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An Early Cretaceous extinct spreading center in the northern Natal valley

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Abstract

We have identified an extinct E–W spreading center in the northern Natal valley on the basis of magnetic anomalies which was active from chron M11 (~ 133 Ma) to ~ 125.3 Ma, just before chron M2 (~ 124 Ma) in the Early Cretaceous. Seafloor spreading in the northern Natal valley accounts for approximately 170 km of north–south motion between the Mozambique Ridge and Africa. This extension resolves the predicted overlap of the continental (central and southern) Mozambique Ridge and Antarctica in the chron M2 to M11 reconstructions from Mesozoic finite rotation parameters for Africa and Antarctica. In addition, the magnetic data reveal that the Mozambique Ridge was an independent microplate from at least 133 to 125 Ma. The northern Natal valley extinct spreading center connects to the spreading center separating the Mozambique Basin and the Riiser-Larsen Sea to the east. It follows that the northern Mozambique Ridge was either formed after the emplacement of the surrounding oceanic crust or it is the product of a very robust spreading center. To the west the extinct spreading center connects to the spreading center separating the southern Natal valley and Georgia Basin via a transform fault. Prior to chron M11, there is still a problem with the overlap of Mozambique Ridge if it is assumed to be fixed with respect to either the African or Antarctic plates. Some of the overlap can be accounted for by Jurassic deformation of the Mozambique Ridge, Mozambique Basin, and Dronning Maud land. It appears though that the Mozambique Ridge was an independent microplate from the breakup of Gondwana, ~ 160 Ma, until it became part of the African plate, ~ 125 Ma.

Keywords: Natal valley; Africa; Antarctica; Mozambique; Mozambique Ridge; Dronning Maud land; Gondwana; Mesozoic; Reconstructions; Finite rotations

1. Introduction

The northern Natal valley is a small but potentially crucial area in discerning various tectonic scenarios for the Mozambique Ridge and the relative plate motions of Africa and Antarctica in the Late Jurassic–Early Cretaceous (160–124 Ma). The Natal valley lies between the southeast African continental margin and the Mozambique Ridge, a large submarine plateau in the Southwest Indian Ocean (Fig. 1). The southern Natal valley is interpreted to be underlain by oceanic crust based on the identification of Mesozoic seafloor spreading magnetic anomalies (Goodlad et al., 1982). The northern Natal valley has been variously interpreted as being underlain by continental crust (e.g.

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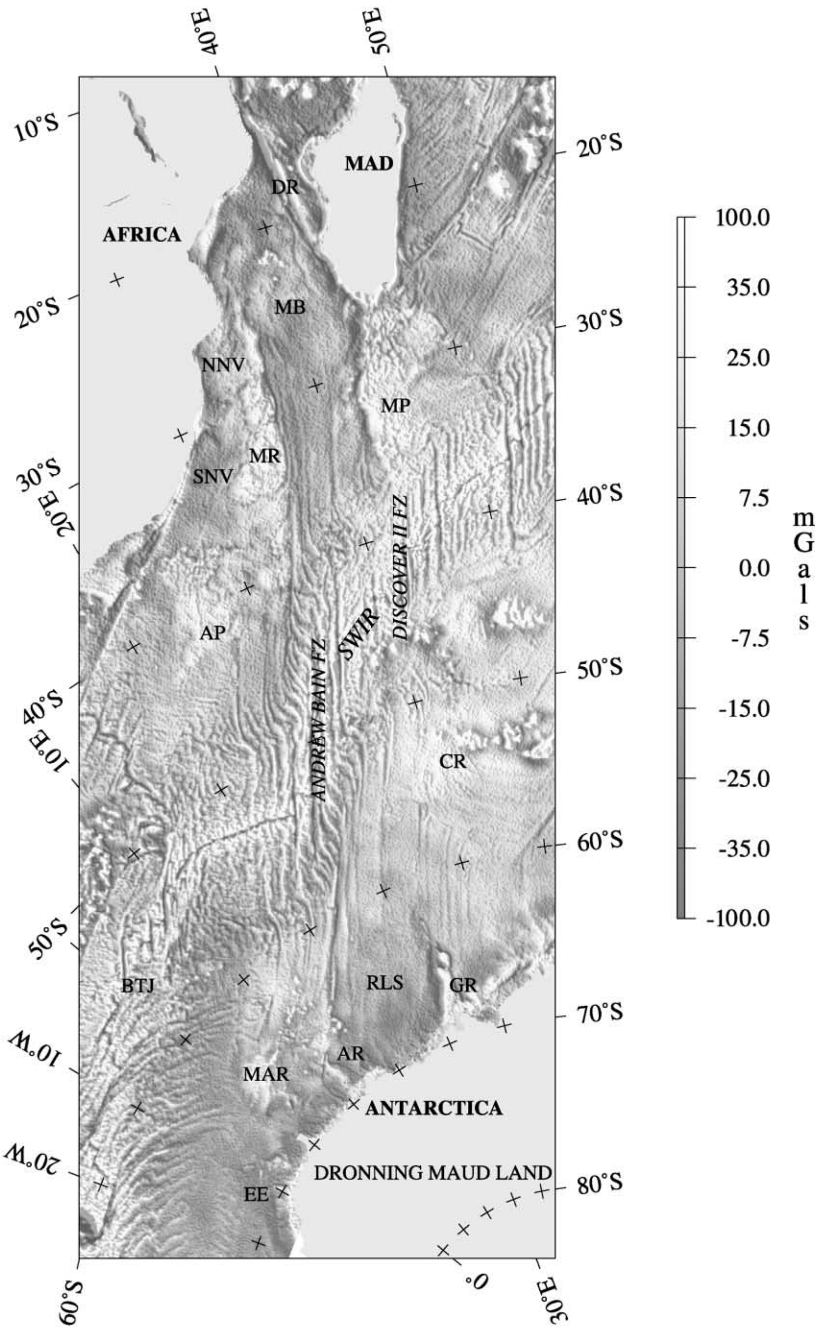


Fig. 1. Satellite-derived free-air gravity field map of the western Southwest Indian Ocean. The features labeled on the map include the northern Natal Valley (NNV), the southern Natal Valley (SNV), the Mozambique Ridge (MR), the (oceanic) Mozambique Basin (MB), the Riiser-Larsen Sea (RLS), the Agulhas Plateau (AP), the Davie Ridge (DR), the Madagascar Plateau (MP), the Maud Rise (MAR), the Astrid Ridge (AR), the Gunnerus Ridge (GR), the Conrad Rise (CR), the Southwest Indian Ridge (SWIR) the Bouvet triple junction (BTJ) and the Explora Escarpment (EE). The gravity field (Sandwell and Smith, 1997) is illuminated from N270°E and projected in an oblique mercator projection with the Andrew Bain fracture zone as the oblique equator.

Dingle and Scrutton, 1974) or oceanic crust (e.g. Green, 1972).

Mesozoic reconstructions of Africa and Antarctica using the finite rotation parameters of Segoufin and Patriat (1981), Martin and Hartnady (1986) and Livermore and Hunter (1996) display a pronounced overlap of the Mozambique Ridge and the Dronning Maud land margin of Antarctica that is persistent prior to chron M2 (124 Ma) (e.g. Fig. 2a and b). [All Mesozoic ages are referenced to the time scale of Gradstein et al. (1994)]. These reconstructions are based on the interpretation of the Mozambique Basin and the Riiser-Larsen Sea as conjugate Mesozoic basins. The overlap does not have any significance if it is assumed the Mozambique Ridge is younger than 124 Ma, but recent sampling of the central and southern Mozambique Ridge reveals Archean and Precambrian (> 540 Ma) rocks (Mougenot et al., 1991; Ben-Avraham et al., 1995). Therefore, the overlap suggests either deformation in the vicinity of the Mozambique Ridge and/or Dronning Maud land or a different plate boundary configuration between the breakup of Gondwana (~ 160 Ma) and 124 Ma. A likely place for some such deformation or an additional plate boundary is the northern Natal valley.

Whether there is an overlap of the Mozambique Ridge onto Antarctica in the Mesozoic reconstructions has been a matter of controversy attributable to an alternate interpretation of Meosozoic African–Antarctic spreading corridors (e.g. Norton and Sclater, 1979; Lawver et al., 1985; Veevers et al., 1980; Lawver et al., 1991) (e.g. Fig. 2c and d). This alternate interpretation infers that the eastern scarp of the Mozambique Ridge is not conjugate to the Astrid Ridge, although this interpretation is not consistent with the trend of the Andrew Bain fracture zone, or the other fracture zones in the Mozambique Basin and Riiser-Larsen Sea (e.g. Bergh, 1987) (Fig. 1). The only constraints on Mesozoic African–Antarctic finite rotation parameters are from the magnetic anomaly identifications and fracture zones in the Mozambique Basin (Segoufin, 1978; Simpson et al., 1979) and Riiser-Larsen Sea (Bergh, 1977, 1987; Roeser et al., 1996). Some of the magnetics in these areas, particularly in the southern and eastern Riiser-Larsen Sea and eastern Mozambique Basin, are difficult to model.

The overlap of Mozambique Ridge onto Antarctica has largely been unaddressed, particularly as the continental versus oceanic origin of the ridge was previously not known definitively (Maia et al., 1990; Docouré and Bergh, 1992). Martin and Hartnady (1986) considered that the Mozambique Ridge might be a displaced continental fragment, and included an M10N (~ 131.5 Ma) reconstruction in which they have displaced the Mozambique Ridge to the north to alleviate the overlap (Fig. 3a). This scenario implies the existence of an extinct spreading center, which Martin and Hartnady (1986) suggest may exist in the northern Natal valley prior to chron M2 (~ 124 Ma) when the Mozambique Ridge abuts the Antarctic continental shelf in their reconstruction (Fig. 3b).

This paper presents new M11o-M4y (~ 133–126.7 Ma) magnetic anomaly identifications in the northern Natal valley that support the existence of an extinct spreading center. According to our interpretations the spreading center became extinct ~ 125.3 Ma, just prior to chron M2o (~ 124.7 Ma). Spreading in the northern Natal valley accounts for ~ 170 km of motion between the Mozambique Ridge and the African continent. At chron M2 time, the spreading center assumed its current configuration when the Mozambique Ridge became attached to the African plate. Examination of whether the northern Natal valley spreading center is part of African–Antarctic spreading reveals that the spreading rates are different, strictly that the rates cannot be satisfied by a two-plate motion model, and therefore that different finite rotations are required for the extinct spreading center. This implies that the Mozambique Ridge was an independent microplate prior to 125.3 Ma.

