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Continental Rifting and the Implications For Plate Tectonic Reconstructions

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Previous plate tectonic reconstructions have tried to recreate the pre-rifting (Pangea) configuration of the continents by matching contours or lineaments that are thought to represent the continental boundaries. Such reconstructions have the inherent assumptions that no extension occurs within the continent during rifting, that the continental boundaries are isochrons, and that the continents rift without distortion. This paper proposes a model for continental breakup with distortion, where ocean basins are formed by propagating rifts. This model challenges the assumptions made by previous reconstructions and presents a new method for representing the pre-rift geometry of the continents. As rifts propagate through a continent, the region in front of the rift extends by continental faulting and crustal thinning while the region behind the rift expands by seafloor spreading. The propagating rift model implies that large amounts of continental extension (up to 150 km) occur and that the continental boundaries are not isochrons. This extension due to rifting results in 'apparent' overlap when the continents are returned to their original configuration. Because of the gradational nature of this extension, the best representation of the pre-rift configuration is obtained by matching the initial rifting point and having overlap increase in the direction of rift propagation. The overlap is equivalent to the amount of extension that has taken place on both continental edges. Reconstructions based on this model are presented for the Gulf of California, the Gulf of Aden, the Norwegian-Greenland Sea, and the South Atlantic Ocean. They are able to resolve the discrepancies that occur when rigid plate tectonics are applied. This model has implications that can be used to predict the age and structure of the continental shelves and the location and orientation of the oldest magnetic isochrons.

Introduction

Plate tectonic reconstructions rely mainly upon the superposition of magnetic isochrons to infer the past relative positions of the continents. The superposition of isochrons is accomplished by moving the plates around a pole of rotation and is therefore based upon the assumption that the plates behave rigidly. This assumption of plate rigidity accurately describes the plate motion back to the oldest continuous magnetic isochrons.

In going back to the initial rifting and determining a closure (Pangea) configuration of the plates, several different criteria have been used. *Bullard et al.* [1965] used a least squares fit of the 500 fm isobath to match the continental shelves. *LePichon et al.* [1977] recognized that one particular isobath did not necessarily mark the true edge of the continent. They argued that different margins should be at different isobaths depending on the age of the rift. The difference would then be attributed to subsidence and the modification of continental margins with time. *Rabinowitz and LaBreque* [1979] went a step further and, instead of using isobaths, used the presence of lineated magnetic and gravity anomalies bordering the continental margins as being diagnostic of the ocean-continent boundary.

Once the locations of the continental boundaries were determined, they were superimposed by a finite rotation around a pole of opening in order to arrive at a pre-rift configuration. Yet assumptions used to create a pre-rift configuration are in effect assumptions about how continents rift. Since all the openings were described as a rotation that matched continental edges, these reconstructions imply that continents rift rigidly (without distortion) and therefore oceans open instantaneously.

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This paper argues that continents do not rift instantaneously but, rather, they open by a propagating rift. As long as a continent rifts progressively, there must be variable amounts of continental extension. The area where seafloor has not been created must thin and extend to equal the area of seafloor that is created within the oceanic rift. Therefore, a continental boundary must undergo variable amounts of extension and is not an isochron. Thus in making reconstructions of the pre-rift configuration, no single boundary line can be used. Although a single boundary line may represent the edge of the continent, when two such lines are superimposed they do not represent the pre-rift configuration. A more accurate representation of the pre-rift configuration is obtained by matching the initial rifting point of the continent and having overlap increase in the direction of rift propagation. The overlap represents the amount of extension that occurred in the continent while the rift propagated through the continent.

We will begin with a discussion of how the propagating rift provides a model for continental breakup and then consider the implications of this model for plate tectonic reconstructions and related features of the ocean basins and continental shelves. The Gulf of California and the Gulf of Aden are used as examples of current propagating rifts, and the characteristics of these areas are compared with those that would be predicted by the propagating rift model. Finally, pre-rift configurations as described by this model are shown for the Norwegian-Greenland Sea and the South Atlantic Ocean, and supporting evidence for these reconstructions is presented.

Propagating Rift Model for Continental Breakup

The term 'propagating rift' is used simply to mean noninstantaneous rifting and is considered synonymous with progressive rifting and asynchronous rifting. Although the concept of propagating rifts is not new [*Herron*, 1972; *Bowin*, 1974; *Molnar et al.*, 1975; *Shih and Molnar*, 1975; *Hey*, 1977; *Hey and Vogt*, 1977; *Courtillot*, 1980; *Hey et al.*, 1980], the implications of such a model have never been considered when making plate tectonic reconstructions of the continents.

Hey et al. [1980] present a propagating rift model for continental breakup where the compression (angular closing) in front of the rift is equal to the angular opening behind the rift tip. In contrast to this model, we propose a propagating rift model with extension rather than compression in front of the rift tip. Our model is similar to that suggested by *Courtillot* [1980] to describe the progressive opening of the Gulf of Aden. Although we suggest extension in front of the rift tip, the actual propagation of the rift is based on crack propagation theory. As a rift propagates through a continent, it orients itself to the stress field of the lithosphere and progresses in a direction normal to the direction of least compressive stress. Any irregularities in the lithosphere would serve to change locally the regional stress field, and this in turn would cause the direction of rift propagation to shift and remain perpendicular to the resulting direction of least compressive stress. Such a local deflection of the regional stress field has been noted in the Spanish Peaks [*Ode*, 1957; *Johnson*, 1961; *Muller and Pollard*, 1977], where an intrusion in the area created a local stress field. Cracks associated with dike emplacement tended to follow the resulting stress. In the case of a hotspot beneath a continent, the associated swell and thinned lithosphere would create a local stress field. This local stress field could cause a deflection of the regional stress trajectories. Thus a hotspot, or any other local stress field, could act as a stress guide for the initial rifting. The hotspot-triple junction rifting model [*Burke and Dewey*, 1973] states that when a continent comes to rest over a hotspot, a dome swells up that is subject to fracturing. The model suggests that these rifts are the seed from which oceans grow, and the fracture would move away from the hotspot. As an alternative to the Burke and Dewey model, we suggest that with a propagating rift the thinned lithosphere over a hotspot would act merely as a stress guide, and the rift would move along the 'pre-weakened' track either toward or away from the hotspot. This agrees with the reconstructions of *Morgan* [1980] which show that many hotspot tracks become the locus of later rifting.

As a rift propagates through a continent, it may reach areas where the rift either bifurcates or changes direction. This could be caused by a local stress field that creates a least work propagation direction different from the regionally favored direction. As a rift develops in a locally favored direction, it may find that another direction of propagation is easier from a regional point of view. Thus, the local direction may be abandoned, leaving an aulacogen. Failed rifts would not be restricted to areas of doming caused by hotspots or to being at any particular orientation from the main rift. Failed rifts could also be of varing size and advancement depending on the size of the deflection of the regional stress field.

IMPLICATIONS FOR PLATE TECTONIC RECONSTRUCTIONS

Previous reconstructions have been based on the assumption that if one could find the boundary lines which represent the edge of the continental crust, then these boundary lines should match in a closure orientation that represents the prerifting configuration of the continents. However, we argue that the continents rift by means of propagating rifts rather than by splitting instantaneously. Therefore, no geometric fit of the continental edges can represent their pre-rifting geometry.

