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Rifting of Old Oceanic Lithosphere

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Geophysical data from five regions in the Pacific and Indian oceans reveal that long distance (>400 km) spreading center jumps have occurred in the past. The present-day seafloor morphology is used to develop a scenario for a spreading center jump. The major events are (1) thinning and weakening of the lithosphere at the future rifting site, (2) rifting of the weakened lithosphere (during rifting, the crack is filled from above by normal faulting and wedge subsidence; viscous upwelling fills the crack from below), (3) spreading at the rift site results in a ridge bounded by two troughs (spreading ceases at the dying spreading center, resulting in a deep central graben surrounded by flexural ridges; periods of slow spreading at both spreading centers produce rough topography), (4) ageing and cooling that produce a general deepening of the abandoned spreading ridge and also reduce the thermal contrast across the fossil rifting site. The new spreading center develops into a normal spreading rift. The major topographic expressions apparent in the seafloor today are the deep trough of the abandoned spreading center and the proximal and distal troughs which formed when the emerging spreading center bisected the fossil rifting site. The proximal trough (nearer the new spreading ridge) and the distal trough (farther from the new ridge) are first-order topographic features, 100–1000 km long and 300 km wide, resembling fracture zones with which they are often confused. They share with fracture zones the characteristic of bringing together fragments of lithosphere of different ages, but unlike fracture zones they are generally parallel to magnetic lineations.

INTRODUCTION

Creation of new oceanic lithosphere at spreading ridges is primarily a steady phenomenon on a longtime basis. The continuous spreading model explains many of the first-order features of the seafloor such as the ocean rises and basins, the fracture zones, and the magnetic striations [e.g.,*Cox*, 1973]. There are, however, a number of prominent topographic lineations that cannot be explained by the steady spreading model. These other first-order tectonic and topographic features result from rapid accelerations or decelerations in spreading. The two extreme cases are rifting (i.e., transition from a zero spreading rate to constant spreading rate) and dying (i.e., transition from constant spreading rate to zero spreading rate). Because of geometric constraints, an emerging rift is usually accompanied by a dying spreading center. The overall result is a jump in the location of the spreading center.

Short distance spreading center jumps may be occurring at overlapping and propagating spreading centers [*Hey*, 1977; *Lonsdale*, 1983; *MacDonald and Fox*, 1983] where the lithosphere is still very thin. In a few well-documented cases (Galapagos [*Hey*, 1979], Gorda Rise [*Hey*, 1977], and East Pacific Rise 18°N [*Mammerickx*, 1984]), a rift propagates into young lithosphere, <2 m.y. The dying rift receeds at the same rate as the new rift propagates, and they are connected by a zone of intense shearing [*Hey*, 1980].

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In this study we summarize existing evidence and present new evidence that spreading center jumps have occurred over much greater distances (>400 km). These major spreading center jumps differ, in at least three respects, from the well-documented cases of rift propagation and overlap. First, they imply rifting of older (>8 m.y.) and thicker lithosphere. Second, since the long distance spreading center jumps have not been observed in detail, there is little evidence that their propagating and dying rifts are connected by a shear zone. Third, the rifting and dying events do not always occur simultaneously. While there are numerous papers dealing with the physics of continental rifting (e.g., see *Tectonphysics* special issue on "Processes of Continental Rifting" [*Morgan and Baker*, 1983], the physics of rifting oceanic lithosphere has not been studied. To determine the processes that are important in oceanic rifting, we have adopted the physical principles of the continental rifting models. We also extrapolate the results from constant rate, seafloor spreading models [*Sleep*, 1969; *Lachenbruch*, 1973] to explain the topographic characteristics of the abandoned spreading centers.

Below we propose a scenario for rifting of old oceanic lithosphere and describe large-scale topographic features that develop at these sites. Having presented the model, we discuss five sites where these landforms have been observed in detail. We first investigate three areas where magnetic anomalies are well identified. We will then identify these symptomatic landforms in two other areas devoid of magnetic anomalies, and with the help of our model we will constrain plate reorganization in magnetic quiet zones.

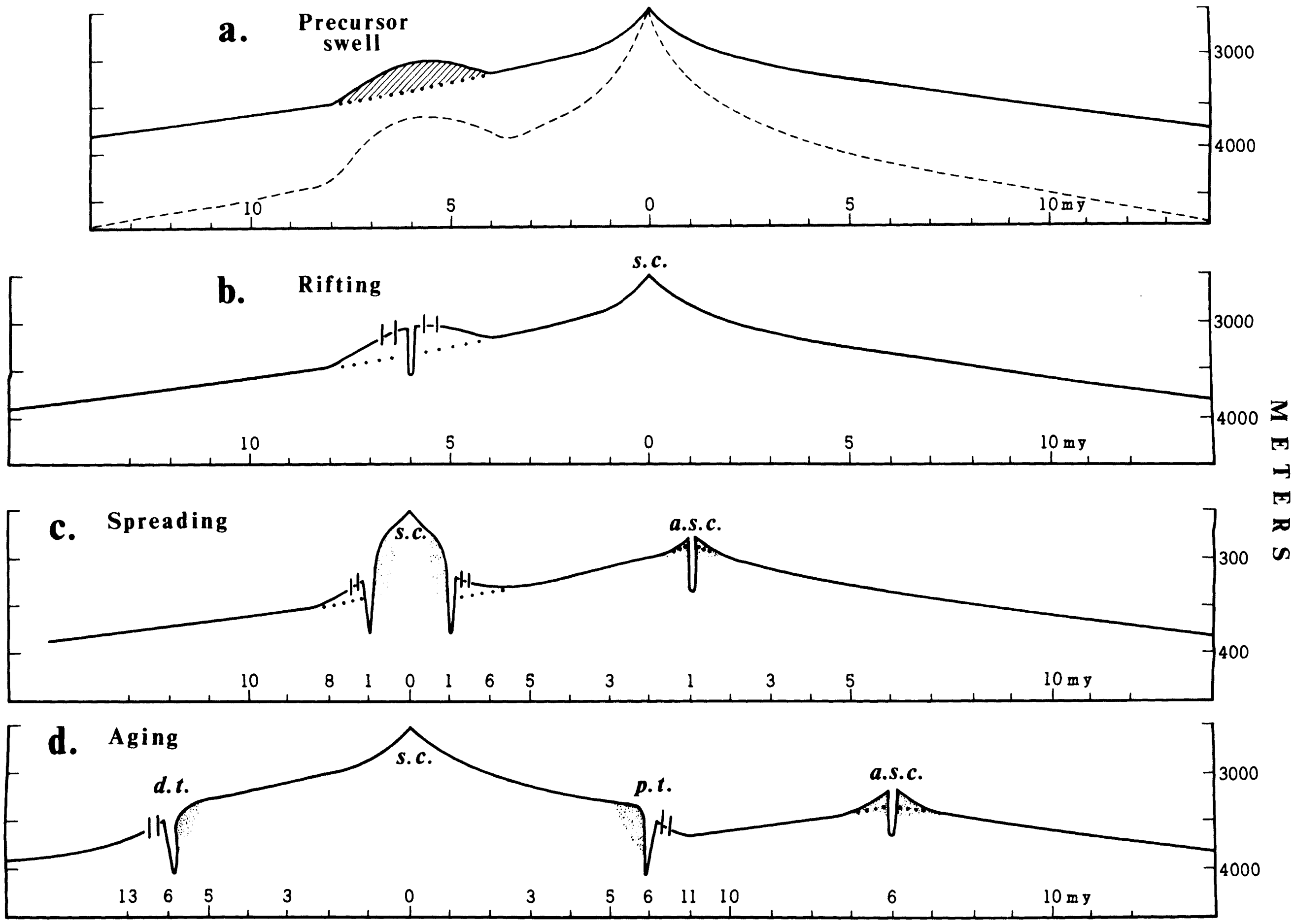

Fig. 1. Evolutionary sequence of events taking place at a site where old oceanic lithosphere breaks up. (*a*) Solid line; $d=2500$ m + $350\sqrt{\text{age}}$; dashed line, 700° isotherm, its depth not at scale. 9*b*) Vertical lines, normal faulted seafloor surrounding initial graben. (*c*) Vertical lines, same as above; strippled pattern; rough topo due to initial episode of slow spreading. On all profiles, arrows show direction of aging. (*d*) Topographic elements apparent today. The new spreading ridge is framed by conjugate troughs. The abandoned spreading ridge subsides while retaining the morphology of a slow spreading ridge.

TECTONIC MODEL

On the continents an evolutionary sequence of events takes place at the sites where old lithosphere is ruptured [*Burke and Whiteman*, 1973]. We speculate that a parallel evolutionary sequence takes place on the seafloor. Figures 1*a*–1*d* are illustrations describing the sequence of events that take place where old oceanic lithosphere breaks up. Not all of the stages of our model are observed today. These missing stages are inferred from geophysical observations and analogies with continental rifting models.

Uplift and Thinning

Figure 1*a* shows an idealized profile of ocean floor subsiding with age along a thermal contraction curve [*Sclater et al.*, 1971; *Parsons and Sclater*, 1977]. A rift is about to occur in 6-m.y.-old crust. The depth to the base of the mechanically strong part of the lithosphere, defined by the 700° isotherm [*Goetze and Evans*, 1979] is indicated by the dashed curve in Figure 1*a*. Two aspects of lithosphere thinning promote rifting. First, lithospheric necking and perhaps reheating substantially reduce the strength of the lithosphere. Second, the thinning produces a swell-push force. Lithospheric weakening is by far the more important factor. A swell or depth anomaly develops over the reheated lithosphere (hatched pattern in Figure 1*a*). The dotted line shows the thermal contraction curve under the depth anomaly.

