The Separation of Madagascar and Africa

Abstract. *Identification of a sequence of east-west trending magnetic anomalies of Mesozoic age in the western Somali Basin helps define the position of Madagascar in the Gondwana reconstruction. The anomalies are symmetric about ancient ridge segments and are flanked to the north and south by the Jurassic magnetic quiet zone. The motion of Madagascar relative to Africa was from the north and began in the middle Jurassic, about the same time as the initial breakup of Gondwanaland. Seafloor spreading ceased when Madagascar assumed its present position in the Early Cretaceous.*

The plate tectonic evolution of the Indian Ocean has been extensively studied during the past 20 years. McKenzie and Sclater (*1*) and Norton and Sclater (*2*) used marine geomagnetic measurements and results of deep sea drilling to date the ocean floor and, together with other available measurements (heat flow, seismic reflection and refraction, bathymetry, seismicity), to describe the plate tectonic evolution of the Indian Ocean on a regional scale. Although these data were comprehensive, there have been persistent problems in interpreting them. One controversial area is the reconstruction of the separation of Madagascar from the African continent.

The most famous proposal about the Africa-Madagascar separation is the classic Gondwana reconstruction of DuToit (*3*), which is based largely on coastal outlines. A revision was made by Smith and Hallam (*4*), who used a least-squares fit of the 500-fathom bathymetric contours. The two reconstructions differ only in the degree of continental margin overlap. In both, Madagascar is in a northerly position adjacent to Tanzania, Kenya, and southern Somalia. Similar northerly positions are also supported by the physiographic, gravity, and magnetic evidence (*5–8*) (Fig. 1, inset), paleomagnetic measurements (*9*), paleogeography (*10*), and location of salt structures (*11*). Other reconstructions have been proposed, such as a paleoposition of Madagascar adjacent to southern East Africa, a proposal based on interpretations of magnetic profiles (*12*). Flores (*13*) and others (*14*), on the basis primarily of onshore stratigraphic correlations, conclude that Madagascar moved northeasterly from a position adjacent to Mozambique. Still others (*15*) suggest that Madagascar has remained in its present position at least since the Permian. Many of the interpretations that indicate either no relative motion or motion of Madagascar from the south were influenced by seismic refraction studies in the deep ocean offshore from northeastern Kenya (*16*). Refraction velocities indicated a thick sequence, presumably sedimentary, that may be seismically correlative with the onshore Karroo rocks.

The discovery of Mesozoic magnetic lineations in the Mozambique Basin (*17*) precludes motion of Madagascar from the west or southwest since at least the late Jurassic. The possibility remains that the relative motion of Madagascar was from the north.

The weight of the paleomagnetic (*9*), physiographic, gravity, and magnetic evidence (*5–8*) supports a northerly fit of Madagascar to Africa. Davie Ridge is observed as a prominent morphologic feature between 20°S and about 9°S (Fig. 1). North of ~ 9°S Davie Ridge trends into a relative gravity high which intersects the coastline near 2.5°S (Fig. 1). It has been suggested that this gravity high represents a buried basement ridge (*6*). Scrutton (*7*) noticed this trend and suggested that the basement ridge inferred from gravity measurements is a northerly continuation of Davie Ridge; he called the entire feature the Davie fracture zone. Bunce and Molnar (*8*) interpreted oceanic basement lineaments north of

