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Crustal construction and magma chamber properties along the Eastern Lau Spreading Center

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ABSTRACT

The L-SCAN active-source seismic tomography experiment maps the crustal structure and magmatic system along a 120-km-long section of the back-arc Eastern Lau Spreading Center (ELSC), where the ridge undergoes abrupt changes in morphology and composition associated with increasing proximity to the Tofua volcanic arc. Using this dataset, we picked ~197,000 P-wave travel times from 57 seismic airgun lines recorded at 83 ocean bottom seismograph stations, and inverted for a 3-D P-wave velocity image. The seismic images reveal a prominent, but narrow, seismic low velocity volume (LVV) located beneath all surveyed ridge segments, consistent with the high temperatures and melt of a crustal magmatic system. Crustal magmatic systems thus underlie spreading axes even where previous seismic reflection surveys did not detect magma lens reflectors, accounting for the heat source of high-temperature hydrothermal vents in these areas. The top of the LVV closely follows the ridge axis and steps across three overlapping spreading centers. As the offset of the overlap increases, the LVV becomes increasingly discontinuous across the ridge limbs. Surprisingly, the LVV is as much as twice as wide, but deeper, in the northern part of the ridge system where the crust is thinner, as compared to the LVV beneath the southern segments, where the crust is relatively thicker. The width of the LVV may be modulated by the degree of deep hydrothermal activity or temporal variations in melt supply, and thus may not correlate directly with the average melt flux as indicated by crustal thickness. Over the past 4 Myr, the location of the ridge has swept across different mantle compositional domains, and the crust produced at the ridge formed a zoned pattern. The interpretation is that thick, highly porous, volcanic layers with felsic compositions cap regions of thick crust; thinner volcanic layers of basaltic composition cap regions of thinner crust. The zonal pattern indicates that the influence of slab-derived water on crustal construction has substantially decreased over time.

1. Introduction

Along intermediate- to fast-spreading mid-ocean ridges, seismic refraction and tomography studies reveal a narrow zone of low velocities beneath the neovolcanic zone, indicating high temperatures and some melt, that extends from ~2 km depth downward into the mantle; seismic reflection studies show that this region of partial melt is often capped by a thin melt lens of high melt fraction (see reviews by Sinton and Detrick (1992) and Dunn and Forsyth (2007)). Typically, as spreading rate decreases, the rate at which melt is supplied to the ridge decreases and crustal magmatic systems deepen and become highly variable in depth, size, and melt content along the length of the ridge; likewise, the melt lens deepens and eventually disappears. The disappearance of a melt lens reflection has often been interpreted as a wholesale absence of melt in the crust beneath the ridge, with important implications for the thermal structure, rheology, and tectonics of the ridge system (e.g., Phipps Morgan and Chen, 1993). At intermediate- to fast-spreading mid-ocean ridges the axial morphology of the ridge and its cross-sectional area have been interpreted as sensitive indicators of the underlying magmatic system (e.g., Macdonald and Fox, 1988; Scheirer and Macdonald, 1993).

Back arc spreading centers are distinct from mid-ocean ridge spreading centers. While spreading rate largely governs mid-ocean ridge systems, back arc spreading centers – because of subduction zone proximity – are strongly influenced by a variable mantle temperature and chemical environment. In the simplest view, back arc spreading follows a sequential development. Spreading initiates near the arc volcanic front (Taylor and Karner, 1983) where crustal production at the spreading center is strongly influenced by subduction,

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especially the presence of slab-derived water. As the basin opens by spreading, the ridge axes separate from the volcanic front, the subduction influence wanes, and crustal production becomes more mid-ocean ridge-like (Hawkins and Melchior, 1985; Pearce et al., 1995). This evolution of the mantle chemical environment has multiple effects on crustal accretion. For example, the presence of water is expected to enhance mantle melt production (e.g., Davies and Bickle, 1991; Stolper and Newman, 1994), ridge crustal melt (and associated heat) supply, crustal thickness, and the degree of spreading that occurs via magmatic emplacement versus tectonic stretching. A further effect of water, which preferentially ends up in the melt (e.g., Hirth and Kohlstedt, 1996), is increased chemical differentiation leading to more silicic lavas (e.g., Nicholls and Ringwood, 1973; Gaetani et al., 1994; Sisson and Grove, 1993) with greater volatile content and vesicularity.

More recently, extensive geophysical (e.g., Goodliffe et al., 1997; Bruguier and Livermore, 2001; Taylor and Martinez, 2003; Dunn and Martinez, 2011) and geochemical mapping studies (e.g., Pearce et al., 2005; Langmuir et al., 2006; Bézos et al., 2009; Escrig et al., 2009) have made significant progress toward piecing together the tectonic history and geochemical evolution of spreading centers in a variety of back-arc environments. Yet the three-dimensional nature of back-arc basin crust and the nature of active magmatic systems beneath these spreading centers remain relatively poorly studied and understood. As a step toward filling this gap in knowledge, we carried out a large active-source seismic tomography experiment along the Eastern Lau Spreading Center, the largest and densest three-dimensional study of its kind. Our first report (Dunn and Martinez, 2011) described large systematic changes in seismic velocity of the crustal volcanic layer (seismic layer 2), and their implication for the structure of the mantle wedge, its volatile content, and how hydrous mantle is advected into back-arc spreading centers. Here we expand on that study by presenting a complete set of seismic images for the upper crust and extending the seismic imaging to greater depth to include the active magmatic system. Our results provide new insight into the thermal and magmatic structure of the ridge segments, in addition to the compositional and structural changes in the crust that were inherited from changes in mantle source chemistry as spreading moved away from the arc.

