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2 **Origin of plagiogranites in oceanic complexes: A case study of the Nicoya and**
3 **Santa Elena terranes, Costa Rica**
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Abstract

The origin of minor leucocratic intrusions known as “plagiogranites” in oceanic complexes dominated by basaltic compositions have been debated in the literature. Here we use well preserved plagiogranites within the contrasting Santa Elena Ophiolite and the Nicoya Complex, NW Costa Rica, to investigate the origin and age of these leucocratic intrusions. Magmatic zircons of plagiogranites of the Santa Elena ophiolite and the Nicoya Complex, yield weighted mean SHRIMP $^{206}\text{Pb}/^{238}\text{U}$ ages of 125.3 ± 2.0 Ma and 90.9 ± 2.0 Ma to 88.5 ± 2.0 Ma ($n = 5$), respectively. These ages record the main magmatic phases of formation of these intrusions preserved in each complex. Relatively flat, unfractionated chondrite-normalized REE patterns of plagiogranites from both complexes mimic signatures of related mafic rocks, which is consistent with formation via fractional crystallization from a mafic source as opposed to partial melting of a mafic (basalt, amphibolite) protolith. In the case of the Nicoya Complex, modelling suggests that the Nicoya plagiogranites are consistent as ~10-15% residual liquids after fractional crystallization from its mafic parental source. Trace element systematics of the plagiogranites are consistent with an oceanic arc origin for Santa Elena and a mostly mid-ocean ridge to oceanic-plateau origin for Nicoya.

Keywords: Plagiogranite; trondhjemite, ophiolite; Central America; Costa Rica; Nicoya; Santa Elena

1. Introduction

Minor volumes of intrusive, leucocratic, quartz-plagioclase rocks are commonly found in association with high-level gabbros and sheeted dikes of ophiolite complexes, oceanic crust and intra-oceanic crust. Their compositions range from albite granite through trondhjemite and tonalite to diorite and are collectively termed as oceanic plagiogranite (Coleman and Peterman, 1975; Coleman and Donato, 1979). Plagiogranite is characterized by very low K_2O but high Na_2O , K/Rb , Rb/Sr , and rare earth element (REE) values that render it distinct from many of its continental equivalents.

Proposed mechanisms for plagiogranite generation can be grouped into four very different processes: (1) Na metasomatism of K-bearing felsic differentiates (e.g., Gilluly, 1933); (2) immiscibility between felsic and conjugate Fe-enriched basaltic liquids occurring under anhydrous conditions (Dixon and Rutherford, 1979); (3) low-pressure differentiation of subalkaline basaltic magma (e.g., Coleman and Peterman, 1975); and (4) anatexis of amphibolite (Pedersen and Malpas, 1984; Flagler and Spray, 1991) or basaltic/gabbroic crust under hydrous conditions (Sigvaldson, 1974; Koepke et al., 2007). It is generally agreed however, that only mechanisms (3) and (4) represent viable means in which to generate plagiogranite. For example, a purely metasomatic origin is now largely discounted on the basis of collective petrologic and geochemical evidence which demonstrates that plagiogranites originate from a melt rather than by Na metasomatism of a K-rich felsic precursor (see references below). Another inherent problem with an origin via metasomatism of K-rich felsic rocks is that these rocks are rare in oceanic settings. The possibility of plagiogranite forming by late-stage silicate liquid immiscibility under anhydrous conditions has been suggested by experimental work (Dixon and Rutherford, 1979); however, this has not been verified in the field from ophiolites or in situ

ocean crust. Furthermore, later experimental study demonstrated that immiscibility is not encountered when basaltic systems are crystallized (or melted) in the presence of significant H₂O concentrations (Dixon-Spulber and Rutherford, 1983).

Conversely, there is ample evidence to support plagiogranite generation via fractional crystallization or anatexis. Differentiation of a basic magma has been shown as a viable mechanism for example, for the generation of many plagiogranites including those of the Oman (Semail) (Pallister and Knight, 1981; Lippard et al., 1986), Troodos (Coleman and Peterman, 1975), Sarikaraman (Turkey) (Floyd et al., 1998) and Oytay (NW China) (Jiang et al., 2008) ophiolites. In these cases, plagiogranite is considered to represent a ~10% residual liquid formed during the low-pressure crystal fractionation of a subalkaline, low-K tholeiitic magma under hydrous conditions. The feasibility of this mechanism has also been substantiated by experimental work (Dixon-Spulber and Rutherford, 1983). Plagiogranite petrogenesis via anatexis has been established for plagiogranites of the Karmoy ophiolite, Norway (Pedersen and Malpas, 1984) and for the Fournier oceanic fragment of the Canadian Appalachians (Flagler and Spray, 1991) and an anatexis origin has been shown to be valid on the basis of experimental work (France et al., 2010). A fractionation vs. anatexis origin can usually be discriminated on the basis of REE chemistry as we propose in Section 4.3. In addition to providing new high-fidelity, SHRIMP U-Pb zircon ages of plagiogranites from the Nicoya and Santa Elena oceanic fragments of NW Costa Rica, we also provide a new major and trace-element data set for Nicoya and Santa Elena plagiogranites. Finally, our work also presents major and trace-element modeling evidence for the derivation of these plagiogranites by fractionation of a parental basic magma.

2. Regional geology and tectonic framework

The Caribbean Plate (Fig. 1) encompasses a considerable proportion of thicker-than-normal oceanic crust and was identified as the first oceanic plateau (Donnelly, 1973), i.e., the Caribbean Large Igneous Plateau (CLIP) (e.g. Hauff et al., 2000a). As such, the Caribbean Plate is mostly comprised of lithosphere of the CLIP oceanic plateau but also embraces subordinate continental fragments along its margin (Dengo, 1985). The thickness of the Caribbean Plate ranges from that of ‘normal’ oceanic crust to thicknesses about three times that of normal oceanic crust akin to other oceanic plateaus and exhibits a seismic velocity structure analogous to that of the Ontong Java Plateau (Mauferrett and Leroy, 1997). West of the Beata Ridge, the Caribbean Plate is about 6-8 km thick whereas it ranges up to 20 km thick in the region between the central Venezuelan Basin and the western part of the Beata Ridge (Diebold and Driscoll, 1999).

The western margin of the Caribbean Plate is composed of the Chorotega and Chortis blocks (Dengo, 1985) and the former characterizes an exposed segment of the CLIP mostly buried by Cenozoic lavas of the Central American Volcanic Arc (see recent reviews of Gazel et al., 2015 and Whattam and Stern, 2016). The relation of the northern margin of the Caribbean Plate with the mostly continental Chortis Block is poorly known but is predicted to extend to the south of the Nicoya peninsula in northwestern Costa Rica to the Hess Escarpment (e.g., Meschede and Frisch, 1998; Hoernle et al., 2004; Hoernle and Hauff, 2007). In southern Nicaragua, the southeastern segment of the Chortis Block is comprised of the Siuna Terrane (Rogers et al., 2007) which is composed of deformed oceanic and island arc lavas and intrusives which were accreted to the southern margin of the Chortis Block in the Late Cretaceous (Venable, 1994).

According to early and mostly still accepted models, the CLIP formed in the eastern Pacific during the Late Cretaceous prior to drifting into its present position over the past 90 m.y. (Burke et al., 1978; Duncan and Hargraves, 1984). Furthermore, most models posit that the CLIP was generated by the Galapagos plume over two major magmatic pulses of CLIP-related magmatism at 92–88 Ma and 76–72 Ma (see Kerr et al., 2003, and references therein). Although most of the CLIP is submerged beneath the Caribbean Sea, many on-land Late Cretaceous igneous complexes in the Circum- Caribbean represent uplifted and/or accreted CLIP fragments. These sub-aerially exposed CLIP complexes are located along the Pacific coast of South and Central America, in western Ecuador and Colombia in the east and in Panama and the Nicoya Peninsula in northwestern-most Costa Rica in the west (Fig. 1). CLIP exposures have also been identified in the Leeward Antilles in Aruba and Curaçao to the north of Venezuela (Fig. 1).

