 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 (Figure 9b). The magnitudes of subsidence anomalies at this time are smaller than at 100-90 Ma, ranging from up to 100 m of uplift to 100-200 m of

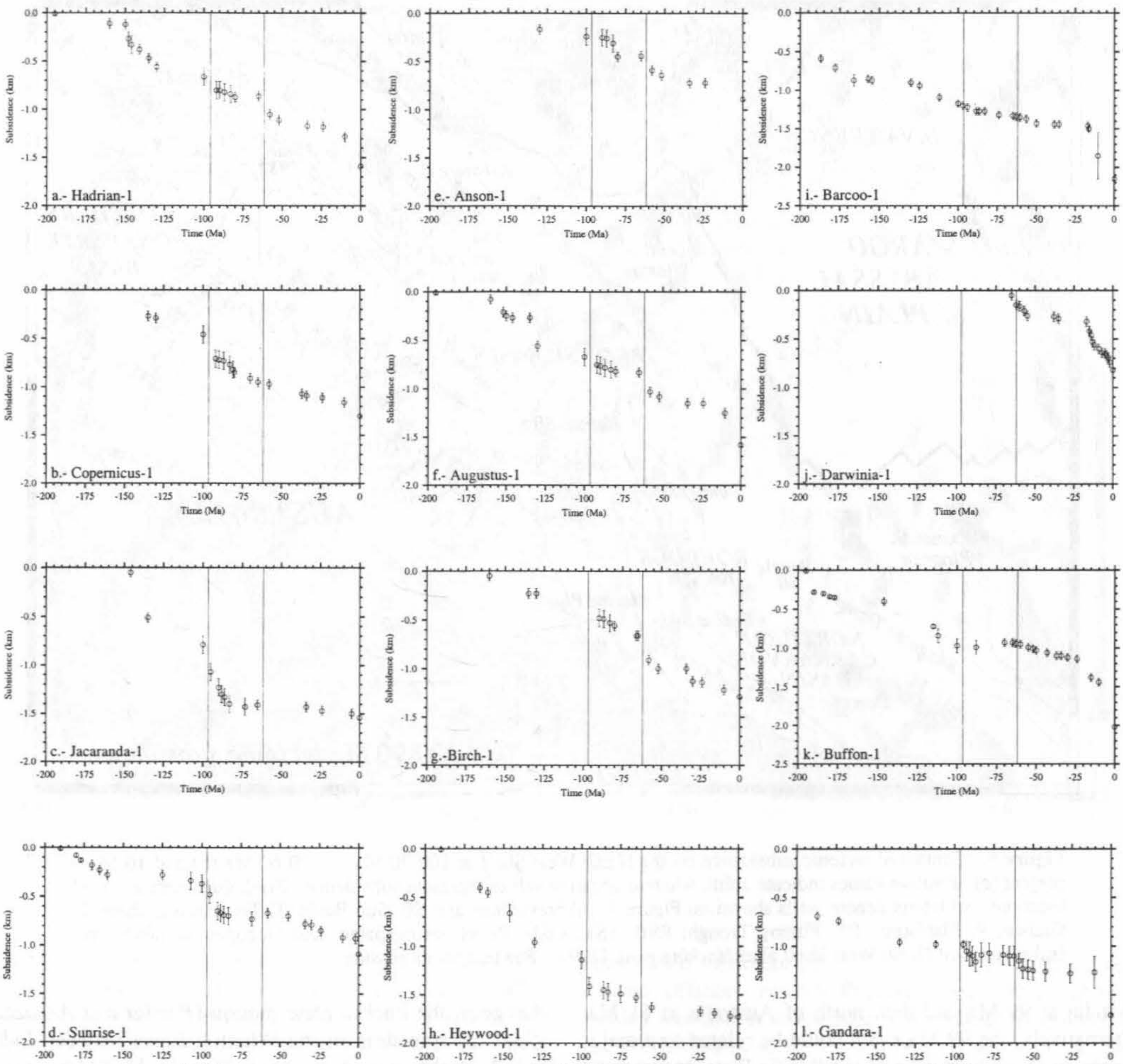

Figure 8. Selected backstripped wells from the northwest shelf of Australia. Well locations are shown on Figures 4b and 9. Water depth uncertainties are shown by vertical error bars. Note deviations from exponential subsidence at about 99 Ma and 61 Ma (thin black vertical lines), and 10 Ma – present.

subsidence. 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 may be related to a number of plate tectonic events at (61.2 Ma) described above. Both the extensional elastic plate deformation on the northwest 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. Both the 99 and 61 Ma events may have originated from the stepwise subduction of the Neo-Tethyan Ridge, first north