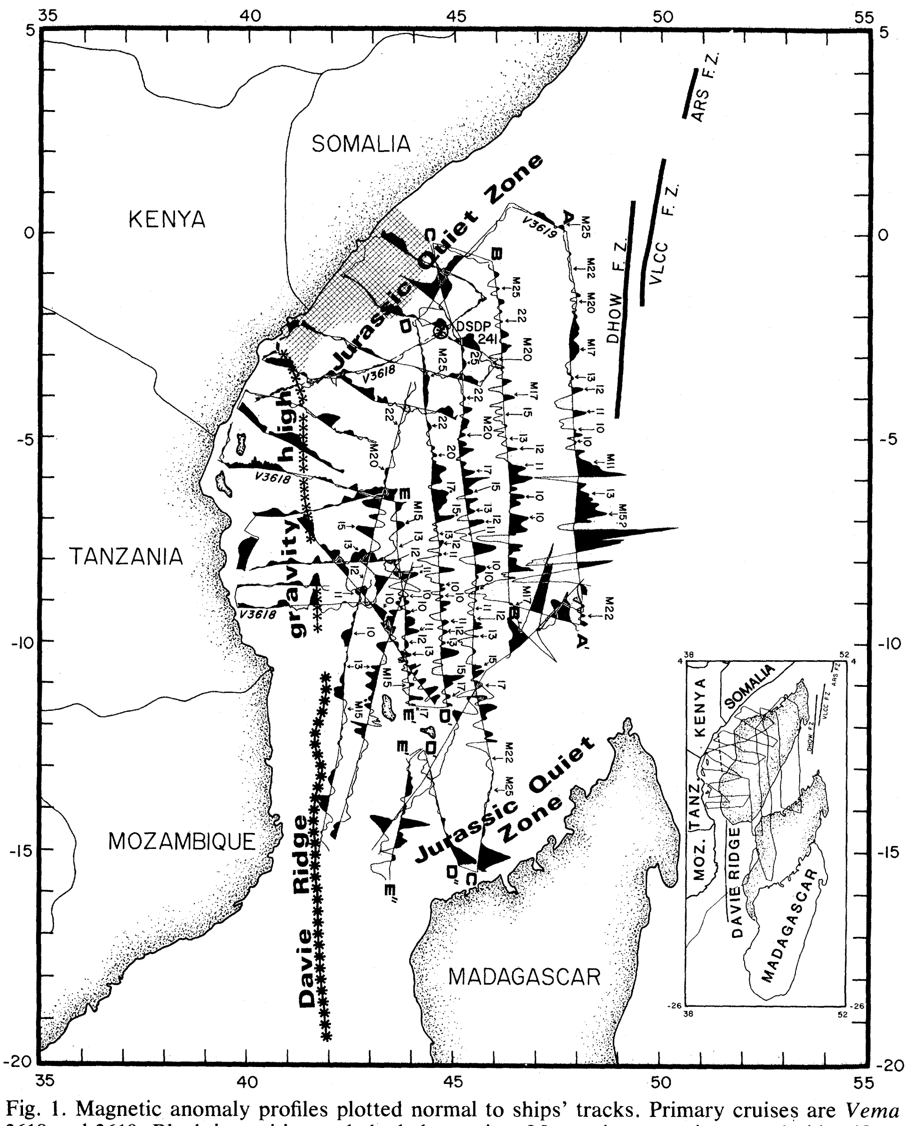

Fig. 1. Magnetic anomaly profiles plotted normal to ships' tracks. Primary cruises are *Vema* 3618 and 3619. Black is positive and shaded negative. Mesozoic magnetic anomaly identifications, Jurassic magnetic quiet zone, location of diapirs (hatched area off coast of northern Kenya and southern Somalia), DSDP site 241, Davie Ridge, and gravity high (Davie fracture zone) and other fracture zones (*DHOW*, *VLCC*, and *ARS*) (*8*) are shown. Letters along north-south trending tracks refer to projected profiles (see Fig. 2). The inset shows Madagascar rotated back to its position adjacent to East Africa before breakup, according to Bunce and Molnar (*8*).

