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Petrogenesis and structure of oceanic crust in the Lau back-arc basin

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ABSTRACT

Oceanic crust formed along spreading centers in the Lau back-arc basin exhibits a dramatic change in structure and composition with proximity to the nearby Tofua Arc. Results from recent seismic studies in the basin indicate that crust formed near the Tofua Arc is abnormally thick (8–9 km) and compositionally stratified, with a thick low-velocity (3.4–4.5 km/s) upper crust and an abnormally high-velocity (7.2–7.4+ km/s) lower crust (Arai and Dunn, 2014). Lava samples from this area show arc-like compositional enrichments and tend to be more vesicular and differentiated than typical mid-ocean ridge basalts, with an average MgO of ∼3.8 wt.%. We propose that slab-derived water entrained in the near-arc ridge system not only enhances mantle melting, as commonly proposed to explain high crustal production in back-arc environments, but also affects magmatic differentiation and crustal accretion processes. We present a petrologic model of Lau back-arc crustal formation that successfully predicts the unusual crustal stratification imaged in the near-arc regions of the Lau basin, as well as the highly fractionated basaltic andesites and andesites that erupt there. Results from phase equilibria modeling using MELTS indicate that the high water contents found in near-arc parental melts can lead to crystallization of an unusually mafic, high velocity cumulate layer. Best-fit model runs contain initial water contents of ∼0.5–1.0 wt.% H_2O in the parental melts, and successfully reproduce geochemical trends of the erupted lavas while crystallizing a cumulate assemblage with calculated seismic velocities consistent with those observed in the near-arc lower crust. Modeled residual melts are also lower density than their dry equivalents, which aids in melt segregation from the cumulate layer. Low-density, water-rich residual melts can lead to the eruption of vesicular lavas that are unusually evolved for an oceanic spreading center.

1. Introduction

Back-arc basins are productive centers of crustal formation that generate extensive regions of oceanic crust through rifting and organized spreading. Because their mantle melting regions are influenced by mantle flow, thermal structure, and chemistry above a subducting lithospheric slab, back-arc spreading centers host a diversity of crustal structure, composition, and processes not typically found at mid-ocean ridges. Several petrological and geophysical studies along back-arc spreading centers have shown changes in melt production and lava chemistry that correlate with proximity to the active arc (e.g., Stolper and Newman, 1994; Martinez and Taylor, 2002; Langmuir et al., 2006). Current models and observations suggest that back-arc spreading centers located close to an active arc entrain water (and other related components) released from the dehydrating, subducting slab, which enhances mantle melting beneath the spreading centers (e.g., Kelley et al., 2006). This leads to a higher melt flux to the ridge and erupted lavas that are more arc-like in composition than typical mid-ocean ridge basalts (MORB).

While increases in melt production and crustal thickness in back-arc settings are often ascribed to high water contents, recent evidence in the Lau back-arc basin points to associated differences in crustal structure as well. The L-SCAN active source seismic tomography experiment along the Eastern Lau Spreading Center identified large regions of an anomalously thick crust with an unusual vertical stratification formed at back-arc spreading centers located close to the active Tofua arc (Dunn and Martinez, 2011; Arai and Dunn, 2014). This near-arc crust has a thick upper layer of unusually low seismic velocities and a lower layer of very high seismic velocities (7.2–7.4+ km/s) just above the base of the crust. The lavas that form the volcanic layer of this crust are both more vesicular (e.g., Pearce et al., 1994) and more differentiated than is typical of mid-ocean ridge basalts (e.g., Pearce et al., 1994; Escrig et al., 2009), with an average of ∼3.8 wt.% MgO, and carry trace element and isotope signatures derived from