The trench and continental shelf in front of Guatemala along the Pacific coast of Central America were drilled during DSDP Leg 67 and Leg 84 (Geldmacher et al., 2008) to determine the nature of the basement beneath the Central American forearc. Basement rocks include ultramafic and mafic igneous rocks including basalts, dolerites, gabbros, serpentized peridotites and harzburgites (Geldmacher et al., 2008) and geophysical data from the lower Nicaraguan margin wedge suggest a comparable dense basement spanning the front of its margin (Walther et al., 2000). Seismic velocities intimate that the complete shelf between Costa Rica and southern Mexico is underlain by igneous basement possibly similar to the subaerially exposed Santa Elena and Nicoya igneous oceanic complexes (Ye et al., 1996; Walther et al., 2000) in northwestern Costa Rica (Fig. 1). Plagiogranites of the Nicoya and Santa Elena complexes are the focus of this contribution and we provide a synopsis of the nature and age of these complexes below.

3. The Nicoya and Santa Elena complexes

Four oceanic igneous complexes are located at or just to the south of the assumed Chorotega-Chortis Block boundary in NW Costa Rica and from north to south, comprise the Santa Elena, Nicoya, Tortugal and Herradura complexes, with Nicoya (Fig. 1) being the largest and best studied of them (e.g., Dengo, 1962; Kuijpers, 1980; Hauff et al., 1997; Sinton et al., 1997; Beccauluva et al., 1999; Hauff et al., 2000a; 2000b; Hoernle et al., 2004).

The Nicoya Complex largely consists of aphyric pillow and massive lava flows, which are locally intruded by gabbros and plagiogranites (Hauff et al., 2000a) but also includes dolerites, volcanic breccias and hyaloclastites (Denyer and Gazel, 2009). Magmatic ages of Nicoya complex rocks range from ~140-70 Ma (Hauff et al., 1997; Sinton et al., 1997; Hauff et al., 2000a; Hoernle et al., 2004) though the majority of these ages are post 100 Ma as noted by Whattam and Stern (2015), and dismembered radiolarite sequences of up to ~100 m thickness range from Callovian to Santonian (164-84 Ma) (e.g., Baumgartner, 1984; Schmidt-Effing, 1979). Rare occurrences of fossil-bearing intrapillow sediments, for example at Montezuma (south Nicoya), indicate Cenomanian/Turonian (94 Ma) eruption ages (Azéma and Tournon, 1980; Tournon and Alvarado, 1997). $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating analyses on seven lavas from Nicoya yield a tight clustering of plateau ages which range from 92.5 ± 5.4 Ma to 88.0 ± 0.7 Ma (Sinton et al., 1997). Two intrusive rocks of the study of Sinton et al. (1997) returned plateau ages of 83.8 ± 1.1 Ma and 83.2 ± 1.3 Ma. Via $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating experiments, Hauff et al. (2000a) dated a pillow lava from south Nicoya at 94.7 ± 1.8 Ma and plagioclase from a plagiogranite from north Nicoya at 87.5 ± 1.8 Ma. Collectively, and despite the range to much older ages (~140 Ma) obtained by Hoernle et al. (2004), the radiometric age data suggest formation of the

bulk of the CLIP-derived igneous basement over a relatively short time interval between circa 95 and 83 Ma, which is in sharp contrast to the extensive biostratigraphic record of the radiolarites (164-84 Ma). On the basis of a survey of literature data of biochronological and radiometric age dates of circum-Caribbean oceanic magmatic complexes, Whattam and Stern (2015) suggested the existence of two major pulses of oceanic plateau magmatism at 140-110 Ma, and a younger, volumetrically dominant one after 100 Ma. Thus, the older biostratigraphic and radiometric ages at Nicoya may be a record of an ‘old’ plateau whereas the post-100 Ma ages are a record of a ‘younger’ plateau.

At Santa Elena, a predominantly ultramafic nappe composed of serpentized mantle peridotites, and associated diabase intrusions, overthrusts a basalt-radiolarite assemblage that also include layered gabbros, basaltic intrusions and plagiogranites (e.g. Azéma et al., 1985a; Hauff et al., 2000a; Denyer et al., 2006; Gazel et al., 2006; Denyer and Gazel., 2009) (Fig. 1b). Originally interpreted as part of the Nicoya Complex (Dengo, 1962; Kuipers, 1980), the Santa Elena Complex is now considered to represent a distinct oceanic magmatic entity (Gazel et al., 2006; Madrigal et al., 2015). For example, though the ultramafic nappe and the mainly basaltic Nicoya complex were considered as a genetically related ophiolitic suite (Azéma and Tournon, 1980; Beccaluva et al., 1999; Frisch et al., 1992), subsequent geochemical, geochronological and isotopic studies established that basalts of Santa Elena are different from those of Nicoya (Hauff et al., 2000a; Denyer et al., 2006; Denyer and Gazel, 2009; Madrigal et al., 2015).

As constrained by the age of the youngest underlying sediments, the Santa Elena ultramafic nappe was emplaced after the Cenomanian (DeWever et al., 1985) but before the late Campanian as constrained by the age of rudist reefs which lay atop the exhumed nappe (Schmidt- Effing, 1980), which corresponds to an emplacement age of 93-75 Ma. This age range

is supported by a radiometric K/Ar age of 88 ± 4.5 Ma from a secondary amphibole sampled from a recrystallized diabase dike (Bellon and Tournon, 1978) and most probably dates amphibolite metamorphism along shear zones related to the nappe emplacement.

On the basis of trace element and isotope chemistry, the Santa Elena nappe was subdivided into four lithological units by Hauff et al. (2000a). The first unit (also termed the ‘Santa Rosa Accretionary Complex’, Baumgartner and Denyer, 2006; Denyer et al., 2006; Denyer and Gazel, 2009) comprises oceanic island basalt (OIB)-like alkaline pillow lavas and dikes (Hauff et al., 2000a) which are discordantly associated with circa 190-93 Ma radiolarian cherts. The second and third units are comprised of basalts and layered gabbros, respectively for which $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 109 ± 2 Ma and 124 ± 4 Ma were obtained (Hauff et al., 2000a). According to the subdivision of Hauff et al. (2000a), the ultramafic nappe comprises the fourth unit and in terms of ultramafic nappe formation age, Madrigal et al. (2015) report $^{40}\text{Ar}/^{39}\text{Ar}$ ages of ~ 131 Ma and 121 Ma for the timing of the Santa Elena peridotite cooling event as constrained by pegmatitic gabbro intrusion and the formation and intrusion of later-formed diabase dikes, respectively. Apart from the OIB-like alkaline basalts and dikes of Unit 1 of Hauff et al., (2000a), the remaining Santa Elena lavas, gabbros and dikes which range from tholeiitic basalts to basaltic andesites and trachyandesites have trace element and isotopic signatures consistent with formation in a subduction zone environment (e.g., Hauff et al., 2000a; Gazel et al., 2006; Hoernle and Hauff, 2007), possibly a back-arc basin (Madrigal et al., 2015).

4. Methods

4.1. Petrography and mineral chemistry

Ten polished thin sections of plagiogranite samples from Nicoya ($n = 8$) and Santa Elena ($n = 2$) were described under a petrographic microscope and petrographic features of these are included below. Minerals of these samples were analyzed via a JEOL JXA-8600 SX electron probe micro-analyzer (EPMA) at Korea University, Seoul, South Korea. Accelerating voltage, beam current, and probe conditions were 15.0 kV, 3.0 nA, and 3 μm , respectively.

