Reports

Madagascar's Paleoposition: New Data from the Mozambique Channel

Abstract. *The main paleopositions that have been proposed for Madagascar are examined after a recent geological and geophysical survey in the Mozambique Channel. Results from that survey show a north-south ridgelike feature and favor the theory that Madagascar fitted against Somalia rather than against Mozambique to the west.*

With the general acceptance of the theory of sea-floor spreading, the pre-drift locations of continental masses have been studied for all the oceans. In the Indian Ocean the island of Madagascar (Fig. 1) is an old continental structure whose paleoposition has been particularly enigmatic. Three possible positions have been proposed for the island.

First, several authors (*1–5*) have concluded that Madagascar has remained in its present position with respect to Africa since at least mid-Mesozoic time. Flower and Strong (*4*) found sandstone inclusions in the lavas of the Comoro Islands, between Madagascar and Africa, and concluded that the Mozambique Channel, between Africa and Madagascar, is underlain by continental crust. However, Wright and McCurry (*6*) have noted that the presence of sandstone does not make an unambiguous case for continental crust. Dixey (*1*) originally proposed that late Carboniferous subsidence resulted in the formation of a geosyncline and the concurrent deposition of the Karroo sequence with up to 14 km of sedimentary rocks. Holmes (*3*) states that Madagascar is directly connected to Africa by continental crust that has been "thinned out." Pepper and Everhart (*2*) constructed two hypothetical east-west sections across the channel, on the basis of outcrops and wellholes on either side. These sections indicate that the channel area has subsided along several normal faults, with subsequent sedimentation.

Second, as other authors have proposed (*6, 7*), Madagascar could have moved east from the African coast. Wright and McCurry (*6*) show Madagascar against Mozambique with the southern end of the island opposite Lourenço Marques (26°S). Heirtzler (*7*), in piecing together continental fragments in and around the Indian Ocean, found it convenient to place Madagascar in a position against Mozambique, to the west. According to his reconstruction, Madagascar moved to its present position sometime since the Cretaceous period.

Third, some authors (*8, 9*) have proposed that Madagascar has moved south and slightly east from a position in which its southern end was opposite Cape Delgado, at 10°S. DuToit (*8*) made such a fit based on matching similar lithologic units in the Karroo series and on some paleontological and structural evidence. Smith and Hallam (*9*) used a computer fit of 500-fathom contours to obtain a detailed position for the island against Somalia and Kenya. The resulting fit placed the southern limits of marine Jurassic material adjacent in Africa and Madagascar. Breakup occurred during or after the Cretaceous, on the basis of volcanism and faunal assemblages (*9*).

Most ship's tracks have been oriented north-south in marine reconnaissance geophysical surveys of the Mozambique