The extinct spreading center we propose is not sufficient to resolve all of the overlap of the Mozambique Ridge onto the Dronning Maud land margin of Antarctica prior to M11 predicted in the M21 reconstruction using the Segoufin and Patriat (1981) finite rotation parameters. But as we establish that the Mozambique Ridge was an independent microplate from 125 to 133 Ma, it is not likely that the Africa–Antarctica finite rotation parameters would apply to the Mozambique Ridge prior to 133 Ma (chron M11). More significant revision of the plate tectonics, which would include the Mozambique Ridge as a microplate prior to chron M11, may be called for to resolve the remaining overlap that cannot be resolved in accounting for Jurassic deformation of Dronning Maud land, Antarctica and the continental Mozambique Basin of Africa.

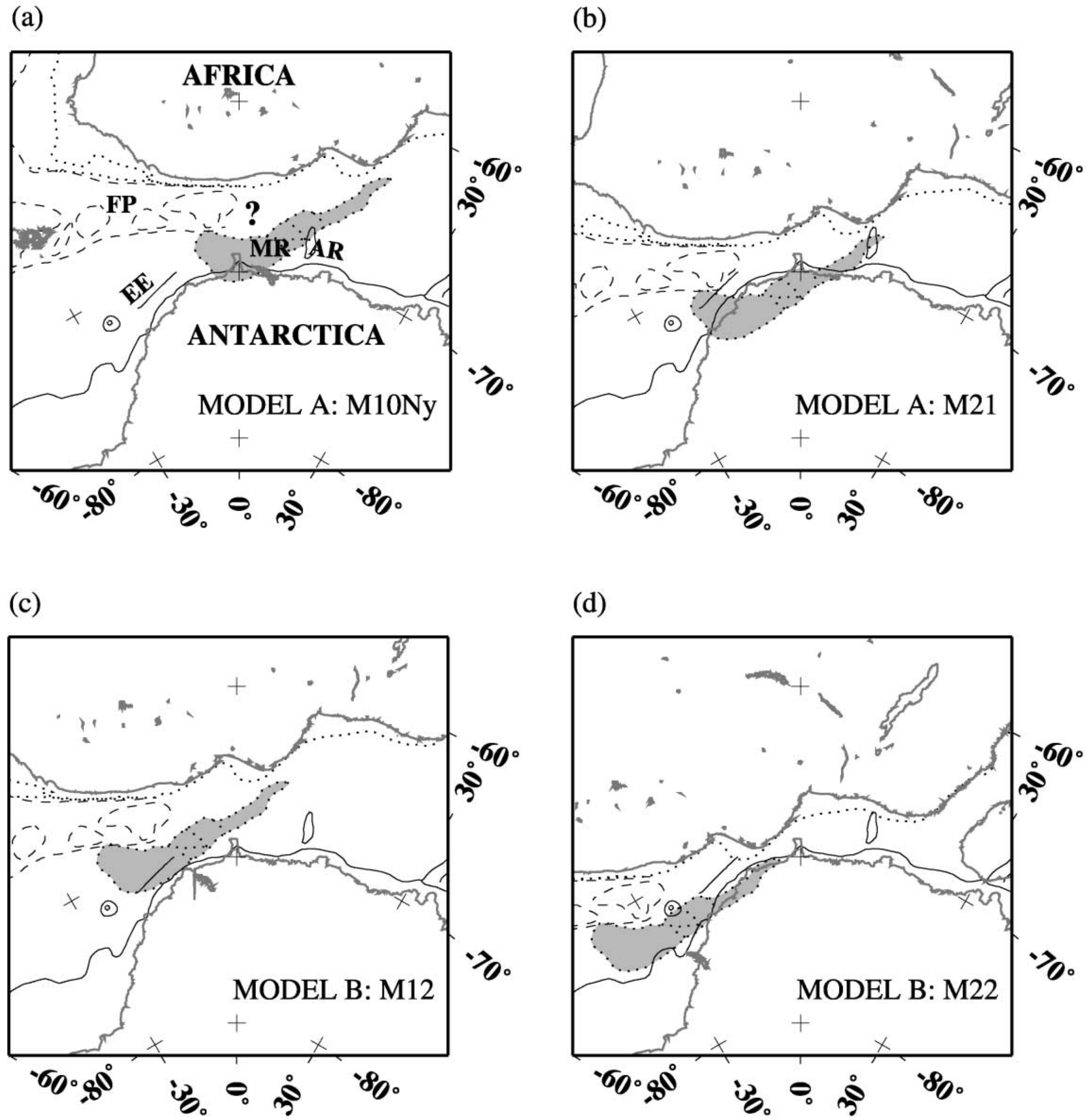


Fig. 2. Four Mesozoic reconstructions of the Mozambique Ridge (MR), Africa, Antarctica, and the Falkland Plateau (FP)/South America illustrating two different tectonic models. [Also shown are the Astrid Ridge (AR) and the Explora Escarpment (EE)]. The Mozambique Ridge and African continental shelves are the dotted lines; the Falkland Plateau and South American continental shelves are dashed lines; the Antarctica continental shelves are solid lines. All the continental shelves and tectonic features have been interpreted/digitized from the satellite-derived free-air gravity field of Sandwell and Smith (1997). (a) Model A: M10Ny reconstruction. This reconstruction uses the finite rotation parameters of Martin et al. (1982) for South America–Africa and those of R.A. Livermore (2000, personal communication—see Table 1) for Africa–Antarctica. (b) Model A: M21 reconstruction. This reconstruction uses the finite rotation parameters of Martin et al. (1982) [M10] for South America–Africa and those of Segoufin and Patriat (1981) for Africa–Antarctica. (c) Model B: M12 reconstruction. This reconstruction uses the finite rotation parameters of Rabinowitz and LaBrecque (1979) for South America–Africa and Norton and Sclater (1979) for Africa–Antarctica. (d) Model B: M22 reconstruction. This reconstruction uses the finite rotation parameters of Rabinowitz and LaBrecque (1979) [M12] for South America–Africa and Norton and Sclater (1979) for Africa–Antarctica.

2. The northern Natal valley

The northern Natal valley (Fig. 4a and b), north of ~ 29°S, is bound by the northern Mozambique Ridge to the east, the Naude Ridge to the south, the Almirante Leite Ridge and the Mozambique Basin to the north and west (e.g. Dingle et al., 1978). The South African Lebombo monocline, draped by Jurassic Karoo volcanics, bounds the Mozambique Basin to the west. We also note that in the free-air gravity field there are at least six well-defined gravity low lineaments in the eastern end of the northern Natal valley that are concave with respect to the continental margin (Fig. 4b).

These lineaments appear to be tectonic escarpments possibly related to the Pliocene extension of the western branch of the East African Rift (Fig. 5). These escarpments/faults are fit well by small circles about a pole at 31.75°E, 22.25°S (Fig. 4b). This pole is near the border of the 95% confidence ellipsoid of the 36.2°E, 27.3°S Somalia–Nubia present-day pole (averaged over the last 3.2 Ma from the middle of chron 2A) given by Chu and Gordon (1997) (Fig. 4b). It is also within the area of acceptable Somalia–Nubia poles determined by Jestin et al. (1994) although far from their "best-fit" pole at 143.5°E, 61.1°S. Although there is some seismicity in the vicinity of the escarpments (Fig. 4b), there is no age control on the activity of the escarpments themselves. Nonetheless, it does appear that these free-air gravity lineaments may be indicators of Pliocene activity on the western branch of the East African Rift that disrupted the older Mesozoic crust in the northeastern Natal valley. This interpretation is speculative as the extension of the western branch of the East African Rift south of Lake Malawi (Fig. 5) is not well known. It is not clear whether the rift terminates at the Zambezi transform fault (south of Lake Malawi) or whether is continues along the Urema and Dombe troughs (as indicated on Fig. 5) (e.g. Chorowicz, 1983). A potentially analogous situation for what we propose is the extension of the eastern branch of the East African Rift into oceanic crust. In this case, the rift extends along a reactivated portion of a Mesozoic fracture zone, the Davie Ridge (Fig. 1) (Mougenot et al., 1986).

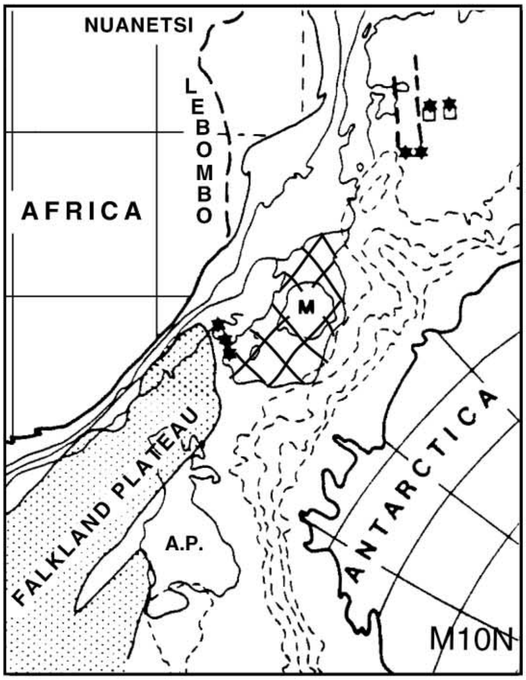
The oldest interpreted seismic sedimentary unit in the northern Natal valley, McDuff, is estimated to be Cenomian–Turonian (Dingle et al., 1978) (~ 93.5 Ma on the Gradstein et al. (1994) timescale). Basement rock has not been sampled in the northern Natal valley, and it is not conclusively known to be either oceanic or continental in origin. The central valley is overlain by the Tugela Cone and Limpopo Cone in the west and northwest, respectively (Fig. 4a), with sediment thicknesses in these regions reaching up to 4900 m (Dingle et al., 1978). Dingle and Scrutton (1974) postulated that the northern Natal valley is underlain by thinned continental crust, based on estimates of intermediate thickness (~ 20 km) crust (e.g. Daracott, 1974).

