Abrupt transition from magma-starved to magma-rich rifting in the eastern Black Sea

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ABSTRACT

The amount of magmatism that accompanies the extension and rupture of the continental lithosphere varies dramatically at rifts and margins around the world. Based on widely spaced geophysical transects, some margins are known to preserve a transition from magmatically robust to magmatically starved rifting along strike, but the nature of the transition is unknown. Wide-angle seismic data from the Black Sea provide the first direct observations of such a transition and show that it is abrupt, occurring over only ~20–30 km, and coincides with a transform fault. This abrupt transition cannot be explained solely by gradual along-margin variations in mantle properties, since these would be expected to result in a smooth transition from magma-poor to magma-rich rifting over hundreds of kilometers. We suggest that the abruptness of the transition results from the development of three-dimensional (3-D) melt migration due to along-strike variations in extension and thus the thickness of the lithosphere at the time of rifting. Localized magmatic addition attributed to melt focusing has been observed in modern mid-ocean ridges and active rift environments, but here we show that such processes can also produce abrupt along-strike changes from magma-poor to magma-rich rifting.

INTRODUCTION

Variations in magmatism during rifting have been attributed to variations in mantle temperature (White and McKenzie, 1989; Reston and Phipps Morgan, 2004), rifting velocity or duration (Bown and White, 1995), active upwelling (Holbrook et al., 2001), or small-scale convection (Boutilier and Keen, 1999). The volume of magmatism can change by an order of magnitude or more along individual rifts and margins (e.g., northwestern Australia, Hopper et al., 1992; offshore eastern Canada, Keen and Potter, 1995; offshore south Greenland, Nielsen et al., 2002; Gulf of California, Lizarralde et al., 2007), but little is known about the length scale of this transition because existing data sets usually sample margins at >100 km intervals. Here we present seismic velocity models of the crust and uppermost mantle based on wide-angle seismic data from the eastern Black Sea that reveal a change over only ~20–30 km along the margin from highly thinned (~7–9 km) continental crust without a significant amount of associated synrift magmatism to thick (~11–13 km) oceanic crust formed by voluminous magmatism.

TECTONIC SETTING

The eastern Black Sea basin formed by backarc extension behind the northward subduction of the Neotethys Ocean in latest Cretaceous to early Cenozoic time (Zonenshain and Le Pichon, 1986; Okay et al., 1994; Shillington et al., 2008). Basin opening occurred in a northeast-southwest direction by the rotation of the Shatsky Ridge away from the Mid-Black Sea High (Zonenshain and Le Pichon, 1986; Okay et al., 1994), resulting in increasing extension to the east (Fig. 1) (Shillington et al., 2008). Previously, it was unclear whether extension culminated in lithospheric rupture and seafloor spreading because it was not known whether the thin crust in the center of the basin was of a continental or oceanic affinity (Belousov et al., 1988); our new data allow the affinity of this crust to be determined. During the past 20 m.y., the eastern Black Sea region has undergone shortening due to the northward movement of the Arabian plate. However, seismic reflection, seismicity, and geodetic data indicate that most of this deformation, and therefore any associated modification of crustal structure, is focused around the edges of the easternmost part of the basin (Reilinger et al., 2006) and therefore does not affect our key observations.

DATA ACQUISITION AND ANALYSIS

An onshore-offshore wide-angle seismic data set was collected in 2005 to determine the deep structure of the basin. Four-component ocean-bottom seismometers (OBSs) and three-component land seismometers were deployed along four lines with a spacing of 7–13 km (Fig. 1A), and they recorded seismic shots generated from an air gun array with a total volume of 3140 in^3 that was triggered every 60 or 90 s (shot spacing 100–200 m). Data quality is exceptionally good, allowing the identification of clear refractions and reflections that sampled the sedimentary section, crust, and uppermost mantle. We used reflection-refraction tomography (Hobro et al., 2003) to determine the P-wave velocity structure along lines 1–3 (Fig. 2), and hence variations in crustal thickness and affinity, using reflected and refracted phases interpreted in these data (picking errors 20–150 ms). Tomographic inversion determines a minimum-structure velocity model that fits the data within its errors. Sedimentary structure was obtained by inversion of two refracted and two to three reflected phases. Interfaces were also constrained by picks from coincident seismic reflection data (e.g., Fig. 1B). Crustal and mantle structure were then obtained by inversion of crustal refractions, Moho reflections, and mantle refractions, while the sedimentary structure was held fixed. A grid spacing of 2 × 1 km (horizontal versus vertical) was used for line 1, and 1 × 1 km was used for lines 2 and 3. All models employed similar inversion pathways and smoothing parameters. The models were parameterized to be smoother horizontally than vertically, and were parameterized to slightly favor rougher interfaces rather than rougher velocities. All models have chi-squared values (traveltime residual normalized by picking error) of 1–1.5. Resolution tests indicate that features with dimensions of ~30 × 6 km can be recovered on line 1, which has the sparsest

