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Effects of plate boundary geometry and kinematics on mantle melting beneath the back-arc spreading centers along the Lau Basin

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ABSTRACT

The back-arc spreading centers that extend along the Lau Basin exhibit trends in axial morphology, crustal thickness, and geochemistry, which are opposite those typically observed at mid ocean spreading centers. We develop 2D numerical models of mantle flow, thermal structure and melting of the Lau back-arc–Tonga subduction system for each of three Lau spreading centers—Valu Fa Ridge, the Eastern Lau, and the Central Lau. Our goal is to determine whether along-strike variability in the circulation pattern or hydration within the mantle wedge could explain the trends observed. We use present-day plate and subducted slab geometries and velocities to explore a range of mantle potential temperature and water content scenarios and test whether predictions match observations of crustal thickness and water content of the magmas erupted at the spreading ridges.

Within the range of mantle parameters tested, we find that a potential temperature of 1300 °C and source water contents greater than 0.22% wt are required to match observed crustal thickness and lava water contents at Valu Fa. Substantially less water in the sub arc mantle source is required to match the Eastern Lau and Central Lau observations at the same or higher mantle potential temperatures. A small background hydration of 0.01% wt water in the mantle wedge is required to match the observations of water in the Central Lau magmas. We predict that the arc and back-arc melting regions are interconnected for all potential temperatures and sub arc water contents at the Eastern Lau spreading center and at the Valu Fa Ridge, while at the Central Lau, they are only connected for cases when mantle potential temperature is 1400 °C or greater. We hypothesize that the longer-lived Eastern Lau and Central Lau rifting and axial volcanism may have dehydrated the mantle wedge and slowed melt production beneath these spreading centers. The Valu Fa Ridge, which is actively propagating into a more hydrated wedge associated with the Tofua arc, experiences enhanced melting relative to the other two spreading centers.

For the Valu Fa case, we show fast subduction in combination with the proximity of the trench and spreading center results in enhanced upwelling and, therefore, increased crustal production. Slower subduction, with a convergence rate of 45 mm/yr, a dry mantle, and a 1350 °C mantle potential temperature reduces the difference in crustal thickness between the Central Lau and Valu Fa to within 1.2 km. In contrast, for present-day kinematics with a dry mantle and 1350 °C mantle potential temperature, our models predict the crustal thickness at Valu Fa to be 3.1 km thicker than Central Lau, much closer to the observed values.

1. Introduction

The Lau back-arc spreading centers challenge fundamental hypotheses for oceanic rifting and lithospheric accretion by showing trends in ridge morphology, chemistry, crustal structure with spreading rate that are opposite to what is observed globally at mid ocean ridges. The standard paradigm (Forsyth, 1992) suggests that fast spreading results in a greater volume of hot mantle upwelling beneath the ridge and, thus, deeper and higher extents of decompression melting (Klein and Langmuir, 1987). Faster spreading ridges generate a greater volume of crust, and have dynamically supported, anomalously shallow axial rise topography (Forsyth, 1992). On the other hand, slower spreading ridges induce less upwelling, are generally colder, supporting lower extents of partial melting (Klein and Langmuir, 1987), and have median valley axial morphology dominated by rifting (Macdonald, 1982). Intermediate spreading centers range between the two end members exhibiting a variety of behaviors; however, the fundamental control on magmatism is determined by the mantle upwelling rate. In contrast, the Lau back-arc spreading centers exhibit evidence for high degrees of melting. An axial rise, similar to a fast spreading ridge, occurs in the southern part of the basin at what would be considered a slow to slow intermediate

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spreading ridge (40–60 mm/yr). Lower degrees of melting for the intermediate spreading rates (between 60 and 90 mm/yr) are indicated for basalt samples in the northern spreading centers in the Lau Basin (Kelley et al., 2006, Macdonald et al., 1991, Martinez and Taylor, 2002, Taylor and Martinez, 2003, Langmuir et al., 2006). Thus, the essential question is whether rifting and magmatic processes at the Lau spreading centers are intrinsically different from global mid ocean ridge systematics because of interaction with the Tonga subduction zone.

The Lau spreading system is unique because in less than 600 km there are significant along-strike variations in the geometry and kinematics of the subduction-arc–back-arc system (Fig. 1a). The Lau system consists of the Valu Fa Ridge in the south nearest the trench, through the Eastern Lau and Central Lau spreading centers to the north, which are increasingly farther from the trench. There is also increasing separation between the spreading axes and the volcanic arc from south to north (Martinez and Taylor, 2002). This has been attributed to southward propagation of the back-arc rifting at a rate of 120 mm/yr (Parsons and Hawkins, 1994) into weakened crust behind the Tofua arc over the past 4 Ma since initiation of rifting in the Northern Lau basin at ~6 Ma (Hawkins, 1995). Correlated with the decreasing separation between trench and spreading center is a decrease in full spreading rate from ~80–90 mm/yr in the Central Lau and northern Eastern Lau to 40–60 mm/yr at Valu Fa (Martinez and Taylor, 2002). Plate convergence rate at the Tonga trench increases northward, with subduction of ~120 mm/yr in the south near Valu Fa, compared to ~190 mm/yr in the north near the Central Lau (Bird, 2003). Although there is a change in the velocity of subduction, there does not appear to be any appreciable change in dip of the slab and the strike of the ridge and trench are at low angles to each other (Syracuse and Abers, 2006).

