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A TIGHT FIT-EARLY MESOZOIC GONDWANA, A PLATE RECONSTRUCTION PERSPECTIVE

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Abstract: Gondwana, with East Antarctica as its center, began to break up during Late Triassic to Early Jurassic time. Use of the satellite derived gravity map to approximate the ocean-continent boundary allows us to generate a much tighter fit for the reconstructed supercontinent then previously attempted. Major mantle plumes such as the Karoo-Ferrar Plume that first split Gondwana at about 182 Ma, the Paranã-Etendeka plume at 132 Ma that split South America and Africa, the Marion plume at 88 Ma that split Madagascar and India and finally the Reunion hotspot that split the Mascarene Plateau from India at 64 Ma, were all critical events in the break-up of Gondwana. Our tight-fit produces overlap between cratonic East Antarctica and the Limpopo Plain of Mozambique but there is no evidence that the crustal material underlying the Limpopo Plain pre-dates the break-up of Gondwana. Likewise Madagascar has been reconstructed so that it substantially overlies coastal East Africa in the vicinity of the Anza Trough, an early Jurassic rift in Kenya. The western margin of the island of Madagascar may in fact be crustal material that is younger than the break-up. It may have been produced as a result of the Karoo mantle plume or some may have been the result of the Marion hotspot. Between South America and Africa there are three significant overlaps. Two of them are deltaic, and the third is the Abrolhos and Royal Charlotte banks which post-date Gondwanide breakup by 80 to 100 million years.

key words: Gondwana break-up, Mesozoic Paleoreconstructions, ocean-continent boundaries, Karoo-Ferrar Mantle Plume, overlap

1. Introduction

In most parts of the world, sufficient seafloor data are now available that it is unlikely relative plate rotations will change significantly from those now used. Our tight fit reconstruction of Gondwana is based on identified marine magnetic anomalies, other seafloor age determinations, seafloor bathymetric features and tectonic lineations inferred from satellite altimetry data that presumably indicate past plate motion directions (LAWVER *et al*., 1992). We also assume uniform seafloor spreading rates over reasonable periods of time. Even so, it is important to work out the interval locations of the continental blocks that broke up from Gondwana because we must essentially work backwards to determine the correct original tight-fit. Once we have a tight-fit then we work forward in time, to make sure that nothing overlaps as the subsequent relative positions are determined.

The latest satellite gravity data (SMITH and SANDWELL, 1995), particularly south of

30°S, have an advantage in that the Geosat geodetic mission satellite altimetry data set has been declassified so seafloor tectonic lineations (GAHAGAN *et al.*, 1988) are quite prominent. The satellite gravity data reveal seafloor lineations that can be matched, for instance from the margin of South America all the way across the South Atlantic to the western margin of Africa. We assume that these striking seafloor lineations were formed on post-Gondwanide breakup oceanic crust and we use them to produce our original configuration of Gondwana. While the satellite gravity data allows us to reconstruct relative positions, marine magnetic anomalies are required to determine the timing of the positions. Unfortunately, during the Cretaceous Normal Superchron, Chron M0 (120 Ma, GRADSTEIN *et al.*, 1994) to Chron 34 (83.5 Ma), there are no identifiable magnetic reversals, so relative as well as absolute plate locations are not known precisely. In fact, in the Central Atlantic, KLITGORD and SCHOUTEN (1986) found a spreading rate of 10.7 mm/year (half-rate) between Chron M4 (now renamed M5 by GRADSTEIN *et al.* (1994), 126.7 Ma) and 120 Ma, a spreading rate of 22.7 mm/year between 120 Ma and Chron 33 (80 Ma), and a rate of 16 mm/year until 67 Ma (Note: the KLITGORD and SCHOUTEN (1986) spreading rates which used the KENT and GRADSTEIN (1986) timescale have been recalculated using the GRADSTEIN *et al.* (1994) timescale). No one knows how long the 10.7 mm/year rate lasted after the beginning of the Cretaceous Normal Superchron nor how soon the 16 mm/yr rate began before 80 Ma, but any period of slow spreading after 120 Ma or before 80 Ma would require a spreading rate even faster than 22.7 mm/year during some shorter period between 120 Ma and 80 Ma. Until Cretaceous Normal Superchron period basement rocks are drilled and dated from the Central Atlantic, precise relative positions of North America with respect to Africa for the period from 120 Ma to 83.5 Ma will remain unknown. Relative motions between the other major plates between Chrons M0 and A34 are also tenuous.

Few M-series (pre-84 Ma) magnetic anomalies have been reliably identified in the Southern Oceans, so exact locations of the continental masses through time are not well known between break-up and Chron A34 (83.5 Ma). Post A34, ROYER and SANDWELL (1989) used 2500 magnetic anomaly identifications in the Indian Ocean to determine relative positions of the continents at ten different times between 83.5 Ma and 9.8 Ma and SHAW and CANDE (1990) and NÜRNBERG and MÜLLER (1991) have done a similar job for the South Atlantic. The identified marine magnetic anomalies and tectonic lineations deduced from Geosat altimetry data which were used to insure that the tight fit shown here for East Antarctica, matches with later seafloor spreading, are summarized in ROYER *et al.* (1990). Relative plate reconstructions can be checked by determining closure around triple junctions, by ensuring there are no discrepancies when isochron charts are produced (*i.e.* the same seafloor was seemingly produced by two different spreading centers), and by comparing the geology of the conjugate margins of the rotated plates. For areas without identifiable marine magnetic anomalies to constrain plate locations, paleomagnetic poles may constrain relative north-south motion, but only if the north-south motion has been great.

