Contents lists available at SciVerse ScienceDirect

Lithos



journal homepage: www.elsevier.com/locate/lithos

Age and origin of earliest adakitic-like magmatism in Panama: Implications for the tectonic evolution of the Panamanian magmatic arc system

Scott A. Whattam ^{a,b,*}, Camilo Montes ^{b,c}, Rory R. McFadden ^d, Agustin Cardona ^{b,c}, Diego Ramirez ^b, Victor Valencia ^e

^a Department of Earth and Environmental Sciences, Korea University, Seoul 136-701, Republic of Korea

^b Smithsonian Tropical Research Institute, Apartado Postal 0843-03092, Balboa, Ancon, Panama

^c Corporación Geológica Ares, Calle 44a #53-96 Bogotá, Colombia

^d Department of Geological Sciences, Salem State University, 352 Lafayette Street, Salem, MA 01970, United States

^e School of Earth and Environmental Sciences, Washington State University, Pullman, WA, 99164-2812, United States

ARTICLE INFO

Article history: Received 31 October 2011 Accepted 27 February 2012 Available online 22 March 2012

Keywords: Panama Panamanian magmatic arc system Central American arc system Magmatic arc Adakite Adakite

ABSTRACT

40-20 Ma marks a fundamental interval in the evolution of the 70-0 Ma Panamanian magmatic arc system. During this period, there is no evidence of Panamanian magmatic arc activity to the east of the Panama Canal Basin while to the west and in localized regions to the east of the Panama Canal Basin a phase of intrusiveonly activity is recorded. Fundamentally, geochemical and geochronological evidence presented herein indicate that this intrusive activity was predominantly 'adakitic-like' and becomes younger from west to east along an approximately W-E striking lineament. Granodiorites of the Petaquilla batholith, western Panama vield LAM-ICP-MS ²⁰⁶Pb/²³⁸U zircon ages of 29.0 + 0.7, -0.6 Ma, 28.5 + 0.7, -0.5 Ma, 28.3 + 0.5, -0.4 Ma and 26.2 + 0.5, -0.9 Ma. To the east of the Panama Canal Basin zircons from a hypabyssal diorite of the mainly intermediate Majé subvolcanic suite, cedes a mean 206 Pb/ 238 U age of 18.9 + 0.4 Ma. Relative to other 70–5 Ma Panamanian magmatic arc lavas and intrusives, Majé and Petaguilla intrusives yield adakitic-like major and trace element abundances (e.g., >15 wt.% Al₂O3, generally >3.5 wt.% Na₂O, >400 ppm Sr, <1.9 ppm Yb, <18 ppm Y, Sr/Y that ranges to >120) and strongly fractionated HREE patterns. These 30–26 Ma (Petaquilla) and 19 Ma (Majé) suites are also compositionally similar to a subvolcanic suite of rare, circa 25 Ma adakitic-like, andesitic intrusives which occur within the Panama Canal Basin midway between Petaguilla and Majé and at the same approximate latitude as Petaguilla and Majé. Collectively, the geochemical and geochronological data for the adakitic-like intrusives arc consistent with formation via partial melting of lowermost, mafic crust above a sub-horizontal slab tear that propagated from the west (Petaquilla) to the east (Majé) between 30 and 19 Ma. Our new tectonic model postulates that collision between the Panamanian magmatic arc system and an 'indentor' (e.g., a tract of thickened buoyant, oceanic crust or plateau) occurred at about 40 Ma, a time of which coincides with the initiation of left-lateral offset of the Early (i.e., 70–40 Ma) Arc system. This collision resulted in the shutdown of the Early Arc system, possible steepening of the subducting Farallon slab and ultimately slab break-off and the phase of mainly adakiticlike intrusive activity. Subsequent to slab removal by \sim 20 Ma, NE-dipping subduction jumped to the south and initiated production of the Later (i.e., post 20 Ma) Arc system soon thereafter.

Crown Copyright © 2012 Published by Elsevier B.V. All rights reserved.

1. Introduction

Two main pulses of arc magmatism spanning the Campanian to the latest Miocene have been identified in Panama (Fig. 1). An Early Arc (as coined by Wörner et al., 2009) was constructed between ~70 and 40 Ma (Buchs et al., 2010; Montes et al., 2012; Wegner et al., 2011) and dominates the Sona and Azuero peninsulas in western Panama and the Chagres–Bayano region in eastern Panama (Fig. 2). A

E-mail address: whattam@korea.ac.kr (S.A. Whattam).

Later Arc system was initiated predominantly after 20 Ma and was active until about 5 Ma and occupies the region to the west of the Panama Canal Basin (Fig. 2) (e.g., Drummond et al., 1995; Wörner et al., 2009). As well, within the Panama Canal Basin, extensional-related arc activity (Farris et al., 2011; Montes et al., 2012) occurred between ~28 and 18 Ma (Montes et al., 2012; Wegner et al., 2011) and rare circa 21–18 Ma arc products have been identified to the east and south of the Panama Canal Basin in the Pearl Islands and Bahia Piña (Fig. 2) (Lissinna, 2005). An intermediary stage of arc-related plutonism is recorded in central Panama and Costa Rica at 30–26 Ma (e.g., Drummond et al., 1995; Kesler, 1978; Kessler et al., 1977; this paper). We term the three temporally distinct phases of arc activity



^{*} Corresponding author at: Department of Earth and Environmental Sciences, Korea University, Seoul 136-701, Republic of Korea. Tel.: +82 2 3290 3172.

^{0024-4937/\$ -} see front matter. Crown Copyright © 2012 Published by Elsevier B.V. All rights reserved. doi:10.1016/j.lithos.2012.02.017



Fig. 1. Tectonic configuration of the Central American-Circum-Caribbean region showing extent of Early and Later Arc products in Panama and Costa Rica and the location of other "ophiolites" of plateau and intra-oceanic arc affinities. Sketch is based on maps from Buchs et al. (2009), Hoernle et al. (2002) and Kerr et al. (2003)and references cited therein. The thick vectors accompanying the Cocos and Nazca plates represent the approximate direction of plate motion. Abbreviations: LAA–Lower Antilles Arc system: PO–Petaquilla; S–A–Sona–Azuero peninsula.

at 70–40 Ma, 30–26 Ma and 28–5 Ma as the Early, Middle and Later Arc systems (EAS, MAS and LAS respectively; and we designate LAS products to the east and west of the Panama Canal Basin as LAS-east and LAS-west, respectively).

Termination of 'normal' arc-related magmatism in Panama occurred about 5 Ma and gave way to a phase of spatially restricted, extreme-HREE-depleted, dacitic, 'adakitic-like' magmatism that began ~4 Ma and continues until the present day (Defant et al., 1991a,b, 1992; Gazel et al., 2009, 2011; Hidalgo et al., 2012). Adakites are highalumina, intermediate to felsic rocks composed predominantly of phenocrysts of plagioclase, amphibole and mica which, on the basis of trace element characteristics (extreme depletion in HREE and Y), suggest derivation from a garnet-bearing residuum (Defant and Drummond, 1990). Originally used to describe lavas interpreted solely as subducted slab-derived partial melts (Defant and Drummond, 1990) due to their compositional similarity to Tertiary lavas on Adak Island interpreted as slab melts (Kay, 1978), the term 'adakite' is now generally used to describe a chemically distinct suite of lavas and intrusives irrespective of the inferred petrogenetic origin or tectonic setting. These young Panamanian adakites have been identified from the El Valle and La Yeguada volcanoes (Fig. 2) (Defant et al., 1991a,b; 1992) in western Panama and were initially interpreted as products of slab melting (Defant et al., 1991a,b; 1992). Until very recently, the only such Panamanian rocks described as 'adakitic-like' are these young, <4 Ma dacites from El Valle and La Yeguada. However, Rooney et al. (2010) identified a subvolcanic suite of hornblendenodule-bearing, circa 25 Ma adakitic-like andesites from Cerro Patacon of the Canal Basin, thus indicating that adakitic-like magmatism in Panama is not temporally restricted to relatively recent activity. It was concluded that these andesites arose via fractional crystallization of water-saturated arc magmas in the lower crust, a similar interpretation of which was subsequently posited for the much younger post-Miocene adakites in El Valle (Hidalgo et al., 2012). In the case of the <5 Ma adakites in Costa Rica, Gazel et al. (2009, 2011) concluded that formation was the result of slab melting, based on isotopic signatures that suggest derivation from partial melting of the Cocos/Coiba Ridge.