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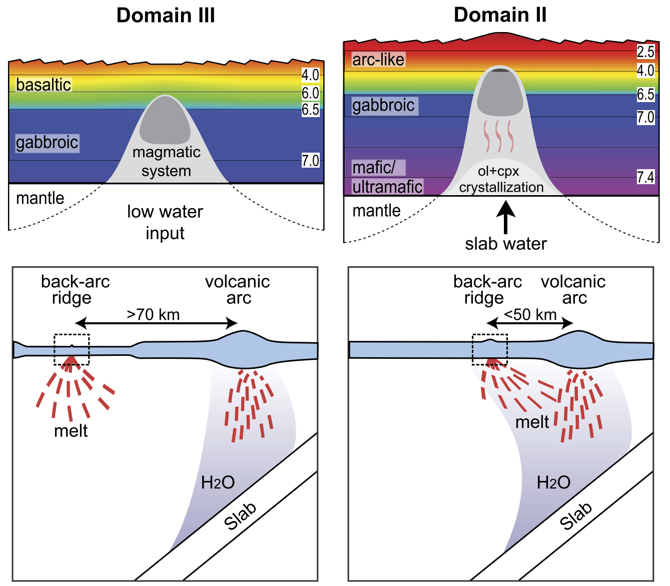

Fig. 1. A schematic cartoon illustrating hypothesized crustal formation processes at arc-distal (Domain III) and arc-proximal (Domain II) regions of the ELSC. Figure modified from Arai and Dunn (2014). In this model, slab-derived water is entrained in the ridge melting zone near the active arc (right column), leading to an increase in melt supply to the ridge and producing a thicker crust. As these melts cool and evolve in the crustal magmatic system (gray fields, upper right), their moderately high magmatic water contents lead to suppression of plagioclase crystallization relative to olivine and clinopyroxene, leading to more mafic cumulate phases during the early stages of crystal fractionation. The buoyant, water-rich residual melts segregate and rise into the upper crust where they form an axial melt lens (dark gray) and continue to crystallize, eventually forming a thick, unusually evolved volcanic layer. Where the spreading center is further than ~70 km from the active arc (left column), the water content of melts is low and water-induced differentiation is minimal.

the nearby subducting slab (e.g., Escrig et al., 2009; Bézos et al., 2009). In contrast, spreading centers located farther from the arc form crust with a more normal geophysical structure for their spreading rate, and primarily erupt basalts. The transition between these two types of crust occurs over just a few kilometers, and closely correlates with major changes in bathymetric depth and morphology, Bouguer gravity, and the depth to the top of the sub-ridge magmatic system (e.g., Dunn and Martinez, 2011; Dunn et al., 2013).

The process that generates this unusual crustal stratification is currently unknown. Similar high velocity lower crusts have been reported in other back-arc regions, including the Yamato Basin in the Japan Sea (Sato et al., 2014; Hirahara et al., 2015), the Izu–Bonin–Mariana Arc (Kodaira et al., 2007; Takahashi et al., 2008, 2009), and the Aleutian arc (e.g., Shillington et al., 2004; Behn and Kelemen, 2006), as well as rifted continental margins (Korenaga et al., 2000). Sato et al. (2014) propose that the anomalous back-arc crust in the Japan Sea is the result of higher mantle potential temperature (e.g., Kelemen and Holbrook, 1995; Korenaga et al., 2002). However, this is likely not the underlying mechanism in the Lau basin, where mantle potential temperature is thought to be hottest in the northern areas of the basin, decreasing to the south where the anomalous crust is actually observed (Kelley et al., 2006; Wiens et al., 2006; Wei et al., 2015).