2. Study area

The Eastern Lau Spreading Center (ELSC) is located within the Lau back arc basin (Fig. 1a), a triangular-shaped extensional zone bordered by the Lau Ridge remnant arc to the west and the currently active Tofua arc to the east (Karig, 1970; Hawkins, 1995). The basin opening is thought to be a consequence of trench roll back that began by 6 Ma (Hawkins, 1994). The ELSC formed later, at approximately 4 Ma, and propagated southward into existing back arc crust (labeled Domain I in Fig. 1a) with its tip near the arc volcanic front (Parson et al., 1990; Taylor et al., 1996). As spreading continued, the arc volcanic front migrated eastward away from the spreading center. Gravity, bathymetry, and seismic data (Martinez and Taylor, 2002; Dunn and Martinez, 2011; Arai and Dunn, 2012) indicate that the earliest crust formed along the ELSC, labeled Domain II-type crust in Fig. 1a, is relatively thick with a thick low-velocity/high-porosity upper crustal layer. The few rock samples from this area have variable compositions from basaltic to arc-like (Hawkins and Melchior, 1985; Hawkins, 1995; Langmuir et al., 2006). The velocity structure (Fig. 2) is similar to that found along the Valu Fa Ridge

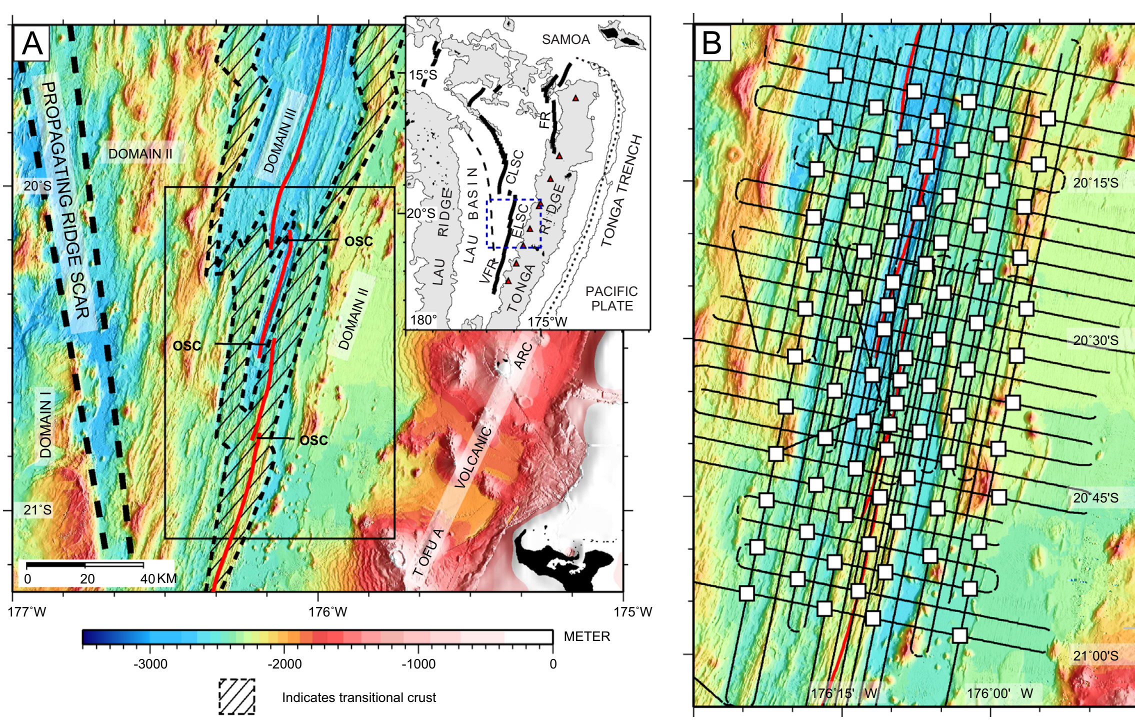

Fig. 1. The seismic experiment was located along the Eastern Lau Spreading Center (ELSC) in the Lau back-arc basin. Panel (a) shows the location of the seismic experiment relative to the Lau basin (inset) and seafloor bathymetry. Red lines show the axis of the ELSC. A black box indicates the area shown in panel (b). The ELSC propagated into pre-existing crust (labeled Domain I) and subsequently formed two types of seafloor morphologies (labeled Domains II and III), separated by a variable transitional region that is indicated by a hatched region bounded by dashed lines (Dunn and Martinez, 2011). Domain II has complex volcanic landforms and an average depth of roughly 2100 m. Domain III has an average depth of 2600 m with a flat seafloor and linear abyssal hill fabric. Note that near the active Tofua volcanic arc, volcaniclastic sediments largely cover the Domain II terrains. The dashed lines indicate the boundaries of the domains and are drawn on the basis of seafloor morphology, Bouguer gravity, and seismic structure (Dunn and Martinez, 2011). A previous seismic reflection survey of the ridge axis (Jacobs et al., 2007) discovered a shallow melt lens reflector beneath the southern two ridge segments in the tomography survey area, but not beneath the northern two segments in the survey area. In panel (b), the open squares indicate the positions of 83 ocean bottom seismograph stations that recorded P-wave arrivals from nearly 9000 airgun shots located along the black lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)