Via new LA-ICP-MS U–Pb zircon ages and geochemical data from granodiorites of the 30–26 Ma Petaquilla batholith of the MAS in western Panama and 19 Ma andesites and dacites of the subvolcanic Majé complex of the LAS-east, we demonstrate that adaktic-like magmatism in

Panama, similar to that described by Rooney et al. (2010) for the circa 25 Ma Cerro Patacon (Panama Canal Basin) andesites, is indeed older and more widespread than originally presumed. Fundamentally we also illustrate that there exists a west to east regression in the age of Oligo-Miocene adakitic-like intrusive activity that defines a near horizontal lineament (Fig. 2). For example the 30–26 Ma, 25 Ma and 19 Ma adakitic-like intrusives from Petaquilla (western Panama), Cerro Patacon (central Panama) and Majé (eastern Panama) respectively, all lie at the same approximate latitude (~8° 50′N–9° 00′N, see Figs. 2, 3).

A circa 40–28 Ma hiatus in arc activity was identified by Montes et al. (2012) which they correlated with an interval of deformation as recorded by the 70–40 Ma EAS. In this communication, we discuss the fundamental significance of these Oligocene to Early Miocene adakitic-like intrusives in relation to the post-40 Ma tectonic evolution of the Panamanian magmatic arc system.

2. Regional geological and tectonic setting

The Panama-Choco block is located at the junction between the Nazca, Cocos, Caribbean and South American plates (Fig. 1) (Molnar and Sykes, 1969). The northern boundary of the Panama block is a submarine, westward-tapering deformed belt (Silver et al., 1990, 1995) recording incipient underthrusting of the Caribbean plate beneath the Panama Block between 69 and 52 Ma (Adamek et al., 1988; Bowin, 1976; Camacho et al., 2010; Wolters, 1986). To the south, leftlateral transforms separate the Panama Block from the Nazca Plate (Jordan, 1975; Kellogg and Vega, 1995; Westbrook et al., 1995), while normal subduction has been documented west of the Azuero Peninsula (Moore and Sender, 1995). An allochthonous belt of basaltic and associated pelagic sequences crops out from Costa Rica to western Panama, south of the Azuero-Sona Fault zone where Galapagos-related seamounts (Baumgartner et al., 2008; Di Marco et al., 1995; Hoernle et al., 2002, 2004, 2008) have been accreted to the forearc region (Buchs et al., 2009, 2011; Lissinna, 2005). To the east, the Uramita fault marks the boundary between the Panama Block to the east and the Andean Cordilleras to the west (Duque-Caro, 1990). To the west, a strike-slip fault (Wolters, 1986) covered by recent deposits of the El Valle volcano is sometimes called the Canal Fracture Zone (CFZ, Fig. 2) with leftlateral (De Boer et al., 1991) or right lateral (Lowrie et al., 1982) movement. The CFZ separates the Panama block from the Chorotega block (Fig. 2) i.e., the region of the Panama micro-plate to the west of the CFZ that comprises oceanic crust and which lies to the immediate SE of continental crust of the Chortis block (Dengo, 1985; Tournon et al., 1995).

Originally interpreted as solely representing uplifted and exposed edges of the southernmost Caribbean Plateau (or Caribbean Large Igneous Province, CLIP) (Hoernle et al., 2002) many oceanic terranes in Costa Rica and Panama have recently been reinterpreted as representing instead a complex association of temporally and geochemically distinct stages of arc construction atop the CLIP (Buchs et al., 2010; Wegner et al., 2011; Wörner et al., 2009) and later accreted younger Galapagosrelated tracks (Gazel et al., 2009; Buchs et al, 2009, 2011). Early Arc construction involved the production of proto-arc lavas and associated intrusives interpreted as marking a transition from intra-plate to arc magmatism which was followed by generation of exclusively arc-like lavas and related intrusives (Buchs et al., 2010; Wegner et al., 2011; Wörner et al., 2009). The circa 89-85 Ma oceanic plateau segment of the CLIP upon which the EAS is interpreted to have been constructed (Buchs et al., 2010; Wegner et al., 2011; Wörner et al., 2009) represents a southernmost extension of the CLIP, which is generally interpreted as constituting the bulk of the Caribbean Plate (Fig. 1) (e.g., Kerr et al., 2003).

As the result of an apparent major tectonic reconfiguration for reasons that remain poorly understood and thus for the most part unexplained, arc activity terminated at ~38–28 Ma (Montes et al., 2012). Arc volcanism may have been continued uninterrupted to the west of



Fig. 2. Sketch of Panama based on the topographic map of Wegner et al. (2011) and Wörner et al. (2009), and the tectonic map of Drummond et al. (1995) illustrating the distribution of the Early Arc system (EAS) (EAS), Middle Arc System (MAS) and the Later Arc system (LAS); localities referred to in the text; and the locations and radiometric ages of the adaktic-like intrusions of Petaquilla (29–26 Ma), Cerro Patacon (25 Ma) and Majé (19 Ma). Also shown are the locations of the much younger (<4 Ma) adakties identified from the El Valle and La Yeguada volcanoes (Defant et al., 1991a,b, 1992; Hidalgo et al., 2012). The asterisk beside the cited age range for Petaquilla indicates the high uncertainty in the upper limit, e.g., a maximum age of 32.6 ± 2 Ma was obtained on a hornblende separate (see Kesler, 1978) whereby a feldspar separate from the same sample yielded a circa 29 Ma age similar to the upper limit of our U–Pb dated Petaquilla granodiorite samples. Note also that the lone age available for El Baru also yields a high uncertainty (32.25 ± 2.25 Ma, diorite, Drummond et al., 1995).

the Panama Canal Basin where evidence for this is possibly buried by younger rocks; to date however, only sporadic arc-related plutonism is evident as recorded by the circa 30–26 Ma Petaquilla (Fig. 2) batholith (Kesler, 1978; Kessler et al., 1977; Speidel and Faure, 1996; this paper) and the ~30 Ma El Baru plutonic complex of western Panama (Drummond et al., 1995) (Fig. 2). After 20 Ma, the focus of arc-related magmatism shifted some 75 km to south of the focus of EAS magmatism (Lissinna, 2005; Montes et al., 2012).

2.1. Petaquilla batholith

According to Kessler et al. (1977) the largest intrusive bodies of granodiorite in Panama are located at (Cerro) Petaquilla (Fig. 3a) which is approximately 120 km west of Panama City in Colon Province (Fig. 2) and Cerro Colorado (Nelson, 1995) some 100 due west of Petaquilla. As the Petaquilla batholith hosts porphyry copper–gold and was the first place in Panama that copper mineralization was discovered, (Ferenčić, 1970) interest in the batholith and the region has primarily been from a metallogenesis standpoint (e.g., Kesler, 1978; Kessler et al., 1977; Speidel and Faure, 1996).

2.2. Majé intrusive complex

Previous studies of the Majé Range (Fig. 3b) consisted of reconnaissance mapping and Canal engineering feasibility studies which resulted in generalized stratigraphic columns and maps of the northern flank of the range (Anonymous, 1972). Pillow basalts of Bahia Piña to the southeast of Majé (Fig. 2) yielded ⁴⁰Ar/³⁹Ar whole-rock ages of ~85–70 Ma and are interpreted to represent CLIP basement (Lissinna, 2005) but it is uncertain as to whether this basement extends beneath Majé.

Lithologies encompassing the Majé intrusive complex include limestones, tuffs, tuffaceous sandstones and siltstones (Fig. 3b). These lithologies may unconformably overlie the San Blas Complex basaltic basement (see Coates et al., 2004) that represents an accretionary lithofacies consisting of pillow basalts and associated radiolarian chert and diabase collectively referred to as the Punta Sabana Volcanics (Bandy and Casey, 1973). The Punta Sabana Volcanics are intruded by subvolcanic, porphyritic and mainly intermediate intrusives but which range from gabbro through granodiorite and these subvolcanic intrusives represent the sample set of the current study. These hypabyssal intrusive rocks predominantly comprise porphyritic amphibole–andesites and commonly enclose circa 5–10 cm mafic enclaves which appear to be akin to those described elsewhere, e.g., from ~25 Ma adakitic-like, hypabyssal andesites from Cerro Patacon of the Panama Canal Basin region (Rooney et al., 2010).

