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Geochemistry of the mantle source and magma feeding system beneath Turrialba volcano, Costa Rica

A. Di Piazza [a,*], A.L. Rizzo [b], F. Barberi [c], M.L. Carapezza [a], G. De Astis [a], C. Romano [c], F. Sortino [b]

[a] INGV — Istituto Nazionale di Geofisica e Vulcanologia sez. Roma 1, Rome, Italy
[b] INGV — Istituto Nazionale di Geofisica e Vulcanologia sez. Palermo, Palermo, Italy
[c] Dipartimento di Scienze, University of Roma Tre, Rome, Italy

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ABSTRACT

Turrialba volcano lies in the southern sector of the Central American Volcanic Front (CAVF) in Costa Rica. The geochemistry of major and trace elements, and Sr and Nd isotopes of a selected suite of volcanic rocks ranging in composition from basaltic andesite to dacite and belonging to the last 10 ka of activity of Turrialba volcano is described, together with the He-, Ne-, and Ar-isotope compositions of fluid inclusions hosted in olivine and pyroxene crystals. Most of the variability in the rock chemistry is consistent with typical trends of fractional crystallization, but there is an outlying group of andesites that displays an adakite-like composition (with a consistent depletion in high-field-strength elements and a marked enrichment in Sr) and low $^3He/^4He$ ratios (7.0–7.2 Ra). The trace-element composition of these rocks is typical of subduction-related magmas influenced by an OIB-like component at the source associated with the subduction of the Galapagos seamounts. The $^{87}Sr/^{86}Sr$ (0.703612–0.703678) and $^{143}Nd/^{144}Nd$ (0.512960–0.512984) ratios of the bulk rocks vary within narrow ranges, and are among the least-radiogenic isotope signatures of the CAVF volcanoes. The $^3He/^4He$ ratios measured in fluid inclusions hosted in olivine crystals (up to 8.1 Ra) are among the highest for the CAVF, and indicate that radiogenic ^4He from fluids derived from the subducting slab contribute negligibly to the mantle wedge. The difference in He isotopes between most of studied rocks and those showing adakite-like features reasonably reflects two distinct components in the local mantle: (1) a MORB-like component, characterized by the highest He-isotope ratios (7.8–8.1 Ra), and (2) an OIB-like component, characterized by lower He-isotope ratios (7.0–7.2 Ra), coming from the subduction of the Galapagos seamounts. An overview at the regional scale indicates that high He-isotope ratios are peculiar to the two extreme sectors of the CAVF (Costa Rica to the south and Guatemala to the north), whereas in the central sector (Nicaragua) the magma source is probably contaminated by slab fluids.

For the past few years Turrialba volcano has been in a volcanic unrest phase that has included a series of explosions, the most recent of which occurred between October 2014 and May 2015. The volcano is subject to an ongoing safety alert due to the possibility of a magmatic eruption. One of the crucial questions to be addressed is the kind of eruption that can be expected, and hence what type of magma is likely to be involved. The high $^3He/^4He$ ratios (7.8–8.0 Ra) measured during 2011 at high-temperature fumaroles of Turrialba craters are comparable to those measured in fluid inclusions of basaltic andesites that erupted in 1864–1866, suggesting that the magma currently feeding the shallow plumbing system has similar geochemical characteristics to the most recently erupted magma.

1. Introduction

Turrialba is a 3349 m-high active stratovolcano belonging to the Cordillera Volcanica Central of Costa Rica (Fig. 1). This is a 80-km long northwest-southeast-oriented volcanic belt associated with the subduction of the Cocos Plate beneath the Caribbean Plate at a convergence rate of ~9 cm/year (Protti et al., 1995). Turrialba is offset 10 km northeastward of the main axis of the volcanic front, in a back-arc setting, and it is close to Irazu volcano, forming the largest volcanic massif of Central America (Carr and Stoiber, 1990). The most recent eruption of Turrialba occurred during 1864–1866 after a long period of fumarole activity (González-Viquez, 1910; Reagan et al., 2006), and was characterized by phreatic and phreatomagmatic explosions, with various Strombolian episodes, and involving basaltic and basaltic andesitic magmas. After almost 150 years of quiescence, since 2001 the volcano has been showing potential signs of reawakening, with anomalous seismicity, the progressive appearance of new fumaroles, strong temperature increases, and discharging gas with a more-characteristic

* Corresponding author at: Istituto Nazionale di Geofisica e Vulcanologia (INGV), Roma1, Via di Vigna Murata 605, 00143 Roma, Italy. Tel.: +39 3294854379.
E-mail address: andrea.dipiazza@ingv.it (A. Di Piazza).