Consider the situation where a continent is under tension (Figure 1*a*), and a section of it begins to rift. As the rift forms in one part of the continent creating oceanic crust (Figure

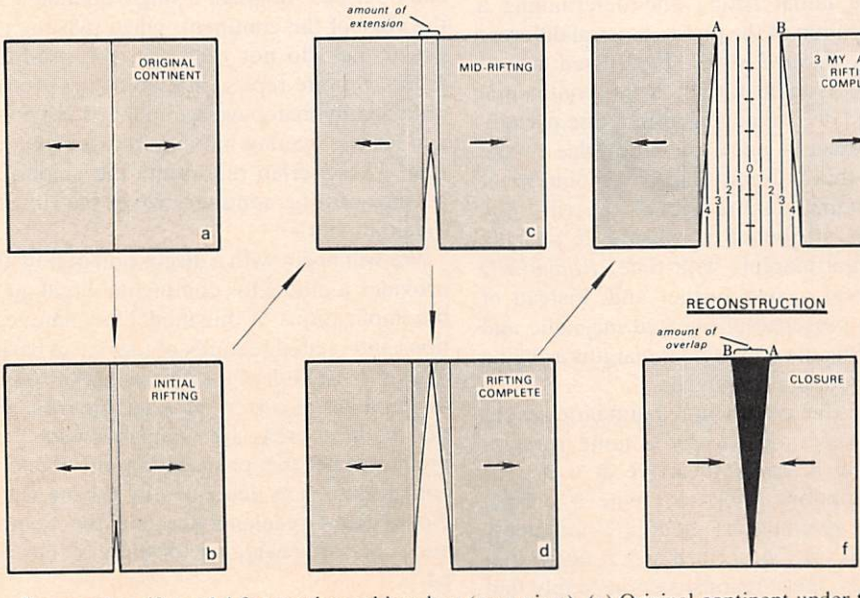

Fig. 1. Propagating rift model for continental breakup (map view). (a) Original continent under tension. (b) Initial rifting with the amount of extension represented between parallel lines. (c) Mid rifting. Seafloor spreading is occuring in the lower half of the continent while crustal thinning and extension occurs in the upper half. (d) Rifting complete. Continental edges have undergone extension that increases in the direction of rifting. (e) 3 my after rifting complete. Oldest seafloor is found in the part of the ocean where rifting began. Oldest isochrons converge with the ocean-continent boundary. Continental edge is not an isochron. (f) Reconstruction of the pre-rift configuration. Extension due to rifting results in 'apparent' overlap when the continents are returned to their pre-rift geometry.

1*b*), the area in front of the rift must undergo extension over a distributed region in order to balance the amount of seafloor being created within the rift. Although the extension is distributed over a large region, in the figures the amount of extension is represented between the two parallel lines. As the rift continues to propagate through the continent (Figure 1*c*), more seafloor is created within the rift, and consequently more extension must occur in the part of the continent that is in front of the rift. Although the amount of extension continually increases at any given area in front of the rift, no more extension will occur within the continent once the rift reaches that point. In other words, it is only the continental area in front of the rift that must thin and extend to compensate for the area of seafloor being created within the rift. Once rifting is complete (Figure 1*d*), no more extension of the continental crust occurs, and the plates move away rigidly (Figure 1*e*). Thus, the continental edges have undergone variable amounts of distributed extension. The distributed extension is least where the rift began and increases in the direction of rift propagation.

After rigid seafloor spreading has taken place, several consequences of the propagating rift can still be seen. As Figure 1*e* shows, the oldest seafloor will occur closest to the point where the rift originated. For an ocean that resulted from a northward propagating rift, the oldest magnetic isochrons and the oldest drilling dates would then be found in the southern part of the ocean. Another consequence of the model is that the continental margin is not an isochron and thus should not be parallel to the magnetic isochrons. The oldest magnetic isochrons converge with the continental margin, and this convergence occurs in the direction of rift propagation. Thus, the results of a propagating rift are distinguishable from rigid opening around a pole of rotation. Rigid opening results in a continental margin that is an isochron, while rift propagation results in the continental margin having an age progression. Furthermore, in rigid opening the oldest magnetic isochrons would be continuous throughout the ocean basin converging toward a pole of opening, while a propagating rift results in the oldest magnetic isochrons converging with the continental margin.

When making plate tectonic reconstructions of the prerifting configuration, the variable amount of continental extension described previously must be taken into account. Because continental extension increases in the direction of rift propagation, the continents should be matched at the initial points of rifting with overlap increasing in the direction of rift propagation (Figure 1*f*). The 'apparent' overlap then represents the amount of continental extension that took place during the rifting process. In principle, the amount of extension that occurred during rifting can be determined. From Figure 1*d* it is seen that the amount of extension at the end of the rift must equal the amount of seafloor at the opening of the rift. Therefore, by looking at the angle at which the magnetic isochrons coverge with the continental boundary, one can determine the amount of extension that has taken place. This amount of extension is the amount of overlap that should be shown in a reconstruction.

GULF OF CALIFORNIA–A CURRENT PROPAGATING RIFT

The large shear component of the rifting in the Gulf of California complicates this areas tectonic structure. As a consequence of this oblique motion, the ocean basin consists of a series of spreading centers separated by transform faults. Although this area is usually thought of as pull-apart on a strike-slip system, it exhibits characteristics that suggest the effects of a propagating rift.

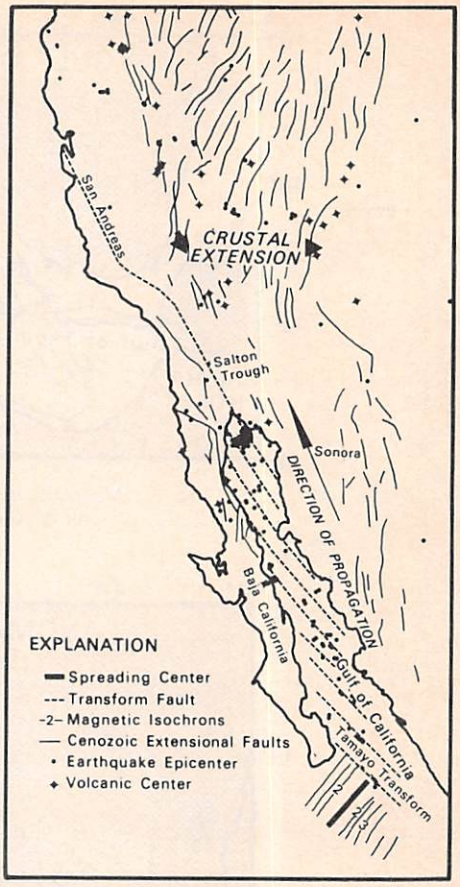

Fig. 2. Gulf of California showing propagating nature of rift. Transition is from mature oceanic crust to thinned continental crust under extension. Earthquakes shown are magnitude 5 or greater not associated with the San Andreas Fault system [redrawn from *Drummond*, 1981].

In applying the propagating rift model to the Gulf of California, the predictions of the model should be confirmed by the regions tectonic structure. We expect that (1) the ocean basin gets younger in the direction of rift propagation; (2) extension occurs within the continental region in front of the rift; and (3) once the rift penetrates into an area, the extension within the continent ceases as expansion within the continent can now be accomplished by seafloor spreading.