3. Nomenclature and petrography

3.1. Petaquilla granodiorites

Petrographic features of granodiorites of the Petaquilla batholith (Fig. 2) (Kessler et al., 1977) have been summarized by others (e.g., Kesler, 1978; Kessler et al., 1977; Speidel et al., 2001) and in various Panama Inmet Mining technical reports (e.g., Speidel and Faure, 1996). Below, we provide a synopsis of the main petrographic features of the Petaquilla intrusive samples (060109, 060116, 060120, 060124) that have been dated via LA-ICP-MS U–Pb analysis (see Section 4).

Samples comprise primarily plagioclase feldspar, quartz, potassium feldspar and hornblende (45, 30, 15 and ~10–15 modal %, respectively). Samples are generally fresh, coarse grained and equigranular. An exception is sample 060116 which is strongly altered, medium grained and porphyritic, defined by 2–3 mm plagioclase feldspar and potassium feldspar phenocrysts. In the equigranular samples, plagioclase feldspar is 3 to >5 mm and exhibits well defined oscillatory zoning whereby in the porphyritic samples, zoning in plagioclase feldspar is not apparent due to alteration and replacement products (sericite, carbonates). In the equigranular granodiorites hornblende occurs as fibrous, light green and pleochroic (colorless/pale yellow to dark green) masses and is interstitial to quartz. In the porphyritic samples hornblende tends to occur instead as discrete, prismatic crystals.



Fig. 3. Geological sketch map of the (a) Petaquilla (geology is generalized from Anonymous, 1969; see Kessler et al., 1977) and (b) Majé regions in eastern and central Panama and the distribution of igneous rocks of the Majé Igneous Complex and the Petaquilla batholith. Note that all of the Majé rocks sampled in the current study are best described as subvolcanic intrusives and range in composition from basalt to dacite while all Petaquilla samples are granodioritic. The locations of collected samples from Petaquilla and Majé are indicated by triangles and circles, respectively. Only those samples which have been radiometrically dated (U–Pb, zircons) are indicated by sample numbers. Also shown on (a) and indicated by an asterisk are the locations of a radiometrically dated hornblende separate, (K–Ar) diorite (32.6 ± 2.0 Ma, see details in Kessler et al., 1977) with a large uncertainty and granodiorite (sample M-1001) which yields a hornblende and a feldspar separate age of 36.4 ± 2.1 Ma and 29.0 ± 0.4 Ma, respectively, via K-Ar dating methods, (Kessler et al., 1977). We prefer the younger age for Petaquilla which falls within the range of U–Pb ages from this study.

3.2. Majé subvolcanic intrusives

The Majé igneous complex comprise porphyritic and hypabyssal intrusives that range in composition from gabbro through to granodiorite (see Section 5). Gabbros are robustly porphyritic defined by phenocrysts of volumetrically dominant plagioclase and subordinate clinopyroxene (ratio of plagioclase: clinopyroxene~65:35) set in a variably altered (e.g., sericitized, chloritized) cryptocrystalline to microcrystalline groundmass. Gabbroic diorites display similar texture but comprise amphibole (hornblende) as the dominant mafic phase with lesser clinopyroxene. The intermediate diorites and granodiorites are distinguishable from the gabbros and gabbroic diorites by the absence of pyroxene; hornblende is the sole mafic phase. Similar to the basic intrusives, all diorites and granodiorites are strongly porphyritic but defined by hornblende in addition to plagioclase phenocrysts. Hornblende occurs as yellow-brown, pleochroic, commonly euhedral, prismatic or tabular, circa 0.5 mm phenocrysts and sub-mm crystallites. Hornblende appears to represent ~5-10 modal % but the actual percentage could be significantly higher and masked by alteration products.

4. U-Pb geochronology

4.1. Methods

U–Pb–Th geochronological analyses were done at the Arizona LASERCHRON Center, University of Arizona. We have combined analytical procedures as outlined in Gehrels et al. (2006, 2008) and Valencia et al. (2005).

Zircon crystals were extracted from samples after crushing and grinding. This was followed by hydraulic separation with a Wilfley® table and magnetic separation with a Frantz® magnetic separator. Final zircon concentrates were obtained with heavy liquids (methylene iodide). Magmatic zircon crystals were handpicked and mounted on a

1" epoxy mount together with fragments of in-house standard Sri Lanka zircon CV3 (see Pidgeon et al., 1994). The mounts were sanded down to a depth of ~20 μ m, polished, and cleaned with ultrasonic bath prior to isotopic analysis.

The U-Pb geochronological analyses were conducted in an Isoprobe equipped with an ArF Excimer laser ablation system, which has an emission wavelength of 193 nm. The collector configuration allows measurement of ²⁰⁴Pb in the ion-counting channel while ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³²Th and ²³⁸U were simultaneously measured with Faraday detectors. All analyses were conducted in static mode with a laser beam diameter of 35 um, operated with output energy of \sim 32 mJ (at 23 kV) and a pulse rate of 8 Hz. Each analysis consisted of one 12-second integration on peaks with no laser firing and twenty 1-second integration on peaks with the laser firing. The ablated material is carried with helium gas into the plasma source. Hg contribution to the ²⁰⁴Pb mass position was removed by subtracting on-peak background values. Inter-element fractionation was monitored by analyzing an in-house zircon standard, which has a concordant TIMS age of 564 ± 3.2 Ma (2σ) (Gehrels et al., 2008). The lead isotopic ratios were corrected for common Pb, using the measured ²⁰⁴Pb, assuming an initial Pb composition according to Stacey, and Kramers (1975) and respective uncertainties of 1.0, 0.3 and 2.0 for ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, and ²⁰⁸Pb/²⁰⁴Pb.

Uranium-lead ages were calculated using Isoplot 3.62 (Ludwig, 2003a, 2003b). Reported and calculated ages are $^{206}Pb/^{238}U$ as all the analyzed samples are of Cenozoic age. The final crystallization ages that we report were calculated using the algorithm of TUFFZIRC. This algorithm was constructed by Ludwig and Mundil (2003) to minimize the effect of inheritance or subtle Pb loss. The final age error calculated for each sample used two uncertainties: the first is derived from the uncertainty of the TUFFZIRC age calculation alone, and the second represents the systematic uncertainty during each session (~1.1%). The age uncertainty is determined as the quadratic sum of the TUFFZIRC error plus the total systematic error for the set of analyses (~1.2%). The systematic error, which includes



Fig. 4. Zircon U-Pb concordia plots for (a-d) Petaquilla granodiorites 060120, 060124, 060109 and 060116 and (e) Majé diorite 310139.

contributions from the standard calibration, age of the calibration standard, composition of common Pb, and U decay constants, is generally $\sim 1-2\%$ (2-sigma).

4.2. Results

140 U–Pb single zircon crystal ages were obtained in five granitoid samples from Petaquilla and Majé (Table A1). Zircon crystals from all the samples are prismatic with length/width ratios of 2:1 and 3:1 similar to higher crystallization growth rates in magmatic zircons (Corfu et al., 2003). Crystal lengths vary from 175 µm to 300 µm.

More than 24 single crystals were analyzed for each sample. As cathodoluminescence imaging was not originally possible (however, see below) during the analytical session, we followed the analytical procedure as outlined by Valencia et al. (2005). Magmatic zircon crystal tips were analyzed as they commonly record the last magmatic crystallization event and allow for avoidance of inherited cores (Corfu et al., 2003; Hoskin and Schaltegger, 2003). Excluding three zircon crystals, the entire suite of crystals in each of the analyzed samples yield comparable U–Pb ages which suggest a relatively simple crystallization history. U/Th ratios from all the zircons are below 12, a feature that is also typical of magmatic related zircons (Hoskin and Schaltegger, 2003; Rubatto, 2002).

Cathodoluminescence imaging was firstly conducted on a single sample (060116) subsequent to U–Pb analysis at the Center for Electron Microscopy & Microanalysis of the University of Idaho in order to evaluate zircon growth history. Sample 060116 exhibits a typical magmatic zircon zoning with relatively simple growth patterns. We subsequently conducted cathodoluminescence imaging on the remaining Petaquilla and Majé samples which yielded results similar to sample 060116 (Fig. A1).

