

Steady-state creation of crust-free lithosphere at cold spots in mid-ocean ridges

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ABSTRACT

Mid-ocean ridges create oceanic lithosphere consisting normally of basaltic crust a few kilometers thick overlying a peridotitic mantle. However, lithosphere free of basaltic crust formed during the past ~30 m.y. at an ~50-km-long stretch of Mid-Atlantic Ridge south of the Romanche Fracture Zone, giving rise to a >500-km-long strip of ocean floor exposing mostly mantle peridotites that have undergone an unusually low ($\leq 5\%$) degree of melting, mixed with peridotites that reacted with a small fraction of basaltic melt. This lithosphere contains <10% of scattered gabbroic pockets, representing melt frozen above 25 km depth within a relatively cold subaxial lithosphere. Numerical modeling excludes dry melting below this crust-free lithosphere, because of the cooling effect of the long-offset Romanche transform combined with a regional mantle thermal minimum; however, modeling allows a limited extent of hydrous melting. This unusual lithosphere, unable to expel the melt fraction, characterizes cold spots along mid-ocean ridges.

Keywords: oceanic lithosphere, mid-ocean ridges, mantle cold spots, mantle flow numerical model.

INTRODUCTION

Classic models of the oceanic lithosphere call for a 4–6-km-thick igneous (basaltic) crust overlying a peridotitic mantle; the igneous crust is produced by decompression partial melting of mantle ascending below mid-ocean ridges. However, the thermal structure of the equatorial Mid-Atlantic Ridge is unusual insofar as it is affected by a regional mantle thermal minimum and by the cooling effect of long-offset, slow-slipping transforms (Bonatti et al., 1993, 1994; Schilling et al., 1995). We describe here how this cold stretch of mid-ocean ridge has produced continuously for more than 30 m.y. a peculiar lithosphere, free of basaltic crust, although containing scattered blobs of frozen melt.

LITHOSPHERE FREE OF BASALTIC CRUST

The Romanche transform offsets the equatorial Mid-Atlantic Ridge by ~950 km (Fig. 1), corresponding to an age offset of ~55 m.y. if we assume the present ridge-transform geometry and an average spreading half-rate of 17 mm/yr (Cande et al., 1988). Multibeam bathymetry of the Romanche eastern ridge-transform intersection (Fig. 1) failed to detect a deepening of the Mid-Atlantic Ridge axial valley as it approaches the transform (Bonatti et al., 1996). Thus, the predicted transform cold-edge effect (Fox and Gallo, 1984) is ab-

sent. Approaching the Romanche Transform from the south, the axial valley fades gradually and almost disappears ~50 km south of the Romanche eastern ridge-transform intersection. Close-spaced sampling of this area shows a near absence of basalts and a prevalence of mantle-derived ultramafic rocks (Fig. 1).

The ubiquitous exposure of ultramafic rocks in an ~50-km-long stretch of ridge is surprising, particularly because the Mid-Atlantic Ridge here lacks a well-developed axial valley, where normal faults could have helped uplift and expose deep-seated rocks. The scarcity of basaltic crust might be the result of a present-day nearly amagmatic extension phase that alternates in slow-spreading ridges with periods of magmatic accretion in ~1 m.y. cycles (Kappel and Ryan, 1986). Reduced crustal thickness during amagmatic extension could lead to denudation of mantle domains along low-angle normal faults (Karson and Dick, 1983). We tested this hypothesis by carrying out systematic sampling of the ocean floor south of the Romanche Fracture Zone, along ridge-parallel profiles located at increasing distance from the ridge axis, in a seafloor-spreading flow corridor of progressively older lithosphere (Fig. 1). The ages, estimated assuming a 17 mm/yr average spreading half-rate (Cande et al., 1988) within a present-day ridge transform geometry, range from near

zero close to the Romanche eastern ridge-transform intersection to older than 30 Ma >600 km west of the ridge axis (Fig. 1). The results (Fig. 2) show that mantle peridotites are strongly prevalent and the basaltic crust is nearly absent within an ~50-km-wide, >500-km-long strip of ocean floor south of the transform, corresponding roughly to an ~30 m.y. time interval.

