Earth and Planetary Science Letters 355–356 (2012) 283–298

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

A global-scale plate reorganization event at 105 – 100 Ma

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ARTICLE INFO

Article history:
Received 6 July 2012
Received in revised form
14 August 2012
Accepted 19 August 2012
Editor: Y. Ricard

Keywords:
plate reorganizations
mid cretaceous
eastern Gondwanaland
fracture zone bends
plate driving forces
Bouvet plume

ABSTRACT

A major plate reorganization is postulated to have occurred at approximately 100 Ma. However, this reorganization has received limited attention, despite being associated with the most prominent suite of fracture zone bends on the planet and many other geological events. We investigate tectonic events from the period ~110 to 90 Ma and show that the reorganization occurred between 105 and 100 Ma, was global in scale, and affected all major plates. Seafloor evidence for plate motion changes is abundant during this period, with either fracture zone bends or terminations preserved in all ocean basins. Long-lived eastern Gondwanaland subduction ended along a 7000 km long section of the margin, while elsewhere around the proto-Pacific rim subduction continued and there is evidence that compressional stresses increased in the overriding plates. Thrusting in western North America, transpression and basin inversion in eastern Asia, and development of the present-day Andean-style margin along western South America occurred contemporaneous with the development of an extensional regime in eastern Gondwanaland. Basin instability in Africa and western Europe further demonstrates that lithospheric stress regime changes were widespread at this time. Considering the timing of the reorganization and the nature of associated plate boundary changes, we suggest that eastern Gondwanaland subduction cessation is the most likely driving mechanism for the reorganization. Subduction is the dominant driver of plate motion and therefore this event had the potential to strongly modify the balance of driving forces acting on the plates in the southwestern proto-Pacific and neighboring plates, whereby producing widespread changes in plate motion and continental lithospheric stress patterns. We propose that major changes in ridge–trench interaction triggered the cessation of subduction. The progressive subduction of two closely spaced perpendicular mid ocean ridges at the eastern Gondwanaland subduction zone, to the east of Australia and New Zealand, respectively, resulted in very young crust entering the trench and we suggest that by 105 – 100 Ma there was insufficient negative buoyancy to drive subduction. Finally, we propose that the plume push force of the Bouvet plume, that erupted near the African–Antarctic–South American triple junction, contributed to plate motion changes in the southern Atlantic region.

1. Introduction

Long periods of relatively uniform plate motion are punctuated by short intervals of rapid change (e.g. Engebretson et al., 1985; Torsvik et al., 2008) evident in kinks in plate motion paths recorded by fracture zones (FZs) (Matthews et al., 2011) and hotspot trails (Wessel and Müller, 2007). Abrupt changes in the speed and/or direction of plate motion are associated with changes in the orientation or location of plate boundaries, and the forces acting on them. Continental margins, which are sensitive to plate margin processes in terms of the geochemical signature of magmatism, the vertical motion of basins and movement at major fault zones (e.g. Bailey, 1992; Cloetingh et al., 1990; Jelsma et al., 2009; Moore et al., 2008; Sun et al., 2007), can also record evidence for major plate reorganization.

Plate reorganizations are recurrent in Earth's history and form an integral component of the plate tectonic cycle, yet there remains much debate over the driving mechanisms responsible for major episodes of plate motion change (e.g. Bercovici, 2003), including the importance of top-down (plate-derived) (Anderson, 2001) versus bottom-up (mantle flow-derived) (e.g. Cande and Stegman, 2011; King et al., 2002) processes. Richards and Lithgow-Bertelloni (1996) concluded that rapid plate reorganizations that take place over a period of less than a few million years occur too rapidly to be attributed to changes in mantle buoyancy forces that develop over longer timescales, instead they highlighted the importance of plate boundary forces in driving rapid plate motion changes. Several authors have also presented subduction initiation and cessation as viable top-down driving mechanisms of plate reorganizations based on their ability to modify the balance of driving forces acting on plate boundaries (Austermann et al., 2011; Faccenna et al., 2012;

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0012-821X/$ - see front matter
http://dx.doi.org/10.1016/j.epsl.2012.08.023

Knesel et al., 2008; Seton et al., submitted for publication; Wessel and Kroenke, 2000). Conversely, King et al. (2002) and Lowman et al. (2003) concluded that rapid plate motion changes, on the order of <4–5 Myr, can occur in response to mantle convection processes. These bottom-up models indicate that during subduction heat builds up around subducting slabs, reducing their negative buoyancy and pull on the subducting plate, allowing the plate to move rapidly in a different direction away from the mature subduction zone (King et al., 2002; Lowman et al., 2003). Mantle plumes impinging on the base of the lithosphere are another potential bottom-up driver of rapid plate motion changes. Ratcliff et al. (1998) proposed that the lubrication provided by plumes at the base of the plates enable them to become decoupled from the dominant mantle flow field and change direction, and Cande and Stegman (2011) proposed that the lateral plume head push force can modify the speed of plate motion.

A major plate reorganization at ~50 Ma is widely accepted and has received much attention due to its association with the Hawaiian-Emperor seamount chain, the most dramatic hotspot track bend observed on the seafloor, and implies a major swerve of the Pacific plate at this time (Morgan, 1971). In the mid Cretaceous, approximately 50 Myr earlier, a suite of prominent 50° FZ bends formed in the Wharton Basin (Fig. 1), reflecting a major change in the direction of spreading between the Australian and Indian plates (e.g. Johnson et al., 1980; Müller et al., 1998; Powell et al., 1988) and subsequent rapid northward acceleration of India (Johnson et al., 1980). This reorganization has received limited attention, despite being associated with the most prominent FZ bends currently observed on the seafloor.

In this paper we investigate this lesser-studied plate reorganization that occurred around 100 Ma (Veevers, 2000). We present the first global compilation of major tectonic and volcanic events that occurred at this time, in both the oceanic and continental domains, in order to determine the temporal and spatial scale of the reorganization. The driving mechanisms of major plate reorganizations are not well understood and remain disputed even for the intensively studied 50 Ma event. India–Eurasia collision (Patriat and Achache, 1984), subduction cessation and initiation events in the western Pacific (Faccenna et al., 2012; Seton et al., submitted for publication) and the time-dependence of the plume push force of the Reunion plume (Cande and Stegman, 2011) have all been proposed as viable mechanisms for the 50 Ma event. By determining the nature, timing and spatial distribution of events associated with the 100 Ma reorganization we will describe the likely driving mechanisms, which may assist future efforts to re-assess the driving forces of other sudden plate boundary reorganizations, such as the 50 Ma event.

We have converted the ages of mid Cretaceous tectonic and volcanic events to the timescales of Gradstein et al. (1994) for ages older than magnetic anomaly 34 (83.5 Ma), and Cande and Kent (1995) for younger ages. This is consistent with the recent global plate reconstruction model of Seton et al. (2012), which we

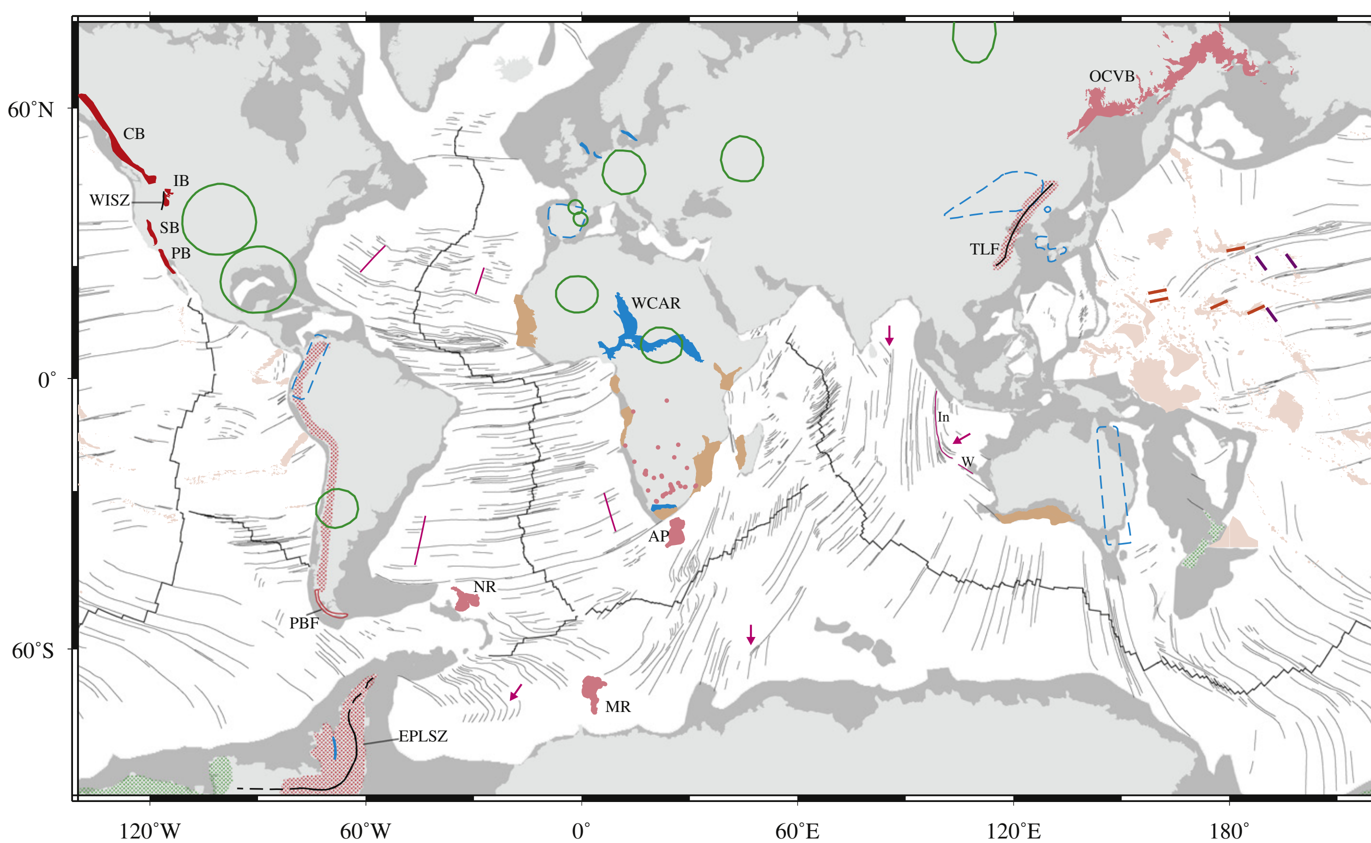


Fig. 1. Present-day distribution of tectonic and volcanic observations from ca. 100 Ma; events are described in text. Solid black lines are major faults, green circles show regional unconformities identified by Zorina et al. (2008), FZ indicators of plate motion change are highlighted in magenta, North American batholiths are red, products of magmatism are pink, red hatched areas correspond to compression related events, green hatched areas correspond to extension related events, basins that underwent increased subsidence are brown, regions showing evidence of uplift are blue. On the Pacific plate orange and purple lines show the orientation of hotspot tracks from 110 to 100 Ma and 100 to 80 Ma, respectively (from Koppers et al., 2001). Mid ocean ridges are derived from Sandwell and Smith (2009), FZ traces are from Matthews et al. (2011), and large igneous provinces and seamount chains are from Coffin and Eldholm (1994). The Investigator FZ (In) and Wallaby–Zenith FZ (W) are magenta. AP, Agulhas Plateau; CB, Coast Mountains Batholith; EPLSZ, Eastern Palmer Land Shear Zone; IB, Idaho Batholith; MR, Maud Rise; NR, Northeast Georgia Rise; OCVB, Okhotsk-Chukotka Volcanic Belt; PB, Peninsular Ranges Batholith; PBF, Punta Barrosa Formation; SB, Sierra Nevada Batholith; TLF, Tan-Lu Fault; WCAR, West and Central Africa Rift System; WISZ, Western Idaho Shear Zone. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

use to reconstruct the data back to 100 Ma. Although Gradstein et al. (2004) replaces Gradstein et al. (1994), the ages of stage boundaries in the mid Cretaceous remain largely unchanged. A notable difference is the age of the Albian/Cenomanian boundary, which becomes 99.6 Ma (Gradstein et al., 2004) compared to 98.9 Ma (Gradstein et al., 1994).

