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Formation of the Troodos Ophiolite at a triple junction: Evidence from trace elements in volcanic glass

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ABSTRACT

Fresh volcanic glasses from the extrusive section of the Troodos Ophiolite in Akaki Canyon are tholeiitic and basaltic to dacitic in composition. Compared to normal MORB they have extremely low fractionation corrected Na_8, Fe_8 and Ti_8 and are enriched in fluid-mobile trace elements, including U, Ba, Rb, Sr and Pb, relative to non-fluid mobile elements of similar incompatibility. Trace element compositions of Akaki lavas define an array extending between 'back-arc lava'-like compositions, and the field defined by Troodos boninites from the upper part of the lava sequence. Troodos lavas were derived from a mantle source that underwent early melt depletion, and later enrichment by both fluids and small degree melts. These processes can explain the unusual negative correlation of Pb/Ce with Zr/Nb and Ba/Nb in Troodos extrusives. Although some Troodos lavas are similar in composition to lavas from back-arc spreading centres, the boninites from the upper parts of the lava pile do not appear to have exact compositional equivalents among lavas from fore-arcs, back-arcs or other tectonic settings where similar rocktypes have been recovered. We suggest that the geochemical evolution inferred for the mantle source of Troodos lavas, together with geological evidence is most consistent with an origin for the Troodos Ophiolite at a spreading centre close to a ridge–trench–trench, or ridge–trench–transform triple junction, where highly depleted, subduction-modified, fluid-enriched mantle wedge material was able to upwell and decompress to shallow depths in a 'fore-arc' location. In such a tectonic setting, arc volcanism is captured by the spreading centre, explaining the lack of evidence for subaerial arc magmatism in Troodos. Rapid lateral migration of the triple junction could account for the similar ages of other Tethyan supra-subduction zone ophiolites.

1. Introduction

Oceanic crust created at mid-ocean ridge spreading centres covers approximately 60% of the Earth's surface, yet much of this crust lies at water depths of >2.5 km, and is covered by sediments. Since there have been very few deep-penetration (>500 m) boreholes into oceanic crust, much of our current understanding of the chemical and physical structure of the oceanic crust is based on the study of ophiolites, which are generally thought to represent fragments of obducted oceanic lithosphere. In many ophiolites, the full spectrum of rocktypes thought to characterise the oceanic crust, from submarine tholeiitic basalts, sheeted dykes, to gabbros overlying depleted mantle peridotites can be examined, temporal variations in the chemical composition of the extrusive crust can be determined, and models for the generation and evolution of mid-ocean ridge basalts can be tested by analysis of associated melt residues (peridotites) and cumulates (gabbros). However, many ophiolites have chemical compositions unlike mid-ocean ridge basalts (MORB) erupted at presently-active mid-ocean ridges. In particular, high H_2O contents and relative enrichments in fluid mobile elements such as Pb, U, K, Rb indicate that the lavas were apparently erupted at spreading ridges in the neighbourhood of subduction zones ('supra-subduction zone ophiolites'), although the precise tectonic setting in which they formed is debated (see recent reviews by Pearce, 2003; Robertson, 2004; Dilek and Furnes, 2011). It is therefore uncertain to what extent the geological structure of ophiolites, or the mantle melting and magma evolution processes inferred from ophiolites is representative of 'normal' oceanic crust.

The occurrence of boninitic lavas in several ophiolites has been used to argue for a fore-arc origin, since this relatively rare rocktype characterises the Marianas fore-arc region (e.g. Stern and Bloomer, 1992; Ishizuka et al., 2011). However, boninites have recently been reported from active volcanoes in both back-arc (Resing et al., 2011) and arc settings (Cooper et al., 2010) and so are apparently not restricted to fore-arc regions. If ophiolites generally form in fore-arc settings, and if fore-arc crust is created during subduction initiation, then the mantle melting and melt evolution processes inferred from ophiolites may help in understanding the mechanisms of subduction initiation (Stern et al., 2012).

Trace element studies of lavas from ophiolites can place important constraints on their petrogenesis and thus the tectonic environment of formation, since trace elements can be used to infer the degree of source

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depletion and fluid input, and the nature of the mantle melting process. However, most ophiolites have undergone extensive low- and moderate-temperature alteration (Alt and Teagle, 2000), which has significantly modified the chemical composition of the lavas. Many previous trace element studies of ophiolites were carried out on variably altered whole-rock samples. Since the more mobile elements that are characteristic of subduction zone environments are particularly affected by alteration, many previous studies of ophiolites have been restricted to using only the more immobile trace elements (e.g. Pearce, 1975).

Here we present major and trace element analyses of fresh, unaltered volcanic glasses from the extrusive section of the Troodos Ophiolite of Cyprus, determined using electron probe and laser-ablation ICP-MS. The use of fresh glasses together with microanalytical methods allows us to circumvent the problem of alteration. We have determined the chemical stratigraphy of Troodos lavas in the Akaki Canyon section in order to examine igneous processes responsible for changes in lava composition over 10^4–10^5 y timescales. We use incompatible trace element compositions of the lavas to provide some constraints on the tectonic setting in which this fragment of oceanic crust was formed.

