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Anomalous opening of the Equatorial Atlantic due to an equatorial mantle thermal minimum

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Abstract

The geology of the Equatorial Atlantic is dominated by a broad east–west megashear belt where a cluster of large fracture zones offsets anomalously deep segments of the Mid-Atlantic Ridge (MAR). The origin and evolution of this megashear region may lie ultimately in an equatorial mantle thermal minimum. The notion of a mantle thermal minimum in the Equatorial Atlantic is supported by an equatorial minimum of zero-age topography, a maximum in mantle shear waves seismic velocity and a minimum in the degree of melting, indicated by the chemistry of MAR basalts and peridotites. This thermal minimum has probably been a stable feature since before the Cretaceous separation of Africa from South America; it caused a pre-opening equatorial continental lithosphere thicker and colder than normal. The Cretaceous Benue Trough in western Africa and the Amazon depression in South America are interpreted as morphostructural depressions created or rejuvenated by strike-slip, transpressional and transtensional tectonics during extension of the cold/thick equatorial lithosphere. The oceanic rift propagating northward from the South Atlantic impinged against the equatorial thicker, colder and, therefore, stronger than normal continental, lithosphere that consequently acted as a 'locked zone'. This, and a low magmatic budget due to the cold upper mantle, caused a lower than normal rate of propagation of the oceanic rift into the equatorial belt, with diffuse deformation during mostly amagmatic extension. The thick/cold lithosphere prevented major Cretaceous igneous activity from the St. Helena plume. Eventually initial 'weak' isolated nuclei of oceanic lithosphere were emplaced, separated by E–W continent/continent transforms. Opening occurred largely by strike-slip motion along these initial transforms. The consequences were that the Equatorial Atlantic opened prevalently along an E–W direction, in contrast to the N–S opening of the North and South Atlantic, and that sheared continental margins are particularly well developed in the Equatorial Atlantic. After further continental separation the cold equatorial mantle caused a low degree of melting (with Na-rich MORB and alkali basalt rather than normal MORB and with undepleted mantle peridotites), thin crust, depressed ridge segments and a prevalence of amagmatic extension. Similar conditions still exist today. Long transforms offsetting short ridge segments kept sea floor spreading unstable and dominated by transform tectonics, with transform migration, transpression, and transtension causing strong vertical motion, emersion and subsidence of lithospheric blocks, development of deep pull-apart basins, and preservation of relict slivers of old lithosphere (occasionally even of continental lithosphere) within younger crust. The equatorial transforms are caused ultimately by a long lived thermal minimum in the upper mantle and not vice versa; however, they then create second-order 'rebound' thermal effects that help maintain the thermal minimum in the upper mantle. It can be speculated that mantle thermal minima at the Earth's equator might be related to true polar wander triggered by subduction of dense masses into the mantle.

Keywords: Mid-Atlantic Ridge; fracture zones; continental drift

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1. Introduction

It is generally accepted that the Atlantic Ocean originated by the gradual separation of Eurafrica from the Americas. According to this view, the present configuration of the Atlantic basin depends on: (1) the geometry of the original split; and (2) the direction and velocity of motion of the sub-Atlantic lithosphere after the initial split. The second parameter has been the subject of many studies, based mainly on the Vine-Matthews interpretation of sea floor magnetic anomalies. The geometry of the original split is also known reasonably well, thanks to pre-Atlantic rift reconstructions starting with that of Bullard et al. [1]. However, the question of what determined the geometry of the initial split is still unresolved. It is widely assumed that the distribution of mantle positive thermal anomalies (upwelling convection currents, plumes, and the like) determined the geometry of the initial split [2], because the thermal anomalies weakened the continental lithosphere. On the other hand, thermal and mechanical heterogeneity of the pre-rift continental lithosphere must also have affected the initial geometry of opening.

This paper inquires as to why the initial split between South America and Africa took place in the equatorial region on a prevalently E–W trend, in contrast to the general N–S trend of opening that prevailed in the Atlantic outside the equatorial region; furthermore, it discusses why some of the longest transforms of the MAR are clustered in the Equatorial Atlantic where they offset unusually deep segments of the MAR. I suggest that the geological processes that caused the anomalous opening of the Equatorial Atlantic were caused ultimately by a long-lived negative thermal anomaly in the underlying mantle.

2. Distribution of transforms in the Atlantic

Most of the transform offsets of the MAR axis are short (< 20 km) and represent probably transient discontinuities [3]. The larger (> 100 km) offsets are marked generally by a strong topographic and gravity signature that may extend outside the ridge/ridge active zone. Several of these large fracture zones have been traced across the Atlantic from the American to the Europe/Africa continental shelves, and may even correspond to offsets of the continental margins, indicating that they already existed during the initial separation of Europe–Africa from the Americas. Early topographic maps and recent SeaSat/GeoSat/ERS-1 satellite imagery [4] show that these larger 'initial' transform boundaries are not randomly distributed, but are clustered prevalently in the equatorial region (Figs. 1–3).