In order to reduce effects of inheritance of subtle Pb loss, zircon ages were calculated with the TUFFZIRC algorithm, ISOPLOT 3.62 (Ludwig and Mundil, 2003). Analyses that are statistically excluded from the main cluster are visible within the Concordia plots (Fig. 5) and are indicated by gray bars on the TuffZirc age vs. *n* plots (Fig. 5, right hand side). Reported age errors in each sample include the systematic and

Magmatic crystallization ages of the Petaquilla granodiorite samples 060120, 060124, 060109 and 060116 vary from circa 26.2 Ma to 29 Ma (Fig. 5a–d) whereas the Majé diorite (sample 310139) yields a younger magmatic zircon age of circa 19 Ma (Fig. 5e).

5. Bulk rock chemistry

5.1. Methods

Samples of the Majé subvolcanic complex and Petaquilla batholith were crushed and ground to powders for whole rock major and trace element determinations (Table 1). Table A2 provides replicate analyses of reference standards and various samples. Major and trace element contents were determined by ICP-AES at ACME Laboratories, Vancouver, Canada. Major element abundances were determined on 0.2 g of pulp sample (LiBO₂ fusion). Major element detection limits were about 0.001–0.04%. For trace and rare earth elements, 0.2 g of sample powder and 1.5 g of LiBO₂ flux were mixed in a graphite crucible and consequently heated to 1050 °C for 15 min in a muffle furnace. Trace element detection limits were 0.01–0.5 ppm. Molten samples were subsequently dissolved in 100 mL of 5% HNO₃ (American Chemical Society-grade nitric acid in demineralized water). Sample solutions were then shaken for 2 h before an aliquot was poured into a polypropylene test tube and aspirated into a Perkin-Elmer Elan 600 ICP mass spectrometer. Calibration and verification standards together with reagent blanks were added to the sample sequence. Elemental abundances of the samples were obtained using external USGS standards BCR-2 and BIR-2. Detection limits range from 0.01 to 0.5 ppm.

In our geochemical plots we compare Majé and Petaquilla intrusives with lavas and associated intrusives of the ~70–40 Ma EAS, the 30–26 Ma MAS and the 28–5 Ma Panama Canal Basin and LAS-west. We do this to illustrate (1) compositional differences that exist between Majé and Petaquilla intrusives and lavas and intrusives of the other arc systems; and (2) compositional similarities that exist between Majé and Petaquilla intrusives and the adakitic-like andesites from Cerro



Fig. 5. Discrimination of Majé subvolcanic intrusives and Petaquilla intrusives vs. lavas and plutonics of the Early, Middle and Later arc systems on the andesite series discrimination plot of Gill (1981). Boundary between the high-K calc-alkaline and shoshonite series are from Peccerillo and Taylor (1976).

Table 1	
---------	--

Whole-rock XRF and ICP-MS analyses of Majé subvolcanic intrusives and Petaquilla granodiorites.