Green (1972) suggested an oceanic origin for the northern Natal valley based on the interpretation of the northern Mozambique Ridge as a N–S spreading center and seismic refraction results (Ludwig et al., 1968), but this is inconsistent with the interpretation of the E–W trending Mesozoic magnetic anomaly lineations in the Mozambique Basin (Segoufin, 1978; Simpson et al., 1979). Isostatic analysis of the Mozambique Ridge has also been interpreted as indicating an "on-ridge" origin (Maia et al., 1990). This result was interpreted as implying anomalous volcanism on presumably the easternmost segment of the proposed E–W extinct spreading ridge in the northern Natal valley (Martin and Hartnady, 1986) between M10N and M2 to form the northern Mozambique Ridge. This later interpretation would also imply the northern Natal valley is underlain by oceanic crust. This interpretation may be valid, but only for the northern Mozambique Ridge. Dredges DR1, DR3, and DRQ (Fig. 4a), on the central and southern Mozambique Ridge (discussed in detail below), are of continental affinity and not consistent with an "on-ridge" origin. We interpret an oceanic origin for the northern Natal valley based on an identification of seafloor-spreading magnetic anomalies.

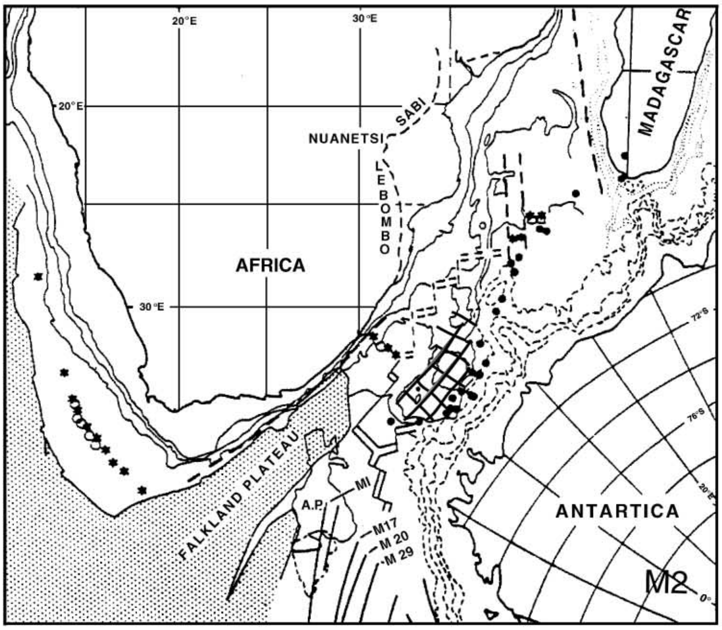
3. The Mozambique Ridge

The Mozambique Ridge is wider (~ 350 km) near its southern end, ~ 35°S, narrowing to the north (~ 50 km) at ~ 24°S. As seen in the free-air gravity field, there are distinct northern, central, and southern domains (Fig. 4b). The eastern scarp of the Mozambique Ridge is coincident with the Andrew Bain fracture zone that bounds the Mozambique Basin on

(a)


NUANETSI
LEBOMBO
AFRICA
M
FALKLAND PLATEAU
A.P.
ANTARCTICA
M10N

(b)


20°E
30°E
20°E
30°E
MADAGASCAR
SABI
NUANETSI
LEBOMBO
AFRICA
FALKLAND PLATEAU
A.P.
MI
M17
M 20
M 29
72°S
76°S
ANTARTICA
M2

the west. There is evidence for a continental origin for the southern and central domains of the Mozambique Ridge (Mougenot et al., 1991; Ben-Avraham et al., 1995), but none for the northern domain.

Three dredges provide evidence for a continental core of the southern and central Mozambique Ridge (Mougenot et al., 1991; Ben-Avraham et al., 1995). Dredge DR1 (Fig. 4a and b), on the southwestern margin of the ridge, obtained on the R/V Marion Dufresne (MD60-MACAMO) in February 1986, bore kinzigites (amphibolite facies metapelites) with garnet and sillimanite inclusions (Mougenot et al., 1991) that the authors correlate with a Precambrian orogeny in South Africa. Fragments of Archean basement, cited as being similar in composition to the Rhodesian craton, were collected from DR3 on the northeastern margin of the ridge, obtained on the same cruise (Mougenot et al., 1991). Dredge DRQ (Fig. 4a and b) on the southwestern tip of southern Mozambique Ridge, collected on the R/V Professor Logachev in 1991, recovered a metamorphic rock including a garnet-bearing metapelite correlated to the Natal Belt in South Africa (Ben-Avraham et al., 1995). The history of the Mozambique Ridge though is more complicated than these three dredges alone may indicate.

There is also petrologic evidence for subsequent emplacement of basaltic rocks on the Mozambique Ridge in the Jurassic, Cretaceous and much more recently in the Quaternary/Pliocene. Dredge DR2 (Fig. 4a and b) on the eastern margin of the southern Mozambique Ridge yielded tholeiitic basalts compositionally similar to Jurassic age Karroo basalts on the South African continent (Mougenot et al., 1991). Deep Sea Drilling Project (DSDP) site 249 on the central Mozambique Ridge (Fig. 4a and b) bottomed out 3 m into weathered basalt overlain by silty claystone-bearing volcanic ash dated as early Cenomanian to Late Aptian (~ 112–99 Ma) in the Early Cretaceous (Simpson et al., 1974). Major and trace element analyses of the basement rock are compositionally similar to weathered mid-ocean ridge (MOR) tholeiites (Erlank and Reid, 1974; Thompson et al., 1982). Dredge DRQ on the southwestern end of the ridge yielded fresh volcanic glass (in addition to the aforementioned metamorphic rock) (Ben-Avraham et al., 1995).

Seismic reflection data from the Mozambique Ridge helps further constrain the tectonics. Mougenot et al. (1991) present a synthesis of predominantly E–W to SE–NW trending grabens and half grabens on the Mozambique Ridge indicative of approximately N–S extension of the ridge in the Early Cretaceous. This extension would be roughly contemporaneous with the emplacement of the basalt at DSDP site 249 and the seafloor spreading in the northern Natal valley that we present.

There is also supporting evidence for young basaltic intrusions into Oligocene and Miocene sedimentary units from seismic reflection data on the southern Mozambique Ridge which is suggestive of deformation within the last few thousand years (Ben-Avraham et al., 1995). Ben-Avraham et al. (1995) relate the neotectonic activity on the Mozambique Ridge to that on the Aghulas Plateau and attribute both to lithospheric breakup caused by the thermal effects of the African Superswell (e.g. Nyblade and Robinson, 1994) and/or the diffuse extension of the Somalia/Nubia plate boundary south of the East African Rift (e.g. Hartnady, 1990; Jestin et al., 1994; Chu and Gordon, 1997).

4. Previous reconstructions

The magnetic anomaly constraints on the Martin and Hartnady (1986) Africa–Antarctica Mesozoic reconstructions are conjugate M0-M22 identifications in the Mozambique Basin (Segoufin, 1978; Simpson

Fig. 3. Two Mesozoic reconstructions (Africa held fixed) from Martin and Hartnady (1986) with similar tectonic elements as in Fig. 2. (a) M10N reconstruction with the Mozambique Ridge held fixed to the Antarctic plate between M2 and M10N. (b) M2 reconstruction with a proposed extinct spreading center in the northern Natal Valley, and active spreading center about the proto-Bouvet triple junction. Antarctic bathymetric contours are dashed lines; bathymetric contours for Africa, the Mozambique Ridge (M) [hatched area] and Agulhas Plateau (AP) are solid lines; bathymetric contours for Madagascar are dotted lines. Bold dashed lines are fracture zones; dots are half-rotated epicenters; stars are anomaly identifications on the African plate; open squares are anomaly identifications on the Antarctic plate (rotated to the African plate); open circles are anomaly identifications on the South American plate (rotated to the African plate). Solid lines west of Antarctica are lineated magnetic anomalies in the eastern Weddell Sea (from LaBrecque and Barker (1981), which are considered by Martin and Hartnady (1986) to be incorrect).

et al., 1979) and the Riiser-Larsen Sea off Dronning Maud land (Bergh, 1977). These reconstructions align the eastern scarp of the Mozambique Ridge with the Astrid Ridge off Dronning Maud land. Roeser et al. (1996) present and interpret additional Mesozoic magnetic anomaly data from the Dronning Maud land margin of Antarctica. Livermore and Hunter (1996) present Mesozoic finite rotation parameters, which include the Roeser et al. (1996) identifications and match up corridors of spreading in the Mozambique Basin with the Riiser-Larsen Sea identifications similar to Bergh (1987). This interpretation includes an additional corridor on the western end of the Mozambique Basin that Martin and Hartnady (1986) did not recognize.

Some reconstructions align or overlap the eastern scarp of the Mozambique Ridge with the Explora Escarpment (EE) in the northeastern Weddell Sea (Norton and Sclater, 1979; Lawver et al., 1985, 1991; Veevers et al., 1980) (Fig. 2c and d). These reconstructions *do not* create any overlap of the Mozambique Ridge onto Antarctica. Such a configuration implies that the Mesozoic magnetic anomaly identifications in the western Mozambique Basin have conjugates in the spreading corridor between the Maud Rise and the Astrid Ridge (Fig. 1), although none have been identified where such models predict. These models have not been conclusively shown to be implausible based on magnetic anomaly constraints due partly to lack of sufficient data. This configuration is also not consistent with the fracture zone trends between the Discover II fracture zone and the Andrew Bain fracture zone (Fig. 1) (e.g. Bergh, 1987; Marks and Tikku, 2001). Significant (~ 500 km) westward displacement of Africa and the Mozambique Ridge with respect to Antarctica is required to reconcile the mid-Mesozoic reconstructions based on an updated M10Ny pole of Livermore and Hunter (1996) (R.A. Livermore, 2000, personal communication) and the M12 pole extrapolated from Norton and Sclater (1979) in the reconstructions of Lawver et al. (1985) (Fig. 2). Strong evidence contrary to the interpretation of the Explora Escarpment as a sheared margin conjugate to the eastern Mozambique Ridge comes from seismic interpretations of seaward-dipping seismic reflectors off the Explora Escarpment indicative of a rifted margin (e.g. Kristoffersen and Haugland, 1986; Jokat et al., 1996)

