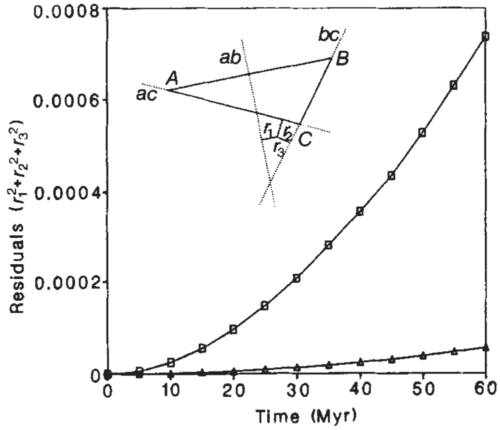

Fig. 4 Changes in the degree of geometric instability (residuals) as the RRR (☐) and RFF (△) configuration of the Bouvet triple junction drifts away from the isosceles line. The orientations of the boundaries are assumed to be fixed, and spreading is assumed to be symmetrical. Instability arises because the relative velocities change with time. The RFF configuration is least affected by small changes in the velocity triangle, and it seems to be the preferred configuration in the vicinity of the isosceles line. The inset illustrates the geometric significance of the residuals.

such that the growing transforms develop a small component of extension. In other words, they become progressively 'leaky'. The actual rotations amount to only 1° over a period of 20 Myr, but this may be sufficient to make them mechanically feasible.

When the triple junction finally changes to RRR configuration, the newly generated slow spreading ridge segments must undergo rotation as the relative action vector changes during north-west migration. The MAR must also undergo a change in the spreading direction (Fig. 2*b*). This rotation is possibly accommodated by the generation of secondary transform faults along these ridge segments.

Questions also surround the reason why the junction switches from a RRR mode to RFF in the vicinity of the isosceles line. A partial answer may be suggested by the relative geometric instabilities of the two configurations. The location of the triple junction in two-dimensional velocity space is given by a set of three equations involving the three-plate velocities and boundary orientations. If these equations have a unique solution, the junction is stable in the sense of McKenzie and Morgan[2] and the velocity of the triple junction is well defined. If no solution exists, the triple junction is unstable. We suggest that the residuals of a least-squares fit in the case of an unstable junction can be used as a measure of the degree of geometric instability (see inset, Fig. 4).

For the Bouvet junction, the residuals for the RRR and RFF modes are plotted in Fig. 4 as a function of their travel time away from the isosceles line. In these calculations, the boundary orientations are fixed, and the spreading is considered to remain symmetric. The residuals increase for RRR and RFF modes as the junction migrates. However, the instability of the RFF junction builds up much more slowly than RRR configuration. In the vicinity of the isosceles line (the origin of Fig. 4), the RFF junction is less susceptible to changes in the relative velocities perhaps explaining why it is the preferred state.

We conclude that the Bouvet triple junction is trapped in the vicinity of an isosceles line in the South Atlantic. Along this locus, the junction can exist in either RRR or RFF configuration, although RFF seems to be more stable. As the absolute motion of the RFF junction carries it away from this locus, it eventually becomes mechanically unstable and switches to a RRR configuration. The RRR junction has an absolute motion which drives it back to the isosceles line where it reverts to its original RFF configuration. Because the orientations of the absolute triple junction trajectories straddle the isosceles line, the Bouvet junction is destined to alternate between episodes of RRR and RFF as long as the absolute plate velocities remain unchanged.

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Geometry of propagating continental rifts

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Reconstruction of past plate configurations through palinspastic restoration of continental margins[1-4] requires a detailed knowledge of the geometries of horizontal continental extension. Extension is often restricted to discrete, linear zones termed rifts[5,6], and rift models that invoke propagating vertical dykes and cracks[7-10] are useful for assessing the relative significance and timing of uplift, subsidence and extension in the tectonic evolution of rift basins. However, many models do not adequately account for the observed asymmetry of rifts. I describe here the general three-dimensional character of young and aborted continental rifts, which can be used to derive a structural model for the propagation of rifts in continental lithosphere. The rifts become asymmetric as a consequence of the role played by low-angle normal faults in the overall rift geometry.