Absolute plate positions in a global framework depend on relative plate rotations, on paleomagnetic data from marine cores and terrestrial samples, and on assumptions about the fixity of hotspots with time (MÜLLER *et al.*, 1993). Paleomagnetic data, combined with a datable hot spot reference frame, can be used to determine absolute plate positions

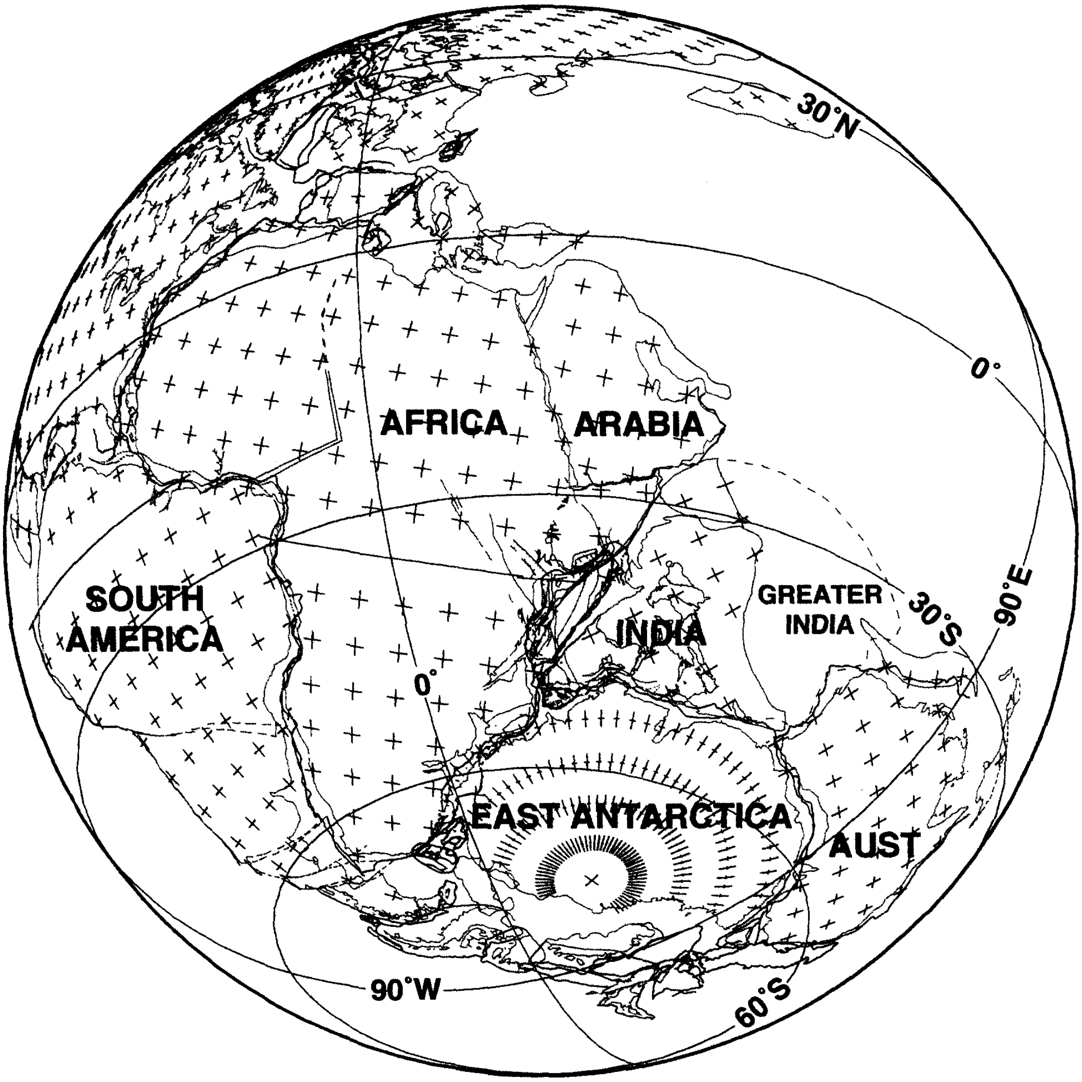

Fig. 1. *Tight fit reconstruction of Gondwana at 200 Ma in an absolute reference frame based on hotspots and paleomagnetic data (MÜLLER et al., 1993; VAN DER VOO, 1993). West African rift has been closed using outline of FAIRHEAD and BINKS (1991). Much of the overlap between East and West Gondwana between the Limpopo region to north of Madagascar and between India and East Antarctica were discussed in LAWVER et al. (1992). The closure of the pieces of southern South America places the Falkland Islands block (Lafonian microplate) into its reconstructed position with respect to the Karoo Basin geology of southern Africa (MARSHALL, 1994), while maintaining the present-day distance between it and continental South America. This new reconstruction does not require unknown post-breakup motion of the Falkland Island block (Lafonian microplate) towards coastal continental South America. Present-day coastlines = green. Present-day 5-degree graticule = black. Plate sutures = red. Ocean-continent boundaries = blue. Geologic lineations and craton outlines = purple.*

through time if one also assumes that true polar wander is negligible. An absolute reference frame that neglects true polar wander has been devised for the last 130 million years by MÜLLER *et al.* (1993), but is considered most reliable for the last 84 Ma. They have extended their absolute position of Africa to 180 Ma (MÜLLER, personal communication), and we in turn have used the paleomagnetic poles of VAN DER VOO (1993) in conjunction with the hotspot locations of COFFIN and ELDHOLM (1994), to calculate a new absolute framework for 200 Ma. We used the new 200 Ma absolute position of Africa to produce the paleolatitute of the tight-fit of Gondwana shown in Fig. 1.