The Romanche, with an offset of about 900 km, the longest active transform of the Atlantic, is located close to the equator (Fig. 3); it is flanked to the north by the St. Paul Fracture Zone (F.Z.) (offset ~ 400 km if we include some small en echelon offsets on the eastern end of the transform) and to the south by the Chain F.Z. (offset ~ 300 km). The cumulative length of offset of the MAR axis in the area from 3°N to 3°S is over 1700 km, while the cumulative length of the MAR axial segments in the same area is < 600 km. The ratio of length of offsets versus length of ridge axial segments along the MAR integrated per each 6° of latitude (Fig. 3)

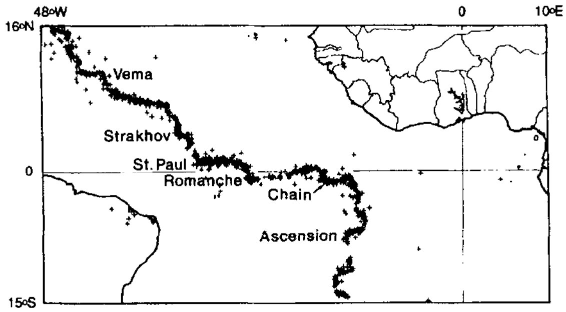
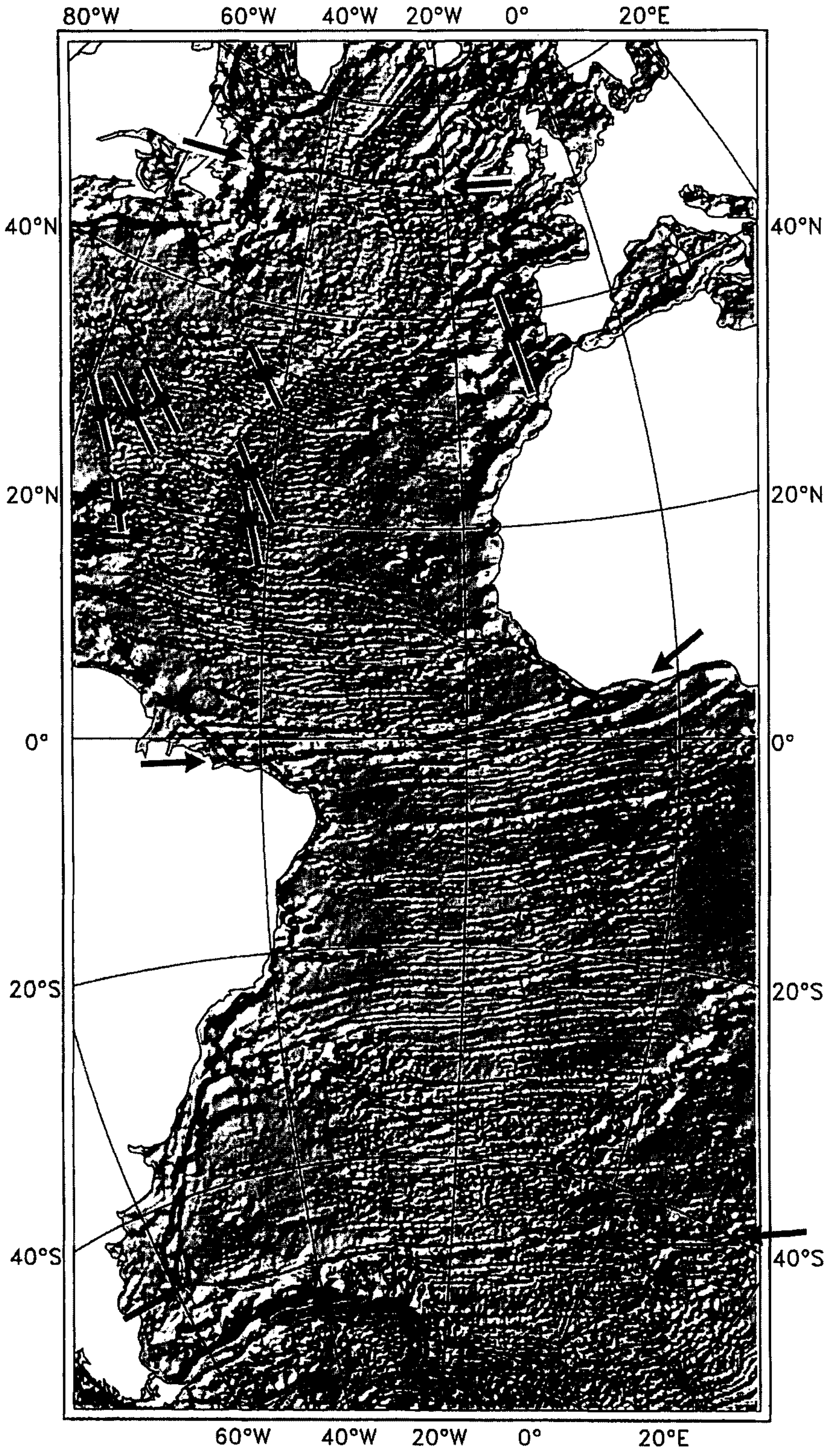


Fig. 1. Distribution of earthquake epicenters (magnitude > 4, from the LDEO data bank, error ±20 km) marking plate boundaries in the equatorial Atlantic. Accretionary boundaries (axis of the Mid-Atlantic Ridge) strike roughly N–S; transform boundaries strike roughly E–W. The major transform boundaries are identified.

Fig. 2. Satellite gravity imagery (Seasat/Geosat/ERS 1) over the Central Atlantic, from [5]. Note the trace of the large equatorial fracture zones extending from South America to Africa. Superimposed vectors indicate the direction of upper mantle flow in the North Atlantic, derived from seismic anisotropy data of Yang and Fisher [14]. Arrows indicate long-lived transform boundaries and sheared continental margins.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has a strong maximum in the equatorial region. Sheared continental margins are particularly well developed in the Equatorial Atlantic along the extension of the large fracture zones [5].