2. Background to the "100 Ma event"

Several authors have discussed the mid Cretaceous Australian–Indian spreading ridge reorientation, that produced 50° FZ bends in the Wharton Basin, in terms of an Indian Ocean-centered plate reorganization. The ridge reorientation was synchronous with a late Albian–Cenomanian break-up unconformity along the southern Australian margin (Müller et al., 1998; Veevers, 1984), and coeval with conjugate FZ bends in the Enderby Basin and Bay of Bengal (Fig. 1), representing India–Antarctica spreading (Rotstein et al., 2001). Furthermore, Bernard et al. (2005) suggested that very broad FZ bends showing changes in the direction of spreading between Africa and Antarctica at the Southwest Indian Ridge of a few degrees formed at about 96 Ma, corresponding to the change in spreading direction in the Wharton Basin discussed by Müller et al. (1998). The FZ bends observed throughout the Indian Ocean are contemporaneous with a swerve of the Pacific plate indicated by hotspot trail bends (Fig. 1), and a series of tectonic and stratigraphic regime changes in Australia, New Zealand and the Pacific-rim (Veevers, 1984, 2000).

It is difficult to directly date seafloor events that occurred in the mid Cretaceous between 120.4 and 83.5 Ma, as this interval corresponds to the Cretaceous Normal Superchron (CNS), a period in Earth's history where there were no reversals of Earth's magnetic field. Yet it is possible to indirectly compute approximate age-ranges for events via relative dating and interpolating between magnetic anomalies, constrained by seafloor ages obtained from ocean drilling expeditions. Consequently, a range of ages has been assigned to the timing of formation of the Wharton Basin FZ bends, which occurred roughly mid way through the CNS. Johnson et al. (1980) determined a minimum age of 90 Ma for India's northward acceleration by backwards extrapolating the spreading rate between magnetic anomalies 33–34 (79–83.5 Ma) to the end of the north–south trending Investigator FZ (Fig. 1). This was based on Larson et al.'s (1978) conclusion that the Investigator FZ evolved from the northwest–southeast trending Wallaby–Zenith FZ (Fig. 1) following the spreading reorganization in the Wharton Basin. Powell et al. (1988) later assigned an age of 96 Ma to the reorientation of both the Australian–Indian and Indian–Antarctic spreading ridges. They based this age on the break-up age of Australia and Antarctica which was interpolated by Veevers (1986) to be 96 Ma, and additionally backwards extrapolating the average rotation between India and Antarctica, between magnetic anomalies 28–34 (63.6–83.5 Ma), to the estimated seafloor position of the reorganization. Müller et al. (1998) determined an age of 99 Ma for the reorganization. They combined their post anomaly M0 (120.4 Ma) spreading rate with the 101 Ma age of seafloor dredged at DSDP site 256 to obtain an estimated minimum age of 97 Ma for the FZ bends. They further considered the Albian–Cenomanian (98.9 Ma) timing of Australia–Antarctica break-up (Veevers, 1984) to be contemporaneous with the reorganization, and adjusted their estimate of the timing of the reorganization to match this independent observation. Due to the difficulties in dating events that occur during the CNS, and considering that a range of ages have previously been assigned to the Wharton Basin spreading reorganization, we therefore focus our investigation on the period 110 – 90 Ma.

3. Major tectonic and magmatic events from ~110 to 90 Ma

Seafloor structures that form as a result of seafloor spreading processes (e.g. FZs, abyssal hills), or the interaction of mantle thermal anomalies with overriding plates (hotspot trails), preserve information about relative and absolute plate motion and facilitate understanding of the tectonic evolution of ocean basins. Most of the seafloor that existed at ~110 – 90 Ma, however, has since been subducted (Fig. 2), for instance the entire NeoTethys ocean basin has been subducted beneath Eurasia, and the Izanagi plate has been subducted beneath eastern Asia. Therefore, in order to assess how widespread plate motion changes were at this time we strongly rely on the onshore geological record, such as patterns in magmatism, major faulting events, and basin vertical motions.

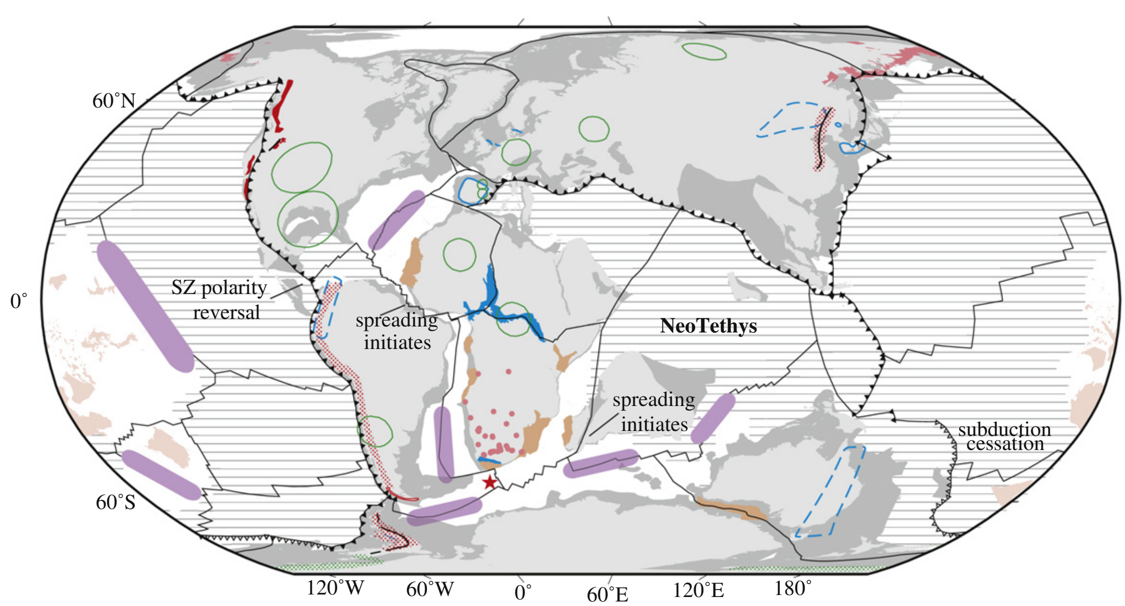
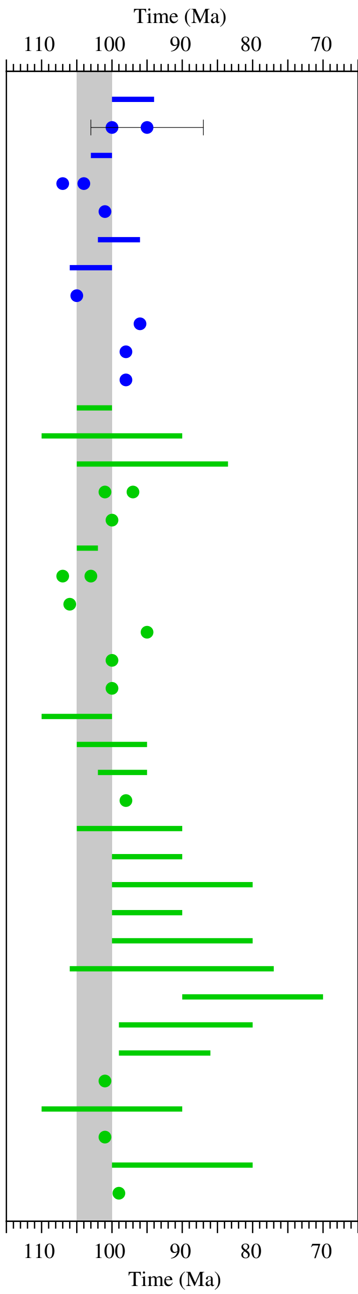


Fig. 2. Plate reconstruction at 100 Ma (Seton et al., 2012), showing data from Fig. 1. Spreading ridges where a change in the speed and/or direction of spreading is reflected by FZ patterns are highlighted in purple. Red star shows location of the Bouvet plume. Seafloor that has since been subducted is hatched. Plate boundaries and continental crust (gray) are from Seton et al. (2012). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)



Area	Observation
OB	Bouvet plume eruption.
	Change in absolute Pacific plate motion*.
	Pacific FZ bends form.
	Wharton Basin FZ bends form.
	Spreading rate increase in the Central Atlantic.
	Spreading rate increase in the South Atlantic.
	Equatorial Atlantic separation.
	Weddell Sea FZ bends form.
	Southwest Indian Ridge FZ bends form.
	Enderby Basin and Bay of Bengal FZ bends form.
	India–Madagascar separation.
EG	Subduction is replaced by strike–slip motion along eastern Gondwanaland.
	Uplift and denudation in eastern Australia.
	Accelerated subsidence at southern Australian margin.
	A–type magmatic events in New Zealand.
	Major angular unconformity forms in New Zealand.
	A–type magmatism begins in Marie Byrd Land.
	Antarctic Peninsula compressional episodes (Palmer Land Event).
	Alexander Island uplift.
WSA	Rocas Verdes Basin closure.
	Andean compressional regime initiates.
	Deformation event in the northern Andes.
C	Caribbean subduction polarity reversal.
WNA	Increase in compressional stress at the Peninsular Ranges Batholith.
	Changes in faulting patterns at the Sierra Nevada Batholith.
	Idaho Batholith magmatism commences.
	Main phase of deformation at the Western Idaho shear zone.
	Thrusting at the Coast Mountains Batholith.
	High flux magmatism at the Coast Mountains Batholith.
EA	Transpression at the Tan–Lu fault zone.
	Uplift in eastern Asia: Japan, Korean Peninsula, eastern China, Mongolia.
	Okhotsk–Chukotka volcanic belt forms.
A	Pulse of alkaline magmatism in southern Africa.
	Exhumation of southern Cape region of South Africa.
	Rapid tectonic subsidence in marginal African basins.
	Folding events in the West and Central African Rift System.
WE	Uplift and exhumation in the North Sea region.
	Regional unconformity in Iberia.
NT	Magmatic pulse and possible MOR subduction event in southern Eurasia.
G	Global distribution of unconformities.

Fig. 3. Timeline and brief summary of events described in Section 3; ordered by region (Supporting details in Table A1 and Appendix B). These are the results of our survey of the period 110–90 Ma, and therefore do not include events that initiated earlier or later. Refer to Figs. 1 and 2 for present-day and paleo-locations, respectively. Most events initiate during the period 105 – 100 Ma (gray shaded region), coinciding with subduction cessation along eastern Gondwanaland. OB, Ocean Basins; EG, eastern Gondwanaland; WSA, western South America; C, Caribbean; WNA, western North America; EA, eastern Asia; A, Africa; WE, western Europe; NT, NeoTethys; G, Global. *100 Ma is from Duncan and Clague (1985) and Koppers et al. (2001), and 95 ± 8 Ma is from Wessel and Kroenke (2008).