Northward through the gulf, the spreading centers become progressively less well developed than the mature, fully oceanic structure found south of the opening [*Lonsdale and Lawver*, 1980]. In the northern part of the gulf, the seafloor structure consists of shallow troughs with tensional faulting [*Henyey and Bischoff*, 1973; *Lonsdale and Lawver*, 1980]. North of the gulf, in the Salton Trough (Figure 2), the crust is under extension with spreading found in the offsets of the strike-slip faults [*Weaver and Hill*, 1978]. Tension is also characteristic of the continental crust north of the rift, where at least tens of kilometers of crustal extension accompanied by late Cenozoic block faulting have occurred in the southern Basin and Range Province. The crust is thinner (averaging 32–34 km) under the Basin and Range Province than

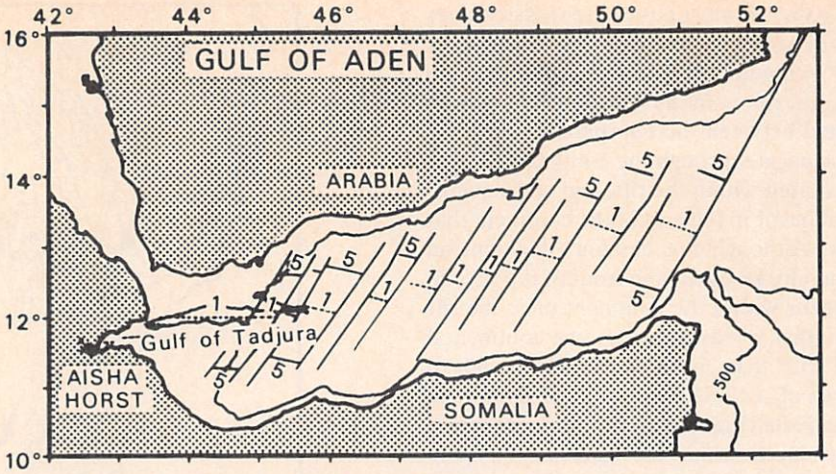

Fig. 3. Magnetic anomaly correlations and fracture zones in the Gulf of Aden [redrawn from *Cochran*, 1981].

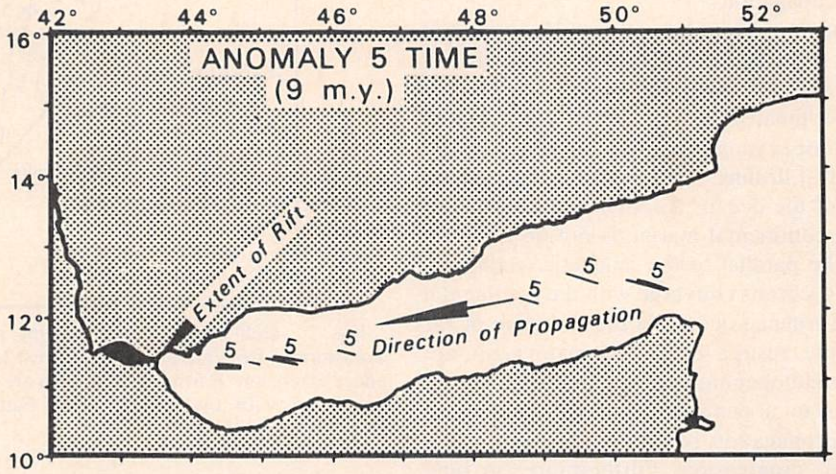

Fig. 4. Paleographic reconstruction of the Gulf of Aden after *Laughton et al.* [1970], based on the *LePichon* [1968] pole of rotation at 26°N, 21°E. Western end of the Gulf is closed out by continental crust even though eastward the Gulf is underlain by oceanic crust.

under the provinces to either side. Furthermore, this thinned crust reaches a minimum (29–30 km) as one approaches the region just north of the Gulf [*Prodehl*, 1970]. Thus the Gulf of California is characterized by the transition from mature oceanic crust to thinned continental crust under extension. Such asynchronous rifting implies a northward propagating rift with continental extension occurring in front of the rift.

According to the propagating rift model, the amount of extension continually increases within the continental area in front of the rift in order to compensate for the amount of seafloor being created within the rift. Therefore, we expect continental extension in coastal Sonora prior to the time the rift penetrated that far north. Once the rift reached Sonora, we predict this continental extension to stop as seafloor spreading takes place within the rift.

The late Cenozoic structure of coastal Sonora and northern Baja supports the temporal predictions of the model. The following discussion of the timing of events in this region is taken from *Dokka and Merriam* [1982], and the reader is refered to them for references. The late Cenozoic structure of coastal Sonora is similar to that of northeastern Baja. The area was broken and tilted by north to northwest trending faults between 12 and 8 m.y. ago. However, rocks less than 8 m.y. old are not tilted extensively although they are cut by northwest trending stirke seperation faults of the San Andreas system. In northwestern Baja extension occured between 17 and 9 m.y. ago, transforming a region of low relief to one dominated by north trending basins and ranges. Faults of the San Andreas system that lie south of the Transverse range were initiated between 8 and 6 m.y. ago. *Dokka and Merriam* [1982] concluded that these dates suggest a pre-8 m.y. interval extension in coastal Sonora could not have been transform related. The proposed propagating rift model provides an explanation for this period of extension. The extension is attributed to expansion north of the rift to compensate for the amount of spreading within the rift (as shown in Figure 1). Once the rift progressed as far north as this area, the continental extension ceased as spreading became localized within the rift. As seen in Figure 2, although there are many earthquakes within the gulf, there are presently very few earthquakes within continental crust south of the rift tip.

Although the Gulf of California has been generally thought of as pull-apart on a strike slip system, another explanation