3. Geometry of the initial split of the Equatorial Atlantic

The distribution of earthquake epicenters indicates that the present boundary between the South American and the African plates has a strong E–W component in the Equatorial Atlantic (Fig. 1), where the boundary is prevalently transform rather than accretionary. Moreover, the orientation of the South American and particularly African coastline or continental slope indicates that, contrary to the prevailing N–S trend (in present day coordinates) of the line of split between Africa and South America, the line of split in the equatorial region has a strong E–W component (Fig. 2). Granted the uncertainty of paleomagnetic reconstructions, it appears that the position of the paleo-equator relative to the future Atlantic coastlines of Africa/South America at the time of the initial separation (Cretaceous) was not very different from the present position (Fig. 4). Paleomagnetic reconstructions [6] suggest that the equator has oscillated since the Jurassic between the present position and about 20°N of the present position relative to Africa/South America. Moreover, if Africa has rotated counterclockwise by about 20–30° since the initial Atlantic rift [6], the equator at the time of the initial opening must have crossed Africa on a SW/NE direction relative to present day coordinates. Therefore, the present equatorial portion of the Atlantic margin of west Africa was also probably close to the paleo-equator ~ 100 My B.P. (i.e., at the time of initial development of the Atlantic rift). Taking into account the 20–30° counterclockwise rotation of Africa since the initial Atlantic rift, those stretches of coastline or of continental slope that constitute the extension of the large equatorial frac-

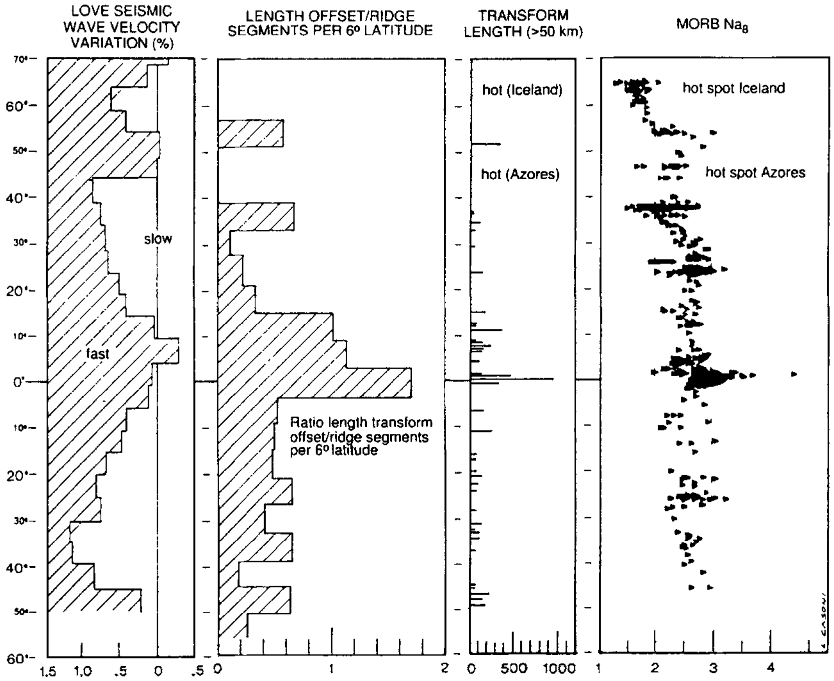

Fig. 3. Geophysical and geochemical parameters plotted versus latitude along the Mid-Atlantic Ridge. From left to right: Love wave seismic velocity variation along the Mid-Atlantic Ridge, from [13]; ratio of the length of transform offsets versus length of ridge segments integrated per each 6° of latitude; distribution and length of the > 50 km transform offsets of the Mid-Atlantic Ridge; MORB Na_8 content along the MAR axis, from [7,10].

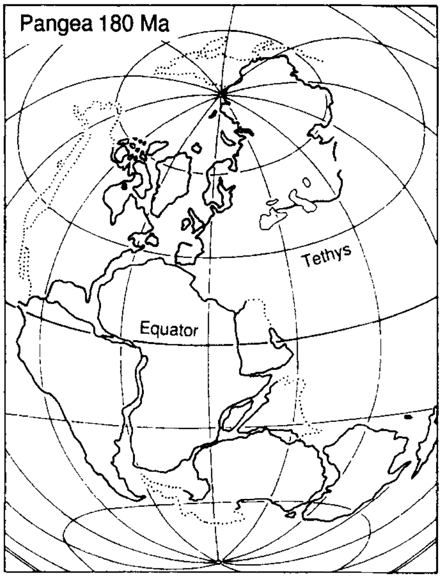

Fig. 4. Reconstruction of Pangea at 180 my ago, from Morel and Irving [7]. Paleolatitudes are based on paleomagnetic evidence. Position of the paleo-equator relative to Africa/South America is shown.

ture zones had initially a roughly E–W equatorial orientation.

We thus have two basic observations: (1) the present day offset length of the MAR axis and the ratio of the length of transform offset/length of axial ridge segments have strong maxima in the equatorial region; (2) the initial split between Africa and South America had a prevalently E–W latitudinal orientation in the Cretaceous equatorial region, in contrast to a prevalently N–S orientation of Mid-Atlantic rift outside of the equatorial region. These observations can either be regarded as fortuitous, or an explanation may be sought for them. We explore the latter alternative.

4. A thermal minimum in the Equatorial Atlantic lithosphere and upper mantle

Independent lines of evidence, some petrological, some geophysical, suggest that the thermal structure of the Equatorial Atlantic lithosphere and upper mantle is anomalous, having a temperature minimum relative to mantle temperatures in the Northern and Southern Atlantic.