A)

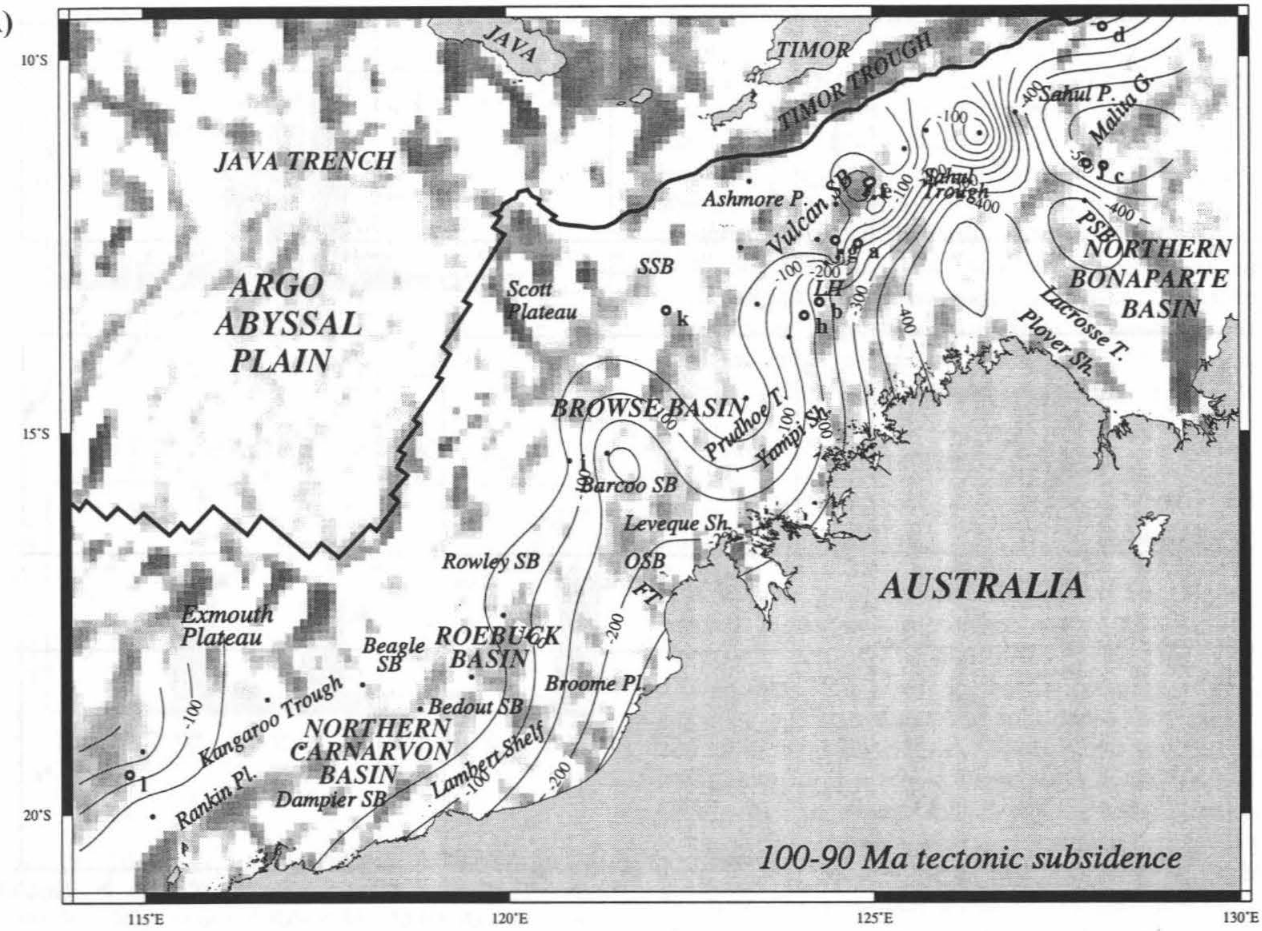

Figure 9. Contoured tectonic subsidence on the North West Shelf at 100-90 Ma (a), 70-60 Ma (b) and 10 Ma – present (c). Positive values indicate uplift, whereas negative values represent subsidence. Black dots represent well locations and letters denote wells shown on Figure 8. Abbreviations are: SB, 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]. See text for discussion.

of India at 99 Ma and then north of Australia at 61 Ma. Alternatively, the 99 Ma event could be related to a major change in absolute motion of the Pacific Plate documented for about the same time [*Duncan and Clague*, 1985].