While spreading at the slowest rate, the Valu Fa appears to be the most magmatically robust of the three spreading centers under consideration here and it is closest to the arc, coming to within 40 km. This ridge has the shallowest depths in the region with axial depths of 1600–2000 m and a narrow, linear ridge axial morphology suggesting enhanced volcanism relative to rifting (Martinez et al., 2006). Seismic refraction results indicate the crust in the axial zone is 7–8 km thick in the Valu Fa region, with a prevalent low velocity zone beginning at ~3 km depth (Turner et al., 1999), which is consistent with multi-channel seismic (MCS) estimates of an axial magma chamber (AMC) at 2.8 km depth beneath the axis (Jacobs et al., 2007). Layer 2a and 2b (interpreted as the extrusive and sheeted dike layers, respectively) have slower than expected compressional velocities and are thickest

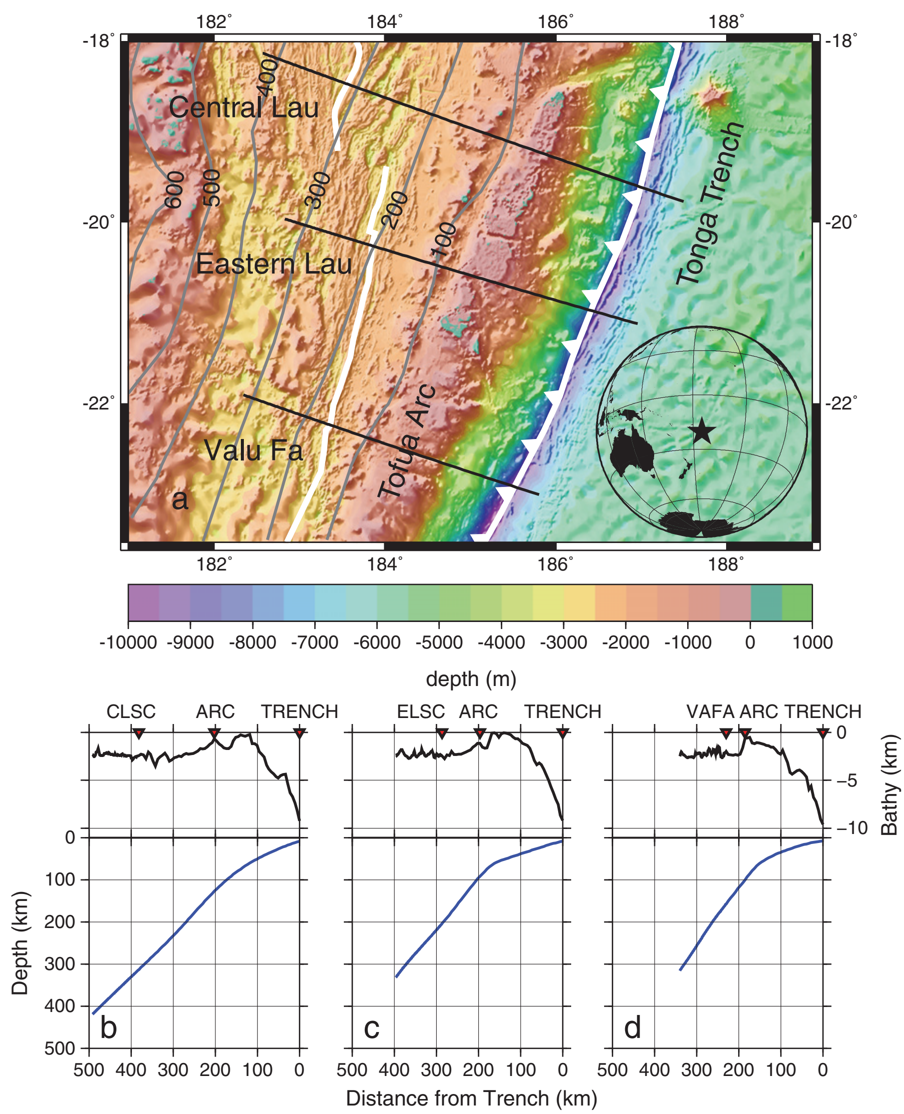

Fig. 1. (a) Map of Lau Basin Tonga Trench regional bathymetry, major tectonic features are labeled. White lines show plate boundaries, grey lines show contours of depth of the subducting slab (in km) from Syracuse and Abers (2006). Inset map shows location of the region on the globe. Transects for the three cases examined in this study are shown in black lines with the cross section of bathymetry and depth to slab for Central Lau (CLSC) shown in panel (b), Eastern Lau (ELSC) shown in panel (c) and Valu Fa (VAFA) shown in (d).