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Diffuse impact of the Mid-Atlantic Ridge with the Romanche transform: an ultracold ridge-transform intersection

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Abstract. The Romanche is a long offset (~950 km), slow slip (~1.7 cm/yr) transform; thus a hot ridge axis should meet a ~50-m.y.-old, thick and cold lithosphere at the ridge-transform intersection (RTI). A strong thermal/topographic "transform cold edge effect" is therefore predicted. A morphobathymetric, seismic reflection and petrologic study of the eastern Romanche RTI shows that as the Mid-Atlantic Ridge approaches the transform, a well-formed axial rift valley disappears about 80 km from the RTI and is substituted by short en echelon, poorly developed axial ridge segments; they too disappear about 30 km from the edge of the transform valley. The predicted gradual deepening of the ridge axis toward the transform was not observed. An active nodal deep and an "inside corner high" are also absent. These observations, and the distribution of earthquake epicenters, suggest a poorly developed, diffuse RTI. An inactive rift valley ~80 km west of the present RTI suggests ridge jumping within the last ~4 m.y. The present poorly developed RTI may reflect the attempts of an embryonic spreading axis to become established and to propagate toward the transform. We infer from bottom rock sampling that the basaltic crust is patchy or absent and mantle-derived serpentinized peridotites outcrop ubiquitously on the seafloor starting ~30 km from the edge of the transform valley. The unusually deep (~4 km below sea level) axial ridge segments, the lack of crust, and the chemistry of the peridotites suggest a prevalently amagmatic regime due to an ultracold upper mantle in this region. Absence of basaltic crust would favor massive serpentinization of a several kilometers thick peridotite column. Mass balance modeling suggests that the decrease of density and volume expansion resulting from serpentinization could explain the absence of the predicted deepening of the seafloor as it approaches the transform. These results suggest that the topographic effect of the transform edge thermal contrast may disappear at ultracold RTIs and that ultracold RTIs are magma starved, short lived, and unstable in time and space.

Introduction

The impingement of a mid-ocean ridge segment against a transform causes structural and petrological complexities that are particularly dramatic in large offset, slowly slipping transforms. These complexities are related to the juxtaposition of young hot and thin ridge axis lithosphere against the old cold and thick lithosphere found across the transform boundary. Studies of ridge-transform intersections (RTI) in slow spreading. Atlantic-type systems have led to the following generalizations [*Fox and Gallo*, 1984; *Bender et al.*, 1984; *Karson and Dick*, 1983; *Phipps Morgan and Forsyth*, 1988; *Blackman and Forsyth*, 1989]: (1) the floor of the axial rift valley deepens and widens approaching a transform boundary; (2) a characteristic, areally limited topographic depression ("nodal basin") occurs as the rift valley enters the transform valley; (3) a large topographic high ("inside corner high") is observed commonly at the transform side of the rift valley as it approaches the transform valley; (4) morphostructural lineations oriented obliquely to both ridge axis and transform occur in the transform side corner but not in the non transform side corner; and (5) a systematic change in the geochemistry of axial rift basalts occurs approaching a transform. These features, and particularly the deepening of the axial valley as it approaches a transform, and the depth of the nodal basin are related partly to the age offset of the transform [*Fox and Gallo*, 1984] but also to the length of the ridge segment impinging on the transform and to crustal thickness and regional depth [*Phipps Morgan and Forsyth*, 1988; *Blackman and Forsyth*, 1989].

We have obtained morphobathymetric, seismic reflection, and petrologic data from the eastern intersection of the Mid-Atlantic Ridge (MAR) with the Romanche transform in the equatorial Atlantic. The Romanche has a very large age offset (~50 m.y.) and its RTI should have a correspondingly extreme contrast of lithospheric thickness, zero on the young side versus about 60 km on the old side if we assume the *Parker and Oldenburg* [1973] lithospheric thickness versus age relationship. We would therefore predict strongly enhanced "transform cold edge" effects, including some of the topographic features mentioned above. We report here some observations that do not follow these predictions.

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Eastern Romanche Ridge-Transform Intersection

Background

The Romanche transform offsets the MAR by about 950 km (Figure 1), which gives an age offset of about 50 m.y. if we assume constant ridge/transform geometry and an average half spreading rate of 1.75 cm/yr for the lithosphere adjacent to the transform [*Cande et al.*, 1988]. Early topographic compilations based on sparse track lines showed the eastern MAR segment between the Chain Fracture Zone (FZ) and the Romanche FZ as a well formed rift valley impinging orthogonally against the Romanche [*Heezen et al.*, 1964; *Gorini*, 1977; *Bonatti et al.*, 1979]. However, recent GLORIA and multibeam data suggest a more complex morphotectonic situation. According to *Monti and Mercier* [1991], *Mamaloukas-Frangoulis* [1992], and *Searle et al.* [1994], the MAR axis in the vicinity of the RTI is broken in a series of short en echelon segments that form an overall oblique trend impinging against the transform valley between 17° and 17°10'W. *Bonatti et al.* [1994] suggested tentatively that the valley opening into the transform valley between 17°10' and 17°20'W is an inactive aborted rift valley segment and that the presently active rift meets the Romanche at about 16°30'W. Magnetic anomalies cannot help in locating unequivocally the spreading center because they are subdued or absent in the equatorial region. The uncertainty in locating the RTI reflects the absence of a well-formed unequivocal active rift valley opening into the transform valley, as is observed normally in RTIs of other large Atlantic transforms. New multibeam and seismic reflection surveys as well as intensive new collection of bottom samples have given us the opportunity to reconsider this peculiar RTI .

Methods and Results

Dense coverage multibeam surveys were carried out in selected areas within the RTI region (Figure 2, 3, and 4). The ship's position was determined with a Global Position System (GPS) NAVSTAR satellite navigation system, with an accuracy of ±25m. Morphobathymetry was obtained with Hollming Echos 625 multibeam system, consisting of 15 (12 kHz) beams covering a swath of seafloor roughly 2/3 the water depth in width. The resulting bathymetry was collated with French [*Monti and Mercier*, 1991] multibeam and British [*Searle et al.*, 1994] conventional bathymetry (Figure 5). Conventional single-channel seismic reflection profiles were obtained along the multibeam tracks.

A high-resolution, multichannel seismic reflection profile was obtained in the same area (line ROM-4, Figure 5). A cluster of three Sodera GI-GUNs were employed as sound source. They were operated in harmonic mode configuration, with the

