Arc magmatic evolution and the construction of continental crust at the Central American Volcanic Arc system

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ABSTRACT

Whether or not magmatic arcs evolve compositionally with time and the processes responsible remain controversial. Resolution of this question requires the reconstruction of arc geochemical evolution at the level of a discrete arc system. Here, we address this problem using the well-studied Central American Volcanic Arc System (CAVAS) as an example. Geochemical and isotopic data were compiled for 1031 samples of lavas and intrusive rocks from the ~1100 km-long segment of oceanic CAVAS (Panama, Costa Rica, Nicaragua) built on thickened oceanic crust over its 75 million year lifespan. We used available age constraints to subdivide this data set into six magmatic phases: 75–39 Ma (Phase I or PI); 35–16 Ma (PII); 16–6 Ma (PIII); 6–3 Ma (PIV); 5.9–0.01 Ma (PVa arc alkaline and PVb adakitic); and 2.6–0 Ma (PVI, Quaternary to modern magmatism, predominantly ≪ 1 Ma). To correct for magmatic fractionation, selected major and trace element abundances were linearly regressed to 55 wt.% SiO$_2$. The most striking observation is the overall evolution of the CAVAS to more incompatible element enriched and ultimately continental-like compositions with time, although magmatic evolution took on a more regional character in the youngest rocks, with magmatic rocks of Nicaragua becoming increasingly distinguishable from those of Costa Rica and Panama with time. Models entailing progressive arc magmatic enrichment are generally supported by the CAVAS record. Progressive enrichment of the oceanic CAVAS with time reflects changes in mantle wedge composition and decreased melting due to arc crust thickening, which was kick-started by the involvement of enriched plume mantle in the formation of the CAVAS. Progressive crustal thickening and associated changes in the sub-arc thermal regime resulted in decreasing degrees of partial melting over time, which allowed for progressive enrichment of the CAVAS and ultimately the production of continental-like crust in Panama and Costa Rica by ~16–10 Ma.

1. Introduction

Subduction zone magmatism results primarily from the dehydration of subducted oceanic crust and sediment melting and the subsequent transfer of these liquids to the overlying mantle wedge where partial melting occurs (White and Patchett 1984; McCulloch and Gamble 1991; Plank and Langmuir 1993; Hawkesworth et al. 1993a, 1993b; Pearce and Peate 1995; Ishikawa and Tera 1997; Kimura et al. 2014). The diagnostic chemical signatures of subduction zone magmatism include: (1) abundant felsic rocks; (2) a tendency to minimize Fe-enrichment during magmatic fractionation; (3) elevated abundances of large ion lithophile elements (LILEs) relative to the light rare earth elements (LREEs); and (4) depletion of high field strength elements (HFSEs) (e.g. Arculus 1994) (see Table 1 for a list of the most common abbreviations and acronyms used here and their definitions). These characteristics are largely due to the fluid-mediated nature of convergent margin magmatism and to the fact that, in contrast to igneous activity at mid-ocean ridges and hotspots, arc magmatic activity stays in the same place relative to the underlying crust for tens of millions of years.

Study of arc igneous rocks must also consider the role of the underlying crust, because this crust can be involved in magmagenesis, obscuring the geochemical and isotopic signature of mantle-derived magmas. Thick granitic continental crust favours the establishment of MASH (melting, assimilation, storage, and homogenization, Hildreth and Moorbath 1988) zones, with massive involvement of especially the lower crust in the resultant magmas. Intra-oceanic arc (IOA) systems (see review of Stern 2010 and references therein) – where the crust is thinner, more mafic, and more refractory – are sites
Table 1. Abbreviations and definitions of commonly used terms (Whattam and Stern 2015).

| Abbreviation/| Definition |
|---------------|------------|
|BAB | Back arc basin |
|BCC | Bulk continental crust |
|CAVAS | Central American Volcanic Arc system |
|CLIP | Caribbean Large igneous Province (an OP) |
|GAA | Greater Antilles Arc |
|HFSE | High-field strength element (e.g., Nb, Zr, Ti) |
|HREE | Heavy REE |
|IBM | Izu-Bonin–Mariana (a convergent margin in the western Pacific) |
|IOA | Intra-oceanic arc (or magmatic arc) |
|IODE | International Ocean Drilling Program (now International Ocean Discovery Program) |
|LILE | Large ion lithophile element (e.g., Rb, Ba) |
|LREE | Light REE |
|MASH | Melting, assimilation, storage, and homogenization |
|MORB | Mid-ocean ridge basalt (pure asthenospheric melt) |
|OPB | Oceanic plateau basalt (plume basalt) |
|PI, ,...PVI | (Temporal) Phase I, Phase II...Phase VI |
|REE | Rare earth element |
|THI | Tholeiitic index: tholeiitic suites have THI > 1; calc-alkaline suites have THI < 1 |
|VAB | Volcanic arc basalt (subduction-modified basalt) |

where contributions from the crust of the overriding plate are minimized. IOAs are thus preferred for inferring subduction-related magmatic processes. IOAs represent the most important sites of juvenile, mantle-derived, continental crust formation and arc–continent collision and the subsequent accretion of arc-related terranes is believed to be key for the growth of continental crust (Taylor and McLennan 1985; Rudnick 1995; Rudnick and Fountain 1995). Approximately 85–95% of the mass of continental crust is estimated to have formed at magmatic arcs above subduction zones (Rudnick 1995; Barth et al. 2000).

It has been recognized since the earliest discussions of Plate Tectonics that convergent margin magmatism shows strong spatial controls, which are a function of slab depth, i.e. from the production of depleted tholeiites above shallow subduction zones to the generation of enriched alkali basalts over deep subduction zones (Kuno 1966; Dickinson and Hatherton 1967; Sugimura 1968; Gill 1970; Ringwood 1974). More recent studies demonstrated fundamental relations between subduction zone chemical systematics and variations in the mantle wedge melting regime (Plank and Langmuir 1988) and chemical variability as a function of slab or wedge processes (Turner and Langmuir 2015). It is less certain whether or not arc magmas evolve compositionally with time. Some early (Jakeš and White 1969, 1972; Jakeš and Gill 1970) and more recent (Jolly et al. 1998a, 1998b, 2001; duBray and John 2011; Zernack et al. 2012; Gazel et al. 2015) studies of the chemical evolution of magmatic arcs argued for evolution from early low-K tholeiitic magmas to later incompatible element-enriched, high-K calc-alkaline and shoshonitic magmatism. Jakeš and White (1972) suggested that the most important chemotemporal (chemical changes with time) trends exhibited by magmatic arcs include: a switch from the eruption of early tholeiites followed by later calc-alkaline and finally shoshonitic magmas; progressive enrichments in K and other fluid-mobile LILE elements such as Rb, Ba, and Sr and other large cations (Th, U, Pb) and LREE; increases in K2O/Na2O ratios; and decreases in iron enrichment and K/Rb ratios. Arculus and Johnson (1978) challenged this interpretation by pointing out several exceptions including a decrease in incompatible elements with time for the Cascades and Lesser Antilles. In a similar vein, recent studies of stratigraphically constrained tephras in IODP cores indicate that the composition of Izu-Bonin-Mariana arc magmas has changed very little over the past ~40 Ma (Lee et al. 1995; Bryant et al. 2003; Straub 2003; Straub et al. 2015).

Resolving the controversy as to why some convergent margin magmatic systems evolve with time whereas others do not is important for understanding convergent margin processes and how continents form. The first step is to reconstruct the magmatic history of the arc; the second step is to understand what this tells us about the processes controlling magma evolution, which could reflect variations in slab contributions, mantle contributions, crustal contributions, local tectonics, or all four. Our chemotemporal study of the Central American Volcanic Arc system (CAVAS) is restricted to the ~75–0 Ma arc segment constructed upon oceanic crust in Nicaragua, Costa Rica, and Panama; we do not consider the part of the arc in El Salvador and Guatemala, which may be built on the continental crust of the Chortis Block. Our studied time interval is identical to that of the study of Gazel et al. (2015), which also documents the physical and chemical evolution of the arc in Panama and Costa Rica. The study of Gazel et al. (2015) differs spatially from ours as theirs does not encompass Nicaragua or the Late Cretaceous Golfito Complex of southernmost Costa Rica. Moreover, the study of Gazel et al. (2015) does not include key geochemical data from the studies of Lissinna (2005) and Buchs et al. (2010), which provide important constraints on the geochemical composition of earliest arc magmas erupted in Panama and southernmost Costa Rica. Nevertheless, our results mostly support their conclusions.

Although a number of studies have documented the chemical variability in CAVAS magmas (e.g. Patino et al. 2000; Plank et al. 2002; Hoernle et al. 2008; Heydolph et al. 2012), all of these deal with magmatic activity, which spans a maximum of ~30 million years duration (30 Ma to the present); some of
these (e.g. Heydolph et al. 2012) encompass only Nicaragua and segments of the CAVAS to the west of Nicaragua constructed upon continental crust. Other studies have dealt with longer-duration studies of CAVAS evolution but only of Panama (Wegner et al. 2011). To date, no studies have explicitly considered the chemotemporal evolution of the entire segment of the CAVAS constructed on oceanic crust in Panama, Costa Rica, and Nicaragua. Here, we present the first synergistic chemotemporal treatment of the CAVAS from establishment by ~75 Ma to the present. We first demonstrate that many of the chemotemporal trends outlined by Jakeš and White (1972) hold true for the oceanic CAVAS system between 75 and 16 Ma (sometimes between 75 and 6 Ma), and show how this is reflected in trace element and isotope systematics. Second, we explain CAVAS chemotemporal evolution in terms of varying degrees and modes of melting; the nature and relative ‘depletedness’ of the source; relative contributions of fluids and sediments; subducted seamount and mantle plume contributions; and the role of major tectonic, tectonomagmatic, and oceano- graphic events over the course of CAVAS evolution. Our goal is to understand what the CAVAS teaches about arc magmatic evolution. This compilation thus serves two purposes: it represents a report on CAVAS arc evolution and it illustrates the challenges facing any effort to capture the long-term magmatic evolution of convergent plate margin igneous activity.

2. Synopsis of CAVAS magmatic history: distribution in space and time

The modern CAVAS volcanic front stretches ~1100 km along the western margin of the Caribbean plate from Costa Rica through Nicaragua, El Salvador, and Guatemala to the Guatemala–Mexico border at the southern margin of the North American plate (Figure 1). CAVAS also extended into Panama, but this part of the arc shut down within the last few millions of years. Unequivocal CAVAS magmatic activity began ~75 Ma (Buchs et al. 2010) (however see also Whattam and Stern 2015) when the Farallon Plate (now the Cocos Plate) began to subduct beneath thickened Caribbean Large Igneous Province (CLIP) oceanic plateau (e.g. Hauff et al. 2000b and references therein; Whattam and Stern 2015). Today, the CAVAS reflects the eastward subduction of the Cocos plate at ~70–85 mm/year beneath the western edge of the Caribbean plate (Carr et al. 2003).

The oldest CAVAS sequences (Phase I, PI) are best exposed in the 73–39 Ma Sona–Azuero Arc of western Panama and the 70–39 Ma Chagres–Bayano Arc of eastern Panama (Figure 2). The Golfito Complex was originally interpreted as a CLIP segment (Hauff et al. 2000b), but more recently as a 75–66 Ma arc segment (Buchs et al. 2010), an interpretation that we follow here on the basis of geochemical considerations (Section 4, see also Whattam and Stern 2015). Oligocene and early Miocene igneous rocks are best exposed in Costa Rica, western Nicaragua, and isolated regions in Panama (Figure 2). Middle and late Miocene arc sequences are broadly exposed west of the Canal Zone in central Panama, whereas late Miocene–Pliocene CAVAS sequences are best exposed in Costa Rica (Figure 2). Quaternary bimodal lavas and adakitic intrusions are concentrated in SE Costa Rica and western Panama and behind the volcanic front in NW Costa Rica (Figure 2). A detailed treatment of the chemotemporal evolution of the CAVAS over its 75 Ma history is provided in the Supplementary data.

Figure 1. (a) Present-day tectonic configuration of the Circum-Caribbean region (modified from Meschede and Frisch 1998). Abbreviations: CR, Costa Rica; LAA, Lesser Antilles Arc; GAA, Greater Antilles Arc; NIC, Nicaragua; PAN, Panama. (b) Sketch of Middle America showing the distribution of Chortis Block terranes and the Siuna Terrane of Nicaragua, El Salvador, and Honduras (modified from Rogers et al. 2007b). Abbreviations: COBB, Continental–oceanic basement boundary; ES, El Salvador; GUAT, Guatemala; MFZ, Motagua Fault Zone.
Figure 2. Detail of the study area (boxed region in Figure 1) showing the distribution of PI to PVI (75–0 Ma) magmatism in Panama, Costa Rica, and Nicaragua as bracketed by this study. Note that the present-day CAVAS volcanic front trends to the northwest from northwest Nicaragua through Honduras, El Salvador, and Guatemala to the southwest margin of the North American Plate as shown in Figure 1. An approximate boundary between the Southern Chortis Terrane (SCT) to the southwest and the Siuna Terrane to the northeast is shown for southern Nicaragua (see text and Rogers et al. 2007a, 2007b). Distribution of PI–PVI magmatism in Panama is based on the studies of Lissinna (2005); Buchs et al. (2010); Wegner et al. (2011); Rooney et al. (2010); Farris et al. (2011); Montes et al. (2012a, 2012b); and Whattam et al. (2012 and references therein). Distribution of PI–PVI magmatism in Costa Rica is based on the studies of MacMillan et al. (2004); Gazel et al. (2005, 2009); and Buchs et al. (2010). Distribution of PII–PVI magmatism in Nicaragua is based on the studies of Ehrenborg (1996); Elming et al. (2001); Plank et al. (2002); and Sagnor et al. (2011). Distribution of PV magmatism in Panama and Costa Rica is based on the studies of Defant et al. (1991a, 1991b, 1992); Drummond et al. (1995); MacMillan et al. (2004); and Lissinna (2005); see also Gazel et al. (2009 and references therein). Distribution and extent of the Neogene arc (i.e. light green-blue shade that encompasses our PII–IV magmatism) are from Elming et al. (2001) and Buchs et al. (2010). Phases I–V magmatic products shown as circles as opposed to larger shaded regions indicate either a smaller extent of magmatism or situations in which in the extent of magmatic products is uncertain. In the case of Phase IV magmatism, each red circle represents a discrete Quaternary (2.6–0 Ma) volcano (locations and distribution taken from Mann et al. 2007). Distribution of the Seamount Province to the immediate west of the Cocos Ridge is from Gazel et al. (2009) and location and distribution of adakite localities are as shown in Wegner et al. (2011). Abbreviations of localities, discrete volcanoes, and oceanic features: BDT, Bocas del Toro; BH, Bahia Pina; Cord de Pan, Cordillera de Panama; Cord de Tal, Cordillera de Talamanca; CI, Coliba Island; EB, El-Baru (volcano); EV, El Valle (volcano); LY, La Yeguada (volcano); MJ, Maje; MN, Managua; PC, Panama City; PI, Pearl Islands; PQ, Petaquilla; PROV, Province; SJ, San Jose. Abbreviations of arcs and arc-related units and formations: AG, Aquacate; C-B, Chagres-Bayano; CY, Coyoel; DM, Dominical (unit); GF, Golfito; LC Fm, La Cruz Formation; PR, Paso Real; S-A, Sona-Azuero; SP, Sarapiquí; TD, Trinidad; TM Fm, Tamarindo Formation; TR, Talamanca Range. Abbreviations of units interpreted as CLIP oceanic plateau: HD, Herradura; NC, Nicoya Complex; TG, Tortugal. Abbreviations (legend): ALI, adakitic-like intrusives (Whattam et al. 2012); CLIP, Caribbean Large Igneous Province (oceanic plateau). Superscripts: 1, Buchs et al. (2010); 2, Elming et al. (2001); 3, Hoernle et al. (2008).