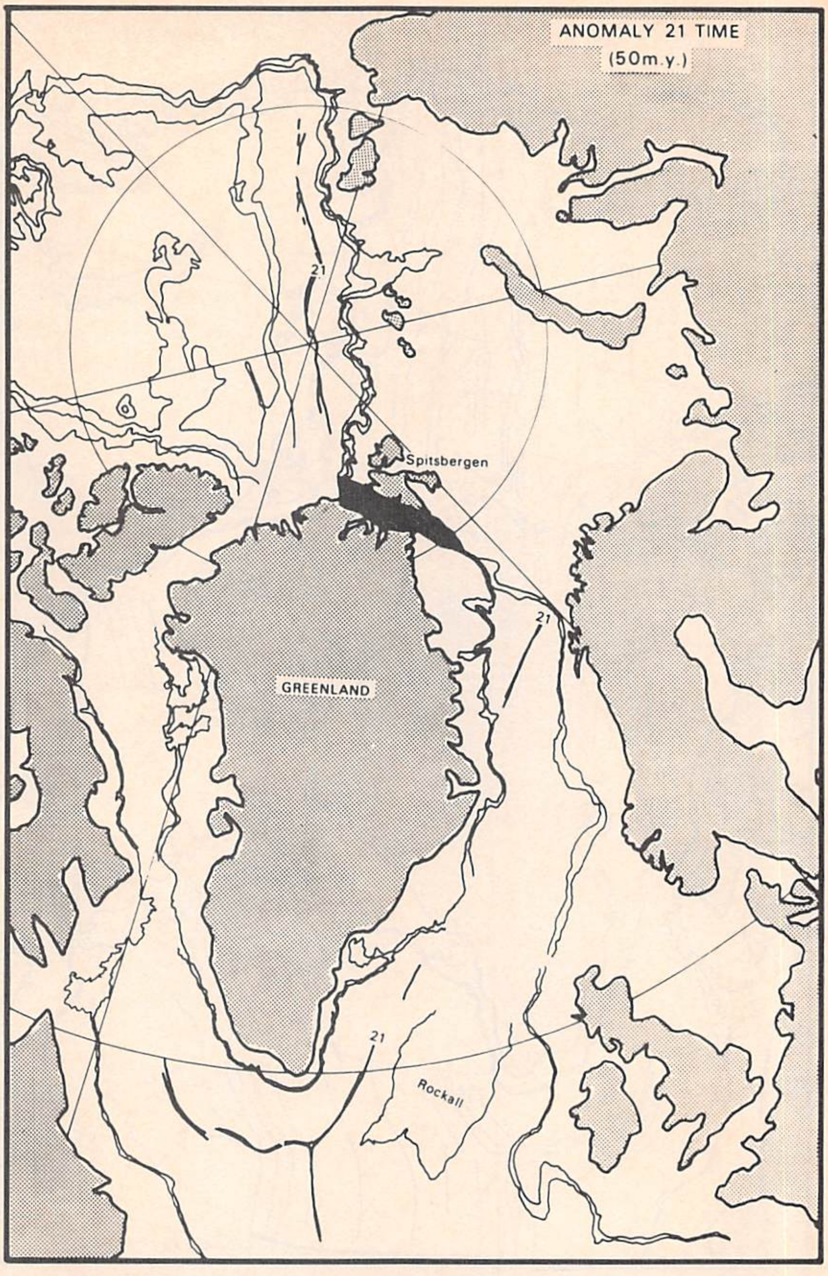

Fig. 5. Reconstruction of the Norwegian-Greenland Sea and Arctic Ocean at anomaly 21 time. Area of 'apparent' overlap is blackened. Stereo polar projection with Greenland at its present location. Eurasia is rotated 9.20°cw around the pole at 53.50°N, 133.10°E. North America and the Lomonosov Ridge are rotated 3.20°ccw around the pole at 63.97°N, 76.60°W (redrawn from G. E. Vink, manuscript in preparation, 1982).

for this area, which does not require transcurrent faults through Baja to some offshore 'pre-San Andreas' strike-slip fault, can be provided by the propagating rift model. What this area further illustrates is that in some 'future' time reconstructions that will match the shelf edge of Baja to Mexico and the 'shelves' of 'Nevada' to 'Utah' will be wrong, because, as we can see today, the Gulf of California already has 250 km of ocean floor before any breakthrough has occurred in Nevada.

GULF OF ADEN: A RECENTLY RIFTED OCEAN BASIN

As described in the discussion of the model, one result of propagating rifts is the convergence of the oldest isochrons with the continental boundary. This is clearly evidenced in the Gulf of Aden, where *Courtillot* [1980] has used the age of the earliest magnetic anomalies and the first tholeiitic basalts to propose that the Gulf of Aden opened as a result of a rift that propagated westward into the African continent at a rate of 30 mm/yr.

Magnetic anomaly data from the Gulf of Aden indicate a clear sequence of seafloor spreading out to anomaly 5 (9 m.y. BP) in the eastern part of the gulf (Figure 3). However, anomalies 4 and 5 are not found west of 44°W [*Laughton et al.*, 1970; *Cochran*, 1981]. Continuing westward into the Gulf of Tadjurah, the oldest anomalies are 2′ (2.5 m.y.), while further westward in the Ghoulbet-Asal rift only the axial anomaly is found (<1 m.y.) [*Courtillot*, 1980]. Reconstructions of the Gulf of Aden support this proggressive rifting model.

Laughton et al. [1970] made a paleogeographic recon-

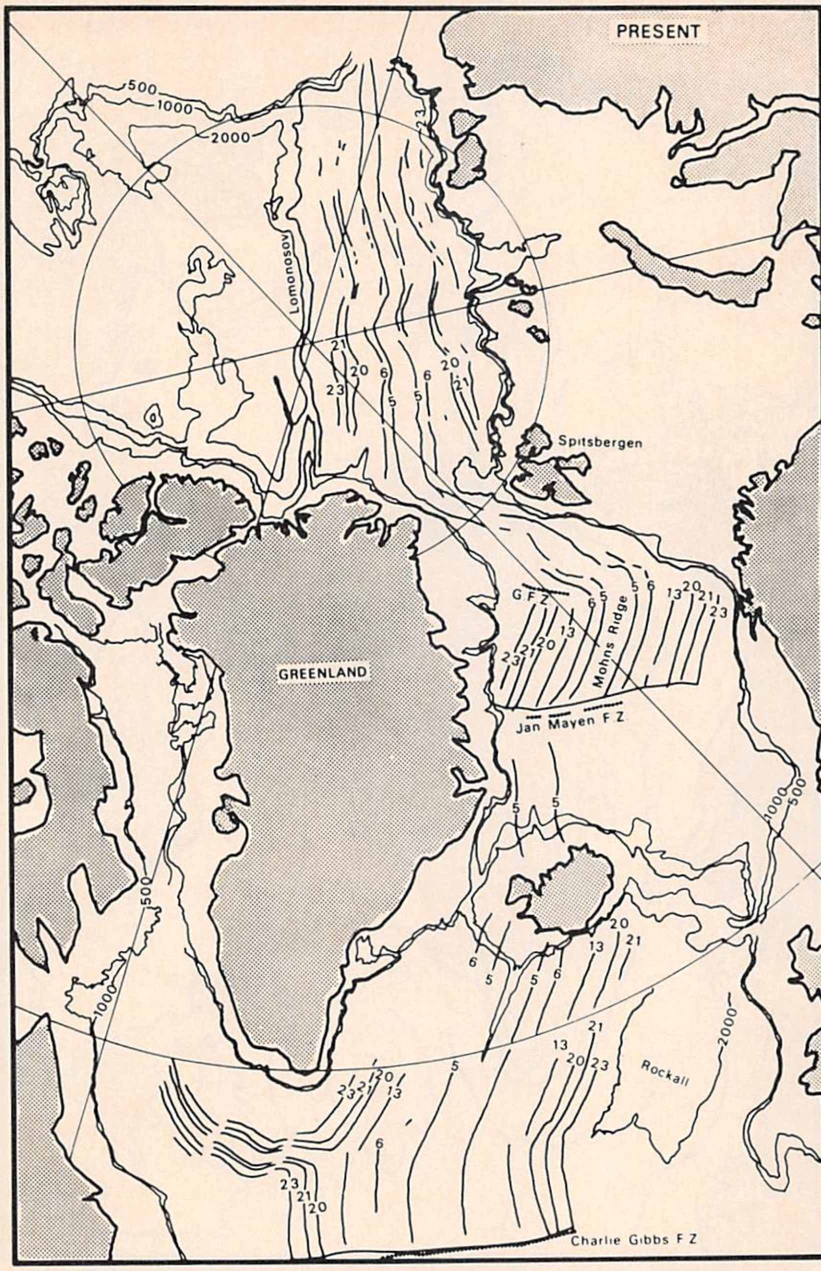

Fig. 6. Present day map of the Norwegian-Greenland Sea and Arctic Ocean showing magnetic anomaly correlations, flow lines and fracture zone trends (redrawn from G. E. Vink, manuscript in preparation, 1982).

struction of the Gulf of Aden by removing all crust younger than anomaly 5 and closing Arabia and Somalia along the small circles of the transform faults (Figure 4). A problem pointed out in their reconstruction was that 'If the Aisha Horst has not moved relative to the Somalia Plateau, then at this time the western end of the Gulf of Aden would have been closed by continental crust even though eastwards the Gulf itself was underlain by oceanic crust' [*Laughton et al.*, 1970, p. 263]. This problem becomes more pronounced when the seafloor older than anomaly 5 is considered. Each successive reconstruction results in more continental overlap with the point of convergence moving eastwards. Detailed compilation maps of the geology on both sides of the Gulf of Aden were prepared by *Beydoun* [1970]. Reconstructions were then made to match the 100- and 500-fathom bathymetric contours. *Beydoun* [1970] noted that although the reconstructions were supported by the continuity of geological features across the two sides, overlap of basement and Mesozoic rocks occurred in the west. This amount of overlap increased appreciably when the ocean was further closed to the 100-fathom fit. The overlap also began further to the east for the 100-fathom fit than for the 500-fathom fit.