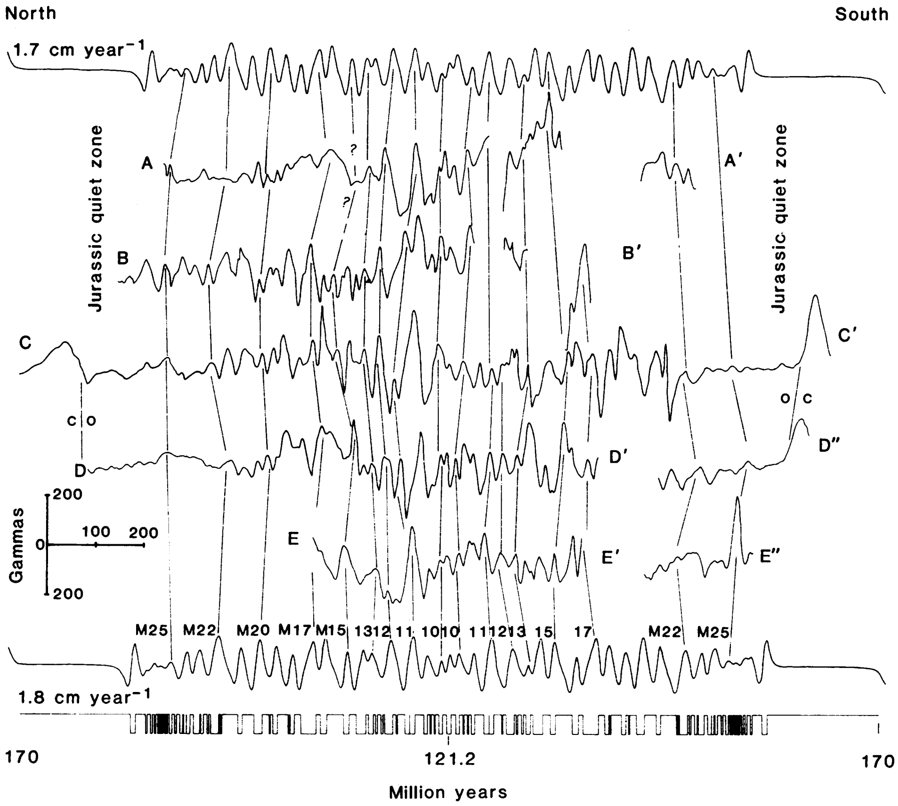

Fig. 2. Magnetic anomaly profiles in the western Somali Basin (see Fig. 1 for location of profiles). Magnetic block model was created by combining the Mesozoic reversal time scales (*21*) with published paleopole information (*9*): inclination, −32°; declination, −13°. Other parameters are: present inclination, −39°; declination, −4°; magnetization, 0.007 EMU cm^{-3}; top of source layer, 8 km; layer thickness, 0.5 km; phase shift parameter, θ, −108°; smoothing, σ, 3.0 km; and spreading half-rate, 1.7 to 1.8 cm $year^{-1}$. Note that the skewness of the calculated anomalies is considerably different from that of the observed anomalies. Also note the large amplitude positive anomaly between M10 and M11 in the north. The same anomaly to the south has a smaller amplitude.

Madagascar (which approximately parallel the Davie fracture zone) as fracture zone traces of the Madagascar-Africa separation. If Madagascar moved from the north, then the Davie fracture zone and the continental margin bordering Tanzania and most of Kenya are manifestations of the transform motion between Madagascar and Africa, and the margin of northeast Kenya and southeast Somalia was formed by the rifting and drifting between Madagascar and Africa.

From November 1980 through January 1981 (cruises 3618 and 3619) investigators on the research vessel *Vema* of Lamont-Doherty Geological Observatory studied the East Africa continental margin and the western Somali Basin (Fig. 1). Multi- and single-channel seismic reflection, sonobuoy wide-angle reflection and refraction, gravity, magnetics, and echo-sounding data were collected. We describe marine magnetic measurements that strongly indicate that the motion of Madagascar relative to Africa was from the north.

Most of the previous magnetic data were collected along approximately east-west tracks and thus are nearly parallel to the strike of the presumed isochrons. The tracks of *Vema* cruise 3619 (Fig. 1) were therefore run approximately north-south in order to best observe the magnetic lineations. Fracture zones or anomalous bathymetric features were avoided. Magnetic profiles along the ship's