4.2. Whole rock chemistry

We sampled fresh outcrops of plagiogranites for subsequent geochemical analysis (Table 1) along the coasts of the Santa Elena and Nicoya peninsulas in NW Costa Rica (Fig. 1). In the Nicoya peninsula, the oceanic plutonic rocks are generally restricted to the northwest section of the uplifted oceanic complex and are in metamorphic contact with radiolarian cherts or intruding basaltic sequences (Fig. 1) (e.g., Denyer and Gazel, 2009). In the Santa Elena peninsula, the collected samples are from a layered intrusion sequence that range from cumulate peridotites to granites, and are limited to blocks within the metamorphic sole of the ophiolite and most likely belonging to autochthonous lithologies below the peridotite nappe (Fig. 1) (Madrigal et al., 2015).

All samples were processed in the geochemistry laboratory at the Department of Geosciences at Virginia Tech, following the procedures described in Mazza et al. (2014). Major and trace element data were collected at the certified Activation Laboratories (<http://www.actlabs.com/>) in Ancaster, Canada. The methods used included a lithium metaborate/tetraborate fusion of the whole rock, which was then dissolved and analyzed by Perkin Elmer Sciex ELAN 9000 ICP-MS. Three blanks and five controls (three before sample group and two after) were analyzed per group of samples. Duplicates were fused and analyzed

every 15 samples. The instrument was recalibrated every 40 samples. The accuracy for standards BIR-1a, W-2 and J-1 run with samples is better than 5% relative to the certified values for the trace elements and better than 1% for major element data (with the exception of Na₂O and MnO, better than 3%). The blanks run with the samples were below the detection limit for all the elements reported.

In addition to new geochemical data of Santa Elena and Nicoya plagiogranites (Table 1) we also compile existing geochemical data of lavas and intrusives from Santa Elena (Beccaluva et al., 1999; Hauff et al., 2000; Arias et al., 2002) and Nicoya (Ragazzi, 1996; Beccaluva et al., 1999; Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2004) for comparison with our data. On our geochemical plots, all samples plotted are normalized to 100% in a volatile-free basis..

4.3. U-Pb SHRIMP dating

After sample pulverizing, zircons ranging from 63 µm to 245 µm were separated using magnetic separation and heavy liquids. Separated zircons together with standard grains were mounted in epoxy resin, polished to expose the middle of grain. The measured ²⁰⁶Pb/²³⁸U ratio was calibrated using the FC1 zircons (1099.0 Ma) standards, which were collected from the gabbroic anorthosite of the Duluth Complex in Minnesota (Paces and Miller, 1993). Sri Lankan gem zircon SL13 (U=238 ppm) was also used for calibration of U and Th concentrations. Cathodoluminescence (CL) and backscattered electron (BSE) images were obtained using the scanning electron microscopes of JEOL 6610LV at Korea Basic Science Institute (KBSI). The phase identification of zircon and its inclusion were performed by INCA x-act energy dispersive spectrometer (EDS). Zircon U-Pb dating was carried out using the SHRIMP-IIe/MC at KBSI. The analytical procedures for SHRIMP dating were mostly based on Williams (1998). A 20-25 µm

spot size was used for all analyses under a negative ion oxygen beam (O_2^-) in 3-4 nA of beam current. The data were collected in sets of five scans throughout the mass measurements for each isotope. For common Pb the $^{206}Pb^*/^{238}U$ ages were corrected on the basis of the measured $^{207}Pb/^{206}Pb$ ratio (Williams, 1998). FC-1 standard grains were repeatedly analyzed after every three unknown analyses. Data reduction and processing were carried out using the Squid 2.50 and Isoplot 3.71 program of Ludwig (2008, 2009). When the drift in Pb/U ratios of repeated FC-1 standard were obvious, the drift correction of secular variation was chosen on SQUID 2.5 software. Mean age of each specimen was calculated using ^{207}Pb -corrected $^{206}Pb^*/^{238}U$ ages after excluding outliers under statistical t -test. Concordia diagrams were plotted using ^{208}Pb -corrected ratios of $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$. All uncertainties in Tables 1 and 2 and Fig. 2 are given in 1σ .

5. Results

5.1. Petrography and mineral chemistry

5.1.1. Nicoya diorites and plagiogranites

The SHRIMP-dated Nicoya diorite (3-23-11-10) and plagiogranites (1-23-11-10, 2-23-11-10, 4-23-11-10 and CN-6-14-7-1) primarily comprise plagioclase and quartz with subordinate but conspicuous large calcic amphibole (ferro-actinolite, typically <5%) laths. Apatite, ilmenite, magnetite and rare (<1%) potassium feldspar occur as accessory phases. In the plagiogranites, plagioclase and quartz constitute about 50-60% and 40-50% of the mode, respectively, whereas in the diorite, plagioclase and quartz compose approximately 80-85% and 15-20% of the mode, respectively. Both intrusive types are moderately altered and plagioclases are usually completely saussuritized or sericitized and typically exhibit Carlsbad twins but no polysynthetic twins or

obvious zonation. Plagioclase is generally more Na-rich in the diorite than in the plagiogranites but both types comprise compositions that range to Ab₁₀₀. Compositions of plagioclase cores and rims of each intrusive type overlap and range from albite to andesine (diorite and plagiogranite plagioclase cores exhibit Ab₁₀₀₋₅₅). Micrographic granophyric intergrowths of albite and quartz are common in both the diorite and the plagiogranites, similar to plagiogranites in general. Actinolite occurs as discrete 0.2-5 mm pleochroic, green laths, the color owing to its Fe-rich nature (33 wt. % FeO), which are commonly altered to chlorite and present as inclusions that occur with apatite needles within magnetite. Orthoclase occurs as micro (~5 µm) angular inclusions within albite cores.

5.1.2. Santa Elena plagiogranites

The Santa Elena plagiogranite (SE-0401611-9) is petrographically and compositionally distinct from the Nicoya diorites and plagiogranites. SE-0401611-9 is fresher and finer-grained than the Nicoya felsic intrusives, contains relatively more quartz (up to ~60%) but lesser plagioclase (~40-50%) than the latter and comprises a small volume of clinopyroxene (<5%) instead of amphibole; potassium feldspar is absent. Some plagioclases are sericitized but not to the degree of those in the felsic intrusives from Nicoya and many plagioclases exhibit polysynthetic twins. Santa Elena plagiogranite plagioclase is also markedly more Ca-rich than those of the Nicoya intrusives with cores and rims primarily of andesine (An₁₈₋₅₂); one plagioclase core is oligoclase. Clinopyroxene is diopside (Wo₄₈₋₅₀En₂₅₋₃₄Fs₁₆₋₂₈, one core is hedenbergite) and is present as 1 mm subhedral and anhedral light green, stubby prisms that are usually altered to epidote and chlorite. Granophyric intergrowths of plagioclase and quartz which are well-developed in the Nicoya intrusives are absent in the Santa Elena plagiogranite.

5.2. U-Pb SHRIMP dating

Concordia plots are shown in Fig. 2 and individual spot analyses are given in Tables 2 and 3. CL images of selected zircon grains are shown in Fig. 3.

5.2.1. Zircon ages

Zircons from a total of six felsic samples, five from Nicoya and one from Santa Elena, were dated via U-Pb SHRIMP methods. The five Nicoya samples include one diorite (4-23-11-10) and four plagiogranite samples (1-23-11-10, 2-23-11-10, 3-23-11-10, CN-6-14-7-1) whereas the lone Santa Elena sample (SE-040611-9) is a plagiogranite (these sample numbers and ages obtained on these samples are shown in Fig. 1). The Nicoya samples yield $^{206}\text{Pb}/^{238}\text{U}$ ages which range from ~87-93 Ma while the Santa Elena plagiogranite yields a $^{206}\text{Pb}/^{238}\text{U}$ age of 125.3 ± 2.0 Ma (Fig. 2). Specifically, zircons from Nicoya diorite sample 4-23-11-10 yields a $^{206}\text{Pb}/^{238}\text{U}$ age of 88.9 ± 2.1 Ma whereas plagiogranite samples 1-23-11-10, 2-23-11-10, 3-23-11-10 and CN-6-14-7-1 yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 88.5 ± 2.0 Ma, 88.6 ± 1.7 Ma, 89.1 ± 1.1 Ma and 90.9 ± 2.0 Ma.