Major tectonic and magmatic events initiating ~110 – 90 Ma are shown in Fig. 1 (see also Table A1 for a summary of events). These data are reconstructed to 100 Ma to illustrate the spatial distribution of events and plate boundary configuration at this time (Fig. 2), and a timeline is presented in Fig. 3 to illustrate the temporal distribution of events.

3.1. *Proto-Pacific domain*

A change in the orientation of Pacific hotspot trails from roughly west-southwestward to northwestward indicates the occurrence of a major change in absolute Pacific plate motion (Duncan and Clague, 1985; Koppers et al., 2001; Wessel and Kroenke, 2008). Wessel and Kroenke (2008) assign an age of 95 ± 8 Ma to the change in Pacific motion, while Duncan and Clague (1985) and Koppers et al. (2001) assign an age of 100 Ma, which is within the margin of error of Wessel and Kroenke's (2008) analysis. Closely preceding this change in Pacific plate motion was the cessation of subduction of proto-Pacific seafloor beneath eastern Gondwanaland at ~105 – 100 Ma (e.g. Laird and Bradshaw, 2004), initiation of strike-slip motion (Veevers, 1984), and the establishment of an extensional regime in eastern Australia, New Zealand and Marie Byrd Land. In response to subduction termination, uplift and denudation occurred along the eastern Australian margin (Gallagher et al., 1994; Russell and Gurnis, 1994). From northeast Queensland, south to the Bass Strait and Tasmania, apatite fission track analyses reveal cooling and denudation from 110 to 90 Ma removed up to 2–3 km of sediment (e.g. Kohn et al., 1999; Marshallsea et al., 2000; O'Sullivan et al., 1995; O'Sullivan et al., 2000; Raza et al., 2009). Conversely, wells along Australia's southern margin record a late Albian pulse of accelerated subsidence that was unrelated to upper crustal extension (Totterdell et al., 2000). In New Zealand a major near continent-wide angular unconformity, dated at ~100 Ma, reflects the change from compressional to extensional tectonics (Laird and Bradshaw, 2004). The similarity in ages above and below the unconformity indicates a rapid switch in tectonic regime (Laird and Bradshaw, 2004). In New Zealand and Marie Byrd Land (West Antarctica) there is a distinctive shift from subduction-related to anorogenic magmatism at ~100 Ma. Two widespread A-type magmatic events occurred in New Zealand at 101 and 97 Ma (Tulloch et al., 2009), and in Marie Byrd Land A-type magmatism initiated ~105–102 Ma (Adams et al., 1995; Mukasa and Dalziel, 2000). While extension characterized the east Gondwanaland margin from Australia south to Marie Byrd Land, subduction continued beneath the Antarctic Peninsula until the Cenozoic (McCarron and Larter, 1998). At 107 and 103 Ma two phases of a major compressional event, the Palmer Land event, affected the Antarctic Peninsula and produced mid Albian uplift on Alexander Island (Vaughan et al., 2012).

The remaining proto-Pacific continental margins record compressional events at this time. In eastern China transpression, involving sinistral shear deformation, initiated at the 3000 km long margin-parallel Tan-Lu fault zone between 100 and 90 Ma (Zhang et al., 2003). This was accompanied by inversion of adjacent early Cretaceous basins (Zhang et al., 2003). Choi and Lee (2011) recognized a regional exhumation event in eastern Asia at this time that affected southwest Japan, the Korean peninsula and northeastern China, and further inland coeval unconformities are observed in several basins in eastern Mongolia and neighboring regions of China (e.g. Graham et al., 2001; Meng et al., 2003). Further north in northeast Siberia, formation of the 3200 km long silicic Okhotsk-Chukotka volcanic belt occurred between 106 and 77 Ma (Akinin and Miller, 2011). In western North America four of the major Cordilleran batholiths preserve evidence of compression and magmatic episodes. At ~100 Ma high flux magmatism and thrusting initiated at the Coast Mountains Batholith (Girardi, 2008; Rubin et al., 1990), magmatism initiated at the Idaho Batholith (Gaschnig et al., 2010) accompanied by a major phase of deformation at the Western Idaho Shear Zone (Giorgis et al., 2008), changes in faulting occurred in the Sierra Nevada Batholith (Memeti et al., 2010; Nadin and Saleeby, 2008; Tobisch et al., 1995) and there was an increase in compressional stress in the Peninsular Ranges Batholith (Busby, 2004). At the Caribbean–Farallon plate margin (Fig. 2) a subduction polarity reversal across the Greater Antilles Arc occurred at ~110–100 Ma according to several authors, based on studies that dated thrusting, uplift and local melting events from locations near the paleo-margin (e.g. Choi et al., 2007; Corsini et al., 2011; Stöckhert et al., 1995). As a result, subduction of the proto-Caribbean plate replaced subduction of the Farallon plate. Along western South America, the modern day "Andean" compressional regime initiated following a late Jurassic-early Cretaceous intra-arc extensional phase (Ramos, 2010), accompanied by a deformation event in the northern Andes involving uplift and development of unconformities (Jaimes and de Freitas, 2006). In Patagonia there is evidence that crustal shortening initiated closure of the Rocas Verdes back-arc basin at ~95 Ma (Fildani et al., 2003), based on dating of the Punta Barrosa formation which marks the first influx of arc-derived sands into the basin (Wilson, 1991).

3.2. Atlantic domain

Final separation in the Equatorial Atlantic began ~106–100 Ma (Eagles, 2007; Heine et al., in preparation; Torsvik et al., 2009), accompanied by an increase in spreading rate at the Central and South Atlantic ridges as indicated by FZ trends (see Appendix B), and a minor change in the direction of spreading at the South Atlantic ridge as indicated by broad FZ bends ~102–96 Ma (Eagles, 2007). This acceleration followed a period from ~120 to 100 Ma during which South America underwent a polar standstill (Somoza and Zaffarana, 2008). FZ bends in the Weddell Sea reveal a major 75° counterclockwise change in the direction of spreading between South America and Antarctica at ~105 Ma (see Appendix B). Near the South American–African–Antarctic triple junction, the Bouvet plume erupted ~100–94 Ma to produce the Agulhas Plateau, Maud Rise and Northeast Georgia Rise; later rifted apart by spreading (Parsiegla et al., 2008).

Patterns in intra-plate volcanism, faulting, and basin sedimentation within continental domains bordered by passive margins or located far from plate margins, indicate changes in the lithospheric stress field related to plate motion changes. Uplift events in western Europe during the period 110 to 90 Ma (Japsen et al., 2007), and unconformity development in Iberia at 101 Ma followed by a 4 Myr period of rapid subsidence (Martín-Chivelet, 1996), reflect tectonic instability. Marginal African basins record rapid subsidence (40–100 mm/yr) from 99 to 86 Ma (Janssen et al., 1995), while folding events are recorded in basins across the West and Central African Rift System in the late Albian, ~101 Ma (Guiraud et al., 2005). In southern Africa uplift and denudation occurred from 100 to 80 Ma, removing 2.5–3.5 km of sediment, possibly related to Agulhas Plateau emplacement (Tinker et al., 2008). A kimberlite emplacement pulse that initiated at 90 Ma as part of a major episode of alkaline volcanism in southern Africa, may be related to a plate reorganization close to 100 Ma (Moore et al., 2008), as these events alter intra-continental stress regimes, whereby facilitating the ascent of magma and fluids through new and pre-existing faults and other lines of lithospheric weakness (Bailey, 1992; Jelsma et al., 2009).

3.3. NeoTethys–Indian ocean domain

At 105–100 Ma the NeoTethys ocean basin was subducting beneath Eurasia. Due to its final closure in the Tertiary, deciphering its evolution is complex and largely relies on structural and geochemical studies of ophiolites and highly deformed rocks in remote locations along the southern Eurasian margin, where collision of India, island arcs and older continental blocks occurred (e.g. Ali and Aitchison, 2008; Yin and Harrison, 2000). At the time of the reorganization the NeoTethys was very large, and except along southern Eurasia it was bordered by passive margins (Fig. 2). As geological indicators of plate motion changes tend to be concentrated near plate boundaries, adjustments at the NeoTethys ridge systems in response to plate motion changes may not have resulted in major tectonic changes at its distal passive margins.

Adakitic rocks from eastern Tibet are interpreted as representing a mid ocean ridge subduction event from ~100 to 80 Ma (Zhang et al., 2010), or alternatively as flat slab subduction from 83 to 80 Ma until the latest Cretaceous (Wen et al., 2008). In northwestern Pakistan there is evidence that the Kohistan–Ladakh intra-oceanic arc sutured to southern Eurasia due to back-arc basin closure during the late Cretaceous. The exact timing of this event is not well constrained, with a wide variety of ages having been proposed covering the period ~104–75 Ma (Heuberger et al., 2007; Petterson, 2010; Ravikant et al., 2009; Searle et al., 1999; Treloar et al., 1996). Until the age of suturing can be better constrained, we avoid interpreting this event in the context of a plate reorganization event at 105–100 Ma.

The Indian Ocean was very narrow in the mid Cretaceous. According to the global plate kinematic model of Seton et al. (2012), seafloor spreading between east Africa and Madagascar–India initiated at 160 Ma, followed by spreading between India and Antarctica in the Enderby Basin, and India and Australia in the Cuvier and Perth abyssal plains at 132 Ma. Along with the afore mentioned readjustments at the Antarctic–African, Australian–Indian and Antarctic–Indian ridges (Section 2), Gibbons et al. (submitted for publication) propose that dextral transtension between India and Madagascar initiated at 98 Ma, and this lead to break up at ~94 Ma in the south and ~84 Ma in the north.

Our investigation of the tectonic and volcanic events that occurred during the period 110–90 Ma reveals that all major plates were affected by plate motion changes at this time. From the distribution and number of events it is evident that the reorganization event was global in scale and affected both the oceans and the continents. In the Indian and Pacific ocean basins and the Weddell Sea, FZ bends show changes in the direction of relative plate motion, and in the Central and South Atlantic FZs preserve evidence for an increase in the speed of plate motion without major spreading ridge reorientations. Contemporaneous with these changes in plate motion were major margin-wide to continent-wide tectonic regime changes. In eastern Gondwanaland there was a change from compression to extension that eventually led to opening of the Tasman Sea, along western South America a compressional regime replaced the previous period of back-arc extension, and in the Antarctic Peninsula the compressional Palmer Land Event initiated. In eastern Asia and western North America, fault movements, shear zone deformation, basin uplift, and patterns of magmatism can be linked to compressional tectonics. Tectonic instability in western Europe and Africa, associated with uplift and accelerated subsidence events, and kimberlite magmatism, also reveal widespread changes in the lithospheric stress field at this time in response to plate motion changes. Zorina et al. (2008) attempted to correlate regional sedimentation breaks that occurred in Africa, Europe, and North and South America. According to their study, unconformities that formed at the Upper-Lower Cretaceous Albian–Cenomanian boundary (98.9 Ma) are globally distributed, having occurred in 10 regions across all four continents they investigated. Our review of tectonic events from 110 to 90 Ma also highlights that the formation of unconformities was widespread at 100 Ma, and occurred in additional locations to those considered by Zorina et al. (2008).