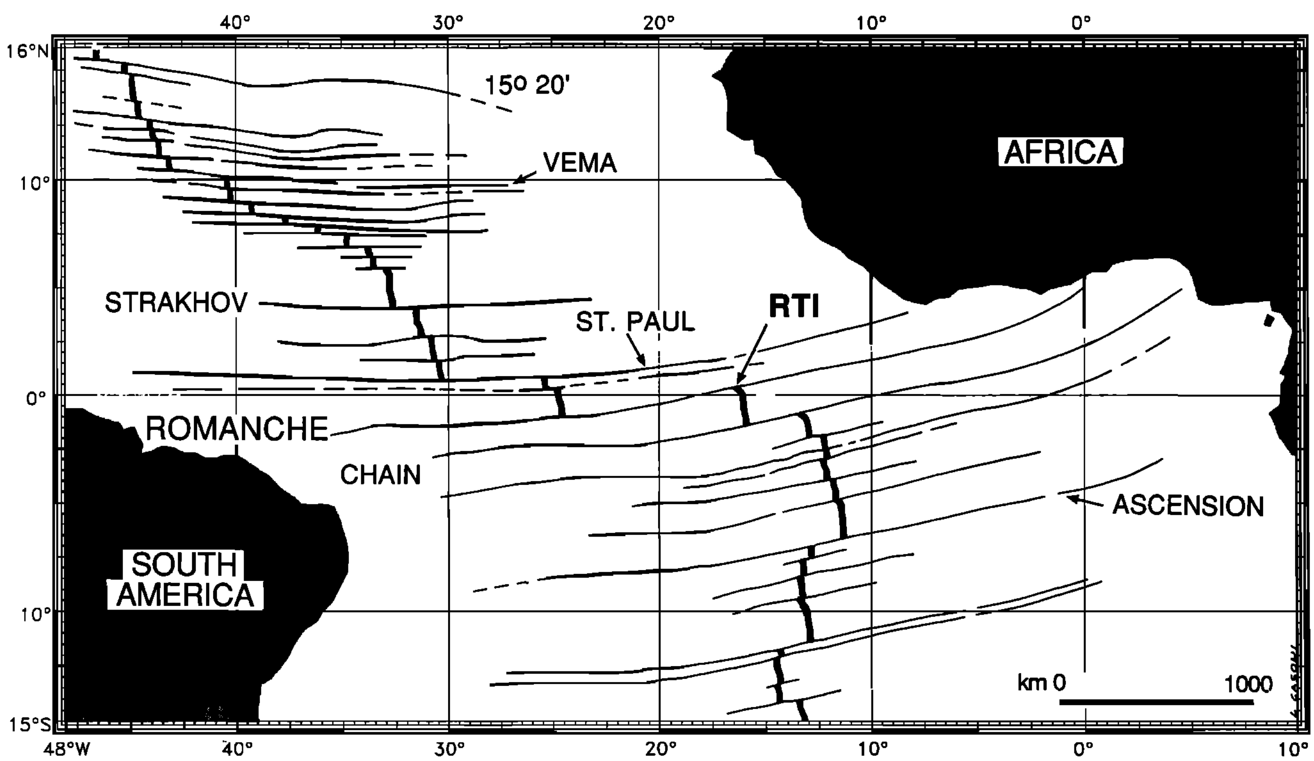

Figure 1. Schematic geometry of plate boundaries in the equatorial Atlantic. Accretionary boundaries (axis of the Mid-Atlantic Ridge) strike roughly N-S. Transform boundaries strike roughly E-W. The major transform boundaries are identified. Arrow points to the eastern Romanche RTI.

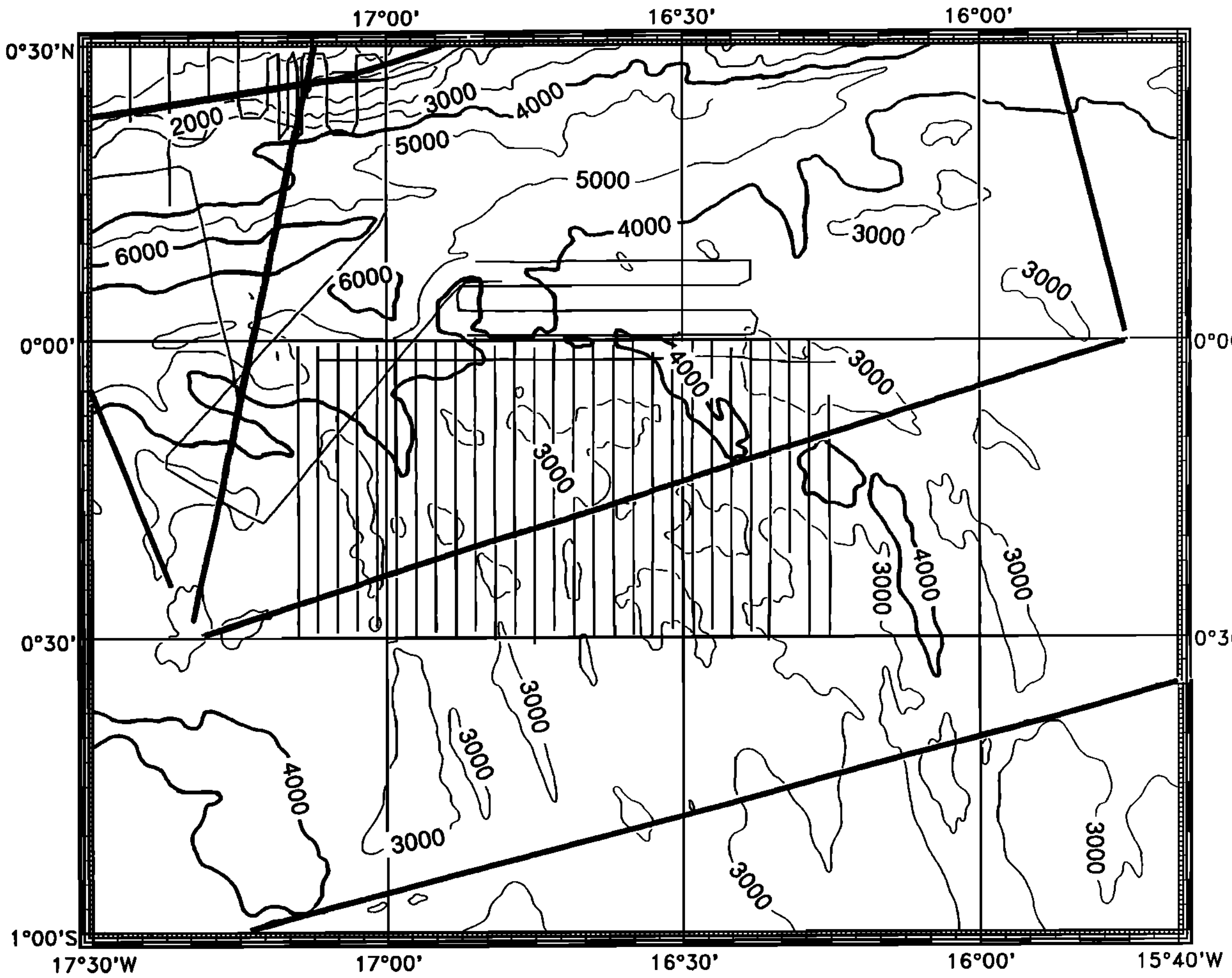

Figure 2. Tracks of multibeam/magnetics/seismic reflection surveys carried out during cruises S-13 and S-16 in the eastern Romanche RTI region. Thin lines indicate tracks of multibeam, magnetics and single-channel seismic reflection profiles. Thick lines indicate multichannel seismic reflection profiles.

capacity of 105 cubic inches for the generator as well as for the injector, at the pressure of 2000 psi. The receiving streamer, made by Teledyne, employed 24 channels (each with 20 hydrophones) spaced 25 m apart. Seismic source and nearest channel were spaced 150 m apart. Shot interval was 50 m, allowing sixfold coverage. Digital acquisition was carried out with a Geometrics 2420, with a sampling rate of 1 ms, record length of 11 s, and an antialias filter of 180 Hz. Seismic data have been processed at Bologna's Institute of Marine Geology of the CNR using an industrial standard package (DISCO) made by CogniSeis.

An intensive program of bottom rock sampling was carried out in this area by conventional dredging. The distribution of different lithologies is shown in Figure 5. In addition, the locations of 1970-1990 earthquake epicenters (magnitude >4) have been plotted on our morphobathymetric map (Figure 5) in order to help locate the accretionary plate boundary and its meeting with the transform boundary.