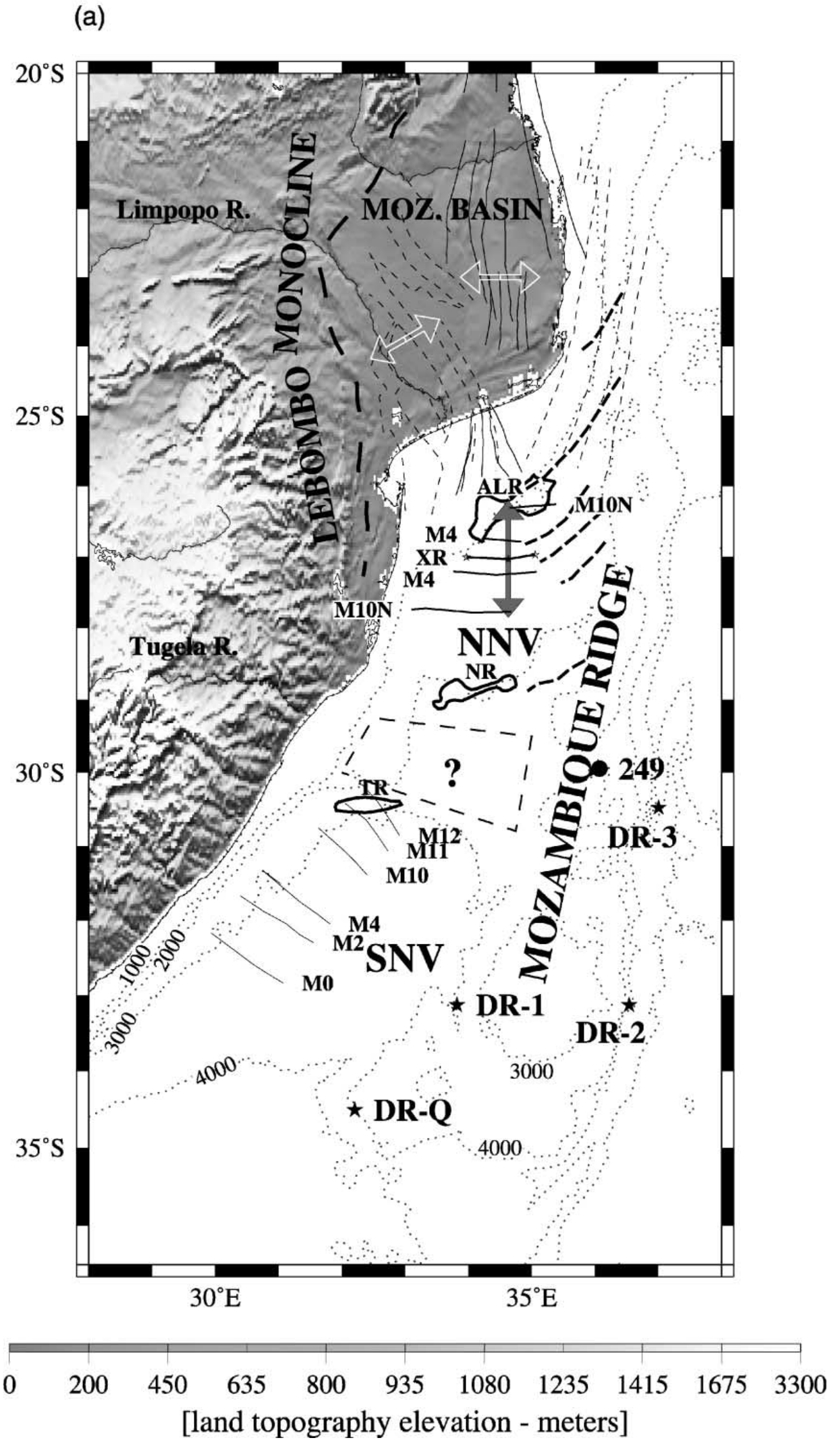
The Segoufin and Patriat (1981), Martin and Hartnady (1986) and Lawver et al. (1991, 1998) 160–200 Ma Africa–Antarctica reconstructions are all consistent with the more general geological constraints which juxtaposition southeast Africa and Dronning Maud land from correlating Archean and mid-Proterozoic age cratons (Groenewald et al., 1991).

The continental nature of the Mozambique Ridge and the pronounced overlap of the ridge onto Dronning Maud land in the Mesozoic reconstructions prior to chron M2 strongly suggest Mesozoic spreading in the northern Natal valley.

5. Seafloor spreading in the northern Natal valley

We have identified a Mesozoic magnetic anomaly sequence and an extinct spreading center in the north-

Fig. 4. Topography and satellite-derived free-air gravity field maps of Southeastern Africa, the Natal Valley and the Mozambique Ridge. (a) Topography map, which merges the GTOPO30 digital elevation model land topography from the USGS at a 2-min-grid interval (see http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html) and 1-km bathymetric contours in the Southwest Indian Ocean from Fisher (1997). Superimposed on the topography are the Mesozoic isochrons in the southern Natal Valley [SNV] (Goodlad et al., 1982) and the northern Natal Valley [NNV] presented in this paper. Also included in the map are key structural features, namely, the Lebombo Monocline, Jurassic rift structures in the continental Mozambique sedimentary basin from Nairn et al. (1991) [dashed lines] and Salman and Abdula (1995) [solid lines], subsurface topographic features: the Almirante Leite Ridge (ALR) and the Naude Ridge (NR) from Dingle et al. (1978), and the Tugela Ridge (TR) from Goodlad et al. (1982), and tectonic escarpments observed in the free-air gravity field of the northeastern Natal Valley [thick black lines with white dots]. DSDP site 249 (Simpson et al., 1974) is denoted by a circle symbol; dredges DR1-DR3 (Mougenot et al., 1991) and DRQ (Ben-Avraham et al., 1995) are stars. (b) Satellite-derived free-air gravity field (Sandwell and Smith, 1997) map, which includes the continental gravity field. Superimposed on the gravity field are the isochrons and tectonic escarpments in the northeastern Natal Valley [thick white lines with black crosses]. Also included are the earthquakes from 1909 to 1997 extracted from the International Seismological Centre (ISC) online catalogue (see http://www.isc.ac.uk) [small white circles]. The pole at 31.75°E, 22.25°S [white diamond] and its associated small circles [dotted white lines] fit the observed tectonic escarpments in the northeastern Natal Valley. The Nubia–Somalia present day finite rotation pole of Chu and Gordon (1997) [grey star] is plotted for comparison.


(a)
20°S
25°S
30°S
35°S
30°E
35°E
Limpopo R.
LEBOMBO MONOCLINE
MOZ. BASIN
ALR
M10N
M4
XR
M4
M10N
NNV
Tugela R.
NR
MOZAMBIQUE RIDGE
?
249
TR
DR-3
M12
M11
M10
M4
M2
SNV
M0
1000
2000
3000
DR-1
DR-2
3000
4000
DR-Q
4000
0
200
450
635
800
935
1080
1235
1415
1675
3300
[land topography elevation - meters]

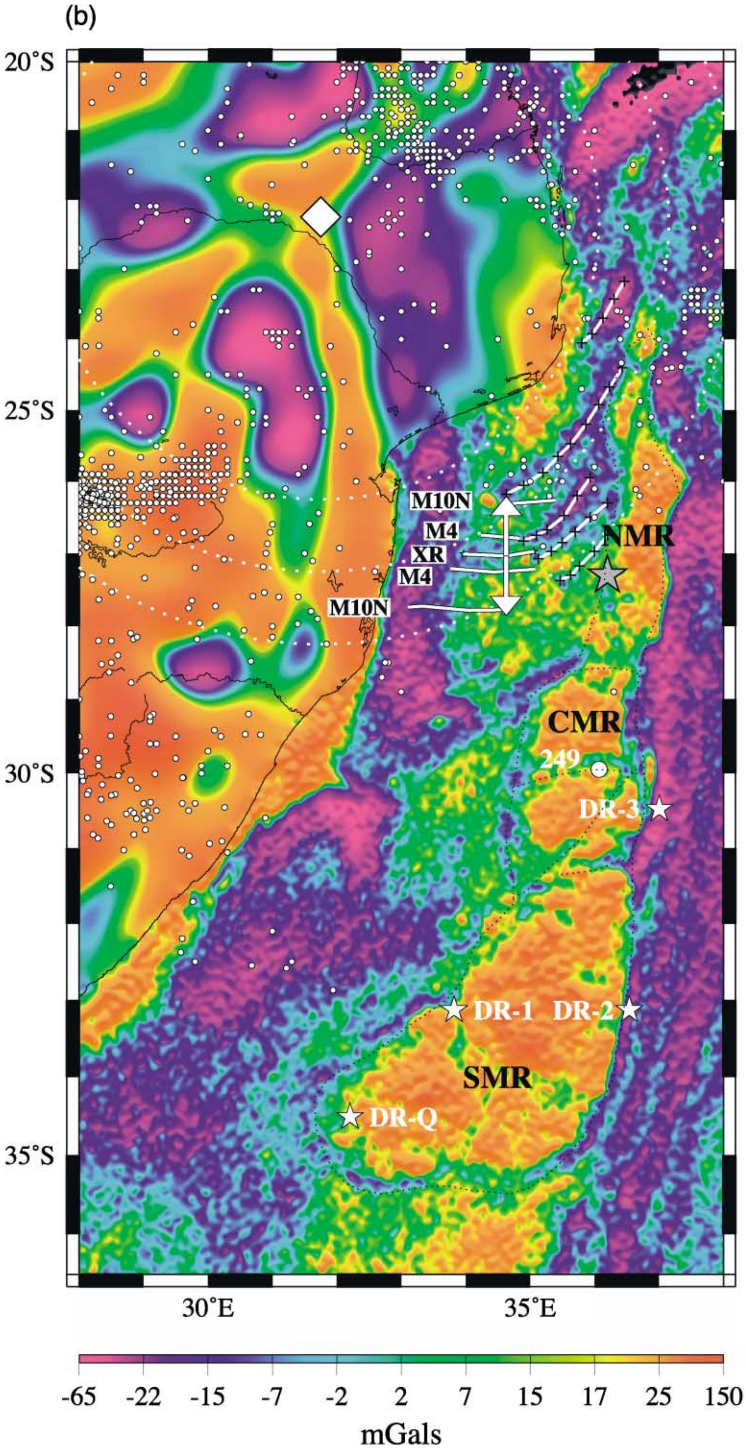


Fig. 4 (*continued*).