Accordingly, the hypothesis of ~1 m.y. alternating cycles of basaltic accretion and nearly amagmatic extension at a ridge axis cannot be applied in this region. A nearly continuous nonmagmatic, tectonic emplacement and extension of lithosphere at this ridge axis for more than 30 m.y. is in contrast with other observed exposures of mantle ultramafics at the Mid-Atlantic Ridge, as near the Kane and the 15°20' Fracture Zones, where the emplacement of ultramafic lithosphere free of basaltic crust appears to have been intermittent (Cannat et al., 1995, 1997).

MANTLE PERIDOTITES FROM THE EQUATORIAL MID-ATLANTIC RIDGE

Two types of peridotites have been recovered near the Romanche Fracture Zone. One type (normal mid-ocean ridge peridotite, or N-MORP) displays various degrees of deformation and serpentinization, but contains olivine, orthopyroxene, clinopyroxene, and spinel as relict, mantle-equilibrated phases. These rocks are similar to peridotites from elsewhere along the Mid-Atlantic Ridge, insofar as they appear to be the residue after partial melting due to decompression of mantle upwelling below the ridge. However, the Romanche peridotites have an exceptionally fertile composition, as shown by the chemical composition of their mantle-equilibrated phases, such as the Al content of orthopyroxene and the 100 Cr/(Cr + Al) ratio of spinel (Fig. 3). Spinel 100 Cr/(Cr + Al) was calibrated from experiments where fertile pyrolite-like lherzolites were partially melted under a range of temperature-pressure (*T-P*) conditions (Jaques and Green, 1980; Mysen and Kushiro, 1977), and from correlations with the clinopyroxene content of heavy rare earth elements such as Dy and Yb