Morphostructural Observations

A fairly linear and well-developed axial rift valley with a normal clustering of epicenters runs north of the Chain FZ up to about 0°20'S. The average strike of this MAR segment is between 160° and 170°N. Our own detailed multibeam survey covers an area to the north of 0°30'S and topographic control is very tight (Figure 2). A MAR axial valley segment (segment A), approximated in Figure 5 by the area deeper than 4000 m, runs linearly from the south along a 160°-170°N direction up to about 0°15'S, where it appears to shallow slightly and to curve around to 110°-120°N. At about 0°10'S it joins with an other short segment (segment B) running about 160°N up almost to the equator. Fresh basalt was recovered at a few locations within these depressions (Figure 5) by us and by *Schilling et al.* [1994]. This and GLORIA reflectivity data [*Searle et al.* 1994] support the idea that they are short segments of active axial rift valley.

On the basis of topography alone it is not clear if and where the axial rift valley segment meets the transform valley. A number of valleys open into the transform valley from the south. One of them, marked by a major indentation in the 4000-m isobath, is located between 17°00' and 17°20'W, striking between 120°N and 160°N (Figure 5). However, this valley probably is not active at present. It is floored by a significant (~200 m) thickness of sediments (Figure 6); moreover, earthquake epicenters appear to be located more than 50 km to the east (Figure 5), implying that the active

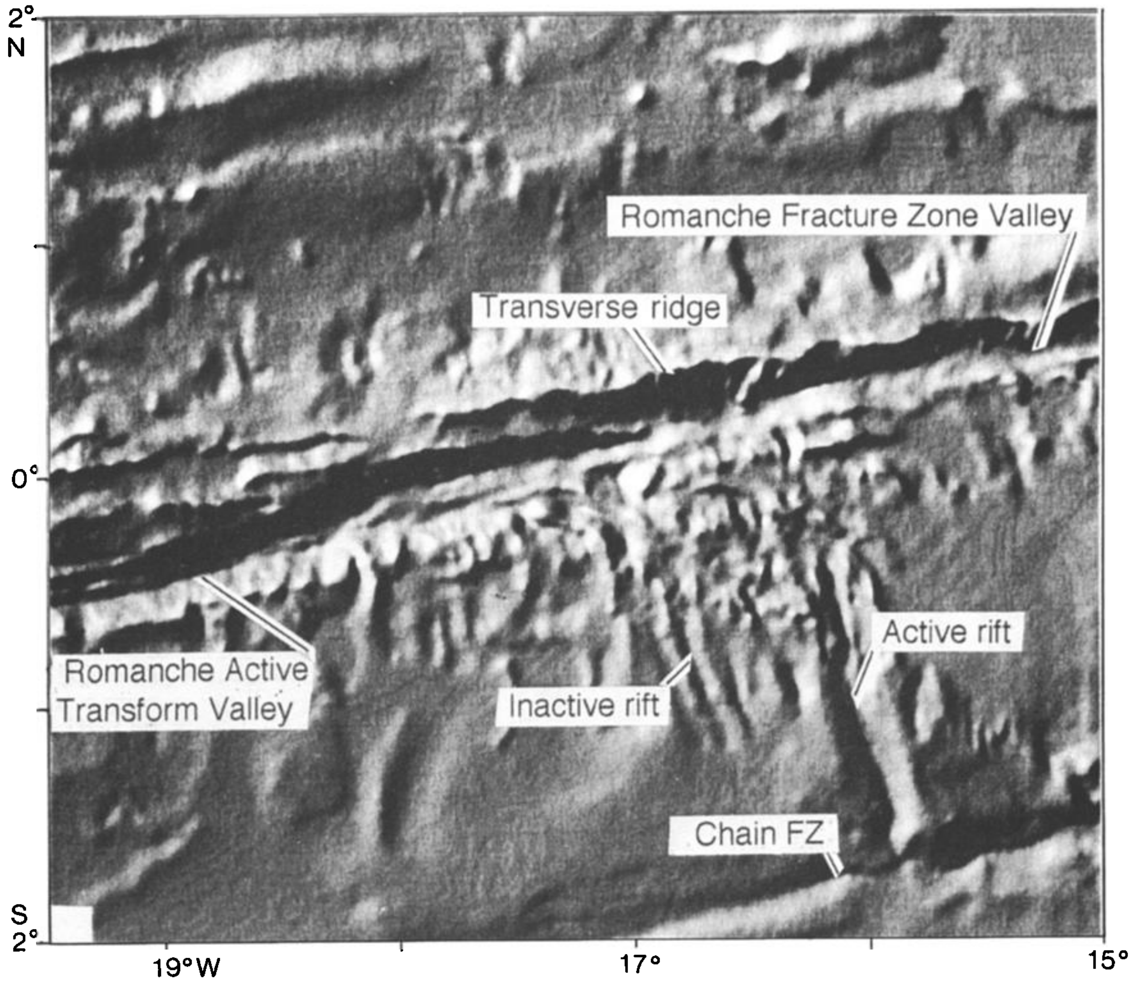

Figure 3a. Shaded relief topography of the Romanche eastern RTI area. The topography is based on our own multibeam surveys (track coverage is shown in Figure 2), combined with data by *Searle et al.* [1994], *Honnorez et al.* [1992], *Monti and Mercier* [1991], and *Bonatti et al.* [1994]. The shaded relief was obtained assuming illumination from NW 45° over the horizon. Horizontal resolution is 0.5 km and vertical exaggeration is x4. Mercator projection at 0°.

transform continues east of this valley. A triangular depression reaching ~6400 m below sea level is located between 17°00' and 17°10'W, at the foot of the southern wall of the transform valley. It has the morphology of a nodal basin such as is found at RTIs of several long offset Atlantic transforms. If it were an active nodal basin, the fracture zone valley east of 17°W could not be an active boundary because it would be located on the nontransform side of the nodal basin. However, epicenters are located well to the east of 17°W, suggesting that the active boundary continues east of the alleged nodal basin. This implies a RTI east of 17°W and that the nodal basin is not presently active.

Searle et al. [1994] using GLORIA data suggested that the accreting plate boundary after reaching about 0° and 16°30'W swings into an oblique ~120°N direction and merges into the transform valley at around 17°W. The boundary would have then to swing back to a more N-S strike in order to meet the nodal basin. This solution would require that some epicenters are located in the nontransform portion of the fracture zone valley (Figure 5). A significant thickness of sediment (~200 m) appears abruptly ~50 to 60 km east and west of the inferred presently active RTI, suggesting that this RTI was emplaced recently within older crust.

A gradual deepening of the axial valley floor as it approaches a RTI has been commonly observed [*Fox and Gallo*, 1984]. This deepening is roughly 1 km per 30 km horizontally in a transform with a age offset of ~20-25 m.y. such as *Vema [Phipps Morgan and Forsyth*, 1988]. We would expect an even larger drop for a ridge axis approaching the Romanche RTI, with a ~50 m.y. age offset. However moving from the northern tip of axial segment B (arbitrarily chosen as including the area >4000 m) toward the edge of the transform valley, the seafloor does not become deeper; on the contrary, it appears to shallow slightly. It then drops precipitously when it reaches the edge of the transform valley (Figure 7). In other words, the ~30-km-wide band of the seafloor at the edge of the transform valley is slightly more elevated than the area farther away from the transform (Figure 7), in contrast to observations obtained from other long offset/slowly slipping transforms.