Central America is a collage of several terranes, continental in the north (Chortis Block) and oceanic (CLIP) in the south (Figure 2) (e.g. Mann et al. 2007). To avoid biasing our reconstruction of magmatic evolution because of the interaction of arc magmas with pre-existing continental crust, we limited our investigation to the ~1100 km-long portion of the CAVAS constructed on oceanic crust in Nicaragua, Costa Rica, and Panama. We note here that the exact nature (continental vs. oceanic) of segments of the basement of Nicaragua and the contact between continental and oceanic

3. Geochemical, geochronological, and isotope data set compilation, manipulation, and sources

Detailed methods are provided in the Supplementary data. Below we summarize our methodology for data compilation, manipulation, and filtering.

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basement units are controversial and we use the interpretations of Venable (1994) and Rogers et al. (2007a, 2007b) for westernmost Nicaragua. These workers conclude that both the Siuna Terrane of western Nicaragua and the westernmost Chortis Block (southern Chortis Terrane, SCT, Figure 1b) comprise Early Cretaceous volcanic arc fragments constructed on oceanic basement that accreted to the eastern Chortis Terrane and the Central Chortis Block, respectively, in the Early Cretaceous (e.g. see Table 2 of Rogers et al. 2007b; see also Baumgartner et al. 2008). CAVAS samples from Nicaragua used in our study (Ehrenborg 1996; Elming et al. 2001; Plank et al. 2002; Gazel et al. 2011; Saginor et al. 2011) are limited to those from northwestern, southwestern, and eastern Nicaragua, which comprise the Siuna Terrane and the SCT (Figure 2) and hence are the ones interpreted as having been constructed upon an oceanic basement. We do not consider CAVAS samples from the north of the Siuna Terrane in Nicaragua, or the ones from El Salvador and Guatemala, which may be underlain by Palaeozoic and older continental crust of the Chortis Block. Conversely, there is little dispute as to the nature of the basement beneath Panama and Costa Rica, which is universally considered as a CLIP oceanic plateau (e.g. Hauff et al. 2000a, 2000b).

We compiled all relevant geochemical, geochronological, and isotopic data available in the literature for CAVAS samples from Panama, Costa Rica, and Nicaragua. Collective (i.e. Panama plus Costa Rica, Panama plus Costa Rica plus Nicaragua, or Costa Rica plus Nicaragua) linearly regressed data (see Section 3.3. below) for each temporal phase is provided in Table 2; Supplementary Table S1 provides an expanded version of Table 2 at the level of specific region. Raw geochemical data and the sources for these data are provided in Supplementary Table S2. Sources for the isotope data sets are provided in the caption for relevant figures in Section 5 and also in Supplementary Table S3. We amassed 1031 pertinent samples with a full set of major element chemistry analyses but with varying completeness of trace element and isotopic data. Both volcanic (n = 922) and plutonic (n = 109) samples are included. (In cases where it was not specified whether the sample was volcanic or plutonic, we assume these to be volcanic in our calculation of relative abundance of each. Samples described as basaltic dikes are considered as plutonic). As it is difficult to determine where the magmatic front was over the 75 million year lifespan of the CAVAS, we have not distinguished between magmas emplaced at the magmatic front from those emplaced behind the magmatic front except for Quaternary lavas. We do not think this significantly

![Table 2](https://example.com/table2.png)
Table 2. (Continued).

| Phase I | Phase II | Phase III | Phase IV | Phase V | Phase VI |
|---------|----------|-----------|----------|---------|---------|
| Zr      | 68.44    | 86.16     | 100.33   | 129.88  | 137.38  |
| Nb      | 2.45     | 4.74      | 1.60     | 3.05    | 5.56    |
| K       | 3.25     | 5.25      | 2.34     | 4.12    | 1.52    |
| Ba      | 241.11   | 468.84    | 773.85   | 876.82  | 924.96  |
| La      | 6.34     | 10.29     | 14.94    | 19.24   | 25.66   |
| Ce      | 2.12     | 3.22      | 4.31     | 4.46    | 5.04    |
| Pr      | 4.13     | 6.24      | 9.02     | 10.87   | 12.69   |
| Nd      | 1.14     | 1.91      | 2.63     | 3.25    | 4.27    |
| Sm      | 0.57     | 0.68      | 0.70     | 0.84    | 1.07    |
| Eu      | 3.33     | 4.05      | 4.43     | 4.82    | 5.34    |
| Gd      | 2.57     | 3.45      | 4.13     | 4.67    | 5.47    |
| Tb      | 0.35     | 0.46      | 0.48     | 0.55    | 0.63    |
| Dy      | 2.34     | 2.46      | 2.54     | 2.62    | 2.71    |
| Ho      | 0.81     | 0.92      | 1.05     | 1.14    | 1.23    |
| Er      | 2.36     | 3.01      | 3.21     | 3.41    | 3.61    |
| Tm      | 0.35     | 0.46      | 0.48     | 0.55    | 0.63    |
| Yb      | 2.34     | 2.46      | 2.54     | 2.62    | 2.71    |
| Lu      | 0.81     | 0.92      | 1.05     | 1.14    | 1.23    |
| ΣREE²   | 50.81    | 70.73     | 88.61    | 93.99   | 102.02  |
| Pb      | 1.44     | 2.88      | 4.08     | 4.67    | 5.21    |
| Th      | 0.86     | 1.74      | 2.18     | 2.47    | 2.83    |
| U       | 0.08     | 0.22      | 0.36     | 0.42    | 0.49    |
| V       | 269.67   | 245.21    | 234.85   | 217.42  | 134.92  |
| K/Rb    | 642.76   | 739.22    | 841.43   | 726.31  | 546.31  |
| Ba/La   | 28.04    | 42.42     | 51.81    | 63.94   | 45.57   |
| Pb/Zr   | 0.11     | 0.26      | 0.30     | 0.37    | 0.41    |
| Ba/Zr   | 3.52     | 4.57      | 3.91     | 4.06    | 4.16    |
| U/Th    | 0.03     | 0.11      | 0.14     | 0.18    | 0.22    |
| Pb/Ce   | 0.01     | 0.01      | 0.01     | 0.01    | 0.01    |
| Sr/Nd   | 25.83    | 23.93     | 32.21    | 37.77   | 37.09   |
| Ba/Th   | 28.17    | 32.25     | 35.74    | 43.92   | 50.53   |
| Ba/Nb   | 98.58    | 109.97    | 105.89   | 107.17  | 107.87  |
| Th/Nb   | 0.35     | 0.04      | 0.03     | 0.04    | 0.04    |
| Zr/Nb   | 27.98    | 27.63     | 27.48    | 27.84   | 27.76   |
| Ba/Ti   | 0.05     | 0.05      | 0.05     | 0.05    | 0.05    |
| Zr/Y    | 3.05     | 3.66      | 4.22     | 4.67    | 5.07    |
| Nb/Yb   | 1.05     | 1.93      | 2.44     | 2.85    | 3.21    |
| La/Nb   | 2.59     | 2.93      | 2.26     | 2.64    | 2.90    |
| La/Sr   | 2.26     | 2.12      | 2.34     | 2.50    | 2.74    |
| La/Yb   | 2.11     | 0.24      | 0.33     | 0.45    | 0.59    |
| Ti/V    | 18.74    | 21.83     | 21.54    | 21.43   | 21.58   |

Bold text of some linearly regressed values indicate increasing values of the listed incompatible major and trace elements and ratios that increase from the previous phase; PI data are also in bold text for visual aid. See Supplementary data for methods of linear regression. Abbreviations: NA, not analyzed or not applicable; NC (for THI), not calculable where total number of FeO was < 1. Superscripts: 1, 2 for THI and ΣREE are to indicate that errors for these are STD (for all other element and element ratios, uncertainties are standard error, SE, of the mean).

Notes: (1) This table represents a condensed version of Supplementary Table 1, which provides the same regressed data in addition to region specific regressed data (i.e. regressed data provided at the level of region—Panama, Costa Rica, etc.). (2) The data in this table are represented as large, light grey ‘x’s in our various geochemical plots. The coloured symbols represent distinct regions and the data for these are provided in Supplementary Table 1 (see Note 1 above). (3) FeO₄ and FeO₃ are based on non-normalized abundances of FeO and MgO. (4) References for datasets are provided in Section 3.2. (5) Raw data from which values were calculated are provided Supplementary S2.
biases the data as there is no evidence to suggest ‘behind arc’ activity prior to Quaternary time.

3.1. Temporal subdivisions

Based on radiometric and biostratigraphic ages reported in the literature, we temporally subdivide CAVAS magmatism into six phases at 75–39 Ma (Phase I, PI, Panama, Costa Rica), 35–16 Ma (PII, Panama, Costa Rica, Nicaragua), 16–6 Ma (PIII, Panama, Costa Rica, Nicaragua), 6–3 Ma (PIV, Costa Rica, Nicaragua), 5.9–0.02 Ma (PVI, the Quaternary and modern volcanic front, Costa Rica, Nicaragua) (Figure 2). Further details on age bracketing are provided in the Supplementary data. We are unsatisfied with the coarse temporal resolution in PI (75–39 Ma), PII (35–16 Ma), and PIII (16–6 Ma); one positive outcome of this study would be to stimulate future integrated geochronologic studies of CAVAS PI, II, and III. Geochemical analyses were compiled for lavas and intrusives of the aforementioned temporal phases PI (n = 139), PII (n = 67), PIII (n = 122), PIV (n = 19), PV (PVA, n = 15, PVb, n = 86), and PVI (n = 583) (Table 2) provides mean data linearly regressed to 55 wt.% SiO$_2$ (see Section 3.3. below). We include chemical data only for those samples that are confidently assigned to a particular formation and thus age range.

3.2. Geochemical data set compilations

Details of geochemical data set compilations employed including references are provided in the Supplementary data.

3.3. Geochemical data manipulation

It would be optimal to correct all data to primitive basalt, with Mg$\# = 65$, but the paucity of these samples makes this impractical. To compare the compiled suites of geochemical data, selected major and trace element concentrations are expressed as X$_{55}$, where X represents the linearly regressed oxide or trace element. This parameter must be interpreted thoughtfully, given the processes that could contribute to CAVAS lava compositional diversity. We discuss the implications of interpreting the chemotemporal trends of regressed elemental abundances in Section 6.1.

![Figure 2](image-url)

Figure 2. Total alkali-silica (TAS) (Le Bas et al. 1986) classification of (a) PI and PII (75–39 Ma, 35–16 Ma), (b) PIII and PIV (16–6 Ma, 6–3 Ma) and (c) PV and PVI (5.9–0.02 Ma, 2.6–0 Ma) lavas and intrusives. Abbreviations in (b): BDT, Bocas del Toro; TR-TIS, Talamanca Range-Talamancas Intrusive Suite (see Figure 2 for locations). See Table 2 for the number of samples of each phase plotted here and in subsequent plots. References for all phases here and in succeeding figures are provided in the Supplementary data.

![Figure 3](image-url)

Figure 3. Total alkali-silica (TAS) (Le Bas et al. 1986) classification of (a) PI and PII (75–39 Ma, 35–16 Ma), (b) PIII and PIV (16–6 Ma, 6–3 Ma) and (c) PV and PVI (5.9–0.02 Ma, 2.6–0 Ma) lavas and intrusives. Abbreviations in (b): BDT, Bocas del Toro; TR-TIS, Talamanca Range-Talamancas Intrusive Suite (see Figure 2 for locations). See Table 2 for the number of samples of each phase plotted here and in subsequent plots. References for all phases here and in succeeding figures are provided in the Supplementary data.

large ranges in MgO at a given SiO$_2$ content, e.g. PI lavas and intrusives that range from ~3.8 to 7.5 wt.% MgO at 55 wt.% SiO$_2$ further justifies our normalization to silica. The regressed oxide and trace element concentrations are expressed as X$_{55}$, where X represents the linearly regressed oxide or trace element. This parameter must be interpreted thoughtfully, given the processes that could contribute to CAVAS lava compositional diversity. We discuss the implications of interpreting the chemotemporal trends of regressed elemental abundances in Section 6.1.
In all but one case, the data sets employed provide non-normalized major element compositions; in these cases we have filtered the data such that only samples that yield major element concentrations that sum to 97–102 wt.% (excluding volatiles) are used, in an identical manner to the CentAm Database (Jordan et al. 2012). In the one case where data adjusted to sum to 100% is presented (Plank et al. 2002), we filtered the data such that only those with <3% loss on ignition were used (46 of 48 samples). An exception to the 97–102 wt.% rule is our use of three Phase IV (6–3 Ma) Nicaraguan samples (CO-Nic-6, CO-Nic-17, C51, Saginor et al. 2011), which have sums between 96.42 and 96.75 wt.%. As there is only one Phase IV Nicaraguan sample (C-06-Nic-3) with 97–102 wt.% oxides, we also use these three other samples. Samples with trace element data only were not used because these could not be normalized to 55 wt.% SiO₂. Geochemical data from the modern volcanic front in the CentAm Database is subjected to various other filters (see Jordan et al. 2012, at http://www.earthchem.org/grl). In our geochemical plots, oxides are shown in wt.% and sums are recalculated to 100% anhydrous. Trace element concentrations are expressed in ppm.