Continental rifts are typically a few tens of kilometres in width, and several tens to a few hundred kilometres in length (Figs 1, 2). That these rifts are in some cases precursors to the complete rupturing of continental lithospheric plates seems to

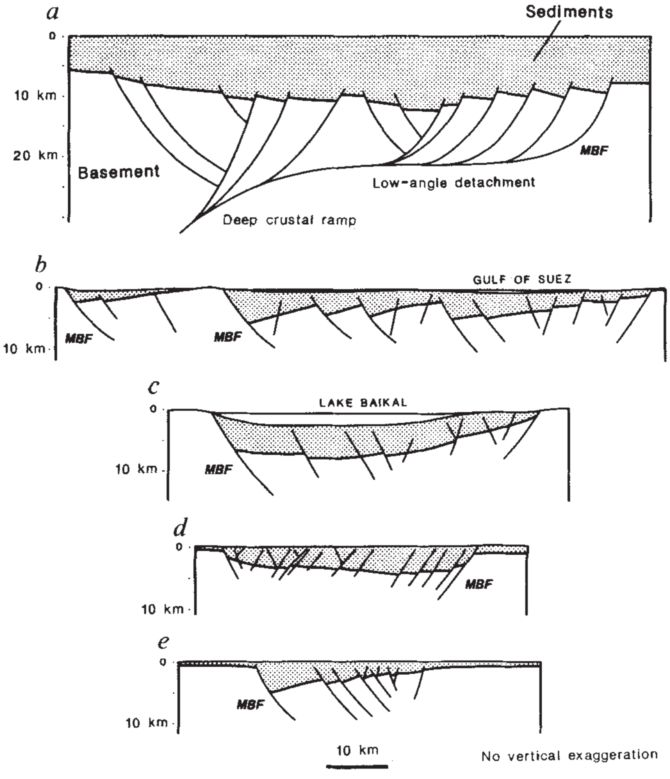

Fig. 1 Asymmetry of continental rifts in cross-section. Rifts commonly show half-graben-like forms in cross-sections taken normal to their long axes, with most basin relief generated by a single rift bounding fault (main bounding fault, MBF), or a system of a few main faults, which are inferred to bottom out to a low-angle detachment surface. *a*, Central Graben, North Sea, section (a submerged continental rift) is an approximate depth conversion of a time section presented by Gibbs[23]. *b*, Section crossing southern Gulf of Suez, constructed from industry well and seismic data. *c*, Baikal Rift, sediment thicknesses from ref. 43, but internal faulting is largely schematic. *d*, Rhine Graben, from ref. 20. *e*, White Nile Rift, in part based on the gravity work of Browne *et al.*[19].

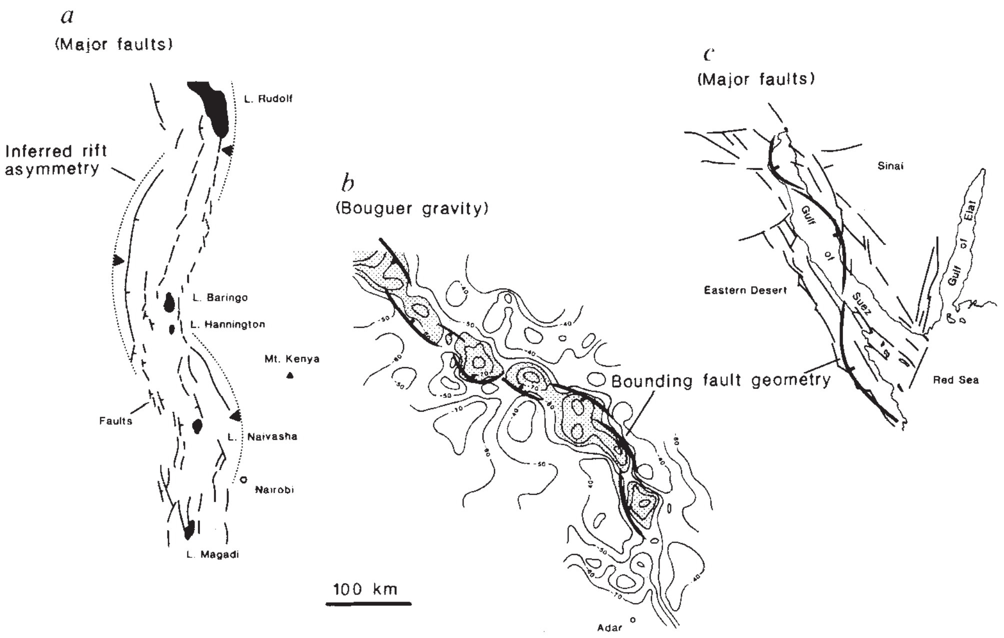

Fig. 2 Geometry of continental rifts in plan view. The major faults of continental rifts follow curvilinear patterns in map view, defining a sub-basin geometry that repeats generally every 50–150 km. Similar curvature is seen in the bounding faults of the Basin and Range Province[44]. The asymmetry of the rifts in cross-section commonly reverses at each successive sub-basin, although not in every case. *a*, Gregory Rift, Kenya. Surface traces of major faults are from ref. 45. *b*, White Nile Rift, Sudan. Gravity data are from ref. 19. *c*, Suez Rift, Middle East. Surface faulting from ref. 17. Sub-basin geometry in the Gregory Rift (*a*) is more complex than portrayed here.

be well established by studies of the African-Arabian plate boundary (Red Sea and related rifts)[11-15]. At the other extreme, continental extension may be distributed over broad zones, measuring hundreds of kilometres in each horizontal direction, as in the Basin and Range of the western United States. Whether the Basin and Range structure evolves from a few, initially discrete rifts, and whether it can eventually lead to continental breakup, are unanswered fundamental questions of continental tectonics.