Based on the temporal distribution of continental and oceanic events the plate reorganization initiated during the period 105–100 Ma (Fig. 3). From the timeline of events shown in Fig. 3 it can be seen that plate motion changes that were dated from seafloor tectonic fabric features all initiated during this timeframe, with the exception of changes in motion at the Indian–Antarctic spreading ridge and between India and Madagascar, which occurred shortly after at ~98 Ma. This 105–100 Ma timeframe also captures the onset of the vast majority of volcanic events and events related to continental stress regime changes (Fig. 3). It is at 100 Ma when we see most of the continents responding to the reorganization, which suggests that the reorganization was triggered earlier to allow time for the event to propagate.

4. Driving mechanisms for plate motion change

Several studies have investigated the occurrence of a major Indian Ocean plate reorganization at about 100 Ma, due to the prominent suite of FZ bends in the Wharton Basin (Fig. 1) (Müller et al., 1998; Powell et al., 1988; Rotstein et al., 2001). To-date however, limited work has been undertaken on linking Indian Ocean plate motion changes with plate motion changes in the Atlantic and Pacific ocean basins, and continental tectonic regime changes (Somoza and Zaffarana, 2008; Veevers, 2000). This study has presented widespread and abundant evidence, from the continents and ocean basins, confirming a global-scale plate reorganization at 105–100 Ma, which begs the question of what event could have initiated such a major reconfiguration of the global plate network.

In order to determine what drove the reorganization we first attempt to constrain where it nucleated. We observe a clustering of events at 105–100 Ma coinciding with eastern Gondwanaland subduction cessation (e.g. Veevers, 1984) and Bouvet plume eruption south of Africa. Due to the ongoing debate concerning what drives sudden plate motion changes, specifically the importance of top-down (plate-derived) or bottom-up (mantle-derived) processes (Bercovici, 2003), we present top-down and bottom-up mechanisms separately.

4.1. Top-down driving mechanism

Slab pull is believed to be the dominant driver of plate motion (Conrad and Lithgow-Bertelloni, 2004), therefore initiation or cessation of subduction can modify the balance of driving forces acting on a plate. Subduction initiation and cessation have been discussed as driving mechanisms of Cenozoic plate reorganizations (Austermann et al., 2011; Faccenna et al., 2012; Knesel et al., 2008; Seton et al., submitted for publication; Wessel and Kroenke, 2000, 2007). Alternative scenarios have been proposed for the collision of the Ontong Java Plateau with a subduction zone in the southern Pacific (e.g. Knesel et al., 2008; Wessel and Kroenke, 2000, 2007), yet regardless of a debate over the timing of collision (latest Oligocene versus latest Miocene) there is agreement that this event had the propensity to initiate plate motion changes and a reorganization of plate boundaries at least in the southern Pacific region. According to Knesel et al. (2008) the Ontong Java Plateau collided with the Melanesian Arc in the latest Oligocene, and this resulted in a change in Australian plate motion that lasted for 3 Myr during which time the plateau choked the subduction zone. Alternatively, Wessel and Kroenke (2000, 2007) linked a change in Pacific plate motion in the latest Miocene to the Ontong Java Plateau interacting with the northern Australian plate margin. Recently, Austermann et al. (2011) quantitatively tested if collision in the latest Miocene, at 6 Ma, could produce a swerve of the Pacific plate using lithospheric geomechanical models, and found that a 5–15° rotation of Pacific plate motion could result from eliminating the southward directed net slab-pull by jamming of the subduction zone by a large igneous province. Faccenna et al. (2012) proposed that the 55–50 Ma initiation of the Izu–Bonin–Marianas subduction zone induced the 50 Ma swerve of the Pacific plate and other plate margin changes at this time. In their model west-southwest directed slab pull associated with Izu–Bonin–Marianas subduction counterbalanced the north/northwest directed slab-pull originating from proto-Japan-Kuril-Aleutian subduction further north.

A significant subduction cessation event occurred between 105 and 100 Ma along a > 7000 km long length of the eastern Gondwanaland margin after more than 150 Myr of activity (Veevers, 1984). This may have driven a change in motion of the plates at the margin (Australian, Antarctic, Pacific, Hikurangi and Catequil plates) and subsequently neighboring plates (Fig. 4a). Mantle flow induced by subducting slabs exerts tractions on the base of plates that drive them towards subduction zones (Conrad and Lithgow-Bertelloni, 2004; Lithgow-Bertelloni and Richards, 1998). Due to eastern

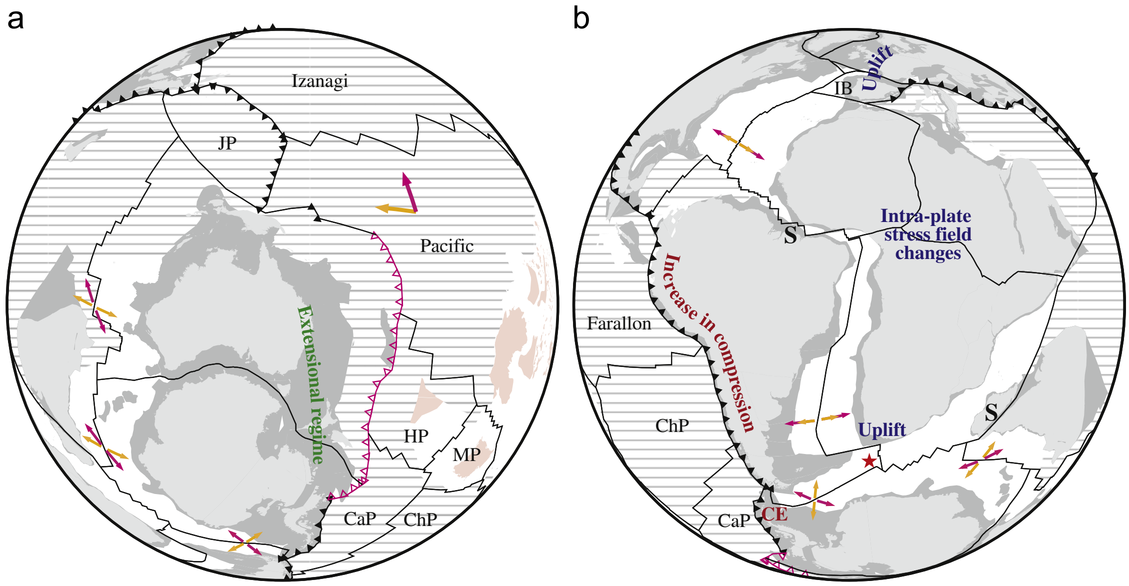


Fig. 4. Regional plate reconstructions for eastern Gondwanaland (a) and the Atlantic (b), indicating the predominant continental tectonic regimes that were established following the plate reorganization at 105–100 Ma (bold colored text). The eastern Gondwanaland subduction zone that terminated at $\sim 105-100$ Ma is pink with hollow teeth. Plate names are given in black. 'S' denotes plate boundaries where seafloor spreading or opening initiated. Red star shows the location of the Bouvet plume. Arrows indicate relative plate motion at spreading ridges, and absolute plate motion of the Pacific plate, before (orange) and after (purple) the reorganization. Arrows are not to scale, and are intended to give an indication of the change in direction or speed of motion. Seafloor that has since been subducted is hatched. Large igneous provinces and seamount chains (light pink) are from Coffin and Eldholm (1994). Plate boundaries and continental crust (gray) are from Seton et al. (2012). CE, compressional event (denotes the location of the Palmer Land Event). CaP, Catequil Plate; ChP, Chazca Plate; HP, Hikurangi Plate; IB, Iberian Plate; JP, Junction Plate; MP, Manihiki Plate. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Gondwanaland subduction cessation, oceanic plates along the margin would no longer have been driven towards the trench by slab pull or flow from actively subducting slabs, although mantle flow induced by detached sinking slabs or lower mantle slabs from past-subduction (Conrad and Lithgow-Bertelloni, 2004) would likely still have exerted a traction on the plates. Prior to the termination of subduction along this margin, the mantle domain underlying the proto-Pacific would have been segregated from the mantle in the Tethyan/Indian domain by a continuous and presumably voluminous wall of downwellings. These downwellings would have acted as a barrier to lateral mantle flow. Once subduction ended along eastern Gondwanaland, and there was slab break-off (Tappenden, 2003), the mantle would have been free to flow through this boundary and this may have contributed to plate motion changes adjacent to this margin.

FZ bends in the Pacific ocean basin indicate changes in relative plate motion occurred at $103-100$ Ma, involving reorientation of the Pacific-Farallon, and Hikurangi–Manihiki ridges (Seton et al., 2012). Absolute Pacific plate motion changed from roughly west-southwestward to more northwestward at about $100-95$ Ma (Duncan and Clague, 1985; Koppers et al., 2001; Wessel and Kroenke, 2008) suggesting that slab-pull forces originating from subduction of the Izanagi plate in the northwest Pacific became dominant in affecting Pacific plate motion once eastern Gondwanaland subduction ended. This is consistent with the reconstruction of Seton et al. (2012) in which the age of Izanagi seafloor subducting under east Asia was more than 20 Myr older than Farallon seafloor subducting under North America, and therefore slab-pull associated with the Izanagi plate may have been stronger. The changes in paleo-Pacific plate motions, including more northerly Pacific and Izanagi motion may be reflected in the transpression recorded at the Tan-Lu fault, uplift and inversion of basins along the east Asian margin, and initiation of the Okhotsk-Chukotka volcanic belt (Figs. 1 and 3). According to Sun et al. (2007) major changes in plate motion in the paleo-Pacific at $\sim 125-122$ Ma strongly influenced the tectonic evolution of southern China, and were likely responsible for compression at the Tan-Lu fault at this earlier time. Additionally, they attributed large-scale lode gold mineralization at this time to onset of the compression in the region, as deformation along fault and shear zones likely released ore forming fluids.

Elimination of eastern Gondwanaland subduction also affected motion of the overriding Australian and Antarctic plates, and evidence for this is seen in FZ bends in the Indian Ocean (Fig. 1) that express a change in relative motion between Australia and India, and Antarctica and India. FZ trends reveal that India's motion became more northward following the reorganization (Fig. 4a). India's northward acceleration following the reorganization (Powell et al., 1988) suggests that northward directed slab pull associated with Tethyan subduction beneath Eurasia exerted a stronger influence over the motion of the Indian plate following the reorganization, compared to the period preceding the reorganization.

At about the same time that eastern Gondwanaland subduction ceased and the motion of India became more northerly, there was an increase in the counterclockwise rotation of Africa (105 ± 5 Ma, Torsvik et al., 2008). Additionally at this time seafloor spreading initiated in the equatorial Atlantic ($106-100$ Ma, Eagles, 2007; Heine et al., in preparation; Torsvik et al., 2009) resulting in complete continental separation of South America and Africa, and formation of a continuous mid ocean ridge stretching from northwest of Iberia, south to the Africa–Antarctica–South America ridge–ridge–ridge triple junction (Fig. 4b). We consider that the initiation of spreading in the Equatorial Atlantic, which saw an end to continental extension, to be a consequence of the plate reorganization event (see also Somoza and Zaffarana, 2008), and specifically it may have been related to the spike in counterclockwise motion of Africa (Torsvik et al., 2008).