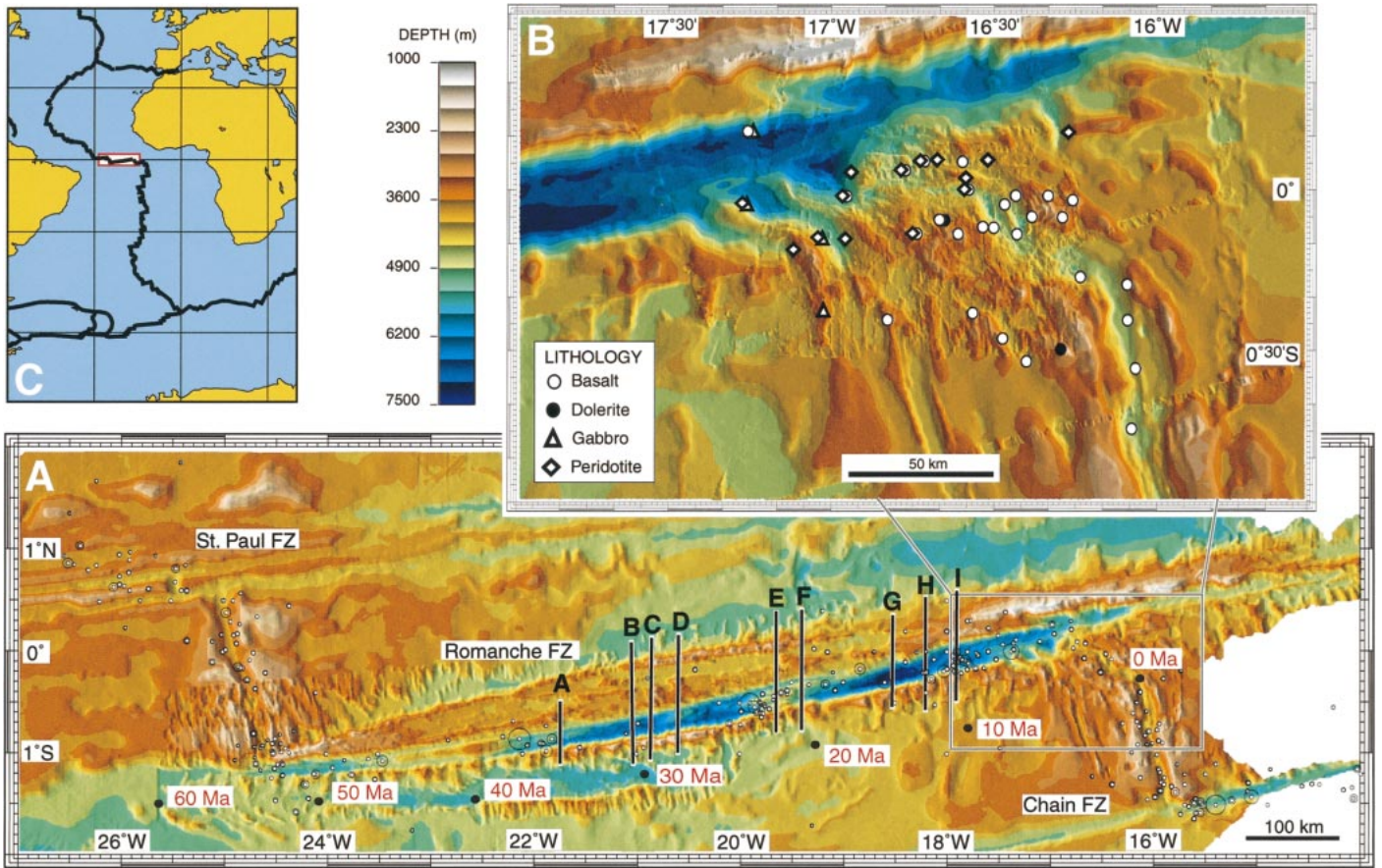


Figure 1. A: Multibeam topography of Romanche region, showing north-south profiles where sampling was carried out. Black dots and red numbers indicate estimated age (in million years) of lithosphere south of Romanche Transform, assuming spreading half-rate of 17 mm/yr within present-day ridge and transform geometry. White dots indicate epicenters of teleseismically recorded 1970–1995 events (magnitude > 4). FZ is fracture zone. B: Topography and petrology at eastern intersection of Romanche Fracture Zone with Mid-Atlantic Ridge. Data were obtained during expeditions S-16, S-19, and G-96 (Bonatti et al., 1994, 1996). C: Location of A along Mid-Atlantic Ridge.

(Hellebrand et al., 2001). The results suggest that the mantle in the Romanche region underwent exceptionally low ($\sim < 5\%$) degrees of melting (Fig. 3). This conclusion, supported independently by estimates derived from basalt composition (Bonatti et al., 1993; Schilling et al., 1995), is consistent with the ob-

servation that a basaltic crust is nearly missing in this area. The upper mantle elsewhere along the Mid-Atlantic Ridge has undergone 10%–15% melting, except in areas influenced by hotspots, where melting can reach >20% (Dick et al., 1984; Michael and Bonatti, 1985; Klein and Langmuir, 1987).

The other type of peridotites recovered in abundance near the Romanche Fracture Zone (metasomatic mid-oceanic ridge peridotites, M-MORP) frequently contains small quantities of plagioclase + clinopyroxene in textural equilibrium with recrystallized olivine. High-temperature mineral compositions are anomalous; e.g., spinel is enriched in Fe, Cr, and Ti relative to spinel of N-MORP (Seyler and Bonatti, 1997). The degree of melting undergone by M-MORP cannot be estimated by the criteria already mentioned, unless mantle-equilibrated mineral relicts, unaffected by secondary reactions, are present. M-MORP has been found in some cases in close spatial association with undepleted N-MORP, i.e., in the same dredge haul or even in the same hand specimen.

