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# The Structure and Development of Rifted Midoceanic Rises[1]

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## ABSTRACT

Midoceanic rises can be divided into two categories: rifted and nonrifted. Rifted rises are characterized by a median valley, high relief, a thick second layer, and the presence of metamorphic and deep intrusive rocks. Rifted rises are believed to have slow spreading rates of less than 2 cm/year. Evaluation of geological and geophysical data for a rifted rise suggests a three-phase history. (i) The rise was constructed from an accumulation of plateau basalts. The thickening of the crust was compensated at depth by the rising of a metamorphic front, below which the Koeningsberger ratio Q is less than unity. This front placed a floor under the magnetic crust. Magnetic symmetry was achieved either by sea-floor spreading (Model 1) or by a gradually contracting volcanic zone (Model 2). As shown in Model 1, relief was created by normal faulting at the flanks as a result of stress caused by a nonlinear increase in the spreading rate away from the axis.

(ii) The first phase was followed by a long period of tectonic quiescence and uninterrupted sedimentation. (iii) The crest of the rise was lifted once more, resulting in the formation of a central graben with subsiding central block and raised rims; the crest and flanks were deformed by gravity-sliding and normal faulting. (The third stage may have occurred as late as the Quaternary.)

This proposed structural development of rifted rises yields a symmetric pattern of positive and negative magnetic anomalies and is consistent with geological data; it does not permit inclusion of recent sea-floor spreading except within the central rift, and one of the models does not require spreading at all. The reasoning presented suggests that there is a need for continuing examination of the reality of the magnetic models and for rigorous proof of the validity of magnetic correlations.

*Introduction.* The sea-floor spreading hypothesis as presented most recently by Vine (1966) is based almost entirely on inferences from geomagnetic data and from broad geologic considerations. Structural interpretations resulting from this hypothesis are usually stated in terms of vertical dike intrusions. Geological data suggest that, as a structural and historical model, this concept is greatly oversimplified; such data are now becoming sufficiently abundant to permit an attempt to formulate a more realistic model.

Menard (1967) and van Andel and Bowin (1968) have suggested that the geological and geophysical data now available indicate that the midoceanic rises can be subdivided in two groups. Some rises (for example, the Mid-Atlantic Ridge north of 30°S, the Carlsberg Ridge, and the Gorda Rise) are characterized by high relief, especially on the crest, and by an average thickness of 2.9–3.5 km (Menard, 1967) of the second layer (seismic velocity 4.3–5.5 km/sec). There is generally a well-developed median valley bordered by crestal ranges. Metamorphic rocks (greenstones and greenschists) as well as peridotites and serpentinites have been found in numerous localities. These characteristics suggest considerable faulting, with large vertical movements. The postulated half rates of sea-floor spreading range from 0.7 to 2.0 cm/year.

Other parts of the rise system (for example, the East Pacific Rise, the Juan de Fuca Ridge, and the Pacific-Antarctic Rise) have fairly smooth topography (except for parts of the flanks), lack a median rift, and possess a much thinner second layer that ranges from 1.0 to 1.5 km. Metamorphic and deep intrusive rocks have not been reported. The postulated sea-floor spreading half rates are 2.9–5.0 cm/year. These differences appear significant, and the two types may represent either different substrates and mechanisms or different stages in the life history of the midoceanic rise.

Recently, detailed geological and geophysical data on various rifted midoceanic rises have become available (Cann and Vine 1966, Loncarevic et al. 1966, van Andel et al. 1967, van Andel and Bowin 1968). Combined with other correlated geological-geophysical data, these data permit some tentative deductions regarding the structure and geologic history of the rifted rises; these deductions are independent of the consequences of the sea-floor spreading hypothesis and provide an independent frame of reference. It is the purpose of this paper to summarize this material, to examine the constraints that the material imposes on structural models for rifted rises, and to present models based mainly on nongeomagnetic evidence. It is not my intention in this paper to argue against sea-floor spreading; rather, I intend to demonstrate that other and more complex models are consistent with the geologic information and that, consequently, the geomagnetic models and correlations in each case require rigorous proof.

*Physiography.* The physiography of the Mid-Atlantic Ridge north of 15°N has been described by Heezen et al. (1959). More detailed studies of local areas (Hill 1960, Loncarevic et al. 1966, van Andel and Bowin 1968) have confirmed this description. Parallel to the Ridge axis over more than 35 degrees of latitude, a series of physiographic zones having distinctly different morphological characteristics is traceable. The crest of the Ridge is generally marked by a median valley having a depth of more than 2000 m below the bordering ranges. These ranges, rising to less than 2000 m below sea level, consist of subparallel ridges and valleys having an internal relief of 800–1200 m
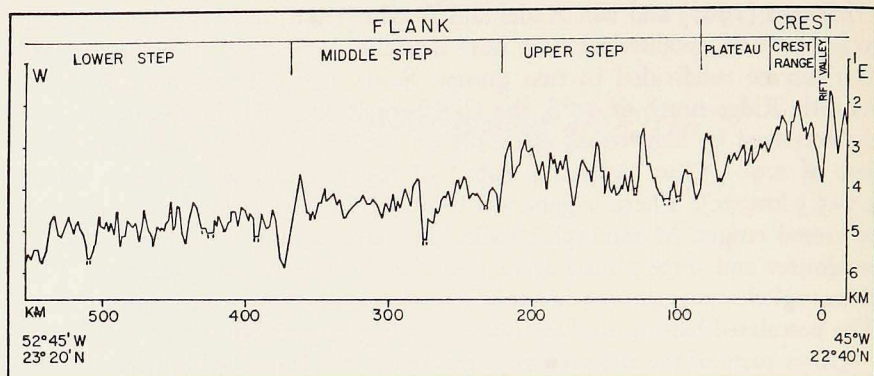
Figure 1. Physiographic divisions of the Mid-Atlantic Ridge in the North Atlantic Ocean; bottom profile from cruise 1965-1 of R/V WASHINGTON. Vertical exaggeration 33 ×. Nomenclature of Heezen et al. (1959).