6.3. 43 MA

This time marks the well-known bend of the Hawaiian-Emperor Chain [*Clague et al.*, 1989]. *Norton* [1995] proposed that the bend had no causal connection to relative plate motions as there is no obvious bend in the Farallon-Pacific fracture zones and a lack of tectonic events along the margins of the northern Pacific Ocean. It has also been suggested that the collision between the Indian plate and Eurasia, dated at about the same time, caused the sudden change in the Pacific plate motion [*Patriat and Achache*, 1984], as spreading in the Wharton Basin between India and Australia ceased at chron 20 (~43 Ma) [*Liu et al.*, 1983]. *Lithgow-Bertelloni and Richards* [1998] tested this hypothesis by modelling global plate velocities and concluded that it is unlikely that the two phenomena were related. Their results confirmed the hypothesis also proposed by *Gordon et al.* [1978] that the 43 Ma event was caused by the sudden change of the Pacific-Australian margin from transform to subduction along preexisting transform faults.

Preliminary reconstructions that include relative motion between East and West Antarctica [*Cande et al.*, 1998] based on recently collected geophysical data north of the Ross Sea and south of the Tasman Sea indicate that a

B)

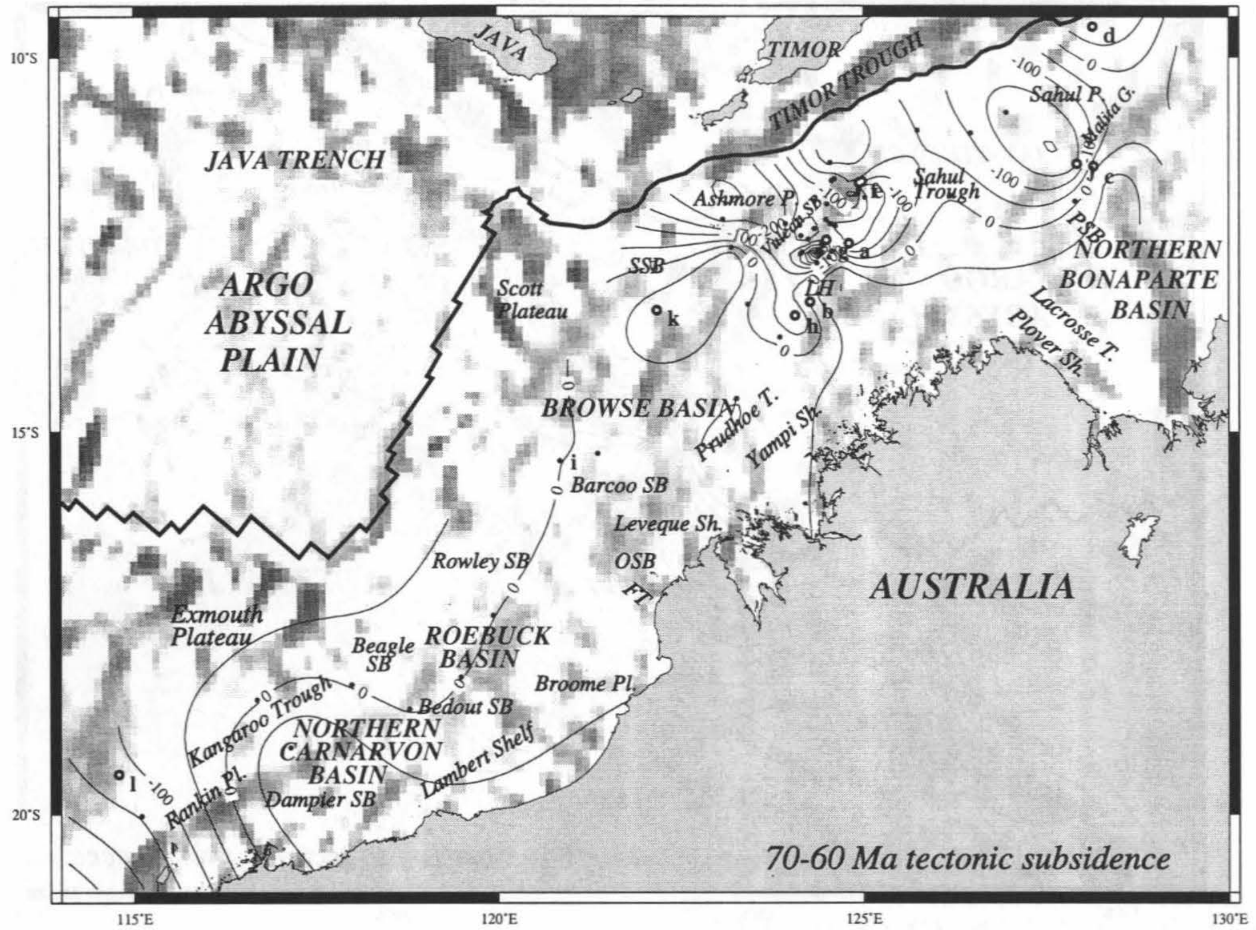

Figure 9b. (Continued.)