We interpret M-MORP as originating from reactions between a basaltic melt and nearly undepleted N-MORP, occurring at shallow levels in the mantle, below the pressure stability limit of plagioclase (~ 900 MPa), within ~ 25 km of the seafloor. The liquid, derived from low extents of melting of slowly upwelling mantle, penetrates shear zones and grain boundaries within the relatively cold

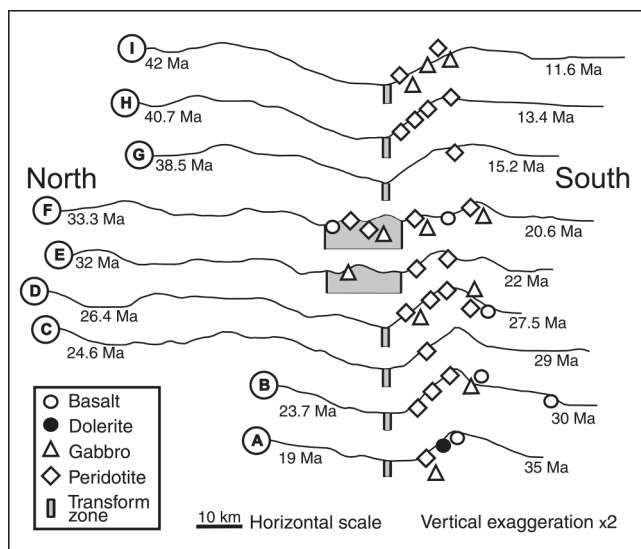


Figure 2. Topographic profiles across Romanche Fracture Zone, and distribution of rock types south of transform boundary within South American plate. Lithospheric ages are estimated assuming that this lithosphere was created at Mid-Atlantic Ridge axis and spread at 17 mm/yr (half-rate) within present ridge and transform geometry. Lithology is from dredgings carried out during cruises P6707, RC2806 (Bonatti and Honnorez, 1976), S-16, S-19, and G-96 (Bonatti et al., 1994, 1996).

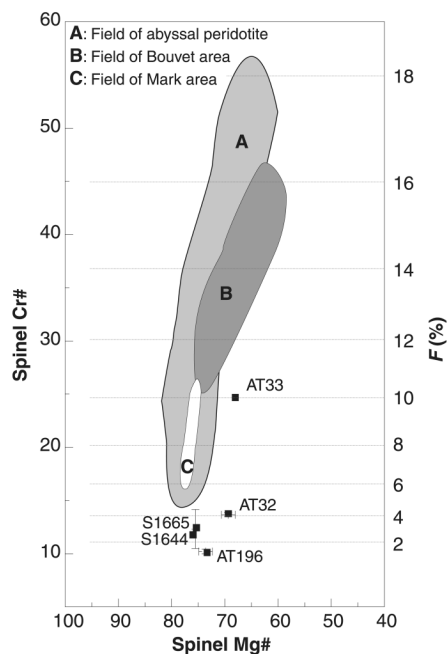


Figure 3. 100 Cr/(Cr + Al) in spinel from Romanche normal mid-ocean ridge peridotite (N-MORP; black squares with 1 σ indicated) compared with N-MORP from elsewhere along mid-ocean ridges. Fields A, B, and C are from Dick et al. (1984) and Michael and Bonatti (1985). Degree of melting (F) was calibrated according to Hellebrand et al. (2001). Data suggest that mantle below Romanche region has undergone unusually low degree of melting.

equatorial lithospheric mantle; it reacts with aluminous phases of N-MORP (clinopyroxene and Al-rich spinel), producing plagioclase and Mg-rich olivine and leaving Cr-Ti-rich spinel (Seyler and Bonatti, 1997). It eventually freezes in thin veins and isolated gabbroic pockets. The melt is unable to accumulate in sizable volumes and hence to segregate from the mantle to form a continuous basaltic crust, as it normally does below mid-oceanic ridges.