Continental rifts are strongly asymmetrical in cross-sections normal to their long axis[12,16] (Fig. 1). This asymmetry is evident in gravity-field gradients[17-19], relative rift shoulder elevations, sediment isopach maps[20,21] and seismic reflection profiles[22,23]. Meinesz[24] suggested that rifts would develop an initial asymmetry corresponding to the first formed bounding fault. As crustal flexure continued, the opposing fault breaks to produce a symmetrical graben form. Most models of rift formation[8,12,25-30] have envisioned continental rifting, and hence the development of continental margins[1,2,31] as essentially a symmetrical process at the scale of the lithospheric plate.

Many workers have suggested that the main faults of rifts pass completely through the crust to a zone of structural decoupling[27,32,33] (Fig. 3). Recent geological and geophysical studies indicate that most of the extension within rifts and the larger Basin and Range framework is accommodated through displacement on low-angle normal faults[22,23,24,29]. If the bounding faults of rifts link into such structures, and these fault systems cut entirely through the crust or lithosphere[34], then an asymmetrical rift structure would be expected. A symmetrical arrangement of opposing low-angle detachments is untenable, as movement on one would offset the other, probably leading to the locking of one of the detachments.

Several geometries have been proposed for the detachments that are thought to underlie rifts. Wernicke[34] has suggested that these faults or fault zones are essentially planar on a regional scale. Alternatively, they may bottom out at a major crustal discontinuity such as the brittle–ductile transition[31], and then plunge downwards at deep crustal ramps[23]. Similarly, great diversity is observed in the internal fault patterns of rifts. Both planar fault arrays and curved (listric) fans are encountered in continental rifts[35,36]. Differential rotation across larger rift faults, however, commonly indicates that they define a listric system. Listric faults curve in plan view as well as cross-section, but only towards the hanging wall block. Curvature towards the footwall is not kinematically viable. This effectively limits the horizontal extent of a single rift bounding fault (or system of parallel faults) to a few tens of kilometres (Fig. 2). Detailed seismic surveys reveal that rifts are typically broken into structurally-coherent compartments by transverse features[31,37] analogous to lateral and oblique ramps in contractional tectonic settings. These structures referred to as 'transfer faults'[23], are a syn-rift feature, although they may inherit a pre-existing structural grain.

On a larger scale, rifts also break up into sub-basins, which may form as isolated depositional systems (Fig. 2). Sub-basin boundaries may be defined by major transfer faults, pre-existing crustal discontinuities, or in some cases by younger strike-slip faults which simply offset an older rift. Significantly, rift asym-

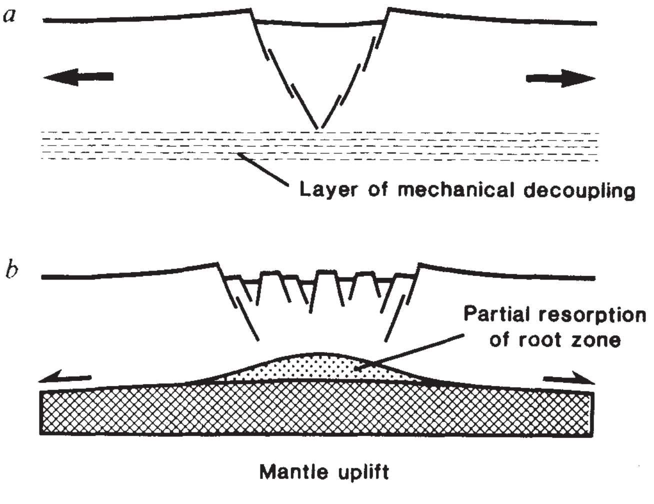

Fig. 3 Classical rift model of a brittle upper crust deforming above a ductile zone of mechanical decoupling (after ref. 30). The principal structural form of the rift itself is that of a symmetric graben, defining a triangular wedge-block at depth.