Assuming seafloor spreading occurs at faster rates than continental extension (Eagles, 2007), as the plates involved are fully separated by a zone of weakness, it is not surprising that an increase in spreading rates at the Central and South Atlantic ridges (e.g. Eagles, 2007; Matthews et al., 2011; Appendix B) was coeval with final Equatorial Atlantic separation. The onset of a compressional regime along western South America at ~100 Ma has been attributed to a change in the subduction regime, caused by Equatorial Atlantic opening and increased westward motion of South America (e.g. Jaimes and de Freitas, 2006; Ramos, 2010; Somoza and Zaffarana, 2008). In the Weddell Sea FZ bends express a major counterclockwise change in the direction of spreading between Antarctica and South America that may also be a result of the increase in westerly motion of South America, as well as changes in the motion of Antarctica due to eastern Gondwanaland subduction cessation (Fig. 4b). Folding events in the West and Central African Rift System, and uplift in western Europe and Iberia all point towards a change in continental lithospheric stresses that were likely corollary of the changes in Africa's motion and subsequent increased mid Atlantic spreading rates. The southern African kimberlite pulse that initiated at ~90 Ma was attributed by Moore et al. (2008) to a change in the state of lithospheric stresses in Africa related to a plate reorganization event around 5–13 Myr earlier (103 – 95 Ma). The timing of this purported reorganization coincides with the global event we have discussed.

4.1.1. Why did eastern Gondwanaland subduction end?

We propose that subduction cessation along eastern Gondwanaland caused a global-scale plate reorganization event at 105 – 100 Ma. This raises the question of what caused subduction to end at this time, as this event would be the ultimate reorganization trigger. The cause of subduction cessation remains debated, with two main schools of thought. Several authors favor a mechanism involving ridge–trench interaction (Bradshaw, 1989; Luyendyk, 1995), while others invoke collision of the Hikurangi Plateau with the trench near the Chatham Rise (Davy, 1992; Davy and Wood, 1994; Lonsdale, 1997).

Bradshaw (1989) proposed that oblique subduction of the Pacific-Phoenix ridge at the eastern Gondwanaland trench caused subduction to end, as the age of the oceanic crust approaching the trench became too young and buoyant to be subducted. Luyendyk (1995) modified Bradshaw's (1989) model and proposed that spreading between the Pacific and Phoenix plates ceased outboard of the trench, the Pacific plate and New Zealand became welded across the extinct subduction zone, and New Zealand then acquired the motion of the Pacific plate. In this model, when the Pacific plate started moving northward it pulled the subducted Phoenix slabs with it, whereby inducing extension in New Zealand and its breakup from eastern Gondwanaland (Luyendyk, 1995). Alternatively, the 105 – 100 Ma collision of the Hikurangi Plateau with the eastern Gondwanaland trench at the Chatham Rise (Davy, 1992; Davy and Wood, 1994; Lonsdale, 1997) has been proposed as a mechanism for subduction cessation along this part of the margin. In this model the Hikurangi Plateau was partially subducted before choking the subduction zone (Davy et al., 2008).

The models presented by Bradshaw (1989) and Luyendyk (1995) are appealing, as the oblique approach of a spreading ridge would have influenced a large portion of the eastern Gondwanaland margin nearly simultaneously. The collision of the Hikurangi Plateau with a ~1100 km long segment of the subduction zone is less appealing considering the size of the plateau with respect to the length of the eastern Gondwanaland subduction zone that became inactive at ~105 – 100 Ma. It has been proposed that the collision of the Ontong Java Plateau with the Melanesian Arc terminated subduction and triggered a plate reorganization at least in the southern Pacific region (e.g. Knesel et al., 2008; Wessel and Kroenke, 2000, 2007), yet the Ontong Java Plateau is much larger than the Hikurangi Plateau and it is comparable in size to the subduction zone segment that became inactive due to the collision. Additionally, there is debate over the timing of Hikurangi collision with several authors supporting later collision ~86 – 80 Ma (Billen and Stock, 2000; Seton et al., 2012; Worthington et al., 2006). Regardless of the timing of collision, we favor a mechanism that influenced a major section of the subduction zone, such as that proposed by Bradshaw (1989) and Luyendyk (1995).

The models of Bradshaw (1989) and Luyendyk (1995) need to be refined in light of a new plate kinematic model for the evolution of the proto-Pacific ocean basin that results in a different configuration of plate boundaries proximal to the eastern Gondwanaland margin from 120 Ma (Seton et al., 2012), compared to previous plate reconstruction models that incorporate the oblique approach of the Pacific-Phoenix spreading ridge at 100 Ma (e.g. Müller et al., 2008). In the recent plate reconstruction model of Seton et al. (2012) the subduction of two perpendicular spreading ridges, separated by ~2500 km, occurs from ~120 to 100 Ma (Seton et al., 2012) (Fig. 5). This plate boundary configuration resulted from fragmentation of the Ontong Java–Manihiki–Hikurangi Plateau at ~120 Ma by a series of spreading ridge triple junctions. We propose a similar model to Bradshaw (1989) in that ridge–trench interaction was responsible for subduction ending. However, we believe that the subduction of two proximal perpendicular ridges was responsible rather than oblique collision of a single spreading ridge. Once

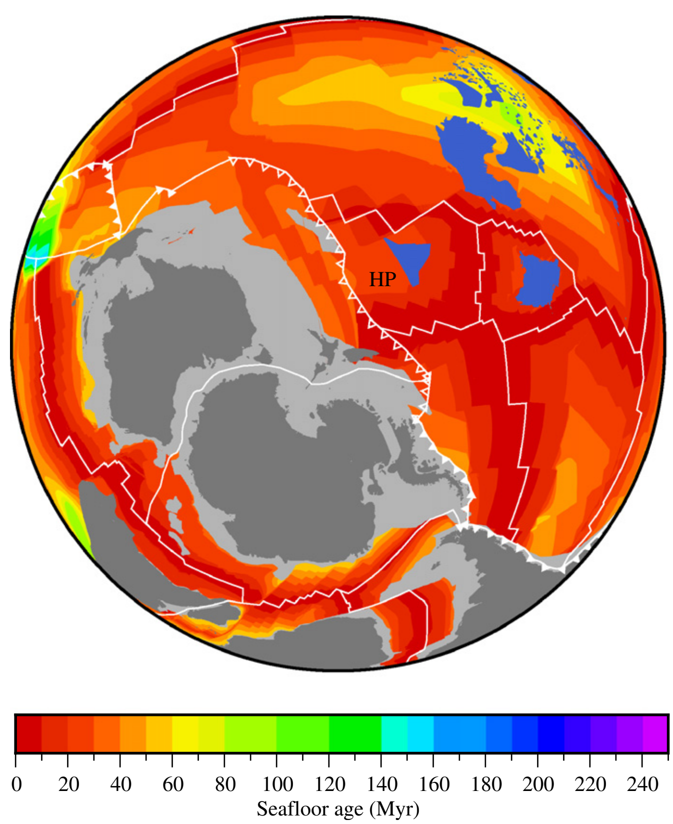


Fig. 5. 100 Ma plate reconstruction for eastern Gondwanaland showing seafloor ages (Seton et al., 2012). Plate boundaries are white (Seton et al., 2012). The two closely spaced spreading ridges intersecting the trench where subduction ends can be observed. Pacific large igneous provinces and seamount chains are dark blue (Coffin and Eldholm, 1994). Based on the plate model of Seton et al. (2012), the Hikurangi Plateau (HP) is located outboard of the trench, although several authors date collision at 105 – 100 Ma (Davy, 1992; Davy and Wood 1994; Lonsdale, 1997). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Table A1
Summary of tectonic and volcanic events from the period 110 to 90 Ma.

Timing (Ma)[a]		Reference(s)
Ocean basins		
100–94	Agulhas Plateau, Maud Rise and Northeast Georgia Rise are erupted together as a single LIP by the Bouvet plume and subsequently rifted apart; this occurs in close proximity to the Antarctica–Africa–S. America triple junction	Parsiegla et al. (2008)
100, 95 ± 8[b]	A change in absolute motion of the Pacific plate is indicated by a change in the orientation of hotspot trails	Duncan and Clague (1985), Koppers et al. (2001), Wessel and Kroenke (2008)
103–100	FZs in the proto-Pacific ocean basin indicate a change in the direction of spreading occurs at the Pacific-Farallon ridge and the Hikurangi–Manihiki ridge[c]	Seton et al. (2012)
107,104	FZs in the Wharton Basin preserve evidence of two changes in the direction of spreading between Australia and India, an initial minor clockwise change followed by a major counter-clockwise change	See Appendix B
101	FZs and seafloor roughness indicate that an increase in spreading rate initiates at the Central Atlantic ridge	Matthews et al. (2011), see Appendix B
102–96	FZs indicate an increase in spreading rate initiates at the South Atlantic ridge	Eagles (2007)
106–100	Final separation in the equatorial Atlantic	Eagles (2007), Heine et al., in preparation, Torsvik et al., 2009
105	FZs in the Weddell Sea indicate a major counter-clockwise change in spreading between S. America and Antarctica	See Appendix B
96	Broad FZ bends at the Southwest Indian Ridge show a minor clockwise change in spreading between Africa and Antarctica	Bernard et al. (2005)
98	FZs in the Enderby Basin and Bay of Bengal indicate a clockwise change in spreading between Antarctica and India	Gibbons et al. (submitted for publication), see Appendix B
98	Dextral transtension initiates between India and Madagascar, leading to breakup	Gibbons et al. (submitted for publication)
Eastern Gondwanaland		
105–100	Subduction beneath E. Gondwanaland ends, giving way to strike-slip motion	Laird and Bradshaw (2004), Veevers (1984)
110–90	Cooling and denudation episodes initiate along the eastern margin of Australia, from northeast Queensland south to Bass Strait. More than 2 km of sediments are removed in some locations	Kohn et al. (1999), Marshallsea et al. (2000), O'Sullivan et al. (1995, 2000), Raza et al., 2009
105–83.5	Late Albian–Santonian accelerated subsidence at the S. Australian margin is recorded in the Recherche and Ceduna sub-basins – unrelated to upper crustal extension	Totterdell et al. (2000)
101,97	Two widespread igneous events involving A-type magmas occur in New Zealand and indicate that a slab is no longer subducting along the New Zealand margin	Tulloch et al. (2009)
100	Major angular unconformity in New Zealand reflects the change from a compressional to extensional tectonic regime	Laird and Bradshaw (2004)
105–102	A-type magmatism initiates in Marie Byrd Land, ending the preceding period of I-type subduction related magmatism	Adams et al. (1995), Mukasa and Dalziel (2000)
107,103	A major compressional event, the Palmer Land Event, initiates in the Antarctic Peninsula and involves two phases of deformation. It involves dextral-oblique terrane collision at the Eastern Palmer Land Shear Zone	Vaughan et al. (2012)
106	Mid Albian uplift occurs in Alexander Island off the margin of the Antarctic Peninsula, likely in response to thrusting associated with the Palmer Land Event (see above). This is followed by late Albian subsidence	Vaughan et al. (2012)
Western South America		
95	Crustal shortening initiates closure of the Rocas Verdes back-arc basin in Patagonia. Timing constrained by changes in basin sedimentation and deposition of the Punta Barrosa formation	Fildani et al. (2003)
100	Compressional tectonic regime initiates in the Andes, following late Jurassic to early Cretaceous extension	Ramos (2010)
100	Deformation event in the northern Andes, involving fault reactivation, uplift and development of unconformities	Jaimes and de Freitas (2006)
Caribbean		
110–100	Subduction polarity reversal across the Greater Antilles Arc results in a change from subduction of the proto-Pacific to subduction of the proto-Caribbean plate[d]	Choi et al. (2007), Corsini et al. (2011), Stöckhert et al. (1995)
Western North America		
105–95	Increase in compressional stress, including reverse fault reactivation, at the Peninsular Ranges Batholith	Busby (2004)
102–90	Movement on shear zones and major fault activation (proto-Kern Canyon fault) and deactivation (Mojave-Snow Lake fault) at the Sierra Nevada Batholith	Memeti et al. (2010), Nadin and Saleeby (2008), Tobisch et al. (1995)
98	Idaho Batholith magmatism commences	Gaschnig et al. (2010)
105–90	Main phase of deformation at the Western Idaho Shear zone	Giorgis et al. (2008)
100–90	Thrusting and crustal shortening at the Coast Mountains Batholith	Rubin et al. (1990)
100–80	High flux magmatism at the Coast Mountains Batholith	Girardi (2008)
Eastern Asia		
100–90	Transpression initiates at the 3000 km long Tan-Lu fault zone of eastern China, involving sinistral shear deformation, and inversion of adjacent early Cretaceous basins that had formed in the preceding extensional tectonic regime	Zhang et al. (2003)
100–80	Eastern Asia continental margin uplift and inversion of basins in South Korea, Japan, northeastern China and eastern Mongolia	Choi and Lee (2011), Graham et al. (2001), Meng et al. (2003)
106–77	Formation of the 3200 km long Okhotsk-Chukotka belt; a silicic subduction related volcanic province	Akinin and Miller (2011)
Africa		
90–70	Pulse of alkaline magmatism in southern Africa linked with a plate reorganization around 100 Ma that changed the state of stress of the lithosphere and facilitated the ascent of the magma	Moore et al. (2008)

