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Rapid Continental Breakup and Microcontinent Formation in the Western Indian Ocean

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Two of the main factors that determine the nature of a rifted continental margin are rheology and magmatism during extension. Numerical models of lithospheric extension suggest that both factors vary with extension rate; yet until now extension rates of studied margins, as indicated by the rate of initial seafloor spreading, are mostly less than ~30 mm/yr on each margin. This article presents the first geophysical results from the Seychelles-Laxmi Ridge conjugate pair of rifted margins which separated at ~65 mm/yr.

The Seychelles, with its spectacular exposures of Precambrian granite, was the earliest scientifically recognized microcontinent and arguably remains the classic example of one [*Wegener*, 1924; *Matthews and Davies*, 1966]. However, it is still unknown whether microcontinents result from plumes, changes in plate-boundary forces, lithospheric heterogeneity, or a combination of these factors.

In 2003, a major seismic experiment was completed, with controlled-source and passive seismic elements, across the Seychelles-Laxmi Ridge conjugate margins and the Seychelles microcontinent. The experiment drew together scientists from three U.K. universities, two German institutes, and the Seychelles for deployments of land and ocean seismometers. The project was designed to provide new constraints on lithospheric extension, mantle thermal structure, and melting processes during continental breakup, and the deep structure of a mature micro-continent.

Tectonic Setting

The Seychelles microcontinent formed by rifting from Madagascar in the mid-Cretaceous followed by rifting from India at the end of the Cretaceous. Reconstructing this final rift phase, which is thought to have occurred relatively rapidly, is aided by well-defined seafloor-spreading magnetic anomalies and fracture zones [*Royer et al.*, 2003], but is hampered by the presence of basement ridges and troughs just seaward of the broad India/Pakistan continental shelf (Figure 1a). The uncertain crustal affinity of these features, principally the Laxmi Ridge and Basin, results partly from the blanket of thick Indus Fan sediments. However, it has been suggested, on the basis of magnetic and gravity data, that the Laxmi Basin is underlain by oceanic crust and the Laxmi Ridge by continental crust [*Bhattacharya et al.*, 1994; *Miles et al.*, 1998]. If correct, the Laxmi Ridge represents a further continental sliver isolated during the Seychelles/India breakup.

The age of the oldest oceanic crust between the Seychelles and the Laxmi Ridge (just before magnetostratigraphic chron 27, 63–62 Ma) is similar to that of the Deccan flood basalts of northwest India (68.5–62 Ma), and it has been suggested that the initiation of the Réunion plume resulted in the jump in seafloor spreading from south to north of the Seychelles. However, scant Deccan-related magmatism has been found on the Seychelles Bank itself.

An objective of this work, therefore, is to determine the distribution and volume of melt across the conjugate rifted margins in order to estimate mantle temperature during breakup, and concurrently evaluate the mechanism of microcontinent formation. Numerical models of rapid lithospheric extension will also be used to place bounds on the original rifting process.

The 2003 Experiment

During the controlled-source part of the experiment, a deep seismic reflection/refraction transect was made across the reconstructed Seychelles-Laxmi Ridge margins using an airgun array, ocean bottom seismographs (OBS), and land stations installed on the central Seychelles islands (Figure 1b). At some of the latter stations, P_n (the sub-Moho refracted arrival) is observed out to a shot-receiver offset of 380 km, together with a later mantle arrival. After the controlled source work, land seismometers were redeployed widely across the Seychelles islands and recorded (at 20 samples/s) for an additional 10 months.

Initial Results

The new transect shows the rifted margins to be highly asymmetric—the Laxmi Ridge side appears wide and complex, and the Seychelles side is narrow and simple. Good seismic reflection images of the deeply buried Laxmi Ridge, Gop Rift, Palitana Ridge, and India/Pakistan continental rise were achieved (Figure 2). The Laxmi Ridge is seen as an elevated basement feature with bright reflectivity similar to the confirmed continental crust at the north end of the profile [*Malod et al.*, 1997]. Both regions, the Laxmi Ridge and the confirmed continental crust, have negative gravity anomalies consistent with the thickened crust determined by preliminary wide-angle modelling (Figure 3).

Presently, it remains unclear whether the Gop Rift is underlain by oceanic, or highly stretched continental, crust. Seaward-dipping reflectors are seen on the southern edge of the Laxmi Ridge and close to the foot of the Seychelles Bank (Figure 2). Such reflectors, often found near continent-ocean boundaries, are thought to represent intense, subaerial volcanism at a late stage of rifting. Highly vesicular trachytic basalts were also dredged from three Seychelles seamounts, which similarly suggest shallow water or subaerial volcanism. Surprisingly, however, the data suggest that the oldest oceanic crust is anomalously thin. No evidence is seen of exhumed mantle in the acoustic basement.