The "tight fit" reconstruction (Fig. 1) attempts to take into consideration some pre-breakup continental stretching. In our reconstructions, the ocean-continental boundary (OCB) as the pre-breakup plate boundary is assumed to be coincident with the major gravity anomaly (Fig. 2) as picked off the most recent satellite gravity dataset (SMITH and SANDWELL, 1995). In those areas where post-breakup changes are quite evident overlap is accepted. Post-rifting subsidence, as well as the rapid sedimentation that commonly occurs during the first phases of continental separations, has not been considered in detail, but use of the gravity anomaly seems to place most of the post-rift subsidence and seaward dipping reflectors to the oceanward side of the gravity anomaly as picked in Fig. 2. The determination of pre-rift ocean-continent boundaries requires not only seismic reflection and refraction data, but also deep drilling data to determine the subsidence history of the continental margins. Even so, our simple assumption actually matches very closely the ocean-continent boundary determined by GLADCZENKO *et al.* (1997) for the Namibian margin of southern Africa based on deep seismic reflection and refraction work. Their seaward dipping reflectors are shown outlined in white on Fig. 2. While some seismic refraction information is available and has been considered elsewhere, it can not be assumed that a uniform subsidence history applies to the entire length of a rifted margin. Consequently, it is difficult to ascertain if narrow gaps between reconstructed major plates were actual gaps, or if we have failed to identify all pre-breakup stretching. Nonetheless the model in Fig. 1 leaves very few gaps and no overlaps that can not be explained by post-breakup conditions. As a consequence we assume that the major gravity anomaly change from about -20 mgal on the oceanward side to $+3$ mgal on the landward side of the ocean-continent boundary is a good proxy for the pre-breakup configuration of the continental blocks.

Our tight fit, based primarily on satellite gravity data, seems to be unequivocal in most instances. In particular, several aspects lead us to believe that we have achieved a much tighter fit of pre-breakup East Gondwana than achieved previously (DE WIT *et al.*, 1988; LAWVER and SCOTESE, 1987). Most notable are the fit of the transform boundaries, such as the North Falkland Escarpment and the southeastern margin of Southern Africa, major directional changes in the gravity anomaly that are mirrored on the conjugate rifted margins, and the remarkable fit between Mozambique and Gunnerus Ridge (LAWVER *et al.*, 1992). For West Gondwana, and in particular for West Antarctica, this reconstruction is partially based on the paleomagnetic work of GRUNOW *et al.* (1991). Unfortunately, there are insufficient quantitative data to definitively place the pieces of West Antarctica in their absolute context in Gondwana. Figure 1 shows essentially our best approximation for the locations of the pieces of West Antarctica based on reasonable geological and geomagnetic assumptions. Note, however, that we have not attempted to reconstruct relative motion from eastern and western portions of Marie Byrd Land (DIVENERE *et al.*, 1996).