tectonic event at 43 Ma may indeed mark the onset of renewed subduction east of Australia [*Gaina*, 1998] (Figure 5b). There is abundant evidence that compression affected the eastern and northeastern Australian plate close to 43 Ma. Overthrusting of New Caledonia that has been dated Middle-Late Eocene is the result of a compressional event [*Collot et al.*, 1987]. Middle Eocene foredeep sediments and olistostromes record the collision of the Norfolk-New Caledonia Ridge continental ribbon with the forearc region of the intra-oceanic Loyalty-d'Entrecasteaux arc [*Aitchison et al.*, 1995]. In addition, *Kroenke et al.* [1993] suggested that the age of hiatuses described for rock samples from DSDP Site 289 and ODP Site 803 (both on the Ontong Java Plateau) are close to 43 Ma, indicating a tectonic event in the Southwest Pacific. The tectonic event that occurred at 43 Ma also influenced the northern Australian margin. *Pigram and Symonds* [1991] constructed basement subsidence curves from three wells located offshore eastern Papuan Basin, which show a sudden increase in subsidence at 43 Ma, most evident for the northernmost well. Similarly, two wells in the Bass Strait exhibit accelerated subsidence at this time (Figure 10).

In summary, contrasting *Norton* [1995], there is a wealth of evidence for a tectonic event at the southwestern margin of the Pacific Plate at 43 Ma. However, even if subduction between the Pacific and Australian plates was re-initiated at around 43 Ma, this does not prove that it was the ultimate cause of the Hawaiian-Emperor bend. Exactly how to reconcile relative and absolute plate motions, and large-scale differential motion in the mantle, is the subject of ongoing work, in particular involving the reconstruction of the history of relative motion between East and West Antarctica.

C)