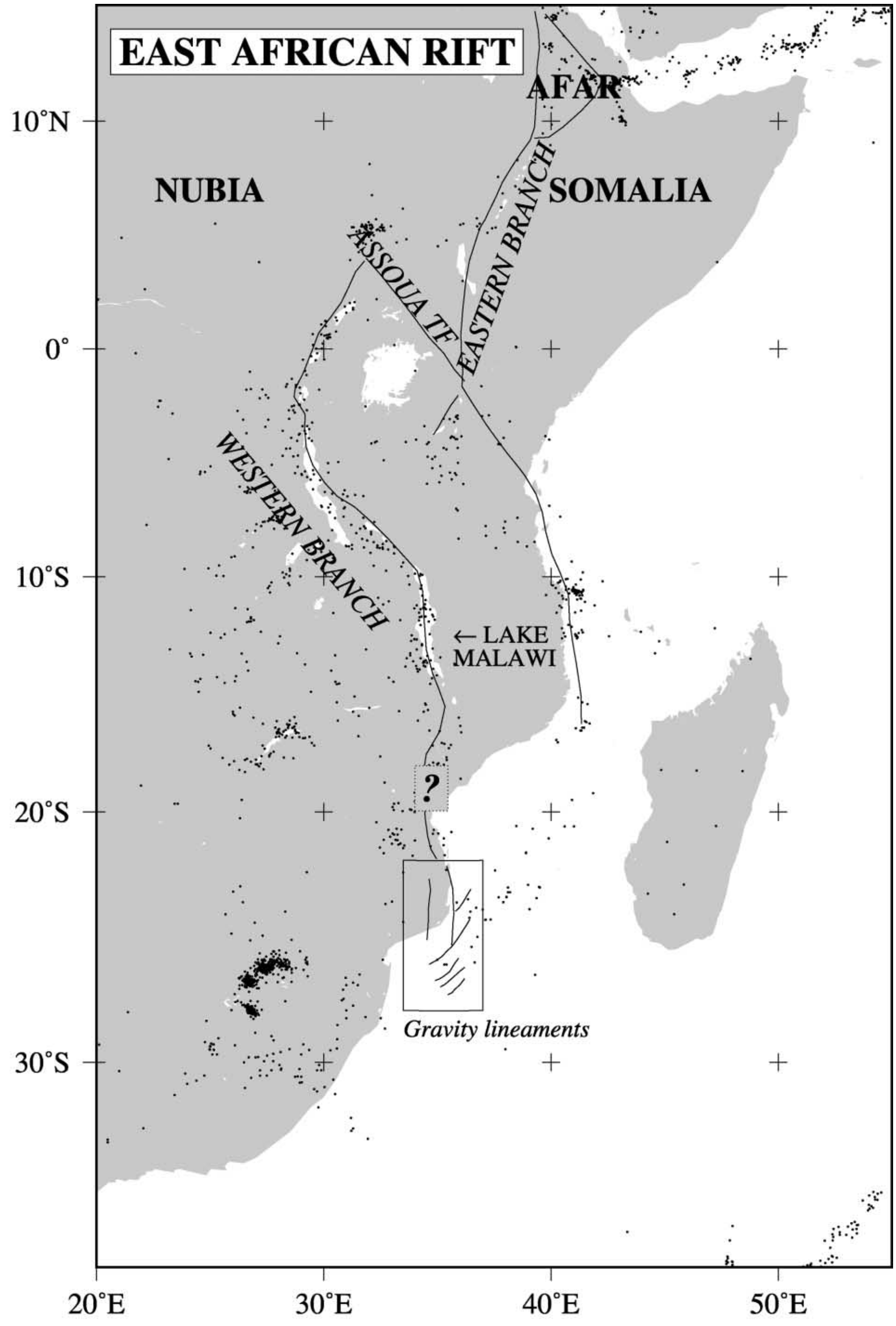


Fig. 5. The East African Rift. The location of the East African Rift structural features is from Mougenot et al. (1986), which was interpreted from Chorowicz (1983). The earthquakes [black dots], from 1973 to 1999, are extracted from the USGS National Earthquake Information Center (NEIC) online earthquake catalogue (see http://wwwneic.cr.usgs.gov). The gravity free-air lineaments in the northern Natal Valley (boxed area) are identified in Fig. 4b.

ern Natal valley from an examination of shipboard magnetic anomalies in the NOAA-National Geophysical Data Center database (NGDC, 1998). There is symmetry in the N–S shipboard magnetic anomaly profiles in the northern Natal valley about a latitude of 27°S (from 26°S to 28°S) between 32.5°E and 35.5°E (Figs. 6 and 7). The profiles which best display a symmetry are profiles A, B, and C from the southern flank, and profiles C and D from the northern flank. The northern flank of profile F looks similar to profiles C and D with the exception of a large positive step in the magnetics at ~26.75°S. The large step in the magnetics on the northern flank of the extinct spreading center in profile F is coincident with one of the curved gravity lineaments in the eastern end of the northern Natal valley (Fig. 4b) and may indicate an offset due to a younger tectonic escarpment. The sediments are thicker and show more fine-scale topographic structure in the northern Natal valley compared to the south due to the influence of the Limpopo Cone (Fig. 4a and b), which obfuscates any topographic expression of the extinct spreading center. Profiles D, E, and F are noisy, particularly on the southern flank of the ridge (Figs. 6 and 7a). The noise is likely due to the signal from remanent sedimentary magnetization and possibly alteration of the crustal magnetization and influence of post-Mesozoic tectonics on the Mesozoic seafloor-spreading magnetic signal.

The northern Natal valley extinct spreading center appears to have been continuous to the east of the northern Mozambique Ridge at chron M10N (Fig. 6) with the westernmost spreading corridor in the Mozambique Basin. However, the spreading rate in the northern Natal valley was much slower than in the Mozambique Basin. This is evident in the more southerly identification of chron M4 in the western Mozambique Basin versus the northern Natal valley (Fig. 6).

The magnetic anomalies in profiles A–F can be modeled with a half-spreading rate of ~13 mm/year from chron M11o (133.0 Ma) to 125.3 Ma, just prior to chron M2o (124.7 Ma) (Fig. 7a). The most easily identifiable anomalies are chrons M4 and M10N. This spreading rate is similar to that in the other basins (~13–17 mm/year) along the eastern margin of Africa recording M22-M0 extension (i.e. the Somali Basin (Segoufin and Patriat, 1980; Rabinowitz et al., 1983; Cochran, 1988), and the conjugate Mozambique Basin (Segoufin, 1978; Simpson et al., 1979) and Riiser-Larsen Sea (Bergh, 1977, 1987; Roeser et al., 1996). The time of initiation and spreading rate are also similar to the adjacent M11-M0 Africa–South America 15 mm/year spreading in the conjugate Georgia Basin (LaBrecque and Hayes, 1979) and southern Natal valley (Goodlad et al., 1982). The coincidence in the time of initiation and spreading rate with the southern Natal valley is compelling evidence for the proposed spreading in the northern Natal valley. In addition, the Early Cretaceous age of the oceanic crust in the northern Natal valley is consistent with the Late Cretaceous age of the oldest seismic sedimentary reflector in the valley (Dingle et al., 1978).

There is only a very small free-air gravity anomaly, on the order of several mGals, that may be associated with the proposed extinct spreading center [e.g. Profile D] (Fig. 7a). The lack of a pronounced expression of the extinct spreading center in the free-air gravity may be due to the combined effect of a thick sediment cover (e.g. Dingle et al., 1978), the old thermal age of the seafloor, and possible uplift and thermal rejuvenation of the general region attributed by some (Hartnady et al., 1992; Ben-Avraham et al., 1995) to the African Superswell (Nyblade and Robinson, 1994). The extinct ridge in the Somali basin, which is similarly heavily sedimented, likewise does not have a pronounced expression in places (e.g. Cochran, 1988). The most prominent gravity anomaly in the northern Natal valley is south of the identification of M11o, 28.5°S, on the southern flank of the extinct spreading center (Fig. 7). This gravity anomaly is associated with a step from the central terrace to the southern Natal valley roughly coincident with the Naude Ridge.

6. Finite rotation poles

We have extrapolated stage poles for Africa–Antarctica relative motion between 125.3 Ma (age of the extinct ridge) and M10Ny from the poles of Bergh (1987)/R.A. Livermore (2000, personal communication), which is a slight revision of the Livermore and Hunter (1996) poles (Table 1). These stage poles overrotate the identification of M10Ny from the southern to