$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Major	310112	310114	310115	310140	310144	310122	310141	310128	310123	310139	310117
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	oxides	gb	gb	gb-dior	gb-dior	gb-dior	gb-dior	dior	dior	dior	dior	dior
SO. TO5. 47.07 (1) 47.07 (1) 45.10 (2) 55.46 (2) 55.82 (2) 55.82 (2) 55.82 (2) 55.81 (2) 56.61 (2) 57.7 (2) 65.61 (2) 66.61 (2) 66.71 (2) 66.71 (2) 66.71 (2) 67.71 (2) 67.71 (2) <th< td=""><td>(11.70)</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td><td>Majé</td></th<>	(11.70)	Majé	Majé	Majé	Majé	Majé	Majé	Majé	Majé	Majé	Majé	Majé
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	SiO ₂	47.67	46.11	47.77	50.02	55.46	52.04	55.82	56.63	56.61	56.42	56.95
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	TiO ₂	1.23	0.71	0.9	0.45	0.48	0.93	0.37	0.73	0.67	0.53	0.57
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	AlaOa	16.47	13.74	14.53	17.36	16.02	16.19	17.07	17.27	16.94	17.37	17.21
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	FeaOa	10.73	92	8.8	11.63	8 97	8 76	746	7 44	6.24	6	6.12
	MnO	0.2	0.15	0.14	0.26	0.17	0.13	0.2	0.13	0.14	0.21	0.12
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	MaO	5.77	9.51	4.02	5.02	5 71	4 22	4.22	2 75	2.57	2 79	2 20
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	NigO CaO	J.//	0.01	4.02	0.05	J.7 I	4.52	4.25	3.75	2.37	5.76	5.20
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	CdU No. O	10.41	9.65	0.02	0.21	7.75	7.27	0.55	7.25	0.05	0.1	5.09
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Na ₂ O	2.47	2.07	3.15	1.88	2.51	3.37	2.94	3.49	3.33	3.66	4.09
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	K ₂ O	0.24	0.52	1.15	0.08	0.9	1.32	0.5	1.28	1.84	1.13	1.46
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$P_{2}O_{5}$	0.2	0.12	0.20	0.10	0.11	0.27	0.08	0.24	0.25	0.29	0.26
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	LOI	4.3	8.7	10.4	3.9	1.7	5	4.8	1.5	5.1	4.2	3.8
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Total	99.74	99.72	99.70	99.79	99.79	99.63	99.81	99.69	99.69	99.67	99.62
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Mg#	37.41	50.70	33.68	35.76	41.42	35.43	38.66	35.90	31.45	41.21	37.30
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	REE (ppm)											
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	La	10.6	6.4	10.3	5	5.9	19.5	5.8	14.7	17.1	19.8	19.2
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Ce	22.8	13.1	21.9	10.1	12.6	39.2	12.5	29.6	33.1	38.1	40.2
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Pr	3.22	1.87	2.98	1 46	1 91	4 75	1.83	3 75	4 27	4 54	4 72
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Nd	15.3	86	13.3	66	9	19.7	7.5	15.1	16.8	17	19.1
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Sm	3.66	2.05	2.95	1.46	2 14	3 92	1.81	3 23	3 3 2	3 29	3 51
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	511	1.10	2.05	2.55	0.61	0.59	1.32	0.50	0.00	1.05	0.06	1.01
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	C.I.	1.19	0.7	0.56	1.00	0.58	1.24	0.55	0.99	1.05	0.90	2.02
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Gu	4.40	2.4	3.15	1.00	2.02	3.70	1.9	3.09	3.2	2.7	3.03
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	ID Du	0.76	0.41	0.53	0.29	0.30	0.57	0.33	0.51	0.5	0.41	0.45
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Dy	4.94	2.61	3.02	1.65	2.17	3.17	1.97	2.96	2.99	2.2	2.43
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Ho	1.03	0.5	0.63	0.36	0.47	0.62	0.43	0.63	0.58	0.44	0.45
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Er	3.06	1.55	1.8	1.11	1.47	1.81	1.38	1.88	1.72	1.35	1.38
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Tm	0.44	0.22	0.27	0.18	0.22	0.28	0.21	0.28	0.28	0.2	0.22
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Yb	2.87	1.43	1.69	1.18	1.47	1.72	1.37	1.81	1.65	1.27	1.32
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Lu	0.44	0.22	0.28	0.2	0.24	0.3	0.24	0.29	0.27	0.22	0.22
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\sum REE$	74.77	42.06	63.78	31.86	40.55	100.54	37.86	78.82	86.83	92.48	97.24
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$[La/Sm]_{C=N}$	1.60	2.06	1.07	1.61	2.52	0.48	0.64	1.57	14.62	0.84	0.93
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$[La/Gd]_{CN}$	1.90	2.24	1.16	1.96	3,39	0.56	0.76	1.72	16.58	0.99	1.09
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	[La/Yh]c N	2 47	3 73	2.00	2.82	493	1.00	1 34	3 58	16.82	1.52	1 64
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$[Cd/Vb]_{e_N}$	130	1.66	1 73	1 / 3	1.35	1.00	1.78	2.00	1.01	1.52	1.51
HESE (ppm) V 338 276 305 311 247 234 1.17 1.14 2.55 0.55 0.55 Y 338 276 305 311 247 234 183 180 146 121 177 Y 27.4 13.5 17.5 10 12.5 17.2 12.4 17.3 16.7 13.1 13.9 Zr 103.1 47.9 73.5 24.5 39.9 113.1 44.7 100.5 104.5 118.5 114.3 Hf 2.8 1.5 1.9 0.8 1.2 3.4 1.2 2.8 3.4 3.1 3.1 Nb 5.2 2.1 3 0.7 1.1 7.9 1.3 7.4 8 7.7 5.8 Ta 0.3 0.1 0.2 <0.1 <0.5 <0.1 0.5 0.5 0.4 0.3 ILLE (ppm) Rb 2.9 7.6 20.9 0.8 26.1 23.8 7.5 22 36 14.3 21.3	Fu/Fu*	0.90	0.00	0.62	0.90	2.84	0.87	1.70	2.05	2.05	0.83	0.87
HFSE (ppm) V 338 276 305 311 247 234 183 180 146 121 177 Y 27.4 13.5 17.5 10 12.5 17.2 12.4 17.3 16.7 13.1 13.9 Zr 103.1 47.9 73.5 24.5 39.9 113.1 44.7 100.5 104.5 118.5 114.3 Hf 2.8 1.5 1.9 0.8 1.2 3.4 1.2 2.8 3.4 3.1 3.1 Nb 5.2 2.1 3 0.7 1.1 7.9 1.3 7.4 8 7.7 5.8 Ta 0.3 0.1 0.2 <0.1	Lu/Lu	0.50	0.50	0.02	0.50	2.04	0.07	1.17	1.14	2,35	0.05	0.07
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	HFSE (ppm)											
Y27.413.517.51012.517.212.417.316.713.113.9Zr103.147.973.524.539.9113.144.7100.5104.5118.5114.3Hf2.81.51.90.81.23.41.22.83.43.13.1Nb5.22.130.71.17.91.37.487.75.8Ta0.30.10.2<0.1	V	338	276	305	311	247	234	183	180	146	121	177
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Y	27.4	13.5	17.5	10	12.5	17.2	12.4	17.3	16.7	13.1	13.9
Hr Hois His Hois <t< td=""><td>7r</td><td>103.1</td><td>47.9</td><td>73.5</td><td>24.5</td><td>39.9</td><td>113.1</td><td>447</td><td>100.5</td><td>104 5</td><td>118.5</td><td>1143</td></t<>	7r	103.1	47.9	73.5	24.5	39.9	113.1	447	100.5	104 5	118.5	1143
Int Lo <thlo< th=""> Lo Lo <th< td=""><td>Hf</td><td>2.8</td><td>15</td><td>19</td><td>0.8</td><td>12</td><td>3.4</td><td>12</td><td>2.8</td><td>34</td><td>3.1</td><td>3.1</td></th<></thlo<>	Hf	2.8	15	19	0.8	12	3.4	12	2.8	34	3.1	3.1
No 3.2 2.1 3 0.7 1.1 1.3 1.3 1.4 0 1.4 0 1.4 3.5 Ta 0.3 0.1 0.2 <0.1 <0.1 0.5 <0.1 0.5 0.5 0.4 0.3 <i>LLE</i> (ppm) Rb 2.9 7.6 20.9 0.8 26.1 23.8 7.5 22 36 14.3 21.3 Ba 237 284 604 86 214 1374 462 1282 1425 1234 1723 Pb 2.5 1.3 2 2.2 0.9 0.8 1.9 0.8 1.9 1.5 0.7 Th 2 0.9 2 0.5 0.8 3.5 1.3 2.9 2.6 3.9 4.4 U 0.6 0.5 0.7 0.2 0.3 1.2 0.4 0.9 1 1.5 1.3 Sr 344 397.9 744.3 324.9 359.1 703.1 421.1 579.9 659.2 824.4 751.4 <th< td=""><td>Nb</td><td>5.2</td><td>2.1</td><td>3</td><td>0.7</td><td>11</td><td>79</td><td>13</td><td>7.4</td><td>8</td><td>77</td><td>5.8</td></th<>	Nb	5.2	2.1	3	0.7	11	79	13	7.4	8	77	5.8
Ind0.50.10.20.10.10.10.30.10.30.30.40.3 <i>LLE</i> (ppm)Rb2.97.620.90.826.123.87.5223614.321.3Ba2372846048621413744621282142512341723Pb2.51.322.20.90.81.90.81.91.50.7Th20.920.50.83.51.32.92.63.94.4U0.60.50.70.20.31.20.40.911.51.3Sr344397.9744.3324.9359.1703.1421.1579.9659.2824.4751.4Other (ppm)Sc3839323935242721151216Ni3268<20	Тэ	0.2	0.1	0.2	<0.1	<01	0.5	<01	0.5	05	0.4	0.2
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	la	0.5	0.1	0.2	<0.1	<0.1	0.5	<0.1	0.5	0.5	0.4	0.5
Rb 2.9 7.6 20.9 0.8 26.1 23.8 7.5 22 36 14.3 21.3 Ba 237 284 604 86 214 1374 462 1282 1425 1234 1723 Pb 2.5 1.3 2 2.2 0.9 0.8 1.9 0.8 1.9 1.5 0.7 Th 2 0.9 2 0.5 0.8 3.5 1.3 2.9 2.6 3.9 4.4 U 0.6 0.5 0.7 0.2 0.3 1.2 0.4 0.9 1 1.5 1.3 Sr 344 397.9 744.3 324.9 359.1 703.1 421.1 579.9 659.2 824.4 751.4 Other (ppm)Sc 38 39 32 39 35 24 27 21 15 12 16 Ni 32 68 <20 22 28 28 <20 24 <20 67 33 Cs <0.1 0.2 1.2 <0.1 0.9 0.5 0.1 0.2 0.6 <0.1 0.3	LILE (ppm)											
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Rb	2.9	7.6	20.9	0.8	26.1	23.8	7.5	22	36	14.3	21.3
Pb 2.5 1.3 2 2.2 0.9 0.8 1.9 0.8 1.9 1.5 0.7 Th 2 0.9 2 0.5 0.8 3.5 1.3 2.9 2.6 3.9 4.4 U 0.6 0.5 0.7 0.2 0.3 1.2 0.4 0.9 1 1.5 1.3 Sr 344 397.9 744.3 324.9 359.1 703.1 421.1 579.9 659.2 824.4 751.4 Other (ppm) Sc 38 39 32 39 35 24 27 21 15 12 16 Ni 32 68 <20 22 28 28 <20 24 <20 677 33 Cs <0.1 0.2 1.2 <0.1 0.9 0.5 0.1 0.2 0.6 <0.1 0.3	Ba	237	284	604	86	214	1374	462	1282	1425	1234	1723
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Pb	2.5	1.3	2	2.2	0.9	0.8	1.9	0.8	1.9	1.5	0.7
U 0.6 0.5 0.7 0.2 0.3 1.2 0.4 0.9 1 1.5 1.3 Sr 344 397.9 744.3 324.9 359.1 703.1 421.1 579.9 659.2 824.4 751.4 Other (ppm) Sc 38 39 32 39 35 24 27 21 15 12 16 Ni 32 68 <20 22 28 28 <20 24 <20 67 33 Cs <0.1 0.2 1.2 <0.1 0.9 0.5 0.1 0.2 0.6 <0.1 0.3	Th	2	0.9	2	0.5	0.8	3.5	1.3	2.9	2.6	3.9	4.4
Sr 344 397.9 744.3 324.9 359.1 703.1 421.1 579.9 659.2 824.4 751.4 Other (ppm) Sc 38 39 32 39 35 24 27 21 15 12 16 Ni 32 68 <20	U	0.6	0.5	0.7	0.2	0.3	1.2	0.4	0.9	1	1.5	1.3
Other (ppm) Sc 38 39 32 39 35 24 27 21 15 12 16 Ni 32 68 <20	Sr	344	397.9	744.3	324.9	359.1	703.1	421.1	579.9	659.2	824.4	751.4
Sc 38 39 32 39 35 24 27 21 15 12 16 Ni 32 68 <20	Other (ppm)											
Ni 32 68 <20 22 28 28 <20 24 <20 67 33 Cs <0.1	Sc	38	39	32	39	35	24	27	21	15	12	16
Cs <0.1 0.2 1.2 <0.1 0.9 0.5 0.1 0.2 0.6 <0.1 0.3	Ni	32	68	<20	22	28	28	<20	24	<20	67	33
	Cs	< 0.1	0.2	1.2	< 0.1	0.9	0.5	0.1	0.2	0.6	<0.1	0.3

Patacon, Panama Canal Basin (Rooney et al., 2010). Databases used for comparison are those of Wegner et al., 2011 and Wörner et al. (2009) (EAS, LAS-east, Canal and LAS-west, Central Cordillera); Buchs et al. (2010) (EAS); Kessler et al. (1977) (MAS); Drummond et al. (1995) (MAS and LAS-west); Farris et al. (2011) (Canal); Lissinna (2005) (Pearl Islands and Bahia Piña of the LAS-east,); and Rooney et al.

