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A melt-focusing zone in the lithospheric mantle preserved in the Santa Elena Ophiolite, Costa Rica

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ABSTRACT

The Santa Elena Ophiolite in Costa Rica is composed of a well-preserved fragment of the lithospheric mantle that formed along a paleo-spreading center. Within its exposed architecture, this ophiolite records a deep section of the melt transport system of a slow/ultra-slow spreading environment, featuring a well-developed melt-focusing system of coalescent diabase dikes that intrude the peridotite in a sub-vertical and sub-parallel arrangement. Here we present an integrated analysis of new structural data, $^{40}Ar/^{39}Ar$ geochronology, major and trace element geochemistry and radiogenic isotope data from the diabase dikes in order to elucidate the tectonic setting of the Santa Elena Ophiolite. The dikes are basaltic and tholeiitic in composition. Petrological models of fractional crystallization suggest deep pressures of crystallization of >0.4 GPa for most of the samples, which is in good agreement with similar calculations from slow/ultra-slow spreading ridges and require a relatively hydrated (~0.5 wt.% H_2O) MORB-like source composition. The diabase dikes share geochemical and isotope signatures with both slow/ultra-slow spreading ridges and back-arc basins and indicate mixing of a DMM source and an enriched mantle end-member like EMII. The $^{40}Ar/^{39}Ar$ geochronology yielded an age of ~131 Ma for a previous pegmatitic gabbroic magmatic event that intruded the peridotite when it was hot and plastic and an age of ~121 Ma for the diabase intrusions, constraining the cooling from near asthenospheric conditions to lithospheric mantle conditions to ~10 Ma. Our findings suggest a complex interplay between oceanic basin and back-arc extension environments during the Santa Elena Ophiolite formation. We propose an alternative hypothesis for the origin of Santa Elena as an obducted fragment of an oceanic core complex (OCC).

1. Introduction

To understand the evolution of our planet, it is fundamental to constrain melt generation and transport processes that occur in the mantle. In an extensional environment, when the upper mantle crosses its solidus through decompression, melting initiates as an inter-granular network of melt (Dasgupta and Hirschmann, 2006; Faul, 2001; Karato and Jung, 1998; Kelemen et al., 2000). Then, physical and chemical changes during reactive melt transport allow segregation of the partial melts increasing the porosity of the upper mantle host (Kelemen et al., 1997; Kelemen et al., 2000; Spiegelman et al., 2001). At extensional environments like mid-ocean ridges (Fig. 1), basaltic melts separate from the peridotite residue and react with the lithospheric mantle as they rise buoyantly through this network of melt (Bouilhol et al., 2011; Kelemen et al., 2000). After these ascending melts coalesce and evolve beneath the ridge axis they erupt to produce new oceanic crust (O'Hara, 1985).

Because it is difficult to reach deep segments of extensional regimes (i.e., mid-ocean ridges, fore-arc basins, back-arc basins) we rely on more accessible geologic features as analogous to these environments, such as ophiolites. Ophiolites consist of ultramafic and mafic mantle lithologies that formed along spreading centers and get subsequently obducted or exposed onto continents by tectonic processes. Conceptually, ophiolite assemblages are composed from bottom to top, of peridotite (including lherzolite, harzburgite and dunite) variably altered to serpentinite; gabbro and diabase intrusions; and extrusive sequences of pillow lavas and massive flows that are typically overlain by deep-sea sediments (Coleman, 1971; Dewey, 1976; Dewey and Bird, 1971; Dilek and