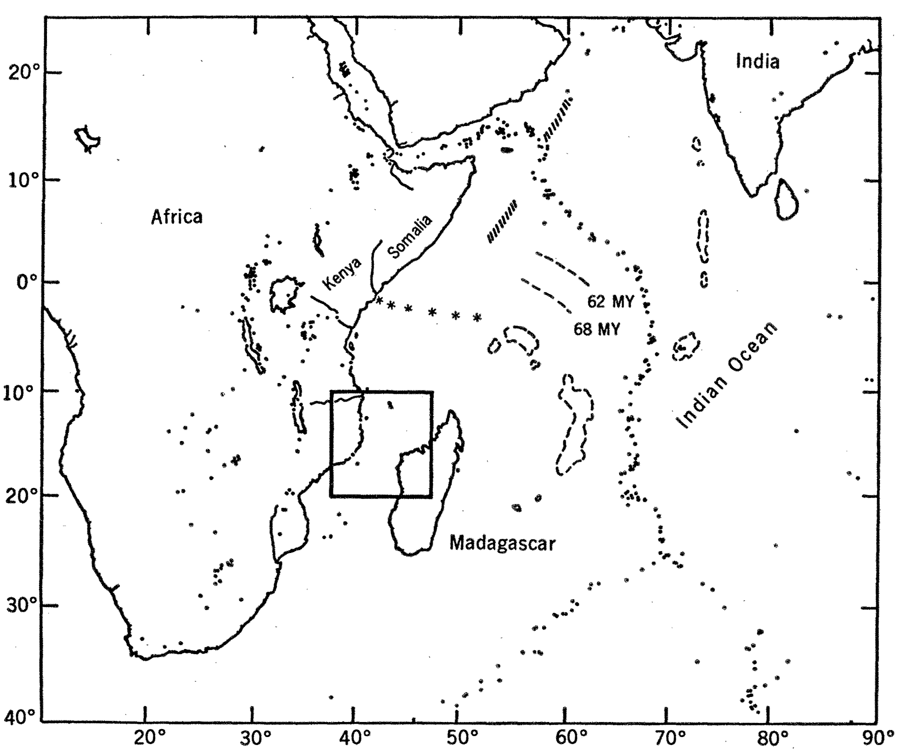

Fig. 1. Western and central Indian Ocean. The dots are the locations of earthquake epicenters recorded from 1961 to 1969 (*14*). The alignment of these epicenters in the Indian Ocean defines the axis of the mid-Indian Ocean Ridge. The hatchured line to the northeast of the ridge is the Owen fracture zone, and to the southwest is the Chain Ridge. Stars show the locations of seismic refraction stations (*11*) in the Somali Basin, northwestern Indian Ocean, and straight dashed-line segments show the age of the ocean basement, from magnetic anomalies (*15*). The square defined by bold lines is the area shown in Fig. 2.

Channel. In November and December of 1970 the R.V. *Chain* made a series of traverses in an east-west direction (Fig. 2). The northeastern section of the Mozambique Channel, south of the Comoro Islands, can be described as an abyssal plain. In the northwest part of the channel a ridgelike feature was observed (Fig. 3). The feature trends approximately north-south along the 41°30′E meridian. Time did not permit exploring it south of 17°S nor north of 9°S. An examination of the Lamont-Doherty Geological Observatory's marine bathymetric and seismic records, taken to the south, did not indicate a continuation of the ridge farther south.

In six of the crossings the feature appears as a topographic high. Four crossings show a single steep scarp, facing west, with a true slope of approximately 27°. One or more anticlines occur to the west of the steep face in all four cases. They are similar to the anticlinal structures in the crossings where there is no topographic expression of the feature. Shallow focus epicenters also lie near but slightly to the west of the feature (see Fig. 1). In seven crossings an acoustically transparent layer of approximately 1 second thickness lies to the east of the feature and pinches out on its flank.

Magnetic anomalies in the vicinity of this structure generally are 50 to 200 gammas in amplitude. Their wavelength indicates a deep burial of magnetic basement, below the deepest layer indicated by seismic reflection experiments. There are no lineations in the magnetic anomaly pattern, and the anomalies are not uniquely situated over topographic features.

These data may be used to test the proposed predrift positions for Madagascar. If Madagascar moved to the east to reach its present position, the linear feature might be a spreading axis. However, neither the morphology nor the magnetic anomalies are typical of a spreading axis. Thus, such a fit is not supported by the present data.

In a similar fashion, the present data add little to the hypothesis that Madagascar has remained stationary and that a geosyncline developed in the Mozambique Channel. The appearance of a ridgelike feature as a local structural hiatus does not suggest a simple geosynclinal regime.

A third possibility is that Madagascar has moved north-south relative to Africa. In this case the ridgelike feature could be a strike slip fault, indicating the direction of movement. This possibility was suggested on a map of the Mozambique Channel made by Langseth and Heezen (*10*). A plausible reconstruction along that line would put thick sedimentary deposits in northern Kenya and Somalia adjacent to thick deposits in Madagascar. In executing such a motion the island would have had to move through the western Somali Basin, which shows no topographic or seismic features to support such movement. Francis *et al.* [(*11*) and Fig. 1], after completing a series of seismic refraction stations between Kenya and the Seychelles, found a 4.7 to 4.8 km/sec velocity layer almost as far east as 45°. This was interpreted as a possible seaward extension of the East African Karroo sequence, which is essentially nonmarine. If Madagascar moved through this area, another explanation for that layer must be found. Chain Ridge (Fig. 1) would be out of the path of movement, and the Cretaceous material found there by Bunce *et al.* (*12*) could predate the movement. Paleomagnetic and radiometric studies of the Deccan traps of India (*13*) indicate that the traps were still at 30°S latitude as recently as 42 to 65 million years ago (early Cenozoic). The close fit of India to Africa makes it unlikely that Madagascar started moving south before India started north. If Madagascar began moving steadily south at that time, and is continuing its motion today (as indicated by recent epicenters near the fracture