2. Geological setting and sampling

The Troodos Ophiolite covers an area of approximately 3000 km^2 in the central part of the island of Cyprus in the eastern Mediterranean. It is one of the best preserved ophiolites and exposes a complete sequence of marine sediments, lavas, sheeted dikes, isotropic gabbros, layered gabbros and ultramafic rocks representing the oceanic crust and uppermost mantle (Gass, 1968). Zircon ages from plagiogranites and Ar–Ar ages of lavas indicate an age for the main part of the Troodos Ophiolite of 90–92 Ma (Mukasa and Ludden, 1987; Osozawa et al., 2012). Structural and paleomagnetic studies have identified possible north–south striking former ridge axes in the northern part of the ophiolite (Varga and Moores, 1985; MacLeod et al., 1990), most notably the Solea Rift (Fig. 1A). The tectonic situation is more complex in the southeastern region, the Limassol Forest complex (Murton and Gass, 1986), which is separated from the northern part of the ophiolite by the Arakapas Fault Zone, interpreted as a fossil transform fault (Fig. 1A). Troodos lavas have previously been divided into the Upper and Lower Pillow Lavas. The latter consists of tholeiitic basalts, andesites, dacites and rhyolites, with the more evolved rocktypes apparently more common at lower stratigraphic levels. The Upper Pillow Lavas include picrite and boninite-like lavas; the most depleted boninites may be restricted to the southern margin of the ophiolite (Osozawa et al., 2012).

The presence of a sheeted dyke complex indicates that the Troodos Ophiolite formed in an extensional regime, whereas the major and trace element characteristics of the lavas, in particular the enrichment in volatiles and fluid-soluble elements as well as radiogenic isotope compositions shows that it formed in a 'supra-subduction zone' setting (e.g. Rautenschlein et al., 1985; Muenow et al., 1990; Sobolev et al., 1993; Pearce and Robinson, 2010). However, the exact geodynamic

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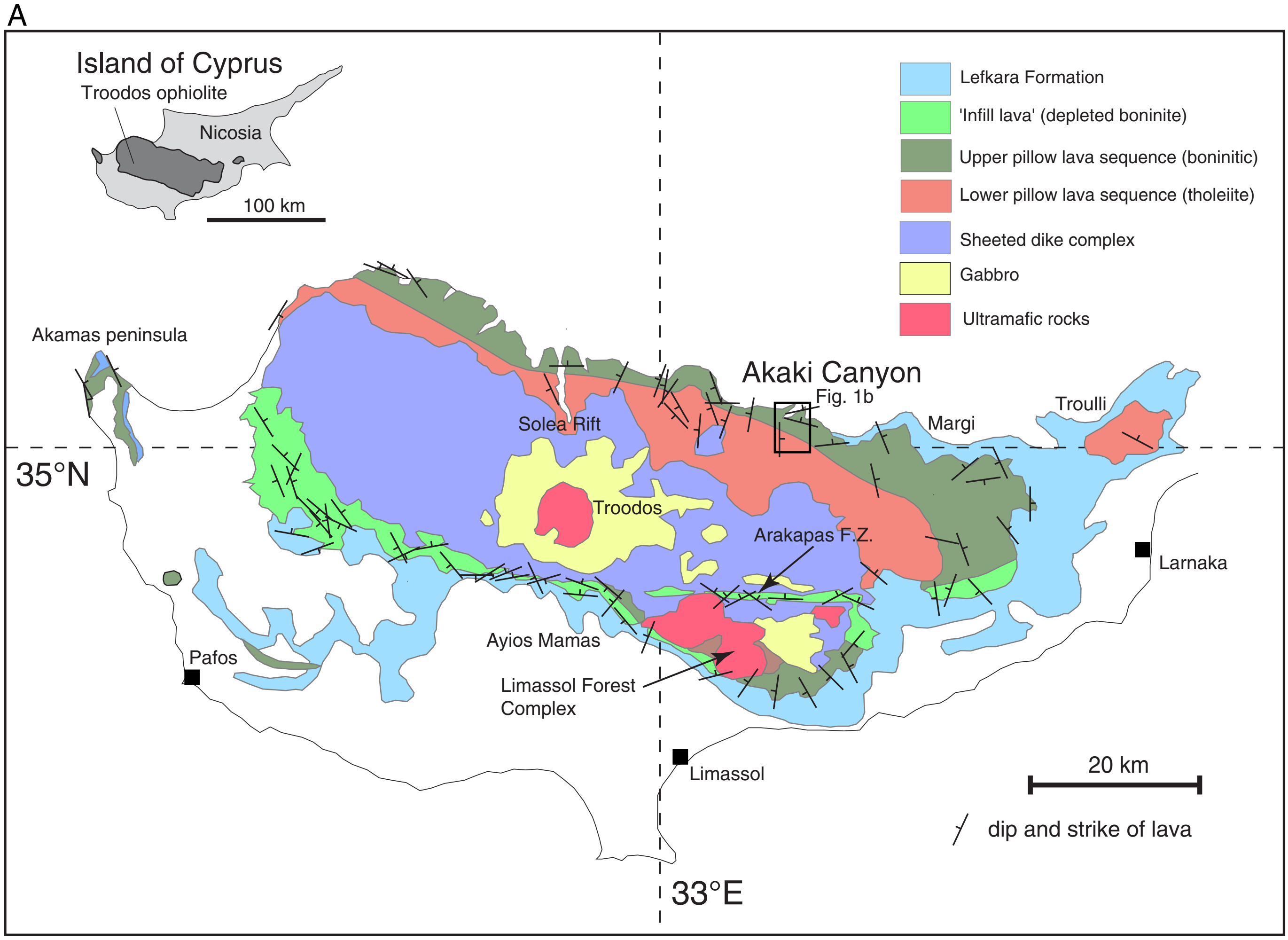

Fig. 1. (A) Simplified geological map of the Troodos Ophiolite in Cyprus modified from Osozawa et al. (2012) showing the location of Akaki Canyon and the area in Fig. 1B, (B) topographic map of Akaki Canyon area showing the locations of the samples analysed in this study, together with volcanic units A–L as defined by Schmincke et al. (1983) and the sediment lava boundary from Bear (1975). Units A and B correspond approximately to the Upper Pillow Lavas as mapped by Bear (1975). Grid squares in (B) are 1 km across.