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# Melt-rock interaction near the Moho: Evidence from crystal cargo in lavas from near-ridge seamounts

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**Abstract**

The Taney Seamounts are a NW-SE trending linear, near mid-ocean ridge chain consisting of five volcanoes located on the Pacific plate 300 km west of San Francisco, California. Taney Seamount-A, the largest and oldest in the chain, is defined by four well-exposed calderas, which expose previously infilled lavas. The calderas can be differentiated in time by their cross-cutting relationships, creating a relative chronology. The caldera walls and intracaldera pillow mounds were sampled systematically by a remotely operated vehicle (ROV) to obtain stratigraphically-controlled samples, a unique aspect of this study.

The geochemistry of the seamount varies from more differentiated to more primitive with time (6.2–8.6 wt.% MgO), suggesting that the sub-caldera reservoir is open and undergoes periodic collapse, replenishment, crystallization, and eruption. The youngest and least differentiated lavas entrained a crystal cargo of plagioclase ($An_{80-90}$) with melt inclusion volatile saturation pressures indicating entrapment in the lower oceanic crust and upper mantle (6–12 km, with 45% between 8 and 10 km below the sea floor). Melt inclusions exhibit high $Al_2O_3$, low $SiO_2$, positive Sr and Eu anomalies and negative Zr and Nb anomalies when normalized to typical Pacific mid-ocean ridge basalt (MORB). In comparison, the host lavas exhibit positive Sr anomalies, but no concurrent Zr, and Nb anomalies. Based on thermodynamic modeling using alphaMELTS, we develop a melt-rock interaction model defined by melting and assimilation of plagioclase-rich cumulates by hot, primitive mantle-derived melts. Significantly, the variability of the negative Zr and Nb anomalies cannot be explained by either cumulate melting or AFC alone. We propose that the melt inclusions record the interaction between cumulate partial melts and the assimilating melt, demonstrating the importance of cumulate melting during the assimilation process. Later percolating melts underwent diffusive interaction with, and entrained, recrystallized plagioclase cumulates resulting in the positive Sr signal without the concurrent Eu, Zr, or Nb anomalies observed in the host lavas. These results demonstrate that melt-rock interaction at the lower crust or upper mantle is an important process at Taney Seamount-A, and potentially other magmatic systems associated with seamount chains and ridge axes.
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*Keywords:* Near-ridge; Seamount; Melt-rock interaction; High $CO_2$; Melt inclusion; Moho; MORB; Assimilation-fractional crystallization; AFC; Plagioclase ultraphyric basalt; Cumulate melting

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## 1. INTRODUCTION

The mid-ocean ridge system is the longest continuous chain of volcanoes, responsible for more than two-thirds of Earth's annual volcanic output (Crisp, 1984). Mid-ocean ridge basalt (MORB) is generated by decompression melting of the upwelling mantle beneath the ridge axis followed by transport through the crust. Petrologic studies indicate that MORB is too low in MgO to represent primary melts in equilibrium with its mantle source. This has been attributed primarily to fractional crystallization in shallow magma reservoirs. Hence measured compositions are back-calculated in order to reconstruct mantle melt compositions (Klein and Langmuir, 1987; Langmuir et al., 1992; Niu and O'Hara, 2008; Gale et al., 2014). These models assume that interaction with the oceanic crust is minimal during magma transport, and that shallow fractional crystallization exerts the dominant control on magma composition after segregation from the mantle. However, studies of oceanic plutonic rocks suggest that interaction between mantle-derived melt and cumulates in the lower oceanic crust and upper mantle could be as important as fractional crystallization in MORB petrogenesis (Bedard et al., 2000). A number of melt-rock interaction scenarios in the oceanic crust have been proposed based on studies of oceanic glasses and plutonic rocks, phenocryst melt inclusions, and xenoliths (Danyushevsky et al., 2004; Gurenko and Sobolev, 2006; Ridley et al., 2006; Kvassnes and Grove, 2008; Laubier et al., 2012; Lissenberg et al., 2013; Sanfilippo et al., 2015).