5.2.2. Zircon morphology and zonation

Nicoya plagiogranite zircons (Figs. 3a-f) range from ~20-200 μm , are mainly subhedral or anhedral and angular and typically exhibit complex zonation patterns (Figs. 3a, b). Subordinate circa ~70-160 μm grains comprise elongated, subhedral to euhedral tabular prisms which either lack zonation or exhibit thin, closely spaced, concentric zonation (Figs. 3c, d). A small subset of 140-180 μm grains are subhedral to anhedral and amorphous, and exhibit the most complex zonation patterns (Figs. 3e, f). Santa Elena plagiogranite zircons are subhedral and

commonly euhedral and typically smaller than most Nicoya plagiogranite zircons (~70-140 μm). In contrast to Nicoya plagiogranite zircons, some of the Santa Elena plagiogranite zircons exhibit simple zonation with broad, diffuse sector zones whereas others exhibit narrow, closely spaced concentric zonation patterns similar to some Nicoya zircons (Figs. 3g, h).

5.2.3. U and Th concentrations and Th/U ratios

Metamorphic zircons typically have low Th/U ratios <0.1 which in many cases discriminate these from magmatic zircons which usually exhibit much higher ratios (e.g., Rubatto, 2002). All analyzed Santa Elena and Nicoya plagiogranite zircons have high Th/U ratios >0.2 (Santa Elena, 0.2-0.6 and Nicoya, 0.4-2.3, Fig. 4, Tables 2, 3) which demonstrates the magmatic origin of both plagiogranite units. In addition to ranging to much higher Th/U than Santa Elena plagiogranite zircons, the Nicoya complex plagiogranite zircons also range to much higher U and Th concentrations than zircons of the Santa Elena plagiogranite. Nicoya plagiogranite zircons exhibit a higher range in U and Th (79-1054 ppm and 35-1409 ppm) relative to the Santa Elena plagiogranite which yields 57-357 ppm U and 13-202 ppm Th (Tables 2, 3).

5.3. Plagiogranite whole rock major element chemistry

Our suites of Nicoya ($n = 8$) and Santa Elena ($n = 2$) plagiogranites span 63-72 and 75-76 wt. % SiO_2 , respectively. Chemical analyzes of Nicoya and Santa Elena intrusives are provided in Table 1. Below we summarize the general major and trace element chemistry characteristics of each plagiogranite suite.

5.3.1. Chemical classifications

The Nicoya and Santa Elena plagiogranites ($n = 8, 2$, respectively) have SiO_2 contents that range from 62.99-71.68 wt. % and 75.30-75.53 wt. % corresponding to dacite and rhyolite compositions on the SiO_2 vs. total alkalis classification scheme of Le Bas et al. (1986) and Al_2O_3 concentrations of 11.68-13.37 wt. % and 13.16-14.43 wt. %. Both plagiogranite suites have very low potassium (0.25-0.45 wt. % K_2O , Nicoya and 0.06-0.14 wt. % K_2O , Santa Elena) typical of all oceanic plagiogranites (e.g., Coleman and Donato, 1979) and each suite is enriched in Na_2O (4.67-5.92 wt. %, Nicoya and 3.31-3.39 wt. %, Santa Elena). The simple relation of Nicoya and Santa Elena plagiogranites relative to mafic lavas and intrusives in SiO_2 vs. K_2O space (not shown) suggests derivation of the former via fractional crystallization from the latter, which is supported by the morphology of plagiogranite REE plots (see section below).

On the basis of petrography and the relative concentrations of plagioclase and quartz in QAPF space, the Nicoya and Santa Elena plagiogranites are tonalities whilst the Nicoya diorite is a quartz diorite-tonalite. However, on the basis of their molecular normative An-Ab-Or compositions, all of our Nicoya and Santa Elena plagiogranites plot as trondhjemite and tonalite, respectively, while one Nicoya plagiogranite from the literature also plots as tonalite (Fig. 5). Plagiogranites of both Nicoya and Santa Elena are metaluminous according to the molecular $\text{Al}/(\text{Ca}+\text{Na}+\text{K})$ vs. $\text{Al}/(\text{Na}+\text{K})$ and SiO_2 vs. alumina saturation index (ASI, molecular $\text{Al}/(\text{Ca}+1.67\text{P}+\text{Na}+\text{K})$) (Fig. 6) (Shand, 1947; Zen, 1988) discrimination plots of Maniar and Piccoli (1989) and Frost and Frost (2008), respectively. Based on the $\text{Ga}(10^4)/\text{Al}$ vs. Zr plot of Whalen et al. (1987), all Santa Elena plagiogranites are I- and S-type granites (Chappell and White, 1974) whilst all but one Nicoya plagiogranite (with 57-63 wt. % SiO_2 which plots as an I- or S-type granite) are A-type granites (Fig. 7). Nevertheless,, as is shown below, it is apparent that both the

Nicoya and Santa Elena plagiogranite suites were derived via fractional crystallization and hence are most accurately termed as M-type (mantle derived) granites (Chappell and White, 1974).

5.3.2. REE patterns

Oceanic plagiogranites have been shown to form principally in two very different ways (Summary in 1), either by fractional crystallization from a hydrous gabbroic source or less commonly, via anatexis of mafic rocks. The particular formation mechanism can usually be discriminated on the basis of REE patterns (e.g., Pedersen and Malpas, 1984). Whereas plagiogranites formed by crustal melting will exhibit highly LREE fractionated patterns dissimilar to associated mafic lavas and intrusives (e.g., Pedersen and Malpas, 1984), plagiogranites formed via fractional crystallization will instead exhibit REE patterns with morphologies that mimic associated mafic rocks (e.g., Bonev and Stampfli, 2009). Via comparison of plagiogranite REE signatures and those of associated mafics, an origin via fractionation appears accurate for both the Nicoya and the Santa Elena plagiogranites (Fig. 8). Moreover, via comparison of Nicoya and Santa Elena plagiogranites with global plagiogranites constrained as forming via fractionation or anatexis (Fig. 9), the data appears to suggest formation of the former via fractional crystallization. Below we provide fractional crystallization and REE models to place constraints on the petrogenesis of Nicoya plagiogranites.

5.3.3. Fractional crystallization models and implications for origin of felsic magmas in oceanic settings

In order to provide additional evidence for the origin of the plagiogranites found in the Nicoya Peninsula within the CLIP oceanic suites, we produced fractional crystallization models

using rhyolite-MELTS (Gauda et al., 2012). For these calculations, liquid lines of descent (LLD) are plotted in Fig. 10, where every discontinuity in the line indicates a new crystallizing mineral phase. We input a primary magma composition derived from CLIP primitive sample BH11 (Hauff et al., 2000a) by Herzberg and Gazel (2009). The calculations were made using the QFM buffer appropriate for tholeiitic series (e.g., Zimmer et al., 2010). To evaluate the effect of pressure we used two models at 0.5 and 5 kbars, and to assess the effect of water we incremented water contents from anhydrous conditions to 1 wt%, keeping the pressure constant during each run. All the calculations were done at decreasing temperature intervals of 10 °C, starting at the liquidus temperature and ending at 600 °C.