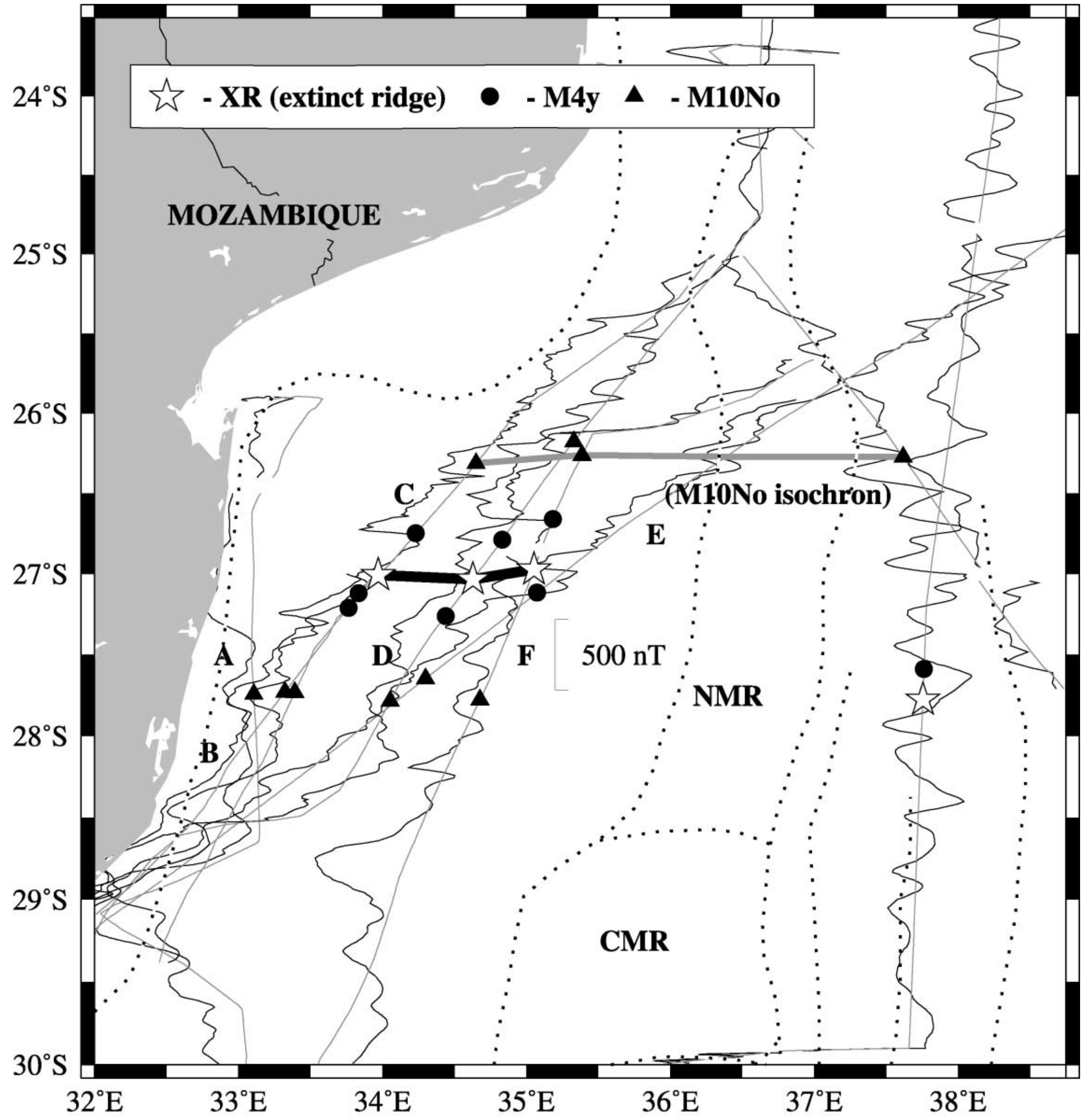


Fig. 6. Shipboard magnetic anomaly data in the northern Natal Valley and western oceanic Mozambique Basin projected at an azimuth of N270°E. The magnetic data are from the archived database at the NOAA National Geophysical Data Center (NGDC, 1998). Superimposed on the magnetics are the identifications of the extinct ridge [stars], chron M4y [circles] and chron M10No [triangles]. The African continental shelf and both the northern and central Mozambique Ridge (NMR and CMR) outlines [dotted lines] are identical to Fig. 2. Fracture zones in the oceanic Mozambique Basin (interpreted from the free-air gravity field) are also indicated as dotted lines.

the northern flank of the extinct spreading center by ~ 60–70 km (Fig. 8). This implies that the Mozambique Ridge was not fixed with respect to the Antarctic plate between M11 and 125.3 Ma, analogous to Madagascar during the opening of the Somali Basin, but rather behaved as an independent microplate.

We have derived a Mozambique–Africa stage pole that fits the M10Ny anomaly identifications in the northern Natal valley (Fig. 8 and Table 1). Adding this stage pole to the M10Ny Africa–Antarctica pole of R.A. Livermore (2000, personal communication) yields a new Mozambique–Antarctica finite rotation pole. Using this new pole to correct the location of the Mozambique Ridge solves the overlap of the Mozambique Ridge onto the Antarctic continent for chron M10Ny (Fig. 9). The extinct spreading center in the northern Natal valley is thus able to reconcile the geological constraints on the continental origin of the Mozambique Ridge with reconstructions of Africa, Antarctica, and the Mozambique Ridge.

7. Northern Natal valley ridge configuration

The ridge configuration and triple junction required to accommodate the extinct spreading center that we propose is somewhat different from that suggested by Martin and Hartnady (1986). Their proposed ridge was not based on any magnetic anomaly identifications. Whereas Martin and Hartnady (1986) imply that the southern and central Mozambique Ridge were attached to Antarctica, our magnetic anomaly identifications suggest that the Mozambique Ridge was actually an independent microplate. They also show an unstable ridge-ridge-fault triple junction solution for the extinct ridge hypothesis involving South America–Africa–Antarctica (Fig. 3b). Their proposed extinct Africa–Antarctic ridge in the Natal valley is left-stepping and connects the Mozambique Basin/Riiser-Larsen ridge with the southern Natal valley/Georgia Basin ridge. They show four spreading segments on the extinct ridge. The westernmost transform fault is approximately aligned with the Lebombo monocline. The extinct ridge we identify in the northern Natal valley consists of only one E–W segment at 27°S.

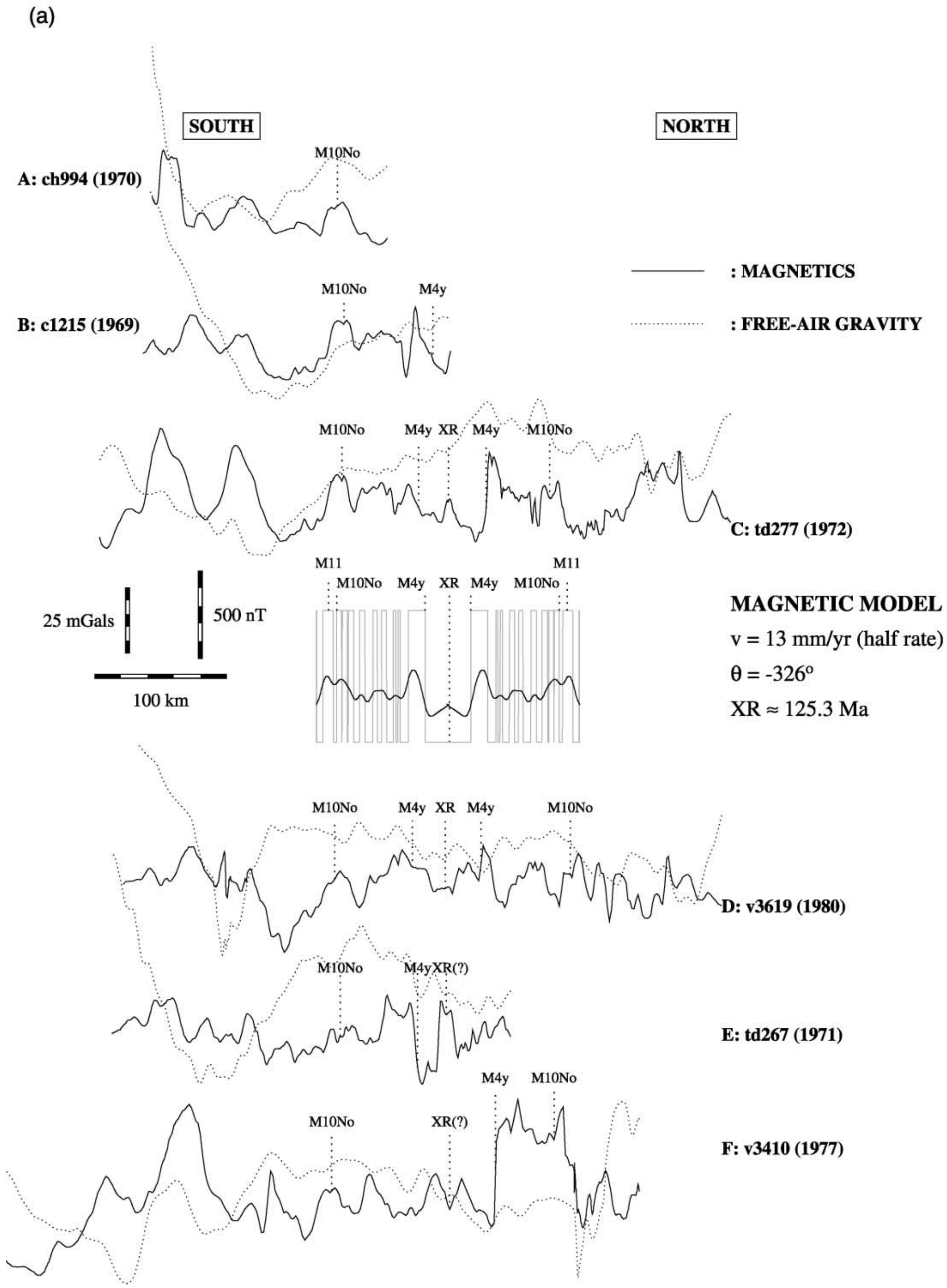
We agree with the interpretation of a continuous spreading segment across the northern Mozambique Ridge connecting the northern Natal valley to the Mozambique Basin as suggested by Martin and Hartnady (1986) (Fig. 3b). If the spreading center was continuous across the northern Mozambique Ridge, it implies that this portion of the ridge is either a product of excess volcanism on a N–S-oriented spreading center, as suggested previously (Maia et al., 1990), or, alternatively, that the northern Mozambique Ridge was formed after the northern Natal valley spreading center became extinct.

Our interpretation differs from Martin and Hartnady (1986) in that the northwestern end of the southern Natal valley/Georgia Basin is connected to the northern Natal valley spreading center via a transform fault (Fig. 10a) along the southeastern African continental margin at chron M10N. This would result in a stable ridge–fault–fault triple junction with the Agulhas/Falkland transform fault. It would also imply that the southern Natal valley/Georgia Basin is a segment of South America–Mozambique rather than South America–Africa seafloor spreading. We also show an active Mozambique–Antarctica plate boundary for chron M10N (Fig. 10a). After the northern Natal valley ridge is abandoned ~ 125 Ma, the Mozambique plate becomes part of the African plate and the Mozambique–Antarctica spreading center south of the Mozambique Ridge becomes an Africa–Antarctica spreading center segment (Fig. 10b) as in the present-day configuration.