To estimate the strength of the lithosphere and its variation with age, we integrated the yield stress over depth

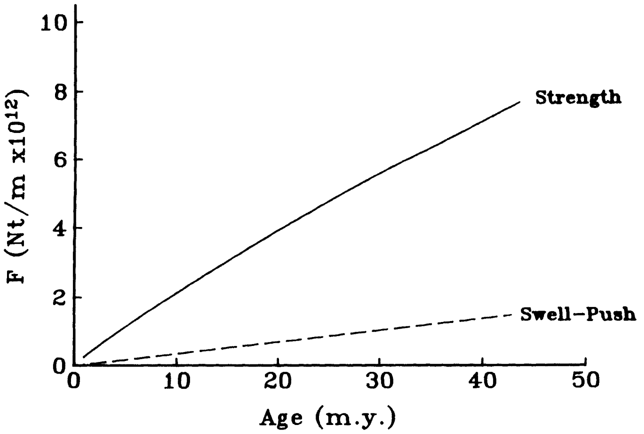

Fig. 2. Swell-push force (dashed line) and force required to tear the lithosphere (solid line). At all ages the swell-push force is too small to tear the lithosphere unless the force is concentrated at the crack tip.

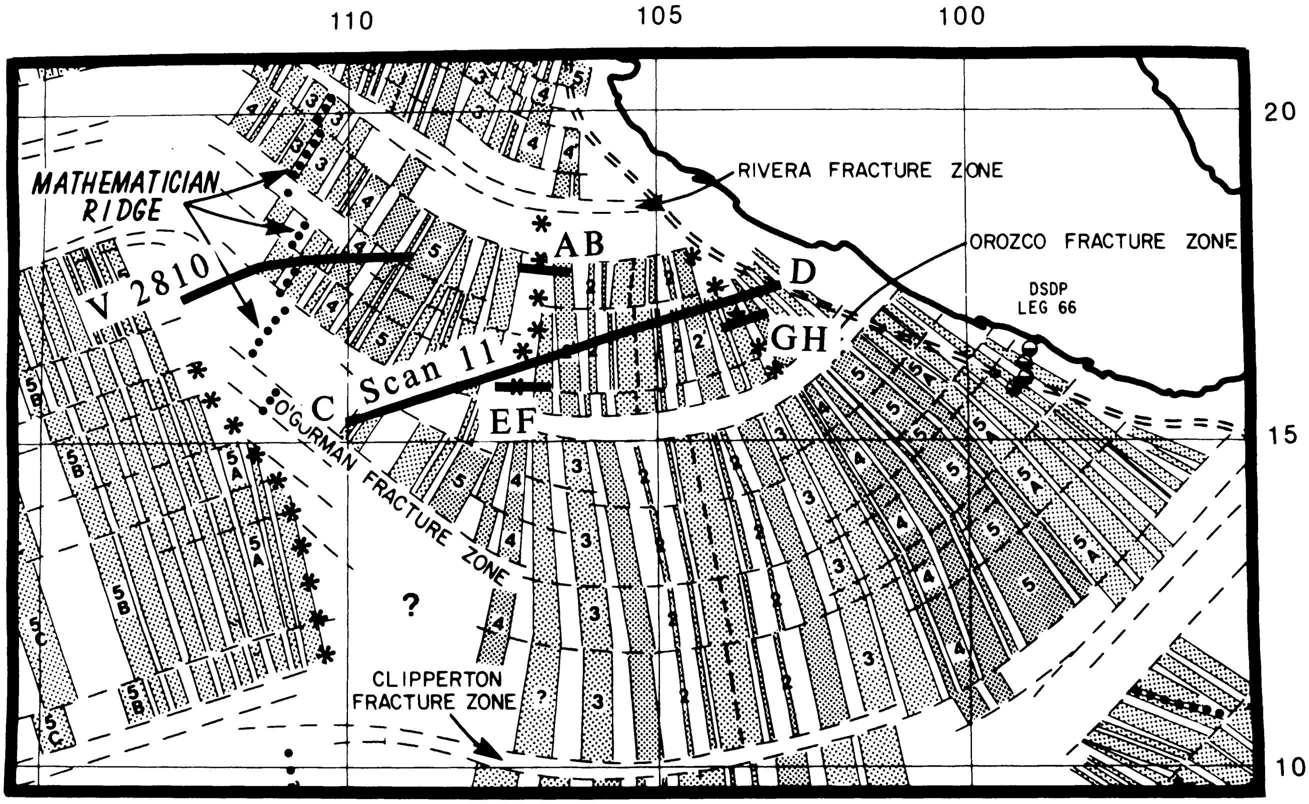

Fig. 3. Magnetic lineations of the East Pacific Rise between 10° and 20°N [*Klitgord and Mammerickx*, 1982].

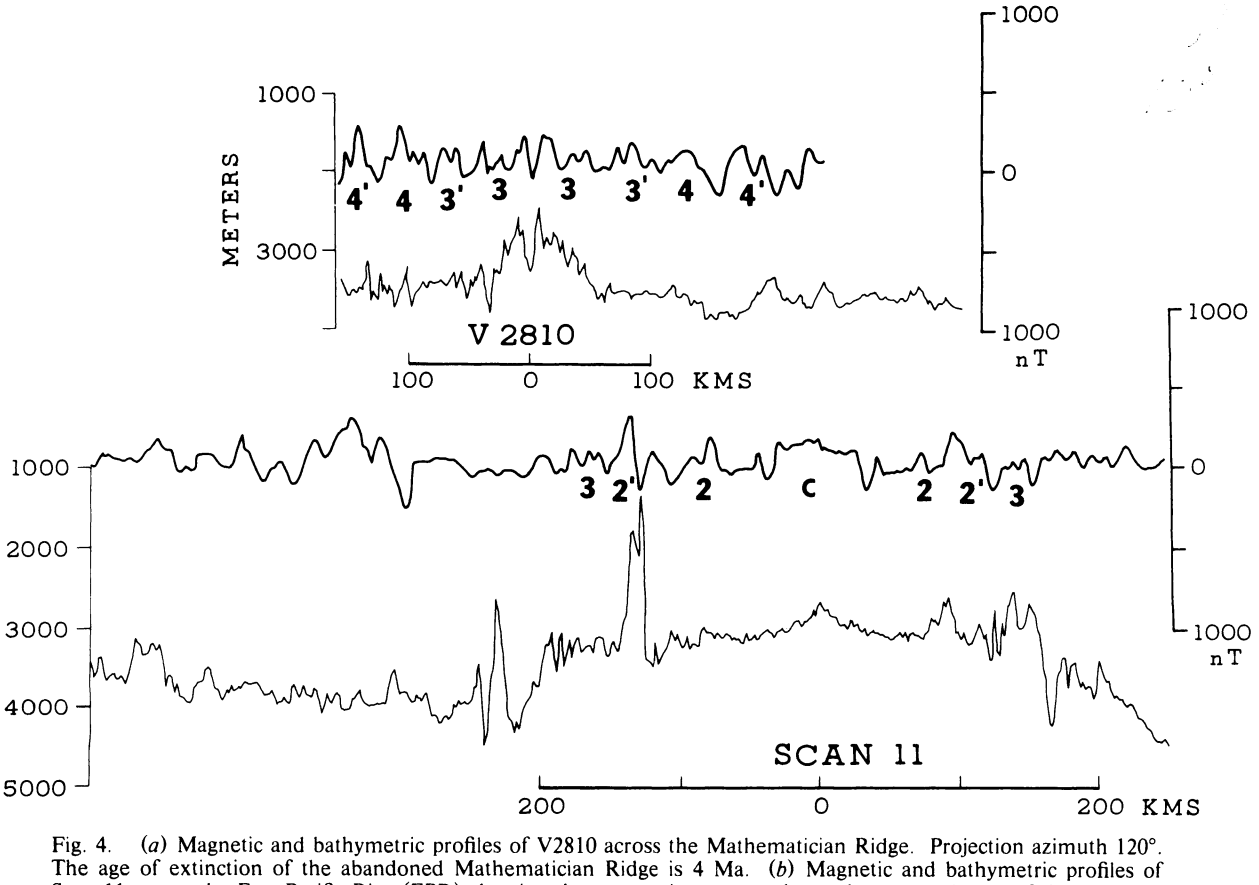

Fig. 4. (*a*) Magnetic and bathymetric profiles of V2810 across the Mathematician Ridge. Projection azimuth 120°. The age of extinction of the abandoned Mathematician Ridge is 4 Ma. (*b*) Magnetic and bathymetric profiles of Scan 11 across the East Pacific Rise (EPR) showing the two conjugate troughs to the east and west of the presently active spreading ridge. Projection azimuth 85°. Four peaks of anomaly 3 are seen on the east side of the Moctezuma Trough dating the time of initiation of spreading at that site at 3.5 Ma. The youngest of the four anomaly 3 peaks is poorly developed. On the west side of the eastern conjugate trough, only three peaks of anomaly 3 are observed.