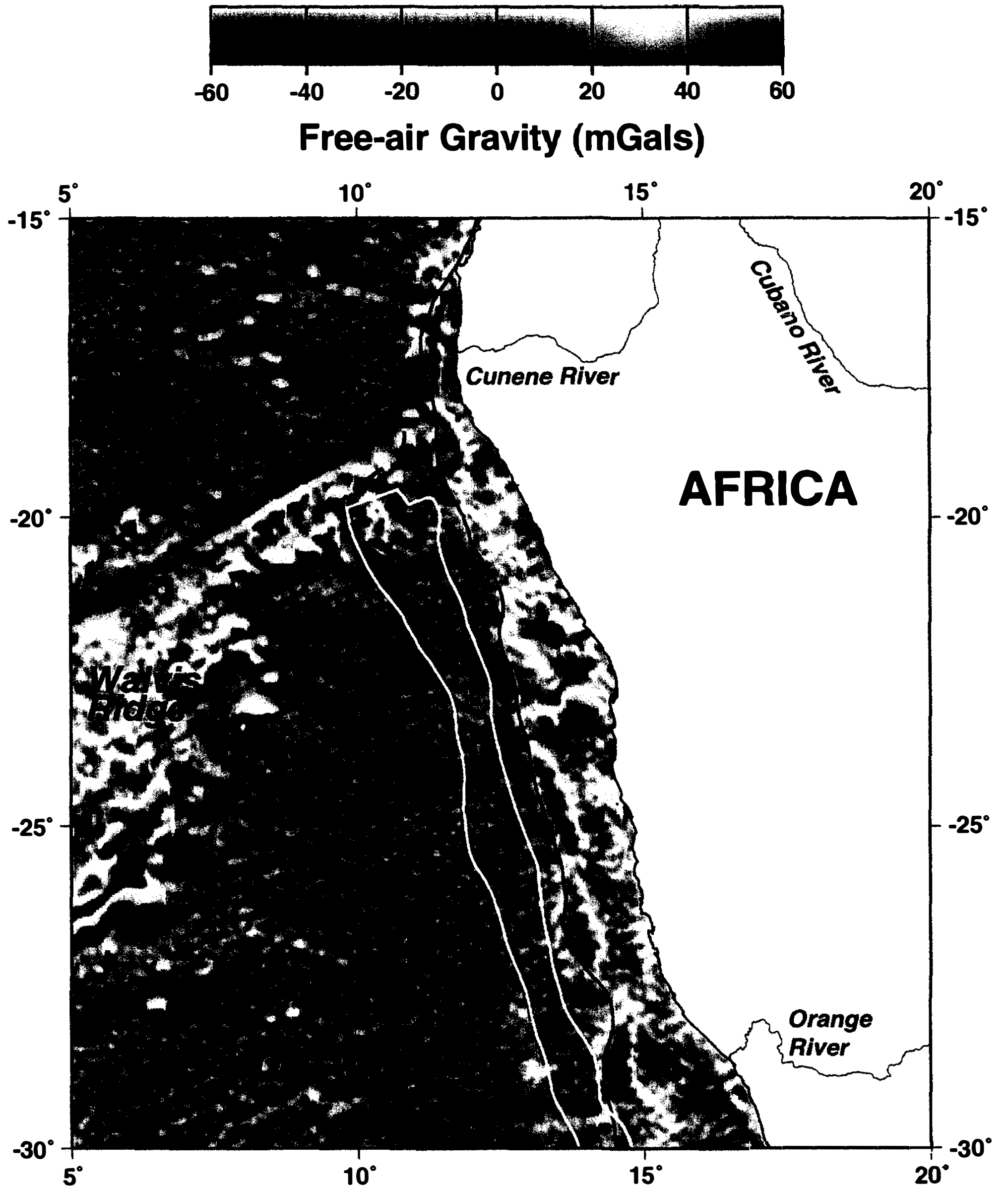

Fig. 2. *Satellite gravity data (*Smith *and* Sandwell, *1997) showing the west coast of Southern Africa. The Orange River is in the lower right while the Cunene and Cubano rivers are shown in the upper right. The red line is our pick for the ocean-continent boundary (OCB) based on the dramatic change in the derived free-air gravity. The region outlined in white is the area of seaward dipping reflectors as determined by* Gladczenko *et al. (1997). Our OCB is approximately half-way between the landward edge of the* Gladczenko *et al. (1997) seaward dipping reflectors and the rift unconformity pinchout of* Gladczenko *et al. (1996). The Orange River delta moves our OCB as picked off the satellite gravity data out beyond the landward edge of the seaward dipping reflectors of* Gladczenko *et al. (1997).*

2. Pre-Break up Reconstruction

The break-up of Gondwana seems to have resulted from the interaction of a series of hotspots or mantle plumes that impinged on or between the cratonic regions of Gondwana.

The first major Gondwanide hotspot probably resulted in the splitting of East and West Gondwana. The Karoo mega-plume (White and Mckenzie, 1989) is dated close to 183 Ma (Encarnación *et al.*, 1996), while the Paraná/Etendeka plume at 132 Ma (Renne *et al.*, 1992, 1996) seems to have been at least partially responsible for the splitting of South America from Africa. Whether or not the Kerguelen/90° East hotspot broke India from East Antarctica is unknown since seafloor spreading had probably begun by M7 (128 Ma) and the oldest dated basalts are 110 Ma (Pringle *et al.*, 1997; 114 Ma - LeClaire *et al.*, 1987). The Bunbury basalts of western Australia may be a better candidate for splitting of India from Australia and perhaps East Antarctica since they are dated as old as 130 Ma (Frey *et al.*, 1996). The Marion hot spot/mantle plume at 88 Ma split India from Madagascar and initiated seafloor spreading in the Mascarene Basin (Storey *et al.*, 1997), while the Deccan Traps/Reunion hotspot split India from the Mascarene Plateau (Royer and Sandwell, 1989). These hotspots and mantle plumes provide a framework for an absolute as well as a relative plate tectonic reconstruction of Gondwana. In discussing the breakup of Gondwana, we start with the Karoo mantle plume and the break between East