Reconstructions of the Gulf of Aden result in large amounts of overlap which, as the ocean basin is closed out, occur first in the western part of the Gulf. Possible explanations for this overlap are that either the Aisha Horst moved as a microplate relative to the Somalia block along transform and transcurrent faults or the initial stage of separation of Arabia from Somalia was accompanied by complex faulting that resulted in a stretching and thinning of the crust [*Laughton et al.*, 1970]. The propagating rift model provides a mechanism for creating the crustal extension seen as 'apparent' overlap in the reconstructions. A westward propagating rift would also explain why the overlap occurs first in

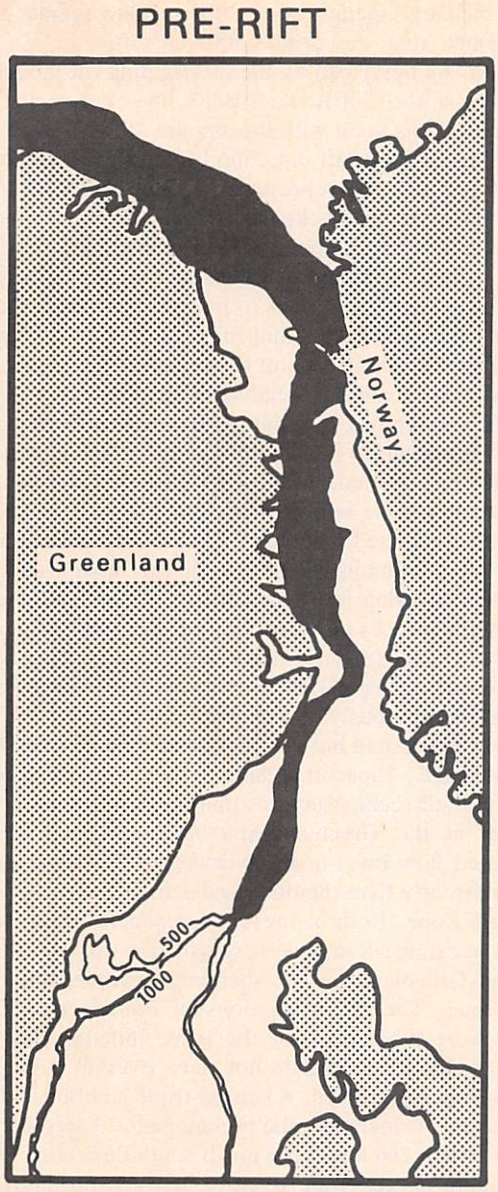

Fig. 7. Pre-rift representation of the Norwigian-Greenland Sea with area of 'apparent' overlap shown in black. Continental extension is equivalent to one-half the amount of overlap shown. This representation was obtained by rotating Eurasis 14.50°cw around the pole at 52.34°N, 124.90°E.

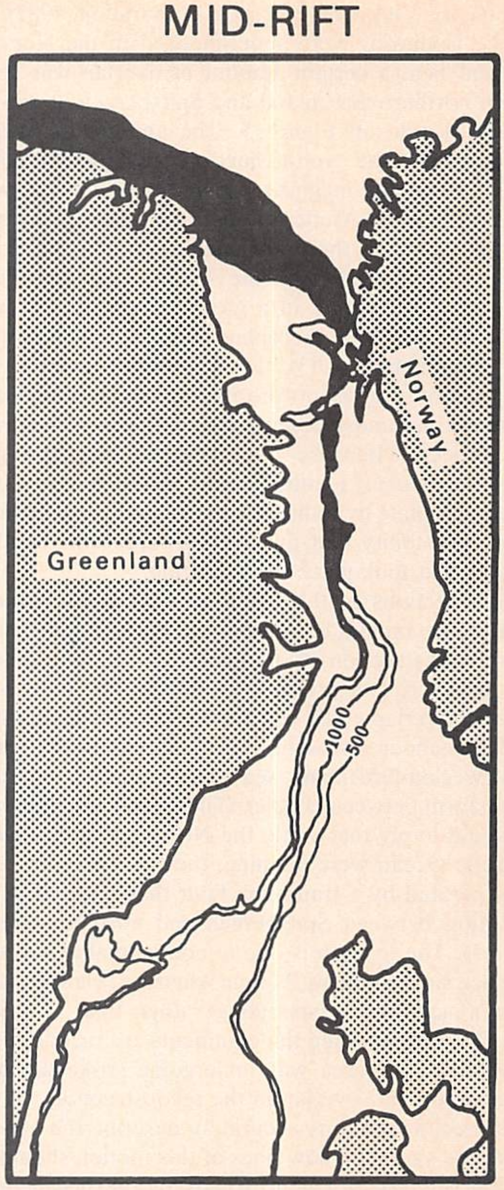

Fig. 8. Mid-rift representation of the Norwegian-Greenland Sea with areas of 'apparent' overlap blackened. This representation was obtained by rotating Eurasia 13.38°cw around the pole at 52.34°N 124.90°E.

the westward direction, because the propagating rift model requires that continental extension increases in the direction of rifting. In the anomaly 5 reconstruction (Figure 4), overlap exists at 43.5°W, because at this time 43.5°W was the extent of the rift and thus explains the observation that no identification of anomaly 5 or older anomalies are found west of this point [*Laughton et al.*, 1970; *Cochran*, 1981]. If the furthest extent of the rift is presently west of the Gulf of Tadjura, then this would mean that the rift has propagated at least 230 km since anomaly 5 time. Based on the reconstruction, this yields a minimum propagation rate of 25 mm/yr, which is similar to the rate of 30 mm/yr suggested by *Courtillot* [1980] based on magnetic anomaly data. Continental extension of 65–200% in a zone approximately 200 km wide prior to the initiation of seafloor spreading at a single discrete spreading center has been postulated [*Cochran*, 1981]. Judging by the amount of overlap produced by the reconstructions and predicted by a 25 mm/yr rift propagation rate, extension of this magnitude is reasonable.

The premises of rigid plate tectonic reconstructions fail to provide a pre-rift configuration or to explain the magnetic anomaly pattern in the Gulf of Aden. Recent detailed aeromagnetic surveys of this region [*Courtillot et al.*, 1980] indicate that the rifting was progressive and moved in a westward direction. A westward propagating rift that causes continental extension does provide an explanation for the 'apparent' continental overlap and the absence of the anomaly 5 magnetic isochron west of 44.5°W, thereby resolving discrepancies seen in the rigid-plate reconstructions.