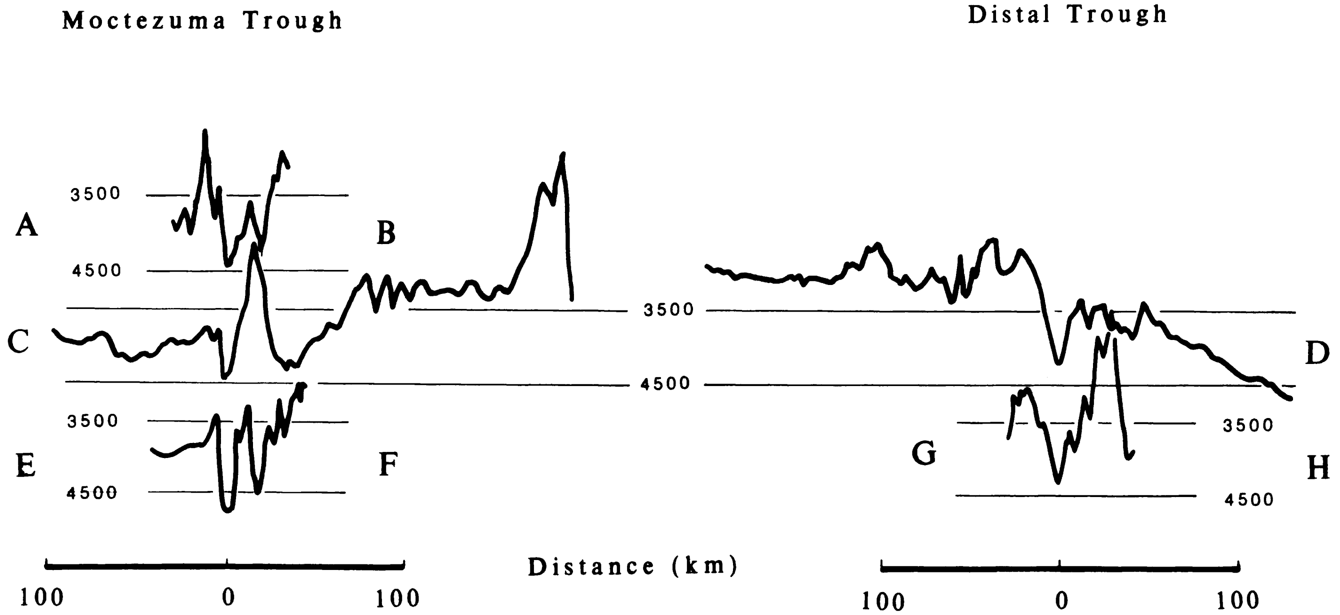

Fig. 5. All profiles are located on Figure 3. The three profiles across the proximal trough (Moctezuma Trough, left) and the two profiles across the distal trough (right) show the high-amplitude hills surrounding the conjugate troughs. East of the distal trough on profile D, the seafloor descends toward the Middle America Trench.

using the brittle-plastic yield envelope model of *Goetze and Evans* [1979]. The force per ridge length required to tear the lithosphere is plotted as a function of the age of the lithosphere in Figure 2 (solid curve). Note that the regional stress field will be concentrated at the rift tip, so the required tearing forces may be significantly less than shown in Figure 2. The nearly linear increase in strength with age indicates that it is easier to tear young lithosphere than old lithosphere. The strength of older lithosphere can be substantially decreased by replacing the lower lithosphere with hot mantle material. This thinning could be due to erosion by a thermal plume or by necking. Once the lithosphere is thinned, its temperature profile matches that of younger lithosphere [*Detrick and Crough*, 1978]. Thus older oceanic lithosphere can be rifted but only after it has been thermally rejuvenated to an age of a few million years.

The uplift due to lithospheric thinning produces a "swell-push" force, as discussed by *Crough* [1983]. Assuming that the swell height approaches the height of the ridge crest we have estimated the maximum swell-push force versus the age of the seafloor (dashed curve in

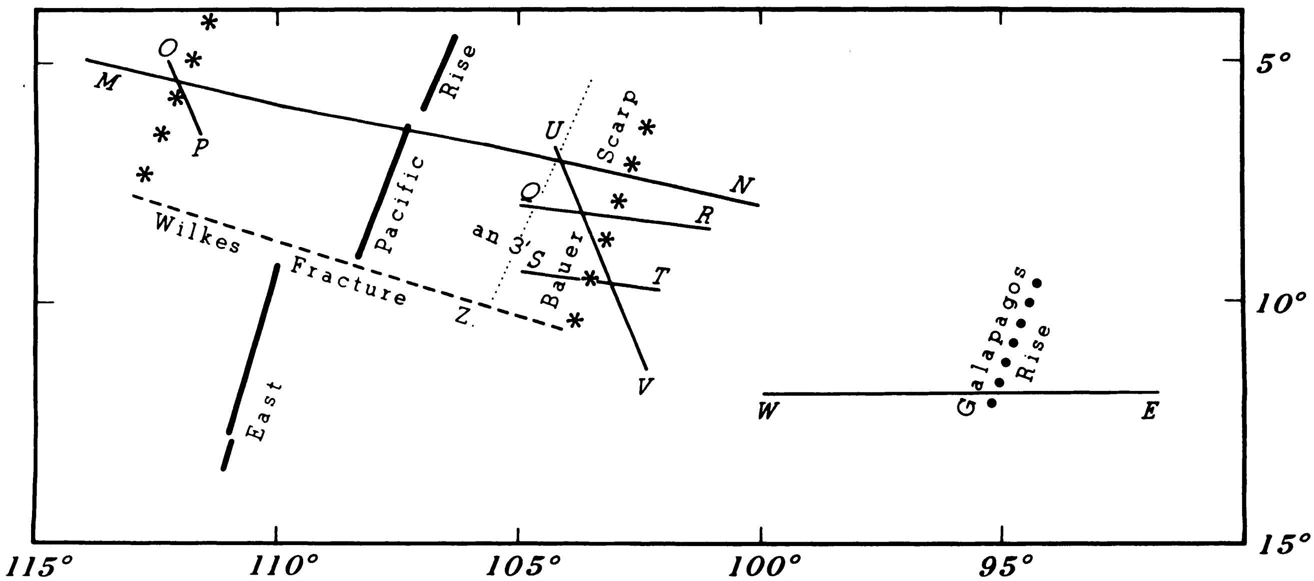

Fig. 6. The East Pacific Rise between 5° and 10°S. Anomaly 3' is from *Rea* [1976]. Heavy solid line, spreading axis; dotted line, abandoned spreading ridge; asterisks, conjugate troughs. Profile MNWE is shown on Figure 7. All profiles are of Figure 8.

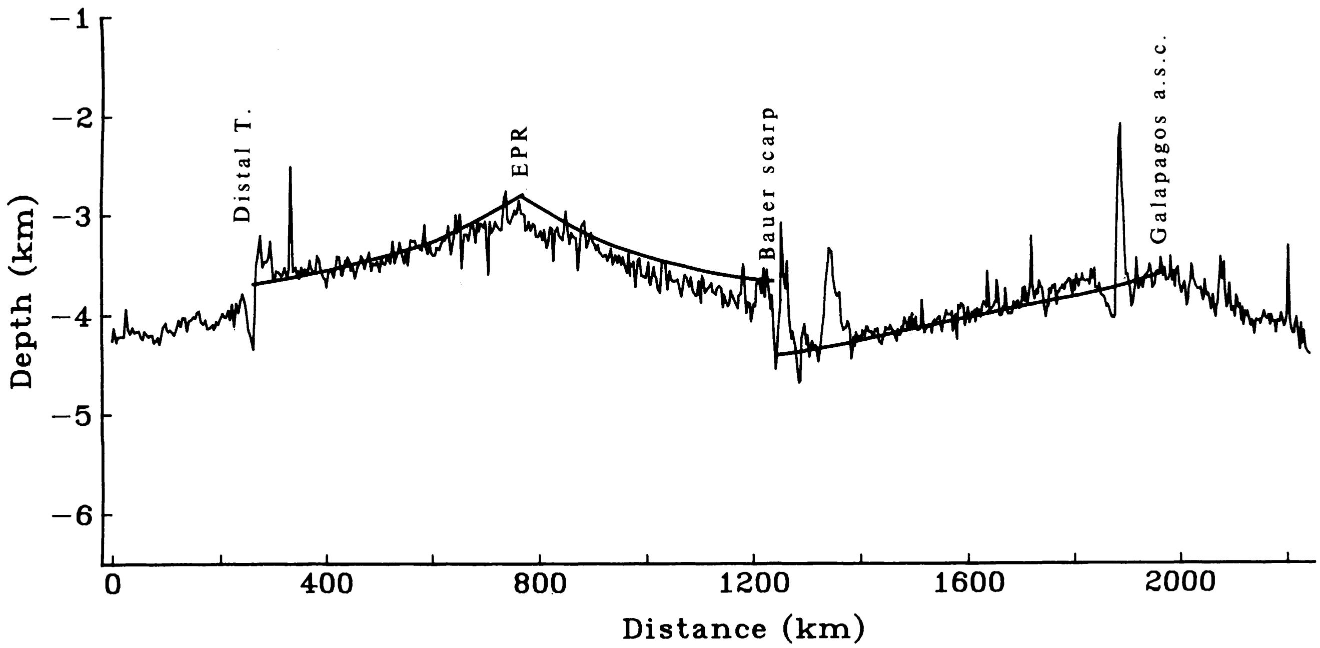

Fig. 7. Composite profile across the East Pacific Rise (at 7°S) and the Galapagos abandoned spreading ridge (at 12°S). The smooth line is the depth versus age curve defined by *Parsons and Sclater* [1977]. The profile is located on Figure 6 as MNWE.