and widths of about 20 km. These crestal ranges or rift mountains are in turn bordered by plateau areas of smaller linear hills and valleys having spacings of 5–10 km and relief of a few hundred meters. Together, these units form the crestal province. Between the crestal province and the ocean basin floor lie three additional zones: the upper, middle, and lower steps (Fig. 1), each with successively greater depths and sharp drops in elevation at the zone boundaries. Commonly, the mean level of each step is tilted either outward (Heezen et al. 1959; fig. 46) or inward (Fig. 1).

Thus, the Ridge topography is characterized by a sequence of zones that differ greatly in mean depth, in degree of linearity, and in the trend, width, and spacing of hills and valleys. The flank topography does not represent a simple repetition of the crestal relief at greater depth and distance from the axis; in fact, its direct derivation from the crest-rift valley complex by lateral transfer is difficult to envision.

South of approximately 15°N, the Ridge is much narrower. The crestal province is developed as described above, but the flanks consist of isolated and widely spaced hills emerging from a largely sediment-covered slope (Fig. 2), probably as a result of much deeper burial of the basement. In the South Atlantic, between 5° and 30°S, the Ridge broadens again and its development appears to have been similar to that north of 15°N (Heezen and Tharp 1961).

A similar appearance is presented by the Carlsberg Ridge in the western Indian Ocean (Heezen and Tharp 1964, 1966). Here also, a median rift bordered by crestal ranges is usually present, and zones of divergent physiographic character parallel the Ridge axis. Detailed surveys (Udintsev 1965, Matthews et al. 1965) have shown topography that is similar to that of the Mid-Atlantic Ridge.
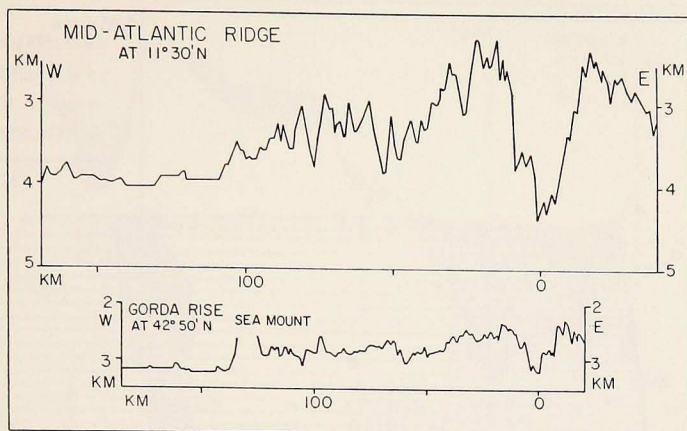
Figure 2. Topographic profiles of the Mid-Atlantic Ridge north of the Vema Fracture Zone (top) and of the Gorda Rise in the northeastern Pacific (bottom). Top, from R/V Atlantis-II, cruise 20, vertical exaggeration 27 ×; bottom, modified from McManus (1967: fig. 4), vertical exaggeration 23 ×.

The Gorda Rise in the northeastern Pacific (McManus 1967) is another rifted rise that also exhibits a well-developed median rift bordered by crestal ranges and a high plateau (Fig. 2). The total width and relief are less than that of the Mid-Atlantic Ridge, but the character and zonation of the relief are similar. A characteristic upper step can be distinguished, but the lower flank shows a subdued relief of small hills rising from a sedimentary plain as a result of rapid burial near the continent. An abrupt drop of 400 m separates the upper step from the middle flank.

*Sediments and Stratigraphic Age.* The crest of the Mid-Atlantic Ridge in the North Atlantic appears to be free of sediment or to have a patchy cover that is too thin for resolution by seismic reflection methods (Ewing et al. 1964, Ewing and Ewing 1967, van Andel et al. 1965, van Andel and Bowin 1968). Coring and dredging have usually yielded only rock; when sediment was found, it was gritty and contained material of local derivation. Ewing and Ewing (1967) have reported a gradual increase in sediment thickness away from all of the rise axes, to a distance of 100–400 km, where an abrupt increase occurs. Beyond that point, the mean thickness remains almost uniform. The distance between the rise axis and the point of large increase appears to be related to the estimated rate of sea-floor spreading; on the basis of the extrapolated geomagnetic chronology, this point has an age of approximately 10 million years. On the Mid-Atlantic Ridge north of the Equator, the discontinuity occurs at about 100 km from the crest.