8. Pre-chron M11 reconstructions

Even when the extinct spreading center in the northern Natal valley is accounted for, there are still

Fig. 7. (a): A seafloor-spreading rate model for the northern Natal Valley. Magnetic anomalies identified on the model and profiles A–F (Fig. 6) are chrons M4y and M10No. The observed profiles have been projected at an azimuth of N0°E. The synthetic magnetic anomaly profile is derived from the following model input parameters: top of magnetic source layer is 6 km, bottom of magnetic source layer = 6.5 km, (remanent inclination) Ir = − 69.25°, (remanent declination) Dr = 3.66°. Also included are the free-air gravity profiles for the projected profiles extracted from the satellite-derived field (Sandwell and Smith, 1997). (b): Select projected bathymetric profiles from the northern Natal Valley. Profiles C, D and F are extracted from the NGDC database (NGDC, 1998) and projected at an azimuth of N0°E. The bathymetry is dominated by the Limpopo cone, which tapers out to the south. The extent of seafloor spreading is shown for comparison with the magnetic anomaly profiles identical to (a).


(a)
SOUTH
NORTH
A: ch994 (1970)
M10No
B: c1215 (1969)
M10No
M4y
: MAGNETICS
: FREE-AIR GRAVITY
M10No
M4y
XR
M4y
M10No
C: td277 (1972)
M11
M10No
M4y
XR
M4y
M10No
M11
25 mGals
500 nT
100 km
MAGNETIC MODEL
v = 13 mm/yr (half rate)
θ = -326°
XR ≈ 125.3 Ma
M10No
M4y
XR
M4y
M10No
D: v3619 (1980)
M10No
M4yXR(?)
E: td267 (1971)
M4y
M10No
M10No
XR(?)
F: v3410 (1977)

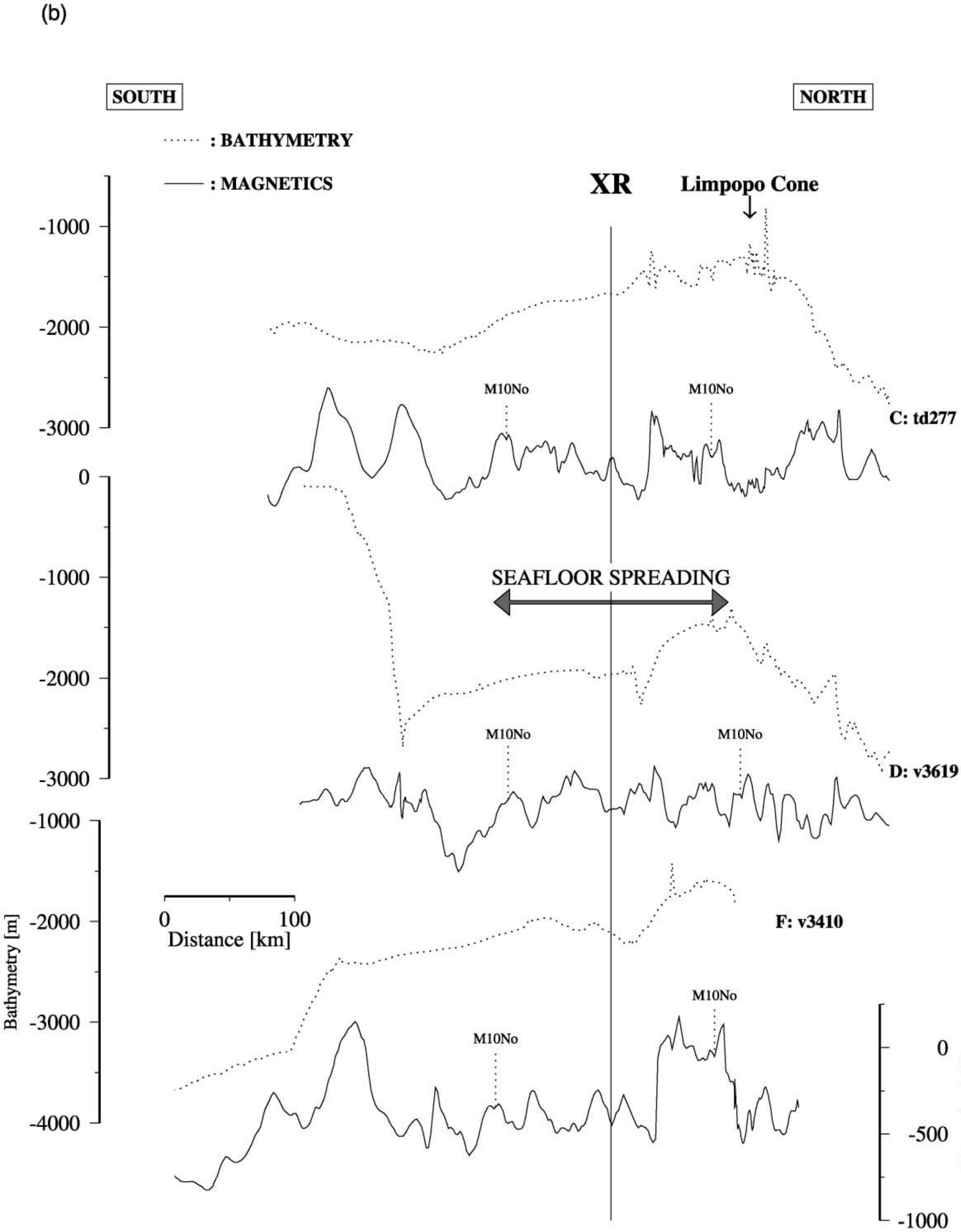


Fig. 7 (*continued*).

Table 1
Mesozoic finite rotations of relative plate motion of Antarctica, Africa and the Mozambique Ridge

Anomaly	Age (Ma)	Latitude (°N)	Longitude (°E)	Angle (°)	Source
M2 (ANT-AFR)	124.39	− 9.5	− 27.6	43.04	1/2
M10Ny (ANT-AFR)	130.87	− 8.8	− 29.1	46.27	2
M10Ny (ANT-AFR)	130.87	− 8.9	− 28.8	45.52	3
M21 (ANT-AFR)	147.23	− 7.22	− 31.12	50.20	4/2
XR (ANT-AFR)	125.31	− 9.41	− 27.78	43.39	1/2 and 3
XR-M10Ny (ANT-AFR)		− 6.76	− 50.26	2.29	1/2 and 3
XR-M10Ny (MOZ-AFR)		− 6.0	− 50.0	1.45	5
M10Ny (MOZ-ANT)	125.31	− 9.24	− 28.18	47.17	3 and 5

Note: All ages are with reference to the Mesozoic timescale of Gradstein et al. (1994). 1—Bergh (1987); 2—Livermore and Hunter (1996); 3—R.A. Livermore (2000, personal communication); 4—Segoufin and Patriat (1981); 5—this paper.

overlap problems of the Mozambique Ridge onto Antarctica in the pre-M11 reconstructions, such as the chron M21 reconstruction using the finite rotation parameters of Segoufin and Patriat (1981) (Fig. 11 and Table 1). We consider three cases for the Mozambique Ridge. In the first case, the Mozambique Ridge is part of the African plate and yields significant overlap onto Antarctica even when accounting for seafloor spreading in the northern Natal valley (Fig. 11a). In the second case, the

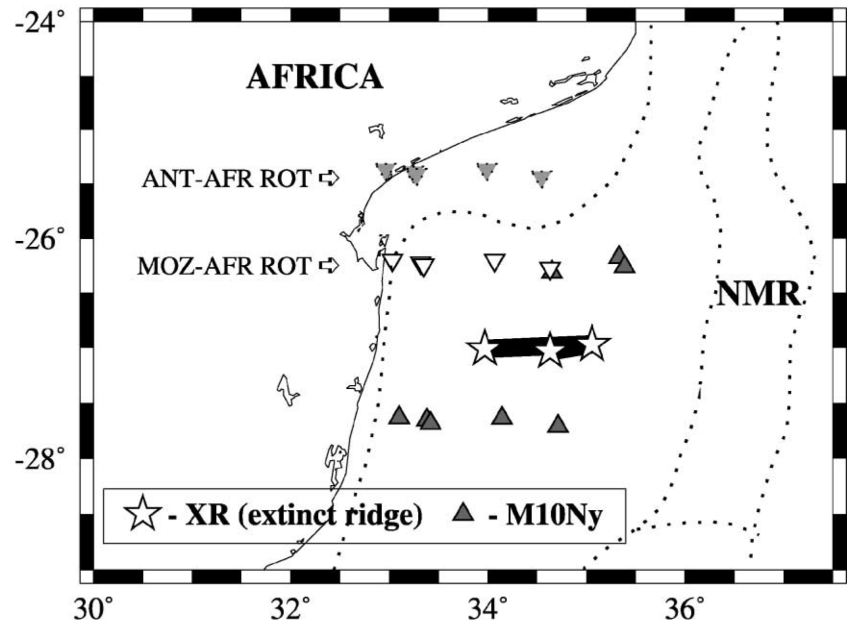


Fig. 8. Fit of the magnetic anomalies in the northern Natal Valley. The M10Ny picks [dark grey fill triangles] from the southern flank of the extinct ridge are rotated to the northern flank (Africa) with the stagepole derived using the ANT-AFR rotation parameters of Bergh (1987)/Livermore and Hunter (1996) and R.A. Livermore (2000, personal communication) [dotted light grey fill inverted triangles] and the new MOZ-AFR stagepole derived in this paper [solid white fill inverted triangles] (see Table 1). The outline of the African continental shelf and the northern Mozambique Ridge (NMR) are identical to Fig. 2.