(2010) (Cerro Patacon, Canal). The EAS samples are from the Sona and Azuero peninsulas in southern Panama and the Chagres and Bayano regions and San Blas range in eastern Panama (Fig. 2) (i.e., the Sona-Azuero and Chagres–Bayano arcs of Wörner et al. (2009). The MAS (El Baru, Petaquilla) and LAS-west samples are primarily from the Cordillera of western Panama Figs. 1, 2).

Major	310110	310131	310124	310143	310118	310142	60109	60116	60120	60124
oxides (wt %)	dior	dior	dior	granodior	qtz-monzo	qtz-monzo	granodior	granodior	granodior	granodior
(111.0)	Majé	Majé	Majé	Majé	Majé	Majé	Petaquilla	Petaquilla	Petaquilla	Petaquilla
SiO ₂	55.85	58.4	60.09	61.03	60.8	63.55	67.28	64.13	66.84	64.5
TiO ₂	0.66	0.6	0.54	0.42	0.38	0.32	0.53	0.42	0.25	0.43
Al_2O_3	15.36	16.79	16.96	17.8	17.92	17.55	16.35	16.01	15.39	16.21
Fe ₂ O ₃	5.26	5.68	4.88	4.45	3.96	3.34	4.09	5.69	4.38	3.42
MnO	0.11	0.12	0.12	0.14	0.12	0.14	0.03	0.05	0.05	0.06
MgO	3.01	4.55	1.95	1.61	1.55	1.33	1.82	1.63	0.96	1.58
CaO	6.84	6.27	5.43	4.8	3.87	2.7	2.34	2.57	3.46	2.23
Na ₂ O	3.74	4.07	3.85	3.87	4.95	5.1	3.97	3.46	3.92	1.98
K ₂ O	1.56	1.68	1.36	2.38	2.02	2.36	1.35	2.24	2.02	3.73
P_2O_5	0.22	0.29	0.2	0.22	0.2	0.16	0.23	0.17	0.1	0.19
LOI	7.1	1.2	4.3	2.9	3.9	3.2	1.8	3.4	2.4	5
Total	99.71	99.67	99.69	99.63	99.61	99.71	99.77	99.79	99.78	99.33
							0.05	0.04	0.02	0.04
Mg#	38.88	47.09	30.72	28.62	30.34	30.73	12.82	8.61	6.42	13.59
REE (ppm)										
La	16.2	19	20.1	21.7	22.9	15.6	25.9	20.3	22.1	12.8
Ce	30.6	38.4	39.9	40.3	42.7	28.3	47.3	36.4	37.1	24.7
Pr	3.89	4.87	4.69	4.84	4.84	3.26	5.23	3.97	4	3.06
Nd	14.9	18.7	17.9	1/	17.9	12.1	19.2	15.8	14.6	12.8
SIII	3.07	3.05	3.17	3.05	2.93	2.01	3.04	2.47	2.29	2.37
Cd	2 75	3.21	0.95	2.46	2.35	1.69	2.25	2.75	1 00	0.82
Th	0.43	0.5	0.43	0.37	0.32	0.25	0.29	0.35	0.3	0.41
Dv	2 39	2.82	2 44	2.03	1.82	1.42	1 29	1.96	1.57	2.4
Но	0.45	0.52	0.5	0.44	0.34	0.29	0.22	0.4	0.3	0.51
Er	1.32	1.62	1.39	1.23	1.08	0.79	0.58	1.21	0.9	1.57
Tm	0.2	0.23	0.23	0.18	0.17	0.13	0.09	0.19	0.15	0.24
Yb	1.31	1.46	1.46	1.28	1.16	0.89	0.53	1.29	0.97	1.7
Lu	0.2	0.26	0.24	0.22	0.19	0.15	0.08	0.22	0.16	0.27
							<20	<20	<20	<20
$\sum REE$	78.65	96.41	96.19	95.95	99.56	67.45	106.90	87.57	87.14	66.06
$[La/Sm]_{C-N}$	1.64	3.39	na	3.68	1.35	0.92	5.26	5.07	5.95	3.33
$[La/Gd]_{C-N}$	1.40	3.79	10.22	5.51	1.56	1.32	9.66	7.47	9.32	4.46
[La/Yb] _{C-N}	1.98	3.97	9.31	9.93	2.70	2.32	32.68	10.52	15.24	5.03
[Gd/Yb] _{C-N}	1.41	1.05	0.91	1.80	1.73	1.75	3.38	1.41	1.64	1.13
Eu/Eu*	0.84	1.04	na	1.11	1.74	1.60	1.06	0.95	1.02	1.05
HFSE (ppm)										
	454	104	100	00	01	50	3.7	8.5	4.8	23.1
V	151	131	100	82	81	56	/5	//	46	90
Y Zz	13	15.5	15.4	11./	10.2	8.5	5.9	12.4	9.8	15.2
	97.5	123.8	127.0	138.1	129.8	108.9	134.1	134.0	104	99
ПI Nb	2.7	200	2.9	5.5	5.0	2.7	5.5	5.4	2.0	2.4
Ta	0.5	0.5	0.7	0.3	0.3	0.5	0.5	0.6	0.5	0.8
LILE (ppm)	20.7	20.0	26.9	22.0	27 1	40 C	26.1	16.9	40 7	70.2
KD Ro	29.7	30.0	20.8	33.0	37.1	42.0	30.1	40.8	48./	79.2
Ph	1255	1255	3.8	2000	17	17	15	35	17	047
Th	2.1	2.4	3.4	0.7 ⊿ २	1./	1./	5.5	J.J ⊿ 1	3.5	3.0
U	11	1.7	15	15	16	15	14	15	14	0.9
Sr	478	759.9	672.1	747.2	787.3	665	739.5	416	626.7	613.2
			0,2,1						020.7	010.2
Other (ppm)				-	_		_		_	
SC	16	13	10	/	/	6	7	8	5	8
	20	148	<20	<20	<20	<20	16.2	0.0 1 1	3.4	3.l
US .	Z	0.3	0.8	0.2	0.9	0.4	0.4	1.1	0.5	1

Acronyms: dior, diorite; gb, gabbro; qtz-monzo, quartz monzonite.

5.2. Major and minor elements

All Panamanian magmatic arc samples including the Petaquilla and Majé intrusives from this study span the compositional gamut from basalt to dacite (Fig. 6). Apart from Bocas del Toro (BDT, Fig. A2) lavas from the LAS-west and the majority of lavas of the Pedro Miguel Formation (PMF, Fig. A2) of the Canal Basin, lavas and intrusives of the Panamanian magmatic arc system are almost exclusively subalkaline (e.g., Buchs et al., 2010; Wegner et al., 2011; Wörner et al., 2009) (Fig. A2). It remains uncertain if lavas of the Pedro Miguel Formation are altered with respect to other Canal lavas (LOI values are not available for these samples) but lavas from Bocas have unique traceelement characteristics that are consistent with a shoshonite designation on the andesite-series discrimination plot of Gill (1981) (Fig. 5).

Shown for comparison with the Majé and Petaquilla intrusives and other magmatic products of the MAS and LAS on the andesite series discrimination plot (Fig. 5) is the field occupied by volcanic and intrusive counterparts of the Chagres–Bayano and Sona–Azuero arcs of the 70–40 Ma EAS. The vast majority of lavas and plutonic equivalents of the EAS plot within the low-K tholeiitic series field with overlap into the medium-K calc-alkaline series field; lavas and intrusives of the LAS-west on the other hand, span the fields of low-K tholeiitiic through to med-K, high-K calc-alkaline and shoshonite. MAS intrusives including those of Petaquilla from this study, plot primarily within the medium-K andesite series as do the Majé intrusives and Cerro Patacon andesites and other LAS-east lavas and intrusives (e.g., lavas from Bahia Piña and the Canal).