A detailed survey at 22°N (Fig. 3) has shown that thick flat-floored valley fills appear rather abruptly at approximately 75–100 km from the Ridge axis.
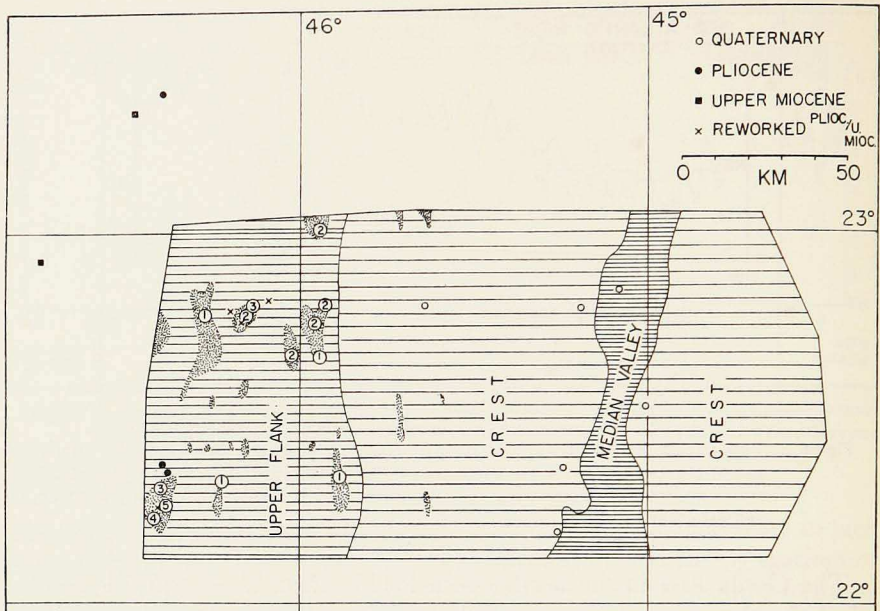
Figure 3. Sediment distribution and biostratigraphic ages of the crest and upper flank of the Mid-Atlantic Ridge between 22° and 23°N. Stratigraphic ages based on Cifelli (1965, 1967), Cifelli et al. (1966), and Saito et al. (1966). Stippled areas are flat-floored sediment-filled valleys; approximate sediment thickness indicated to the nearest 100 m.

The sediments in the valleys contain reworked upper Tertiary Foraminifera derived from nearby outcrops (Cifelli 1967). In-situ Upper Miocene and Pliocene sediments have been recovered from adjacent hillsides (Cifelli 1965, 1967, Cifelli et al. 1966). Samples from the Ridge crest contain only Quaternary material.

The major age discontinuity indicated by these observations coincides approximately with the boundary between the crest and the upper step, and it separates the youthful and lineated sediment-free crestal relief from the sediment-covered and much-less-linear flank relief. Therefore, it may be concluded that the flanks have been the site of uninterrupted sedimentation, at least since the late Miocene and possibly since the early Tertiary or late Cretaceous (Saito et al. 1966, Ewing et al. 1966, Ewing and Ewing 1967). Riedel (1967) has also reported an approximate coincidence of the boundaries of occurrence of Miocene and Pliocene sediments on the nonrifted East Pacific Rise. Phillips (1967) has identified a discontinuity in the magnetic anomaly pattern on the northern Mid-Atlantic Ridge at approximately the same position; he attributes this discontinuity to a change in spreading rate that occurred 5–10 million years ago. Discontinuities in the magnetic anomaly pattern also occur in the northwestern Indian Ocean (Fisher et al. 1968).
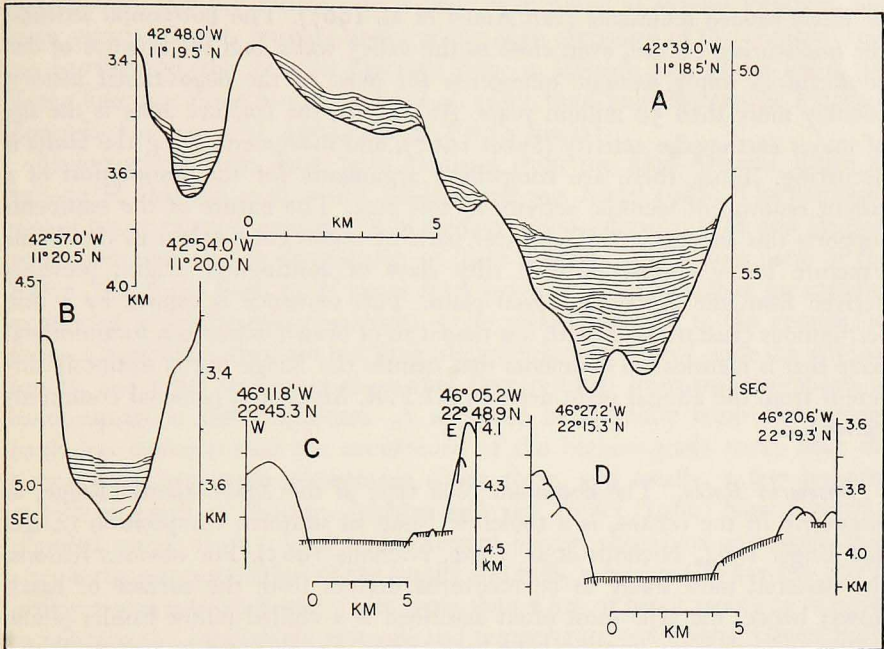
Figure 4. Evidence for recent deformation of sediments on the flanks of the Mid-Atlantic Ridge in the North Atlantic. Profiles A and B: seismic reflection profiles from the east flank of the Ridge north of the Vema Fracture, approximately 100 km east of the axis. Profiles C and D: tracings of slow speed echsounder records of two sediment-filled valleys on the upper western flank of the Ridge at 22°N, at approximately 120–140 km from the Ridge axis, showing terraces bordered by scarps, and tilted sediments on the crest side of the valleys. Vertical exaggeration of A and B: 11 ×; of C and D: 12.5 ×.