The teleseismic experiment recorded 240 events of $M_b>5.8$. These events have been used to study upper-mantle anisotropy using shear-wave splitting in core phases such as SKS (Figure 1b). In general, the degree of splitting is similar to global averages (~1 s). The orientation of the anisotropy suggests that it results from deformation associated with mantle extension during the breakup of Madagascar/Seychelles/India, rather than current plate motions.

Future Work

The analysis of the seismic data is still preliminary. Key aspects of future work include verifying the continental origin of the Laxmi Ridge, and the continental or oceanic origin of the Laxmi Basin. On the Seychelles side,

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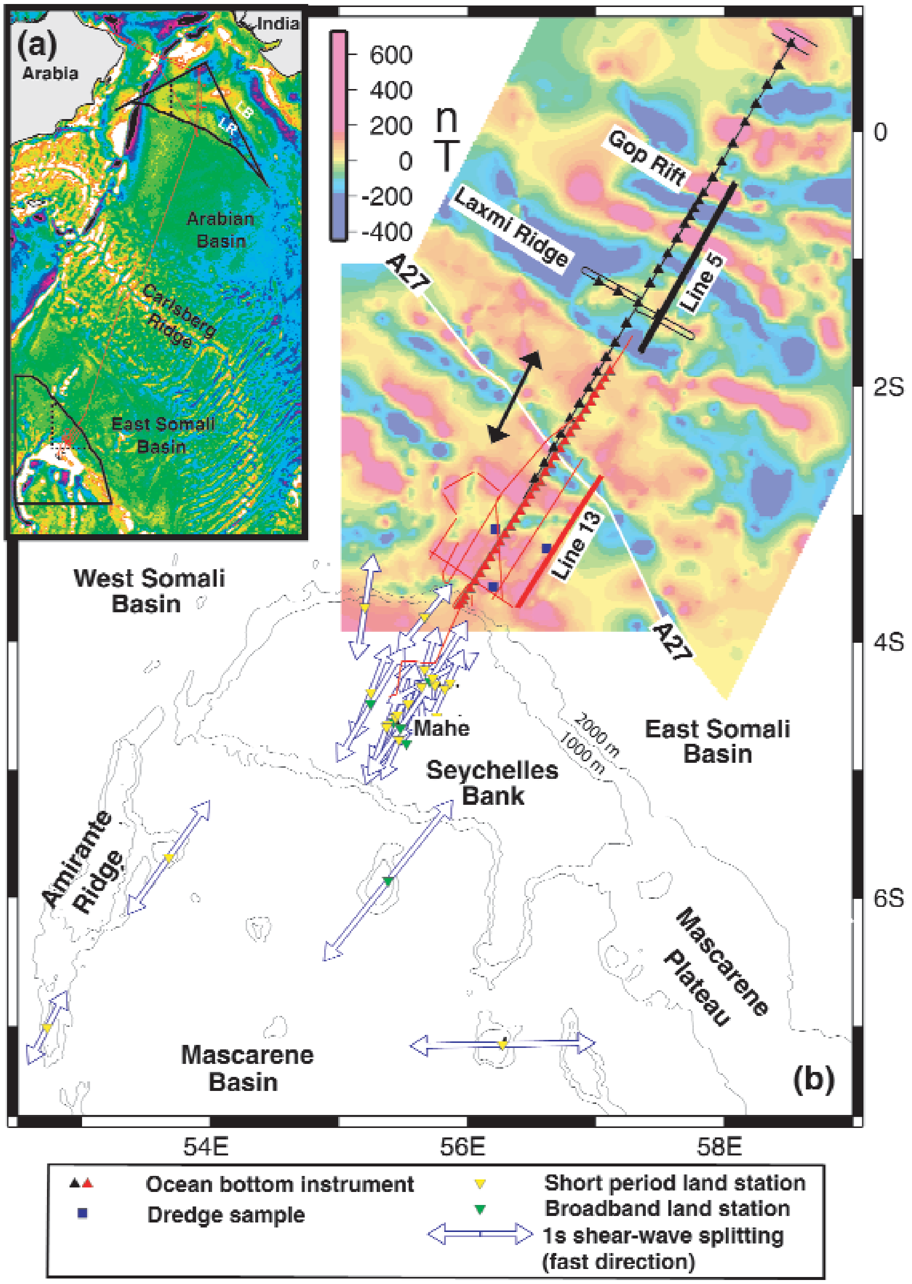