Figure 2). At all ages the swell-push force is 5 times smaller than the force required to tear the lithosphere. Thus plate boundary forces or shear tractions on the base of the lithosphere must initiate rifting rather than the swell-push force.

Rifting

When the strength of the lithosphere drops below the stress level, a crack develops and grows in width. The surface expression of rifting is a result of the mantle flowing upward into the widening crack and normal faulting of the brittle surface layer. A model for flow of viscous mantle material into a widening crack was recently developed by *Schubert and Garfunkel* [1984] to explain the Salton Trough. Initially, the crack is empty, but soon it begins to fill because of hydraulic pressure. Both the rate of crack opening and the viscosity of the mantle material flowing into the crack govern the crack filling history. The transition from zero spreading rate to a constant spreading rate is adequately described by this simple model. The model begins to break down when the upwelling material freezes onto the edges of the crack. Eventually, the freezing rate equals the spreading rate, and conduit of viscous upwelling stabilizes in width. A model for constant spreading was developed by *Lachenbruch* [1973].

In the following section we show that the crack filling history is recorded in the morphology of the seafloor. The simple crack filling model [*Schubert and Garfunkel*, 1983] predicts that for a brief period of time, the crack extends from the seafloor to the base of the lithosphere. Bathymetric surveys of propagating rift tips [*Searle and Hey*, 1983; *Mammerickx*, 1984] shows that an open crack does not extend very deep into the lithosphere (~500 m). The crack is immediately filled in from above by fracturing and wedge subsidence of the brittle surface layer [*Bott and Mithen*, 1983]. This normal faulting results in a deep central graben surrounded by rugged, normal faulted seafloor.

Spreading

Figure 1*c* shows a topographic profile 1 m.y. after the rift developed. During this time the spreading rate of the new spreading center has increased to a constant value. In our simple model the spreading rate of the dying ridge has simultaneously decreased to zero. Note that this is not a requirement of the model; both spreading centers could be active at the same time. The new spreading center has emerged from the rift and has reached a height of 2500 m (below sea level), leaving behind two conjugate and deep troughs. There is an overall depth offset across the troughs reflecting the age offset of time of rifting. There is usually a ridge on the old side. It has complex topography perhaps reflecting initial stages of volcanism and or the upward flexural response of the lithosphere to the mass deficits of the trough. Depths decrease rapidly on the young side of each trough. We speculate that this is the emergence of the ridge crest from the deep rift. Both the central trough of the abandoned ridge and the rough topography on the young side of the conjugate trough marked in Figure 1*c* (stippled) may be due to an episode of slow spreading. Slow spreading ridges generally have deep central rifts (1–2 km) and rugged topography on the flanks of the ridge. Fast spreading ridges, on the other hand, are characterized by central volcanoes and smooth flank topography [*Menard*, 1967*a* and *b*]. If the overall spreading rate across both spreading ridges remains constant, then they either must turn on and off instantaneously or each must have a period of slow spreading. The time it takes for the emerging rift to turn on and the dying rift to turn off may govern the width of rough topography.

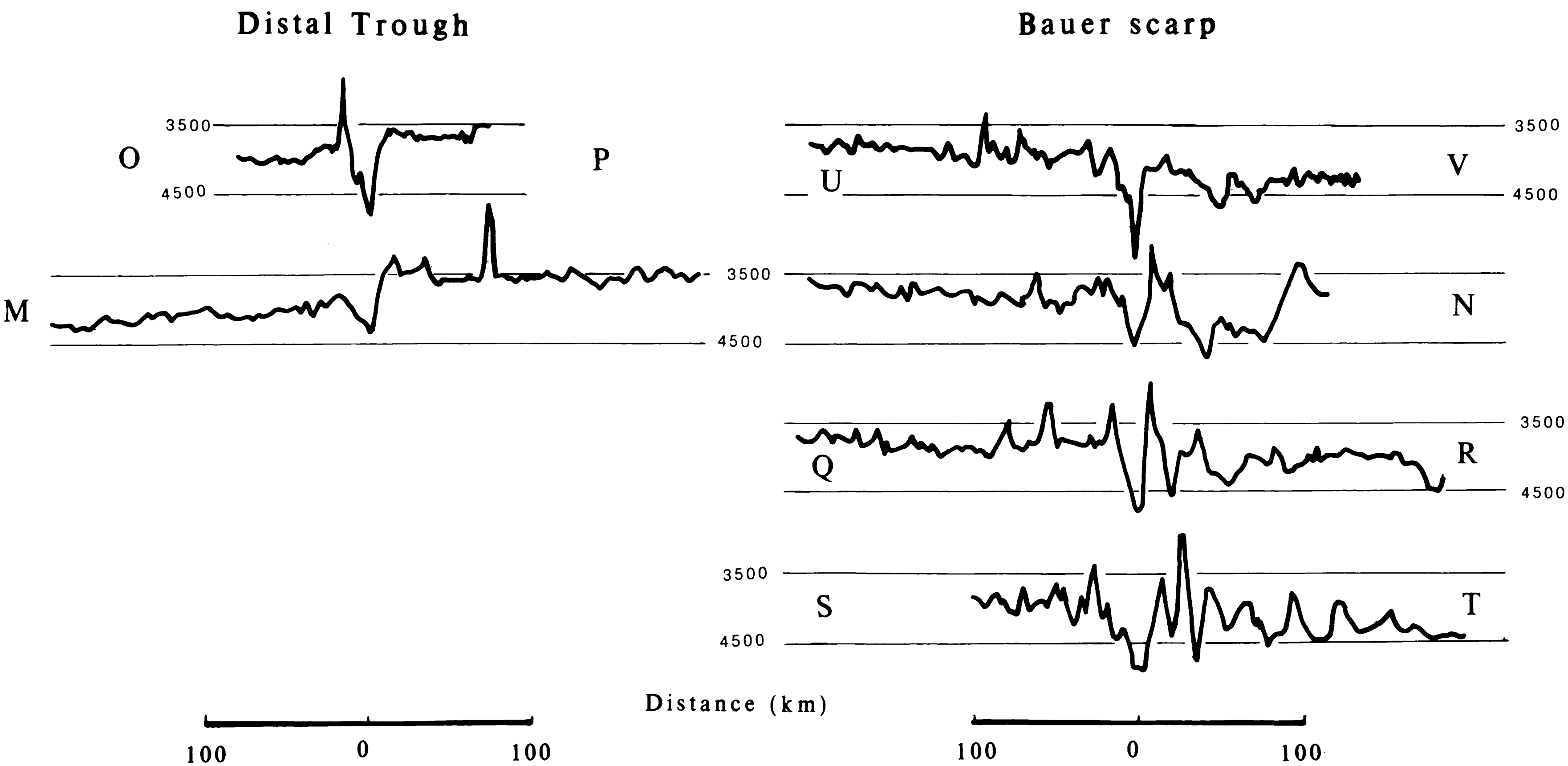

Fig. 8. All profiles are located on Figure 6. Two profiles across the distal trough (left) and four profiles across the proximal trough (Bauer Scarp) show the high-amplitude topography on both sides of the conjugate troughs and normal amplitude abyssal hills beyond.