Thus, the structural evolution of the Mid-Atlantic Ridge seems to have taken place in at least two stages separated by a long period of tectonic quiescence and sedimentation. The sparse data for the Gorda Rise (McManus 1967) may be interpreted in the same way (Fig. 2), and Ewing and Ewing's information indicates that a long break in the growth of midoceanic rises may be a world-wide phenomenon.

Other evidence supports the conclusion that tectonic activity on the Mid-Atlantic Ridge has recently been reactivated. Between 22° and 23°N, and more clearly on the Ridge just north of the Vema Fracture Zone, the sediment fills in the valleys have been faulted, deformed, and uplifted since the deposition of most of the fill (Fig. 4). Invariably, it is the side toward the Ridge crest that has been raised; on that side, many valleys show a high uneven terrace bordered by a scarp, and scismic reflection records indicate deformation. Similarly deformed valley fills have been noted by Ewing et al. (1964) at other locations on the Mid-Atlantic Ridge.

The trough occupying the Vema Fracture Zone contains well over 1000 m

of finely bedded sediments (van Andel et al. 1967). The horizontal attitude, the undisturbed nature, even close to the valley walls, and the absence of disconformities imply tectonic quiescense for most of the depositional history, possibly more than 50 million years. At present, the fracture zone is the site of major earthquake activity (Sykes 1967), and movement along the faults is occurring. Thus, there are compelling arguments for the assumption of a recent renewal of tectonic activity in this area. The nature of the sediments supports this assumption. The lower parts of piston cores taken in the Vema Fracture valley consist of dark silty clays of continental origin, probably derived from the Amazon abyssal plain. This sequence is capped by a thin ferruginous crust overlain with less than 1 m of brown calcareous foraminiferal ooze that is identical to sediments that mantle the Ridge but is distinctly different from the abyssal plain deposits (D. F. R. McGeary, personal communication).

*Basement Rocks.* The dominant rock type of the Mid-Atlantic Ridge, as elsewhere in the oceans, is a tholeiitic basalt of uniform composition (Engel and Engel 1964, Nicholls et al. 1964, Nicholls 1965). For obvious reasons, the material most likely to be recovered derives from the surface of basalt flows; hence, the type most often described is a chilled pillow basalt; pillow shapes and columnar jointing have been commonly observed in bottom photographs. Such rocks and volcanic glass are dominant in collections from the floor of the median valley (van Andel and Bowin 1968). However, complete examination of the contents of rock collections, in particular those from steep scarps, has commonly revealed the presence of coarser-grained material of doleritic and diabasic texture derived from the interior of thick flows (Muir and Tilley 1964, van Andel and Bowin 1968). In collections from the area of 22°N, aquagene tuffs, sometimes containing numerous and occasionally large basalt fragments, occur in fair abundance.

In general, the rocks dredged from the floor of the median valley at 22°N are fresh, the glass is unaltered, and manganese coatings are absent, indicating a very young age for the flows and the exposed surfaces of the escarpments. Rocks from a transverse ridge at the northwestern end are more altered and have a fairly thick manganese coating. They may be slightly older. Fresh basalts have also been found at 45° to 46°N (Muir and Tilley 1964) and at 11° and 9°N in the median valley (van Andel et al. 1967).

Only a few isotopic ages have been obtained for Mid-Atlantic Ridge basalts. Grasty and Miller (in Muir and Tilley 1964) have reported potassium-argon ages of 0.23 to 8.5 million years (with one older specimen of 18 million years) for rift-valley basalts obtained at 45°N. Such relatively high ages for rocks in the axial zone of the Ridge recall the finding of Miocene Foraminiferal ooze on the axis at 30°N (Saito et al. 1966).

Rocks other than basalt occur on the Ridge, but they are less common.

Serpentinites and peridotites, which have been found at several locations, are often associated with fracture zones where deep exposures of the oceanic crust can be expected (the Atlantis Fracture Zone in Heezen and Tharp 1965, the Vema Fracture Zone in van Andel et al. 1967, the Chain-Romanche Fracture Zones in Heezen et al. 1964, and St. Paul's Rocks).