Fig. 1. (a) Satellite gravity of the northwest Indian Ocean, showing the Seychelles and Laxmi Ridge margins in their present position. Cool (black/purple/blue) colors mark gravity lows. Black lines outline the two roughly triangular regions reconstructed in Figure 1b, with dashed black lines marking the outline of the magnetic anomaly grids shown. The red line marks the CD144 cruise track. LB marks the Laxmi Basin, and LR marks the Laxmi Ridge. (b) Magnetic anomaly map of the conjugate survey areas reconstructed to A27 (the Seychelles were held fixed and the India plate rotated back using the Chron 27ny pole of Royer et al. *[2003]. It is estimated that any along-margin error in matching the two main profiles is less than 50 km. Black arrow marks the spreading direction between A27 and A26. Triangles mark instrument deployments, and open blue arrows show shear-wave splitting fast directions.*

work will include establishing the origin of the deep mantle reflector (not included in Figure 3) seen in the wide-angle data. To help determine the structure across the plateau, teleseismic P-waves and reverberations converting to S-waves near the surface (receiver functions) will be used to estimate crustal thickness and the depth of mantle discontinuities. Receiver functions will also be used to look for evidence of an underlying mantle plume suggested by a recent global tomography study [*Montelli et al.*, 2004].

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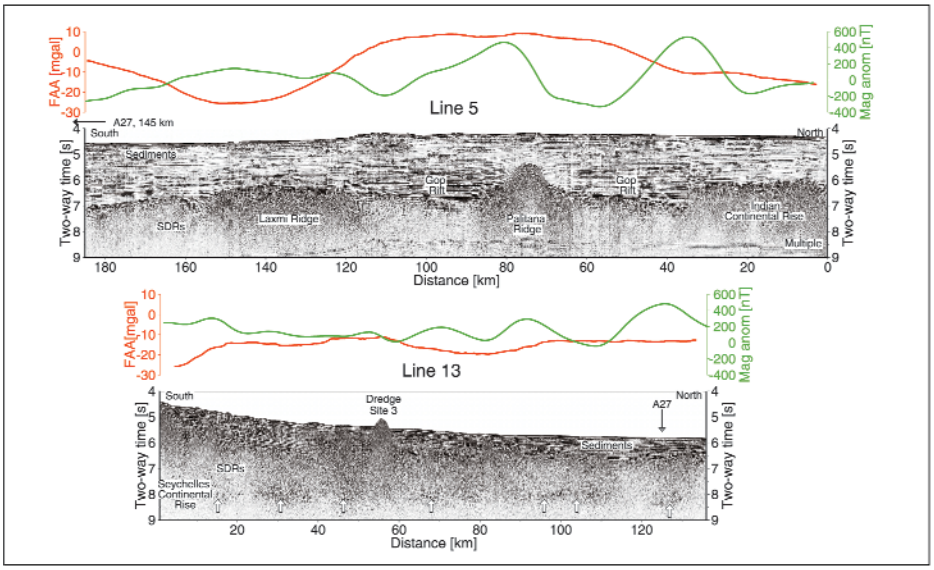

Fig. 2. Examples of deep multichannel seismic reflection profiles. The data were collected with a 2.4-km, 96-channel streamer and a 12-element, 3890 cubic inch airgun array fired every 30s. The data are unmigrated. Plotted above each seismic section are the free-air gravity and magnetic (reduced to the pole) anomaly profiles. SDRs are seaward dipping reflectors, and white arrows on line 13 mark the reflection Moho between 8 and 8.5s TWT.

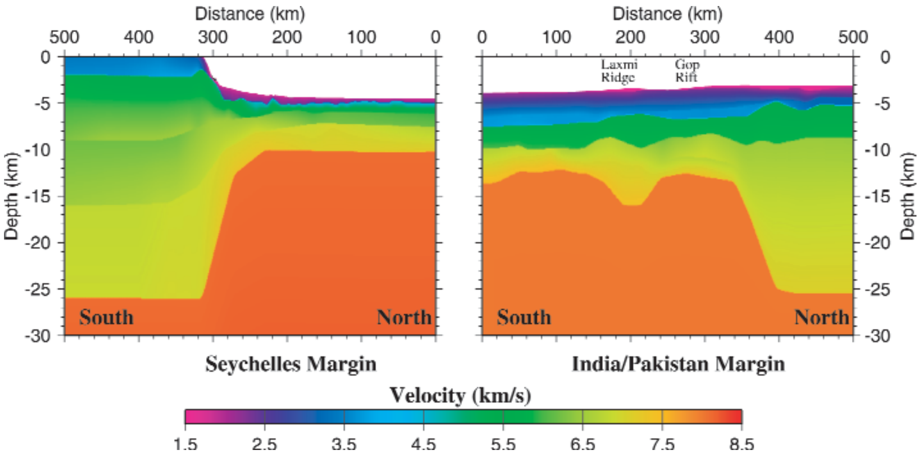

*Fig. 3. Preliminary P-wave velocity models of the two halves of the transect generated by forward modeling and inversion of first arrivals (P_g and P_n) and PmP phases [*Zelt and Smith, *1992].*

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