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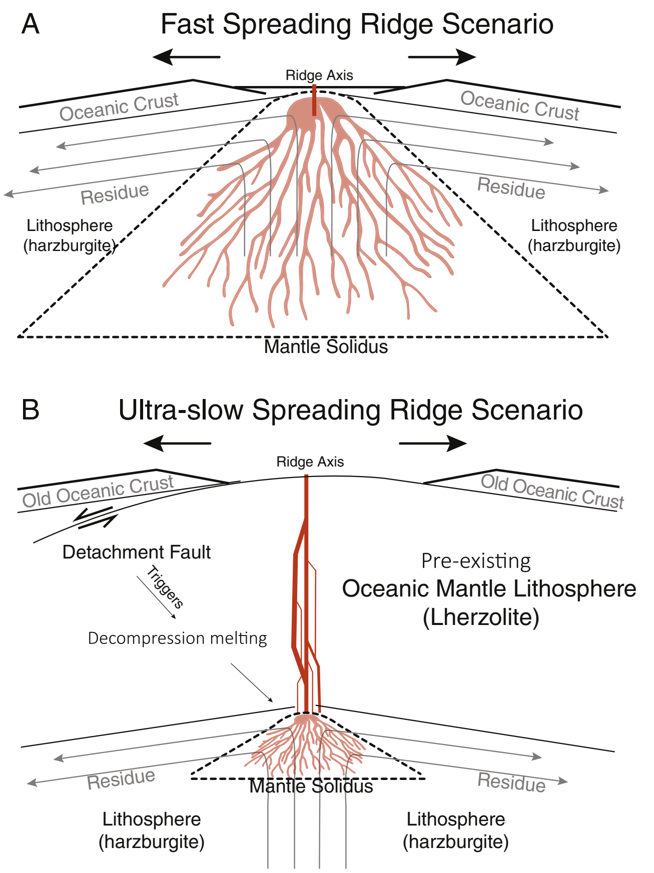

Fig. 1. Two models of the architecture of the oceanic crust modified from Kelemen et al. (2000) and Cannat (1996). A) At a fast spreading ridge, magmatic supply is abundant and melting occurs at shallower levels in the lithosphere; these melts ascend and form coalescing channels (Kelemen et al., 2000). Melt fractions are higher than at slow spreading ridges, which allow the development of an oceanic crust on top (Cannat et al., 2006). B) At ultra-slow spreading centers, melts are triggered by detachment faulting which drives a much deeper melting regime. Slower magma generation and lower melt fraction are characteristic of this environment. In this model, melt travels along a pre-existing oceanic mantle lithosphere composed predominantly of lherzolite (Cannat et al., 2009; Dick et al., 2003).

Furnes, 2011, 2014; Steinmann et al., 2003). Although such lithological associations have commonly been attributed to mid-ocean ridge or back-arc origin, other interpretations for ophiolite origins also exist, such as supra-subduction zone (SSZ) ophiolites, plume-related ophiolites and continental margin ophiolites (see Dewey and Casey, 2011; Dilek and Furnes, 2014 and references therein).

Based on geochemical affinities and order of mineral crystallization, Dilek and Furnes (2011) developed a first order classification, separating ophiolites as subduction-related and subduction-unrelated types. Within their classification, mid-ocean ridge (MOR) type ophiolites show geochemical consistency with normal mid-ocean ridge basalt (MORB). Depending on the proximity to features like mantle plumes, the geochemical affinity may fluctuate from MORB all the way to enriched MORB (EMORB). In contrast, subduction-related ophiolites show a progressive geochemical affinity from MORB-like to Island Arc Tholeiite (IAT) and Boninite in the later stages of SSZ ophiolites (Dilek and Furnes, 2011).