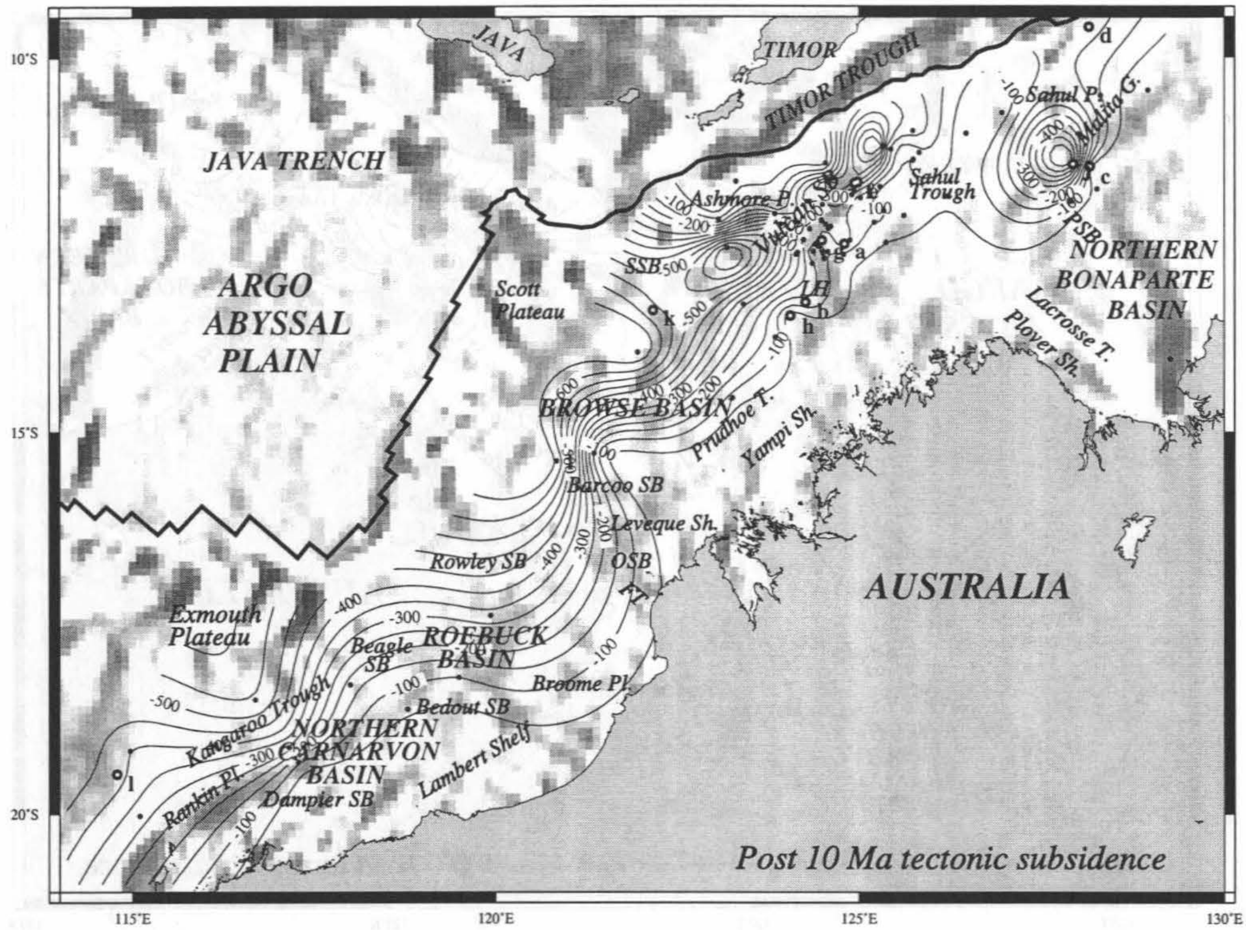

Figure 9c. (Continued.)

6.4. 25 MA TO PRESENT

At 23 Ma subduction along the Melanesian trench ceased after the Ontong Java Plateau docked with the Melanesian Arc [*Kroenke*, 1984]. From this time until 10 Ma subduction was accommodated along the Tonga-Kermadec Trench (Figure 5b). At 12 Ma, after a period of tectonic quiescence along the Melanesian arc, the Vitiaz-New Hebrides-Fiji-Lau-Tonga arc split and led to extension behind the Vitiaz Trench. Subduction along New Guinea ended and subduction and volcanism started along the Solomon Islands [*Yan and Kroenke*, 1993] (Figure 5b). In the last 10 Ma the Vitiaz Trench became inactive, and subduction was transferred to the New Hebrides Trench, which began a clockwise rotation (Figure 5b).

Subduction along the Solomon Trough and other changes in plate boundaries north of Australia favoured an extensional regime northeast of Papuan Peninsula and created the Woodlark Basin starting at 5 Ma [*Taylor et al.*,

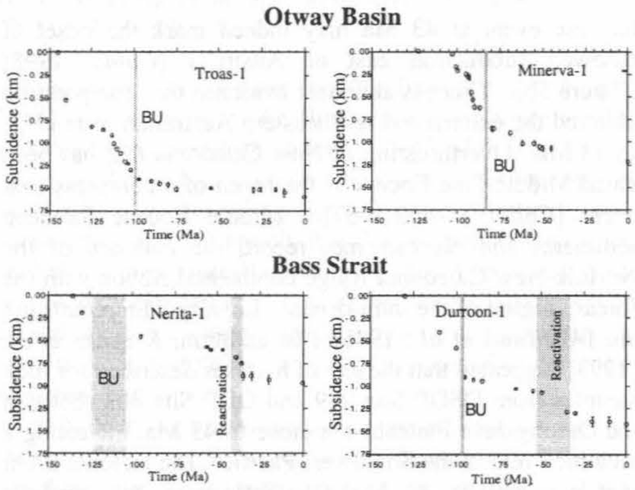

Figure 10. Water loaded tectonic subsidence for four wells in the Otway and Bass basins. BU: Breakup unconformity. Note Paleogene accelerated subsidence in Bass Basin.