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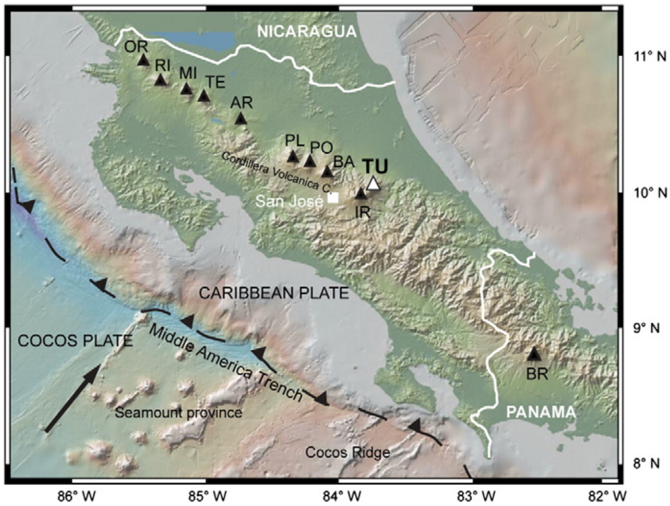

Fig. 1. Regional and geodynamic map of Costa Rica showing the locations of the main volcanoes, which are identified with the following labels: TU, Turrialba; IR, Irazu; BA, Barva; PO, Poás; PL, Platanar; AR, Arenal; TE, Tenorio; MI, Miravalles; RI, Rincon de la Vieja; and OR, Orosì (based on maps available at www.geomapapp.org). The black arrow indicates the movement direction of the Cocos Plate relative to the Caribbean Plate. The location of Baru (BR) adakitic volcano in Panama is also indicated.

magmatic signature (Martini et al., 2010). From 2010 until May 2015 a series of explosions occurred at the Southwest Crater, emitting fragments of altered preexisting material. Because Turrialba is located eastward of the Central Valley of Costa Rica, which includes the capital city of San José and a wide metropolitan area, its magmatic reactivation would represent a serious hazard. The eruptive activity is currently ongoing, and involves repeated explosions that emit ash and sporadic bombs with a maximum column height of 2.5 km (OVSICORI-UNA, 2015).

The eruptive products from this sector of the arc are characterized by an OIB-like signature that has been the subject of various studies and interpretations (e.g., Feigenson et al., 2004; Gazel et al., 2009, 2011; Hoernle et al., 2008; Reagan and Gill, 1989). Feigenson and Carr (1993) proposed that two distinct mantle sources are present: (1) a MORB-like one and (2) veins of enriched mantle that transect the first source. Melting of this veined mantle source and its interaction with the subduction component would produce magmas with a typical arc signature (Carr et al., 2003; Feigenson et al., 2004). Herrstrom et al. (1995) proposed that a mantle flow from the termination of the Cocos slab and that is parallel to the trench drives the enriched component from the South American mantle wedge in this sector of the arc. Johnston and Thorkelson (1997) proposed the existence of a window in the Cocos slab, which was interpreted by Abratis and Woerner (2001) as the gateway via which the Galapagos-modified asthenosphere could flow into the Caribbean realm. More recently, Benjamin et al. (2007), Hoernle et al. (2008), and Gazel et al. (2009, 2011) attributed this OIB signature of Central Costa Rica (i.e., Platanar, Poás, Barva, and Irazu volcanoes) and of Panama (i.e., Baru) magmas to the subduction of the Galapagos seamounts originating along the Galapagos hot-spot track. This anomalous OIB signature in the volcanic products from central-southern Costa Rica, similar to the Galapagos OIB lavas, contrasts with those usually observed in the CAVF, which are typical of convergent margins.