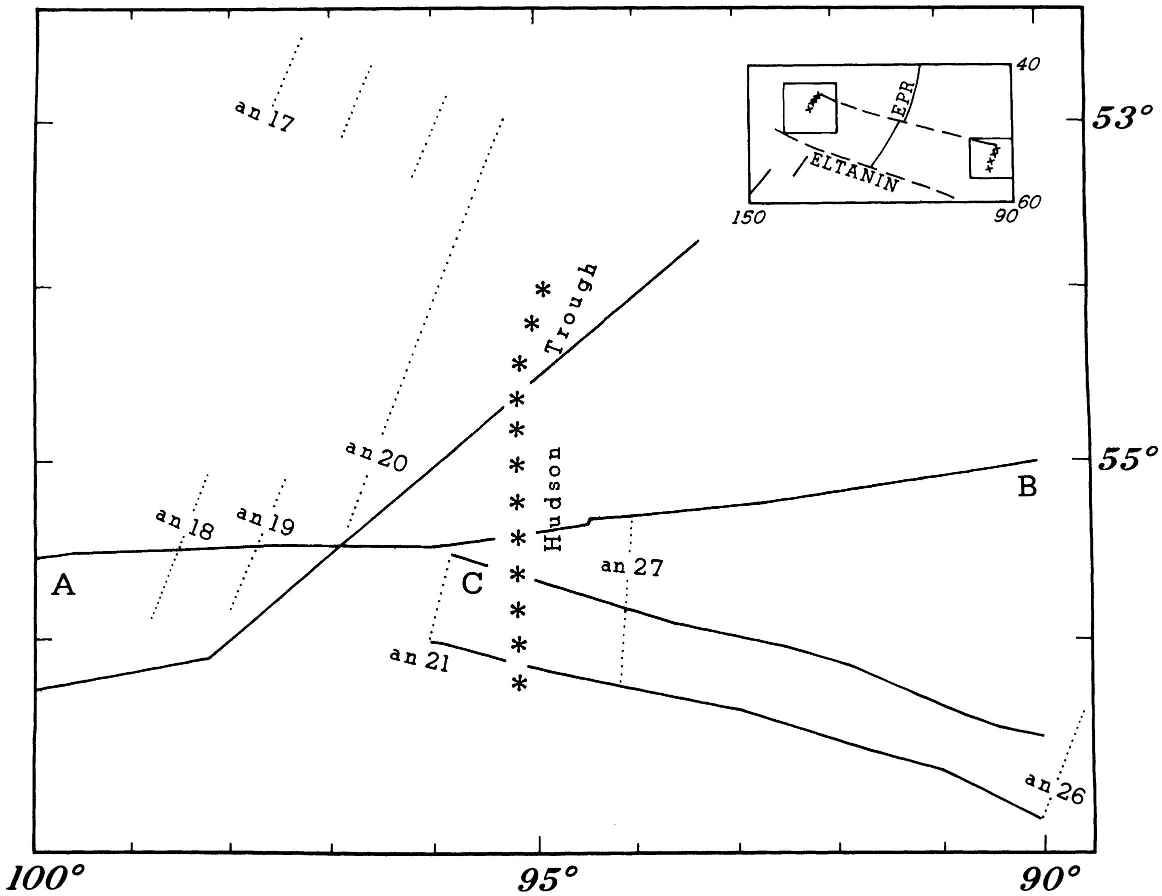

Fig. 9. Regional map of the Hudson Trough area. Magnetic anomalies identifications are from *Cande et al.*, [1982]. At 56°S, the age contrast between crust dated 48 Ma (anomaly 21 [after *Harland et al.*, 1982]) and crust dated 61 Ma (anomaly 27) is approximately 10 m.y.

Aging

Figure 1*d* shows that as time passes, the new spreading center (s.c.) evolves. The rifting site remains recorded in the topography by conjugate asymmetric troughs. One of the conjugate troughs is close to the abandoned spreading ridge and we call it the proximal trough (p.t.). The other one is the distal trough (d.t.). The abandoned spreading center (a.s.c.) appears in most of our examples as a regional topographic high marked by a symmetrical and deep rift. While the flanks of the older abandoned rift fit well on the thermal subsidence curve, its edges are shallower than expected.

OBSERVATIONS

Examples from five regions were used to develop the model presented above. A first group of three are located in areas of well-identified magnetic anomalies. They are (1) the East Pacific Rise (EPR) at 17°N and the Mathematician abandoned spreading center, (2) the EPR at 7°S and the Galapagos abandoned spreading center, and (3) the Hudson and Henry troughs region in the South Pacific. A second group considers two regions located in magnetic quiet zones. They are the Nova-Canton Trough in the central Pacific and the Diamantina Fracture Zone in the Indian Ocean. These examples are now discussed in some detail.

The data base is the collection of underway bathymetric data of the Scripps Institution of Oceanography. Soundings were taken every nautical mile, and the profiles were projected on a trajectory perpendicular to the axis of the features discussed. Most profiles use identical scales to facilitate comparisons. Crustal ages are taken from the published literature.

East Pacific Rise (EPR) and Mathematician Seamounts

In their paper discussing the relationship between depth and age of the lithosphere, *Sclater et al.* [1971] showed that the Mathematician seamounts were an abandoned spreading ridge. A recent reevaluation of the tectonic history of that area used a larger data base to arrive at a more detailed picture of the region (Figure 3 and *Klitgord and Mammerickx* [1982]). When the Mathematician ridge became extinct, a new spreading center broke to the east in 8.5-m.y.-old crust (now 15 m.y. old). The site where rifting initiated is a set of troughs west and east of the present day EPR (106°W). Limited segments of these conjugate troughs were subsequently surveyed with the Seabeam system [*Mammerickx*, 1984]. The pelagic sediment cover is less than 100 m thick and does not alter the morphology in a significant way.

The observations made in the area are illustrated on Figures 4*a* and 4*b*. The crossing of the Mathematician

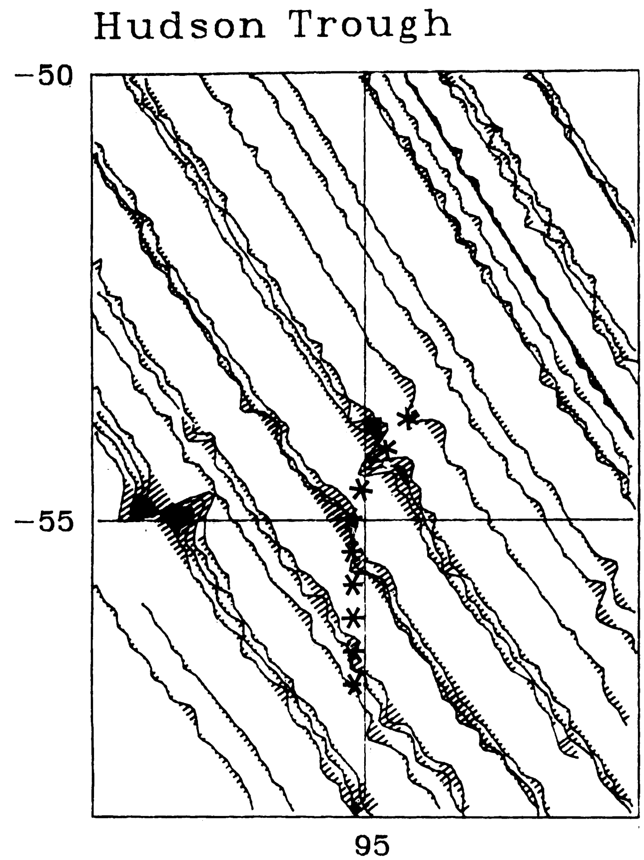

Fig. 10. The characteristic northeasterly bend of the Hudson Trough (asterisks) is shown on this display of along-track deflections from the vertical of the Seasat altimeter observations. One large uncharted seamount is also observed at 99°W and 55°S.

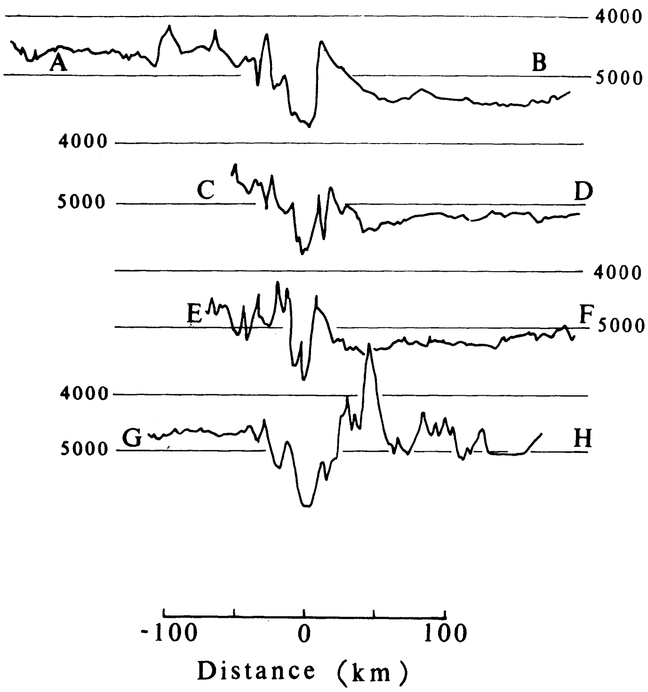

Fig. 11. Four profiles across Hudson Trough are located on Figure 8. Depths are in meters.

Ridge (V2810 on Figure 3) show that the axis of the Mathematician Ridge is a deep rift. The magnetic anomalies of the Vema 2810 profile shows that the axis of the rift is on the young side of the second peak of anomaly 3 or 4 Ma. The profile shows upward flexure over a distance of 50 to 100 kms east and west of the axial rift.

The Moctezuma Trough (Figures 3 and 4*b*) separates crust 15 m.y. old to the west from crust 5 m.y. old to the east (old side of anomaly 3). The age offset is 10 m.y., and the expected depth offset at the boundary should be 324 m. The boundary between the old and the new crust is not a simple steplike feature reflecting the age offset but is a ridge and trough topography of about 1500 m in amplitude. The fact that three of four peaks of anomaly 3 are found on both sides of the Mathematician Ridge and that the three peaks of the same anomaly are recognized on the young side of the Moctezuma Trough (with possibly a poorly developed fourth peak) leads us to believe that both the dying and the new jumped ridge may have operated simultaneously for ~1 m.y. Several magnetic profiles that run along a small circle with respect to the pole of rotation would of course demonstrate this more convincingly than the profiles from ships of opportunity of Figure 4.