MODELING OF COLD LITHOSPHERE FREE OF BASALTIC CRUST

The thickness of the basaltic crust is affected by the temperature of the upwelling mantle, the spreading rate, and mantle viscosity and permeability (Shen and Forsyth, 1992; Sparks et al., 1993). Numerical experiments (Su et al., 1994) suggest that small changes in mantle potential temperature have a strong effect on crustal thickness, particularly at low spreading rates. For example, a 20 °C decrease of mantle potential temperature from an initial 1317 °C at 100 km deep would lower crustal thickness by ~2 km at a spreading rate of 10 mm/yr. Thus, a mantle thermal minimum in the equatorial Atlantic (Bonatti et al., 1993; Schilling et al., 1995) could in part explain the lack of basaltic crust south of the Romanche Fracture Zone. Superimposed on this regional

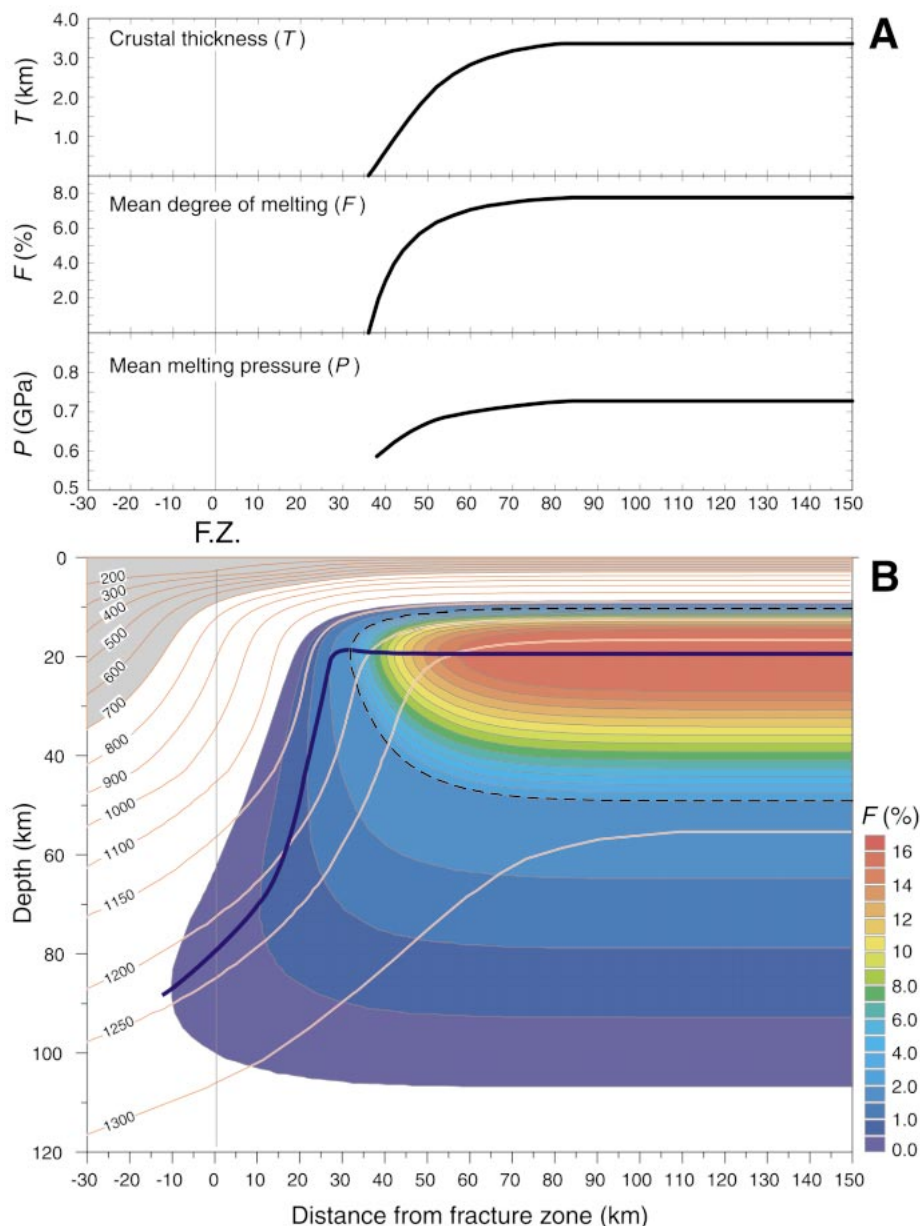


Figure 4. Melt production as mid-ocean ridge segment approaches Romanche-type, long-offset, slow-slipping transform. Melt generation was modeled assuming adiabatic fractional melting in region where temperatures are above solidus. Latent heat of fusion due to freezing of melt, and hydrothermal cooling have been neglected. Mantle temperatures before onset of melting were estimated by solving steady-state advection-diffusion heat equation of Phipps Morgan and Forsyth (1988) through three-dimensional domain of mantle-flow calculations, using variable grid spacing (512 \times 256 \times 101). Mantle potential temperature of 1330 °C was kept at 1300 °C 150 km deep in mantle, assuming lower than normal mantle temperatures estimated from Schilling et al. (1995) geochemistry of mid-ocean ridge basalt from ridge segment south of Romanche Fracture Zone (F.Z.). Mantle-flow velocities were estimated assuming steady-state plate-thickening passive flow (Blackman and Forsyth, 1992) in calculation domain with area of 2048 \times 1024 km and depth of 150 km (grid spacing = 1 km). Base of rigid plates corresponds to depth of 700 °C isotherm. It was obtained iteratively, starting from constant-thickness plate-flow model. A: Crustal thickness (top diagram), mean degree of melting (middle), and mean depth of melting (bottom), estimated according to Langmuir et al. (1992), assuming dry fractional melting with solidus given by $T_{sol}^{dry} = 1100 + 0.0039z$, where T is temperature (in °C) and z is depth (in m). B: Fraction of melt, including effects of H₂O. Thick dashed line marks region where dry melting is likely to happen. Melt generated for given amount of adiabatic decompression in hydrous melting region (dark blue) calculated following Braun et al. (2000). Solid thick purple line marks maximum degree of melting, i.e., upper boundary of region that contributes to melt production. Red solid curves represent isotherms.