4. Results

4.1. Chemotemporal trends

A major concern is whether or not it is useful to treat the chemotemporal evolution of an arc as a whole, or subdivide it further. To address this concern, we consider both collective CAVAS chemotemporal trends (changes in magma chemistry with time irrespective of geographic location) and region-specific chemotemporal trends. We emphasize that some chemotemporal trends, particularly for PI magmatism, which was the longest of all phases (~36 million years), must reflect an aggregate of shorter episodes and trends that require more radiometric ages to be resolved. For example, PI magmatism appears to have begun at about 75 Ma in western Panama in the Sona–Azuero Arc and easternmost Costa Rica in the Golfito Arc. Magmatism continued until about 39 Ma in the Sona–Azuero Arc (according to Lissinna 2005), but the lifespan of the Golfito Arc was much shorter, terminating by ~66 Ma (see Buchs et al. 2010 and references therein). Similarly, Chagres–Bayano magmatism in eastern Panama did not begin until about 70 Ma and ended at about the same time (39 Ma) (Wegner et al. 2011) as the Sona–Azuero Arc. Thus, PI magmatism reflects complex aggregations of trends characteristic of three chemically and temporally discrete arc segments. For this reason, we have

Figure 4. SiO₂ versus K₂O plot (Peccerillo and Taylor 1976) of (a) PI and PII (75–39 Ma, 35–16 Ma), (b) PII and PIV (16–6 Ma, 6–3 Ma), and (c) PV and PVI (5.9–0 Ma, 2.6–0 Ma) lavas and intrusives. In (d) the lines represent best-fit linear trend lines of collective data (i.e. all geographic regions within a given phase) of phases I, II, III, IV, and VI. The relatively low R² values of PI data are likely the result of element mobility and alteration and in general for all phases because the data is collective, e.g. linearly regressed best-fit lines for discrete regions generally yield much higher R² values (see Supplementary Figure S1). Abbreviations in top box: bas/gabb, basalt, gabbro; b-a/ g-a, basaltic- and gabbroic-andesite; and/dior, andesite, diorite; grandior and gran, granodiorite, granite.

| Phase, interval (Ma) | K₂O wt.% | R²  |
|----------------------|-----------|-----|
| PI (75–39)           | 0.61      | 0.09 |
| PII (35–16)          | 1.01      | 0.51 |
| PIII (16–6)          | 1.45      | 0.45 |
| PIV (6–3)            | 1.89      | 0.18 |
| PV (2.6–0)           | 2.11      | 0.45 |
4.2. Synopsis of major element chemical evolution

Below we summarize the main features identified from our compilations to delineate CAVAS major element evolution (Figures 3–6). We provide a more detailed treatment of major element chemotemporal evolution in the Supplementary data.

CAVAS evolved from an early, primitive, mafic construct to an increasingly fractionated and enriched arc up until the end of PIII (Nicaragua) or PIV (Costa Rica) (Figures 3–6). Mean SiO$_2$ increased only slightly over the first three stages for Panama from 56.3, 58, and 58.4 wt.%; whereas it dropped from 52.3 to 51.4 wt.% between PI and PII for Costa Rica, before climbing to 59 wt.% during PIII (Nicaragua mean SiO$_2$ remained the same during PII (55.5 wt.%) and PIII (55.1 wt.%)) (Figure S1). The first three phases span ~75 to 6 Ma, or ~92% of the CAVAS history. The overall trend towards increasingly fractionated magmas reversed in the last 6 Ma, as the arc erupted more mafic lavas during PIV, with a mean of 51.4 wt.% SiO$_2$ (Costa Rica and Nicaragua record mean SiO$_2$ of 51 and 53 wt.%, respectively). CAVAS erupted increasingly enriched lavas over the first ~69 million years of its history, from low-K lavas during PI to medium-K lava during PII to high-K lavas.

Figure 5. (a) Subalkaline affinity discrimination diagram on the basis of SiO$_2$ versus FeO$^t$/MgO (Miyashiro 1974) superimposed with the high-, medium-, and low-Fe subdivisions of Arculus (2003) of lavas and intrusives of (from bottom to top) PI and PII, PIII and PIV, and PV and PVI magmatism. Two PI PAN, one PIII NIC, one PVa, and two PVI CR with high silica plot outside the plot with FeO$^t$/MgO $>$ 8. (b) Subalkaline affinity discrimination diagram on the basis of total alkalis-FeO$^t$-MgO (AFM, Irvine and Baragar 1971) superimposed with the trends of increasing arc maturity (from 1 to 4, as labelled in the top plot) from Brown (1982) of (from bottom to top) PI and PII; PIII and PIV; and PVa and PVI lavas and intrusives. Arc maturity trends are from the following arc systems: 1: Tonga-Marianas, South Sandwich; 2: Aleutians-Lesser Antilles; 3: New Zealand, Mexico, Japan; and 4: Cascades, northern Chile, New Guinea. (c) Tholeiitic index ($\text{Fe}_{5.0}$/$\text{Fe}_{8.0}$ where $\text{Fe}_{5.0}$ and $\text{Fe}_{8.0}$ represent the average FeO$^t$ of lavas and intrusives with 3–5 and 7–9 wt. % MgO, respectively) (Zimmer et al. 2010) versus time of phases in which THI was calculable (see Supplementary data). The light grey ‘X’s represent mean THI of both or all regions for a particular (temporal) phase.
during PIII (Figure 4). During the late Miocene (PIV), the CAVAS began to erupt less-enriched magmas, earlier in Nicaragua than in Costa Rica and PIV through PVI was characterized by medium-K calc-alkaline magmatism. A plot of tholeiitic index (THI, Zimmer et al. 2010, see Supplementary data for further details of THI) demonstrates that the overall enrichment of the CAVAS was accompanied by a trend from early tholeiitic and calc-alkaline affinities to stronger calc-alkaline affinities apart from PIII Nicaragua, which exhibits a weakly tholeiitic affinity (Figure 5c).

Collectively, the CAVAS evolved over its 75 million year lifespan from an initial low-K, tholeiitic to a weakly calc-alkaline system in its infancy during PI (75–39 Ma) to a medium-K calc-alkaline system in PII (35–16 Ma) to a high-K calc-alkaline system during PIII (16–6 Ma). After normal arc magmatism ended in Panama by 6 Ma, magmatic activity was dominated by the production of adakites and arc alkaline basalts in Panama and Costa Rica and a return to medium-K calc-alkaline igneous activity in Costa Rica and Nicaragua thereafter. PVI lavas in particular returned to greater iron enrichment.

Figure 6. Concentrations of (a) TiO$_2$, (b) P$_2$O$_5$, and (c) K$_2$O and the ratios of (d) K$_2$O/Na$_2$O of magmatic products of PI (75–39 Ma), PII (35–16 Ma), PIII (16–6 Ma), PIV (6–3 Ma), PV (5.9–0.02 Ma), and PVI (2.6–0 Ma) and phases further discriminated into regions linearly regressed to 55 wt.% SiO$_2$ versus time. MORB and OIB values are from Sun and McDonough (1989) and mean Izu–Bonin–Mariana volcanic arc basalt (IBMVAB) data is calculated from data as compiled by Jordan et al. (2012, N = 517). In (a) and (b), the upper limit (mean plus standard error of the mean, SE) of TiO$_2$ of PVa arc alkalic basalts is 1.68 and the linearly regressed P$_2$O$_5$ of the PVa arc alkalic basalts is 0.69 ± 0.04 (SE). Note also that in (a), the TiO$_2$ of PII PAN and CR overlap and in (b–d), P$_2$O$_5$, K$_2$O, and K$_2$O/Na$_2$O almost completely overlap in PII PAN, CR, and NIC, thereby making symbol discrimination difficult. The light grey 'X's here and in subsequent plots represent the mean of both or all three regions of a particular phase. In most instances, the vertical uncertainty (SE of the mean of regressed compositions) is smaller than the symbol size. To avoid clutter, the horizontal SE (age) is shown for phases only (i.e. this is not shown for regional within-phase data).
CAVAS lavas show similar increases in other incompatible major elements in addition to potassium between PI and PIII, especially P₂O₅ and K₂O/Na₂O for Costa Rica and Panama, but less so for K₂O and K₂O/Na₂O for Nicaragua between PI and PIII (Figure 7). A clear divergence between Costa Rica and Nicaragua is seen during PIV (6–3 Ma), whereas Costa Rica continues to more enriched P₂O₅, K₂O, and K₂O/Na₂O, and Nicaraguan magmas decrease to lower concentrations (Figures 6b–6d). The behaviour of TiO₂ is more complex because it is incompatible until magnetite precipitates. Apart from Nicaragua exhibiting anomalously high TiO₂ relative to Panama and Costa Rica, other normalized major incompatible element concentrations of Panama, Costa Rica, and Nicaragua were nearly identical during PII.

4.3. Trace element chemical evolution

4.3.1. Incompatible element trends

Mean abundances of all LILEs, Th, U, Pb, Zr, LREEs, LREEs/HREEs, and ZRREEs (normalized to 55 wt.% SiO₂) increase between PI (75–39 Ma) and PII (16–6 Ma) and usually until 3 Ma (PIV, 6–3 Ma), with a maximum exhibited by PVa adakites before decreasing slightly in Quaternary lavas (PIV, 2.6–0 Ma) (Figures 7 and 8, Table 2). For example, Ba₅₅ rises from PI (~240 ppm) to PII (~470 ppm), PIII (~770 ppm), and PIV (~880 ppm) before reaching a maximum in PVa arc alkalic basalts (~900 ppm) and PVb adakites (~980 ppm); subsequently, PVI arc basalts record a Ba₅₅ of 640 ppm, intermediate to that of PII and PIII (Figure 7b, Table 2). The remaining fluid-mobile LILEs (Rb, Sr; Figures 7a and 7c) and K demonstrate similar trends. Trends for LILEs could partially reflect greenschist-facies alteration-derived mobility (e.g. K, Rb, Ba) and the effects of plagioclase fractionation (Sr); however, the fact that alteration-resistant incompatible element concentrations also increase with time suggests that the trends mostly reflect an overall progressive enrichment of incompatible elements in CAVAS magmas.

Regressed Th, U, Pb, and Zr concentrations show evolutionary trends that are similar to those of the LILEs, with progressive increases between PI and PIV (Th₅₅, U₅₅) (Figures 7d and 7e) or PI and PIII (Pb₅₅, Zr₅₅) (Figures 7f and 7g), with a maximum reached in the PVa adakites or PVb arc alkali lavas in the case of U₅₅.

LREE₅₅ (La₃₉–Nd₃₉) (Ce₅₅ shown only in Figure 8a), LREE₅₅ fractions (La₅₅/Sm₅₅, La₅₅/Yb₅₅) (Figures 8b and 8c), and ΣREE₅₅ (Figure 8d) collectively increase similarly from PI to PIV with a maximum exhibited by the PVa adakites followed by a drop back to approximately PIV abundances during PVI.

Figure 7. Concentrations of (a) Rb, (b) Ba, (c) Sr, (d) Th, (e) U, (f) Pb, and (g) Zr of magmatic products of PI, PII, PIII, PIV, PV, and PVI linearly regressed to 55 wt.% SiO₂ versus time. References for MORB, OIB, and mean IBM (arc basalt) and other relevant details are given in the caption for Figure 8 and the value for bulk continental crust (BCC) is from Rudnick and Gao (2003). Mean oceanic plateau basalt (OPB, thick grey line) is calculated from data of references provided in the Supplementary Document.

The aforementioned trends with time are summarized in collective and region-specific chondrite-normalized REE and N-MORB-normalized plots on Figures 9 and 10, respectively. The most striking feature of the
Concentrations and ratios of (a) Ce, (b) La/Sm, (c) La/ \( \Sigma \)REE, and (d) \( \Sigma \)REEs of magmatic products of PI, PII, PIII, PIV, PV, and PVI linearly regressed to 55 wt.\% SiO\(_2\) versus time.

Collective plots is the progressive enrichments in linearly regressed LREEs (La-Nd), LREE fractionations (La/Sm, La/Yb), \( \Sigma \)REE, and all but the least incompatible elements (Figures 9a and 8c) as also demonstrated in Figures 6-8. Compositions of the CAVAS ultimately became 'continental-like' by PIII11 or certainly by PIV (6-3 Ma) (Figures 9, and 9d). The plots in Figure 9 also demonstrate that the progression to bulk continental crust (BCC) compositions was gradual and not sudden.

It is important to note, however, that when data are parsed into discrete regions, although Panama and Costa Rica usually follow progressive enrichments with time as described above, Nicaragua does not, as is readily apparent in Figure 10. For example, concentrations of Th, U, and Zr decrease between PII and PIII Nicaragua, whereas Pb remains unchanged during this interval, in contrast to Costa Rica and Panama, which (apart from U, which remains unchanged in Costa Rica between PI and PII) show increases in these elements between PI and PII (Figure 7). Similarly, when parsed into region, LREEs, LREE fractionations, and \( \Sigma \)REE deviate from overall trends, suggesting progressive enrichment. For example, only \( \Sigma \)REEs exhibit higher concentrations with time in both Costa Rica and Panama between PI and PII; LREE fractionations generally stay the same during this interval apart from PII Panama, which exhibits anomalously high La/Sm (Figure 8). Only slightly increased LREE fractionations and \( \Sigma \)REEs are shown by Nicaragua between PII and PIII, before moderate to significant drops in Ce, LREE fractionations, and \( \Sigma \)REEs are recorded during PIV. In contrast, Ce, LREE fractionations, and \( \Sigma \)REEs show significant positive spikes during PIV in Costa Rica before dropping to values similar to Nicaragua during PVI and Costa Rica and Panama during PII.