In the Seabeam surveys of the Moctezuma Trough, *Mammerickx* [1984] systematically observed two troughs, but most other profiles discussed later in the paper show only one major trough at the boundary between old and new crust. The Seabeam survey of the Moctezuma

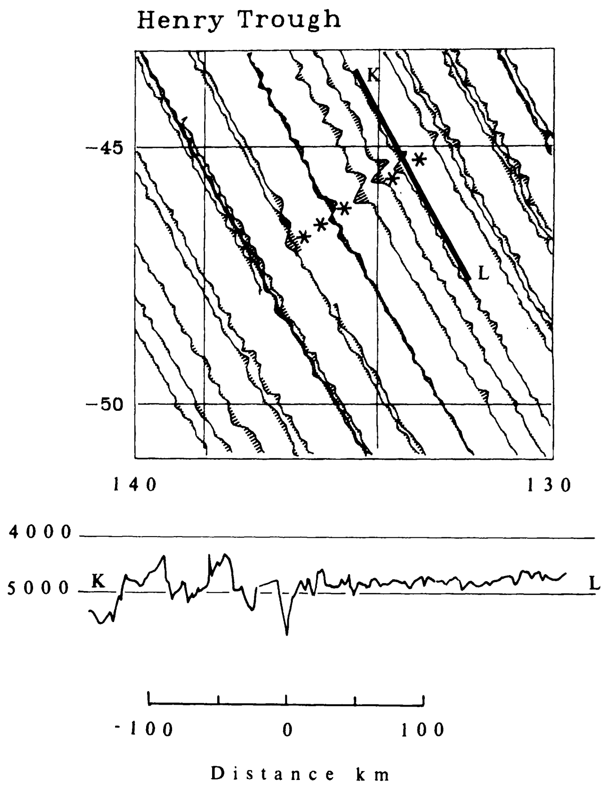

Fig. 12. Henry Trough (asterisks on top illustration) shows very well on the display of along-track deflections from the vertical of the Seasat altimeter observations. The track of South Tow 1 expedition is KL on top. Its profile is at the bottom.

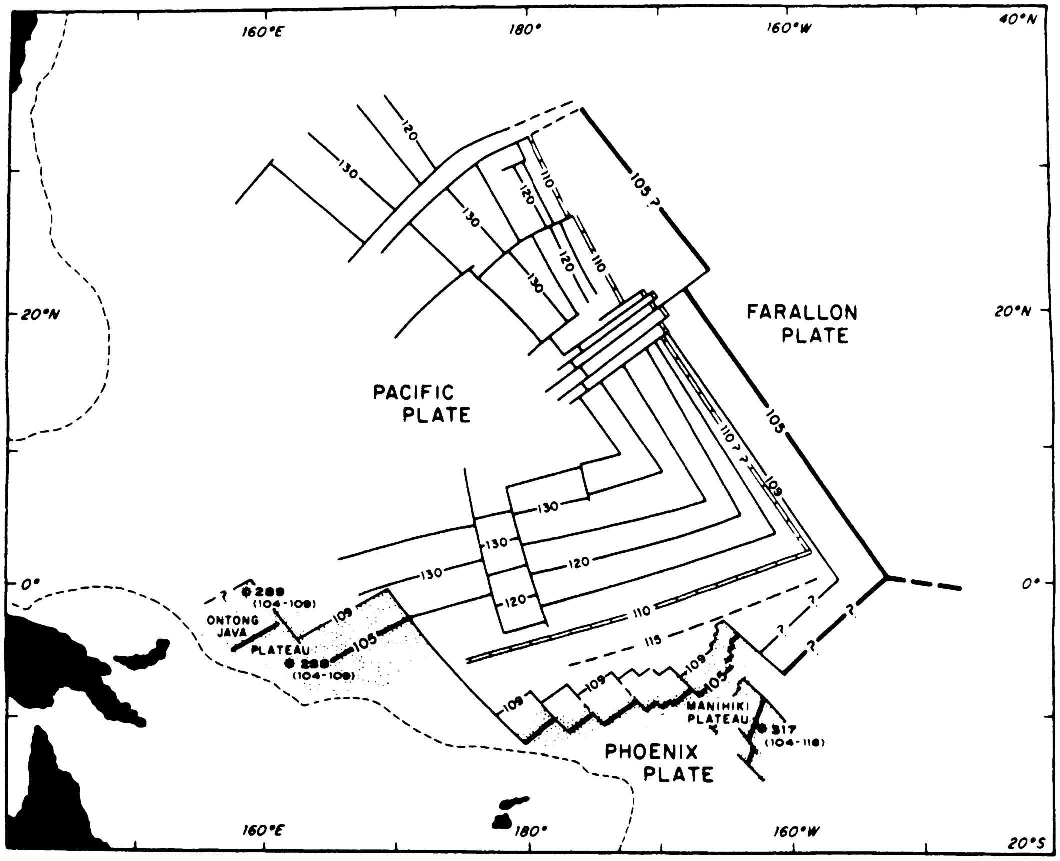

Fig. 13. Configuration of plates in the central Pacific about 105 Ma. The former spreading ridge at Nova-Canton Trough was abandoned during a change in orientation of the Pacific-Phoenix spreading ridge. The new ridge was located on the Manihiki Plateau, but its connections to the Pacific-Farallon Ridge are not known. There may have been a small extra plate on part of the Manihiki Plateau. The history along the Pacific-Farallon Ridge during this time is not known. *Deep Sea Drilling Project Scientific Staff* [1973, 1974*a*] [from *Winterer*, 1976].

Trough (proximal trough) shows orthogonal lineations on the old side of the trough. This may imply that the new rift evolved by propagation. Figure 5 presents several transverse profiles across both the distal and the proximal troughs and shows their similarities in width and height, as well as high the amplitude topography east and west of the trough.

East Pacific and Galapagos Rises

Numerous studies have discussed various aspects of the tectonic evolution of the Nazca plate [*Anderson and Sclater*, 1972; *Herron*, 1972; *Handschumacher*, 1976; *Rea*, 1976, 1981, 1983; *Mammerickx et al.*, 1980; *Campsie et al.*, 1984]. North of the Wilkes Fracture Zone (Figure 6), magnetic anomalies have only been identified from anomaly 0 to 3′. The age of the Bauer Scarp, which marks the initiation of spreading at this location, has been extrapolated assuming constant spreading rate by *Rea* [1976, 1981] to 6.5 Ma, while the age of extinction of the Galapagos Rise is speculated by *Anderson and Sclater* [1972] to be also 6.5 Ma. An extrapolated age for the crust into which the Bauer Scarp developed is 24.5 Ma. Thus, at the time that the Galapagos Rise became extinct, the spreading center jumped 900 km westward in crust 18 m.y. old. The magnetic data in these areas are limited, so ages are based on extrapolations of these limited observations (see magnetic lineations in Figure 6).

Figure 7 shows a composite profile across this region. From west to east, one observes the distal trough, the East Pacific Rise (EPR), the proximal trough (Bauer Scarp) and the Galapagos Rise. A conspicuous feature of

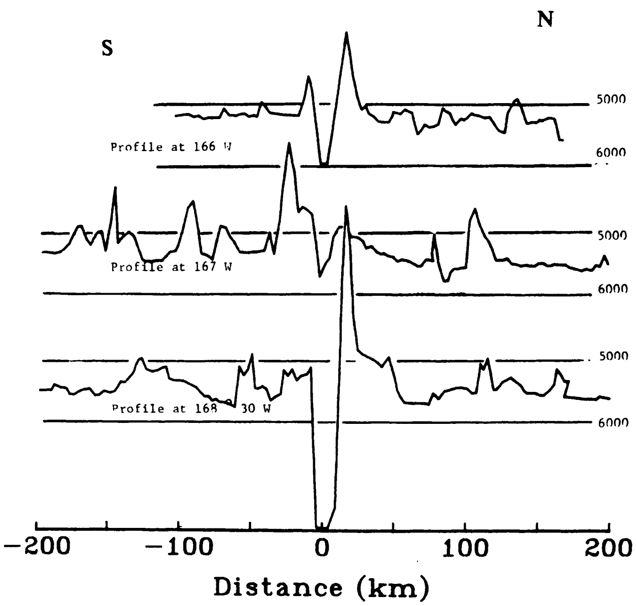

Fig. 14. North-south profiles across the Nova-Canton Trough.