The major element variations are controlled by crystallization of different mineral phases as temperature decreases and for oceanic suites is particularly important when the cotectic of plagioclase and pyroxene starts. When this cotectic is reached, it is reflected by the negative correlation between SiO₂ and Al₂O₃ vs. MgO (Figs. 10a, b). The relative abundance of Al₂O₃ will also increase as crystallization pressure increases, as the liquids in equilibrium with olivine+clinopyroxene will increase their Al₂O₃ content and this can lead to a higher modal plagioclase content (Herzberg, 2004). If plagioclase crystallized before clinopyroxene, then FeO_t and TiO₂ (not shown) will increase as these elements are not compatible in plagioclase (Zimmer et al., 2010). Finally, the CaO vs. MgO systematics can also be used to evaluate whether or not a melt has crystallized clinopyroxene because CaO contents increase during the L+olivine and L+olivine+plagioclase steps of crystallization and decrease as soon as the liquid starts to crystallize olvine+plagioclase+clinopyroxene. The sensitivity of CaO to pressure effects was evaluated by Langmuir et al. (1992), Herzberg (2004) and Madrigal et al. (2015). The felsic Nicoya samples are too fractionated to constrain their pressures of fractionation, but the rest of

the data are consistent with a range from shallow (0.5 bars) to relatively deep (5 kbars) fractionation sequences.

We explored different water contents as the effect of small amounts of H₂O which result in a displacement of the cotectic points due to the suppression of plagioclase crystallization relative to olivine and clinopyroxene is significant (e.g., Danyushevsky, 2001). The range of water from anhydrous to 1 wt% is necessary to explain our data falling into range of MORB (Asimow and Langmuir, 2003; Danyushevsky, 2001; Hirth and Kohlstedt, 1996) and plume-derived magmas from Hawaii (Dixon and Clague, 2001). Nevertheless, felsic (>65 wt. % SiO₂) MELTS model results with water contents of 1 wt% included primary hydrous phases (e.g., muscovite) not found in the Nicoya samples. Additionally, when modeled at pressures >5 kbars and 1% water, garnet resulted as a stable phase, not consistent with the composition of these samples. Therefore, we suggest that at least 0.5% wt water was necessary to produce the felsic magmas via fractional crystallization but not more than 1 wt%.

As a proof of concept we also produced fractional crystallization models using the REE contents of the same primitive melt (BH11, Hauff et al., 2000a) via Rayleigh Fractionation. We were able to successfully reproduce the composition of the plagiogranites in Nicoya by 85-90% crystallization of a liquid that left fractionated 40% olivine/orthopyroxene, 20% clinopyroxene, 20% plagioclase +10% spinel (Fig. 11). We acknowledge that this is of course not a unique solution but the importance of the internal consistency between the MELTS models and the simple REE fractionation model point towards fractional crystallization as the probable process that produced these leucocratic intrusions.

As a note of caution, MELTLS models satisfied the major element geochemistry and are based on thermodynamic parameterization of experimental work (see Gauda et al., 2012). The

REE modeling was done to confirm fractional crystallization as the possible process to produce the rocks but it is a forward modeling constrained not by thermodynamics but by trace element partition in theoretical phases. Nevertheless, the overall mineral phases used to model the REE partition are indeed suggested by MELTS, but the absolute modal abundances are model dependent.

5.3.4. Chemical constraints on tectonic environment of formation

On the triangular Hf-Rb/10-Ta(3) granite tectonic discrimination diagram of Harris et al. (1986) (not shown), all of our Nicoya plagiogranites ($n = 10$) plot within the ocean ridge granite field while one Nicoya plagiogranite sample from the literature plots within the within-plate granite domain, in this case related to an oceanic plateau. In contrast, our two Santa Elena plagiogranites plot within the volcanic arc granite field. Similar results are seen when the Nicoya and Santa Elena plagiogranites are plotted on the granite discrimination plots of Pearce et al. (1982). On all four plots (Y+Nb vs. Rb shown only in Fig. 10), the Santa Elena plagiogranites fall within the volcanic arc granite field whereas the Nicoya plagiogranites almost always fall within the ocean ridge granite domain (Fig. 12).

6. Discussion and conclusions

The chemistry of the Nicoya and Santa Elena plagiogranites suggest formation in a MOR/oceanic plateau and an arc environment, respectively. Our findings for the Santa Elena plagiogranites are consistent with the chemistry of associated Santa Elena mafic intrusives which also point to a magmatic arc origin (e.g., Gazel et al., 2006; Escuder-Virute et al., 2015). In the case of Nicoya, many studies have demonstrated a plume-component in the genesis of the Nicoya Complex and a linkage of Nicoya with the CLIP oceanic plateau (see Whattam and Stern,

2015). For example, on various tectonomagmatic plots, the Nicoya plagiogranites consistently plot with the MOR field but compositions do overlap into the within-plate granite field on some plots.

Radiometric age determinations of rocks of the Nicoya Complex have been reported by Sinton et al. (1997), Hauff et al. (2000a), and Hoernle et al. (2004) and ages of rocks comprising the Santa Elena Complex have been documented by Hauff et al. (2000a) and Madrigal et al. (2015). The study of Sinton et al. (1997) yielded $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 90-88 Ma with a weighted mean of 88.5 Ma from basalts and diabases of Nicoya whereas Hauff et al. (2000a) report $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 87.5 ± 1.8 Ma and 94.7 ± 1.8 Ma for a plagiogranite and tholeiitic basalt, respectively, of Nicoya. These ages are in very close agreement with our U-Pb SHRIMP dates for Nicoya plagiogranites which range from 88.5 ± 2.0 Ma to 90.9 ± 2.0 Ma. The study of Hoernle et al. (2004) reported much older $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 139 ± 1 Ma to 110.6 ± 0.9 Ma for Nicoya basalts which Whattam and Stern (2015), on the basis of geochemical considerations, considered to represent an earlier stage of volumetrically subordinate oceanic plateau construction. Rocks of the Santa Elena ophiolite have been dated by radiometric age dating methods by Hauff et al. (2000a) and Madrigal et al. (2015). The study of Hauff et al. (2000a) yields $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 109 ± 2.0 Ma and 124.0 ± 4.0 Ma for a pillow lava basalt and a layered gabbro, respectively whereas Madrigal et al. (2015) provided $^{40}\text{Ar}/^{39}\text{Ar}$ ages that range from ~131-121 Ma. Thus our U-Pb SHRIMP age of 125.3 ± 2.0 Ma is in close agreement with the basalt age of Hauff et al. (2000a) and the range of ages reported by Madrigal et al. (2015). Our ages for both the Nicoya and Santa Elena plagiogranites fall within the midrange of ages from the literature and represent the main magmatic phase of formation of the Nicoya and Santa Elena complexes at ~90 Ma and 125 Ma, respectively.

In conclusion, plagiogranites of the Nicoya Complex yield U-Pb SHRIMP ages of 88.5±2.0 Ma, 88.6±1.7 Ma, 88.9±2.1 Ma, 89.1±1.1 Ma and 90.9±2.0 Ma whereas a plagiogranite of the Santa Elena Complex yields a U-Pb SHRIMP age of 125.3±2.0 Ma. Both sets of ages are in close agreement with ages from the literature and represent the main magmatic stage of each complex. Plagiogranites from both the Nicoya and Santa Elena complexes are consistent with a fractional crystallization, as opposed to a partial melting, origin. In the case of the Nicoya Complex, fractional crystallization models suggest that the plagiogranites formed via 85-90% fractional crystallization from its parental mafic source.

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Figure Captions

Fig. 1 Map of Nicoya peninsula and the Nicoya and Santa Elena complexes and (inset) the Circum-Caribbean region. White stars with associated boxes demarcate sample numbers and their U-Pb ages from this study. The small box in the inset represents the region shown of the Nicoya peninsula in the main map.

Fig. 2 Concordia plots of U-Pb SHRIMP dated (a-e) Nicoya and (f) Santa Elena plagiogranites. In each plot the ²⁰⁸Pb-corrected/data-point error ellipses represent 68.3% confidence.