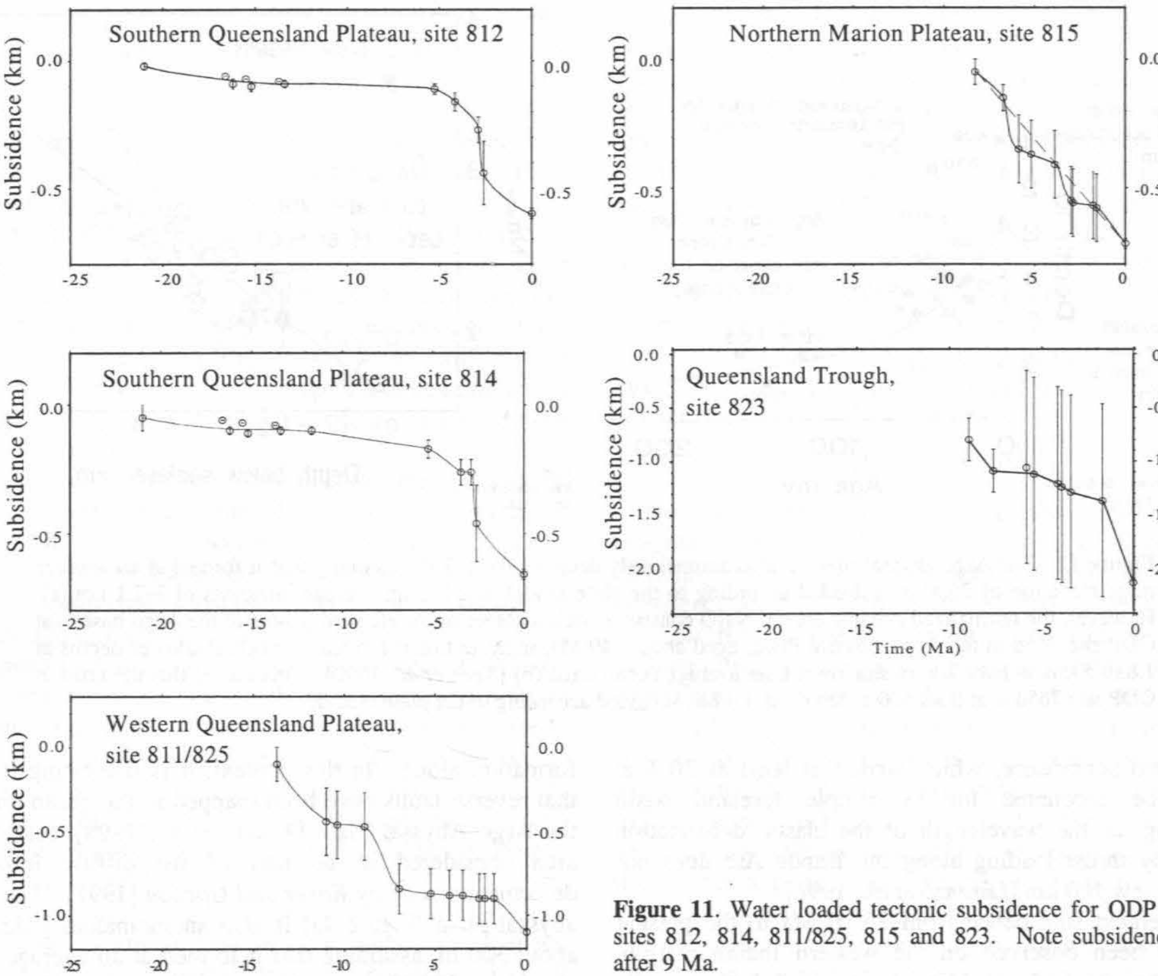

Figure 11. Water loaded tectonic subsidence for ODP Leg 133 sites 812, 814, 811/825, 815 and 823. Note subsidence events after 9 Ma.

1995]. Trench roll-back determined the opening of the Lau Basin (6-5 Ma) [*Scholl*, 1995] between the Lau-Colville and Tonga-Kermadec volcanic arcs. Collision along the Banda Orogen northwest of Australia created a foreland basin including the Timor Trough and the outer North West Shelf post-5 Ma [*Lorenzo et al.*, 1998] (Figure 5 b).

Widespread tectonic reactivation occurred on Australia's northwest shelf in the Late Miocene-Pliocene. Regional tectonic subsidence (Figure 9c) shows widespread accelerated post 10 Ma subsidence of the outer northwest shelf, 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. Barcool, Darwinia1, Figure 8). The tectonic subsidence we show represents a minimum estimate as sea level has generally fallen in the Miocene/Pliocene [*Haq et al.*, 1987]. Including a falling eustatic sea level would increase the backstripped tectonic subsidence.

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]. 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].