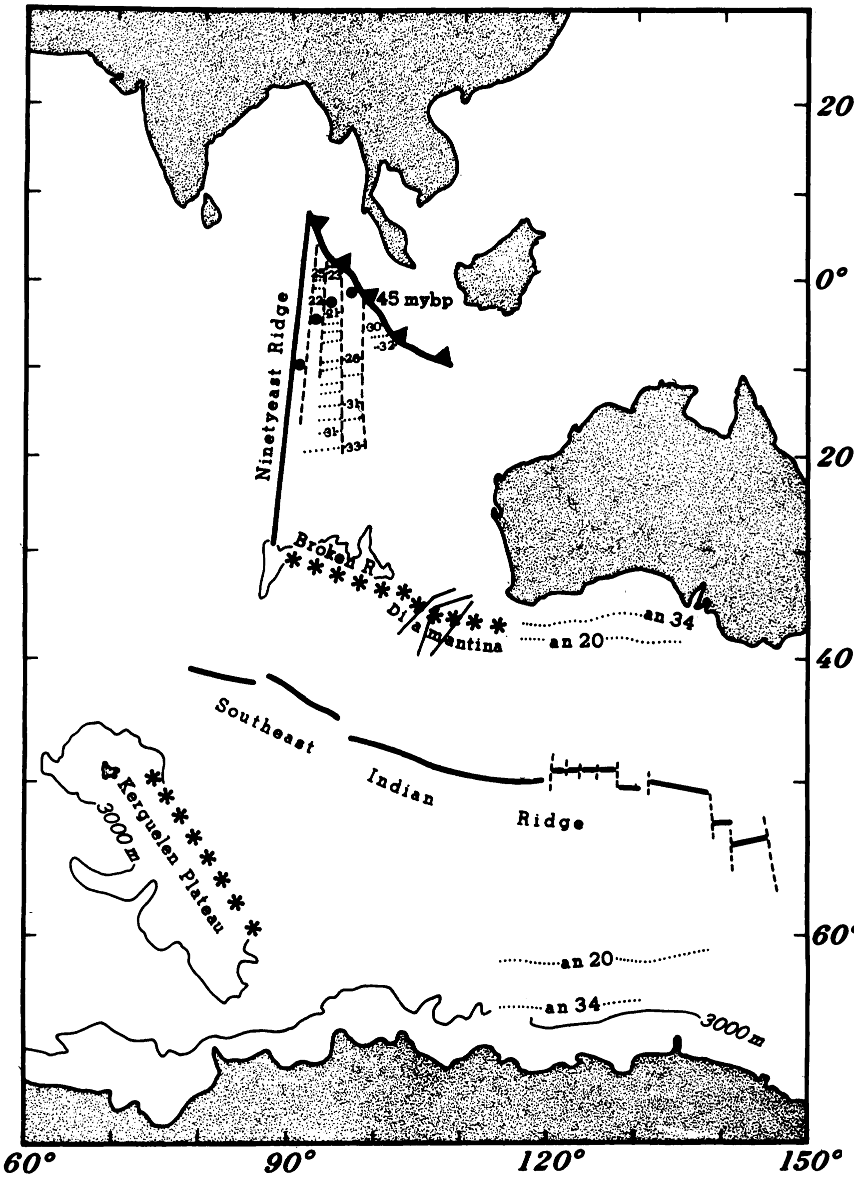

Fig. 15. Regional sketch of the southeast Indian Ocean. It shows that Broken Ridge, the Diamantina Fracture Zone, and anomaly 34 are located on a continuous line and that south of the southeast Indian Ridge, the conjugate feature are the Kerguelen Plateau and anomaly 34 at the foot of Antarctica. The Mercator projection gives the false impression that the southern feature is longer than the northern one. At 10°S, a 45 Ma abandoned spreading ridge is shown by heavy dots. The three profiles across the Diamantina Fracture Zone are shown in Figure 16.

the EPR at 7°S is its asymmetry; it matches the depth/age curve (for $d = 2800$) to the west, and it is significantly deeper than the depth/age curve to the east. As in the case of the EPR at 17°N (Figure 4), the profile shows that the proximal and distal troughs are 1000–1500 m deep features, with high-amplitude topography over a distance of ~100 km east and west of the trough axis. The abyssal hills topography ranges between 200 and 300 m. There is no deep central trough along the abandoned spreading ridge; this may indicate that the dying ridge did not go through a prolonged period of slow spreading. A critical observation made here is that the rift topographies of the Galapagos and Mathematician spreading center jumps have similar amplitudes even though the age offsets are substantially different (18 Ma and 10 Ma, respectively). This may indicate that both plates were thinned to the same thickness prior to rifting.

Figure 8 shows several more profiles of the distal and proximal (Bauer) troughs. Although there is a significant amount of variation from profile to profile, the boundary between the old and the new crust is always a conspicuous trough.

Hudson and Henry Troughs

Cande et al. [1982] identified the Hudson Trough as an old rifting site in the southeast Pacific (Figure 9). They defined it as the topographic scar left by the Pacific-Antarctic ridge when it rifted into the 10-m.y.-old Pacific crust. The Hudson Trough and its bend are also evident on the deflection of the vertical profiles profiles of Figure 10 [*Sandwell*, 1984]. These ascending Seasat profiles show a negative slope on the southeast side of the trough and a positive slope on the northwest side. The trough axis has zero deflection of the vertical.

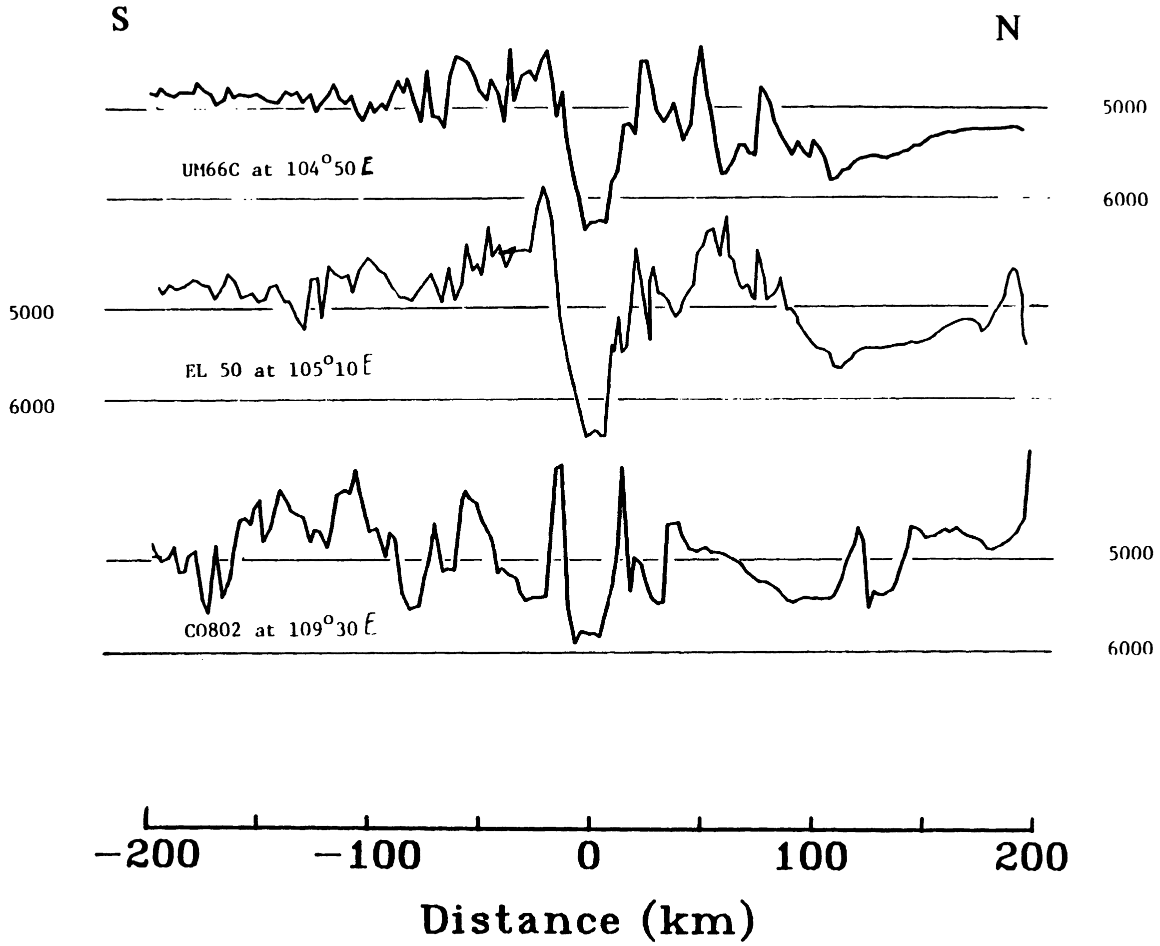

Fig. 16. Three profiles across the Diamantina Fracture Zone. Cruise names and longitudes of the crossings are identified on each profile.

Figure 11 shows four profiles across the Hudson Trough with the now familiar assymmetric appearance of an old rifting site, shallower on the younger western side and deeper on the older eastern side. The ridge and trough topography 100 km on either side of the trough is about 3 times greater than that of abyssal hills.

The conjugate trough of this old rifting site, Henry Trough, is also evident on the deflection of the vertical profiles (Figure 12). The location of the only surface ship crossing by the South Tow cruise is KL. This profile is also shown on Figure 12 and repeats the observations made earlier in the paper.

In the three previous examples, identified magnetic lineations occur near enough the troughs to identify them as rifting sites. In the two following examples, the rifting occurred during times of magnetic silence, and the chronology is more speculative.

Nova-Canton Trough

The Nova-Canton Trough is a linear ridge and trough topographic feature south of the equator, between 180° and the Line Islands. *Menard* [1967*a* and *b*] first interpreted it as the western extension of the Clipperton Fracture Zone. The identification of the Phoenix lineations 300 km north of the Nova-Canton Trough [*Larson et al.*, 1972] led *Winterer* [1976] (also see Figure 13) to reinterpret it as an abandoned spreading center. Three profiles across the Nova-Canton Trough show that the average depth on either side of the trough is the same and that there is therefore no apparent age offset on either side of the trough, as would be expected if this were a fracture zone. Of the three profiles in Figure 14, the northernmost one resembles best the abandoned spreading ridges discussed above. Although not textbook cases, these profiles support the interpretation of Nova-Canton Trough as an abandoned spreading ridge. The new rifting site has not yet been discovered and is probably buried under the Line Islands volcanic edifice.