IMPLICATIONS FOR RECONSTRUCTIONS OF THE NORWEGIAN-GREENLAND SEA

The implications of the propagating rift model were first noted while making reconstructions of the North Atlantic

Ocean (G. E. Vink, manuscript in preparation, 1982). When magnetic isochrons were superimposed in the Norwegian-Greenland Sea, a certain amount of overlap was required between northern Greenland and Spitsbergen as shown for anomaly 21 time in Figure 5. The amount of overlap is constrained by the well-defined triple junction south of Greenland and the magnetic isochrons of the Norwegian-Greenland Sea and Arctic Ocean. To explain this overlap in the reconstructions three alternative possibilities exist: (1) the magnetic anomalies in the North Atlantic have been repeatedly misidentified in a gross manner or (2) the area consists of a series of microplates whose boundaries are no longer identifiable or (3) the amount of overlap in the reconstructions represents the amount of extension that took place in northernmost Greenland and Spitsbergen during the rifting process. Because our synthetic magnetic profiles confirm the anomaly identifications, and because the unidentifiable microplate hypothesis is untestable, we will deal only with the possibility that the overlap represents continental extension that took place during rifting.

Reconstructions of the Norwegian-Greenland Sea show that the same amount of overlap was derived independently for the reconstruction of anomalies 23, 21, and 20 (G. E. Vink, manuscript in preparation, 1982). The only way the amount of overlap could remain the same over this 10 m.y. period of seafloor spreading is if the direction of opening of the Norwegian-Greenland Sea was parallel to the strike of the transform between northern Greenland and Spitsbergen. This would imply that while the Norwegian-Greenland Sea and Arctic Ocean were opening, the two spreading centers were separated by a transform fault that resulted in strike-slip motion between Spitsbergen and northern Greenland (Figure 5). The overlap is due to continental extension that took place since anomaly 21 time when the relative motion in this area acquired a spreading rather than a strike-slip nature. Therefore, when the continents are reconstructed to a time when this area was undergoing strike-slip motion, there is 'apparent' overlap in the reconstruction.

If the reconstructions accurately describe the early plate motion, the synthetic flow lines of this motion should match the observed fracture zone trends of the ocean floor. In Figure 6 both the synthetic flow lines (oblique to magnetic isochrons) and the fracture zone trends (dotted lines) are shown. The trends of the Greenland Fracture Zone (GFZ) and Jan Mayen Fracture Zone are in good agreement with the synthetic flow lines. For the early opening motion, all of these are parallel to the strike of the overlap between northern Greenland and Spitsbergen, thus corresponding to the direction of early strike-slip motion. Because the overlap in the reconstructions does not disappear until a time younger than anomaly 13, the upper limit on the age of the seafloor in this area is 35 m.y. This is confirmed by the anomaly identifications.

With the evidence presented above it is likely that the rifting in the Norwegian-Greenland Sea was accompanied by large amounts of extension. When the continents are returned to their pre-rifting positions, this extension results in 'apparent' overlap in the reconstructions. The overlap between northern Greenland and Spitsbergen remains until a time younger than anomaly 13 because this area did not start spreading, and, hence, the continents on both sides of the transform fault did not undergo extension and thinning until the plate motion changed.

For the early opening of the Norwegian-Greenland Sea, it is assumed that the proto-continent rifted in a northern direction. As described by the propagating rift model, when the rift was north of Rockall Bank, the continental boundaries met at this point with the amount of 'apparent' overlap increasing in the uprift direction. This pre-rifting configuration of the plates is represented in Figure 7 with areas of 'apparent' overlap blackened. If the maximum amount of 'apparent' overlap is about 200 km, this implies that 200 km is the maximum amount of extension for the two continental edges. As the rift continues to propagate through the proto-continent, it will reach a mid-rift configuration as represented in Figure 8. At this point the region behind the rift tip is expanding by seafloor spreading, while the region in front of the rift is extending by faulting and crustal thinning. Once the rift propagation is complete and the Norwegian-Greenland Sea has opened, no more extension of the continental crust occurs. This is represented in Figure 5 where rifting has been complete for at least 10 m.y., the oceanic spreading center is continuous, and the plates move rigidly. The 'apparent' overlap between northern Greenland and Spitsbergen remains, as previously discussed, until the motion in this area changes from a strike-slip to a spreading nature.

Reconstructions of the Norwegian-Greenland Sea have been made previously by *Talwani and Eldholm* [1977] and in a widely distributed but yet unpublished manuscript by J. D. Phillips and C. Tapscott (1980). *Talwani and Eldholm* [1977] noted in their reconstructions that there was a major area of overlap in the Greenland-Spitsbergen fit and that their calculated flow lines in the Norwegian Sea have azimuths more northerly than the observed azimuth of the Greenland Fracture Zone. Both of these discrepancies are resolved if the propagating rift model is used and the 'apparent' overlap between Greenland and Spitsbergen is accepted until anomaly 13 time. The reconstructions of *Phillips and Tapscott* [1980] were made without the triple junction data to the south of Greenland and do not show overlap in the Greenland-Spitsbergen region. When the triple junction and Labrador Sea data is included, the pre-anomaly 13 reconstructions shift by up to 200 km in the north-south direction. With this shift, there is 'apparent' overlap between northern Greenland and Svalbard.

Implications for Reconstructions of the South Atlantic

Hey and Vogt [1977] and *Hey* [1978] have proposed that the Atlantic Ocean opened by a propagating rift. However, this concept has not been implemented when making plate tectonic reconstructions of the South Atlantic. Reconstructions depicting the pre-rift positions of the continents around the South Atlantic have been made by using the isobaths [*Bullard et al.*, 1965], by using gravity and magnetic anomalies to infer the continental edges [*Rabinowitz and Labreque*, 1979], and by matching tectonic features [*Martin et al.*, 1981].

The Bullard fit, shown in Figure 9, matches the 1000 m isobath and minimizes the amount of gaps and overlaps. In the southern part of the reconstruction, however, there remains a gap of up to 250 km of seafloor between the Falkland Plateau and Africa. The Deep Sea Drilling Project (DSDP) leg 36 has confirmed that the Falkland Plateau is a continental remnant [*Barker et al.*, 1976]. Since the Falkland Plateau is a submerged portion of South America, this gap