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instrument spacing (Fig. DR5 in the GSA Data Repository[1]); modeled features described below have similar or greater scale lengths. Crustal thicknesses have maximum uncertainties of ±1 km, and lower-crustal velocities have uncertainties of ±0.1 km/s (Fig. DR6).

CRUSTAL STRUCTURE OF BASIN

Crust along line 3, the western dip line, is 7–9 km thick in the center of the basin and has velocities of 5.5–6.6 km/s (Fig. 2). Maximum lower crustal velocities of 6.4–6.6 km/s are too slow to correspond to gabbros emplaced by synrift magmatism or seafloor spreading (White et al., 1992) (Fig. DR7), indicating that this crust is continental. The thickness suggests a maximum thinning factor (initial/final crustal thickness) of ~4 (Fig. 2), yet there is no evidence for a significant amount of synrift volcanism (e.g., seaward-dipping reflections in seismic reflection profiles) or magmatic underplating.

The velocity model along line 2, the eastern dip line, exhibits thicker crust (~11–13 km) with higher velocities (5.5–7.2 km/s) (Fig. 2). In contrast to line 3, the high velocities in the middle and lower crust (6.8–7.2 km/s) along line 2 are best interpreted as either oceanic or synrift gabbros. Furthermore, the upper crust is characterized by a high-velocity gradient and the lower crust by a low-velocity gradient, both typical of oceanic crust (White et al., 1992). Although the crust along line 2 is thicker than normal oceanic crust (~7 km) (White et al., 1992), its velocity structure is similar to that of thick oceanic crust observed near volcanic rifted margins and oceanic islands (e.g., Holbrook et al., 2001) (Fig. DR7b). Consequently, we interpret this crust as oceanic.

Line 1, the strike line that connects lines 2 and 3, indicates that the transition between the two crustal domains found in lines 2 and 3 is relatively abrupt, occurring over just 20–30 km (between 210 to 240 km model distance on line 1, Fig. 2). The transition from thinned continental crust without synrift magmatism to thick, magmatically robust oceanic crust coincides with one of a series of NE-SW–trending basement scarps (parallel to the inferred opening direction) that cut the easternmost part of the basin (Fig. 1). These scarps are spaced at ~100 km with heights of as much as 2–2.5 s two-way traveltime (~2.5–3.1 km, Fig. 1B). The oldest and deepest identifiable sediments in the basin, which date from latest Cretaceous–early Cenozoic time (Zonenshain and Le Pichon, 1986; Okay et al., 1994; Shillington et al., 2008), show fanned geometries where they abut the basement scarps (Fig. 1B). This observation suggests that these scarps were active during this time interval, which corresponds to the time of basin opening (Banks et al., 1997; Shillington et al., 2008). Younger, overlying sediments do not show significant offsets, suggesting the scarps could not have formed or been active after rifting. A fault dip of ~84° is estimated for the westernmost scarp from seismic reflection data by converting the throw from time to depth using our velocity models. The geometry and timing indicate that the basement offsets represent transform faults, with a small component of extension, that separated rift segments undergoing different amounts of stretching and/or spreading during basin formation.