Petrological evidence: A study of the mineral chemistry of mantle-derived mid-ocean ridge peridotites has shown that peridotites from the Equatorial Atlantic have undergone little (< 5%) or no partial melting [7]. This is in contrast to peridotites from elsewhere along the MAR, that are residual after 10–15% of melting, except in hot spot areas where the peridotites are even more refractory. Assuming that the exceptionally low degree of melting inferred for the Equatorial Atlantic mantle is due to lower that normal upper mantle temperatures, a temperature for the upper mantle lower by roughly 150°C at the equator than elsewhere below the MAR has been estimated [7]. Two-pyroxene peridotite geothermometry also suggests a temperature minimum in the Atlantic equatorial belt [8]. Independent studies of mid-ocean ridge basalts (MORB) support these conclusions. The Na and Fe contents of unaltered MORB, corrected for fractionation effects by normalizing them to 8% MgO (Na_8 and Fe_8), are related to extent and pressure of melting of the source [9]. Na_8 values show a maximum and Fe_8 a minimum in the equatorial Romanche F.Z. area (Fig. 3), indicating a minimum in the degree and pressure of melting and, presumably, of mantle temperature [7,10]. The unusual abundance of alkali basalts in the Romanche region is consistent with an anomalously low extent of melting.

Geophysical evidence: The depth below sea level of the MAR axis (zero-age depth) is related to: (1) the composition of the mantle column to a compensation depth that can be assumed to be 150 km below the sea floor; (2) the temperature of the mantle column; and (3) the thickness of the crust. The composition of the mantle column includes not only the initial mantle composition, but also changes in composition due to partial melting. Partial melting gives rise to a zone of residual mantle with high Mg/Fe ratio and thus low density, and to increasing crustal thickness. Both these factors would tend to swell the mantle/crust column, and to decrease the MAR zero-age depth. If we assume a constant initial upper mantle composition below the entire length of the MAR, variations in zero-age depth would depend on the temperature of the mantle column and on the extent of melting (that would also depend on temperature). MAR zero-age depth shows a maximum in the equatorial area [7], consistent with an equatorial minimum of upper mantle temperature and in agreement with peridotite and MORB data.

According to high resolution S shear body waves and Love surface waves seismic tomography along the MAR [11], a high velocity zone interrupts in the equatorial region the low velocity zone prevalent along the MAR (Fig. 3), in agreement with the idea of a temperature minimum in the equatorial mantle.

Estimates of the thermal anomaly caused in the upper mantle by the large equatorial transforms (i.e., the 'cold edge transform effect' of Fox and Gallo [3]) suggest that the Equatorial Atlantic mantle thermal minimum cannot be accounted for solely by the thermal effect of the transforms [7,10].

Studies of seismic anisotropy from S and SS phases [12] have concluded in favor of an anisotropic North Atlantic upper mantle with the olivine horizontal a axis aligned at an average N24°W direction in the central North Atlantic and at an average of N23°E further to the north, between 40° and 50°N

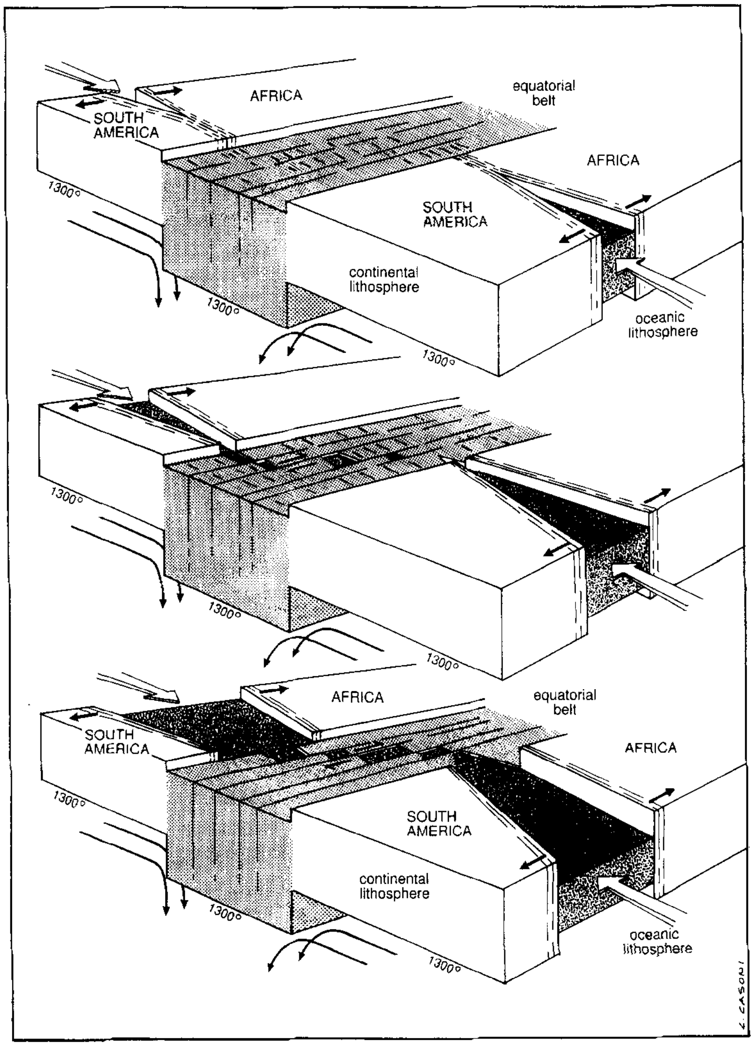

Fig. 5. Cartoon depicting schematically oceanic rifts propagating from the south and from the north towards the equatorial region of the Atlantic, where they will impact against a colder/thicker than normal lithosphere. The 1300° isotherm marks the base of the lithosphere. Downwelling asthenosphere below the equatorial region is shown with arrows. The low mantle temperature will result in magma-starved oceanic rift segments unstable in time and place. Three stages in the evolution of the region are shown, from top to bottom.