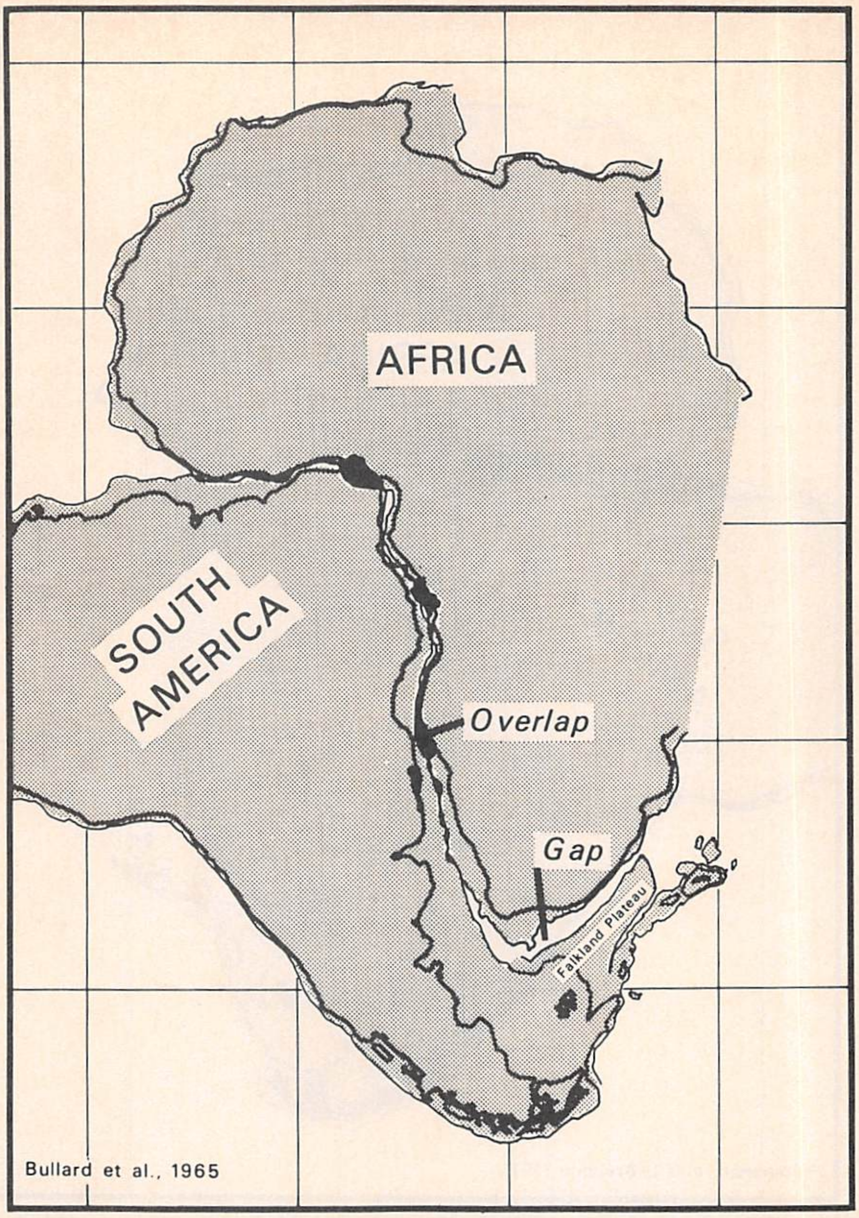

Fig. 9. The fit of *Bullard et al.* [1965] using the 1000-m isobath to represent the continental edge and the 3000-m isobath for the Falkland Plateau. Areas of overlap are blackened.

must be closed in a reconstruction. The choice of another isobath for the Falkland Plateau does not eliminate this gap, because the escarpment of the plateau is so steep that there is no significant distance between isobaths. Even by using a deeper isobath for South America, this gap can be reduced only by about 50 km. The shape of the continents places further constraints on the reconstruction, because any attempt to reduce the gap by moving South America northward results in overlap in the northern part of Brazil. Thus, while the Bullard fit may provide a good fit for the 1000 m isobath in the northern part of the South Atlantic, it does not provide a realistic representation of Pangea.

Rabinowitz and Labrecque [1979] pointed out that the ocean-continent boundary is not necessarily located at any particular isobath. In their reconstructions they used linear magnetic and gravity anomalies to separate oceanic from continental basement. Their choice for the boundary has been criticized because another interpretation of the gravity data suggests that the continent-ocean transition is a wide zone of thinned continental crust with the boundary being situated further seaward at the base of the continental slope [*Scrutton,* 1977]. The reconstruction of *Rabinowitz and Labrecque* [1979] is shown in Figure 10 with the inclusion of the 1000 m isobath so that the reconstruction can be compared with the Bullard fit. Although the gap between the Falkland Plateau and Africa has been reduced to a maximum of about 100 km, this is accomplished only by having large amounts of overlap along the northern part of the reconstruction.

Martin et al. [1981] proposed a revised fit based on tectonic features crossing from one continent to another. The southern part of their reconstruction is looser than that of *Rabinowitz and Labrecque* [1977], although the overlap along the northern coast of Brazil is not significantly reduced. Although their fit improves the alignment of the tectonic features used, *Martin et al.* [1981] recognize that a

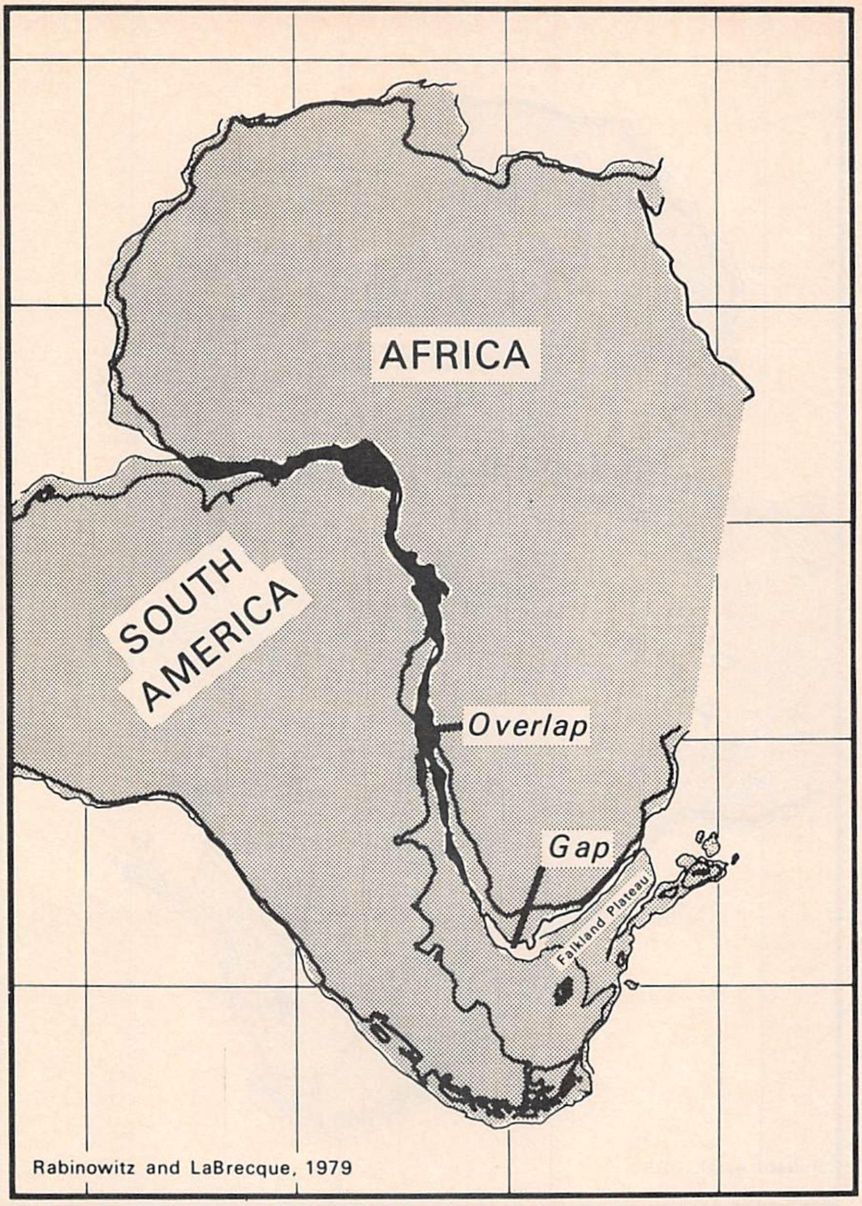

Fig. 10. The fit of *Rabinowitz and LaBrecque* [1979] using the 1000-m isobath for comparison (3000-m for Falkland Plateau). Areas of overlap are blackened.

reconstruction cannot be produced which is everywhere accurate unless second-order movements constituting a breakdown of the assumption of rigid plate behavior are accounted for.