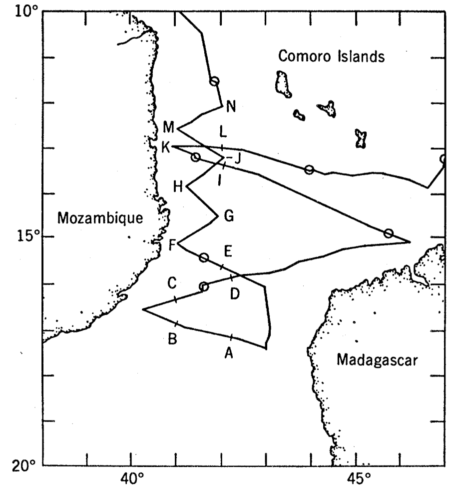

Fig. 2. Track of the R.V. *Chain*, entering the northern Mozambique Channel from the northeast and leaving to the north. The letters identify sections of the track shown in Fig. 3. The open circles mark station locations.

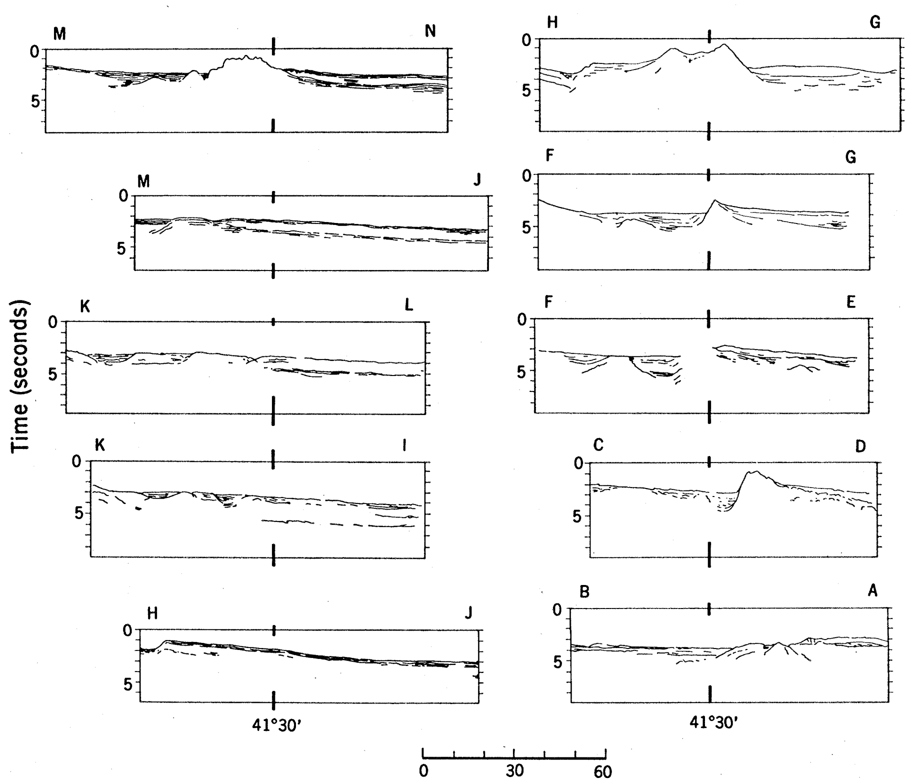

Fig. 3. Tracings of seismic reflection records along sections of track marked in Fig. 2. The ordinate is the round-trip travel time, in seconds, of the acoustic pulse from the surface. The distance between second marks is about 1 km beneath the sea floor (*16*) and 0.7 km in the seawater.

zone), its rate of motion is approximately 2.9 cm/year.

In conclusion, our data suggest that Madagascar could have moved south from Somalia, beginning in the early to middle Cenozoic, but not east from Mozambique. If it is possible to drill to basement with the forthcoming deep-sea drilling program in the Mozambique Channel, one can see if the basement predates the Cenozoic.

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17. We thank Captain Palmieri, the officers, and the crew of the R.V. *Chain*, cruise 99, leg 8, for their help. H. Itzkowitz, J. MacIlvaine, J. Mahoney, W. Nichols, C. Polloni, K. Prada, F. Wooding, and R. Young assisted in data acquisition. E. Bunce provided several helpful comments. This work was supported by ONR contract N00014-66-C-0241; NR083-004. Contribution No. 2693 of the Woods Hole Oceanographic Institution.