Instead to explain the stratified, anomalous crust, Arai and Dunn (2014) proposed that entrainment of slab-derived water in mantle melts alters crystallizing phase proportions by suppressing plagioclase relative to olivine and clinopyroxene, leading to crystallization of a dense layer of mafic-to-ultramafic cumulates at the bottom of the crust and a thick, more silica-rich upper crust (Fig. 1). While this process was not modeled in their paper, water has long been understood to play a major role in the generation, evolution and eruption of magma in subduction zone settings. Slab-derived water lowers the mantle solidus (e.g., Kushiro et al., 1968), driving melt production in the overriding mantle wedge (e.g., Davies and Bickle, 1991; Stolper and Newman, 1994). Water also suppresses mineral liquidus temperatures (e.g., Nicholls and Ringwood, 1973), leading to changes in magma crystallization sequences (e.g., Grove and Baker, 1984; Sisson and Grove, 1993), and is associated with production of silica-rich lavas (e.g., Gaetani et al., 1994). While much attention has been given to water's effects on mantle melting and eruption processes, some of its effects on crustal differentiation and formation are difficult to constrain due to the complicated magmatic processes typical of arc systems (e.g., crustal assimilation and contamination). Back-arc spreading centers are simpler settings to study the effects of water enrichment on the crustal magmatic system, as they entrain water-rich material from the subducted slab while lacking some of the additional complications found at arcs; crustal assimilation, for example, is likely less than at arcs with their thick sequences of heterogeneous crust.

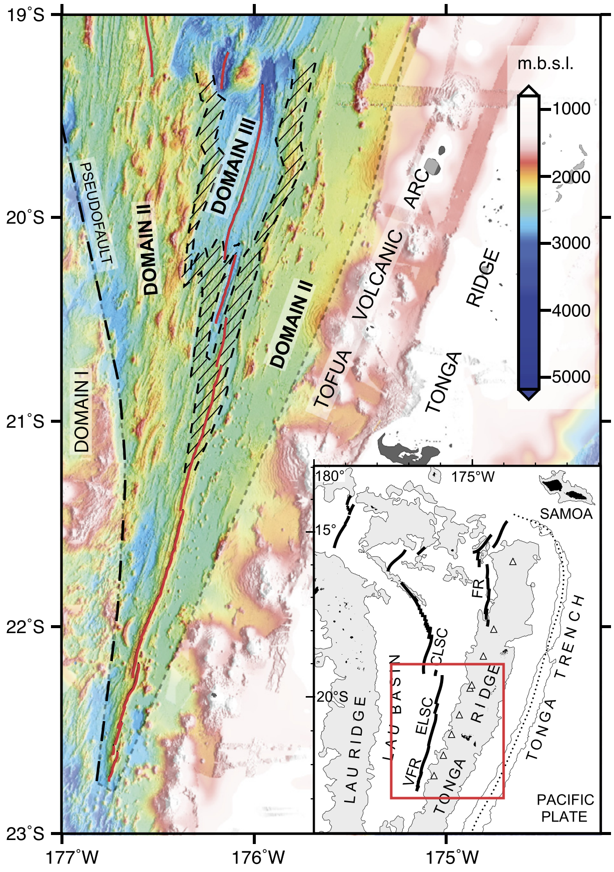

Fig. 2. Shaded relief map of seafloor topography in the southern Lau Basin. ELSC (Eastern Lau Spreading Center) and VFR (Valu Fa Ridge) axes are shown in red. Crustal domains (Martinez and Taylor, 2002; Dunn and Martinez, 2011) are outlined by dashed black lines, separated by a narrow transitional zone (striped). As illustrated in Fig. 1, Domain II is the region of anomalous oceanic crust formed near the active arc; Domain III is the region of crust formed further from the arc. (Inset) Regional map of the Lau basin and surrounding areas. Grey shading indicates areas where the seafloor is shallower than 2000 m below sea level. Open triangles indicate locations of active volcanoes of the Tofua arc. The dotted line denotes the axis of the Tonga trench, which is surrounded by the 7000-m contour. Black lines show the current configuration of spreading centers in the Lau basin: VFR; ELSC; CLSC (Central Lau Spreading Center); FR (Fonualei rift). The red box indicates area of main panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this study, we apply thermodynamic models of phase equilibria to the extensive geochemical datasets available along Lau back-arc spreading centers to test the crustal formation hypothesis