(Fig. 2). The a axes are assumed to reflect strain-induced preferred orientation in the lattice of upper mantle olivine, and to be parallel to mantle flow. Independent analyses of S and SS phases for the North Atlantic have obtained similar results, implying an essentially N–S orientation of the olivine horizontal a axis [13]. These results, suggesting a N–S mantle flow in the North Atlantic decoupled from surface plate motion but roughly parallel to the ridge axis, are consistent with the idea of a North Atlantic upper mantle flowing towards the equator and downwelling in the zone of the thermal minimum (Fig. 5).

We consider next if the inferred colder upper mantle and lithosphere of the Equatorial Atlantic may have any relation to the peculiar geological evolution of this region; that is, to the creation of a wide megashear zone where the regional fabric is dominated by transform rather that axial accretion processes and where the Atlantic basin opened in an E–W rather than a N–S direction.

5. Cold / thick equatorial lithosphere at the time of opening of the Atlantic rift and Mesozoic equatorial lineations in West Africa–South America

Let us assume that the anomalously low temperature of the equatorial upper mantle reflects a long-lasting, relatively stable situation; that is, that an equatorial belt of 'cold' upper mantle existed in the Cretaceous at the time of opening of the Equatorial Atlantic rift. This would imply a pre-opening equatorial continental lithosphere colder and thicker than normal. At present, equatorial South America and western Africa are areas of thick cratonic lithosphere and low heat flow. Some of the lowest heat flows (~ 20 mWm^{-2}) and thermal gradients of the Earth have been reported from the western African shield between 14° and 15°N [14]. These values are about half the average value for Precambrian shields, and less than half the average value for the South African craton. They imply a very large lithospheric thickness (i.e., well above 400 km), if the lower limit of the lithosphere is defined as the transition to a viscosity $< 10^{21}$ poise, or > 300 km if it is defined as the 1300°C isotherm [14]. A survey of lithosphere thickness below Africa based on gravity and teleseismic P wave delay time residuals found relatively high (> 200 km) lithospheric thickness in central western Africa [15].

Crough and Thompson [16] have discussed how the thickness of the lithosphere affects surface topography. Assuming that isostatic compensation is approached at the base of the lithosphere and that the lithosphere has the same composition as the asthenosphere but is colder and denser, it follows that the thicker the lithosphere, the lower is the surface elevation. For instance, if crustal thickness remains constant, a 40 km increase in lithospheric thickness would result in a 1 km decrease in surface elevation [16]. We would expect, therefore, a belt of depressed topography above the inferred thicker than normal equatorial pre-Atlantic lithosphere.

The Equatorial Atlantic large E–W fracture zones appear to extend into the African continent. The Benue Trough is a linear structural depression filled with up to 6 km of Cretaceous sediments extending from the Gulf of Guinea into equatorial Africa. It has been interpreted either as the failed arm of a RRR triple junction located in the Gulf of Guinea [17,18] or as a sinistral wrench fault [19]. In either case, the Benue Trough was tectonically active in the Cretaceous, before and during the opening of the Equatorial Atlantic. The hypothesis that the Benue Trough is the failed arm of a Cretaceous triple junction of three rifts (the other two being branches of the MAR), although conceptually attractive, has been criticized because magmatism has been scarce and localized, and faulting is mainly related to sinistral wrenching, with episodes of transpression and transtension [19]. An alternative interpretation is that the Benue depression developed in the Mesozoic as a response to the presence of a thicker than normal lithosphere above the equatorial mantle thermal minimum. The Benue region became subjected to wrench tectonics in the Cretaceous when the oceanic rifts started impacting on the equatorial area from north and south. Transtensional pull-apart basins and transpressional structures were formed at different stages [19–21]. Considering the 20–30° counterclockwise rotation of Africa since the Cretaceous, the Benue Trough was oriented roughly E–W at the time of the opening. Moreover, important Mesozoic morphotectonic structures extending into Africa further than the Benue Trough, such as the Central African Shear

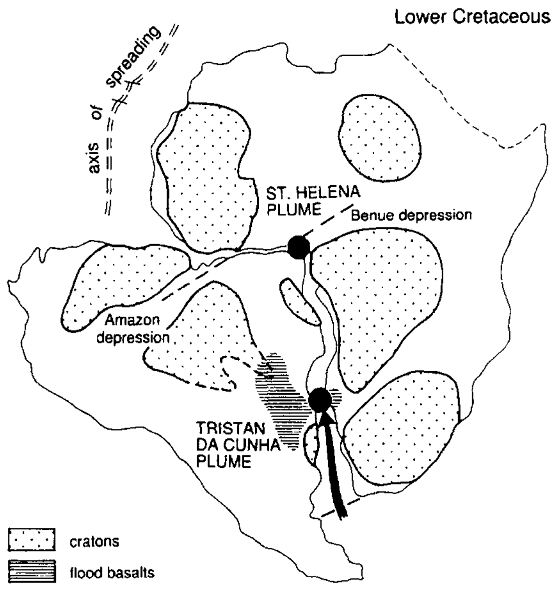

Fig. 6. Lower Cretaceous reconstruction of Africa/South America, showing the location of the Benue and Amazon Depressions, of the Tristan da Cunha and St. Helena plumes, and of Mesozoic flood basalts, modified from [35].

Zone [21], appear also to strike roughly E–W along the Cretaceous equatorial belt (Fig. 6). Some authors have even suggested that the Benue shear zone separated two Mesozoic African plates [17,22], or that the Equatorial Atlantic megashear is part of a global system (Pelusium Line) that extends across South America, Africa and into Asia [23].