Even though the geochemical affinities expected in ophiolites are well-established, secondary processes that occur after the formation of new oceanic crust must also be considered. Hydrothermal systems that transport heat from the magma lenses to the surface interact with the crust resulting in hydrothermal alterations and ocean floor metamorphism (Pearce, 2008; Pearce, 2014 and references therein). Enrichments in large ion lithophile elements (LILE) that are usually attributed to an arc-related fluid interaction between the subducting slab and the mantle wedge, could easily be mistaken with seawater interaction and contamination during the emplacement of hot oceanic crust, and vice versa (Boudier et al., 1988; Nicolas and Boudier, 2003). Therefore, the discrimination between MOR-type ophiolites and SSZ ophiolites has to be done carefully and by integrating several geochemical tools. Consequently, in order to accurately assess the geochemical fingerprinting of ophiolites, it is necessary to look at the fluid-immobile element data. Fluid-immobile elements remain unaltered during weathering and low-temperature alteration. These elements are characterized by high to intermediate charge/radius ratios and include most of the rare-earth elements (REE) and high field strength elements (HFSE) (Pearce, 2014). The concentration of these elements is controlled by the chemistry of the magma source and the crystallization processes that occur during the magmatic evolution. Several authors have worked on creating fluid-immobile element proxies, which are compared to element ratios that correlate with a specific geological process (Cann, 1970; Floyd and Winchester, 1975; Pearce, 1975; Pearce, 2008; Pearce and Cann, 1971; Shervais, 1982; Sun and McDonough, 1989).

Another useful parameter for ophiolite characterization is its preserved architecture. Variations of the magma supply and spreading rates can modify the architecture of the new oceanic lithosphere (Dilek and Furnes, 2011; Nicolas and Boudier, 2003). Ishiwatari (1985) linked petrological and compositional features of ophiolites to their genesis and to variations in the spreading rates (Fig. 1). In this regard, the structure and composition of an ophiolite can aid to the elucidation of the paleo-spreading rate (Cannat, 1996; Cannat et al., 2009; Dick et al., 2003; Godard et al., 2000; Godard et al., 2008; Michael et al., 2003; Till et al., 2012). Additionally, the composition of the constituent peridotites and associated melts can contribute to characterize the origin of an ophiolite. For instance, while harzburgite compositions may represent an uppermost oceanic mantle melt source and higher degrees of partial melting, lherzolite compositions evidence a deeper oceanic mantle, as they represent more fertile residues subject to lesser degrees of partial melting (Fig. 1) (Boudier and Nicolas, 1985; Dilek and Furnes, 2011; Jackson and Thayer, 1972). Thus, ophiolite segments around the globe provide windows into fossilized melt transport systems that once fed the oceanic or arc crust and upper mantle. The presence of a zone of intense dike emplacement that represents the melt-focusing part of the system is a common feature in these exposed sections of the mantle (Robinson et al., 2008). When present, these dike networks provide an insight to the magmatic origin and geochemical evolution of a particular ophiolite.

Our study presents new $^{40}Ar/^{39}Ar$ ages, major and trace element data, and radiogenic isotopes from melts that intruded the Santa Elena Ophiolite, located in the northwestern Pacific coast of Costa Rica. This ophiolite represents an emplaced fragment of 250 km^2 of upper mantle lithologies overthrusting an ancient accretionary complex (Baumgartner and Denyer, 2006; Denyer and Gazel, 2009; Denyer et al., 2006; Escuder-Viruete and Baumgartner, 2014; Gazel et al., 2006; Tournon, 1994; Tournon and Bellon, 2009) (Fig. 2a). Occurrences of diabase dikes around the peninsula are frequent, however the well-preserved diabase dike transport system is largely exposed in two different sections of this ophiolite: the northwestern swarm and the southeastern swarm (Fig. 2c). In both outcrops, the diabases intrude lherzolite peridotite (Gazel et al., 2006; Tournon and Bellon, 2009). The goal of this integrated structural, geochemical and petrological analysis of the diabase melt-focusing system is to elucidate the magmatic origin and evolution of the Santa Elena Ophiolite and the implications of its origin in the understanding of melt transport and the evolution of the lithospheric mantle.

2. Geotectonic background of the Santa Elena Ophiolite

Costa Rica is currently situated near the triple junction of the Cocos, Caribbean and Nazca plates (DeMets, 2001). Across the Middle American Trench, the Cocos plate is being subducted underneath the