Similarly, when PI-IV and PVI data are parsed by region and chondrite-normalized REEs and N-MORB-normalized incompatible plots are considered (Figure 10), a number of salient features are evident: (1) Regressed, mean chondrite-normalized REEs and N-MORB-normalized trace element patterns of all three PI arc segments (Golfito Complex, Sona-Azuero, and Chagres-Bayano) fall within the range of compositions of 98-82 Ma western Costa Rica units interpreted as CLIP (Figures 10a and 10b). This demonstrates similar sources for PI arc segments and the CLIP (as verified by Pb and Nd isotopes, Section 4). (2) The similarity of the Golfito N-MORB-normalized incompatible element signature with that of the Sona-Azuero and Chagres-Bayano segments and its prominent negative Nb anomaly coupled with LILE enrichment (Figures 10a and 10b) clearly favours its interpretation as an arc segment (Buchs et al. 2010) as opposed to a plateau segment (Hauff et al. 2000b). (3) Apart from minor exceptions, the chondrite-normalized REEs and N-MORB-normalized patterns of PII Panama, Costa Rica, and Nicaragua are remarkably similar (Figures 10c and 10d). This suggests that magmas for all three arc segments were likely derived from similar sources during PII. (4) BCC-like compositions are achieved in Panama and Costa Rica arguably during PIII (16-6 Ma) and certainly by PIV (Figures 10e-10h). (5) Nicaragua chemotemporal evolution began to diverge from Costa Rica and Panama during PII (Figures 10e and 10f). Whereas Costa Rica and Panama PIII lavas became more enriched than PII, Nicaragua PIII lavas changed little from PII compositions. (6) Chemotemporal divergence between Costa Rica and Nicaragua is most obvious in PIV when Costa Rica again continued to more enriched compositions and Nicaragua again did not (Figures 10g and 10h). (7) N-MORB-normalized incompatible element patterns of PVI (2.6-0 Ma) Costa Rica and Nicaragua are similar (Figures 5j and 5r); PII thus marks the 'resetting' of production of magmas with more depleted compositions similar to those generated during PIII or even earlier.
The REE and N-MORB-normalized plots discriminated by region and discrete PI arc units (Figure 10) show subtle intra-phase differences not listed above. For example, Figures 10a and b illustrate that the 68–39 Ma Chagres–Bayano Arc lavas of eastern Panama more closely resemble average Izu–Bonin–Mariana (IBM) volcanic arc basalt (VAB) than do lavas from the ~75–66 Ma Golfito segments. Despite this and other minor region-specific differences, the regressed incompatible trace element data demonstrate that CAVAS magmas were initially generated from a depleted mantle source, which was also strongly influenced by plume contributions (see below). The CAVAS changed little over the first half of its lifespan (during PI, 75–39 Ma); segments in Panama, Costa Rica, and Nicaragua were all similar during PII (35–16 Ma), but magma compositions diverged thereafter.

**Figure 9.** (a, c) Chondrite-normalized REEs and (b, d) N-MORB-normalized incompatible element plots of incompatible and REE concentrations of collective (a, b) PI, PII, PIV, PV, and PVI magmatic products linearly regressed to 55 wt.% SiO$_2$ and (c, d) PI and PIV from (a) and (b) versus Bulk Continental Crust (BCC, 60.2 wt.% SiO$_2$, Rudnick and Gao 2003) and mean Izu–Bonin–Mariana volcanic arc basalt composition (as compiled by Jordan et al. 2012, where mean IBM VAB is based on the number of samples with a full suite of REE). References for these tectonomagmatic suites are the same in succeeding figures. Chondrite and N-MORB abundances are from Nakamura (1974) and Sun and McDonough (1989), respectively.

The REE and N-MORB-normalized plots discriminated by region and discrete PI arc units (Figure 10) show subtle intra-phase differences not listed above. For example, Figures 10a and b illustrate that the 68–39 Ma Chagres–Bayano Arc lavas of eastern Panama more closely resemble average Izu–Bonin–Mariana (IBM) volcanic arc basalt (VAB) than do lavas from the ~75–66 Ma Sona-Azuero and 75–66 Ma Golfito segments. Despite this and other minor region-specific differences, the regressed incompatible trace element data demonstrate that CAVAS magmas were initially generated from a depleted mantle source, which was also strongly influenced by plume contributions (see below). The CAVAS changed little over the first half of its lifespan (during PI, 75–39 Ma); segments in Panama, Costa Rica, and Nicaragua were all similar during PII (35–16 Ma), but magma compositions diverged thereafter.

**4.3.2. Trends in magma enrichment/depletion and subduction additions**

Arc magmatic evolution can reflect changing: slab contributions; mantle wedge compositions; degrees of mantle melting; degrees of crustal melting; or a combination of these processes. Incompatible element ratios that gauge source fertility such as Zr/Y and Nb/Yb are useful for elucidating source evolution, i.e. changes in the degree of partial melting or fertility of the source. $Zr_{55}/Y_{55}$ (Figure 11a) and $Nd_{55}/Yb_{55}$ (Figure 11c) both increase with time between PI and the end of PIV in magmatic rocks of Panama and Costa Rica. When parsed into region however, increases in both Zr/Y and Nb/Yb between PI and PII Costa Rica are slight and the collective shift to higher Nb/Yb during PII is due to Panama, which exhibits anomalously high Nb/Yb (~3). The most significant shifts to higher Zr/Y and Nb/Yb occurred between PII and PIV in Costa Rica. As there is no evidence of the presence of garnet in the source of any CAVAS igneous rocks except for PV adakites and arc alkali basalts, higher Zr/Y and Nb/Yb probably represent either a shift to more enriched sources or lesser degrees of partial melting; conversely, as these ratios decrease in Nicaragua between PII and PIII, this suggests either shifts to higher degrees of partial melting or tapping of a more depleted source or both.
CAVAS PI La$_{55}$/Sm$_{55}$ and La$_{55}$/Yb$_{55}$ are similar to OPB in PI; by PII both ratios meet or exceed those of IBM VAB, although the more LREE-enriched nature of Panama PII lavas is apparent (Figure 8). Similarly, Zr$_{55}$/Y$_{55}$ of PII Panama is equivalent to that of mean OPB, whereas PII Costa Rica and Nicaragua are slightly less enriched with values intermediate to that of MORB and OPB (Figure 11a). Apart from the PVa alkalic

**Figure 10.** (a, c, e, g, i) Chondrite-normalized REE and (b, d, f, h, j) N-MORB-normalized incompatible plots of incompatible and REE concentrations (a, b) PI, (c, d) PII, (e, f) PIII, (g, h) PIV and (i, j) PVI magmatic products of Panama, Costa Rica, and Nicaragua parsed into regions and in (a) distinct arc segments. In (a, b) the 98–82 Ma western Costa Rica units interpreted as CLIP comprise the Nicoya Complex (Sinton et al., 1997; Hauff et al. 2000b), and the Herradura and Tortugal complexes (tholeiitic basalts and diabases only, $n =$ number of samples with a complete suite of REE analyses, Hauff et al. 2000b). In (c, d) ALI represents PII ~32–19 Ma adakitic-like intrusives (Whattam et al. 2012) that formed subsequent to the shutdown of PI and via partial melting of mafic arc substrate (see text). Chondrite and N-MORB abundances are from Nakamura (1974) and Sun and McDonough (1989), respectively.
basalts and PVb adakites, which have higher regressed Zr/Y than BCC (~7) and even ocean island basalt (OIB) (9.7) in the case of the adakites (Zr_{55}/Y_{55} of 10.2), CAVAS Zr_{55}/Y_{55} is much less than BCC. Nevertheless, it is evident that both Panama and Costa Rica evolved towards BCC-like compositions during PII with Zr_{55}/Y_{55} intermediate to OPB and BCC, whereas Nicaragua Zr_{55}/Y_{55} decreased slightly in PII. A similar trend is seen in Zr_{55}/Nb_{55} and Nb_{55}/Yb_{55}, which reflect source depletion and/or the degree of partial melting. Overall, these trends demonstrate a shift to strong enrichment beneath Costa Rica, but only slight enrichments in Panama and Nicaragua between 35 and 16 Ma. During PIV, dramatic changes are recorded with divergence between Costa Rica and Nicaragua. Whereas PIV Costa Rica records low, BCC-like concentrations of Zr_{55}/Nb_{55} (16) akin to the PVb adakites (18), PIV Nicaragua alternatively records by far the highest Zr_{55}/Nb_{55} of any phase or region (61). An identical pattern is seen in Nb_{55}/Yb_{55} with PIV Costa Rica magmas recording the highest ratios (5) and Nicaragua the lowest ratios (0.42). This further demonstrates a dramatic compositional divergence between 6 and 3 Ma igneous rocks in Costa Rica and Nicaragua, the possible causes of which are discussed in Section 6.3.3.

Also plotted on Figure 11 (d) is La_{55}/Nb_{55}, which gauges the ‘depth’ of the negative Nb anomaly and is ~1 or less for magmas formed away from subduction zones, e.g. La/Nb of OIB and MORB are 0.8 and 1.1, respectively (Figure 11d). Collectively, La_{55}/Nb_{55} varies little from PI to PIII (2.1–2.6), but jumps to higher values in PIV Costa Rica (4.1), similar to the PVb adakites (4.2) and Nicaragua (5.4), before falling back to values similar to PI–PII in PVI Costa Rica and Nicaragua (2.2, collectively) (Figure 11d, Table 2). PVa alkali basalts record a very low OIB-like La_{55}/Nb_{55} of 0.8.

Ratios of specific fluid-mobile element to HSFE (Sr/Nd, Pb/Ce, U/Th, Ba/La, Ba/Th, Ba/Nb, and Th/Nb) are useful for inferring changes in subducted slab contributions and are plotted on Figure 12 to illustrate how this influence on the CAVAS source has changed over time. These plots generally show increases between PI–PII and PII–PIV, but when considered on the basis of discrete region it is apparent that there is little change in Panama and Costa Rica and the most significant changes are in Nicaragua, which generally show large jumps in these ratios between PII and PIV or PII and PIII. Sr_{55}/Nd_{55} collectively increases from PI (0.11, 3.39, 25.8) to PII (0.26, 5.45, 31.1) to PIII (0.31, 7.74, 33.2) to PIV (0.41, 9.33, 37.8) and is the only ratio that also increases when parsed into regions (Figure 12a). CAVAS U/Th in Panama and Costa Rica scatters with no hint of a trend and is broadly higher than mean IBM VAB even in PI (Figure 12c). However, Pb_{55}/Ce_{55} increases from PI (0.10) to PII (0.13) to PIII (0.14) before dropping to a value (0.08) lower than that of PI during PVI (Figure 12b) and enrichment is dominated by Nicaragua with much higher Pb/Ce than Panama and Costa Rica during PII–PIV. CAVAS Pb_{55}/Ce_{55} never reaches as high a mean as IBM VAB (Figure 12b), but by PII Nicaragua Pb/Ce is identical to that of mean IBM VAB and by PIV it is identical to BCC.

Fluid-mobile Ba and melt-mobile Th are good tracers of total and shallow subducted slab inputs, especially when compared with La and Nb (Pearce and Peate 1995). B_{55}/La_{55}, B_{55}/Th_{55}, B_{55}/Nb_{55}, and Th_{55}/Nb_{55} versus time are also plotted in Figure 12. Variations in Ba/Th in the CAVAS have been interpreted as reflecting differences in the amount or composition of sediments over time (Patino et al. 2000). Ba/Th in general reflects shallow additions of subduction-related fluids to the mantle source (Pearce et al. 2005) (Figure 12e). CAVAS B_{55}/Th_{55} increases from PI (280) to PII (326) to PIII (355) before subsequently dropping to values near those of IBM VAB during PIV, PV, and PVI (Figure 12e, Table 2). However, and similar to other slab contributions

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**Figure 11.** Ratios of (a) Zr/Y, (b) Zr/Nb, (c) Nb/Yb, and (d) La/Nb of magmatic products of PI, PII, PIII, PIV, PV, and PVI linearly regressed to 55 wt.% SiO₂. In (a) the Zr_{55}/Y_{55} of PVb adakites plots outside of the plot 10.23 ± 0.33 and in (c) the PVa arc alkaline basalts and PVb adakites plot outside the plot with Nb_{55}/Y_{55} of 28.56 ± 2.44 and 6.79 ± 0.50, respectively.
discussed above, this collective progression in Ba/Th (and Ba/La) is the influence of Nicaragua (Figures 12d and 12e). For example, Ba/Th remains essentially the same in Panama (~200–300) during PI–PIII and in Costa Rica, although Ba/Th increases slightly between PI and PII (from ~425–450), this ratio drops suddenly in PIII to a value (~250) similar to that of Panama. (Ba/Nb) and deep (Th/Nb) subduction additions (Elliot et al. 1997; Pearce et al. 2005) (Figures 12f and 12g) show no increases between PI and PII and only slight increases in PIII before jumping to high values in PIV. Whereas PIV Ba/Nb is unchanged from PIII in Costa Rica, Ba/Nb jumps to an extremely high value in PIV in Nicaragua (702). Th/Nb is much higher in both PIV Costa Rica and Nicaragua than in PIII Costa Rica and Nicaragua. Similar to other trends described above, PVI Ba/Nb and Th/Nb drop, similar to or slightly less than those of PI-PIII. PVa arc alkaline basalts show low, OIB-like Ba/Nb and Th/Nb and the PVb adakites show Ba/Nb similar to PIII and Th/Nb similar to PIV. The significance in the difference in trends displayed by Ba/Th versus Ba/Nb and Th/Nb is explored in Section 6.

5. Radiogenic isotope trends

We compiled available data for radiogenic isotopes Sr, Nd, and Pb. We do not emphasize Sr isotopic compositions as these are vulnerable to alteration. As Nd and Pb isotopes are much less affected by alteration and record the most obvious trends in CAVAS isotopes source evolution (Figures 13–15), we restrict our discussion here to these isotopes, but provide details of Sr isotopes in the Supplementary data. There are no Hf isotope data for pre-PVI CAVAS sequences, but these should start to appear as LA-ICP-MS zircon geochronology of the region advances. Sources for the compiled isotope data sets are listed in the captions for Figures 13–15.