ROLE OF MANTLE COMPOSITION AND TEMPERATURE

Variations in the amount of magmatism produced during rifting and initial seafloor spreading are commonly attributed to variations in strain rate, asthenospheric temperature, and/or mantle composition. Onshore observations (Ustaömer and Robertson, 1997) and analysis of stratigraphic infill (Shillington et al., 2008) both suggest high strain rates (~0.08 m.y.$^{-1}$) during the opening of the eastern Black Sea, but do not provide evidence for significant variations along the margin. Few constraints are available on mantle properties at the time of rifting in this area. However, gradual lateral variations in both mantle temperature and composition might be produced by changes in the distance of the eastern Black Sea from the paleo-island arc. In most reconstructions, the eastern Black Sea appears to be ~175 km closer to the paleosubduction zone to the east near line 2 than to the west near line 3 (Okay et al., 1994) (Fig. 1A, inset). The mantle beneath island arcs is usually hot (>1200 °C) and rich in volatiles introduced by subduction (Kelemen et al., 2003; Kelley et al., 2006). Water and other volatiles depress the solidus and allow melting to occur at lower temperatures and/or greater pressures. Variations in the distance from the backarc to the island arc therefore might result in signifi-

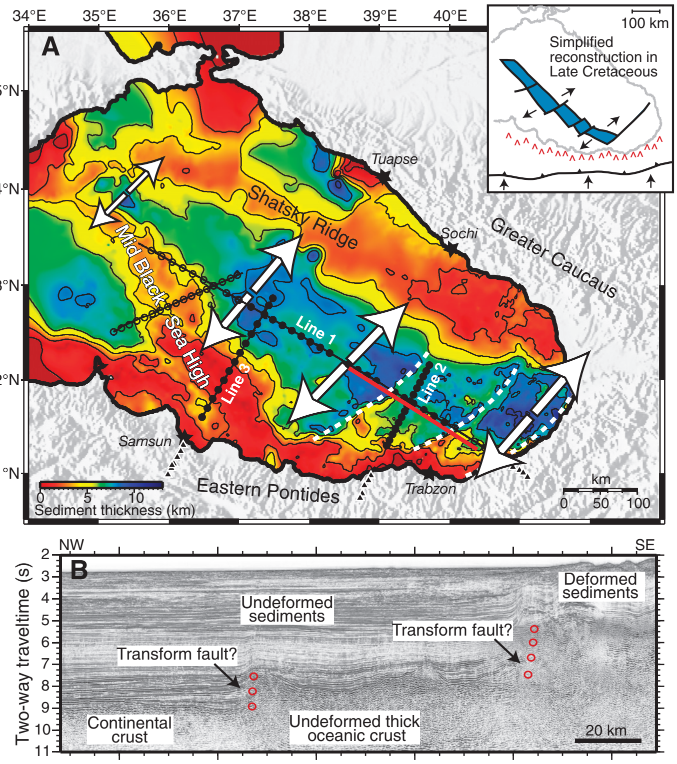

Figure 1. A: Location of 2005 Black Sea wide-angle seismic experiment. Sediment thicknesses estimated from seismic reflection data are shown within eastern Black Sea basin (Shillington et al., 2008), and illuminated elevation from the GEBCO (General Bathymetric Chart of the Oceans) Digital Atlas (published by the British Oceanographic Data Centre on behalf of the International Hydrographic Organization [IHO] and the Intergovernmental Oceanographic Commission [IOC] of UNESCO; IOC, IHO, and BODC, 2003) is shown onshore. Arrows are scaled by the amount of stretching, which was estimated from subsidence analysis (Shillington et al., 2008). Note that extension increases eastward to reach a maximum stretching factor (initial/final crustal thickness) of ~5. Locations of ocean-bottom seismometers, land seismometers, and shot profiles are indicated with black circles, triangles, and lines, respectively. Filled circles indicate parts of each line shown in Figure 2. Red line indicates location of profile in B. Thin dotted white lines indicate locations of interpreted transform faults described in text. Inset shows simplified reconstruction of tectonic structures relevant to this study in the Late Cretaceous (modified after Okay et al., 1994). Blue shaded areas represent either highly thinned continental crust or oceanic crust. Red inverted v symbols represent approximate region of island arc magmatism, and arrows indicate approximate relative plate motions. Subduction zone is indicated by line with triangles (where northern plate was upper plate). B: Seismic reflection profile oriented perpendicular to direction of basin opening in eastern Black Sea. Red dots indicate possible transform faults, which are shown with dotted lines in A.