On the South American side we find the Amazon Basin, a major morphostructural depression with a long and complex history. According to Burke and Lytwyn [24], the Amazon Basin is underlain by a intracontinental rift resulting from a Pan-African continental collision, with renewed rifting in the Jurassic and Cretaceous, before and during the opening of the Equatorial Atlantic. The Mesozoic reactivation of the Amazon depression could be related to wrenching of the thick, cold equatorial lithosphere, due to the attempted equatorial propagation of the proto-Atlantic rifts from north and south.

6. Opening of the South Atlantic by rift propagation

Most models of the opening of the South Atlantic call for a gradual propagation of the oceanic rift from south to north [25]. A first rift phase in the Southern Atlantic (south of about 38°) is dated at 150–130 My B.P.; the rift reached the equatorial area between 116 and 85 My B.P. [25]. We assume that the oceanic rift impinged in the equatorial region against an anomalously thick and cold belt of continental lithosphere (Fig. 5). The rheology of the lithosphere is dependent on its thickness and temperature, on the thickness of the crust and on factors such as composition, grain size and water content [26,27]. A colder/thicker equatorial pre-Atlantic lithosphere implies high strength rheology, which would significantly affect the opening of this region.

As a first alternative, we assume that rift propagation takes the form of a propagating mantle thermal anomaly initiating, for instance, from a thermal plume [2]. The thermal anomaly would consume the continental lithosphere from below by convective heating [28]. In Spohn and Schubert's [28] model the time it takes to thin the lithosphere to 95% of its initial thickness increases with the initial lithosphere thickness and decreases with the extent of the thermal anomaly; that is, with the increase in heat flow at the base of the lithosphere over the initial value. Accordingly, a thermal anomaly causing a ten-fold increase in basal heat flow over the initial value would achieve 95% thinning of a 100 km thick lithosphere in roughly 15–20 My. However, it would take about twice that time for a 150 km thick lithosphere (Fig. 7). An equatorial region of initially thicker and colder than normal lithosphere would thus constitute a 'locked zone' (in the sense of Courtillot [29]) against which the propagating mantle thermal anomaly would impinge. Moreover, an equatorial, initially cold, sublithospheric mantle would cool any approaching positive thermal anomaly, slowing down mantle upwelling below the propagating rift and resulting in a low degree of melting. The melt production rate from a rising hot mantle plume is inversely related to lithospheric thickness [30]. A magma-poor or magma-starved rift would result.

In a different approach, rifting can develop in a plate as a result solely of horizontal extension. The lithosphere is deformed and thinned by faulting in the upper brittle part, and by plastic necking at depth. Continuing thinning would decrease the strength of the lithosphere, and rupture could occur at some nucleation point [29]. The new oceanic rift would then propagate linearly from this point into the thinned, rifted lithosphere, in a mechanism that probably operates today in the Red Sea rift [31]. The mechanical behavior of the rift is probably not uniform along strike, and zones possessing higher than normal strength (the 'locked zones' of Courtillot [29]) might be present, with the strength depending on temperature, thickness of the lithosphere and thickness and composition of the crust [26,32]. The Mesozoic continental lithosphere of the future South American/African margins had probably been stable since the Pan-African event; therefore its age can be assumed to be 400–500 My. Assuming a constant continental crust thickness all along the future Atlantic rift, the larger lithospheric thickness and the lower geotherm of the equatorial region would result in an equatorial lithosphere with an overall strength significantly higher than the strength of the lithosphere at higher latitudes (Fig. 8).

Phipps Morgan and Parmentier [33] used a fracture zone mechanics model whereby a rift is equated to a crack or conduit in the lithosphere into which fluid (asthenosphere) is injected. The rift propagates if a 'stress intensity factor', K, at the rift tip exceeds a threshold value, causing progressive failure of the lithosphere. Factor K increases and the rift propagates due to: (1) 'gravity spreading' stresses, associated with hot/shallow ridge axis; (2) a wide asthenosphere-filled crack or conduit; (3) low viscosity (high temperature) of the fluid (asthenosphere); (4) a thin lithosphere. This model would predict that a thicker/colder than normal lithosphere and a colder than normal upper mantle (asthenosphere), as proposed for the Equatorial Atlantic, would prevent or slow down rift propagation, both in the continental lithosphere before the opening, and the oceanic lithosphere after the opening.

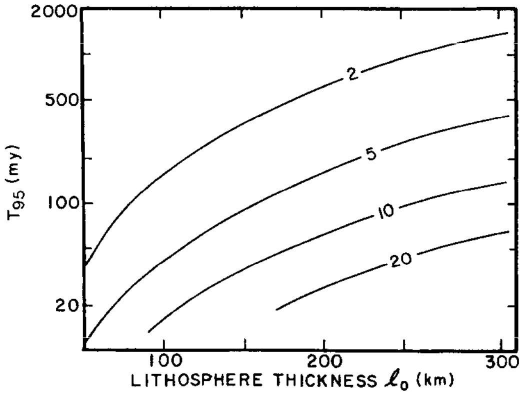

Fig. 7. Thinning of the continental lithosphere due to a thermal anomaly at the base of the lithosphere, from Spohn and Schubert [28]. T95 represents the time it takes to achieve 95% thinning relative to initial lithospheric thickness, l_0. Numbers on the curves indicate the ratio of basal 'anomalous' heat flow over 'normal' heat flow and represent the extent of the thermal anomaly.

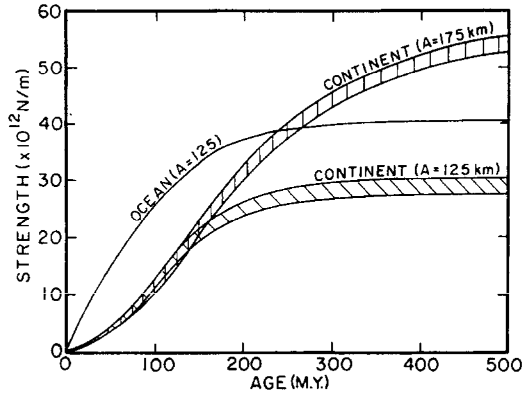

Fig. 8. Strength of the lithosphere in extension versus age. Two different values for lithospheric thickness are shown. The width of the curves for continental lithosphere represents a range of mafic lower crustal rheologies, from [34].