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Motions of Molecules in Liquids: Viscosity and Diffusivity

Abstract. *The fluidity of a simple liquid is proportional to its degree of expansion over the volume,* V_0, *at which its molecules are so crowded as to inhibit self-diffusion and viscous (as distinguished from plastic) flow. The equation of proportionality is* $1/\eta = B[(V - V_0)/V_0]$ *where* η *is the viscosity and* V *is the molal volume. Values of* B *are the same for normal paraffins from* C_3H_8 *to* C_7H_{16} *and then decrease progressively as the paraffin lengths increase. Values for other liquids,* C_6H_6, CCl_4, P_4, CS_2, $CHCl_3$, *and Hg, appear to vary with repulsive forces. Liquids can be moderately fluid when expanded by less than 10 percent; this shows the unreality of some theoretical treatments of the liquid state. Diffusivity begins from the temperature at which* V *equals* V_0 *and can be correlated for temperature dependence, and for solute-solvent interrelations.*

Bird, Stewart, and Lightfoot had this to say in chapter 16 of their extraordinarily fine book on *Transport Phenomena* about the present state of the-ory of diffusion in liquids (*1*):

> If the reader has by now concluded that little is known about the prediction of dense gas and liquid diffusivities, he is correct. There is an urgent need for experimental measurements, both for their own value and for the development of future theories.

I see two reasons for this lack of general theory. One, measurements have not been designed to obtain answers to questions of general significance. Although, for example, diffusion is an example of entropy increasing toward the maximum permissible under the conditions, very few of the vast number of measurements of diffusivity (*2*) were made at more than one temperature. Also, statistical mechanicians have treated transport theory as essentially a problem in mathematics. In papers and symposia dealing with the theory of the liquid state, few of the authors have sought validation by experimental facts. The volume recording the proceedings of the International Symposium on Transport Processes in Statistical Mechanics (*3*), held in Brussels in 1956, is typical. In the first half of the book there is only one paper containing any reference to experiment. Otto Redlich has said that science, unlike mathematics, is not autonomous; its concepts must be referred to nature for validation. Theorists do not always do that.

I approach the problem of diffusion by way of viscosity, the much simpler phenomenon. Viscosity of liquids has been treated copiously in engineering and scientific literature, but nearly all that I have read seems unrealistic in one respect or another, such as the assumption of quasi-lattice structure that ignores clear evidence to the contrary, or that temperature dependence is exponential, or that there is an energy of activation, a notion that disregards the basic distinction between liquid and plastic flow.

Batschinski (*4*), in 1913, published an important paper that has been virtually ignored by authors on transport phenomena; I found it only recently, almost by accident. Batschinski reasoned that viscosity is not a direct function of temperature but of the difference between the specific volume of the liquid, v, and a certain constant, ω, similar to the van der Waals b. He wrote his relation $\eta = c/(v - \omega)$, where c is another constant. He plotted v against fluidity, $1/\eta$, for 87 liquids, obtaining straight lines for those that are not associated. The values he thus obtained for ω fell between specific volumes of liquid and solid and were nearly the same fraction of critical volumes. His effort to evaluate c as an additive of atomic parameters was not successful.

I propose a modification of Batschinski's formulation as follows. Fluidity depends on the the ratio of free volume, $V - V_0$, to intrinsic volume, V_0, the molal volume at which fluidity is zero. I prefer molal volume to specific volume for conceptual reasoning. By analogy with Batschinski's procedure I write

$$\eta = C/(V - V_0) \qquad (1)$$

I plot measured values of fluidity, $1/\eta$, against molal volume, V. All the simple liquids I have examined, added to the scores Batschinski investigated, give straight lines that yield values of V_0 at the intercept, where $1/\eta = 0$. The slopes of the lines give values of C. Typical cases are illustrated in Figs. 1 and 2 showing the variation of viscosity with temperature of C_3H_8, C_6H_6, and CCl_4. Figure 3 is a plot of fluidity against V for C_6H_6 and CCl_4. Values of V_0 and C are given in Table 1 for these and other liquids, determined in this way. Batschinski, by multiplying his values of specific volume at zero fluidity by molecular weight, obtained values of V_0 which quite agree with mine for the same liquids. He discovered that the ratios of his values of V_0