Episodic sill formation by melt ponding and crystallization at the Moho has been suggested as a method of lower oceanic crustal accretion (Kelemen et al., 1997). Evidence for melt ponding near the Moho includes seismic studies of mid-ocean ridges which have detected a significant fraction of melt (2.5–17%) in the lower oceanic crust (Crawford and Webb, 2002; Singh et al., 2006; Canales et al., 2009, 2012; Marjanovic et al., 2014; Zha et al., 2014). Compliance modeling of seismic data at a fast spreading ridge suggests that melt in the lower oceanic crust resides in interconnected melt-filled sills or cracks (Zha et al., 2014). In addition, melt inclusion volatile saturation studies at ridge settings indicate that a fraction of magmatic crystallization occurs in the lower oceanic crust (Shaw et al., 2010; Wanless and Shaw, 2012; Wanless et al., 2014). Since basaltic melt is buoyant with respect to the oceanic crust, physical barriers such as impermeability zones (Korenaga and Kelemen, 1997) or regions of deformation (Natland and Dick, 2001) are required to impede vertical flow. Another scenario invokes a melt charged with olivine phenocrysts (~30%), resulting in a density similar to that of the lower oceanic crust and promoting lateral intrusion and further crystallization (Natland and Dick, 2009).

Previously formed cumulates in the lower oceanic crust with a residual melt fraction (e.g., <17%) inhibit the propagation of tensional cracks through the mushy lower oceanic crust (Bedard and Hebert, 1996). Mushy cumulates are less dense and have higher melt porosity than the underlying peridotite. They are thus easier to intrude, making them subject to infiltration by subsequent magma injections (Natland and Dick, 2009). This process is commonly described for layered intrusions such as the Rum complex (Leuthold et al., 2014), and provides a mechanism to explain the relationship between lower oceanic crust accretion and melt-rock interactions.

Near-ridge seamounts are the predominant manifestation of off-axis magmatism. They are produced by basaltic melt that bypasses the axial reservoir through a separate magmatic plumbing system. For this reason, they have been studied as a "geochemical" window into the MORB mantle (Fornari et al., 1988; Davis and Clague, 2000; Niu et al., 2002; Brandl et al., 2012). A recent geochemical study of the magmatic architecture beneath the Taney near-ridge seamounts, 300 km west-southwest of San Francisco (Fig. 1), demonstrates that crustal modification at various levels is an important process in oceanic environments (Coumans et al., 2015). Erupted lavas exhibit a geochemical signal determined from glass analysis defined by high $Al_2O_3$ and low $SiO_2$. The youngest and least evolved lavas on the seamount, which form pillow cones in the southeastern caldera, have positive strontium anomalies and entrain a crystal cargo of high-anorthite plagioclase that is not in equilibrium with the host glass. The plagioclase crystal cores exhibit complex textures suggesting melt-rock interaction. Using these observations, this paper examines the nature of melt-rock interactions in the deep crustal environment beneath Taney Seamount-A.

The approach of this manuscript is twofold. (1) Analysis of melt inclusion volatile elements, specifically $CO_2$ and $H_2O$, enables us to infer the environment and depth of melt ponding and crystallization of plagioclase in the lowermost crust or upper mantle. (2) Analysis of melt inclusion major and trace elements in plagioclase provides petrologic information associated with melt-rock interaction in the lower oceanic crust or upper mantle.

## 2. STUDY AREA

Near-ridge seamounts form adjacent to fast- to intermediate-spreading ridges in a narrow zone between 5 and 30 km and are often distributed asymmetrically with respect to the axis of the spreading center (Scheirer and Macdonald, 1995). The region of near-ridge seamount formation is located in an area with extensive ridge parallel faulting. These faults probably facilitate melt transport to shallow magma reservoirs that bypass the axial magmatic system. The orientation of seamount chains in the northeast Pacific Ocean is not aligned with relative or absolute plate motion. Instead, they appear to parallel calculated subaxial asthenospheric flow, suggesting that near-ridge seamount chains form from plate motion over a melting anomaly rooted in the upwelling mantle (Clague et al., 2000).

Near-ridge seamounts resemble truncated cones with steep flanks (~25°) modified by complex caldera structures that are commonly offset towards the axis (e.g., Fig. 1b). The observation that offset calderas are breached towards the ridge axis indicates that the volcanoes migrate away from their magma source due to plate motion (Hammond, 1997). The flat-topped nature of these volcanoes has been attributed to the infilling and overflowing

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