It appears, therefore, that whether thinning and rifting of the lithosphere are 'active' (i.e., caused by mantle thermal anomaly) or 'passive' (i.e., due purely to tensional forces and extension of the plates), or, most likely, a combination of both, the equatorial belt of thick/cold lithosphere would constitute a major 'locked zone' where sea floor spreading is likely to be delayed and sluggish relative to normal portions of the rift.

7. Geological evolution of the Equatorial Atlantic

The presence at the time of opening of an equatorial mantle thermal minimum overlain by a belt of colder and thicker than normal lithosphere might have strongly affected timing, rates and mechanisms of opening of the Equatorial Atlantic and its subsequent geological evolution. A qualitative model would include the following points:

(1) Given the poor magmatic budget and the high-strength rheology of the thick/cold equatorial lithospheric slab, the rate of propagation of the oceanic rift into the equatorial cold belt will be lower than that prevailing in normal pre-Atlantic rift lithosphere. Complete break up and separation of the continental lithosphere will, therefore, require a longer time in the equatorial cold belt, where a pre-oceanic rift phase of diffuse deformation under an extensional but amagmatic regime will last longer than in 'normal' portions of the rift.

(2) It has been suggested [34] that the St. Helena mantle hot plume might have contributed to weakening the equatorial lithosphere before the opening in the Cretaceous (Fig. 6). However, the St. Helena hot spot did not produce flood basalts or any major volcanism in the Mesozoic, in contrast to the Tristan da Cunha hot spot further south, (Fig. 6), that generated voluminous flood basalts [34]. A weak and ineffective Mesozoic St. Helena plume is consistent with the hypothesis of an equatorial thick/cold pre-opening lithosphere. Even if we assumed that the St. Helena plume was, during its inferred ascent from the lower mantle, as hot, voluminous and buoyant as the Tristan da Cunha plume, its impact from below against an equatorial cold upper mantle and thick lithosphere would cool and weaken it. An initial thick/cold lithosphere would not only require a long time to be weakened to the point of allowing plume-induced extension [28,35]; it would also prevent significant melt production. The melt production rate from a plume is a function of the thickness of the overlying mechanical boundary layer [30]. Watson and McKenzie [30] estimated that the melt production rate from a plume with a potential temperature of 1550°C impinging below a 125 km thick mechanical boundary layer (corresponding to thick cratonic lithosphere) is close to zero.

(3) As a result of the low degree of melting of the mantle beneath the equatorial zone, initial attempts at breakthrough of oceanic lithosphere would occur in isolated nuclei scattered in the rift within the zone of diffuse lithospheric deformation (Fig. 5). Normal propagation from these nuclei is prevented; the relatively cold upper mantle and low magmatic budget would result in 'weak' and short-lived oceanic rift segments. Amagmatic extension would prevail and would favor the formation of 'initial' transform zones.

(4) Initial opening would occur largely through strike/slip motion along roughly E–W, initial continent/continent transforms. Sheared continental margins would develop prevalently in such settings. In fact, some of the classical examples of sheared margins are found today off equatorial west Africa and Brazil [5]. A prevalently E–W opening of the Equatorial Atlantic, and E–W orientation of the equatorial African coastline would result, in contrast to the prevalently N–S opening of the South and North Atlantic. The offset length of the initial transforms could change during subsequent sea floor spreading, due to ridge jumping or asymmetric spreading (Fig. 9).

(5) Further opening would result in ridge segments separated by long offset transforms, as observed uniquely in the Equatorial Atlantic. The low magmatic budget would cause a reduced thickness of the oceanic crust, emplaced in short en echelon segments, with production mostly of high-Na MORB and alkali basalt. These are in fact the most common lava types recovered from the Romanche area [7,10], where the basaltic crust is thin or absent [36] and where undepleted mantle-derived peridotites, showing relatively low equilibration temperature, are prevalent [7,9]. The low magmatic budget would also favor an unstable spreading regime, with frequent jumping of short-lived ridge segments. Transform migration and reorientation, together with ridge jumping, propagation and decapitation would occur frequently in such a setting, as documented at the Vema and Romanche fracture zones [37]. Intense vertical movements of slivers of lithosphere take place in the long offset transforms, particularly due to transtension and transpression events related to small changes in spreading direction and to transform migration and reorientation [37]. These vertical tectonic movements, particularly well documented at the Vema, Romanche and St. Paul fracture zones, have caused uplifted transverse ridges and depressed pull-apart basins [37], and are mostly responsible for the extremely rugged topography of the Equatorial Atlantic.