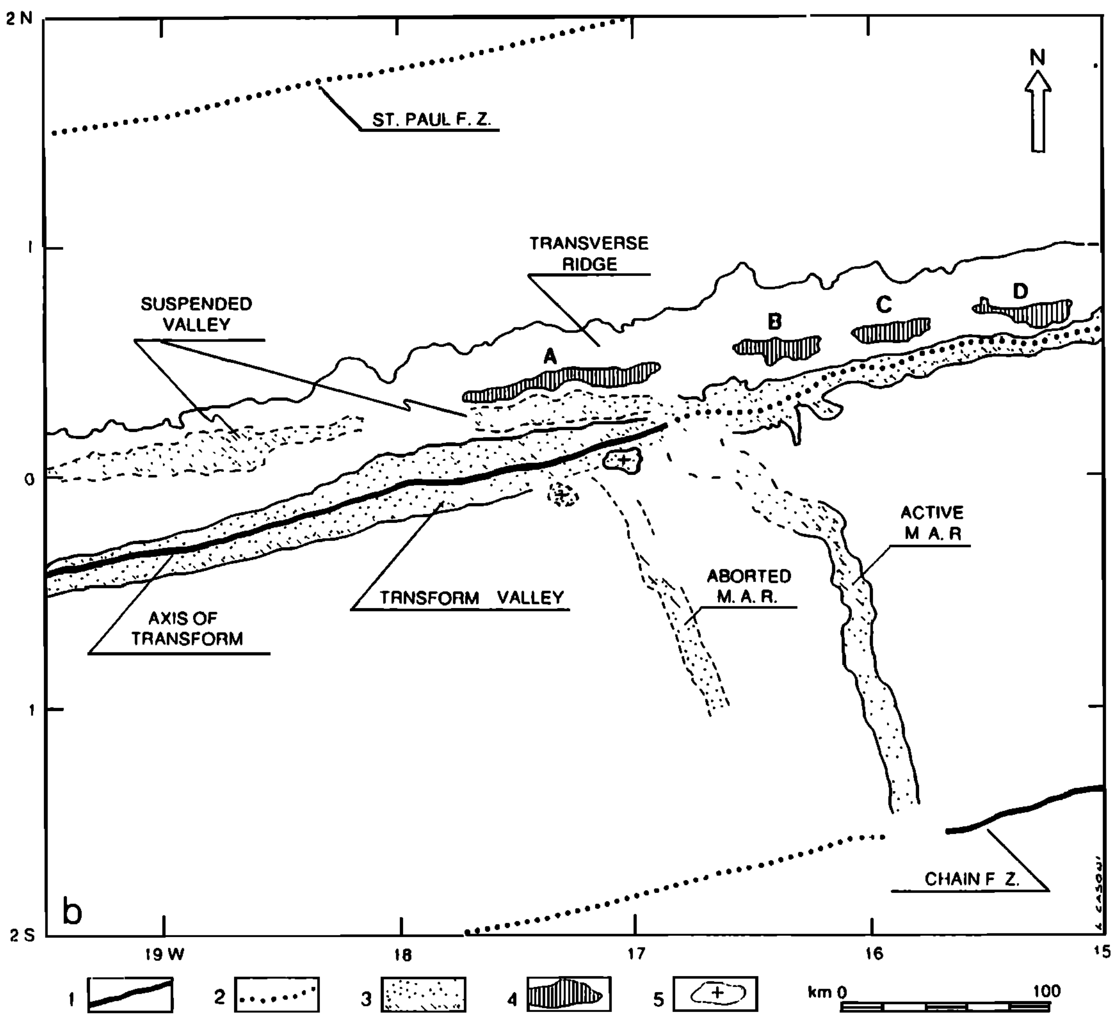

Figure 3b. Simplified interpretation. 1, axis of the active transform valley; 2, axis of inactive fracture zone valley; 3, bottom of valleys; 4, peaks (>2000 m) on the crest of the transverse ridge.

Petrology

Petrology can shed some light on the geology of this RTI. Fresh basalts were recovered from the axial valley south of 0°10'S (segment A). Basalts were also recovered up to 60 km west of this axial segment along inferred spreading flow lines. According to *Schilling et al.* [1994], moving northward from the Chain transform, the chemistry of the axial basalts indicates a gradual decrease of degree and pressure of melting of the mantle source. Independent studies (A. Peyve and N. Sushevskaya [personal communication, 1993]; *Bonatti et al.* [1993]) confirm that basalts from axial valley segment A (Figure 5) are Na-rich and were formed by low extent of melting at relatively low pressure. Moreover, light rare earth element (LREE)-enriched alkali basalts similar to those recovered near St. Peter Paul island [*Melson et al.*, 1967] have also been sampled from segment B.

Basalt becomes rare or absent from segment B to the edge of the steep slope of the transform valley, and mantle-derived serpentinized peridotites outcrop ubiquitously on the seafloor, including on the flanks of the inactive valley between 17° and 17°10', as well as on the rift track suggested by *Searle et al.* [1994]. The composition of mantle-equilibrated minerals in the peridotites from the Romanche FZ suggests that they underwent a very low degree of melting, implying exceptionally low upper mantle temperatures [*Bonatti et al.*, 1992, 1993]. Examination under the microscope of thin sections of these rocks indicates that all the peridotite samples are highly serpentinized with the degree of serpentinization > 50% by volume.

The scarcity or absence of basaltic crust and the dominance of mantle-derived ultramafics at the Romanche eastern RTI contrast with what is observed at RTIs of other major Atlantic transforms such as Vema and Kane, where basalts and gabbros outcrop dominantly [*Mamaloukas-Frangoulis et al.*, 1991; *Tucholke and Shouten*, 1988].

An Ultracold Eastern Romanche RTI

Topography, distribution of earthquakes, and seismic reflection data suggest a diffuse eastern Romanche RTI, lacking a well-defined morphological signature. We suggest that the valley intersecting the transform valley from the

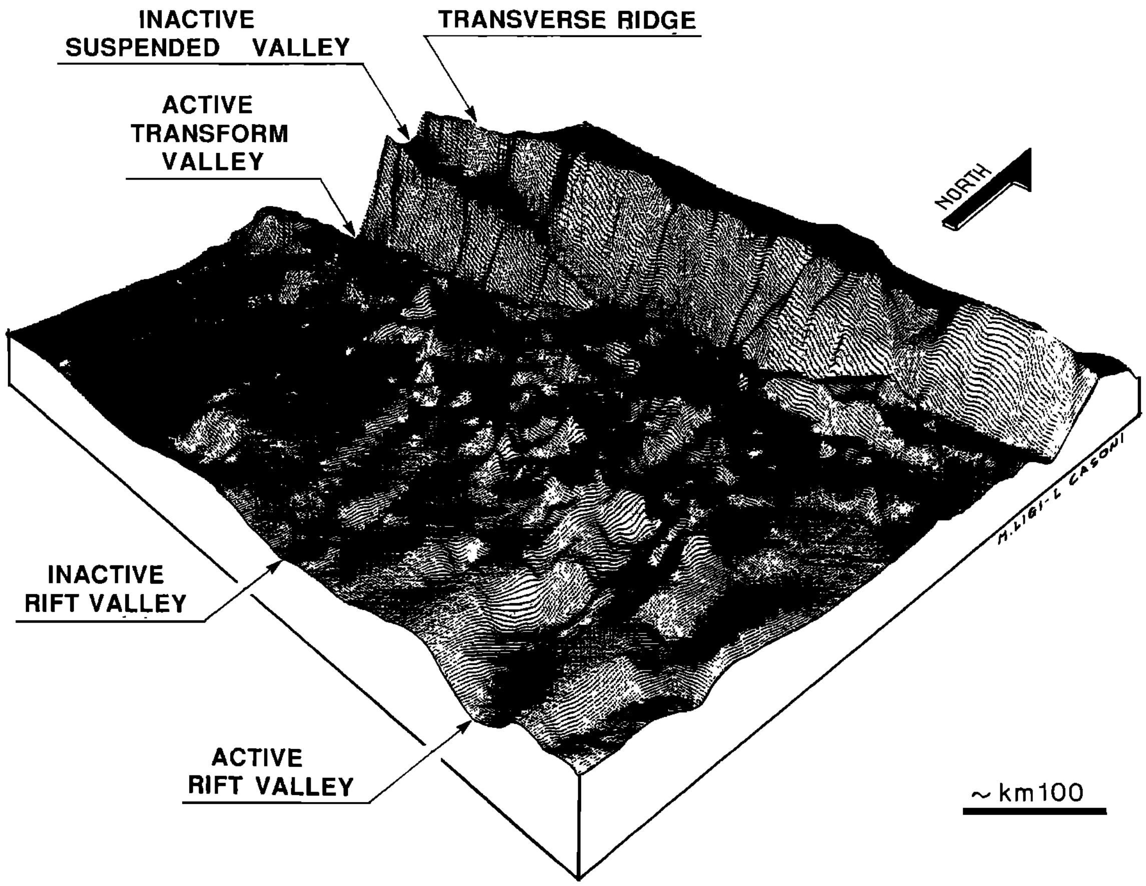

Figure 4. Three-dimensional image of the Romanche eastern RTI area. The source of the data is indicated in the caption of Figure 3. Vertical exaggeration is about x12.5