Recent 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 in the western Roebuck Basin, the western Browse Basin, and the Vulcan Graben (Figure 9c), up to 1000 km south of the active plate boundary. Regional

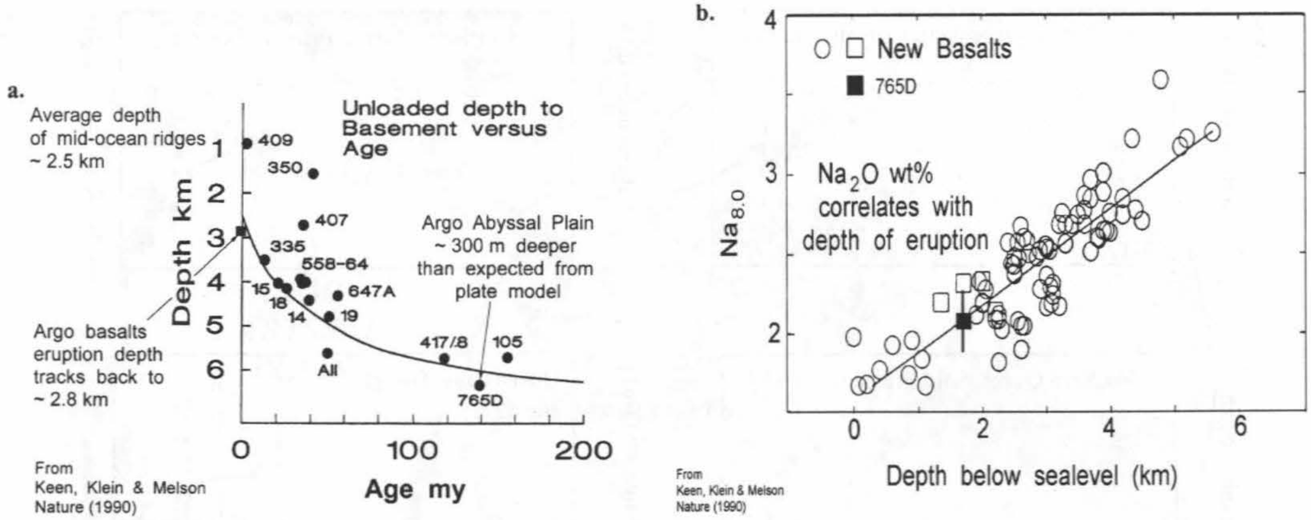

Figure 12. The Argo abyssal plain is also anomalously deep by about 300, assuming that it formed at an average ridge elevation of 2500 m, subsided according to the plate model, and has an average thickness of 7-7.1 km (a). However, the normalized oceanic crustal Na_2O content as well as other major element oxides of the Argo basalts at ODP site 765d in the Argo Abyssal Plain, aged about 140 Ma, indicate that it formed at much shallower depths at 1.8±0.5 km, at least 200 m shallower than average ocean crust (b) [*Keen et al.*, 1990]. This means that the crust at ODP site 765d is at least 500 m too deep if it has subsided according to the plate model.

accelerated subsidence, which started at least at 20 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].

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 and Rogers*, 1988]. *Royer and Chang* [1991] suggested that the break-up of the Indo-Australian plate into two plates began between chrons 6 and 5 (20-10 Ma). *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 with an "ocean fold and thrust belt" extending from the central Indian Ocean to the Northwest shelf [*Royer and Gordon*, 1997]. More recently, *Gordon et al.* [1998] established a minimum age for the relative motion between the Indian and Capricorn plates at about 18 Ma.

The large area affected by Miocene-Pliocene accelerated subsidence on the North West Shelf, together with contemporaneous accelerated subsidence off western India, suggests that 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. In this context, it is interesting to note that reverse faults have been mapped in the ocean crust of the Argo Abyssal Plain [*Kritski et al.*, 1999], east of the area considered to be part of the diffuse intraplate deformation zone by *Royer and Gordon* [1997]. The Argo abyssal plain (Figure 4a) is also anomomalously deep by about 300 m, assuming that it formed at an average ridge elevation of 2500 m, subsided according to the plate model [*Keen et al.*, 1990], and has an average crustal thickness of 7-7.1 km based on seismic refraction data [*Kritski et al.*, 1999] (Figure 12a). However, the normalized oceanic crustal Na_2O content as well as other major element oxides of the Argo basalts at ODP site 765d [*Keen et al.*, 1990] in the Argo Abyssal Plain, aged about 140 Ma, indicate that it formed at much shallower depths of 1.8±0.5 km, at least 200 m shallower than average ocean crust (Figure 12b). It follows that the Argo abyssal plain is at least 500 m deeper than expected, assuming that its original ridge depth was at least as shallow as 2.3 km.