5.1. Pb isotopes

Raw isotope data (Sr, Nd, Pb) (and the sources for these data, in addition to being provided in the captions of Figures 13–15) is provided in Supplementary Table S3. We show the initial $^{206}$Pb/$^{204}$Pb versus $^{208}$Pb/$^{204}$Pb plots of PI–PVI in Figure 13. Similar to other isotope plots presented (Figures 14 and 15, Supplementary Figure S4), we compare the composition of PI lavas and intrusives with those of the 98–82 Ma western Costa Rica igneous units (at Nicoya, Herradura, and Tortugal, see Figure 2 for locations) (Sinton et al. 1997; Hauff et al. a).
Figure 13. $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ isotope data for (a) PI (75–39 Ma) CAVAS magmatic products of Panama and Costa Rica versus lavas from 98–82 Ma western Costa Rica igneous units that include Nicoya, Herradura, and Tortugal (Sinton et al. 1997; Hauff et al. 2000a, 2000b) (locations are shown on Figure 2), which are interpreted by most as CLIP or ‘plume- and arc-related’ (PAR, by Whattam and Stern 2015, see text); 80–60 Ma accreted OIB in western Costa Rica (Hauff et al. 2000b); and 2.8 Ma lavas of the Galapagos Islands (i.e. Galapagos Plume, GP, White et al. 1998); and CAVAS magmatic products of (b) PII–PIV (35–3 Ma), (c) PVa (arc alkaline basalts, 5.90–0.01 Ma) and PVB (adakites, 4.20–0.15 Ma), and (d) PVI (2.6–0 Ma) in Panama, Costa Rica, and Nicaragua. In (a) the PI Sona-Azuero Arc (SAA) samples from central Panama are discriminated from all others from the Chagres-Bayano Arc in eastern Panama to highlight the compositional differences. Also in (a) two accreted OIB samples from Osa (OSA6 and OSA16, Hauff et al. 2000b) and SAA (central Panama, light yellow) samples from central Panama are discriminated from all others from the Chagres-Bayano Arc in eastern Panama to highlight the compositional differences. Also in (a) two accreted OIB samples from Osa (OSA6 and OSA16, Hauff et al. 2000b) exhibit very low $^{206}\text{Pb}/^{204}\text{Pb}$ of 37.946 and 38.025 and plot of the diagram. Note that in (d), as the PVI samples from northwest Nicaragua might have been constructed on continental as opposed to oceanic basement (see Section 1), these have been discriminated (open triangles) from samples of southwest Nicaragua constructed on oceanic basement. Moreover, for visual clarity to see clearer the compositional differences between central versus northwest Costa Rica during PVI, samples from Central Costa Rica (pink squares) are discriminated from those of northwest Costa Rica. Geographical segmentation of PVI magmatism in Costa Rica and Nicaragua (e.g. central Costa Rica, NW Nicaragua) is based on the geographical segmentations of Hoernle et al. (2008, their Figure 1); an exception is our use of ‘eastern Nicaragua’, which comprises samples from the eastern margin of Nicaragua between ~12.3 to 12.6° N and ~83.7 to 84.0° E (e.g. Cuakra Hill, Pearl Lagoon from Gazel et al. 2011). Isotope data from the CAVAS are from Gavel et al. (2009, PII–PIV, Costa Rica); Gazel et al. (2011, PIV, PVA, PVB, PV, Costa Rica); Hoernle et al. (2008, PVA, PVB, Panama; PVA southern and central Costa Rica BVF, PVB southern Costa Rica; PVI NW, central and southern Costa Rica VF; PVI, southwest, and northwest Nicaragua; and the Miocene Costa Rica and Miocene Nicaragua fields); Wegner et al. (2011) (PI–PVA, PV, Panama); the GEOROC data base at: http://georoc.mpch-mainz.gwdg.de/georoc/ (PVI, Costa Rica, and Nicaragua; only dated samples that yield ages of Quaternary are plotted); and the CentAm Database version 1.02 at: http://www.earthchem.org/grl.databases (PVI, Costa Rica, and Nicaragua, as compiled by Jordan et al. 2012). Fields for the subducting Cocos and Coliba ridges (CCR, or Central Galapagos Domain, CGD), Seamount Province (SP, or Northern Galapagos Domain, NGD), and Cocos/Coliba Plate are from Hoernle et al. (2000) and Werner et al. (2003) (as presented in Hoernle et al. 2008). The compositions of (subducting) Cocos sediments are from Feijenson et al. (2004) and the depleted mantle (DM) composition is from Werner et al. (2003; see Gazel et al. 2009 for details). The boundaries of the stippled field with horizontal lines represent mixing lines that connect the three compositional end-members (DM, depleted mantle, SP, and CCR, Cocos and Coliba ridges) required to explain the isotopic variations. In (a) and (b) the numbers beside some PI, PII, and PIII Panama samples represent ages in Ma (from Wegner et al. 2011). The boxes inset in (b) and (d) represent the summaries of temporal isotopic changes without the symbols (the box in (b) represents the summary of (a) and (b) and the box in (d) represents the summary of (d) only). Abbreviations: BVF, behind volcanic front; CCR, Cocos-Coliba ridges; CGD, Central Galapagos Domain; NGD, Northern Galapagos Domain; SP, Seamount Province; VF, volcanic front.

2000a, 2000b), interpreted by most as CLIP oceanic plateau fragments or as (hybrid) plume- and arc-related units generated soon after subduction initiation at the CAVAS via melting of a mixed, plume- and subduction-modified source (Whattam and Stern 2015). We do this particularly as trace element chemistry of PI magmas

2000b, 2000b), interpreted by most as CLIP oceanic plateau fragments or as (hybrid) plume- and arc-related units generated soon after subduction initiation at the CAVAS via melting of a mixed, plume- and subduction-modified source (Whattam and Stern 2015). We do this particularly as trace element chemistry of PI magmas
exhibits a clear affinity for 98–82 Ma units interpreted as CLIP (see Section 4, main text).

Based on isotope and radiometric data amassed for the ~73–69 Ma Sona-Azuero (based on the radiometric age data of Wegner et al. 2011 only), ~70–39 Ma Chagres-Bayano, and the ~20–7 Ma Cordilleran arc complexes of Panama (which encompass PI–PIII of this study) and comparison of their Pb isotope compositions with those of CLIP (from data of Kerr et al. 1997, 2002; Hauff et al. 2000a), Wegner et al. (2011) demonstrated: (1) an overlap in initial 206Pb/204Pb versus initial 204Pb/204pb of the older arc systems with the CLIP; and (2) a shift to

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Figure 14. 206Pb/204Pb versus 143Nd/144Nd isotope data for (a) PI (75–39 Ma) CAVAS magmatic products of Panama and Costa Rica versus 98–82 Ma western Costa Rica units, which include Nicoya, Herradura, and Tortugal (Sinton et al. 1997; Hauff et al. 2000b) and which are interpreted by most as CLIP or as plume- and arc-related units generated soon after subduction initiation at the CAVAS (Whattam and Stern 2015); 80–60 Ma accreted oceanic island basalt (OIB) units in western Costa Rica that comprise the Burica, Osa, and Burica units (Hauff et al. 2000b; see also Hoernle et al. 2002; Hoernle and Hauff 2007; Buchs et al. 2009, 2011); and the Galapagos Plume (GP) at 90 Ma, 60 Ma (fields at 90 and 60 Ma from Hauff et al. 2000a), and 2.8 Ma (i.e. the Galapagos Islands, White et al. 1998); and CAVAS magmatic products of (b) PII–IV (35–3 Ma), (c) PVa (arc alkaline basalts, 5.90–0.01 Ma) and PVb (adakites, 4.20–0.15 Ma), and (d) PVI (2.6–0 Ma) in Panama, Costa Rica, and Nicaragua. In (a): the PI Sona-Azuero Arc (SAA) samples from central Panama are differentiated from the Chagres-Bayano Arc in eastern Panama to highlight the compositional differences; BUR and TAP stand for Burica (an accreted OIB unit in western Costa Rica) and Tortugal alkali picrites, respectively. In (a) and (b) the numbers beside some PI, PII, and PIII Panama samples represent ages in Ma (from Wegner et al. 2011). In (b) the 26–6 Ma CRVF field demarcates samples from the central Costa Rica Miocene volcanic front (superscript ‘H’ for Hoernle et al. 2008). The boxes inset of (b) and (d) represent summaries of temporal isotopic changes without the symbols (the box in (b) represents the summary of (a) and (b) and the box in (d) represents the summary of (d) only). In (d) the geographical segmentation of PV magmatism in Costa Rica and Nicaragua (e.g. central Costa Rica, northwest Nicaragua) is based on the geographical segmentations of Hoernle et al. (2008, their Figure 1); an exception is our use of ‘eastern Nicaragua’, which comprise samples from the eastern margin of Nicaragua between ~12.3 to 12.6° N and ~83.7 to 84.0° E (e.g. Cukra Hill, Pearl Lagoon from Gazel et al. 2011). Isotope data from the CAVAS are from Gazel et al. (2009, PII–PVI, Costa Rica); Gazel et al. (2011, PIV, PVa, PVb, PV, Costa Rica); Hoernle et al. (2008, PVa, PVb, Panama; PVa southern and central Costa Rica BVF; PVb southern Costa Rica; PVI NW, central and southern Costa Rica BVF; PV, southwest and northwest Nicaragua; and the Miocene Costa Rica and Miocene Nicaragua fields); Wegner et al. (2011) (P-IPII, PVb, Panama); the GEOROC data base at: http://georoc.mpch-mainz.gwdg.de/georoc/ (PVI, Costa Rica, and Nicaragua; only dated samples that yield ages of Quaternary are plotted); and the CentAm Database version 1.02 at: http://www.earthchem.org/grl.databases (PVI, Costa Rica, and Nicaragua, as compiled by Jordan et al. 2012). Fields for the subducting Cocos and Coiba ridges (CCR, or Central Galapagos Domain, CGD), Seamount Province (SP, or Northern Galapagos Domain, NGD), and Cocos/Nazca Plate are from Hoernle et al. (2000) and Werner et al. (2003) (as presented in Hoernle et al. 2008). The compositions of (subducting) Cocos sediments are from Feigenson et al. (2004) and the depleted mantle (DM) composition is from Werner et al. (2003); see Gazel et al. 2009 for details). Other abbreviations not defined above: CBA, Chagres-Bayano Arc; CCR, Cocos–Coiba ridges; CGD, Central Galapagos Domain; NGD, Northern Galapagos Domain; SAA, Sona-Azuero Arc.
more radiogenic Pb (higher \(^{206}\)Pb/\(^{204}\)Pb and \(^{208}\)Pb/\(^{204}\)Pb) with time. This plateau-like affinity of the oldest arc samples (Figure 13a) is not surprising as plume emplacement was likely the catalyst for the initiation of the CAVAS (plume-induced subduction initiation, or PISI, Whittam and Stern 2015) and hence early subduction tapped a strongly plume-modified mantle source. Initial Pb isotopic compositions evolve with time during PII to PIV, but show increasingly distinctive regional variations, with Nicaragua always being less radiogenic than Costa Rica–Panama. Similar to the trend to enriched sources with time explained above, Hoernle et al. (2008) and Gazel et al. (2009, 2011) demonstrated a similar trend in Costa Rica after 6 Ma, which is location dependent (Feigenson et al. 2004; Goss and Kay 2006; Hoernle et al. 2008; Gazel et al. 2009, 2011) (Figures 13c and 13d). For example, whereas northwest PVI Costa Rica lavas plot similarly to older PIV Costa Rica magmas (compare Figures 13b and 13d), with relatively low \(^{206}\)Pb/\(^{204}\)Pb (~18.6–19.1) and \(^{208}\)Pb/\(^{204}\)Pb (~38.2–38.8), PVI lavas from central and northeast Costa Rica exhibit higher \(^{206}\)Pb/\(^{204}\)Pb (~19.0–19.3) and \(^{208}\)Pb/\(^{204}\)Pb (~38.7–39.1), with the most enriched samples overlapping the compositional field defined by the subducting Seamount Province (Figure 13d, see location of province on Figure 2). This along-arc isotopic provinciality is one of the main pieces of evidence given that subducted seamounts modified the Costa Rica mantle source after 6 Ma (Hoernle et al. 2008; Gazel et al. 2009, 2011). These workers also demonstrated the low \(^{206}\)Pb/\(^{204}\)Pb and \(^{208}\)Pb/\(^{204}\)Pb nature of Nicaragua arc magmas, the compositions of which have changed little from the Miocene (e.g. compare Figures 13b and 13d).

Figure 13a also shows the \(^{40}\)Ar/\(^{39}\)Ar ages of Panamanian arc samples (Wegner et al. 2011), which further underscores the compositional similarities of PI arc samples with those of 98–82 Ma western Costa Rica CLIP sequences (Sinton et al. 1997; Hauff et al. 2000a, 2000b). However, Figure 13 also demonstrates that samples from the 73–69 Ma Sona–Azuero Arc (Wegner et al. 2011) of central Panama and the ~75–66 Ma Golfito Arc (Hauff et al. 2000a, 2000b; Buchs et al. 2010) of easternmost Costa Rica are markedly less radiogenic than lavas of the CLIP and lavas of the younger (~70–39 Ma) Chagres–Bayano Arc (Wegner et al. 2011) of eastern Panama (at 77.2–79.9° W). Wegner et al. (2011) noted that the Sona–Azuero Arc was less radiogenic with respect to Pb isotopes than the Chagres-Bayano Arc, but did not correlate this observation with data from lavas of the Golfito Complex or other arc-related complexes in Costa Rica and Nicaragua. Whereas the two samples from the Sona-Azuero Arc (72.3 and 67.5 Ma) exhibit \(^{206}\)Pb/\(^{204}\)Pb of 18.53–18.65 and \(^{208}\)Pb/\(^{204}\)Pb of 38.11–38.41 similar to that of the Golfito Arc with \(^{206}\)Pb/\(^{204}\)Pb and \(^{208}\)Pb/\(^{204}\)Pb of 18.57–18.79 and 38.20–38.33 (Hauff

Figure 15. Initial \(^{143}\)Nd/\(^{144}\)Nd versus time for CAVAS magmatic products of PI–PVI in Panama, Costa Rica, and Nicaragua. Large symbols represent undated samples and are plotted at the mean age of the associated unit; small symbols represent dated samples. Colour code schemes with their age brackets (age uncertainties) and encompassed units from left to right are as follows: light grey, 98–82 Ma, western Costa Rica igneous units interpreted as CLIP; light purple, PI (75–39 Ma); light blue, PII (35–16 Ma); light green, PIII (16–6 Ma); PIV (6–3 Ma), light yellow; and PVI (2.6–0 Ma), light pink. The 80–60 Ma accreted OIB field is demarcated by the region between the two solid grey vertical lines and the PV (PVA arc alkalis and PVB adakites, 5.9–0.15 Ma) field is demarcated by the region between the two dotted vertical lines. For Costa Rica and Nicaragua PVI samples, locations were plotted with coordinates provided in each relevant paper based on the way Hoernle et al. (2008, Figure 1) subdivided Costa Rica into northwest central, southwest and Nicaragua into southwest and northwest. In most cases the vertical error (compositional uncertainty) is smaller than the symbol size and is not plotted. References for data sets are as given in the Figure 18 caption.
et al. 2000b), respectively, the oldest Chagres-Bayano Arc sample (68.5 Ma) exhibits 206Pb/204Pb of 18.82 and 208Pb/204Pb of 38.42; lavas of the entire suite of Chagres-Bayano Arc samples display a range in 206Pb/204Pb of 18.75–19.07 and 208Pb/204Pb of 38.33–38.85, which encompasses the composition of the oldest sample and which are higher than those of the Golfito and Sona–Azuero arcs. The fact that Chagres-Bayano Arc samples are typically more radiogenic than similarly aged Sona–Azuero and Golfito Arc lavas and that some relatively old Chagres-Bayano Arc samples exhibit relatively very high 206Pb/204Pb and 208Pb/204Pb (e.g. a 65.9 Ma sample with 206Pb/204Pb and 208Pb/204Pb of 19.07 and 38.83, respectively) suggest not a temporal evolution with time, but rather a location-dependent trend at least in Panama, for reasons that are uncertain; sources to the west were clearly less radiogenic with respect to Pb than sources to the east during PI (Figure 13a) and remained so during PII and PIII (see below).