(6) As a result of transform migration and/or ridge jumping, slivers of lithosphere can be trans-

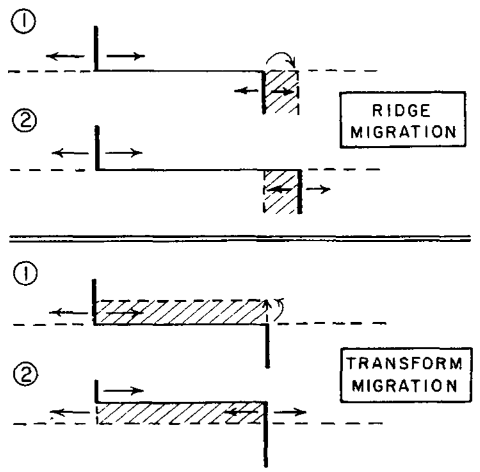

Fig. 9. Schematic representation of the migration of ridge segments (top) and the migration of transform boundaries (bottom). Both cause a reversal in the direction of motion of a block of lithosphere [38].

ferred from the South American to the African plate or vice versa (Fig. 9). The ensuing process of 'oscillatory spreading' [38] would make it possible for relicts of older lithosphere to be caught within younger sea floor; as documented, for instance, at the Vema FZ and the Romanche FZ [37,39]. Even relict fragments of continental lithosphere might be left behind. St. Peter-Paul Island, an uplifted sliver of metasomatized lithospheric mantle with subcontinental rift affinity [40] could be an example. The metasomatic event that affected the St. Peter-Paul peridotite has been dated at about 150 My B.P. [41], when the Equatorial Atlantic was probably in a continental rift stage. The allochtonous fragments of old/cold lithosphere trapped in the Equatorial Atlantic are not the cause, but the effect of the cold equatorial mantle. However, the fragments of cold lithosphere will help maintain the equatorial mantle thermal minimum.

8. Mantle thermal minima cause transform clusters

The proposed scheme of opening and evolution of the Equatorial Atlantic implies a model whereby long-lived clusters of fracture zones were created above long-lived temperature minima in the upper mantle, which had existed since the time of continental separation. Another example is at the Australian/Antarctic Discordance, where the ridge axis is disrupted above a major mantle thermal minimum [42]. MAR secondary thermal minima are in the 50–55°N and possibly 45–50°S regions [11], where major long-lived transform boundaries are located (i.e., Charlie-Gibbs FZ and Aguhlas-Falkland FZ). These long-lived transform boundaries of the MAR correspond to well developed, sheared continental margins, such the Aghulas/Falkland sheared margins at 45–50°S [43] and the Labrador/Rockall margins at 50–55°N [44], in addition to the Ghana/Ivory Coast and the North Brazilian ridge margins [6] in the equatorial region. These major sheared margins may mark 'locked zones' [29], corresponding to mantle thermal minima and thick/cold lithosphere that prevented normal oceanic rift propagation during and after continental separation [45].

It is notable that 'hot' stretches of the MAR, such as the 35–45°N stretch (Azores hot spot) and Rejkjanes ridge (Iceland hot spot) are devoid of major permanent transform boundaries. According to these ideas, mantle thermal minima can be the cause of long-lived transform clusters, and not vice versa [45]. Thermal anomalies created in the mantle by these transforms (the 'transform cold edge effect' of Fox and Gallo [3]) are second-order rebound effects that would help maintain the thermal minima. I stress, however, that not all long-lived transform boundaries are necessarily related to mantle thermal minima; those offsetting the 'hot' southern East Pacific Rise, for instance, might be passive boundaries between broad, stable, hot mantle cells [45].

9. Causes of an equatorial mantle thermal minimum

Whether or not the equatorial position of the sub-Atlantic mantle thermal minimum is coincidental or can instead be related to some global factor, such as the Earth's rotation, has been discussed elsewhere [7]. The inferred equatorial thermal minimum of the upper mantle may not be limited to the Atlantic. The zero-age depth of the East Pacific Rise has a minimum in the equatorial area [46,7]; this was true also in the past. Menard and Dorman [46] demonstrated that the sea floor depth of mid-ocean ridges in all major oceans is not only age-dependent but also latitude-dependent, with topography in the equatorial regions being several hundred meters to 1 km deeper than at high latitudes. These observations led to the suggestion that the equatorial upper mantle thermal minimum is not limited to the Atlantic but is present also in the other major oceans. Hence, it may be related to some global factors, such as the Earth's rotation [7]. This does not imply that all mantle thermal minima are related to rotation: the minimum at the Australian/Antarctic Discordance, for instance, clearly is not. Thermal minima are related to rotation only to the extent that some zones of downwelling within the broad pattern of mantle circulation might be related to rotation.

Several authors have proposed that true polar wander (i.e., the position of the Earth's spin axis relative to the mantle) is strongly affected by the distribution of dense masses in the mantle [47–49]. Thus, the introduction into the mantle of a cold dense slab, as in a subduction zone, would cause true polar wander, in order to maintain the Earth moment of inertia and to minimize the kinetic energy of rotation (Fig. 10).

Given that the viscosity of the mantle increases with depth [48,49], it has been calculated that a dense mass introduced into the mantle would cause migration of the spin axis such that the equator would tend to shift towards the dense mass [49]. This would cause a tendency of dense masses to concentrate in the equatorial mantle, resulting in downwelling and in a thermal minimum [7]. If this hypothesis is correct, the tendency towards developing thermal minima in the equatorial upper mantle should be a steady-state feature of the Earth.

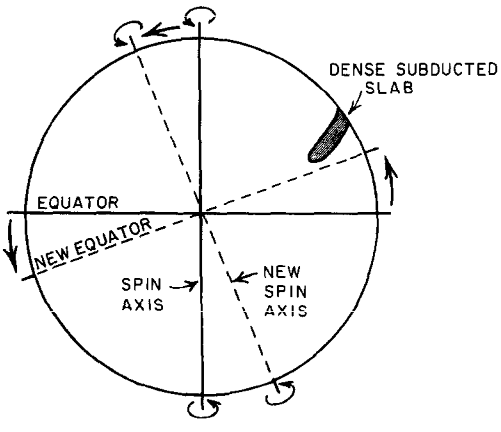

Fig. 10. Cartoon representing the hypothesis that true polar wander is triggered by subduction of a cold dense slab into the mantle. A shift in the spin axis tends to move the equator towards the dense slab.

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