Metamorphic rocks have been obtained from the Mid-Atlantic Ridge at 22°–23°N (Melson et al. 1966, Melson and van Andel 1966). The composition of heavy mineral assemblages in median valley sediments (Fox and Heezen 1965) indicates a wide distribution of these rocks in the median zone of the Ridge. The rocks from 22°N range from low-grade chlorite-albite greenstones to sheared actinolite-epidote-chlorite-albite rocks belonging to the greenschist facies. Chemically, they are but little altered when compared with the original basalts, and relict structures show that they resulted from metamorphism of basalt-aquagene tuff complexes. A sequence of carefully controlled dredge hauls has demonstrated the occurrence of the highest-grade rocks near the bottom, the low-grade greenstones above them, and finally, a few hundred meters of basalt at the top. Melson and van Andel (1966) have favored a regional rather than a local hydrothermal origin; they have estimated that, after surface accumulation of the basalts and tuffs, subsidence below the 300°C isotherm and possibly burial under more than 2 km of basalt would be required to produce the appropriate pressure and temperature conditions. Green hornblende-plagioclase amphibolite, which is an even-higher grade member of this metamorphic series, has been reported, together with basic intrusives (Cann and Funnell 1967), for the Palmer Ridge in the northeastern Atlantic.

Precisely located dredge samples and detailed topographic analysis have led van Andel and Bowin (1968) to postulate the structural interpretation presented in Fig. 5, which leads to the following history of development. During the first phase, surface extrusion of a thick pile of basalts and interstratified aquagene tuffs took place, with concomitant metamorphism of the lower members of the series. This was followed by uplift of the Ridge and by rifting of the median valley along faults dipping 45°–60° toward the center. As a result, the lower parts of the metamorphosed basalt pile were exposed on the flanks of the rift valley. The presence of only a few hundred meters of basalt on top of the metamorphics appears to require removal of some overburden; van Andel and Bowin (1968), who considered removal by erosion unlikely, postulated gravity sliding along low-angle detachment faults that dip away from the axis, perhaps facilitated by intercalated beds of tuff and pelagic sediments. The rifting and uplift were accompanied by extensive outpouring of basalt on the floor of the rift valley and perhaps locally, as suggested by Loncarevic et al. (1966), by the formation of volcanoes along the fault zones.

The structural section in Fig. 5 is oversimplified; the topography presents ample evidence for numerous additional normal faults. Atwater and Mudie (1968), using near-bottom echosounding and seismic profiling techniques, have
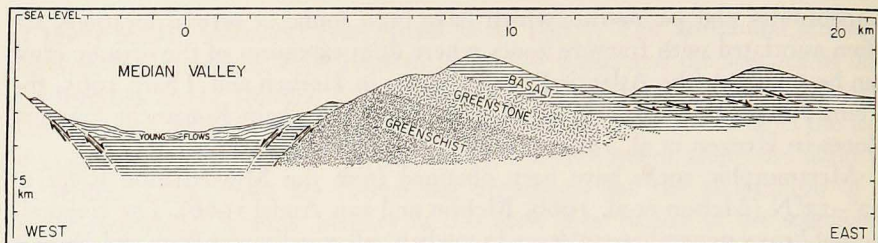
Figure 5. Schematic structural diagram of the rift valley and eastern crest of the Mid-Atlantic Ridge at 22° 30'N. No vertical exaggeration. After van Andel and Bowin (1968: fig. 7). Fault structure greatly simplified.

shown that the rift valley of the Gorda Rise contains a large number of steps descending toward the center of the rift (Fig. 6). Although the throw of the faults in this case is probably inadequate to expose the lower crust, a structure of similar complexity could reasonably be postulated for the Mid-Atlantic Ridge.

Metamorphic rocks of the greenstone facies have been found on other rifted midoceanic rises. Cann and Vine (1966) have attributed the occurrence of greenstones in the Carlsberg Ridge to local hydrothermal activity. The amphibolites of the Palmer Ridge have been explained by Cann and Funnell (1967) as the products of events similar to those described for the Mid-Atlantic Ridge at 22°N. Low-grade and medium-grade greenstones similar to those described by Melson and van Andel (1966) have been recovered from the Blanco Fracture Zone near the Gorda Rise (J. R. Duncan and W. G. Melson, personal communication). In sediments from the upper flank at 22°N, Siever and Kastner (1967) have found detrital minerals derived from local greenstone outcrops.

Thus, wherever exposure of the deeper crustal parts is provided in fracture zones and rift valleys, there is evidence in the lower part of the basalt pile of metamorphism to greenstone, greenschist, and ultimately to amphibolite.
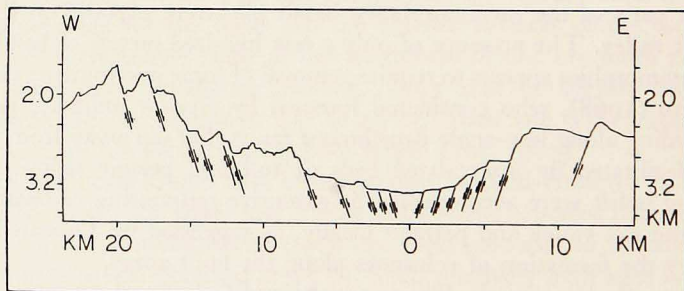


Figure 6. Structural profile of the rift valley and adjacent crestal ranges of the Gorda Rise at approximately 41°10'N. Based on observations with a near-bottom echosounder system, after Atwater and Mudie (1968: fig. 3).