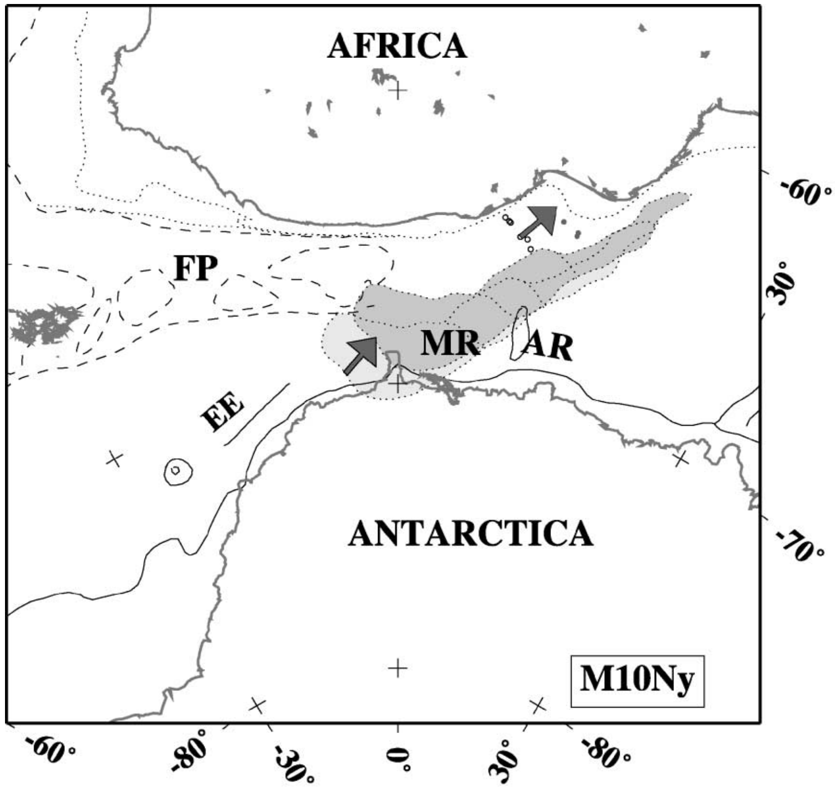


Fig. 9. "Fixed" M10Ny reconstruction of the Mozambique Ridge (MR), Africa and Antarctica. This reconstruction is similar to that in Fig. 2a except that the corrected Mozambique Ridge (dark grey) is rotated with the MOZ-ANT finite rotation pole derived from the MOZ-AFR pole presented in this paper and the M10Ny pole of R.A. Livermore (2000, personal communication) (see Table 1).

Mozambique Ridge is part of the Antarctic plate and yields significant overlap of the central Mozambique Ridge onto Africa (Fig. 11b). In the third case, the Mozambique Ridge behaves as a microplate with motion between the first two cases (Fig. 11c). The second or third cases are the most plausible.

In considering the remaining overlap of the Mozambique Ridge in the pre-chron M11 Mesozoic reconstructions of Africa and Antarctica, we need to account for Mesozoic deformation on the African and Antarctic plates. On the African plate there are prominent N–S oriented rifts indicative of E–W-oriented Jurassic extension in the continental Mozambique Basin (e.g. DeBuyl and Flores, 1984; Nairn et al., 1991; Salman and Abdula, 1995) (Fig. 4a). This same period of extension may relate to the Mozambique Ridge as well. On the Antarctica plate, extension occurs in Dronning Maud land along the Pencksökket, Jutulstraumen, and Heimefrontfjella horsts and grabens (e.g Declair and Van Autenboer, 1982; Hoppe and Thyssen, 1988; Jacobs et al., 1996) although it does not appear to be as diffuse as in the continental Mozambique Basin.

In addition, deformation and growth of the central and southern Mozambique Ridge also needs to be considered. As mentioned earlier, seismic reflection data from the Mozambique Ridge reveals horsts and grabens interpreted to have been emplaced in the Early Cretaceous (Mougenot et al., 1991). The complicated melange of Archean basement (Mougenot et al., 1991) to fresh volcanic glass samples (Ben-Avraham et al., 1995) collected from the Mozambique Ridge indicates that it has grown

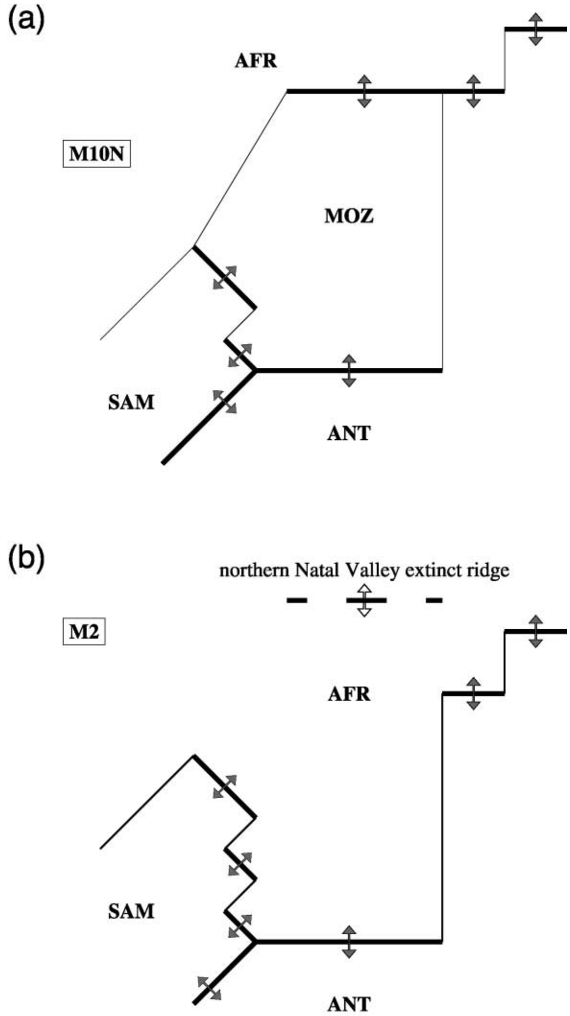


Fig. 10. Schematic ridge configuration figures which includes the northern Natal Valley extinct spreading center and the Mozambique Ridge microplate for chrons M10N (a) and M2 (b). The bold lines are spreading ridges, with arrows that indicate the direction of spreading. The thin lines are fracture zones. The plates considered are the Mozambique Ridge microplate (MOZ), Africa (AFR), Antarctica (ANT) and South America (SAM).

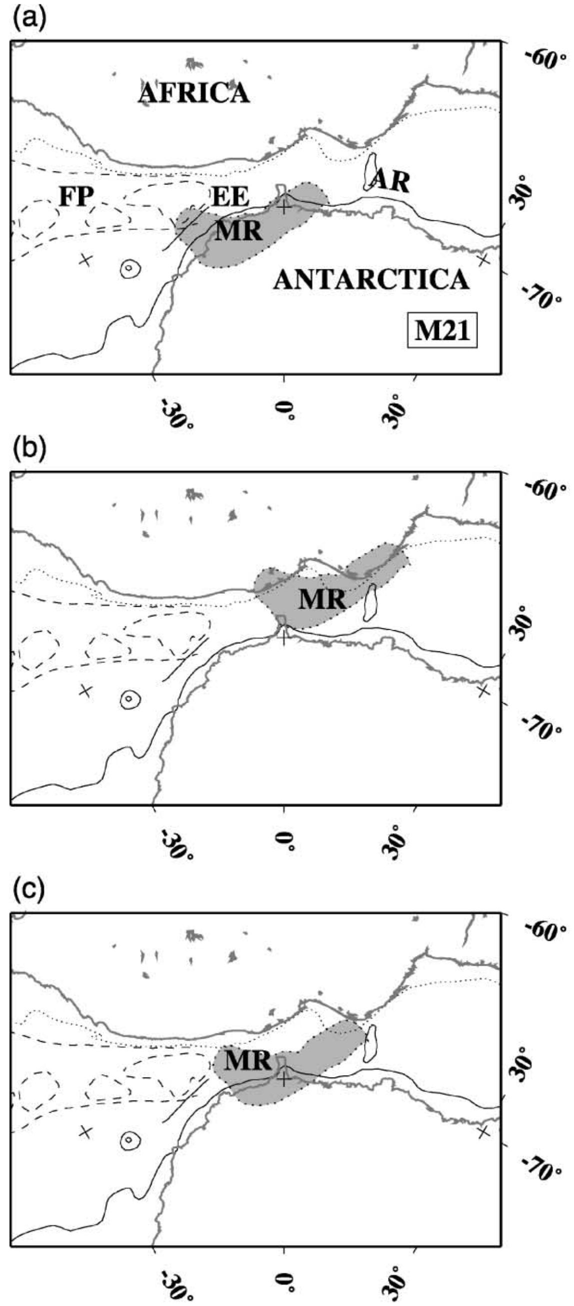


Fig. 11. Three possible M21 reconstruction of the Mozambique Ridge (MR), Africa and Antarctica. These reconstructions are similar to that in Fig. 2b. (a) The Mozambique Ridge is rotated to Antarctica with the pole derived from adding the XR-M10Ny MOZ-AFR stagepole and the M21 AFR-ANT finite rotation pole of Segoufin and Patriat (1981) (see Table 1). (b) The Mozambique Ridge is rotated to Antarctica with the M10Ny MOZ-ANT finite rotation pole (see Table 1). (c) the Mozambique Ridge is rotated with a pole between those in (a) and (b).

through successive volcanic and tectonic events. In the Late Jurassic, its size may have therefore been quite reduced in comparison to its present size, which could significantly reduce the amount of overlap predicted in the pre-chron M11 reconstructions.

9. Conclusion

We have identified conjugate Early Cretaceous, M11 to M4y (~ 133.0 to 126.7 Ma), seafloor-spreading anomalies and an extinct ridge ~ 125.3 Ma in the northern Natal valley. An extinct Mesozoic ridge had been postulated to exist in the northern Natal valley (Martin and Hartnady, 1986) although no magnetic anomaly identifications had been previously identified. Seafloor spreading in the northern Natal valley resolves the predicted overlap of the Mozambique Ridge onto the Dronning Maud land margin of Antarctica for reconstructions older than M2 (~ 124 Ma). The magnetic anomalies we identify require an independent Mozambique Ridge microplate between 125.3 and 133.0 Ma, as the finite rotations for Antarctica with respect to Africa during the time of spreading in the northern Natal valley produce a poor match to the identified anomalies. It also appears likely that the Mozambique Ridge was an independent microplate prior to 133.0 Ma and subsequent to the breakup of Gondwana ~ 160 Ma. This assertion is based on the fit of the Mozambique Ridge in reconstructions of Africa and Antarctica and documented Jurassic extension in the continental Mozambique Basin and Dronning Maud land rather than from evidence for seafloor spreading on the Mozambique Ridge microplate prior to 133 Ma.

We also assert that the northern Mozambique Ridge is a purely volcanic oceanic construct created contemporaneously or subsequent to the surrounding oceanic crust, unlike the central and southern Mozambique Ridge for which there are dredges indicating a continental core. In addition, we postulate that free-air gravity lows in the northeastern Natal valley that are concave with respect to the African continental margin are faults. These faults are at the southern end of the western branch of the East African Rift and as they are well fit by small circles about a pole that is within error bounds of the present-day Somalia–Nubia finite rotation pole, may indicate Pliocene motion between the Somalian and Nubian plates.

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