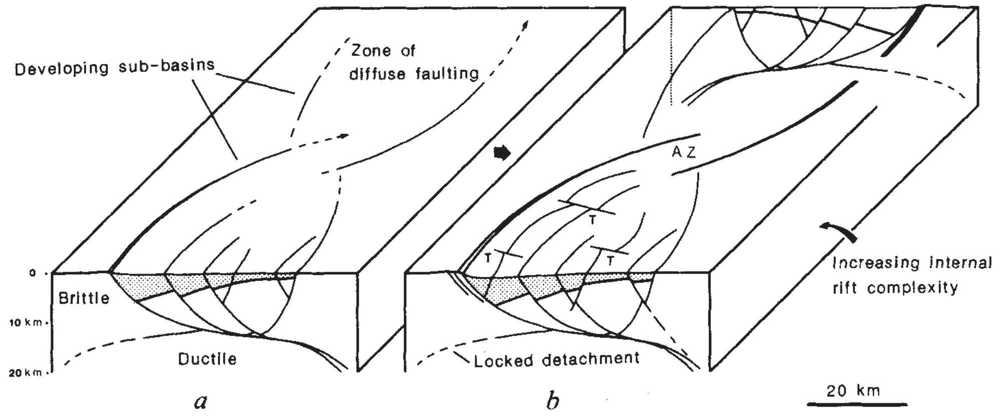

Fig. 4 Proposed model for the propagation of continental rifts. Upper crustal extension may initiate as a broad zone of diffuse faulting (*a*), but quickly evolves to a system composed of a few main listric faults (and perhaps in some cases planar fault-bounded blocks[35]) above two oppositely-directed detachments. For both detachments to remain operative, their deeper sections would need to be repeatedly recut, due to their mutually offsetting geometry. This rarely occurs, judging from the observed asymmetry of most continental rifts (Fig. 1), and one detachment locks. The active detachment propagates along the rift axis (towards the pole of opening), but curves inwards to form a large-scale scoop-like structure[44]. A theoretical treatment of this fault propagation would have to consider how this entire structure evolves—both the growth of the near-surface high-angle faults and the lateral propagation of the shallow-dipping detachments. Eventually the curving, active listric system departs enough from the overall rift trend to favour a new detachment system, which links to the old at a complex area referred to by Derksen and others[39] as an 'accommodation zone' (AZ). Again, opposing detachments may initially form, and the advantage may go to the detachment of opposite polarity. In this case, a reversal of rift asymmetry occurs, with greater down-faulting and sedimentation adjacent to the new main bounding fault (*b*). Detachment systems may overlap or merge at accommodation zones in a variety of configurations, but in the plan view shown here, a cross-section normal to the rift axis at the accommodation zone would actually appear to be a symmetric graben in form[39]. The important cross-faults in rifts referred to by Gibbs[23] as 'transfer faults' (T) are kinematically similar to accommodation zones, on a smaller scale.

metry frequently reverses at sub-basin boundaries, as was early documented for the Gulf of Suez Rift[38] (Fig. 2). The change in asymmetry between adjacent rift sub-basins strongly suggests that the underlying low-angle detachment system also changes polarity. The area of asymmetry reversal was first termed a "hinge zone" by Moustafa[38] for the associated regional dip reversal on rotated fault blocks. As asymmetry remains constant at some sub-basin boundaries, with only an offset in the rift bounding fault (Fig. 2), these major crustal structures have been more appropriately referred to as "accommodation zones"[39].

Young rifts, and those that failed at an early stage of continental extension, can then be thought of as large-scale half graben (mega-half graben of Cohen[40]), which flip more or less regularly along the axis of the rift (Figs 1, 2). When rifting is first initiated, two opposing low-angle detachments may develop simultaneously, and propagate in the direction of the pole of opening for the two diverging continental masses (Fig. 4). One of the detachment systems soon locks, and the half-graben form develops. At some point along the incipient rift zone, the opposing detachment gains the initial advantage, and a reversal of asymmetry is forced on the bounding fault system. There appears to be some degree of regularity in this process (Fig. 2), suggesting that the lateral limits on the dimensions of listric normal faults may, in part, control the spacing of accommodation zones. Extension across the rift zone and concomitant lithospheric thinning eventually become large enough to allow complete decoupling of the two now distinct lithospheric plates and the formation of new oceanic crust. At this point, the fault systems beneath opposite sides of the rift also become isolated and develop independent fault geometries.

Recent models for the propagation of continental rifts have attempted to assess the significance of early continental extension in the development of passive continental margins, and how that extension affects plate reconstructions[1-4]. Asymmetries inherent in the rift scenario described above may be reflected in the structural and stratigraphical record of rifts long after oceanic crust first appears. In particular, a geoseismic model, stratigraphical column or thermal maturation curve derived at one point on a passive margin may not accurately apply to rocks a fews tens of kilometres along strike, especially with respect to the initial rift sequence. Propagating oceanic rifts[41,42], where rift boundaries are almost immediately structurally decoupled, and propagating continental rifts, are undoubtedly quite disparate structural phenomena.

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