south between 17°10' and 17°30'W (that is, roughly 80 km west of the present diffuse RTI) was formerly an active ridge axis. Given a half rate spreading of 1.7 cm/yr [*Cande et al.*, 1988] and the presence of a relatively thick sediment cover ~50-60 km on either side of the inferred present RTI, we estimate that the former rift was active up to <4 m.y. ago, when the accretionary boundary jumped east to its present position [*Bonatti et al.*, 1994]. It is possible that the present ill-defined, diffuse RTI is the consequence of its embrionic stage of development.

Crustal thickness at a ridge axis has been shown to be inversely related to the degree of melting of the underlying upper mantle [*Michael and Bonatti*, 1985; *Klein and Langmuir*, 1987]. Both peridotite and mid-ocean ridge basalt (MORB) compositions suggest independently that the upper mantle underwent a very low degree of melting beneath the equatorial MAR, implying a very small crustal thickness [*Bonatti et al.*, 1992, 1993; *Schilling et al.*, 1994]. The distribution of mantle-derived peridotite samples in the RTI region (Figure 5) shows that the basaltic crust is thin, patchy, or absent in a ~30 km-wide belt from the edge of the fracture zone valley. It appears, therefore, that amagmatic extension prevails in that region. This condition must have prevailed also in the past, because the absence of basaltic crust and the prevalence of mantle-derived ultramafics have been observed on the southern side of the transform at various distances from the RTI in lithosphere of different ages [*Bonatti and Honnorez*, 1976; Bonatti et al., unpublished results, 1994].

The gradual deepening of a ridge segment approaching a transform is probably related to the juxtaposition of a thick lithospheric edge against a hot ridge axis tip. Cooling of the subridge upper mantle near the RTI causes isostatic lowering of the ridge axis due to upper mantle thermal contraction and to reduced production of melt, i.e., reduced thickness of crust [*Fox and Gallo*, 1984; *Forsyth and Wilson*, 1984]. The extent of deepening of a ridge segment approaching a RTI according to this mechanism is related to the age offset of the transform, i.e., to the age contrast of juxtaposed lithosphere at the RTI. Reduced crustal thickness near the RTI would also follow from models whereby asthenospheric upwelling is focused in the central zone of a ridge segment and longitudinal subaxial melt flow takes place from this central zone toward the RTIs [*Francheteau and Ballard*, 1983; *Whitehead et al.*, 1984; *Crane*, 1985; *Parmentier and Forsyth*, 1985]. Although a very large age contrast (~ 50 m.y.) exists at the Romanche eastern RTI, no gradual deepening of the ridge axis as it approaches the Romanche valley is observed (Figure 7). This contrasts with the "normal" behavior of the same ridge segment as it approaches the Chain FZ to the south. A gradual deepening from about 4000 m below sea level 30 km from the western Chain RTI to over 5000 m close to the RTI is observed (Figure 6). The anomalous lack of topographic deepening of the ridge

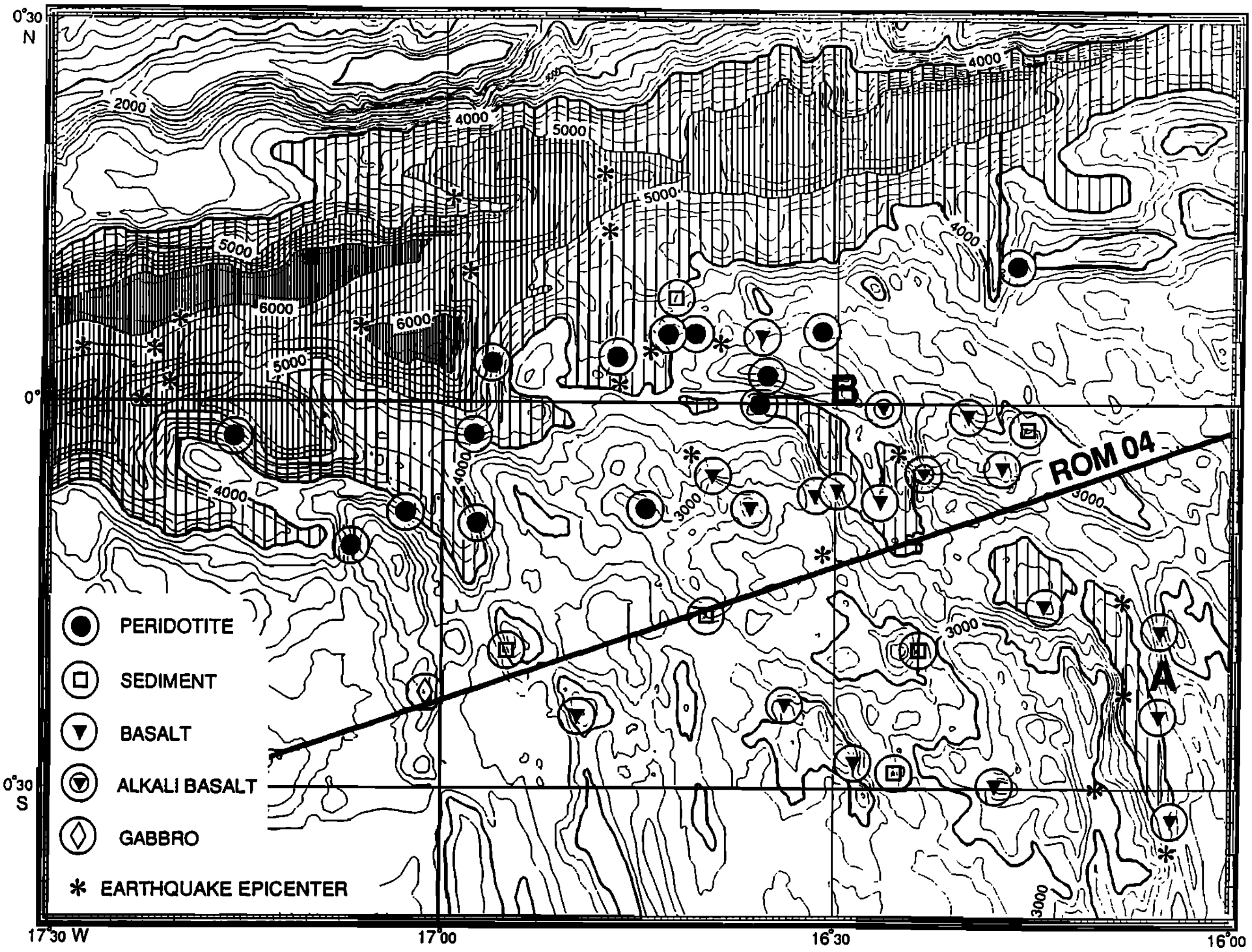

Figure 5. Topography and lithology of the seafloor in the area at the intersection of the Mid-Atlantic Ridge and the Romanche Fracture Zone near the Romanche eastern RTI. The source of the data is indicated in the caption of Figure 3. The 4000-m isobath has been drawn with a thicker line. The location of earthquake epicenters (1970-1990, magnitude > 4) is shown. Also shown is the distribution of different rock types obtained by dredging. The solid line indicates the track of a seismic reflection profile shown in Figure 6. A and B indicate two MAR segments (see text).

axis toward the Romanche RTI goes together with the absence of basaltic crust and the exposure of mantle ultramafics on a ~30 km wide band of seafloor flanking the Fracture Zone valley. These two observations suggest the following scenario.