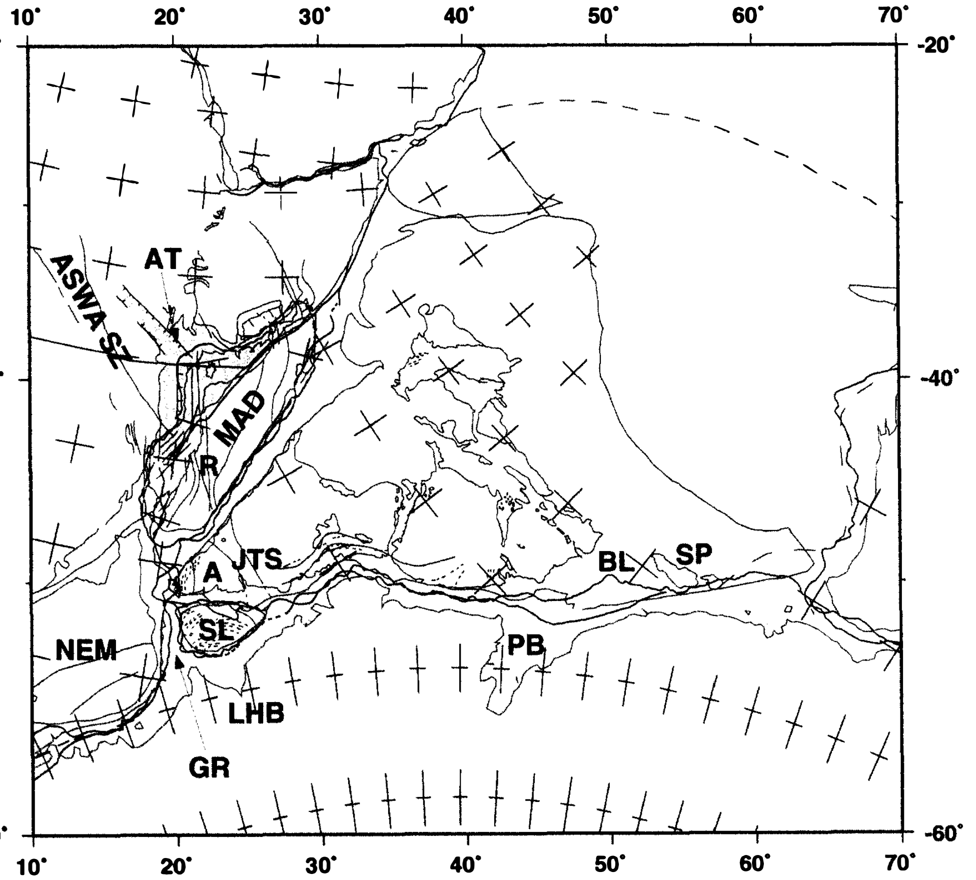

Fig. 3. Detail of tight fit reconstruction shown in Fig. 1. Purple areas outline cratonic regions of Africa, India, Madagascar and Sri Lanka. A = Anchovil Shear Zone. AT = Anza Trough. AswaSZ = Aswa Shear Zone. BL = Bengal Lowlands. GR = Gunnerus Ridge. JTS = Jaffna-Thanjuvur-Salem lineaments. LHB = Lützow-Holm Bay. MAD = Madagascar. NEM = Northeast Mozambique Craton. PB = Prydz Bay. R = Ranotsara Shear Zone. SL = Sri Lanka. SP = Shillong Plateau.

and West Gondwana and work our way eastward to finish with the break between South America and Africa.

Initial stretching between East and West Gondwana probably started in the north, to the east of Africa and progressed southward. CANNON *et al.* (1981) proposed a triradial rift system that included the Jurassic-aged Anza Trough of Kenya (Fig. 3). They show the approximate southern limit of marine Jurassic fauna of eastern coastal Africa and western Madagascar. An extremely tight fit between Madagascar and East Africa restores the southern limits of the Lower Jurassic marine fauna, aligns the Triassic and Permian-aged Karoo sediments, and may provide bounds on both the direction of initial stretching and timing of stretching. Once the Karoo mantle plume erupted, the southern limit of the marine Middle and Upper Jurassic are nearly in line for the post-stretching phase, pre-seafloor spreading reconstruction of Gondwana. The early stretching was finished by the initiation of seafloor spreading during the earliest Late Jurassic in the Somali (SÉGOUFIN and PATRIAT, 1980; RABINOWITZ *et al.*, 1983; COCHRAN, 1988) and Mozambique (SÉGOUFIN, 1978; SIMPSON *et al.*, 1979) basins and by inference in the southwest Weddell Sea.

2.1. *Africa-East Antarctica*

Figure 1 shows a tight fit reconstruction of Gondwana at Early Jurassic times (~200 Ma). One key to the tight-fit reconstruction is the juxtaposition of Jurassic volcanic sequences of the Lebombo Monocline (Fig. 4) in Southeast Africa with the Heimefrontfjella of East Antarctica (GROENEWALD *et al.*, 1991) which is the overlap at 60°S, 0° in Fig. 1. The tight fit superimposes Antarctic continental crust on top of what is now the Limpopo Plain of Mozambique. While our tight fit is similar to the reconstruction of Africa and Antarctica of MARTIN and HARTNADY (1986), ours has been modified on the basis of a better definition of the Heimefrontfjella by the use of AVHRR (Advanced Very High Resolution Radiometry) data (U.S.G.S., 1995). While such a superposition of present-day continental crust would normally imply too tight a fit, there is no evidence for pre-breakup continental material to the east of the Lebombo Monocline in Southeast Africa (DE WIT *et al.*, 1988). One important aspect of our tight fit is the very good match between the northeast Mozambique craton and the curve of the Antarctic Ocean Continent Boundary that includes Gunnerus Ridge (Fig. 3). This tight fit reconstruction also puts the Precambrian A to B rocks (1450 to 950 Ma, DE WIT *et al.*, 1988) of northeastern Mozambique in close proximity to rocks of similar age in Dronning Maud Land, East Antarctica (GROENEWALD *et al.*, 1991). The impact of the Karoo mantle plume at 183 Ma may not have only produced the Karoo flood basalts of southern Africa but may also have produced extended and underplated crust of the Falkland/Malvinas Plateau, the Mozambique Ridge including the very flat, Limpopo region of southern Mozambique, western Madagascar and possibly regions of the continental margin of southern Argentina and the Weddell Sea embayment.

2.2. *Madagascar-Africa*

An additional space difficulty is overlap of the western edge of Madagascar with the Kenyan region of East Africa. REEVES *et al.* (1987) discuss geophysical evidence for consideration of the Anza Trough (Figs. 3, 4) as a failed third arm of a Jurassic-aged