effect is the thermal effect of the large equatorial transforms, which we consider next.

The amount of cooling of the upper mantle due to a Romanche-type transform offset (900 km long, 34 mm/yr slip rate) was estimated through numerical experiments (see Fig. 4). The results show a strong decrease of crustal production as the ridge approaches the transform. No melting is predicted in an ~30-km-long stretch of ridge nearest to the fracture zone, if dry fractional melting is assumed. If, however, we assume a wet solidus, consistent with the small (~0.1%) amount of H₂O expected in the oceanic upper mantle (Hirth and Kohlstedt, 1996), then the model predicts initiation of melting ~110 km deep below the center of the ridge segment, but decreasing toward the Romanche eastern ridge-transform intersection. Hydrous melting only occurs close to the offset (Fig. 4). A small extent of wet melting tends to produce liquids enriched in incompatible elements, which could explain the recovery of H₂O- and alkali-rich basalts near the Romanche (Honnorez and Bonatti, 1970; Bonatti et al., 1979; Schilling et al., 1995). Petrology suggests that most of the little melt produced near the offset freezes within the plagioclase stability field, above the depth of 25 km. If the entire melt is allowed to migrate above this level, with no melt extraction, the upper (<25 km) mantle section will contain 5.5%–6.5% frozen melt, which should affect density, viscosity, and rheology of the lithosphere near the Romanche.

Thus, we have the paradox that in cold stretches of mid-ocean ridges, with low melt production, the lithospheric mantle can retain >5% melt, whereas in hot stretches, with high production of melt, the fraction of melt left behind in the mantle is low, i.e., <~1%, as observed below the East Pacific Rise (Webb and Forsyth, 1998).

CONCLUSIONS

Thicker and colder than normal oceanic lithosphere, unable to release the melt fraction, and therefore lacking a significant distinct basaltic crustal layer, develops preferentially at mid-oceanic ridge cold spots and near transforms with large (>30 m.y.) age offsets. We expect this peculiar lithosphere to be common, in addition to the equatorial Atlantic, in other cold parts of the mid-ocean ridge system such as the Australian-Antarctic Discordance (Christie et al., 1998) and the Southwest Indian Ridge, east of 70°E (Minshull and White,

1996). Some ophiolite complexes, where the basaltic crust is reduced or absent, may have originated at ancient cold ridges.

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