Again, these observations strongly suggest a two-phase history for the rises, the first phase consisting of surface accumulation of basalt accompanied by metamorphism at depth, the second by vertical uplift and rifting. Such a two-phase model would conveniently account for the wide spread in ages cited by Muir and Tilley (1964) and for the Miocene sediments found by Saito et al. (1966). It also recalls the situation on Iceland (Thorarinsson 1965), where a rift valley of Plio-Pleistocene age occurs in older Tertiary plateau basalts.

Measurements of the magnetic susceptibility and intensity of rocks from the Ridge at 22°N show that the alteration to greenstone sharply reduces the magnetic properties and decreases the Koeningsberger ratio Q to less than 1 (Luyendyk and Melson 1967). The basalts show a range of magnetic intensity that extends over four orders of magnitude while the metamorphics are another order lower than the lowest basalts. Similar measurements on Mid-Atlantic Ridge basalts have been presented by Opdyke and Hekinian (1967). With $Q < 1$, only normal polarities would be created in the metamorphics, and, if there is a regional level below which all basalts are metamorphosed to greenstone facies, then this level would be the effective floor of the magnetic layer.

*Structural Development of Rifted Rises.* The observations discussed above can be summarized as follows:

1. There exists a distinct physiographic zonation parallel to the ridge axis. The individual zones have divergent morphological characteristics and cannot be explained by simple transfer of structural-morphological units from the axis to the flanks. It is not clear how the relief of the crestal ranges and valleys could have been produced by a combination of rifting and lateral movement alone.

2. There exists considerable evidence for major vertical movements in addition to the horizontal movements usually assumed. These vertical movements, which have not been restricted to the rift valley, have also produced fault scarps and deformation of sediments on the flanks.

3. Sediment thickness distribution as well as petrologic and stratigraphic data indicate several phases in the history of the rifted rises. During the initial phase, surface accumulation of basalts and tuffs took place on a large scale; this phase was followed by metamorphism of the lower part of the series when it became sufficiently thick. The relief formed during this latter stage was preserved on the flanks (with modifications by later faulting) but is mostly obliterated on the crest. This stage terminated prior to the Upper Miocene and perhaps as early as the late Cretaceous; then a long period of tectonic tranquility and sedimentation followed. Recently, tectonic activity has been resumed, leading to further faulting on the flanks and to intense volcanism, rifting, and faulting on the crest.

Sea-floor spreading is compatible with the first and third stages but is

not required by the geologic data, excluding geomagnetic observations. Continuous spreading, on the other hand, is not supported by the data. The correlations between anomaly patterns of rifted and nonrifted rises, which form the basis for the continuity assumption, are open to question unless the interruption in spreading is world-wide, in which case the extrapolation of the geomagnetic time scale is incorrect.

Below, some models for the structural development of the Mid-Atlantic Ridge and for other rifted rises are presented; these models, which are consistent with geologic observations, appear to be geologically plausible. Although no attempt has been made to reconcile these models with the geomagnetic patterns, such patterns impose additional constraints. The igneous bodies that constitute the magnetic crust must alternate between normal and reverse polarity as they are extruded. However, the thickness of individual bodies may be in part a function of a variable flow rate of the magma and therefore not proportional to the duration of the geomagnetic polarity epochs. Furthermore, there must be approximate symmetry around the axis of the rise. Excellent symmetry has been demonstrated only for some nonrifted rises (Vine 1966, Pitman and Heirtzler 1966); magnetic symmetry of rifted rises has been claimed (Phillips 1967) but not convincingly demonstrated.

The currently favored crustal model is assumed to be a single layer of crustal blocks of alternating normal and reverse polarity, separated by vertical boundaries. Commonly, it is assumed that these blocks consist of vertical dike swarms occupying tension cracks in a spreading crust. Alternatively, they might represent successive shallow rift valleys filled with basalt.

Vertical dike swarms of basalt not accompanied by extensive surface flows are improbable. In all major plateau basalt areas, dike rocks form only a minor component of the volcanic body. For Iceland, Bodvarsson and Walker (1964) have described an aggregate thickness of 2.3 km for dikes in a traverse of 37 km and of 3 km for a traverse of 53 km, with the bulk of the rocks consisting of plateau basalt. They have also estimated that their postulated total thickness of 20–30 km of plateau basalts required an aggregate of 400 km of conduit. This shows that, although the crustal extension may be considerable, a large part of the new crust so formed consists of subhorizontal basalt flows. Thorarinsson (1965) and Bodvarsson and Walker (1964) have estimated that at least one-fourth to one-half of the total magma reached the surface and that layer D (the 3rd layer of marine geophysicists), to a depth of 10–15 km, consists of a mixture of plateau basalts and intrusives.