Fig. 3 Representative cathodoluminescence images of (a-f) Nicoya and (g, h) Santa Elena plagiogranite zircons.

Fig. 4 Th/U compositions of Nicoya and Santa Elena plagiogranite zircons.

Fig. 5 Molecular Ab-An-Or plot of Nicoya and Santa Elena plagiogranites.

Fig. 6 Distribution of Nicoya and Santa Elena plagiogranites on the SiO₂ vs. alumina saturation index (ASI) plot of Frost and Frost (2008). Samples with 57-63 wt. % SiO₂ are marked by crosses; all other samples have >63 wt. % SiO₂. Data from the literature for Nicoya is from Ragazzi (1996), Sinton et al. (1997), Beccaluva et al. (1999) and Hauff et al. (2000a) and data from the literature for Santa Elena is from Arias (2000).

Fig. 7 Distribution of Nicoya and Santa Elena plagiogranites on the 104Ga/Al vs. Zr plot of Whalen et al. (1987). Samples with 57-63 wt. % SiO₂ are marked by crosses; all other samples have >63 wt. % SiO₂.

Fig. 8 Chondrite normalized REE plots of (a) Nicoya and (b) Santa Elena plagiogranites. REE concentrations from Sun and McDonough (1989). Abbreviations within boxes within individual plots: int, intrusive; lit, literature (data).

Fig. 9 Chondrite normalized REE plots of (a) Nicoya and (b) Santa Elena plagiogranites versus ophiolitic plagiogranites formed via fractional crystallization (Semail, Troodos, Visnes) and anatexis (East Karmoy). Ophiolite data sources: East Karmoy and Visnes, Pedersen and Malpas (1984); Semail, Pallister and Knight (1981); Troodos, Thy et al. (1985). Abbreviations within boxes within individual plots: int, intrusive; lit, literature (data).

Fig. 10 Fractional crystallization models for the Nicoya plagiogranites.

Fig. 11 Fractional crystallization models using REE contents for the Nicoya plagiogranites.

Fig. 12 Compositions of Nicoya and Santa Elena plagiogranites on the Y+Nb vs. Rb plot of Pearce et al. (1982). Samples plotted have >63 wt. % SiO₂. Data from the literature for Nicoya is from Beccaluva et al. (1999) and Hauff et al. (2000a) and data from the literature for Santa Elena is from Arias (2000).

Table Captions

Table 1 ICP-MS whole rock major and trace element analyses of Nicoya and Santa Elena plagiogranites.

Table 2 U-Th SHRIMP analyses of zircons from Nicoya plagiogranites.

Table 3 U-Th SHRIMP analyses of zircons from Nicoya plagiogranites.

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Figure 1 Whattam et al. (2016)

Figure 2 Whattam et al. (2016)

Figure 3 Whattam et al. (2016)

Figure 4 Whattam et al. 2016

Figure 5 Whattam et al. (2016)

Figure 6 Whattam et al. (2016)

Figure 7 Whattam et al. (2016)

Figure 8 Whattam et al. 2016

Figure 9 Whattam et al. 2016

Figure 10 Whattam et al. (2016)

Figure 11 Whattam et al. (2016)

Figure 12 Whattam et al. 2016

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Sample No.	4-23-11-10	2-23-11-10	CN-6-14-7-1	1-23-11-10	OC-030512-1	OC-030512-2	OC-030512-3	OC-030512-4		SE-040611-9	SE-040611-A
Complex Lithology	Nicoya diorite	Nicoya plagiogranite	Nicoya plagiogranite	Nicoya plagiogranite	Nicoya plagiogranite	Nicoya plagiogranite	Nicoya plagiogranite	Nicoya plagiogranite		Santa Elena plagiogranite	Santa Elena plagiogranite
major oxides (wt. %)											
SiO ₂	62.23	67.41	63.75	70.25	62.90	65.76	65.21	66.07		75.65	73.88
TiO ₂	0.76	0.70	0.84	0.42	0.91	0.83	0.85	1.09		0.21	0.23
Al ₂ O ₃	11.43	11.75	12.97	12.83	13.03	12.95	12.34	11.54		14.45	12.91
FeO	11.71	9.56	9.67	5.14	12.91	8.01	11.14	8.89		0.74	2.00
MnO	0.10	0.09	0.11	0.07	0.12	0.10	0.11	0.18		0.02	0.03
MgO	0.45	0.33	0.33	0.19	0.29	0.31	0.35	0.70		0.38	0.29
CaO	2.96	2.73	3.12	2.81	3.55	3.43	3.23	4.64		5.22	5.34
Na ₂ O	4.97	5.19	5.74	5.38	5.38	5.53	5.51	4.61		3.40	3.25
K ₂ O	0.44	0.30	0.24	0.30	0.26	0.25	0.26	0.25		0.06	0.14
P ₂ O ₅	0.23	0.22	0.15	0.13	0.24	0.17	0.26	0.32		0.03	0.05
LOI	3.52	1.09	0.07	0.49	0.05	0.15	0.30	0.50		0.59	1.02
total	98.80	99.37	96.99	98.00	99.65	97.48	99.56	98.79		100.16	98.11
trace elements (ppm)											
Cu	4.2	0.4	59.3	2.1	0.6	bdl	bdl	bdl		1.9	0.4
Li	2.6	1.2	3.2	1.5	3.1	2.4	2.4	4.6		0.5	1.5
Cr	9.6	6.9	8.6	7.4	7.9	6.7	5.8	5.0		4.9	9.9
Co	20	6.6	6.9	3.5	8.3	6.1	7.3	9.7		2.8	2.2
Ni	1.1	0.6	21.7	0.7	0.7	0.7	0.6	1		4.3	2.9
Zn	67.9	33.1	61.1	35.2	83.1	61.3	49.2	88.3		79.2	0.6
Ga	19.5	24.8	27.5	29.8	26.7	25.4	23.3	23.3		14.2	14.6
Ge	2.2	1.7	2.1	1.7	2.3	1.9	1.8	2.1		1.0	1.5
Se	0.5	1.8	2.6	1.7	2.2	1.7	1.5	2.1		0.5	0.4
Rb	0.7	1.2	2.1	1.4	2.2	1.9	0.8	3.5		bdl	1.0
Sr	113	80.2	114	108	113	105	75.1	108		149	144
Y	33.1	90.3	88	90.5	91.9	85	55.3	79.1		38.5	27.7
Zr	117	363	425.0	425.0	396.0	370.0	271.0	387.0		45.0	35.0
Nb	5.6	17.2	20.9	11.0	24.1	17.8	16.3	14.3		0.2	0.1
Cs	0.62	0.65	0.66	0.66	0.64	0.64	0.56	0.64		0.62	0.65
Ba	38	91	101.0	91.0	126.0	122.0	119.0	84.0		54.0	16.0
La	4.19	15.8	17.20	16.60	22.40	16.40	13.40	22.40		1.72	1.31
Ce	12.20	42.3	45.30	45.40	59.50	44.50	36.60	54.80		4.49	3.39
Pr	1.99	6.5	6.72	6.92	8.76	6.64	5.63	7.72		0.81	0.64
Nd	11.7	34	35.30	36.40	44.70	35.60	30.10	39.30		5.39	4.36
Sm	4.5	11.00	11.60	12.10	13.80	11.70	10.00	12.20		2.76	2.15
Eu	2.13	3.44	3.78	4.10	4.06	3.92	3.29	3.71		0.77	0.82
Gd	5.47	14	14.00	15.30	15.90	14.50	12.60	14.40		4.18	3.37
Tb	1.02	2.52	2.63	2.81	2.82	2.60	2.24	2.64		0.86	0.69
Dy	6.74	16.7	17.20	18.10	17.90	16.60	14.50	17.00		6.06	5.05
Ho	1.42	3.55	3.57	3.79	3.72	3.45	3.00	3.53		1.35	1.09
Er	4.14	10.3	10.9	11.4	11.1	10.1	8.7	10.4		4.2	3.3
Tm	0.634	1.56	1.6	1.7	1.7	1.5	1.3	1.6		0.7	0.5
Yb	4.2	10	10.7	10.6	10.8	9.6	8.5	10.1		4.6	3.5
Lu	0.706	1.63	1.8	1.5	1.7	1.6	1.4	1.6		0.8	0.6
Hf	3.4	9.9	11.6	11.8	10.7	10.3	7.3	10.4		1.9	1.1
Ta	0.44	1.12	1.35	0.83	1.47	1.09	1.1	1.01		bdl	bdl
Pb	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl		bdl	bdl
Th	0.6	1.51	1.87	1.86	1.84	1.7	1.76	1.77		0.17	0.13
U	0.17	0.53	0.75	0.68	0.65	0.62	0.51	0.63		0.14	0.14
Sc	27	8	12	7	10	14	12	22		14	14
Be	0.7	1.6	1.8	1.6	1.8	1.6	1.5	1.5		0.4	0.3
V	38	bdl	bdl	bdl	bdl	bdl	bdl	bdl		13	11