5.3. REE chemistry

Late Oligocene to Early Miocene Lavas and intrusives of the Majé subvolcanic complex, the Canal Basin, the Pearl Islands and Bahia Piña of the eastern LAS exhibit chondrite-normalized REE concentrations that range from ~15 to $40 \times$ chondrite and $[La/Sm]_{C-N}$ ratios of 1.11–2.52 (Fig. 6a). Moreover, apart from the Late Miocene Cordilleran shoshonites and Talamanca basalts which exhibit the highest LREE-enrichments of all Panamanian magmatic arc system rocks (Fig. 6b), Central Cordilleran

basalts of the western LAS suite exhibit similar signatures to and fall completely within the range of LAS-east basaltic lavas and intrusives. However, the more evolved Majé subvolcanic intrusives (and Petaquilla granodiorites, see below) exhibit extreme REE fractionation when compared with most other Panamanian magmatic arc lavas and intrusives which increases with increasing differentiation (Fig. 6c, e, g). For example, Majé intrusives with 57-63 wt.% SiO₂ exhibit [La/Sm]_{C-N}= 1.98-3.91 (*n* = 8, mean = 3.18) and [La/Yb]_{C-N} = 2.83-10.43 (mean = 7.69); for comparison, lavas and intrusives of equivalent SiO₂ wt.% of the Early Arc system exhibit $[La/Sm]_{C-N} = 0.89 - 2.61$ (n = 22, mean = 1.88) and $[La/Yb]_{C-N} = 0.90-6.04$ (mean = 2.83) whereby those of the Later Arc system (west) exhibit similar, relatively unfractionated patterns with $[La/Sm]_{C-N} = 1.61-2.61$ (n = 14, mean = 2.14) and $[La/Sm]_{C-N} = 1.61-2.61$ (n = 14, mean = 2.14) $Yb]_{C-N} = 2.60-5.34$ (mean = 3.87). Interestingly, the 25 Ma 'adakiticlike' andesites of Cerro Patacon of the Panama Canal Basun (Rooney et al., 2010) display similar REE fractionations to the 19 Ma Majé andesites (Fig. 6e) and have $[La/Sm]_{C-N} = 2.32 - 2.79$ (n = 7, mean = 2.77) and $[La/Yb]_{C-N} = 4.71 - 5.64$ (mean = 5.26) which fall completely within the range of Majé andesites. Fundamentally, the circa 30–26 Ma Petaguilla



Fig. 6. Chondrite-normalized REE patterns of LAS-east lavas and intrusives including Majé subvolcanic intrusives (a, c, e, g) and LAS-west and MAS lavas intrusives (b, d, f, h) including Petaquilla intrusives (h). REE concentrations are from Nakamura (1974). Abbreviations: EAS–Early Arc System; Cord–Cordillera; LAS–Later Arc System; LL–Lower Limit; MAS–Middle Arc System; UL–Upper Limit.

granodiorites from this study exhibit the most extreme REE fractionations of all post-5 Ma lavas and intrusives (Fig. 6h) with [La/Sm]_{C-N} = 3.33–5.95 (n=4, mean = 4.90) and [La/Yb]_{C-N} = 5.03–32.68 (mean = 15.87). These patterns are most similar to Majé subvolcanic intrusives of equivalent (63–70 wt.%) SiO₂ which exhibit similar REE fractionations with [La/Sm]_{C-N} = 4.39–4.82 (n=3, mean = 4.67) and [La/ Yb]_{C-N} = 11.34–13.20 (mean = 12.09). Collectively, the REE data suggest a much different source for intrusives of the Petaquilla, Majé and Cerro Patacon suites than for lavas and intrusives comprising the rest of the Panamanian magmatic arc system.

6. Discussion

6.1. Identification and significance of 'adakitic-like' signatures of Majé and Petaquilla intrusives

A generally agreed upon chemical definition of 'adakite' was provided by Defant and Kepezhinskas (2001) which stipulates that adakites are: high silica ($SiO_2 > 56\%$) and alumina ($Al_2O_3 > 15$ wt.%) igneous rocks with > 3.5 wt. Na₂O, >400 ppm Sr, <18 ppm Y, <1.9 ppm Yb and high Sr/Y (>40) and La/Yb (>20) ratios. Fundamentally, adakites thus exhibit compositional characteristics that would be expected of magma extracted via partial melting of hydrous basaltic crust in the presence of garnet.

The fractionated REE patterns displayed by the 30–19 Ma Majé and Petaquilla intrusives as discussed in Section 5 suggest an 'adakitic-like' affinity which is confirmed on the basis of selected whole-rock and trace element characteristics (Table 2), plots commonly used to discriminate adakitic-like rocks (Fig. 7) and chondrite- and N-MORBnormalized patterns (Fig. 8a). As illustrated in Table 2 and Fig. 7, intrusives of the Majé and Petaquilla suites range to adakitic-like compositions apart from exhibiting relatively low La/Yb ratios (not shown). Moreover, the Petaquilla and Majé intrusives are even more 'adakitic-like' than the hornblende-nodule-bearing suite of circa 25 Ma adakitic-like andesites from Cerro Patacon of the Canal Basin (Rooney et al., 2010), e.g., those of Maje and Petaquilla range to much higher Sr/Y ratios (28–125) than those of Cerro Patacon (Sr/Y = 28–34).

Rooney et al. (2010) concluded that the Cerro Patacon andesites formed as a result of fractional crystallization of water-saturated arc magmas in the lower crust. The chemical evidence for Majé coupled with the fact that a key petrographic characteristic of the Majé suite is the occurrence of abundant cm-scale amphibole nodules (Fig. 4) similar to that described for Cerro Patacon andesites, may suggest similar formational histories. Fundamentally however, interpretation of adakite petrogenesis remains highly contentious (e.g., Garrison and Davidson, 2003), because the geochemical characteristics are not unique to a solitary petrogenetic process or tectonic setting (Atherton and Petford, 1993; Feeley and Hacker, 1995; Xu et al., 2002). In addition to being interpreted as slab-derived partial melts (e.g., Defant and Drummond, 1990; Kay, 1978; Stern and Kilian, 1996) adakites have also been interpreted as either (a) products of partial melting of thickened or delaminated lower mafic crust (e.g., Atherton and Petford, 1993; Barnes et al., 1996; Chung et al., 2003; Gao et al., 2004; Huang et al., 2008; Kay and Kay, 2002; Wang et al., 2004a,b; 2006); or (b) the result of AFC (assimilation-fractional crystallization) of parental basaltic magmas (e.g., Bourdon et al., 2002; Castillo et al., 1999; Gao et al., 2007; Grove et al., 2003).

6.2. Petrogenetic origins

6.2.1. Evidence against fractional crystallization

Generation of adakitic-like magmas has been ascribed to both low- and high-pressure fractional crystallization (LPFC, HPFC) of parental, hydrous basaltic magmas (e.g., Castillo et al., 1999; Gao et al., 2009; Macpherson et al., 2006; Prouteau et al., 2001) involving olivine + clinopyroxene + plagioclase + hornblende + titanomagnetite (LPFC); or garnet, in the case of HPFC. As mentioned in Section 6.1, the 25 Ma Cerro Patacon adakitic-like andesites of the Panama Canal Basin which share similar compositional and petrographic characteristics to Majé intrusives have been interpreted as fractional crystallization products of water-rich magmas (Rooney et al., 2010). Whole-rock geochemical data for the Majé intrusive suite however, is inconsistent with formation by either LPFC (Castillo et al., 1999) or HPFC (Macpherson et al., 2006), both of which display distinct geochemical trends (Fig. 9) that are not followed by Majé intrusives. For example, during both LPFC and HPFC, Al₂O₃ decreases with increasing SiO₂ a trend of which though evident for the EAS and LAS (not shown), is clearly not the case for the Majé suite which instead shows a distinct progression to higher Al₂O₃ with escalating SiO₂ (Fig. 9a). HPFC also manifests decreases in La and steep increases in Sr/Y and Dy/Yb (Fig. 9b, c, d) with differentiation, trends of which clearly are not exhibited by intrusives of the Majé suite. LPFC is usually characterized by trends opposite to that of HFSC, e.g., increasing La and decreasing Dy/Yb (Fig. 9b, d) as well as moderate increases in Ba with differentiation. Again, the Majé intrusives show none of these trends. Due to the restricted range in composition of the Petaguilla (and Cerro Patacon) intrusives it is difficult to comment on their differentiation 'trends' but it is clear that the compositional data for the Majé suite is inconsistent with either LPFC or HPFC; Majé intrusives display no such compositional trends with differentiation (Fig. 9). Another problem with a fractional crystallization model is that no similarly aged coexisting large volume of mafic rocks which could potentially be responsible for LPFC or HPFC of basaltic magma in the region has been identified. Finally, it is apparent that there exists a clear spatial and temporal shift in production of the adakitic-like intrusives that cannot be explained via fractional crystallization (see Section 6.3).