Two alternative models can be suggested for phase I—the constructional phase of a rise. In Fig. 7, three successive stages are shown diagrammatically for each model. In Model 1, sea-floor spreading and tensional rifting of a gently arched pre-existing crust is assumed. The extension caused either open fractures, subsequently occupied by dikes, or tension rifts filled with flows and dikes. A large complex of regionally extensive super imposed surface flows
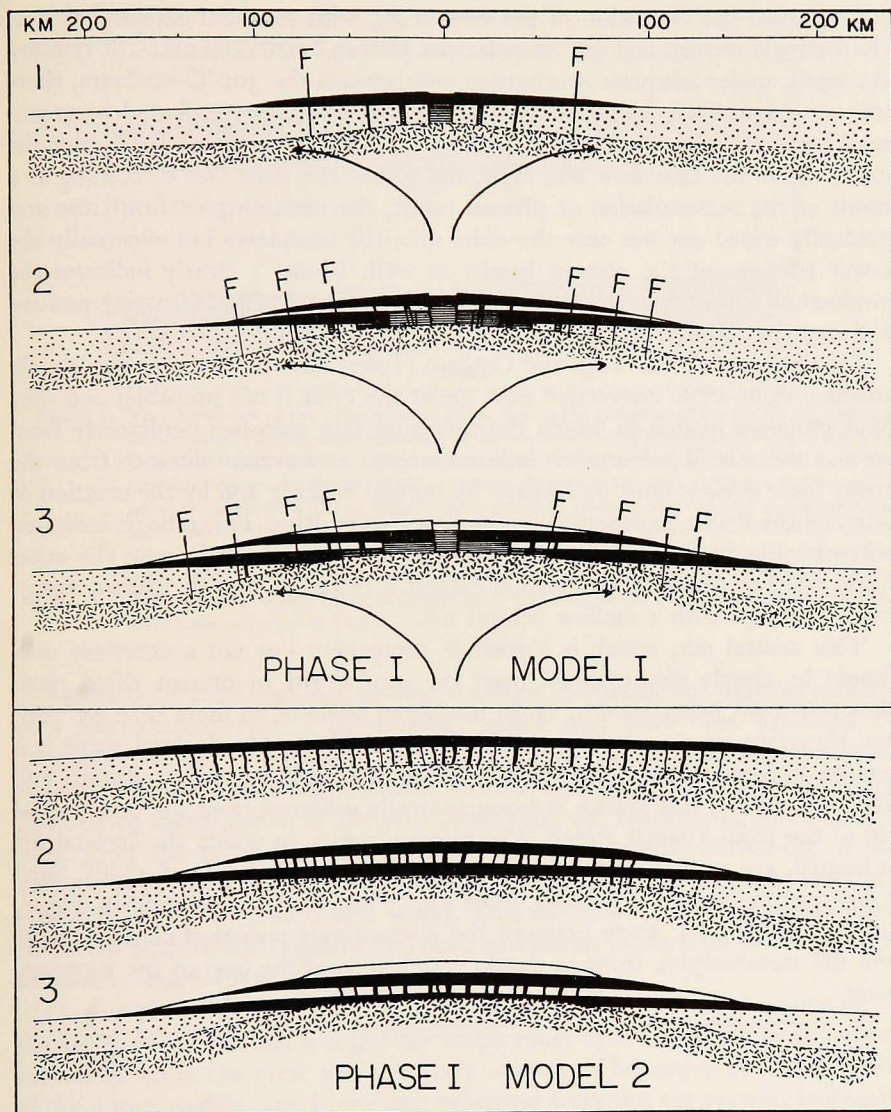
Figure 7. Two models for the development of a midoceanic rise during the constructive phase (phase I). For explanation of models, see text. Black and white horizontal layers are normal and reverse polarized plateau basalts. Horizontal shading: graben fill or dike complex; stippled: preexisting crust; random dashes: metamorphic layer with $Q < 1$; oblique lines labeled F schematically represent deformation by faulting and formation of relief on flanks. Thickness of plateau basalts greatly exaggerated; otherwise vertical exaggeration is approximately $10 \times$. In Model 1, plateau basalts may be downwarped to graben, as shown in Fig. 8; sediment cover, gradually thickening away from the crest, has been omitted.

accompanied the formation of the new crust, with resultant accumulation of alternatingly normal and reverse polarized plateau basalts and dike-rift systems. At depth, under adequate overburden and beneath the 300°C isotherm, there was a metamorphic front, below which the volcanics were altered to green-stones and the Koeningsberger ratio was reduced to less than 1. Under the crest, where the heat flow was high, and where the crust was thickening as a result of the accumulation of plateau basalt, the metamorphic front rose and gradually wiped out not only the older dike-rift complexes but eventually the lower portions of the plateau basalts as well. Model 1 clearly indicates the production of a symmetric magnetic anomaly pattern with alternating positive and negative anomalies.

Orowan (1966) and Vogt and Ostenso (1967) have argued that the usually assumed right-angle convective flow under the crest is not probable; and they have proposed models in which the spreading rate increases nonlinearly from zero at the axis. Their models indicate stresses at a certain distance from the crest; these stresses must be relieved by normal faulting and by the creation of relief on the flanks, as observed on the East Pacific Rise. This relief is indicated schematically in Fig. 7 with fault symbols. The crestal portion, on the other hand, was not disturbed and should exhibit a relatively smooth plateau topog-raphy, perhaps with a shallow central rift.