This observation of an apparent lack of radiogenic enrichment of Pb with time in Panama is largely supported by the fact that PII and PIII (36–6 Ma) Panama samples plot almost entirely within the range of PI Panama with 206Pb/204Pb of 18.79–19.12 and 208Pb/204Pb of 38.55–38.92; however, the broad E-W distribution of these samples from the Panama–Costa Rica border in the west to the Panama Canal near the westernmost border of the Chagres–Bayano Arc in the east makes it difficult to ascertain whether the PII and PIII sources were spatially associated with those of the Sona–Azuero Arc or the Chagres–Bayano Arc. Perusal of Figure 2 of Wegner et al. (2011) suggests that the majority of samples with isotope data (those with corresponding radiometric age data) are from regions to the immediate north and west of the Sona and Azuero peninsulas in the Cordillera de Panama (see also our Figure 2). Hence, based on this spatial distribution, it may then be reasonable to assume a temporal shift to more radiogenic Pb, assuming a Sona–Azuero proximal source for PII and PIII magmas in Panama.

During PII in Costa Rica, 206Pb/204Pb (18.55–18.69) did not rise from PI values (18.57–18.77), but 208Pb/204Pb (38.19–38.45) ranged to higher concentrations (than PI with 208Pb/204Pb of 38.20–38.33). Similarly, throughout PIII, 206Pb/204Pb (18.60–18.80) changed little from initial PI values, but 208Pb/204Pb (38.20–38.48) continued to rise or at least range to higher values. A dramatic change to unequivocally more radiogenic Pb compositions began in PIV (6–3 Ma) in Costa Rica, with 206Pb/204Pb and 208Pb/204Pb reaching values (18.86–19.12 and 38.54–38.86 respectively) similar to (a) Panama during PII and (b) NW Costa Rica during PVI (2.6–0 Ma, see below).

The data for Pb isotopes discussed above demonstrates that while sources for Panama and Costa Rica lavas could be argued as distinct (from each other) throughout PI–PIII, overall the sources can be considered as relatively similar throughout PI–PIV. Apart from the relatively slight increases in 206Pb/204Pb between PI and PIII, Costa Rica magmas remained essentially unchanged with respect to Pb isotope composition between 75 and 6 Ma. Similarly, Panama magmas recorded only slight increases in 206Pb/204Pb and 208Pb/204Pb in PII and PIII relative to PI in Panama, but showed elevated values relative to Costa Rica until the end of PIII (16–6 Ma). It is not until PIV (6–3 Ma) that the source of Costa Rica magmas ‘catch up’ to the more radiogenic Pb isotope compositions of PII and PIII magmas in Panama (Figure 13b) with 206Pb/204Pb of 18.86–19.12 and 208Pb/204Pb of 38.54–38.86, which fall (almost) completely within the range of PII and PIII Panama magmas (206Pb/204Pb of 18.79–19.12 and 208Pb/204Pb of 38.55–38.92).

Several studies have focused on the isotopic nature and evolution of post 6 Ma lavas of the CAVAS (e.g. Feigenson et al. 2004; Goss and Kay 2006; Hoernle et al. 2008; Gzel et al. 2009, 2011). A major finding of these aforementioned studies was the location- (along the volcanic arc) dependent isotopic composition of Quaternary to present lavas. Although PVI Costa Rica magmas span the entire gamut of 206Pb/204Pb and 208Pb/204Pb compositions exhibited by older (PI–PVI) lavas (Figure 13d) and extend to even more radiogenic compositions, their location in 206Pb/204Pb versus 208Pb/204Pb space is conditional upon their geographic location along the volcanic arc. Whereas Costa Rica lavas from NW Costa Rica exhibit a wide range of Pb isotopes extending from relatively unradiogenic compositions (e.g. with 206Pb/204Pb of ~38.26 and 208Pb/204Pb of ~18.63) to moderately radiogenic compositions (with 206Pb/204Pb of ~38.84 and 208Pb/204Pb of ~19.10) similar to maximum values exhibited by older PI (Chagres-Bayano Arc)–PIII Panama magmas and PII–PVI Costa Rica magmas (e.g. compare Figures 13a and 13b with d), PVI Nicaraguan magmas are unradiogenic and uniquely range to very depleted compositions akin to N-MORB (Figure 5d). In contrast, magmas from NE and Central Costa Rica exhibit much higher 206Pb/204Pb and 208Pb/204Pb of ~38.76–39.10 and 19.08–19.29, respectively. Similarly, the PV arc alkalic basalts and adakites exhibit a similar highly radiogenic nature (with respect to Pb) as lavas from central and NE Costa Rica (Figure 13d).

Feigenson et al. (2004) demonstrated the exceptionally unradiogenic nature of local marine sediments (with respect to Pb) and concluded that the high radiogenic nature of central Costa Rica magmas did not require a
subducted component (addition). Various enrichment models for central Costa Rica were proffered by Feigenson et al. (2004), but favoured the ones entailing either the melting of enriched veined mantle or the re-melting of Galapagos Plume-influenced mantle. In contrast, more recent models to explain enrichment include forearc erosion (Goss and Kay 2006) and Seamount Province–subduction interaction (Hoernle et al. 2008; Gazel et al. 2009, 2011). Models are scrutinized in Section 6.

5.2. Nd isotopes

In contrast to Pb isotopes ($^{206}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb), which are clearly less radiogenic in Golfito and Sona-Azuero compared with units interpreted as CLIP and the Chagres–Bayano Arc (Figure 13), the $^{143}$Nd/$^{144}$Nd values of all PI arc segments fall within the range of units interpreted as CLIP (Figures 14 and 15). PI lavas are strikingly similar to those of 98–82 Ma western Costa Rica units interpreted as CLIP in terms of $^{143}$Nd/$^{144}$Nd (Figures 14a and 15); only alkali basalts of the Tortugal Complex exhibit contrasting (lower) $^{143}$Nd/$^{144}$Nd (0.512740–0.512798) (Hauff et al. 2000b) (Figure 14a). In terms of Nd isotopes, PI arc lavas in the west (i.e. Golfito and Sona–Azuero) are similar to those in the east (Chagres–Bayano) (Figures 14a and 15). In detail, the Golfito Complex records significantly higher $^{143}$Nd/$^{144}$Nd (0.512922–0.512959) than the Sona–Azuero Arc (0.512864–0.0512866). Plots of $^{206}$Pb/$^{204}$Pb versus $^{143}$Nd/$^{144}$Nd and $^{143}$Nd/$^{144}$Nd versus time (Figures 14 and 15) also show a temporal trend to more radiogenic Nd relative to Pb, as magma sources beneath both Costa Rica and Panama start to differentiate from CLIP-like $^{143}$Nd/$^{144}$Nd during PII by becoming more radiogenic (Figure 15). Whereas the oldest radiometrically dated Sona-Azuero and Chagres-Bayano samples (72.3–65.9 Ma) (Wegner et al. 2011) exhibit the lowest $^{143}$Nd/$^{144}$Nd and plot along the lower cusp of the compositional field defined by the Galapagos plume at 90 Ma, all younger radiometrically dated PI Panama samples from Chagres–Bayano with ages of 65.9–44.9 Ma display higher $^{143}$Nd/$^{144}$Nd and plot near the lower cusp of the Galapagos plume compositional field at 60 Ma (Figures 14a and b). Furthermore, PII (35–16 Ma) samples from both Panama and Costa Rica record higher $^{143}$Nd/$^{144}$Nd than PI products, but plot within the field of the Galapagos Plume at 60 Ma (Figure 14b). PIII lavas return to slightly lower $^{143}$Nd/$^{144}$Nd than older PI. These data demonstrate a switch to less radiogenic Nd, which was accompanied by more radiogenic Pb (higher $^{206}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb, Figure 13), beginning in PIII and reaching a pre-2.6 Ma peak in PIV Costa Rica.

The PVa arc alkalic basalts and PVb adakites continue the isotopic shift to lower $^{143}$Nd/$^{144}$Nd (Figures 14c) and higher $^{206}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb and overlap the fields of Cocos-Coiba Ridges and Seamount Province fields. Similarly, the PVI lavas from central Costa Rica (with $^{143}$Nd/$^{144}$Nd of 0.512918–0.512979) (Figures 14d and 15), which range to the lowest $^{143}$Nd/$^{144}$Nd, also overlap the Cocos–Coiba Ridges and Seamount Province fields. Analogous to the situation with Pb isotopes where PVa northwest Costa Rica lavas formed from depleted sources relative to those of PVI central and northeast Costa Rica by virtue of exhibiting lower $^{206}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb, the PVI northwest Costa Rica lavas have more radiogenic Nd than PVI lavas in central and NE Costa Rica with $^{143}$Nd/$^{144}$Nd of 0.512922–0.513040. Also similar to the situation with Pb isotope compositions, which changed little in Nicaragua between the Miocene and present, there is little change in this interval in Nd isotope compositions (Figure 14d). An exception is three PVI (2.6–0 Ma) behind the volcanic front alkalic basalts (as described in the Georoc dataset where these samples were listed) in eastern Nicaragua and within the Caribbean Sea (~12.3°N/83.8°W), which plot similarly in the $^{206}$Pb/$^{204}$Pb versus $^{143}$Nd/$^{144}$Nd space as PII Panama and PIV Costa Rica with ~ 18.87–19.90 $^{206}$Pb/$^{204}$Pb and 0.512999–0.515303 $^{143}$Nd/$^{144}$Nd. The remaining (NW and SW) Nicaragua samples plot closest to depleted MORB with high $^{143}$Nd/$^{144}$Nd (~0.51299–0.51311) and low $^{206}$Pb/$^{204}$Pb (Figure 14d).

6. Discussion

The general evolution of the CAVAS towards more enriched compositions suggests that one or more of the several processes became increasingly important with time: a greater depth of melting so that garnet played a role; an increase in sediment fluid and melt additions; an increase in plume or OIB contributions to the mantle source; a decrease in the degrees of partial melting in the mantle wedge; changes in the thermal structure of the slab or wedge; or a combination of two or more of these processes. A noteworthy feature is that incompatible trace element enrichment is accompanied by isotopic evolution to more depleted sources (higher $^{143}$Nd/$^{144}$Nd, lower $^{206}$Pb/$^{204}$Pb) with time (Figure 14). This anti-correlation may reflect that the asthenospheric mantle flowing into the mantle wedge changed with time, from enriched (plume-like) during PI to more depleted (more MORB-like) in Neogene. Strong along-arc isotopic gradients are found in Quaternary lavas,
with MORB-like sources for Nicaragua and plume-like sources for Costa Rica.

We explain below why and how a dual process entailing a first-order mechanism of progressively decreasing degrees of partial melting as a result of arc crustal thickening and associated changes in the mantle thermal structure possibly coupled with subducted seamounts and participation of more depleted mantle represents the one most likely responsible for incompatible enrichment in the CAVAS.

Below, we first discuss how to interpret CAVAS chemotemporal trends. Next, we examine the chemotemporal record to determine whether the roles of crust interaction and tectonics were important in controlling CAVAS magmagenetic evolution. Finally, on the basis of our observations and interpretations of CAVAS chemotemporal evolution, we discuss the larger challenge of determining why some arc magmatic systems evolve with time whereas others do not.

### 6.1. How to interpret CAVAS $X_{55}$ chemotemporal trends

Lavas erupted from long-lived arc systems – like the CAVAS – are likely to reflect more complex magma evolution processes than those erupted from the other two major magmagenetic systems of divergent plate margins (mid-ocean ridges) and hotspots, particularly those on fast-moving oceanic plates. Such complexities include ponding of mantle-derived mafic melts in the crust where fractionation to form intermediate and felsic melts can occur. Such ponding will heat the crust and cause melting to generate felsic melts, and the mixing of mafic and felsic melts can generate intermediate melts (e.g. Stamatelopoulos-Seymour et al. 1990). Thinner mafic oceanic crust like that of CLIP is less likely to re-melt than thicker continental crust, but how much crustal melting occurs in each case is unclear; in both cases, there is likely to be more melting with time as the lower crust is warmed by the passage and ponding of magma, but this depends on magma flux (Annen et al. 2006). The role of the crustal filter must be kept in mind when interpreting CAVAS chemotemporal evolution.

Mantle processes must also be considered when interpreting CAVAS chemotemporal trends. If the mantle source of basalt magmas evolves compositionally, the resultant complex magmatic evolution can be difficult to interpret, as summarized in Figure 16. If the most important process is fractional crystallization, comparison of $X_{55}$ allows different mantle influxes of basalt to be compared at similar stages of evolution. In this case – and assuming that similar degrees of mantle wedge melting occurred to generate all CAVAS basalts – differences in $X_{55}$ largely reflect the variations in mantle enrichment, presumably due to the addition of subduction components. On the other hand, if crustal melting to form felsic melts and the resultant hybridization is the most important controlling compositional diversity, then the compositional spectrum is more difficult to interpret. As magmas with 55 wt.% SiO$_2$ are more akin to the ones recording mantle input ($\sim$50 wt.% SiO$_2$) as opposed to crustal input ($\sim$70 wt.% SiO$_2$), abundances normalized to 55 wt.% SiO$_2$ ($X_{55}$) emphasize mantle input.

### 6.2. Role of the crust

Below we use two approaches to evaluate the extent to which CAVAS chemotemporal trends could reflect...
crustal interactions: trends in K₂O and other incompatible elements versus SiO₂ and Nd isotopic data.

6.2.1. Incompatible elements versus SiO₂ trends

One perspective on the issue of crustal interaction can be gleaned from plots showing best-fit lines through incompatible elements versus SiO₂ (e.g. K₂O vs. SiO₂, Figure 4d, see also Supplementary Figure S2). Mixing of mantle-derived basalts with crustal melt is likely to define magmatic trends that converge on the crustal melt, as shown in Figure 16c. CAVAS magmatic trends do not converge on a likely crustal melt composition, and instead show increasing slopes with enrichment, more consistent with magmatic differentiation from different mafic parents. The slope of the PIV trend is the only exception, and it could be that the lower slope for this sequence reflects the mixing between the mafic melts of enriched mantle and the crustal melt.

A lack of crustal interaction is also readily apparent on various incompatible elements versus SiO₂ plots when considering the best line of fit through the data (not shown). For example, when considering Pl Ba, Rb, Th, U, and Nb versus SiO₂, the low R² values (0.07, 0.01, 0.1, 0.1, and 0.03, respectively) demonstrate that crustal interaction was not a major factor in magmagenesis.