Diamantina Fracture Zone

The Diamantina Fracture Zone is our last example of an old rifting site embedded in midplate. It is located in the Indian Ocean, between Australia and the Ninetyeast Ridge (Figure 15). As in the three earlier examples, we recognize all the tectonic features shown in Figure 1.

From 130 to 45 Ma, spreading occurred between India and Antarctica-Australia. The magnetic anomalies north of the Diamantina Fracture Zone have recorded this spreading episode [*Sclater and Fischer*, 1974]. Recent magnetic anomalies identifications by *Liu et al.* [1983] have recognized the 45 Ma abandoned spreading ridge under the Nicobar fan.

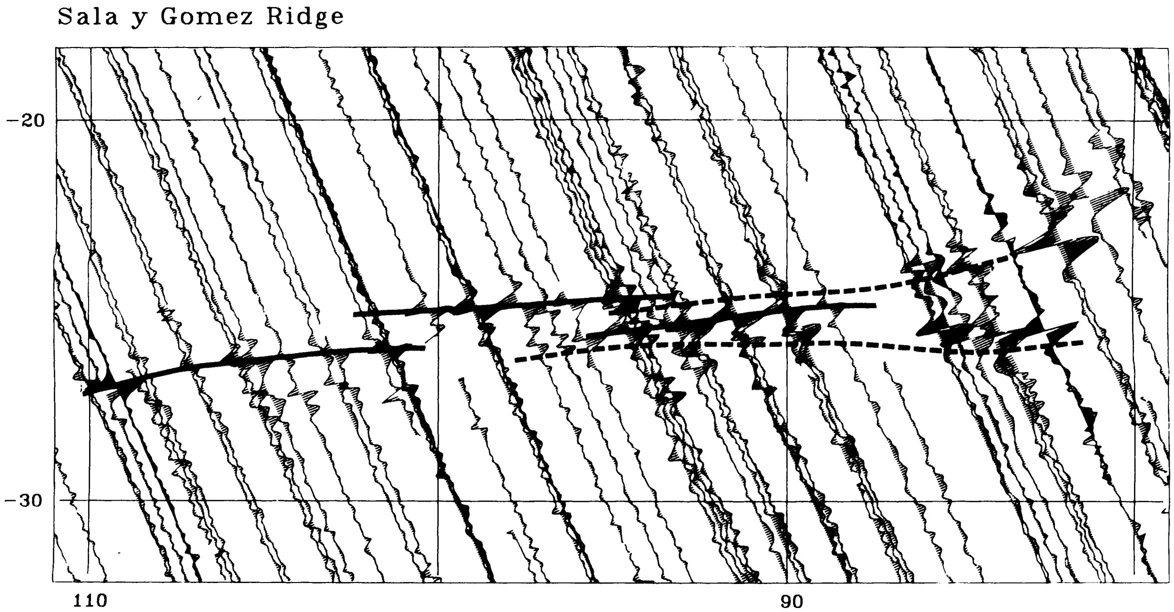

Fig. 17. Ascending deflection of the vertical profiles across the Sala y Gomez Ridge. Ridges (solid lines) and troughs (dashed lines) were identified in these profiles as well as descending Seasat profiles and dense coverage by the GEOS 3 altimeter (not shown). Scale is 60 μrad per degree of longitude.

South of the Diamantina Fracture Zone, the breakup of Australia from Antarctica took place relatively recently. The revised magnetic anomalies identifications of *Cande and Mutter* [1982] place this event on the old side of anomaly 34 (~90 Ma). They determined that a slow spreading regime lasted between 90 and 43 Ma, which is the time of extinction of the abandoned spreading ridge buried under the Nicobar fan. *Mutter and Cande* [1983] also revised earlier reconstructions of the breakup between Australia and Antarctica to eliminate an apparent overlap of the Kerguelen Plateau and Broken Ridge (an aseismic ridge which was broken up by rifting 90 Ma). We believe that the Diamantina Fracture Zone is the scar left in the topography by the same rifting episode which, 90 Ma, separated Antarctica from Australia as well as the Kerguelen Plateau from Broken Ridge. Figure 16 reproduces three of the 16 profiles across the Diamantina Fracture Zone published by *Mutter and Cande* [1983] at the same scale as other similar features we have discussed in this paper. We recognize in the deep main trough the rifting site discussed in our model. On the south and younger side of the trough the average depth is 4000 m, while on the northern and older side the average depth is greater. A single tectonic event, the initiation of spreading into old lithosphere, resulted in different morphological effects whether it took place in continental crust (separation of Antarctica from Australia), in normal and relatively old oceanic crust (Diamantina Fracture Zone), or in the thickened oceanic lithosphere of the Kerguelen-Broken Ridge plateau.

DISCUSSION

The observations presented above document the final stages of a spreading center jump (stages in Figures 1*c* and 1*d*). So far, we have not identified unambiguously on the oceanic lithosphere the thinning and initial stages of rifting (Figures 1*a* and 1*b*). While new continental rifting is observed in several locations at present and widely commented upon in the scientific literature, no examples of new rifting in relatively old and thick lithosphere are reported. We speculate the Sala y Gomez Ridge displays the early stages of thinning and rifting [*Mammerickx*, 1981]. An elongated 500-m-depth anomaly underlies the Sala y Gomez Ridge and a series of very young volcanoes line along its axis from Easter Island to the Peru-Chile Trench [*Bonatti et al.*, 1977].

Dense satellite altimeter coverage of this area reveals trough signatures adjacent to linear chains of young volcanoes. In Figure 17, ridges are marked by solid lines while troughs are marked by dashed lines. There ridge and trough locations were derived from all of the available altimeter data. The GEOS 3 data and half of the Seasat data are not shown. The characteristic width of the complex but lineated gravity signature is similar to proximal and distal troughs presented above. Amplitudes of these ridge and trough signatures (~80 μrad) are greater than is generally observed on such young seafloor, indicating that they are dynamically supported or extremely young. If rifting had already begun in this area, one would expect the ridge to be seismically active. Over the last 10 years, no detectable earthquakes have occurred on the Sala y Gomez Ridge. The observed bathymetry and deflections of the vertical and seismicity indicate that the Sala y Gomez Ridge is in the earliest stage of thinning and uplift.

The concave shape of the Peru-Chile Trench may provide the divergent pull necessary to trigger the opening of the spreading ridge. This setting resembles the early opening espisode of the Cocos-Nazca spreading ridge, 25 Ma along the Galapagos-Grijalva Fracture Zone [*Lonsdale and Klitgord*, 1978].

SUMMARY

1. Using marine geophysical data, we have identified 10 linear troughs in the seafloor and interpreted them as scars caused by rifting of relatively old lithosphere. These troughs are found in pairs. Halfway between them lies an active spreading center. Each fossil rifting site is charac-

terized by rugged topography and usually has one central deep trough. There is also a general depth offset across each rifting site, reflecting the age offset in the seafloor. The origins of many of these troughs were previously unexplained, and sometimes they were misinterpreted as fracture zones or abandoned transform faults.

2. Three of the five fossil rifts have abandoned spreading centers nearby. The abandoned spreading centers are relatively shallow and usually have a deep symmetrical trough which is surrounded by rugged topography. This morphology is characteristic of active slow spreading ridges. Seafloor ages, derived from magnetic lineations, indicate that the abandoned spreading center ceased spreading about the same time the oceanic rift developed. In the Moctezuma-Mathematician area, magnetic profiles suggest that the East Pacific Rise and the Mathematician Ridge (now abandoned) were spreading at the same time for about 1 m.y.

3. The spacial and temporal proximity of the fossil rifting sites and the abandoned ridge demonstrate that there was a long-distance shift in the location of seafloor spreading. For unknown reasons, spreading slowed at one site while rifting began several hundred kilometers away. Spreading eventually dominated at the rifting site, while spreading at the old site ceased.

4. Using these observations along with results derived from published continental rifting models, we developed a senario for a long-distance spreading center jump. The major tectonic events are (1) Uplift and thinning. Lithosphere strength increases rapidly with age so old lithosphere must be thinned to a thermal age of a few million years before rifting can occur. (2) Rifting. Forces on the plate boundaries initiate rifting. The widening crack is filled from above by splinters of crust. Upwelling of viscous material fills the crack from below. (3) Spreading. Seafloor depth decreases rapidly at the rift site as the spreading center approaches isostatic equilibrium. This emergence of the spreading center is recorded in the seafloor. As the emerging rift increases its spreading rate, spreading slows and eventually stops at the old site. We believe that the events occur simultaneously so that the sum of the two spreading rates remains constant. The present-day morphology of the abandoned ridge (i.e., deep central trough and rugged topography) indicates that it must go through a period of slow spreading. (4) Aging. Further development of the active spreading center results in a spreading ridge framed by two troughs. The proximal trough is closer to the abandoned spreading ridge and, in one instance, shows on its old side the topographic fabric associated with propagating rift processes. The abandoned spreading ridge subsides at a rate predicted from the depth versus age relation. Eventually, the broad ridge disappears and only the deep central trough and rugged topography remain.

5. The final stages of a long-distance spreading center jump are well documented in the geophysical data. We also believe that the earliest stage (i.e., the precursor swell) is apparent today as the elevated topography and rugged lineated seafloor of the Sala y Gomez Ridge. The only stage not yet observed is the rifting.

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