[1]GSA Data Repository item 2009003, Figures DR1–DR8 (data examples, ray coverage, resolution and velocity-depth tradeoff tests, comparisons of 1-D velocity profiles, and melt calculations), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

cant along-strike variations in mantle temperature and volatile content (Martinez and Taylor, 2002; Kelley et al., 2006).

The relatively high velocities (6.8–7.2 km/s) in the thick magmatic crust in the eastern part of the basin indicate that this material is mafic (i.e., Mg rich) and was produced by enhanced melting due to a mantle thermal and/or compositional anomaly (Holbrook et al., 2001). Melting calculations using the code of Bown and White (1995) indicate that a ~150 °C difference in mantle temperature would be required to explain the observed along-strike changes in magmatism (Fig. DR8). Likewise, a change of at least ~0.15 wt% H_2O would be required to produce the observed variations in magmatic addition (Robinson et al., 2001). Heat flow measurements suggest that variations in temperature of this magnitude are not usually observed within individual active backarc basins (Currie and Hyndman, 2006). However, an increase in water content from ~0.10 to >0.20 wt% H_2O in the mantle is predicted to the east based on the decrease in the distance between the backarc and the arc in that direction (Fig. 1A, inset) (Okay et al., 1994; Kelley et al., 2006). Therefore, variations in mantle water content, possibly combined with an increase in mantle temperature, could produce sufficiently large but gradual changes in magmatic addition to the crust. However, other processes are required to explain the sharpness of the boundary between magma-poor and magma-rich rifting and initial spreading.

THREE-DIMENSIONAL MELT FOCUSING

The inability of lateral variations in mantle temperature and composition, alone, to account for our observations leads us to propose that another influence was melt focusing. This process is well known from mid-ocean ridges, where melts are generated over a relatively broad region in the mantle, but magmatic addition to the crust occurs primarily at the ridge axis due to melt migration along the base of the lithosphere (e.g., Magde and Sparks, 1997) and/or mantle flow patterns that result in pressure gradients, which influence melt migration (e.g., Spiegelman and McKenzie, 1987). Magmatism also varies along strike; three-dimensional (3-D) melt migration can result in segment centers that are more magmatic than segment edges (e.g., Magde and Sparks, 1997). These along-strike variations in magmatism are closely related to tectonic segmentation defined by transform faults and discontinuities (e.g., Macdonald et al., 1988). Variations in magma production between adjacent segments are often manifested by abrupt changes in bathymetry and/or crustal thickness across transform faults (e.g., Hooft and Detrick, 1995). Similarly, studies from the East Africa Rift, a modern extensional system, demonstrate that magmatic addition to the crust comprises discrete ~20 × 50 km intrusions, although this rift is underlain by a broad mantle thermal anomaly (Hayward and Ebinger, 1996; Keranen et al., 2004), and that variations in lithospheric thickness might guide lateral melt migration (Ebinger and Sleep, 1998).

We suggest that 3-D melt focusing, combined with more gradual along-strike changes in mantle properties, could produce the observed abrupt transition from magma-poor to magma-rich plate separation in the eastern Black Sea. As described earlier, a gradual eastward increase in melt productivity is anticipated due to the decrease in the distance between the backarc and the arc and consequent changes in mantle volatile content and temperature (Fig. 1). Sediment thickness and subsidence patterns indicate that the amount of extension also increases toward the east (Shillington et al., 2008) and suggests a corresponding eastward decrease in lithospheric thickness at the time of rifting. The migration of melts vertically to the top of the melting region and then laterally along the base of the extended continental lithosphere would focus melts toward the eastern part of the basin (Fig. 3A). With continued opening, regions of magmatic intrusions evolve into magmatic segments bound by transform faults in an incipient seafloor spreading system (Fig. 3B).