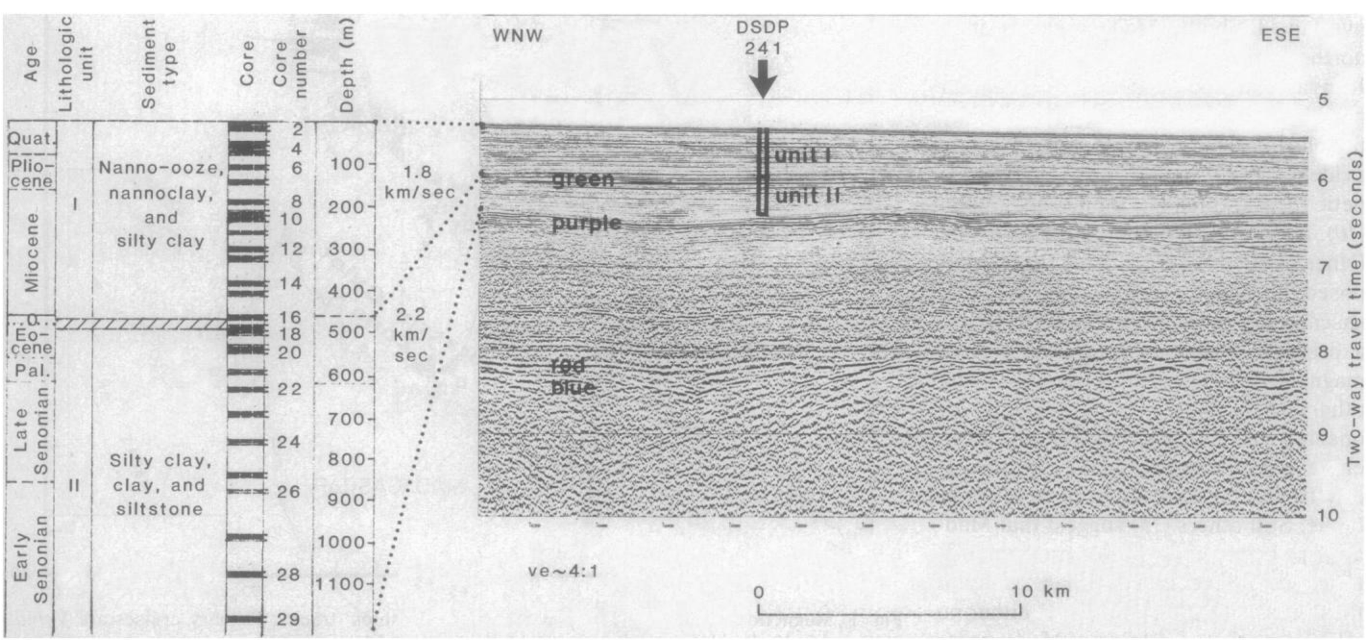

Fig. 3. Correlation of 12-channel stacked seismic reflection profile with results of DSDP site 241. Four major reflectors are identified on this seismic section and they can be traced through much of the western Somali Basin (*24*). The middle Eocene–late Oligocene hiatus between lithologic units I and II coincides well with the green reflector. Drilling in unit II penetrated close to the top of the purple reflector to which we have assigned a mid-Cretaceous age. The top of the oceanic basement is indicated by the blue reflector which is immediately overlain by the Middle to Late Jurassic red reflector. Location of DSDP site is given in Fig. 1. Reflection profile was acquired on NW-SE trending ship crossing the site; *ve*, vertical exaggeration.

tracks (Fig. 1) show that the character of the magnetic anomalies is generally smoother and of longer wavelength for the approximately east-west trending tracks than for the north-south trending tracks.

The Mesozoic sequence of magnetic anomalies from M9 (~ 121 million years old) through M25 (~ 153 million years old) are symmetric about a ridge formed at the time of anomaly M9. These segments appear to be offset left-laterally from east to west and to be normal to the Davie fracture zone, but more magnetic data is required to confirm this and to determine if oblique sea-floor spreading occurred. The Jurassic magnetic quiet zone is observed on both sides of the ridge axes landward of magnetic anomaly M25. We identified a large amplitude magnetic anomaly on both landward sides of the Jurassic quiet zone. This anomaly may represent the ocean-continent boundary, as has been proposed for similar magnetic anomalies bordering other passive continental margins [for example, the magnetic anomaly off eastern North America (*18*) or anomaly G bordering the South Atlantic margin (*19*)]. The magnetic anomalies are disturbed in places by seamounts and islands in the southern part of the basin. Some of the islands have experienced volcanism since the Miocene (*20*).

The magnetic data point to the motion of Madagascar relative to Africa being from the north, with the Africa-Madagascar separation beginning during the time of the Jurassic quiet zone (~ 165 million years ago) and ending at a time of formation of anomaly M9 (~ 121 million years ago). The Africa-Madagascar separation thus began at about the same time as the breakup of Gondwanaland and the separation of North America from Africa. We used the Mesozoic time scales (*21*) for dating these anomalies, and derived half-spreading rates of 1.7 to 1.8 cm year^{-1}. We note that the results of recent deep sea drilling in the North Atlantic on the older parts of the Mesozoic sequence may reduce the age assigned to magnetic anomaly M25 and the Jurassic quiet zone (*22*) and hence increase the spreading rates.

Deep Sea Drilling Project (DSDP) site 241 (*23*) is located on the lower continental rise off northeastern Kenya and southeastern Somalia in the Jurassic quiet zone and just landward of magnetic anomaly M25. A multichannel seismic section from our recent *Vema* cruise across this site (*24*) is shown in Fig. 3.

Relative motion between Madagascar and Africa ceased ~ 121 million years ago, about 25 million years before creation of the purple reflector [Early Senonian (Fig. 3), corresponding to the age of the oldest sediment recovered during drilling]. Schlich *et al.* (*25*) and Simpson *et al.* (*23*) conclude, primarily from the drilling results, that the continental margin off northeastern Kenya and southeastern Somalia has been evolving passively for at least the last 90 million years and argue that it is unlikely that Madagascar occupied a position adjacent to that part of Africa during those 90 million years. Our marine magnetics data and seismic analysis are in good agreement with these drilling results (*23*, *25*).

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Fragile Sites in Chromosomes: Possible Model for the Study of Spontaneous Chromosome Breakage

Abstract. *The tissue culture condition that is required for the type of chromosome breakage seen at most fragile sites, namely, the absence of folic acid and thymidine in the medium, greatly enhanced micronucleus formation in proliferating lymphocyte cultures from normal individuals. This suggests that chromosome breakage at fragile sites and the apparently spontaneous damage that gives rise to micronuclei are controlled by the same mechanism.*

Fragile sites are heritable points on human chromosomes. Expressed as nonstaining gaps during metaphase, they are places where the chromosomes are very susceptible to breakage (*1*). The best evidence for this phenomenon is the formation of multiradial figures at metaphase, which arise from breakage and malsegregation of the chromosome fragment distal to the fragile site (*2*). Fragile