Cooling of a ridge axis by a "transform cold edge effect" [*Fox and Gallo*, 1984; *Forsyth and Wilson*, 1984] causes reduction of crustal thickness and deepening of the ridge axis toward the transform boundary. If, however, a strong transform cold edge effect (i.e., a large age offset) is combined with a regional low thermal regime, we may reach a threshold over which no significant quantities of melt are extracted from the mantle, little or no crust is formed in the vicinity of the transform, and extension is mostly amagmatic. We believe this is the present-day situation at the Romanche eastern RTI. This situation does not represent a short-lived amagmatic phase but must have been prevalent also in the past, because a number of sections on the southern side of the transform at varying distances from the RTI show absence of basaltic crust and dominance of mantle-derived ultramafics [*Bonatti and Honnorez*, 1976; Bonatti et al., unpublished results, 1994].

Several independent observations support the idea of a thermal minimum in the equatorial Atlantic mantle that cannot be explained solely with transform cold edge effects [*Bonatti et al.*, 1993]. Zero-age seafloor depth reaches a maximum in the region between the Chain (1°S) and the Vema (11°N) fracture zones, except for a mini hot spot swell in the 2° to 4°N region. Figure 7 shows that the ridge segment between the Chain and the Romanche FZs is about 4 km below sea level, i.e., several hundred meters deeper than normal. This depressed topography of the MAR is consistent with low upper mantle temperatures in the equatorial region. Studies of peridotites and basalts have indeed shown an exceptionally low extent of melting of the mantle along the Romanche FZ, implying low mantle temperatures [*Bonatti et al.*, 1992, 1993; *Schilling et al.*, 1994]. Seismic tomography also suggests a broad mantle

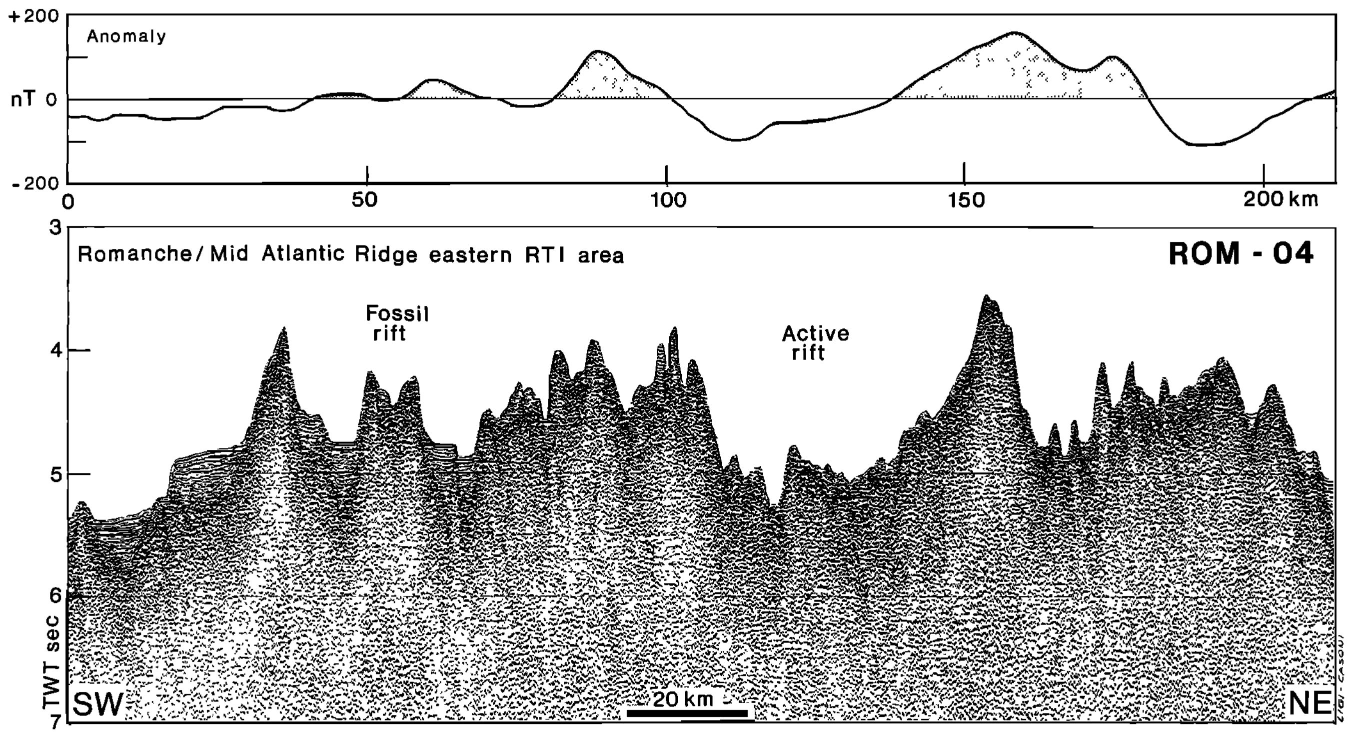

Figure 6. A portion of a multichannel seismic reflection profile south of the RTI. The location is shown in Figure 5. The inferred active and fossil axial rift valleys are shown. Accumulations of ~0.2s-thick sediments are observed in the inferred fossil axial valley. Magnetic anomaly profile is shown superimposed on the seismic reflection profile.

thermal minimum in the equatorial region of the Atlantic [*Zhang and Tanimoto*, 1992]. This thermal minimum may be related to downwelling mantle flow occurring in the equatorial belt of the Atlantic [*Bonatti et al.*, 1993].

Lacking melt production and a crustal layer, the height below sea level reached by the top of the lithosphere depends essentially on the temperature and composition of an upper mantle column down to a "compensation depth" (Figure 8a). Undepleted mantle is denser by ~1% to 2% than a normally depleted oceanic mantle [*O'Hara*, 1975; *Jordan*, 1979; *Oxburgh and Parmentier*, 1977].

Swelling of Topography Due to Serpentinization of Mantle Peridotites

We suggest that serpentinization of ultramafics may explain the absence of a topographic transform cold edge effect at the Romanche eastern RTI. Exposure of mantle ultramafics on the seafloor in the absence of a "protective" carapace of crust will trigger massive serpentinization of the ultramafic rocks. Serpentinization of peridotite primary minerals olivine, orthopyroxene and clinopyroxene will take place below 500°C in the presence of water [*Bowen and Tuttle*, 1949; *Seyfred and Dibble*, 1980]. Hydration of peridotite and formation of serpentinite can result in a ~20% decrease of density, from about 3.3 to about 2.7 g/cm^3. The extent to which serpentinization causes a volume increase of the solid has been much debated [*Thayer*, 1966; *Hostetler et al.*, 1966]. Serpentinization with constant volume implies removal of substantial quantities of MgO and SiO_2 from the rock. Alternatively, reactions of the type

$$\underset{\substack{\text{Olivine} \\ (281\ \text{g};\ 88\ \text{cm}^3)}}{2\,Mg_2SiO_4} + \underset{(45\ \text{g})}{3\,H_2O} = \underset{\substack{\text{Serpentine} \\ (277\ \text{g};\ 111\ \text{cm}^3)}}{Mg_3Si_2O_5(OH)_4} + \underset{\substack{\text{Brucite} \\ (5\ \text{g};\ 25\ \text{cm}^3)}}{Mg(OH)_2}$$

are possible [*O'Hanley*, 1992] where Mg and Si are retained in the system. These reactions imply an increase in the volume of the solids of roughly 50%. Similar but more realistic reactions result in a 25% to 45% volume increase [*Coleman*, 1971]. Evidence of significant volume increase during serpentinization has been obtained in ultramafic massifs exposed on land [*Coleman*, 1971; *O'Hanley*, 1992].