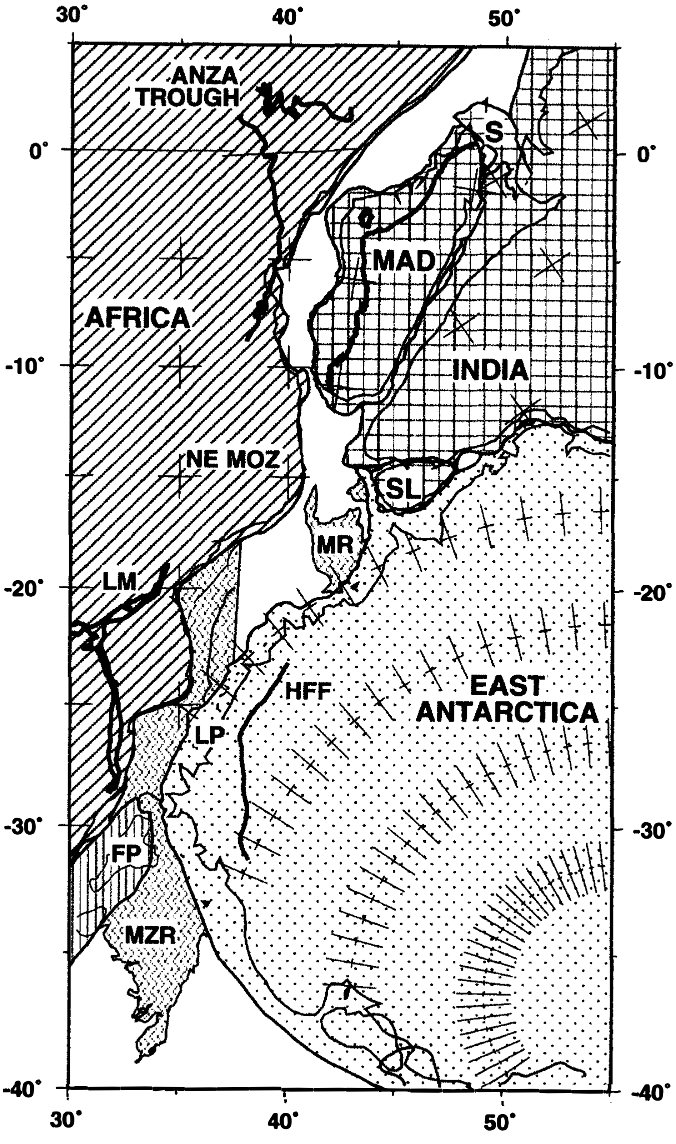

Fig. 4. *Detail of continental regions at 160 Ma (Africa fixed in its present-day coordinates). Colors as in Fig. 1; light blue = bathymetric contour. Solid purple line on southern Africa (diagonal hachures) is edge of Lebombo Monocline taken from the edge of the Jurassic volcanic sequences of* Groenewald *et al. (1991). Solid purple line on Antarctica (dotted continental region) is digitized edge of the Heimefrontfjella taken from the AVHRR map of Antarctica (U.S.G.S., 1991). FP = Falkland Plateau. HFF = Heimefrontfjella. LM = Lebombo Monocline. LP = Limpopo or Mozambique Plains. MAD = Madagascar. NE MOZ = northeast Mozambique. MZR = Mozambique Ridge. MR = Madagascar Ridge. S = Seychelles. SL = Sri Lanka. After* Lawver *et al. (1992).*

triradial rift in coastal Kenya. They conclude that Madagascar can be reassembled as part of Gondwana in a tighter fit than previously thought. If Permo-Triassic rocks of Madagascar are aligned along strike with the linear Permo-Triassic Karoo rocks of Zambia (De Wit *et al.*, 1988) then Jurassic-aged break-up rocks of western Madagascar fit with similar rocks exposed in Tanzania and southern Kenya. Precambrian rocks of coastal northern Mozambique and southern Tanzania fit with similar-aged rocks of Madagascar (Coffin and Rabinowitz, 1987) and further extends a margin that fits tightly against Gunnerus Ridge, the submarine ridge off present-day East Antarctica at 32°E. Coffin and Rabinowitz (1988) summarize selected exploratory well data from coastal and offshore Madagascar and Tanzania that indicate some Upper Triassic and possibly even Permian rocks that may have formed a paleo-seaway between Madagascar and Africa. While Battail *et al.* (1987) found evidence for a Late Permian to Early Triassic marine barrier between Madagascar and Africa, the Early Triassic ichthyofaunas from Madagascar are more closely related to Laurasian faunas from British Columbia, Greenland, and Spitsbergen than to South African fauna. This evidence suggests that a Triassic tight fit of Precambrian rocks of northeastern Mozambique against the Gunnerus Ridge of East Antarctica still existed. Since late Triassic fauna are also most similar between Madagascar and the western part of Laurasia, no substantial stretching may have occurred between East and West Gondwana until at least latest Triassic-earliest Jurassic time. We estimate the tight fit reconstruction of Gondwana shown in Fig. 1 as ~200 Ma was valid until that time and was then disrupted by eruption of the Karoo mantle plume. If such pre-Karoo partial seaways were the result of Permian to Triassic extension, then the very tight-fit reconstruction of Gondwana shown in Fig. 1 may be represent a time older than ~200 Ma.

2.3. *India/Sri Lanka-East Antarctica*

The fit of Sri Lanka-India and Antarctica has been discussed previously (LAWVER and SCOTESE, 1987). The fit of Madagascar with India has always been problematic because the eastern margin of Madagascar is extremely linear. As such it can fit virtually anywhere along the western margin of India. Now though, with the satellite gravity data and assuming that extreme tight fits are reasonable, it becomes apparent that there is only one place where India fits with East Africa and where Madagascar fits within the East Africa/India tight fit. With the fit shown in Fig. 3, there are not many possibilities for alternative fits. The remarkable fit between southern Madagascar, southern most India and the East African margin at the Mozambique/Tanzanian border (10°S) constrains the pre-breakup configuration of Gondwana and hence where Madagascar fits with East Africa. The linear eastern margin of Madagascar seems to indicate that the initial movement between Madagascar and India may have been transform motion. Although there are no seafloor magnetic anomalies that can be cited to directly support such motion, major plate motions seem to indicate that transform motion along that margin was required between at least 140 and 115 Ma.