6.2.2. Nd isotopes

The Nd isotopic data also record no evidence of increased crustal participation with time. CAVAS magmas have very CLIP-like compositions during PI, but the source region evolved to more depleted composition with time, as shown by higher ¹⁴³Nd/¹⁴⁴Nd (Figure 15). This isotopic evolution is most easily explained by the participation of more depleted mantle with time, perhaps by the replacement of the original Galapagos/CLIP plume-like mantle by a more depleted normal asthenosphere.

We conclude that CAVAS chemotemporal evolution does not reflect increased crustal interactions with time, a conclusion also reached by Gazel et al. (2015). Instead, CAVAS chemotemporal variations mostly reflect the fractionation of mantle-derived mafic magmas. In this case, the approach we outlined in Section 6.1 captures mantle source variations, similar to what is shown in Figure 16b.

6.3. Role of local tectonic events

It is important to determine the extent to which long-term arc magmatic evolution is affected by regional tectonic events such as changing slab configurations and upper plate extension. Several major tectonic events occurred in and around CAVAS during its lifetime (Supplementary Figure S4), some of which had specific magmatic expressions for the CAVAS. Such localized tectonic events and their magmatic responses provide few insights into the larger question of overall magmatic evolution, but the extent to which these have affected magma compositions provides fundamental insights into what are the key controls on arc magmagenesis in the CAVAS, provided it is possible to remove this ‘tectonic noise’ from the ‘true’ magmatic signals. It is thus important to identify these so we can disentangle which aspects of the CAVAS record are source evolution signal and which are local tectonic noise.

Three outstanding aspects of CAVAS magmatic evolution that reflect local tectonics are: (1) the divergence in compositions between Costa Rica plus Panama versus Nicaragua, which began between PIII (16–6 Ma) and peaked during PIV (6–3 Ma); (2) the production of PV adakites and arc alkaline magmas in Panama and Costa Rica after 6 Ma; and (3) the ‘resetting’ of the CAVAS source back to more depleted compositions after 3 Ma, which, apart from Nicaragua erupting moderately more mafic lavas than Costa Rica, are otherwise broadly similar in terms of incompatible trace element systematics in both regions. These three issues are addressed further below.

6.3.1. Neogene Nicaragua–Costa Rica compositional divergence

According to our present data set, CAVAS magma chemistries in each region appear to have been similar before beginning to diverge during PIII (16–6 Ma) and dramatically diverging during PIV (6–3 Ma) (e.g. Figures 6–12). Whereas Costa Rica PIV lavas continued an enrichment trend relative to PIII compositions, PIV Nicaragua lavas reverted to derivation from a more depleted mantle source that was more modified by slab contributions (e.g. Figures 11 and 12). These dissimilarities are especially clear for PIV Costa Rica lavas, which exhibit strong LREE fractionations (La₃₈/Sm₃₈ and La₃₈/Yb₃₈) in contrast to the only slightly enriched nature of PIV Nicaragua lavas (Figure 8, Table 2). Other differences apparent on the N-MORB normalized plot (Figure 10) are the lower Th (and higher U/Th) and higher Ba/Th, Ba/La, and Nb/La of PIV Nicaraguan lavas relative to Costa Rican PIV lavas, which partly reflect the greater sediment additions and, in the case of elevated U/Th in Nicaragua lavas, a change in composition of the subducted sediments (Plank et al. 2002).

What was the cause of compositional divergence between Costa Rica and Nicaragua CAVAS beginning ~16–6 Ma? There are several factors related to either changes in what the subducted slab was doing (steeper slab dip), what was coming off the subducted slab...
(change in fluid and/or melt compositions due to changing sediment composition, the onset of OIB seamount subduction beneath central Costa Rica, or higher fluid flux), or what the upper plate was doing (changes in mantle wedge composition and upper plate extension). These possibilities are further described next.

With respect to changes in subducted sediment compositions, the U and Ba enrichment in Nicaraguan magmas has been explained as reflecting a ‘carbonate crash’ ~10 Ma (event 7, Figure S4) when dominantly carbonate sedimentation on the Cocos Plate was replaced by hemipelagic ooze sedimentation as the result of the shallowing of the carbonate compensation depth by ~800 m; this occurred because the Panama ridge cut off deep water flowing westwards out of the Caribbean (Plank et al. 2002). Subduction erosion of forearc igneous units and trench sediments and the addition of changed sediment components to the mantle source (Goss and Kay 2006) have been postulated as an alternative to seamount subduction to explain enrichment. However, Hoernle et al. (2008) note that the isotopic composition of forearc units does not match those of the Seamount Province in contrast to post-6 Ma enriched lavas in (mostly central) Costa Rica, which are isotopically similar to the Seamount Province. Moreover, we showed in Section 4 that enrichment increased dramatically over a short interval in PIV (6–3 Ma), which suggests a rapid, short-lived enrichment process that contrasts with that expected from forearc erosion, which should be modest and prolonged.

The subduction of Cocos Plate seamounts and their metasomatic interaction with the mantle source beneath central Costa Rica (event 9, Figure S4) have been proposed to explain the distinctive enrichments recorded by PVa alkaline basalts and PVb adakites (e.g. Hoernle et al. 2008; Gazel et al. 2009, 2011) as commencing about the same time (10–8 Ma) as the arrival of the Cocos Ridge and the carbonate crash. However, inspection of Figure 13 (206Pb/204Pb vs. 208Pb/204Pb) and Figure 14 (206Pb/204Pb vs. 143Nd/144Nd) shows that Pb and Nd isotopic compositions similar to that of the subducting Seamount Province occurred as early as 20 Ma in Panama (blue circle, with age of 19.2 Ma). Two other PII (16–6 Ma) samples from Panama also plot within the subducting Seamount Province field in terms of both Pb isotopes (206Pb/204Pb and 208Pb/204Pb) and Nd isotopes (Wegner et al. 2011). If seamount subduction was important for enrichment, this might have started much earlier than 8–10 Ma. Seamount subduction thus may explain the presence of OIB-like signatures in ~6 Ma and younger central Costa Rica CAVAS sequences (Reagan and Gill 1989; Hoernle et al. 2008; Gazel et al. 2009, 2011, 2015); however, our regressed data suggests that Ba/La has always been lower in Costa Rica than in Nicaragua (Ba55/La55 of 14–31 in Costa Rica, which peaked in PII, and 61–130 in Nicaragua, which peaked in PIV, Table 2). Similarly, Plank et al. (2002) established that high Ba/La (>70) in the Nicaragua volcanic front is a long-lived feature. Irrespective of the cause of lower Ba/La in Costa Rica, it has been operating over the entire CAresas lifetime, although the discrepancy is the largest during PIV. If Ba/La is indeed related to the subduction and interaction of hotspot tracks, the long-lived nature of the signal suggests that plume–subduction interactions began with initial oceanic island accretion and subduction ~60 Ma (e.g. Hoernle et al. 2002; Hoernle and Hauff 2007; Buchs et al. 2009; 2011; see also Gazel et al. 2015) or even earlier (see Whattam and Stern 2015).

The inferred higher degrees of partial melting in Nicaragua versus Costa Rica (Saginor et al. 2013) are ascribed to the steeper slab dip beneath Nicaragua versus Costa Rica (Syracuse et al. 2008). This resulted in slab-derived fluids being released across a smaller width of the arc beneath Nicaragua, which enhanced melting (Carr et al. 1990). Melting beneath Nicaragua was further enhanced by extension (see below). Furthermore, the slab beneath Nicaragua is more serpentinitized (~10–20% extending some 20–28 km beneath the slab surface) than that beneath Costa Rica (Syracuse et al. 2008; Van Avendonk et al. 2011; see also Heydolp et al. 2012); thus, more fluid might have been released into the asthenospheric mantle wedge beneath Nicaragua relative to Costa Rica. Greater fluid flux would cause more melting beneath Nicaragua than Costa Rica and would also deliver different subduction-related metasomatic components. We do not know when these three differences – slab dip, upper plate extension, and subduction of more serpentinitized slab – between Nicaragua and Costa Rica convergent margins first appeared, but one or more of them starting ~16–6 Ma could explain the observed compositional divergence.

A possible cause of compositional divergence between Costa Rica and Nicaragua lava compositions was the formation of the Nicaragua depression, which began during PII at about 23 Ma and continues until today (Funk et al. 2009). Extension thinned the lithosphere and lengthened the melting columns beneath Nicaragua, allowing for higher degrees of melting, which was further aided by the enhanced water flux from a more steeply dipping, moderately serpentinitized slab. Plank and Langmuir (1988) showed how the height of the mantle column available for melting beneath arcs is a function of arc crust thickness. If melting begins beneath arcs at similar depths, then the column of mantle that undergoes decompression melting is
shorter beneath the thicker arc crust. Hence, the longer mantle column for arcs built on rifted crust will lead to higher degrees of partial melting. However, Turner and Langmuir (2015) concluded that the length of the melting column cannot be the determining factor in controlling the extent of partial melting and that rather a thicker arc edifice would depress isotherms deeper (see also Karlstrom et al. 2014). Hence, if the lithosphere beneath Nicaragua was thinner than that beneath Costa Rica as a result of forming the Nicaragua depression, a taller melting column accompanied by steeper dipping slab and more water flux and the migration upwards of hotter isotherms (Turner and Langmuir 2015) would be expected to lead to higher degrees of partial melting beneath Nicaragua relative to Costa Rica.

6.3.2. Production of PV adakites and arc alkaline magmas in Panama and Costa Rica after 6 Ma
Subduction terminated beneath Costa Rica and Panama soon after 8 Ma as the result of collision and attempted subduction of the Cocos Ridge beneath Central America (Abratis and Wörner 2001); this was followed soon after by the production of adakites and arc-alkaline basalts. It has long been recognized that the end of subduction may be marked by the eruption of alkaline basalts (e.g. Jakeš and White 1969), and sometimes a bimodal arc alkaline basalt and adakite association accompanies the subduction of a hot slab (e.g. Kimura et al. 2014). The formation of alkaline-adakite bimodal magmatic associations have been explained by varying percentages of sediments and altered crust comprising the slab, differing fractions of slab flux, and differing P–T conditions of mantle melting (e.g. Martin et al. 2005). Gazel et al. (2009, 2011) suggest that Costa Rica adakites may form as a result of seamount subduction, but this is not a common explanation for adakites. Nevertheless, in the case of the CAVAS, the isotope evidence provides strong support for seamount subduction and interaction with mantle sources (Gazel et al. 2011). According to the model of Gazel et al. (2011) for instance, post-6 Ma alkali basalt and adakite formation in western Panama and Costa Rica was related to terminal subduction, slab break-off, and subsequent asthenospheric upwelling. In either case, the eruption of adakites and alkali basalts during CAVAS PV reflects local tectonics related to subduction termination and does not reveal much about the overall CAVAS magmatic evolution.

6.3.3. ‘Resetting’ of the CAVAS source back to more depleted compositions after 3 Ma
PVI marks the resetting of CAVAS magma compositions to compositions similar to more depleted compositions such as those of PI–PIII. What was responsible for this apparent reversal of magmatic evolution? As La and Nb have similar, low Kd values (e.g. ~0.05 and 0.005 in basalt clinoproxene, GERM data base) and Zr/Nb can be fractionated only by extremely low degrees of partial melting (F < 0.5%, Sun and McDonough 1989), the higher La/Nb of PIV Nicaragua relative to Costa Rica is more likely to reflect greater additions of La relative to Nb from the subducted slab, consistent with other indicators as discussed previously. However, the higher Zr/Nb and the much lower Nb/Yb of Nicaragua PIV magmas relative to Costa Rica demonstrate either the higher degrees of partial melting or the tapping of a more depleted source or both (Pearce and Peate 1995).

We suggest that the higher degrees of partial melting in Nicaragua, which began about 20 Ma, coincident with the initial formation of the Nicaragua depression, was the result of associated lithosphere thinning and changes in the mantle thermal structure. As lithospheric thickening would displace colder isotherms deeper resulting in a lower degree of partial melting, lithospheric thinning would have an opposite effect, i.e. the displacement of hotter isotherms upwards resulting in a higher degree of partial melting (Turner and Langmuir 2015). It may be that lithospheric thinning propagated eastwards to beneath Costa Rica by the time the ‘modern-day’ CAVAS began to erupt at 2.6 Ma. Alternatively, along-arc, trench-parallel mantle flow may be partly responsible for the recent changes in magma compositions (Hoernle et al. 2008).

6.4. Long-term chemotemporal evolution of the CAVAS
There is strong evidence that, despite significant effects due to regional tectonic changes, the CAVAS system evolved chemically over its 75 million year history, from depleted to enriched magmas. In this section we first consider what processes were responsible, the evolution of CAVAS towards continental crust compositions, the role of mantle plumes in arc evolution, and finally present a synthesis and model for this evolution.

6.4.1. Causes of progressive CAVAS magma enrichment
In Section 6.2, we showed that increasing crustal interaction was probably not responsible for source enrichment over time and we conclude that the long-term enrichments reflect systematic changes in magma sources and/or magmagenetic processes with time. Such systematic changes could include the participation of progressively more enriched mantle, progressively greater slab contributions, or progressively lower degrees of melting. Our conclusions thus echo those
of Turner and Langmuir (2015), who concluded that two distinct explanations could account for the global variations in arc magma compositions: different extents of mantle wedge melting due to differing (mantle) thermal structures, or varying contributions from the subducted slab. We can track mantle evolution with Zr/Y (Figure 11a) and Nb/Yb (Figure 11c), both of which increase with mantle enrichment, but can also vary as a function of the degree of partial melting (or if garnet is involved, which except for PV adakites and arc alkaline basalts does not seem to be the case for CAVAS). Zr/Y increases over the CAVAS lifespan, suggesting either that the mantle feeding the early CAVAS was more depleted than that feeding it now or that the degree of partial melting has decreased over time. Nb/Yb ratios diverge strongly, with higher values for Costa Rica and Panama (indicating mantle source enrichment or lesser melting) and lower values for Nicaragua (indicating mantle source depletion or higher melting). The trace element evidence of progressive enrichment contrasts with the isotopic evidence that more depleted mantle was involved; however, isotopic compositions reflect time-integrated parent/daughter ratios and are insensitive to recent changes in source composition. We conclude from the trace element and isotopic data that the CAVAS mantle source changed significantly over the 75 Ma life of CAVAS, becoming somewhat enriched with time, at least for Costa Rica and Panama.