The extent to which serpentinization of mantle-derived peridotites can account for the peculiar topography of the Romanche eastern RTI depends on the thickness of the layer affected by serpentinization (i.e., the depth below the seafloor of the "serpentinization front") and on the average degree of serpentinization achieved in this layer. The thickness of the serpentinized layer depends on the depth of the 500°C isotherm and on the depth of penetration of water below the seafloor. The distribution of isotherms in the vicinity of a transform can be inferred from theoretical models [*Chen*, 1988]. Judging from the estimated depth of earthquake epicenters, that implies faulting and permeability, the depth of penetration of water below the seafloor in the vicinity of a large transform can be estimated at several kilometers [*Engeln et al.*, 1986; *Francis*, 1981].

MacDonald and Fyfe [1985] have estimated by experiments and theory the rate of serpentinization of peridotites on and

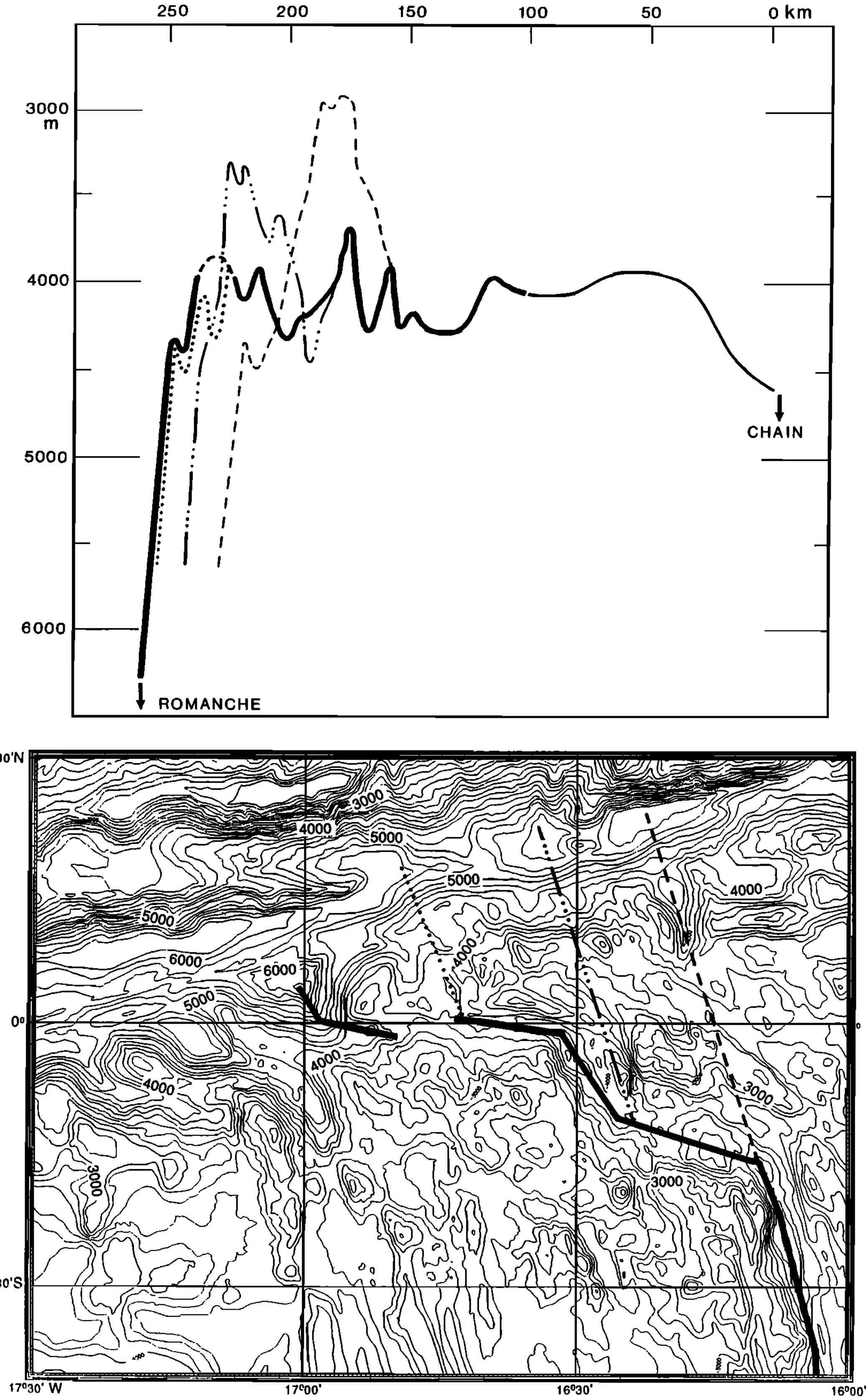

Figure 7. (a) Near-zero-age topographic profile of the ridge segment between the Chain and the Romanche Fracture Zones. (b) The tracks of the profiles north of about 0°. North of about 0°15'S the ridge axis becomes ill-identified morphologically. Four alternative tracks and RTIs are indicated. Note that no gradual deepening of the seafloor as it approaches the Romanche FZ is observed in any of the possible tracks. Note also that the minimum topographic level of this ridge segment is about 4 km below sea level, i.e., several hundred meters deeper than the "normal" level of the MAR outside the equatorial region.

below the seafloor. A crack allowing penetration of water into subseafloor peridotite will create a serpentinization front at the edges of the crack. Water will penetrate serpentinite by diffusive or Darcy-type flow at rapid rates, such that a layer of serpentinite 1 km thick could be formed in about 1 m.y. at 300°C [*MacDonald and Fyfe*, 1985]. Volume increase will cause strain and crack propagation and further help the process of pervasive serpentinization.

Let us imagine a very simplified ridge segment between two transforms (Figure 8a). One portion of the segment (Chain FZ side) has a crust with a thickness $T_c = h_c - h_o$ and density ρ_c. The crust is absent in the other portion (Romanche side) where the mantle (density ρ_m) reaches the seafloor. We assume decoupling of the lithosphere across the RTI, and isostatic equilibrium. Fox and Gallo [1984] have suggested the possibility of "mantle welding" across the RTI, resulting in a narrow and stable strike-slip zone and oblique faulting in the inner corner. However, the Romanche eastern RTI has been unstable in time and space, suggesting decoupling between the young and the old lithospheric blocks across the RTI. The assumption of isostatic equilibrium is thus reasonable. Assuming isostatic equilibrium and uniform distribution of the isotherms below the ridge segment, the depth below sea level of the seafloor in absence of crust, h_w, is