Table A1 (*continued*)

Timing (Ma)[a]		Reference(s)
99–80	Exhumation episode in the southern Cape region of Africa involving removal of 2.5–3.5 km of sediment	Tinker et al. (2008)
99–86	Cenomanian–Coniacian episode of rapid tectonic subsidence (40–100 mm/yr) in marginal and interior African basins	Janssen et al. (1995)
101	Major and minor folding events produce unconformities in basins of the West and Central African Rift System	Guiraud et al. (2005)
Western Europe		
110–90	Coeval uplift and exhumation events in the North Sea region	Japsen et al. (2007)
101	Formation of a major regional unconformity in Iberia, followed by a 4 Myr pulse of rapid subsidence	
NeoTethys		
100–80	Magmatic pulse in the Gangdese batholith and possible mid ocean ridge subduction event as indicated by adakites. Adakitic samples have also been interpreted as reflecting flat slab subduction at 80 Ma	Wen et al. (2008), Zhang et al. (2010)
Global		
99	Global-scale unconformity at the Albian–Cenomanian boundary	Zorina et al. (2008)

[a] Ages have been converted, where possible, to the timescale of Gradstein et al. (1994).
[b] 100 Ma is from Koppers et al. (2001) and Duncan and Clague (1985), and 95 ± 8 Ma is from Wessel and Kroenke (2008).
[c] Rifts apart the Hikurangi and Manihiki plateaus from 120 to 86 Ma, from the plate reconstruction model of Seton et al. (2012).
[d] There is debate over the timing of the reversal. This age range is from studies that have dated thrusting, uplift and local melting events from locations near the paleo Caribbean–Farallon plate boundary.

spreading between the Ontong Java, Manihiki and Hikurangi plateaus initiated the oceanic lithosphere being subducted at the eastern Gondwanaland trench became progressively younger, until the buoyancy was so great and slab pull became so weak that subduction stalled, leading to a margin-wide slab break off event. Decompression melting of the sub-lithospheric mantle wedge following a slab break-off event resulted in the onset of magmatism in New Zealand at the Mount Somers Volcanic Group and the Central Marlborough Igneous Province (Tappenden, 2003).

4.2. Potential influence of a bottom-up process

Eruption of the Bouvet plume between ~100 and 94 Ma, near the Africa–Antarctica–South America ridge–ridge–ridge triple junction, produced the Agulhas Plateau, Maud Rise and Northeast Georgia Rise (Parsiegla et al., 2008) (Fig. 4). These large igneous provinces were emplaced together and subsequently fragmented by spreading (Parsiegla et al., 2008). The plume push force of the Bouvet plume may have triggered or enhanced events observed close to the triple junction. Results of two-dimensional numerical models indicate that the lubricating effects of plume heads can initiate plate reorganizations by decoupling the plates from the dominant mantle flow field (Ratcliff et al., 1998). Cande and Stegman (2011) further suggest that the plume push force can govern the speed of plate motion where a plume head impinges near a spreading ridge, and that the resultant increase or decrease in speed is dependent on the sum of forces acting on the remaining plate boundaries. Therefore, the Bouvet plume eruption may have influenced the motion of South America, Africa and Antarctica. Indeed at this time oceanic and continental observations show changes in motion of these three plates, including a speed up of the South American and African plates (Fig. 4). Additionally, Tinker et al. (2008) suggest that uplift and denudation of the Southern Cape region of Africa is attributed to increased buoyancy associated with emplacement of the Agulhas Plateau.

From at least 250 Ma until the time of the reorganization subduction zones surrounded the entire proto-Pacific ocean basin, accommodating growth of the Pacific plate and leading to consumption of the Izanagi, Farallon and Phoenix plates (Seton et al., 2012). Even after 105 – 100 Ma subduction persisted beneath eastern Asia, North and South America and the Antarctic Peninsula (Seton et al., 2012). These trends in proto-Pacific subduction demonstrate that subduction cessation along eastern Gondwanaland was a major tectonic event, and the resultant changes in plate motion can account for a wide variety of oceanic and continental tectonic events that occurred at 105 – 100 Ma. Determining if it is possible for this driving mechanism alone to have initiated all the events we have compiled needs to be addressed and is beyond the scope of this investigation. Eruption of the Bouvet plume near the Africa–Antarctica–South America triple junction is contemporaneous with subduction cessation, and we suggest it may have independently contributed to altering the lithospheric stress regimes in the region, and producing changes in motion of the African, Antarctic and South American plates.

5. Conclusions

A plate reorganization event at 105 – 100 Ma was global in scale, having (i) influenced relative motion at all of the major spreading systems where oceanic crust is preserved at present-day, (ii) modified the pre-existing continental tectonic regimes along many of the major convergent margins, and (iii) modified lithospheric stress patterns in continental regions far from convergent margins. Based on reviewing the plate boundary reconfigurations during the reorganization we support subduction ending along eastern Gondwanaland as initiating the major tectonic events observed at this time, and favor a top-down driving mechanism for the reorganization. Subduction is the dominant driver of plate motion, and therefore we propose that cessation of subduction over a distance of more than 7000 km modified the motion of plates in the southwestern proto-Pacific region adjacent to the margin, and subsequently the motion of neighboring plates and stress regimes within the continents. Subduction cessation resulted in, for instance, changes in motion of the Australian and Antarctic plates, leading to readjustments of the Australian–Indian and Antarctic–Indian spreading ridges, expressed as FZ bends in the Indian Ocean. Prominent FZ bends in the eastern Indian Ocean are the most dramatic feature produced by the reorganization, and we directly link them to eastern Gondwanaland subduction cessation. We speculate that ridge–trench interaction resulted in the demise of subduction, specifically the subduction of two closely spaced perpendicular mid ocean ridges, rather than oblique collision of the Phoenix-Pacific spreading ridge, as was proposed based on a previous tectonic reconstruction of the proto-Pacific ocean basin (Bradshaw, 1989). Finally, we also propose that eruption of the Bouvet plume near the African–Antarctic–South American triple junction may have been responsible for, or influenced, the events observed in the southern Atlantic region. These driving mechanisms, subduction cessation and plume-triple junction interaction, ultimately must be tested using fully dynamic mantle-convection models.

Acknowledgments

M.S. and R.D.M. were funded through Australian Research Council grants DP0987713 and FL0992245, respectively. All figures were produced using GMTv5.0.0b (Wessel and Smith, 1998). We thank the Editor, John Veevers and an anonymous reviewer for their comments that improved the quality of the original manuscript.

Appendix A. Summary of tectonic and volcanic events

Table A1

Appendix B. Assigning ages to changes in fracture zone trends in the Indian Ocean, Central Atlantic and Weddell Sea

It is difficult to directly date events that occurred during the Cretaceous Normal Superchron (CNS) as during this period (120.4 – 83.5 Ma, Cande and Kent, 1995; Gradstein et al., 1994) there were no reversals of Earth's magnetic field. Yet it is possible to indirectly compute approximate age-ranges for events via relative dating and interpolating between magnetic anomalies, constrained by seafloor ages obtained from ocean drilling expeditions. We combine FZ traces (Matthews et al., 2011) with DSDP data, magnetic anomaly picks (Gibbons et al., 2012; Klitgord and Schouten, 1986) and plate reconstruction models (e.g. Gibbons et al., 2012; Konig and Jokat, 2006; Müller et al., 2000; Robb et al., 2005; Seton et al., 2012) to determine the timing of the observed mid Cretaceous spreading ridge realignments.

B.1 Wharton Basin

A range of ages have been assigned to the mid Cretaceous clockwise change in spreading azimuth between Australia and India that produced the curved FZs clearly visible in bathymetry and gravity maps (see main text for more details). We find that FZs traces in the Wharton Basin (Fig. B1), in the eastern Indian Ocean, combined with magnetic anomaly data reveal three pieces of information that help us determine the nature and timing of spreading ridge readjustments in the region, independent of any plate reconstruction model. From here on we will refer to the Wharton Ridge when discussing the spreading ridge that produced the observed FZ bends in the Wharton Basin.