This central rift, which is a possible component but not a necessary one, should be clearly distinguished from the central rift in present rifted rises; the present rift is bordered by faults having an angle of no more than 45°–60° and therefore must contain a subsided central block. On Iceland there is a tension graben bordered by vertical faults (Thorarinson 1965, Rutten and Wensink 1960); this graben is topographically different from the deep crestal rift of the Mid-Atlantic Ridge. The plateau basalts, in which the Iceland rift is located, are warped downward toward the rift, with slopes of 4°–8°. Such a downwarp, omitted for clarity from Fig. 7 but shown separately in Fig. 8, resulted in a 5°–10° angle between the alternatingly polarized plateau basalts and the metamorphic front at depth, which formed the base of the magnetic layer.
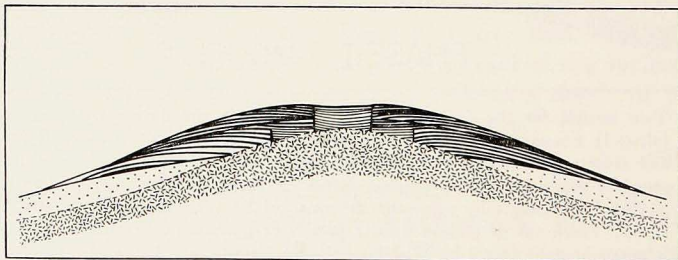


Figure 8. Enlargement of phase 2, Model 1, of Fig. 7, showing downwarping of plateau basalts (black and white layers) toward margins of rift zones. Stippled: preexisting crust; random dashes: metamorphic layer.
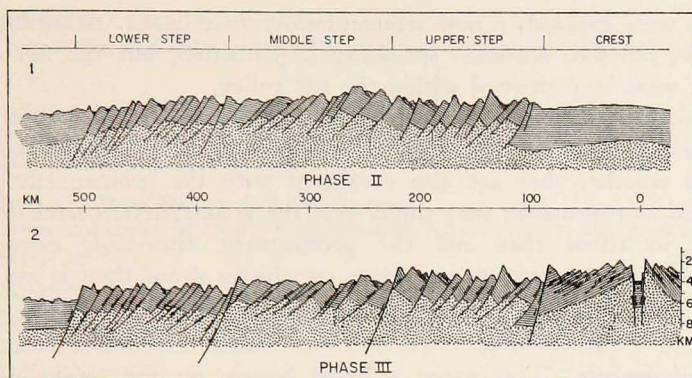
Figure 9. Top. Structure of the Mid-Atlantic Ridge during the quiescent phase (phase II), showing deformation resulting from spreading of the sea floor during phase I in Model 1. Bottom. Profile showing structure after renewed uplift accompanied by rifting of the crest and step faulting on the flanks. Fault pattern is diagrammatic; only minimum number of all possible antithetic faults is shown; fault structure under gravity sliding at the crest has been omitted altogether. Topographic profile of Fig. 1 has been used as the base; vertical exaggeration approximately 10 ×. Black horizontal shading: basalt fill of central graben; wavy lines: complex of alternating normal and reverse polarized basalt flows; random dashes: metamorphic layer. Sediment cover omitted except for major valley fills (black) shown for reference to Fig. 1.

Model 2 (Fig. 7) does not assume sea-floor spreading but only an arching of a pre-existing crust. This arching, which may have been produced by thermal expansion or hydration of the underlying mantle, resulted in a broad zone of tensional fracturing with dike formation and outflow of plateau basalts. Progressive consolidation of the crust, following the upwarping, proceeded inward from the margins of the arch and led to a gradual narrowing of the volcanic belt. Such progressive narrowing of the volcanic zone has been observed in Iceland (Thorarinsson 1965). This model will also yield a symmetric pattern of positive and negative magnetic anomalies; it meets all of the geologic conditions stated above.

During phase II (Fig. 9, top)—a period of quiescence and sedimentation — the flanks of the rise had a uniformly rough relief that was slowly buried under sediments while the crest was relatively smooth. The major boundary faults of the upper, middle, and lower step provinces were not yet present, and some minor faulting (referred to in Fig. 4) as well as the rifting of the crest had not occurred. Probably there was a regional subsidence of the entire rise.

In phase III, during a renewed uplift of the crest, a normal graben developed, with subsidence of the central block, the rims rose, and volcanism occurred in the rift zone. Gravity sliding and normal faulting (not shown in Fig. 9, bottom) disturbed the crestal topography, and on the flanks the stresses that resulted from the uplift of the crest were relieved by major but fairly low-angle faults that created the step topography. Metamorphics and deep

intrusives were exposed; a new sedimentation cycle began. According to this hypothesis, renewed sea-floor spreading is permitted, but the net effect of spreading must be contained within the rift valley.

This sequence of structural models and geologic events satisfies the geologic conditions and hypotheses outlined in this paper. Model testing is necessary to determine whether they are also consistent with the geomagnetic patterns. If accepted as reasonable, they imply that the geomagnetic correlations from nonrifted to rifted rises and the geomagnetic time-scale extrapolations require further examination and more conclusive proof than is available at present.

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