Breakup between India and East Antarctica relies on circumstantial, not direct evidence. Perhaps the best information for constraining India-East Antarctica break-up is the age of seafloor spreading between greater India and the western margin of Australia (LARSON *et al*., 1979; POWELL *et al*., 1988) but there is no guarantee that greater India, the region now north of the Himalayan suture, was rigidly attached to cratonic continental India. One result of our tight fit of India with East Antarctica is the alignment of Prdyz Bay on Antarctica with the Bengal lowlands of India/Bangladesh. ODP Leg 119 results (BARRON *et al*., 1991) suggest that the Lambert Graben section of Prydz Bay predates the rifting of India from East Antarctica.

2.4. *Australia-East Antarctica*

The exact fit of Australia and Antarctica was significantly improved with release of Geosat Exact Repeat Mission data in 1987 (SANDWELL, 1992). VEEVERS *et al*. (1991) and ROYER and SANDWELL (1989) discussed the early break-up of Australia with respect to Antarctica. The southern margin of Australia fits along East Antarctica and ends to the west where the easternmost-recognized continental rocks of the early Indian plate occur at the Shillong Plateau and Mikir Hills (BHANDARI *et al*., 1973).

2.5. *West Antarctica and other pieces*

The remaining southern Gondwana pieces include North and South New Zealand, the Campbell Plateau, Chatham Rise, Marie Byrd Land, the Ellsworth/Whitmore block, the Antarctic Peninsula with the South Orkney block, and Thurston Island. While there are no marine magnetic anomaly or Geosat data to constrain the fit of the West Antarctica blocks, paleomagnetic data (GRUNOW *et al.*, 1987, 1991; DIVENERE *et al.*, 1995), geology (BRADSHAW, 1989, 1993), geometric and other considerations can be used to produce a reasonable representation of the entire Mesozoic pre-breakup configuration of Gondwana (Fig. 1).

Marine seismic reflection and refraction data in the Ross Sea (COOPER *et al.*, 1991) support a 100% stretching of the continental crust. The ~200 Ma reconstruction of Marie Byrd Land with respect to East Antarctica used a 50% closure of the present-day Ross Sea Embayment in both north-south and east-west directions (LAWVER and SCOTESE, 1987). Since Campbell Plateau, Chatham Rise, and North and South New Zealand can be reconstructed to Marie Byrd Land (GRINDLEY and DAVEY, 1982), this also constrains their positions in the pre-breakup configuration of Gondwana (LAWVER and GAHAGAN, 1994). Consequently, if the tight fit reconstruction of Gondwana is valid, there is only a limited space in which to place the Antarctic Peninsula and Thurston Island. Paleomagnetic data (GRUNOW *et al.*, 1991) and geological considerations (DALZIEL and ELLIOT, 1982) suggest that the Antarctic Peninsula can be rotated counterclockwise from its present-day position with respect to East Antarctica, and can be reconstructed along the western margin of southernmost South America. Furthermore, paleomagnetic data (GRUNOW *et al.*, 1991) from Thurston Island indicate an almost 90° rotation with respect to the Antarctic Peninsula subsequent to breakup. Since the Thurston Island block is nearly circular, its exact rotational placement does not affect potential seaways.

2.6. *South America-Africa*

The initial fit between South America and Africa (BULLARD *et al.*, 1965) was one of the cornerstones of plate tectonics. They first determined the fit which was apparent to most school children who contemplated the globe for any length of time. We now realize that continents are not the rigid plates that we once thought them to be. In fact, extension in the Paranã Basin (EXXON MAP, 1985) subsequent to initiation of seafloor spreading in the far South Atlantic can account for some of the obvious misfit that BULLARD *et al.* (1965) found with their initial fit. We have been able to modify the previous fit of South America and Africa (RABINOWITZ and LABRECQUE, 1979; NÜRNBERG and MÜLLER, 1991). In our tight fit between South America and Africa (Fig. 5), there are three significant overlaps. Two of them are deltaic, the Amazon and Niger deltas, and the third is the Abrolhos and Royal Charlotte banks. The deltas seem to have covered the continental shelves with land and extended our designated ocean-continent boundary out onto oceanic crust while the Abrolhos and Royal Charlotte banks post-date Gondwanide breakup by 80 to 100 million years (CHANG *et al.*, 1992). The banks appear at about 38°S in Fig. 5 where there is a very decided overlap of South America over the African margin. Clearly this overlap can be ignored in a tight fit of Gondwana because it resulted from magmatic activity that occurred long after the South Atlantic opened. The rest of the match between South America and Africa exploits post-breakup phenomena that have distorted the shape