Table 1 Whattam et al. (2016)

Table 2
U-Th SHRIMP analyses of zircons from Nicoya plagiogranites

Sample No.	Spot No.	$^{206}\text{Pb}^c$ %	U ppm	Th ppm	Th/U	$^{232}\text{Th}/^{238}\text{U}$	(1) $^{207}\text{Pb}^*/^{235}\text{U}$	$\pm$ %	(1) $^{206}\text{Pb}^*/^{238}\text{U}$	$\pm$ %	error corrected	(2) $^{206}\text{Pb}/^{238}\text{U}$ age
1-23-11-10	123_1.1	19.13	179	143	0.80	0.83	0.109	80	0.01485	6.7	0.5	94.4±6
1-23-11-10	123_2.1	33.45	88	35	0.39	0.41	0.127	89	0.01355	8.7	0.6	84.5±7
1-23-11-10	123_3.1	16.94	191	139	0.73	0.75	0.092	66	0.01363	5.0	0.8	87.1±3
1-23-11-10	123_4.1	32.18	79	28	0.36	0.37	0.116	97	0.01360	12.3	0.6	85.5±8
1-23-11-10	123_5.1	29.12	93	46	0.49	0.50	0.115	100	0.01438	9.4	0.6	90.9±8
1-23-11-10	123_6.1	28.14	81	37	0.46	0.47	0.130	81	0.01378	8.0	0.6	85.9±7
1-23-11-10	123_8.1	14.88	184	80	0.43	0.45	0.084	61	0.01400	4.3	0.5	90.1±4
1-23-11-10	123_9.1	18.02	175	114	0.65	0.67	0.104	65	0.01387	5.4	0.5	88.1±4
1-23-11-10	123_10.1	6.32	716	500	0.70	0.72	0.103	24	0.01392	1.8	0.7	88.4±1
1-23-11-10	123_11.1	23.10	130	67	0.52	0.54	0.085	113	0.01355	8.0	0.7	87.0±6
1-23-11-10	123_12.1	26.03	124	75	0.61	0.63	0.121	80	0.01418	7.5	0.6	89.2±6
1-23-11-10	123_13.1	12.24	195	438	2.25	2.32	0.115	190	0.01411	3.1	0.3	89.0±6

Sample No.	Spot No.	$^{206}\text{Pb}^c$ %	U ppm	Th ppm	Th/U	$^{232}\text{Th}/^{238}\text{U}$	(1) $^{207}\text{Pb}^*/^{235}\text{U}$	$\pm$ %	(1) $^{206}\text{Pb}^*/^{238}\text{U}$	$\pm$ %	error corrected	(2) $^{206}\text{Pb}/^{238}\text{U}$ age
2-23-11-10	223_1.1	1.95	481	325	0.68	0.70	0.095	9	0.01390	1.4	0.3	88.7±1
2-23-11-10	223_2.1	7.88	233	93	0.40	0.41	0.066	37	0.01387	2.5	0.6	90.3±2
2-23-11-10	223_2.2	7.06	335	157	0.47	0.48	0.081	41	0.01360	2.1	0.6	87.5±2
2-23-11-10	223_1.2	1.12	583	395	0.68	0.70	0.078	8	0.01302	5.8	0.5	83.8±4

Sample No.	Spot No.	$^{206}\text{Pb}^c$ %	U ppm	Th ppm	Th/U	$^{232}\text{Th}/^{238}\text{U}$	(1) $^{207}\text{Pb}^*/^{235}\text{U}$	$\pm$ %	(1) $^{206}\text{Pb}^*/^{238}\text{U}$	$\pm$ %	error corrected	(2) $^{206}\text{Pb}/^{238}\text{U}$ age
3-23-11-10	323_1.1	30.24	96	49	0.51	0.52	0.078	104	0.01169	6.8	0.7	78.8±5
3-23-11-10	323_2.1	8.36	273	174	0.64	0.66	0.124	25	0.01352	6.0	0.2	84.5±5
3-23-11-10	323_5.1	2.07	612	862	1.41	1.45	0.101	24	0.01433	1.7	0.3	91.4±1
3-23-11-10	323_6.1	7.54	273	140	0.51	0.53	0.097	27	0.01413	1.5	0.4	90.2±2
3-23-11-10	323_7.1	17.63	188	117	0.62	0.64	0.122	55	0.01402	5.7	0.6	88.0±5
3-23-11-10	323_9.1	5.81	379	450	1.19	1.22	0.102	43	0.01410	2.7	0.6	89.7±2
3-23-11-10	323_10.1	3.05	561	347	0.62	0.64	0.092	12	0.01405	0.9	0.3	90.0±0.9
3-23-11-10	323_11.1	21.00	152	59	0.39	0.40	0.091	91	0.01296	6.2	0.6	87.2±5
3-23-11-10	323_12.1	5.29	312	316	1.01	1.05	0.091	39	0.01418	1.9	0.7	90.9±1
3-23-11-10	323_14.1	9.63	272	139	0.51	0.53	0.105	40	0.01354	4.2	0.6	85.8±3
3-23-11-10	323_15.1	13.37	122	74	0.61	0.63	0.089	78	0.01376	5.7	0.5	88.2±5
3-23-11-10	323_16.1	15.39	202	87	0.43	0.45	0.090	71	0.01329	4.8	0.6	84.9±4
3-23-11-10	323_17.1	4.17	337	193	0.57	0.59	0.064	13	0.01347	1.6	0.8	87.7±0.8
3-23-11-10	323_18.1	20.20	175	88	0.50	0.52	0.129	62	0.01381	7.6	0.6	86.2±6
3-23-11-10	323_20.1	19.68	87	48	0.55	0.57	0.103	58	0.01344	5.6	0.5	85.2±4
3-23-11-10	323_21.1	5.96	459	337	0.73	0.76	0.073	49	0.01275	7.1	0.5	82.3±5