It has been recognized that extensional features such as the Benue Trough were associated with rifting and that rotation parameters to fit the northern part of Africa may be significantly different from the southern fit parameters [*Martin et al.*, 1981; *Pindell and Dewey*, 1982]. The reconstructions of *Pindell and Dewey* [1982] do in fact use a two plate system for Africa, arguing that remnant extension exists today in the Benue Trough and so the present day shape of Africa should not be used in Pangea reconstructions. This is inversely a step toward taking into account the extension due to rifting: One can either close every rift and graben and then match the continental boundaries or else leave the continents in their present shape and have overlap in the reconstruction represent the extension due to rifting. The prospect of closing every extensional feature around the shores of the South Atlantic, plus accurately locating where the ocean-continent boundary would then be, makes the first method untenable. Therefore, this paper presents in Figure 11 a representation of the South Atlantic pre-rift configuration where the continents remain in their present day shape and overlap represents rifting-related extension.

Further evidence for progressive rifting in the South Atlantic is shown by the magnetic isochrons. If we assume that the South Atlantic rift propagated northward, this would explain why the oldest magnetic isochrons—anomaly M11 near the margin of South Africa and anomaly M4 near South America [*Rabinowitz and Labrecque*, 1979]—are found only in the southern part of the ocean. The M4 and M11 isochrons also converge with the continental boundary, and the direction of this convergence is northward in the proposed direction of rift propagation.

In summary, there is clear evidence that the South Atlan-

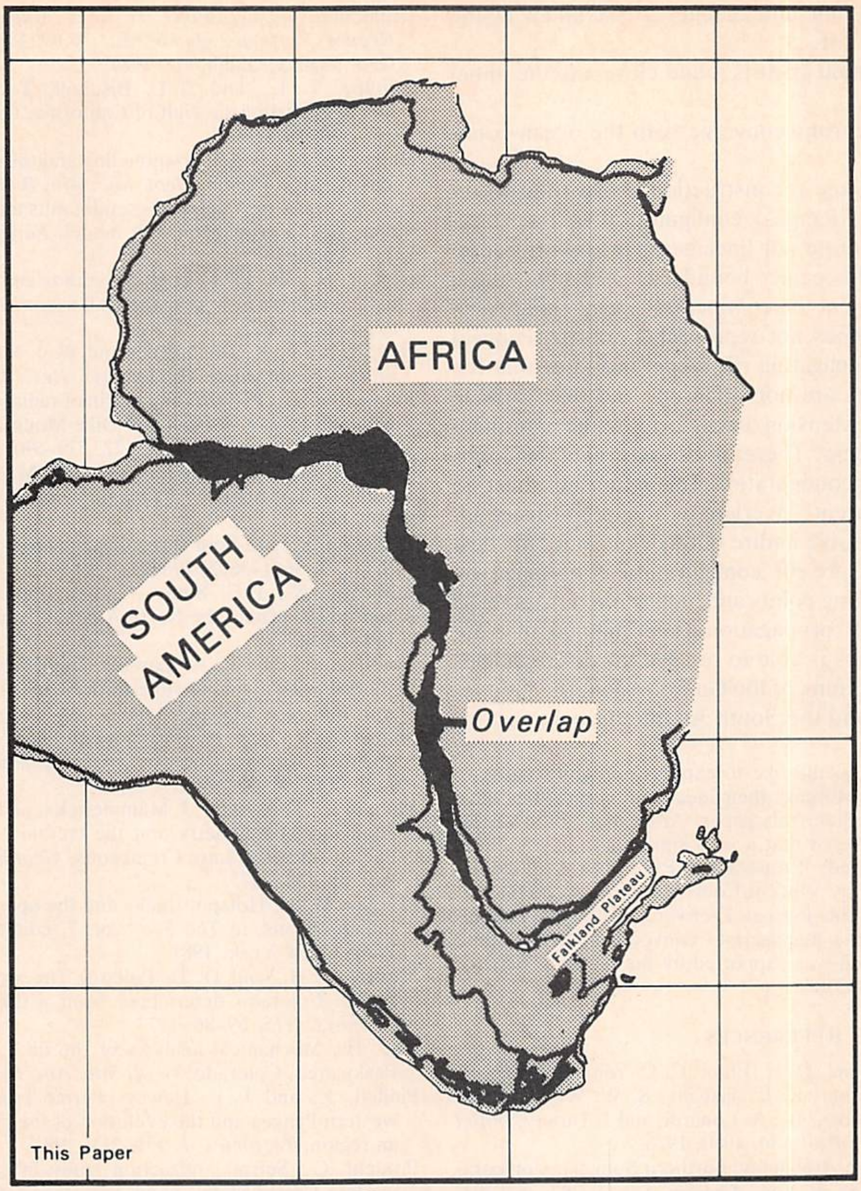

Fig. 11. The fit of this paper as assumed by the propagating rift model, using the 1000-m isobath for comparison (3000-m for Falkland Plateau). This representation was obtained by rotating South America 58.00°ccw around the pole at 47.00°N, 33.80°.

tic opened by means of a rift that propagated northward. This propagating rift resulted in large amounts of continental extension. When South America and Africa are reconstructed to their pre-rifting configuration, this extension results in 'apparent' overlap that increases in the northward direction.

Conclusions

The propagating rift model provides a mechanism for continental rifting and the early formation of ocean basins. In every ocean basin that this paper examined the propagating rift model was able to resolve the discrepancies that occur when rigid (no distortion or extension) plate tectonic models are applied. The propagating rift model provides the following guidelines for continental breakup:

1. Continents do not rift apart instantaneously in a rigid manner but rather an ocean forms by means of a propagating rift.

2. The rifting occurs in a manner similar to crack propagation, progressing in a direction normal to that of the regional least compressive stress.

3. A propagating rift requires continental extension. In front of the rift crustal thinning and extension take place within the continent, while behind the rift all expansion is accomplished by seafloor spreading. As a result of this, progressively larger amounts of crustal extension (up to 150 km) occur in the continent as the rift propagates.

4. Hotspot tracks and other regions of weakened lithosphere act as stress guides for the rifting, and rifting tends to propagate along them.

This model of continental rifting has the following predictions for the ocean basins:

1. The continental-oceanic boundary is not an isochron (since the ocean did not rift instantaneously), but, rather, it gets younger in the direction of rifting.

2. Extension along the continental margin is a minimum

at the initial rifting point and reaches a maximum at the furthest extent of the rift.

3. The oldest oceanic crust is found closest to the initial rifting point.

4. The oldest isochrons converge with the ocean-continent boundary.

Previous plate tectonic reconstructions have tried to recreate the pre-rifting (Pangea) configuration of the continents by matching contours or lineaments thought to represent the continental-oceanic boundary. Although these lineaments may represent the continental-oceanic boundary, superimposing them does not represent a pre-rift (Pangea) configuration. The propagating rift model indicates that the continental boundaries are not isochrons and that variable amounts of crustal extension occur within the continent during the rifting process. Therefore, in returning the continents to their pre-rift configuration, this extension must be represented as 'apparent' overlap in the reconstruction. Because of the progressive nature of this extension, the best representation of the pre-rift configuration is obtained by matching the initial rifting points and having overlap increase in the direction of rift propagation. This method of plate tectonic reconstructions is able to resolve the discrepancies in previous reconstructions of the Gulf of Aden, the Norwegian-Greenland Sea, and the South Atlantic Ocean.

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