Assessed in isolation, this observation may indicate that the Argo Abyssal Plain has subsided according to the thermal boundary layer model, as ocean crust 140 m.y. old would show an excess depth of ~600 m if it subsided as a thermal boundary layer compared with the plate model [*Parsons and Sclater*, 1977]. However, the observed excess subsidence in the Argo Abyssal Plain is of the same order as the tectonic subsidence that occurred within the last 10 million years on the outer northwest shelf of

Australia (Figure 9c). This coincidence may indicate that both subsidence anomalies are due to the same cause. In this case the cause would be unrelated to the thermal boundary layer model, as all excess subsidence would have occurred recently, since about 20 Ma. The wavelength of this deformation points to viscous, rather than elastic processes, as an elastic plate thickness typical for old ocean crust of 30-40 km [*Bodine et al.*, 1981] would be unable to produce the observed deformation as a result of plate boundary forces. Elucidating this regional anomalous subsidence and Miocene reactivation on the North West Shelf and the Indian Plate will require modelling the effects of the breakup of a large plate with a laterally varying yield-stress envelope, as well as viscous flow in the mantle.

The northeast shelf of Australia, i.e. the Queensland Plateau and Trough and the Marion Plateau (Figure 11) also exhibits a phase of accelerated tectonic subsidence in the late Miocene/Pliocene. Five ODP sites show "foreland-basin type" subsidence rates of up to 145 m/my., even though this area is located about 800 km away from the Papuan foreland basin to the north, and about 1000 km away from the thrust load which caused the Papuan Basin to form (Figure 11). Post 9 Ma subsidence amounts to 1300±200 m in the Queensland Trough, 650±200 m on the western margin of the Queensland Plateau, post 5 Ma subsidence of 500±30 m on its southern margin, and 660±50 m on the northern margin of the Marion Plateau [*Müller et al.*, 1999].

A conventional foreland-basin model, in which a foreland basin forms in front of an advancing thrust sheet, cannot explain the observed tectonic subsidence, even if we include compressional in-plane forces and variations in equivalent elastic plate thickness [*Müller et al.*, 1999]. A published model [*Karner et al.*, 1993] for simulating the flexural response to in-plane forces of a margin with an overall structure similar to that given by the Queensland Plateau and Trough also fails to account for the observed large amplitudes of passive margin subsidence [*Müller et al.*, 1999].

It is more likely that the observed post 9 Ma tectonic subsidence of the Queensland and Marion plateaus and the Queensland Trough is largely caused by dynamic surface topography due to Australia's northeastern margin overriding a slab burial ground, modulated by flexural deformation resulting from collision north of Australia. A high-resolution upper mantle shear wave tomography model by van der Hilst et al. [1998] displays a NNW-SSE trending band of anomalously high velocities in the upper mantle at depths of 300 km in Queensland, landward of the southern Queensland and Marion plateaus. An upper mantle shear wave tomography model by Zhang and Tanimoto [1993] confirms that this band of high velocities extends down to 500 km and may stretch from the Queensland Plateau to Indonesia. Taking into account the absolute plate motion history of Australia and the subduction history north of Papua New Guinea, a band of observed positive p and s-wave anomalies in the upper mantle stretching from the Queensland Plateau to Indonesia may reflect subducted slab material originating from Oligocene-Eocene subduction north of the Caroline back-arc basin. The resulting basement subsidence has probably been modulated by flexural deformation resulting from collision north of Australia, even though this effect cannot be quantified in the absence of detailed knowledge of the rifting history of the margin.

7. CONCLUSIONS

We have combined a relative and absolute plate kinematic model with grids of oceanic crustal age, spreading rates and asymmetries as well as tectonic subsidence analyses of the northwest and northeast shelves of Australia to identify major plate tectonic events, evaluate their causes, and investigate their effects on anomalous intraplate subsidence or uplift and on the history of oceanic crustal accretion. From this analysis it appears that the main events that have caused plate reorganizations are spreading ridge subduction, plate collisions, and subduction initiation. Further it is clear that Australia has suffered from large fluctuations in intra-plate stresses due to plate boundary reorganizations, but also due to viscous mantle processes, causing transient vertical tectonic motions. The overriding of subducted slabs may have not only been responsible for Cretaceous flooding of eastern Australia, its subsequent re-ermergence and the formation of the Australian-Antarctic discordant Zone [*Gurnis et al.*, 1998], but is also expressed in asymmetries in accretion at the AAD, and may have caused the drowning of carbonate platforms on the Queensland and Marion plateaus northeast of Australia. Viscous coupling between the lithosphere and the mantle may also be involved in the observed anomalous depth of the Argo Abyssal Plain and the outer northwest shelf of Australia. Plume-lithosphere interaction has caused large asymmetries in crustal accretion north of Kerguelen and in the Tasman Sea. Combining plate kinematics with mantle convection models and geological data in the future should provide us with better constraints for understanding the driving forces of absolute plate motions, and their consequences in terms of the history of uplift, subsidence and deformation of the crust.

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