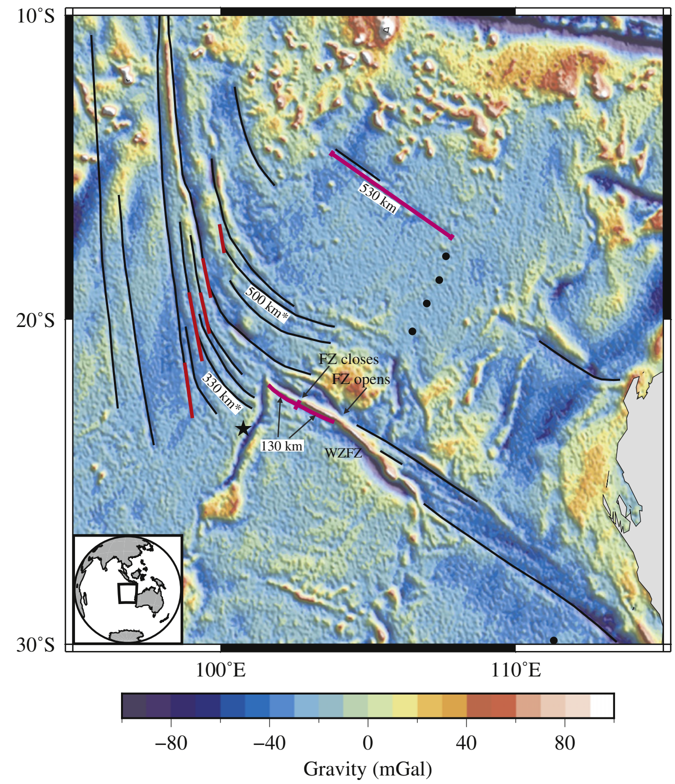


Fig. B1. Gravity map (Sandwell and Smith, 2009) of the eastern Indian Ocean centered on the Wharton Basin, where prominent curved FZs formed due to a spreading reorganization between Australia and India. FZ traces (black lines) are from Matthews et al. (2011) and M0y (120.4 Ma) magnetic anomaly picks (black circles) are from Gibbons et al. (2012). Roughly north to south orientated red lines trace the post-reorganization trend of the FZs, and therefore the locations where the curved FZs meet the red lines indicate when the spreading direction stabilized. A black star denotes DSDP site 256. *500 km is the amount of seafloor that formed during the clockwise reorientation of the Wharton Ridge, and 330 km is the amount of seafloor that was produced between the location of DSDP site 256 and the end of the clockwise rotation of the Wharton Ridge. WZFZ, Wallaby–Zenith FZ. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

1. FZ orientations reveal that there must have been two changes in spreading direction at the Wharton Ridge. Early Cretaceous FZs off Western Australia are oriented 125°, yet the eastern, and therefore oldest, sections of the curved FZs in the central Wharton Basin point in a more northerly direction (~90-110°). This requires that a counterclockwise change in spreading direction occurred prior to the major clockwise rotation that resulted in N–S spreading. Therefore, a flow-line mapping the motion of Australia with respect to India would be S-shaped. This observation is supported by Wallaby–Zenith FZ trends evident in the gravity data. As the Wallaby–Zenith FZ is a large left-offset fracture, we would expect to see evidence for multi-strand formation in response to a counterclockwise change in spreading direction, and subsequent convergence of these threads in response to a clockwise change; this is seen at the Mendocino FZ in the north Pacific (McCarthy et al., 1996). We suggest that at ~104°E the Wallaby–Zenith FZ appears to open and produce a prominent northern strand, and then at ~102.5°E the strands begin to converge (Fig. B1).
2. In the northern part of the Wharton Basin, on seafloor that formed during the CNS, there is an isolated FZ trace oriented 125° (Fig. B1). The youngest end of the trace is located several hundred km west of M0y (120.4 Ma) magnetic anomalies (Gibbons et al., 2012), and therefore the first (counterclockwise) change in spreading direction occurred at least several millions years after the beginning of the CNS, as spreading must have continued in a ~NW–SE direction for some period of time to produce this FZ and the intervening section of seafloor.
3. Based on the dating of nanofossils a minimum basement age of 101 ± 1 Ma was computed for DSDP site 256 (Luyendyk and Davies, 1974) situated in the southern Wharton Basin (Fig. B1, black star). This drill site is located in seafloor that formed during the second (clockwise) change in spreading direction, before north–south spreading had established, therefore providing a minimum age for the initiation of the reorganization.

Therefore, based on FZ trends and magnetic anomaly data alone, the mid Cretaceous reorganizations at the Wharton Ridge initiated at some time between about 100 and 117 Ma. In order to further constrain the maximum age of the first (counterclockwise) change in spreading direction we consider the amount of seafloor that formed between the beginning of the CNS and the youngest end of the 125° oriented FZ in the northern Wharton Basin, and a range of acceptable seafloor spreading rates, to estimate a time period over which seafloor spreading continued at a 125° azimuth after 120.4 Ma.

At least 530 km of seafloor was produced on the Australian flank of the Wharton Ridge before a change in spreading direction occurred (Fig. B1). Although we cannot be certain of the exact spreading rate during the CNS, gravity data show that the seafloor in the Wharton Basin is very smooth, suggesting that spreading was intermediate (3–4 cm/yr, Small and Sandwell, 1992) or fast (> 4 cm/yr) at the Wharton Ridge; slow seafloor spreading (< 3 cm/yr) is associated with rough seafloor and the formation of discordant zones, wavy lineations that form at small non-transform ridge offsets (Grindlay et al., 1991). Müller et al. (2000) modeled a half-rate of 3.6 cm/yr after anomaly M0 (120.4 Ma) time, in support of this assumption. Seton et al. (2012) and Robb et al. (2005) computed similar half-spreading rates for the preceeding M2–M0 period (124–120.4 Ma) (3.5 and 3.8 cm/yr respectively). As there is no noticeable increase in seafloor roughness or change in seafloor fabric at the beginning of the CNS we will take 3.5 cm/yr (Seton et al., 2012) as our minimum seafloor spreading rate. The half-spreading rate at the Wharton Ridge was higher following the CNS. Müller et al. (2008) computed a maximum rate of ~5.5 cm/yr. An increase in the northward motion of India initiated once N–S spreading had established at the Wharton Ridge, until about 50 Ma, reaching anomalously high rates of more than 7 cm/yr (Seton et al., 2012).

Based on the estimated half-spreading rates of 3.5–5.5 cm/yr, 530 km of seafloor can be produced over a period of 15.1–9.6 Myr. Therefore the maximum age of the counterclockwise rotation of spreading at the Wharton Ridge is 110.8 Ma, although it may have persisted until about 105.3 Ma if spreading did not increase significantly after 120.4 Ma. This reduces the age range for the initiation of the reorganizations to 100–110.8 Ma.

In order to better constrain when the second (clockwise) realignment of the Wharton Ridge initiated, we revisit the structure of the Wallaby–Zenith FZ. Approximately 130 km of spreading took place between the postulated opening of the transform fault and associated multi-strand formation, and convergence of the FZs, and a further 130 km of spreading took place between convergence of the multistrands and the location of the seafloor that is dated at 101 ± 1 Ma (DSDP Site 256) (Fig. B1). Based on half-spreading rates of 3.5–5.5 cm/yr, this suggests that there was only about 3.7–2.4 Myr of counterclockwise spreading, and that the clockwise realignment of the Wharton Ridge may have initiated closer to 104.7–103.4 Ma. This line of reasoning therefore suggests that the counterclockwise realignment initiated around 108.4–105.8 Ma, depending on whether we assume intermediate or fast spreading at the ridge. These age estimates are consistent with our above argument that ~NW–SE spreading must have continued for at least 9.6 Myr during the CNS in order to produce the isolated FZ at ~15°S, 530 km west of the 120.4 Ma seafloor.

In order to compute the duration of the clockwise ridge reorganization we consider the length of the FZ bends. North of the Wallaby–Zenith FZ, two FZ strands are continuous over the bend period (Fig. B1). They appear coeval with the closure of the Wallaby–Zenith FZ, which we consider the beginning of the clockwise change in spreading. The portion of these FZs that form during the clockwise change in spreading is ~500 km in length (Fig. B1). Using the spreading rate range of 3.5–5.5 cm/yr that we defined earlier, the bends formed over 14.3–9.1 Myr, and therefore spreading at the Australian–India ridge did not stabilize again until 90.4–94.3 Ma. Alternatively, we computed the cessation of the clockwise reorganization by considering that a 330 km long segment of FZ formed between DSDP site 256 that is dated 101 ± 1 Ma and stabilization of spreading. This method yielded similar ages of ~91.6 Ma and 95 Ma, for spreading rates of 3.5 cm/yr and 5.5 cm/yr, respectively.

B.2 Central Atlantic

In the Central Atlantic DSDP site 137 is located on the eastern flank of the Mid-Atlantic ridge (Fig. B2, black star), 60 –130 km east of where several FZ traces disappear. An age of 101 Ma was assigned to the basement at this site, constrained by nanoplankton fossils located 3 m above the basalt (Pimms and Hayes, 1972). Therefore, the FZ traces stopped forming shortly after this time. Matthews et al. (2011) attributed the mid Cretaceous coeval disappearance of fracture zone traces on either flank of the Mid-Atlantic ridge to an increase in spreading rate, DSDP data therefore help constrain the timing of this change. Cande et al. (1988) linked an increase in FZ traces at C30 time in the southern Atlantic to a decrease in spreading rate between C30-20, and Cande et al. (1995) attributed the sudden appearance of the Pitman FZ, and several other FZs, at the Pacific–Antarctic ridge between C27-26 and a plate reorganization at C27 time. However, while the appearance of FZs in response to plate motion changes appears to be quite sudden, the timing of FZ disappearance following plate motion changes is less well constrained. Therefore, we will take the DSDP age of 101 Ma as the approximate onset of the increase in spreading rate.

Dating of DSDP site 137 alone, without reference to FZ trends, confirms there must have been an increase in spreading during the CNS. Between the onset of the CNS, based on the magnetic anomalies of Klitgord and Schouten (1986), and the formation of

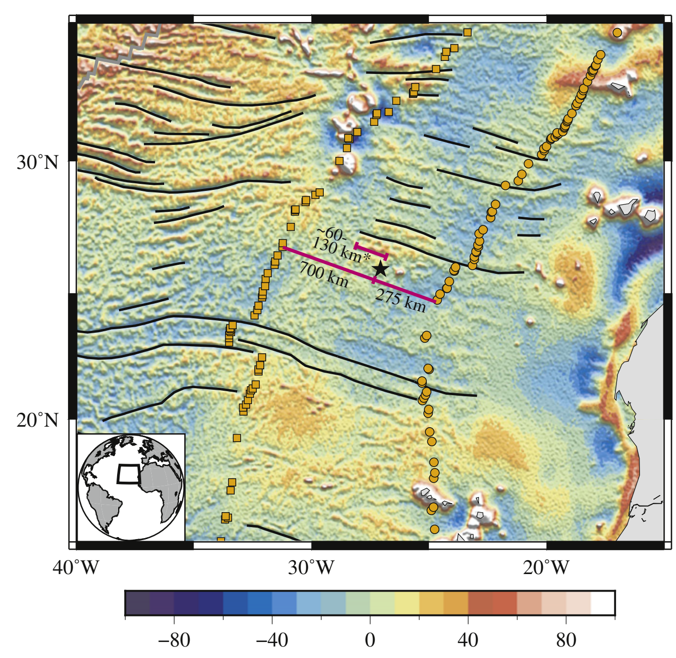


Fig. B2. Gravity map (Sandwell and Smith, 2009) of the eastern Central Atlantic showing FZs (black lines) (Matthews et al., 2011) that formed on the African flank of the African–North American spreading ridge. Circles are M0y (120.4 Ma) magnetic anomaly picks and squares are 34y (83.5 Ma) magnetic anomaly picks from Klitgord and Scouten (1986). A black star denotes DSDP site 137. *Between 60 and 130 km of seafloor was produced between the location of DSDP site 137 and the location where four FZs to the north disappear, indicating an increase in seafloor spreading.

seafloor at site 137 the spreading half-rate was 1.4 cm/yr, given that 275 km of spreading had taken place (Fig. B2). Yet the half-spreading rate in this same region between the Kane and Atlantis FZs averaged over the CNS is 1.9 cm/yr, given that 700 km of seafloor was produced (Fig. B2).

B.3 Weddell Sea

There are no empirical ages available for seafloor formed during the CNS in the Weddell Sea due to a lack of DSDP data. Therefore, assigning an age to the FZ bends in this regions requires interpolation between magnetic anomaly data and spreading rate assumptions. McAdoo and Laxon's (1997) re-processed, re-tracked gravity grid for the Antarctic region enables several FZs to be traced continuously through mid Cretaceous seafloor in the Weddell Sea (Matthews et al., 2011). The direction of spreading between Antarctica and South America recorded by the FZ at 26°W begins to change 116 km from König and Jokat's (2006) M0 (120.4 Ma) anomaly and is roughly coeval with the disappearance of the majority of neighboring Mesozoic NNE trending FZs (Fig. B3). The length of the FZ bend is ~60 km (Fig. B3). The study by König and Jokat (2006) combined several aeromagnetic and shiptrack datasets with recent high-resolution aeromagnetic data from the eastern Weddell Sea (Jokat et al., 2003) that were not previously available, and we will therefore use their anomaly M0 (120.4 Ma) interpretation.