Another possible explanation is that the subduction input has increased with time, or that its nature has changed. Subduction input can be subdivided into those elements that are mobile in hydrous fluids (Rb, Ba, Sr, U, Pb, LREEs) and those that are only transported by melts (Zr, Th, Nb, HREEs). Absolute concentrations of linearly regressed fluid-mobile trace elements K2O, Rb, Ba, Sr, U, and Pb increase over the life of the arc (Figures 6–8), although chemotemporal evolution is more complex when the CAVAS is subdivided into regions. Part of the subduction input can be isolated by focusing on the ratios of fluid-mobile to fluid-immobile incompatible trace elements, which are generally acknowledged to reflect the transfer of fluid-mobile elements from the subducted slab to the mantle wedge. The only such ratio that increases with time in Panama and Costa Rica between PI and PIII is Sr/Nd; U/Th increases between PI and PII only and Pb/Ce remains more or less constant through time (Figure 12). Nonetheless, the patterns of some of these ratios suggest that part of the explanation for the long-term source enrichment of CAVAS magmas might reflect subduction-related metasomatism. Subduction-related progressive enrichment of the CAVAS source could reflect either instantaneous or cumulative processes. In the first case, increased efficacy of fluid transfer from slab to mantle would be responsible for increasing the fluid-mobile to fluid-immobile incompatible element ratios; fluid-mobile elements released from the slab would immediately affect melt compositions, but would have no long-term effect on the mantle wedge composition. In the second case, the cumulative effect of fluids released from the subducted slab would metasomatically enrich the mantle source over time. As we see no reason as to why subduction processes should more efficiently release fluid-mobile elements with time, we prefer the second explanation that the cumulative effect of fluids released from the slab metasomatically enriched the mantle source over time and conclude that the residence time of circulating asthenosphere in the mantle wedge is long relative to subduction-related enrichment processes. We note that the observed anti-correlation of trace element enrichment and especially Nd isotopic evidence for the increasingly depleted mantle source region may reflect that the asthenospheric mantle source flowing into the mantle wedge changed with time, from enriched (plume-like) during PI to more depleted (more MORB-like) in Neogene, especially for Nicaragua lavas.

A change in mantle or slab thermal structure (Turner and Langmuir 2015) may represent alternative mechanisms for varying slab-mantle fluxes over time. In particular, the driving of cold isotherms to progressively deeper depths associated with arc edifice thickening could displace mantle melting to higher pressures and lower temperatures and hence lower degrees of melting. This change in mantle thermal structure could thus result in more enriched magmas than those generated beneath a relatively thinner lithosphere. We expand on this idea in Section 6.4.4.

6.4.2. Continental crust formation at the CAVAS

It is generally agreed that continental crust today mostly forms above subduction zones. Despite difficulties in resolving the differences between the mafic, LREE-depleted nature of igneous rocks generated at IOCs versus those of more siliceous, LREE-enriched continental arcs and their roles in continental crustal genesis (Kay 1985; Ellam and Hawkesworth 1988), the accretion of arc-related terranes due to collision is considered to have been fundamental in the growth and development of continental crust throughout at least the Phanerozoic time (Taylor and McLennan 1985; Rudnick 1995; Rudnick and Fountain 1995).

Based on ~0.3–6 Ma silicic ignimbrites from the Costa Rica volcanic front, Vogel et al. (2004) suggest that continental crust formed there as the result of the
addition of silicic magmas to the subduction-modified, oceanic plateau crust, possibly aided by the foundering of mafic/ultramafic residues and cumulates from the base of the crust. Vogel et al. (2004) suggested that the origin of these silicic magmas was the result of reprocessing initially juvenile, mantle-derived, subduction-related magmas that ponded in the crust similar to the process proposed for converting basaltic crust to continental crust in Costa Rica by Pichler and Weyl (1975). Although this might have been important late in the evolution of the CAVAS in Costa Rica, this does not explain the general enrichment in the CAVAS that began during PII (35–16 Ma). As shown in Figure 10, continental crust-like compositions were achieved in the CAVAS by at least 6 Ma. Furthermore, the transformation from mafic to continental-like compositions started much earlier (by ~35 Ma) and was gradual.

Gazel et al. (2015) concluded that partial melting of enriched subducting Galapagos hotspot tracks produced young andesitic continental crust beginning at ~ 10 Ma as recorded in the Central American Land Bridge (CALB, Panama and Costa Rica) geochemical evolution. As shown in Figure 9, collective compositions of Costa Rica plus Nicaragua are nearly identical to the continental crust at 6–3 Ma, although when parsed into region, it is evident that whereas Costa Rica was clearly continental-like, Nicaragua was not during this interval (Figure 10). Thus, our data mostly agrees with those of Gazel et al. (2015) in the timing of when continental-like compositions appeared, but differs in (1) the rate at which this continental crust composition was reached and (2) the cause of enrichment. We stress that continental-like compositions did not suddenly appear at 10 Ma, but rather that the enrichment was gradual over CAVAS history from PII (35–16 Ma) to the present in Panama and Costa Rica, as shown in Section 4 and summarized in Figure 9. As Galapagos hotspot tracks appear to have been only subducted beneath Costa Rica beginning about 10 Ma (Gazel et al. 2015 and references therein), enrichment during PII cannot only be the result of hotspot track subduction and the associated mantle metasomatism.

Moreover, the if the tenets of the model of Gazel et al. (2015) represent an overarching process necessary for enrichment in other enriched arcs (e.g. the Philippines), this then requires the serendipitous addition and interaction of hotspot-tracks (at other enriched arc systems). Alternatively, with our model, all that is required is the thickening of the arc edifice and a change in the associated sub-arc mantle wedge thermal structure. Enrichment at the CAVAS, and perhaps enriched arcs in general, would be further intensified by the lack of backarc formation behind the arc, a feature of which characterizes, for example, the enriched Greater Antilles Arc (GAA) system. Enrichment at the well-documented GAA (Jolly et al. 1998a, 1998b, 2001) was not sudden but gradual over tens of millions of years, similar to that of the CAVAS. It seems more reasonable to us that an overarching cause of enrichment would be common in different arc systems as opposed to unique in each arc. We conclude that gradual enrichment with time demonstrated by the CAVAS is the result of gradual thickening of the arc substrate and a change in the wedge thermal structure, which allowed for the driving of isotherms downwards to higher pressures and colder temperatures and hence lesser degrees of partial melting (Turner and Langmuir 2015).

6.4.3. Role of mantle plumes in the generation of continental crust

The role of enriched mantle sources in the generation of continental crust has long been proposed (e.g. Hawkesworth and Kemp 2006 and references therein). Primarily via isotopic evidence, we showed the contributions of the Galapagos Plume to CAVAS magmatism, which has been noted by others (e.g. Wegner et al. 2011; for Panama, Whattam and Stern 2015; references therein for various regions around the periphery and centre of the Caribbean Plate). A model of plume-induced subduction initiation (PISI) around the CLIP, the plume head of the Galapagos Plume, to initiate the CAVAS (Whattam and Stern 2015; see also Gerya et al. 2015.) explains its isotopic and trace element similarity during PI with the Galapagos Plume and OPB in general; however, it is evident that plume-like mantle contributions occurred all throughout the lifespan of the CAVAS and continue to this day (see Whattam and Stern 2015 and references therein). Although emplacement of the CLIP oceanic plateau and continual feeding of plume magmatism would have provided a head-start on enrichment via the production of an anomalously thick arc substrate, enrichment cannot be solely attributed to plume contributions. The reason for this is that whereas the isotopic affinities of CAVAS products kept pace with that of the Galapagos Plume, the trace element chemistry subsequently changed to more enriched compositions (than the Galapagos Plume, i.e. the CLIP) after 35 Ma. This also rules out enrichment as the result of OIB subduction accompanying accretion after 60 Ma.
6.4.4. Chemotemporal evolution of the CAVAS: synthesis and model

Based on the results and interpretations of this study, we provide a graphical representation of the chemotemporal evolution of the CAVAS from arc establishment to the present day in Figure 17. PI at 75–39 Ma marked the establishment of the CAVAS magmatic arc and the production of arc tholeiites. Subsequent thickening of the sub-arc lithosphere during PII (35–16 Ma) and PIII (16–6 Ma) drove the isotherms deeper, with the consequent displacement of melting to higher pressures and lower temperatures to form increasingly enriched magmas. This process continued in Costa Rica during PIV (6–3 Ma); however, extension of the sub-arc lithosphere beneath Nicaragua beginning in the early Miocene resulted instead in the upward displacement of hotter isotherms beneath Nicaragua. This, in addition to the more steeply dipping and serpentinized nature of the slab beneath Nicaragua compared with Costa Rica, gave rise to more melting and the production of more depleted magmas. Subsequent to the termination of subduction beneath Panama and southeast Costa Rica during Phase V (5.9–0.02 Ma), subsequent slab melting and partial melting of upwelling asthenosphere resulted in the production of adakites and arc alkalic basalts, respectively. Enrichment after 6 Ma in central and northeast Costa Rica was likely accentuated by seamount–subduction interaction as proposed by others. However, we propose that continued extension, which first began beneath Nicaragua circa 20 Ma with the initial formation of the Nicaragua depression, propagated eastwards to beneath (both Nicaragua and) Costa Rica during PVI (2.6–0 Ma (Figure 17). This resulted in attenuation of the sub-arc lithosphere, resulting in the driving of hotter isotherms upwards, more melting, and the formation of depleted magmas similar in composition to those of PI–PIII.

7. Conclusions

Seven important conclusions about the geochemical evolution of the CAVAS are drawn from this study:

(1) Early CAVAS volcanism (PI, 75–39 Ma) was characterized by low-K, tholeiitic to weakly calc-alkaline activity with compositions that are broadly similar to the depleted, sediment-poor lavas of the IBM arc system. There was an apparent W–E and possibly older to younger transition from MORB-like magmatism in the 73–39 Ma Sona–Azucero Arc to the 70–39 Ma Chagres–Bayano Arc.

(2) Elevated concentrations of some incompatible elements and element ratios, however, are higher than those of the IBM and similar in many cases to mean OPB. This and the fact that early and later magmas kept pace with the isotopic evolution of the Galapagos Plumes demonstrate significant plume–subduction interactions that occurred throughout the CAVAS lifespan.

(3) The most striking feature of CAVAS geochemical evolution was the progression in incompatible-element enrichment with time after 35 Ma. The composition of mean, linearly regressed PII (35–16 Ma) lavas and intrusives of both Panama and Costa Rica and the collective composition of PIV (6–3 Ma, Costa Rica plus Nicaragua) magmas closely resemble that of BCC. The best explanation for CAVAS enrichment is decreasing degrees of partial melting with time as the result of crustal thickening and changes to the sub-arc mantle thermal structure (progressive downwards displacement of isotherms) accompanied by cumulative metasomatic enrichment of the mantle wedge above the subducting Cocos Plate.

(4) A fundamental compositional divergence is recorded in PVI Nicaraguan and Costa Rican magmas manifest in elevated U/Th and Ba/La and a much more depleted source beneath Nicaragua, which is likely the result of higher degrees of mantle melting. The elevated U/Th has been ascribed to the post-10 Ma carbonate crash, which changed the subducting Cocos Plate sediments from U-poor carbonates to U-rich hemipelagic muds, whereas the lower Ba/La in Costa Rica has been interpreted as the result of OIB seamount–subduction interactions. The higher degree of partial melting beneath Nicaragua may be the result of steeper slab dip and upper plate extension, resulting in changes to the sub-arc mantle thermal regime (displacement of the isotherms upwards) accompanying the formation of the Nicaragua depression, the combined effects of which resulted in higher degrees of melting. The higher degree of melting is also likely related to the more serpentinized nature of the Nicaraguan slab.

(5) Chemotemporal enrichments of CAVAS and other arcs partly reflect whether or not an arc system is associated with a backarc basin. Arcs associated with backarc basins are fed by a more depleted mantle and have taller melt columns; unfractured arc lithosphere in contrast thickens with time,
Phase I (75-39 Ma)
development of magmatic arc; contributions from Galapagos Plume result in construction of anomalously thick arc substrate; eruption of arc tholeiites

Phase II (35-16 Ma)
thickening of lithosphere beneath magmatic arc results in shorter melt column - displacement of isotherms downwards - less melting - more enriched magmas; extension beneath Nicaragua (not shown) begins around 23 Ma and results in extension of melt column - displacement of hot isotherms upwards - more melting beneath Nicaragua relative to Costa Rica beginning in PIII

Phase III (16-6 Ma)
continued thickening of lithosphere beneath Costa Rica results in even shorter melt column - continual displacement of isotherms downwards - even less melting and even more enriched magmas; continued extension beneath Nicaragua however, results in incipient divergence in source compositions beneath Nicaragua vs. Costa Rica to more depleted and enriched beneath the former and latter, respectively

Phase IV (6-3 Ma): Costa Rica
continued thickening of lithosphere beneath magmatic arc results in even shorter melt column - continual displacement of isotherms even further downwards - even less melting - even more enriched magmas; subduction of Seamount Province seamounts accentuates enrichment

Phase IV (6-3 Ma): Nicaragua
continued extension thins lithosphere, lengthens melt column - displacement of isotherms upwards - more melting - more depleted magmas

Phase V (5.9-0.02 Ma)
termination of subduction beneath Panama and SE Costa Rica leads to slab melting (adakite formation) and alkalic basalt formation

Phase VI (2.6-0 Ma)
continued extension beneath Nicaragua and NW Costa Rica lengthens melt column - displacement of isotherms upwards - more melting - more depleted magmas

Figure 17. Graphical representation of the chemotemporal evolution of the CAVAS between magmatic arc establishment and the present day based on Turner and Langmuir (2015) and Plank and Langmuir (1988) (see text for details). Note that the green lines beneath the CAVAS arc edifice in Costa Rica and Panama between PII (35–16 Ma) and PIV (6–3 Ma) represent gradual lithospheric thickening, which resulted in the progressive displacement of isotherms downwards, lower degrees of partial melting, and the generation of increasing enriched magmas. An opposite mechanism of lithospheric attenuation/extension occurred beneath Nicaragua beginning ~23 Ma, concomitant with the commencement of Nicaragua depression formation resulting in the displacement of isotherms upwards, higher degrees of melting, and the production of more depleted magmas. By 3 Ma, extension beneath Nicaragua had propagated to the SW beneath Costa Rica, resulting in the resetting to the production of more depleted magma compositions similar to those produced between PI and PIII.
(6) Models calling for the chemical evolution of magmatic arcs from depleted to enriched with time (i.e., early arc evolution studies) are generally supported by the study of the CAVAS system. Tectonic events can complicate simple models for arc evolution, and even the reversal of long-term chemotemporal enrichment trends.

(7) Future studies are needed to improve coarse temporal resolution in especially PI (75–39 Ma), PII (35–16 Ma), and PIII (16–6 Ma). More integrated geochronologic studies of especially CAVAS PI, II, and III are required.

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