Studies of other rifts and passive margins with along-strike changes in magmatism are consistent with our conceptual model, although published data sets cannot constrain the nature of the transition. Magnetic data from offshore eastern Canada hint that the transition between magma-poor and magma-rich rifting could be as narrow as ~20 km along strike (Keen and Potter, 1995) and therefore similar to that observed in the Black Sea. Likewise, studies of the Gulf of California and northwestern Australia reveal that synrift and early postrift magmatism varies between segments (Hopper et al., 1992; Lizarralde et al., 2007), but the abruptness of the changes near segment boundaries is not known. Geophysical transects offshore Greenland indicate contemporaneous magma-poor and magma-rich rifting on the southwest and southeast margins, respectively, separated by 100–200 km (Nielsen et al., 2002). Nielsen et al. (2002) interpreted these

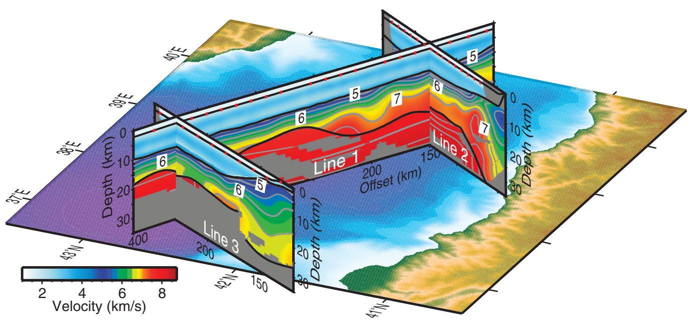

Figure 2. Fence diagram showing velocity models from lines 1, 2, and 3 (see Fig. 1A for locations). Color scale represents variations in compressional wave velocity. Velocities >4 km/s are also contoured every 0.5 km/s. Bold lines mark top and base of the crust. Bathymetry is taken from the GEBCO Digital Atlas (IOC, IHO, and BODC, 2003). Note eastward increase in crustal thickness and increase in lower crustal velocity that occurs at model km 230 on line 1.

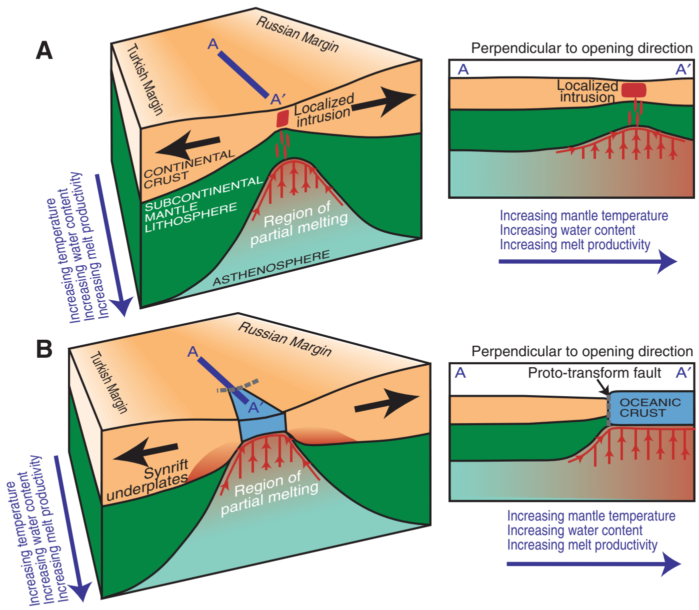

Figure 3. Conceptual model for creation of abrupt transition from magma-poor thinned continental crust to thick, magmatically robust oceanic crust by focused melt migration. A: In first stage of this model, lateral variations in mantle temperature and/or composition create a gradual along-margin change in magma production. However, along-strike variations in lithospheric thickness, resulting from eastward increase in amount of extension, focus melt migration such that magmatic addition to the crust is localized in eastern part of basin. B: Continued extension and magmatism allow regions of focused magmatic addition to evolve into magmatic segments in an incipient seafloor spreading system.

results to indicate that the flow of plume material from the North Atlantic Igneous Province was controlled by variations in lithospheric thickness.

More geological and geophysical studies extending along strike from magma-poor to magma-rich margins are required to better understand the nature of the transition and what factors are most important in controlling its development and evolution through time. Understanding along-strike variations in magmatism at rifts is essential since they provide unique constraints on 3-D processes in Earth's mantle and crust. Our conceptual model predicts abrupt changes in igneous crustal thickness across transform faults between magma-rich and magma-poor rifting at other margins if other effects, such as voluminous hotspot magmatism, do not overwhelm melt focusing mechanisms (Hooft et al., 2006).

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