Sample No.	Spot No.	$^{206}\text{Pb}^c$ %	U ppm	Th ppm	Th/U	$^{232}\text{Th}/^{238}\text{U}$	(1) $^{207}\text{Pb}^*/^{235}\text{U}$	$\pm$ %	(1) $^{206}\text{Pb}^*/^{238}\text{U}$	$\pm$ %	error corrected	(2) $^{206}\text{Pb}/^{238}\text{U}$ age
4-23-11-10	423_1.1	17.36	344	301	0.87	0.90	0.076	63	0.01236	13.1	0.3	79.5±7
4-23-11-10	423_2.1	11.75	583	569	0.98	1.01	0.092	21	0.01341	2.5	0.3	85.6±2
4-23-11-10	423_3.1	9.95	471	584	1.24	1.28	0.041	103	0.01271	3.0	0.5	83.9±2
4-23-11-10	423_4.1	4.42	722	834	1.16	1.19	0.093	37	0.01396	1.7	0.8	89.3±1
4-23-11-10	423_6.1	8.29	705	1070	1.52	1.57	0.059	88	0.01294	4.0	0.4	84.4±2
4-23-11-10	423_7.1	4.68	748	1295	1.73	1.79	0.108	43	0.01369	5.9	0.2	86.6±4
4-23-11-10	423_8.1	30.13	1008	1363	1.35	1.40	0.031	182	0.01389	2.4	0.9	92.4±0.7
4-23-11-10	423_9.1	14.11	394	299	0.76	0.78	0.076	37	0.01245	11.5	0.3	80.1±7
4-23-11-10	423_10.1	4.12	1054	1409	1.34	1.38	0.070	73	0.01384	2.4	0.7	89.8±1
4-23-11-10	423_11.1	14.12	329	302	0.92	0.95	0.047	182	0.01238	5.3	0.7	81.3±4
4-23-11-10	423_13.1	6.28	519	568	1.09	1.13	0.052	51	0.01238	3.1	0.2	81.1±2
4-23-11-10	423_15.1	39.34	588	517	0.88	0.91	0.060	144	0.01332	14.6	0.5	86.9±7
4-23-11-10	423_16.1	12.09	469	662	1.41	1.46	0.105	68	0.01298	4.7	0.5	82.0±3
4-23-11-10	423_18.1	20.52	740	980	1.32	1.37	0.074	159	0.01290	6.3	0.7	83.2±3
4-23-11-10	423_19.1	13.49	429	520	1.21	1.25	0.094	43	0.01358	3.8	0.2	86.7±3

Sample No.	Spot No.	$^{206}\text{Pb}^c$ %	U ppm	Th ppm	Th/U	$^{232}\text{Th}/^{238}\text{U}$	(1) $^{207}\text{Pb}^*/^{235}\text{U}$	$\pm$ %	(1) $^{206}\text{Pb}^*/^{238}\text{U}$	$\pm$ %	error corrected	(2) $^{206}\text{Pb}/^{238}\text{U}$ age
CN-14-7-1	CN_1.1	7.42	546	807	1.48	1.53	0.108	85	0.01441	6.7	0.4	91.5±4
CN-14-7-1	CN_2.1	6.36	366	320	0.88	0.91	0.081	42	0.01310	4.3	0.5	84.2±3
CN-14-7-1	CN_3.1	9.65	317	368	1.16	1.20	0.103	65	0.01440	3.4	0.7	91.7±2
CN-14-7-1	CN_4.1	9.49	340	451	1.33	1.37	0.076	54	0.01340	2.8	0.2	86.5±2
CN-14-7-1	CN_0.1	0.81	1029	1267	1.23	1.27	0.079	14	0.01406	1.4	0.4	90.8±1
CN-14-7-1	CN_1.3	5.21	527	721	1.37	1.41	0.144	19	0.01488	1.2	0.4	92.6±1
CN-14-7-1	CN_4.2	17.00	110	85	0.77	0.80	0.085	98	0.01360	8.5	0.4	87.3±6
CN-14-7-1	CN_6.1	9.48	272	104	0.38	0.39	0.107	35	0.01471	2.5	0.5	93.6±3

Errors are 1-sigma; Pb^c and Pb^* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.14% (not included in above errors but required when comparing data from different mounts).
(1) Common Pb corrected by assuming $^{206}\text{Pb}/^{238}\text{U}$ - $^{208}\text{Pb}/^{232}\text{Th}$ age-concordance.
(2) Common Pb corrected by assuming $^{206}\text{Pb}/^{238}\text{U}$ - $^{207}\text{Pb}/^{235}\text{U}$ age-concordance.

Table 3
U-Th SHRIMP analyses of zircons from Santa Elena plagiogranites

Sample No.	Spot No.	$^{206}\text{Pb}^c$ %	U ppm	Th ppm	Th/U	$^{232}\text{Th}/^{238}\text{U}$	(1) $^{207}\text{Pb}^*/^{235}\text{U}$	± %	(1) $^{206}\text{Pb}^*/^{238}\text{U}$	± %	error corrected	(2) $^{206}\text{Pb}/^{238}\text{U}$ age
SE-040611-9	SE_1.1	18.11	122	40	0.33	0.34	0.150	64	0.01961	4.2	0.6	124±6
SE-040611-9	SE_3.1	2.24	114	57	0.50	0.52	0.127	7	0.01955	2.1	0.4	125±2
SE-040611-9	SE_4.1	11.94	78	24	0.30	0.31	0.061	86	0.02162	3.4	0.7	143±4
SE-040611-9	SE_5.1	23.36	66	18	0.27	0.28	0.116	61	0.01886	9.9	0.2	121±9
SE-040611-9	SE_6.1	10.69	122	51	0.42	0.43	0.123	64	0.01905	4.3	0.5	122±6
SE-040611-9	SE_7.1	13.38	75	22	0.30	0.31	0.137	64	0.02032	5.1	0.6	130±6
SE-040611-9	SE_8.1	15.39	176	66	0.37	0.39	0.077	102	0.02382	3.4	0.7	157±5
SE-040611-9	SE_9.1	2.53	357	202	0.57	0.59	0.137	18	0.02007	1.3	0.6	128±2
SE-040611-9	SE_10.1	8.99	230	56	0.24	0.25	0.148	25	0.02092	1.3	0.2	133±3
SE-040611-9	SE_11.1	15.16	58	13	0.23	0.24	0.193	53	0.02022	2.5	0.2	126±6
SE-040611-9	SE_12.1	28.68	71	18	0.26	0.26	0.343	35	0.02068	9.1	0.2	120±10
SE-040611-9	SE_13.1	18.72	88	31	0.35	0.36	0.115	146	0.01849	7.0	0.6	119±10
SE-040611-9	SE_14.1	19.62	81	30	0.38	0.39	0.116	72	0.01899	6.5	0.6	122±7
SE-040611-9	SE_15.1	11.29	57	15	0.27	0.28	0.178	41	0.01969	4.0	0.7	123±5
SE-040611-9	SE_16.1	5.60	316	186	0.59	0.61	0.144	23	0.01964	1.6	0.6	125±2
SE-040611-9	SE_17.1	31.86	65	24	0.36	0.38	0.235	65	0.01892	11.3	0.6	115±11
SE-040611-9	SE_17.2	9.87	155	61	0.39	0.40	0.140	43	0.01975	2.1	0.4	126±4
SE-040611-9	SE_18.1	6.17	270	88	0.32	0.34	0.120	35	0.01895	2.3	0.7	121±3
SE-040611-9	SE_19.1	6.01	148	45	0.30	0.31	0.140	26	0.01944	2.9	0.3	124±4
SE-040611-9	SE_20.1	7.01	148	60	0.41	0.42	0.122	36	0.01922	2.8	0.5	123±3
SE-040611-9	SE_22.1	8.69	281	126	0.45	0.46	0.116	37	0.01778	4.4	0.4	114±4

Errors are 1-sigma; Pb^c and Pb* indicate the common and radiogenic portions, respectively.
 Error in Standard calibration was 0.14% (not included in above errors but required when comparing data from different mounts).
 (1) Common Pb corrected by assuming $^{206}\text{Pb}/^{238}\text{U}$ - $^{208}\text{Pb}/^{232}\text{Th}$ age-concordance.
 (2) Common Pb corrected by assuming $^{206}\text{Pb}/^{238}\text{U}$ - $^{207}\text{Pb}/^{235}\text{U}$ age-concordance.

Table 3 Whattam et al. (2016)