Noble gases are excellent tracers of both the origin of fluids and magma processes occurring in either the mantle or the crust, and therefore they are the best candidates for investigating the geochemical characteristics of the magma feeding the present fumaroles and potentially involved in a future eruptive crisis. In particular, studies of the $^3He/^4He$ ratios in fumarole gases and fluid inclusions (FI) can reveal various features of the magma/mantle source, such as geochemical heterogeneity and metasomatism, and on the processes occurring in the magma as it ascends to the surface (e.g., magma contamination; Correale et al., 2012, 2014; Hilton et al., 1993; Martelli et al., 2004, 2014; Marty et al., 1994; Nuccio et al., 2008; Ozima and Podosek, 1983; Rizzo et al., 2015a; Shaw et al., 2006). Analyzing both Ar and He isotopes is also useful for identifying processes of magma contamination and degassing, since these processes can modify the characteristics of primary melts rising toward the surface. For this reason, He and Ar are often compared with other markers, such as mineral chemistry (e.g., Hilton et al., 1995; Shaw et al., 2006) and Sr and Nd isotopes (e.g., Condomines et al., 1983; Correale et al., 2012, 2014; Hilton et al., 1993, 1995; Martelli et al., 2004, 2014). The $^3He/^4He$ ratio can play a critical role in evaluating and predicting volcanic unrest (e.g., Padrón et al., 2013; Rizzo et al., 2006, 2009, 2015a,b; Sano et al., 1984), since comparing fumarole gases with FI trapped in crystals from erupted products gives valuable information about the composition of the magma feeding the fumarolic emissions (e.g., Correale et al., 2014; Nuccio et al., 2008; Rizzo et al., 2015a; Shaw et al., 2006).

In this study we investigated the geochemical and petrological characteristics of volcanic products that have erupted at Turrialba during the last 10 ka. Data on the elemental and isotopic compositions of noble gases from FI hosted in mafic minerals separated from these rocks are compared with those from fumarole gases discharged in the crater area. Moreover, Sr- and Nd-isotope ratios measured in the same selected suite of recent Turrialba rocks for which He, Ar, and Ne were measured in olivine and pyroxene FIs have been reviewed in the light of data in the literature. The main aim is to provide new insights into the mantle/magma source of Turrialba and into the magma feeding the present fumarole activity.

2. Volcanological and geochemical background

The CAVF is a Quaternary volcanic arc that extends for about 1000 km from Mexico to Panama and contains about 40 active or dormant volcanoes. This volcanic front runs parallel to the Middle American Trench (Fig. 1), which marks the subduction of the Cocos Plate beneath the Caribbean Plate and the Panama Microplate (deMets et al., 1994). Younger crust of the Galapagos hot-spot track (including the Galapagos seamounts and the Cocos Ridge) is subducted beneath Costa Rica and western Panama (e.g., Hoernle et al., 2008; Werner et al., 1999).

Turrialba is located at the southernmost termination of the Costa Rica volcanic front, in a sector where the crustal tomography is characterized by a large low-velocity zone (beneath the Turrialba and Irazu volcanoes; Husen et al., 2003). This zone narrows at shallow depth and extends directly beneath the two volcanoes. Using gravimetric modeling, Lücke et al. (2008) identified a low-density body beneath the Turrialba–Irazu volcanic complex at a depth of 1–10 km, which they interpreted to be a joint magma reservoir. Anomalous receiver function conversions and tomography analyses by Husen et al. (2003) confirmed the presence of a magmatic body beneath Turrialba volcano extending to a depth greater than 30 km, with an absolute P-wave velocity as low as 6.5 km/s.

The basement of Turrialba volcano is composed of andesitic (2.15 ± 0.30 Ma) and basaltic (5.1 Ma) lavas that overlie sediments of the Limon Basin (Soto, 1988). The first recorded activity dates back to the Paleo-Turrialba stage (250–600 ka; Ruiz-Cubillo, 2012), but the most important construction period of the edifice occurred during the Neo-Turrialba stage (<250 ka; Ruiz-Cubillo, 2012). In particular, at least 20 eruptions of basaltic to dacitic lavas and tephra occurred in the last 10 ka and built the present summit of the volcano (Reagan et al., 2006). Focusing on the last 4 ka, six explosive eruptions were recorded by tephra stratigraphy (Reagan et al., 2006); all of these eruptions were characterized by small erupted volumes (≤0.03 km^3), with the exception of a ~0.2 km^3 Plinian to sub-Plinian eruption fed by andesitic magma at 1.9 ka (Di Piazza, 2014; Reagan et al., 2006). The most recent