$$h_w = h_o + T_c (\rho_m - \rho_c) / (\rho_m - \rho_w).$$

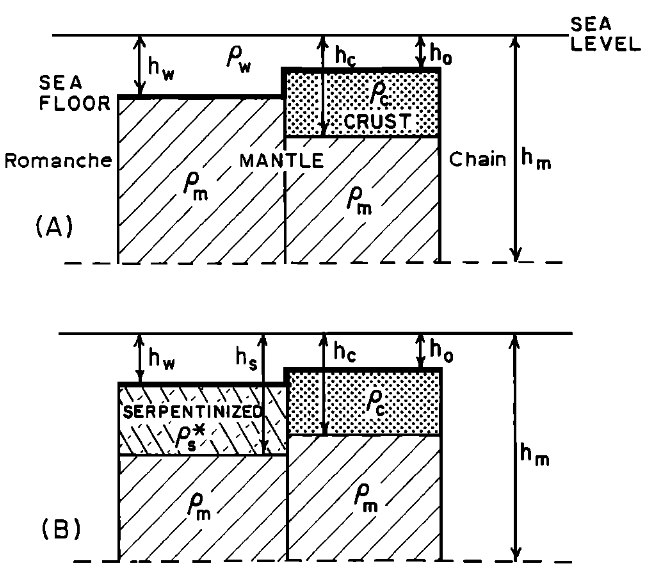

Figure 8. Schematic and simplified profile of near zero-age seafloor topography of MAR segment between the Chain and the Romanche FZ. (a) Two adjacent columns are shown, one with and one without an upper basaltic crustal layer. The crust-free column approximates the near-zero-age area close to the eastern Romanche RTI. Here h_w is seafloor depth below sea level in absence of crust; h_o is seafloor depth below sea level with crustal layer present; h_c is depth below sea level of base of the crust; h_m is depth below sea level of the compensation surface; ρ_w is density of water; ρ_c is density of crust; ρ_m is density of mantle. (b) The same as (Figure 8a), except for the assumption that a layer (with thickness $h_s - h_w$) of the crust-free block undergoes serpentinization. Here ρ_s is density of the serpentinized layer.

For instance, assuming $\rho_w = 1000$ kg/m³; $\rho_c = 2700$ kg/m³, $\rho_m = 3300$ kg/m³ and crustal thickness $T_c = 5$ km, we have

$$h_w = h_o + 1.3 \text{ km}.$$

That is, the stretch of ridge segment where crust is absent is predicted to be 1.3 km deeper than the stretch with a normal 5-km-thick crustal layer.

Let us imagine now (Figure 8b) that a layer (thickness $T_s = h_s - h_w$) in the stretch of ridge segment devoid of crust will be affected by serpentinization. If ρ_s is the density of serpentinite and Φ is the fraction of peridotite in layer T_s that undergoes serpentinization (where $0 < \Phi < 1$), the density of layer T_s (ρ_{Ts}) is

$$\rho_{Ts} = (1 - \Phi) \rho_m + \Phi \rho_s.$$

Assuming isostatic equilibrium, the depth below sea level of the top of the serpentinized layer h_w is

$$h_w = h_o + T_c (\rho_m - \rho_c) / (\rho_m - \rho_w) - \Phi T_s (\rho_m - \rho_s) / (\rho_m - \rho_w).$$

In order for the depth of the crust-free stretch (h_w) to be the same as that of the normal stretch (h_c) (thus approximating the observed topography of the ridge segment between Romanche and Chain), the thickness of the serpentinized layer will have to be

$$T_s = \Phi^{-1} T_c (\rho_m - \rho_c) / (\rho_m - \rho_s).$$

For instance, if we assume the density of the serpentinized layer to be identical to that of the crust (2700 kg/m³), its thickness to be 5 km, and degree of serpentinization to be 50% ($\Phi = 0.5$), we obtain $h_w \geq h_o + 0.65$ km, that is, the crust-free zone is 650 m deeper than the "normal" ridge stretch. Under these assumptions for the crust-free seafloor to be at the same level as seafloor with normal crust ($h_w = h_o$), the thickness of the serpentinized layer should be twice the crustal thickness ($T_s = 2 T_c$).

Let us assume now that serpentinization will involve an isotropic change of volume, where "α" is the fraction of volume increase ($0 < \alpha < 0.5$). Including volume increase, the depth of the crust-free zone will be

$$h_w = h_o + T_c (\rho_m - \rho_c)/(\rho_m - \rho_w) - \Phi (1+\alpha)^{1/3} T_s (\rho_m - \rho_s)/(\rho_m - \rho_w).$$

If $h_w = h_o$, the thickness of the serpentinized mantle layer will be

$$T_s = \Phi^{-1} (1 + \alpha)^{1/3} T_c (\rho_m - \rho_c) / (\rho_m - \rho_s).$$

If we maintain the assumption of the preceding example and if we assume a volume increase of 30% ($\alpha = 0.3$), we have that $h_w = h_o + 0.585$ km. In order to make $h_w = h_o$, the serpentinized layer must be 1.8 times the crustal thickness ($T_s = 1.8 T_c$).

In the real world the crustal thickness in the southern part of the MAR segment between Chain and Romanche is likely to be <5 km, given the depressed (cold) topography of this segment. Accordingly, the required thickness of the serpentinized layer is probably significantly lower than that indicated by our calculations. Crustal thickness probably decreases gradually toward the Romanche RTI and not abruptly as in our scheme.

These simple calculations are consistent with the hypothesis that serpentinization of a several kilometers thick peridotite layer, in absence of crust, may elevate the seafloor so as to erase the predicted transform edge topographic effect.

Conclusions

1. The ridge segment between the Chain FZ and Romanche FZ is over 4 km below sea level, i.e., significantly deeper than the "normal" zero-age level reached by the MAR outside the equatorial region.

2. The eastern Romanche RTI lacks a well-defined morphological signature. The axial rift valley of the MAR breaks down in short ill-defined en echelon segments about 80 km from the edge of the transform valley and disappears altogether ~30 km from it. No gradual deepening of the topography as the ridge approaches the transform was observed. An active nodal deep and inner corner high were not identified. These observations, and the distribution of earthquake epicenters, suggest a diffuse RTI.

3. An aseismic rift valley opening into the transform valley about 80 km west of the inferred location of the present RTI suggests ridge and RTI jumping within the last 3-4 m.y. It is possible that the present RTI is at an embryonic stage of development and that a new portion of ridge axis is presently attempting to form.

4. The basaltic crust is thin or absent in a 30-km-wide band from the edge of the transform valley, where mantle-derived serpenti-nized peridotites outcrop ubiquitously on the seafloor. Na-rich MORB and alkali basalts outcrop near the RTI; peridotites have undepleted composition. These observations suggest low degrees of melting and low upper mantle temperatures in the vicinity of the Romanche, with amagmatic extension prevailing.

5. Conclusions 1, 2, 3, and 4 above can be explained by an upper mantle thermal minimum in the equatorial Atlantic, with a low degree of partial melting and a low magmatic budget. A "transform cold edge" thermal effect is superimposed on a regional thermal minimum in the equatorial upper mantle.

6. The absence of a gradual deepening of the seafloor as the ridge axis approaches the Romanche transform, contrary to what is observed in most other large Atlantic transforms, may be due to massive serpentinization of a peridotite layer in absence of crust, with consequent decrease of density and possible increase in volume. In the absence of a basaltic crustal layer, the topographic "transform cold edge effect" may become masked in ultracold RTIs by the topographic effect of serpentinization. Other factors being equal, the transform cold edge topographic effect should increase with increasing age (thermal) contrast at RTI. Paradoxically, however, at extreme age contrasts in absence of basaltic crust the topographic effect may disappear.

7. The "cold" thermal structure of the MAR segment approaching the Romanche FZ from the south and the corresponding anomalous, diffuse RTI are caused not only by a strong "transform cold edge effect" but also by a regional thermal minimum of the equatorial Atlantic upper mantle. This thermal minimum may be related to downwelling mantle flow occurring in the equatorial belt of the Atlantic [*Bonatti et al.*, 1993].

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