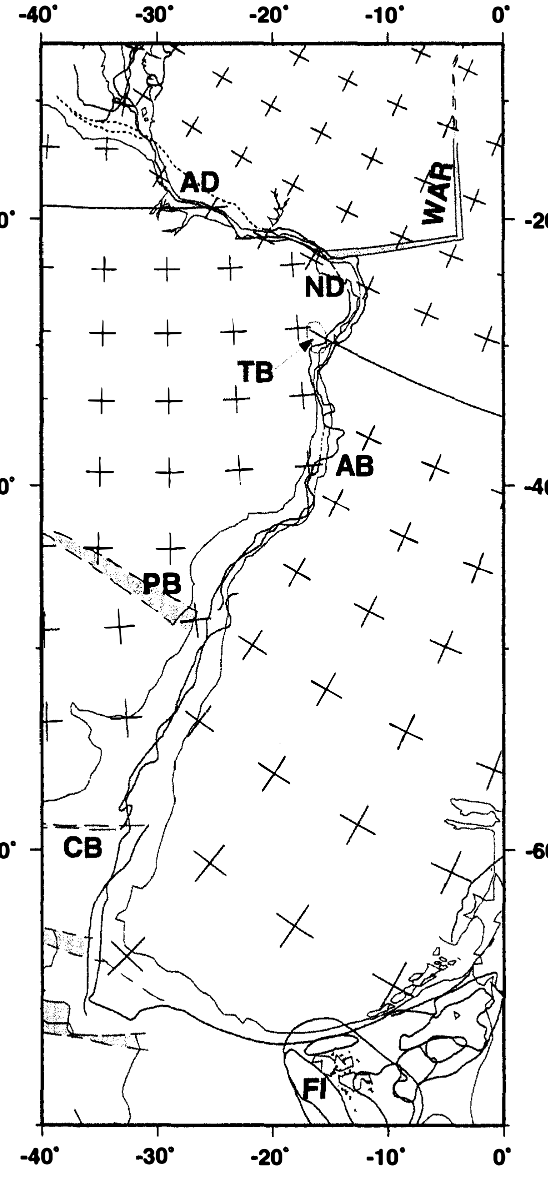

Fig. 5. Detail of tight fit reconstruction shown in Fig. 1. AB = Abrolhos Bank, AD = Amazon Delta. CB = Colorado Basin. FI = Falkland Island block (Lafonian microplate). ND = Niger Delta. PB = Paraná Basin. TB = Tucano Basin. WAR = West African Rift.

of southern South America, including extension in the Paraná Basin, probably coincident with breakup and extension of sedimentary basins in Patagonia including the Colorado and Salado basins.

Seafloor spreading in the southern South Atlantic (Austin and Uchupi, 1982) started at Chron M9 (~130 Ma). Immediately to the north, the first seafloor spreading seems to be Chron M5 (Rabinowitz and LaBrecque, 1979; Austin and Uchupi, 1982; Max *et al.*, 1998). Just prior to that time, 132±1 Ma, the Paraná-Etendeka flood basalts (Renne *et al.*, 1996) were erupted and southern South America rotated slightly away from northern South America. The initial sedimentation in many of the South Atlantic marginal basins are Late Jurassic (Milani and Davison, 1988; Chang *et al.*, 1992; Urien *et al.*, 1995), implying that continental stretching may have predated the eruption of the flood basalts by about 12 million years and possibly as many as 18 million years if the Kimmeridgian age of the Araucarian "orogeny" can be construed as the precursor event (URIEN *et al.*, 1995). The rift subsidence of the Reconcavo and onshore Sergipe-Alagoas basins increased sharply at the end of the Neocomian/Barremian (CHANG *et al.*, 1992), with at least a 2-fold increase from that of the Neocomian. The rift subsidence terminated abruptly during the Aptian (CHANG *et al.*, 1992). The initial South Atlantic opening started up the Reconcavo/Tucano Basin (about 32°S on Fig. 5) and into the Jatoba Basin (MILANI and DAVISON, 1988). The main rift failed first in the North Tucano/Jatoba rift but continued to rift in both the Reconcavo/South Tucano Basin and transferred to the Sergipe-Alagoas Basin with sinstral strike slip along the Itaporanga fault (CHANG *et al.*, 1992). This switch can explain the Vaza Barris Arch as a transpressional ridge formed after the North Tucano Basin ceased to rift. Rifting in both the Reconcavo Basin and the Sergipe-Alagoas basins terminate abruptly during the Aptian (121-112.2 Ma) when seafloor spreading ripped around the Araripe Craton (EXXON MAP, 1985). As it ripped around Recife it left no extended continental margin as seen to the south of 15°S along the South America margin and south of 3°S along the African margin.

3. Summary

Paleogeographic reconstructions can be used to constrain a tight fit reconstruction of Gondwana. At any rifted continental margin, it is important to estimate the amount and rate of thermal subsidence of the margin corrected for what is usually a rapid rate of sedimentation. In our figures, the satellite gravity transition is taken as the edge of the continent. In previous reconstructions of Gondwana, large gaps were left in the Weddell Sea region (LAWVER and SCOTESE, 1987), or the pieces of West Antarctica were packed so tightly together (DEWIT *et al.*, 1989) that now-known crustal thicknesses in the Ross Sea region were violated (COOPER and DAVEY, 1987). Our tight fit only attempts a very cursory look at trans-Gondwanide structures. The Aswa Shear zone of East Africa (SHACKLETON, 1986; EXXON MAP, 1985; WINDLEY *et al.*, 1994) can be aligned with the Achankovil Shear Zone of southern India (WINDLEY *et al.*, 1994). Unlike the WINDLEY *et al.* (1994) reconstruction, our new tight fit has Madagascar sufficiently farther north that the Aswa to Achankovil alignment passes south of cratonic Madagascar. Instead our tight fit suggests possible continuation of the Ranotsara Shear Zone (WINDLEY *et al.*, 1994) of Madagascar with the Jaffna-Thanjuvur-Salem lineaments of KATZ (1978). KATZ (1978) continues the Achankovil of India into the Ratnapura lineament of Sri Lanka which in our reconstruction might then continue on into the Lützow-Holm Bay region of East Antarctica. There are numerous other pre-breakup lineations that need to be tested before this tight fit is accepted.

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