Half-spreading rates in the Weddell Sea decreased at M2 time (124 Ma) (König and Jokat, 2006; Livermore and Hunter, 1996) when "Anomaly T" was produced, a low amplitude gravity anomaly (Livermore and Hunter, 1996), which may mark the transition to rougher basement morphology (Rogenhagen and Jokat, 2002). König and Jokat (2006) further suggest that Anomaly T marks the transition from slow to ultraslow spreading. König and Jokat (2006) calculated a half-spreading rate of 8 mm/yr for the period following the beginning of the CNS until 93 Ma, where 93 Ma is the extrapolated age assigned to the change in pole of rotation (Livermore and Hunter, 1996). Their calculations, however, were based on the timescale of Kent and Gradstein (1986), which dates the CNS at 118–83 Ma. We choose to follow the timescale of Gradstein et al. (1994) for Mesozoic anomalies, which yields a longer CNS lasting from 120.4 to 83.5 Ma. Re-dating of the CNS to comprise a longer time period would result in a decrease to the spreading rate calculated by König and Jokat (2006), as it would require the same amount of seafloor to be produced over a longer period of time. Taking the beginning of the CNS as 120.4 Ma yields new half-spreading rates of 7.3 mm/yr for the period 120.4–93 Ma. As 116 km of crust can be produced in 15.9 Myr, the reorganization likely commenced close to 104.5 Myr and lasted for 8.2 Myr.

Gravity anomalies in the Weddell Sea produce a distinct "herringbone" pattern (Livermore and Hunter, 1996) and the change in motion at the ridge has previously been assigned the age corresponding to the herringbone's spine (e.g. Kovacs et al., 2002, 96–93 Ma). This however, represents the inflection point along the plate motion path and does not necessarily reflect when the onset of the change in spreading initiated. It is most likely that the onset of the reorganization will pre-date the age assigned to the spine.

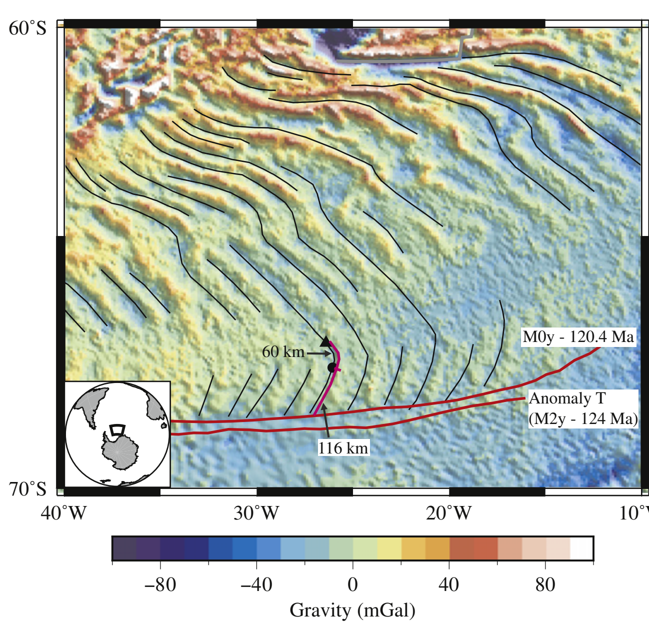


Fig. B3. Gravity map (Sandwell and Smith, 2009) of the Weddell Sea showing FZs (black lines) (Matthews et al., 2011) that formed on the Antarctic flank of the Antarctic–South American spreading ridge. Red lines are M0y (120.4 Ma) and M2y (124 Ma) isochrons from Seton et al. (2012). Black circle and triangle mark the beginning and end of the FZ bend, respectively. 60 km of seafloor spreading took place during the ridge reorganization, and 116 km of spreading took place between 120.4 Ma and the beginning of the reorganization. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

B.4 Enderby Basin and Bay of Bengal (Antarctica–India spreading)

There are no empirical ages available for seafloor formed during the CNS in the Enderby Basin and the Bay of Bengal due to a lack of DSDP data. Therefore, assigning an age to the FZ bends in these regions requires interpolation between magnetic anomaly data and assumptions to be made about spreading rates. The Kerguelen FZ trace in the Enderby Basin is the only continuous FZ trace that records plate motion changes during the reorganization episode (Fig. B4a). It reveals that the change in spreading direction occurred rapidly, as compared to the broad Wharton Basin and Weddell Sea FZ bends, the Kerguelen FZ bend is much sharper. The length of the bend is only ~30 km. Several FZs appear to terminate at the Kerguelen FZ, likely due to changes in ridge segmentation during the reorganization resulting in establishment and growth of a single large-offset FZ (Rotstein et al., 2001). Although fewer conjugate FZ traces were identified southeast of India, a similar pattern is discernible with older pre-reorganization FZs truncated by a younger post-reorgansition FZ (Fig. B4c). FZs in the western Enderby Basin, to the south of the Conrad Rise are discontinuous and it is not possible to estimate the duration of the reorganization from these traces. Their disappearance may be related to a ridge jump, due to the appearance of a FZ-perpendicular ridge-like pattern in the vertical gravity gradient maps that appears to truncate curved FZs that were forming during the reorganization (Rotstein et al., 2001) (Fig. B4b). Similarly, FZs southeast of India and in the Bay of Bengal (Fig. B4c) are also discontinuous, so it is not possible to estimate the duration of the reorganization from their traces.

Sparse data coverage and large sediment thicknesses limit the resolution of satellite-derived gravity, and hinder efforts to interpret the early spreading history between India and Antarctica prior to the CNS. A proposed ridge jump and micro-continent formation (Elan Bank) (Gaina et al., 2003) add further complexity to the history of spreading preserved in the Enderby Basin. Additionally, there are no clear M0 magnetic anomaly identifications south of the observed FZs making it difficult to interpolate spreading rates during the CNS. Therefore, in order to approximate the age of onset of the reorganization we

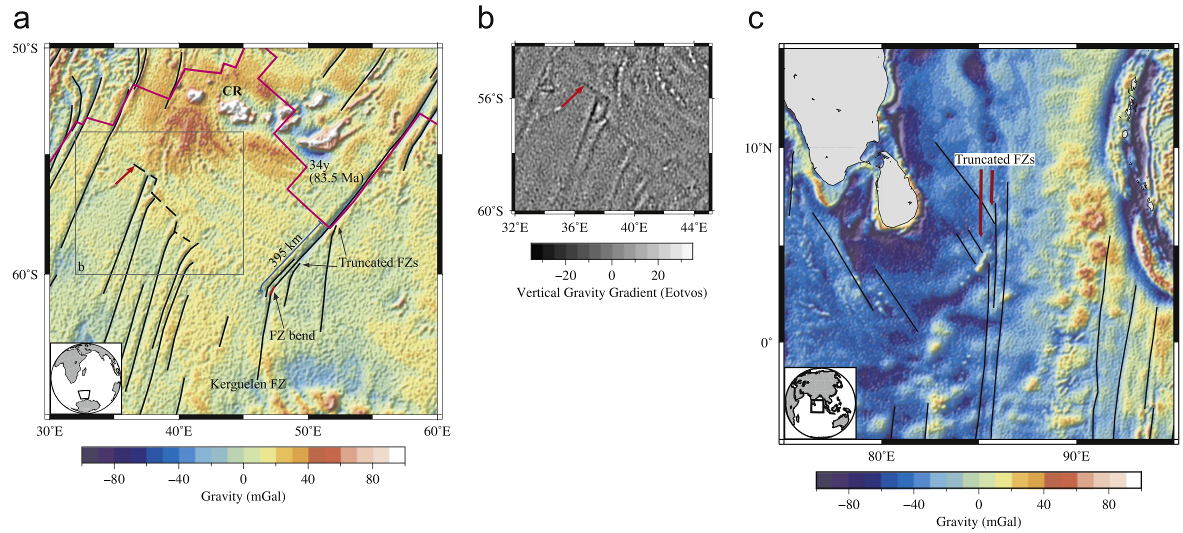


Fig. B4. (a) Gravity map (Sandwell and Smith, 2009) of the Enderby Basin in the southern Indian Ocean, with FZ traces (black lines) (Matthews et al., 2011) and the anomaly 34y (83.5 Ma) isochron (pink) of Seton et al. (2012). Southwest of the Conrad Rise (CR) FZ traces disappear contemporaneously at what appears to be an extinct spreading ridge (dashed line) (Rotstein et al., 2001). The extinct spreading ridge is traced from the vertical gravity gradient grid of Sandwell and Smith (2009) (b). The red arrows in (a) and (b) are at the same location. (c) Gravity map of the northern Indian Ocean showing the Bay of Bengal adjacent to India. Northwest–southeast trending FZs are truncated by north–south trending FZs. This pattern of truncated FZs is mirrored in the Enderby Basin (a). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

will consider the distance of the Kerguelen FZ bend from 34y (83.5 Ma) magnetic anomalies that are more clearly identifiable.

The onset of the reorganization recorded at the Kerguelen FZ occurs approximately 395 km from the anomaly 34y (83.5 Ma) isochron of Seton et al. (2012) (Fig. B4a). If we take a post anomaly 34y spreading rate of ~40–45 mm/yr (Desa et al., 2006; Müller et al., 2008) the reorganization initiated close to 92–93 Ma, however, it is likely that spreading was slower during the CNS with a decrease in the half-spreading rate recorded in the Enderby Basin leading up to M0 time (120.4 Ma) (Gaina et al., 2007; Ramana et al., 2001). In the Central Enderby Basin, where a northward ridge jump near M0y time (120.4 Ma) isolated the Elan Bank from the Indian plate, half-spreading rates decreased significantly immediately prior to the ridge extinction, and may have dropped to as low as 8 mm/yr (Gaina et al., 2007). If the afore mentioned negative gravity lineations south of the Conrad Rise (Fig. B4b) indeed form an extinct ridge, then spreading rates may also have been very slow in the western Enderby Basin at least in the early part of the CNS leading up to the reorganization. Rotstein et al. (2001) assigned an age range of 96–99 Ma to the reorganization between India and Antarctica after Müller et al. (1998) and Powell et al.'s (1988) interpreted age of the plate reorganization between Australia and India.

Eagles and König (2008) calculated a Western Enderby Basin half-spreading rate of 26.5 mm/yr after ~120 Ma from synthetic flow lines, derived from rotation poles calculated primarily from data from the Mozambique and Riiser-Larsen basins. This rate results in the reorganization initiating closer to 98 Ma, and based on a bend length of 30 km suggests that the reorganization occurred over 1 Myr. We take these calculations as the age of initiation and duration of the ridge reorganization.

An age of 98 Ma for the onset of the reorganization between Antarctica and India is consistent with the recent findings of Gibbons et al. (submitted for publication). They combined an analysis of magnetic and gravity data from the Enderby Basin with geological and geophysical observations from around India, Madagascar and the Wharton Basin, and determined an age of 98 Ma for the reorganization.

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