6.2.2. Slab- or lower crust-derived partial melts?

An alternative origin for the Majé and Petaquilla adakitic-like intrusives is via slab melting. Subducted oceanic crust must be relatively young and hot in order to melt and early estimates of the maximum age that subducted oceanic crust would need to be in order to melt was of the order of ~25 m.y. (Defant and Drummond, 1990). Subsequent thermal modeling (Peacock et al., 1994) however, suggests instead that a much younger slab crust age of ~5 m.y. is required which is probably difficult to reconcile in many instances as the age of subducted lithosphere entering most trenches is older than 5 Ma (Peacock et al., 1994). In the case of the Panamanian magmatic arc system in the Late Oligocene to Early Miocene, oceanic lithosphere of the Farallon Plate entering the trench of the Central American arc system at ~23.5 Ma was of the order of ~30 m.y. according to the reconstructions of Lonsdale (2005). If significantly young crust (i.e., 5 m.y. or less) is indeed a prerequisite for melting to occur (Peacock et al., 1994), this suggests that the Majé and Petaquilla are not likely the result of slab melting.



Fig. 7. Y vs. Sr/Y systematics of Majé and Petaquilla intrusives vs. remaining components of the Panamanian Magmatic Arc system. Symbols are as in Fig. 5. Abbreviations: ADR–andesite–diorite–rhyolite (series).



Fig. 8. Chondrite-normalized (a, b) and N-MORB normalized (c, d) plots of Majé (a, c) and Petaquilla (b, d) intrusives vs. adakites formed via partial melting of various crustal materials. Data for pure slab melts is from Kepezhinskas et al. (1995) and Sorensen and Grossman (1989); data for delaminated lower crust-derived adakites is from Wang et al. (2004a,b, 2006) and Xu et al. (2002); data for subducted oceanic crust melting is from Aguillón-Robles et al. (2001); Defant and Drummond, 1990; Defant et al. (2002); Drummond et al. (1996); Kay et al., 1993; Martin et al. (2005); Sajona et al. (2000); Stern and Kilian (1996) and references therein; data for thick lower crust derived adakites is from Atherton (1996); Xiong et al. (2003). Chondrite and N-MORB abundances are from Nakamura (1974) and Sun and McDonough (1989), respectively.

Partial melting of lowermost mafic crust on the other hand, might represent a plausible origin for the Majé and Petaquilla adakitic-like intrusives. On plots of SiO₂ vs. MgO, Mg# (cationic Mg/Mg + Fe²⁺) and K₂O/Na₂O constructed with superimposed fields of adakites generated by partial melting of oceanic slabs or lower crust (Fig. 10), it is apparent that there is considerable compositional overlap between slab- and lower crust-derived adakites when considering MgO (Fig. 10). However, on the SiO₂ vs. MgO plot (Fig. 10a) slab-derived adakites (Wang et al., 2006) clearly range to higher MgO, and some Majé adakitic-like intrusives (i.e., those with $> 56 \text{ wt.\% SiO}_2$) possess relatively high MgO (greater than ~4 wt.%) and plot within the slab-derived field. Nonetheless, all Petaquilla intrusives exhibit very low MgO (<2 wt.%) and the majority (nine of thirteen) of adakitic-like intrusives from Majé have <4 wt.% MgO (Fig. 10a). As well, all Petaquilla adakitic-like intrusives have low Mg# compositions akin to experimentally derived metabasaltic and eclogitic melts (Rapp et al., 1999, 2002 and references therein) (Fig. 10b).

Exluding the four Majé samples with >4 wt.% MgO, the remaining Majé and the Petaquilla adakitic-like intrusives define a linear trend that parallels those exhibited by thickened, lower crust- and delaminated crust-derived adakites (Gao et al., 2004; Wang et al., 2004a,b, 2006; Xu et al., 2006) (Fig. 10a, b). Slab-derived adakites range to relatively high MgO presumably due to interaction with overlying mantle upon their ascent which should not be the case for lower crust-derived adakites. However, adakites with relatively high MgO and Mg# like a minority of the Majé intrusives could alternatively reflect crust melt-mantle interactions. Adakitic-like intrusives from Majé with >4% MgO also range to correspondingly higher Ni and Cr (20–148 ppm and 50–310 ppm) when compared with the Majé intrusives with <4 wt.% MgO (20-60 ppm Ni, 20–140 ppm Cr). In addition to Fig. 10b which illustrates that all Majé and Petaquilla samples plot along a linear trend parallel to the field of delaminated, lower crust-derived adakites and all Majé samples fall within the field of delaminated, lower-crust-derived adakites, this might suggest the influence of melt-mantle interaction in the petrogenesis of some Majé adakitic-like intrusives. The low MgO Petaquilla and Majé intrusives could represent relatively pristine crustal melts whereby those Majé intrusives with relatively higher MgO could represent adakitic-like melts which interacted with mantle possibly above a delaminated crustal section (e.g., Xu et al., 2002) which elevated their Mg# (e.g., Barnes et al., 1996; Petford and Atherton, 1996). Furthermore, on the basis of SiO₂ vs. K₂O/Na₂O variations (Fig. 10c), all Majé and the majority of Petaquilla adakitic-like intrusives are similar to experimental melts of lower, mafic crustal materials (Rapp and Watson, 1995; Sen and Dunn, 1994).

Table 2

Range in selected major, trace and REE abundances of 30–19 Ma Majé and Petaquilla intrusives (this study, with >56 wt.% SiO₂) compared with subvolcanic, 'adakitic-like' andesites from Cerro Patacon, Panama Canal Basin, and the chemical 'definition' of adakites.

Major oxides (wt.%)	Chemical definition of adakites ^a	Majé subvolcanic intrusives	Petaquilla intusives (granodior)	Cerra Patacon subvolcanic intrusives ^b
SiO ₂	>56	57-66	64-67	59-61
M_2O_3 Na ₂ O	>3.5	3-6°	$2-4^{g}$	4
Trace elen	nents (ppm)			
Sr	>400	359–824 ^d	416-740	410-491
Y	<18	3 to 17	6 to 15	15–17
Sr/Y	>40	28-78 ^e	34–125 ^h	28-34
Yb	<1.9	0.9-1.9	0.5-1.7	1.5-1.9
La/Yb	>20	4-20 ^f	8-49 ⁱ	7 to 8
п		12	4	7

Abbreviations: dior, diorite; gb, gabbro; qtz-monzo, quartz monzonite.

Major element concentrations are normalized on an anhydrous basis.

^a Chemical definition of adakites from Defant and Kepezhinskas (2001).

^b Cerra Patacon andesites from Rooney et al. (2010).

^c 10 of 12 samples have > 3.5 wt.% Na₂O.

^d 11 of 12 samples have >400 ppm Sr.

^e 7 of 12 samples have Sr/Y > 40.

^f 1 of 12 samples have La/Yb > 20.

 $^{\rm g}~$ 3 of 4 samples have >3.5 wt.% Na_2O.

^h 3of 4 samples have > 40 Sr/Y.

ⁱ 2 of 4 samples have La/Yb>20.

6.3. Geodynamic scenario

Perhaps the most difficult problem with a lower crustal partial melting origin for the Majé and Petaquilla adakitic-like intrusives is



Fig. 9. SiO₂ vs. (a) Al₂O₃, (b) La, (c) Sr/Y, (d) Dy/Yb, and (e) Ba systematics of circa 30–19 Ma Panama adakitic-like intrusives (see Fig. 9) from Petaquilla, Majé and Cerro Patacon. Also shown are Majé intrusives with <56 wt.%. Cerro Patacon samples are from Rooney et al. (2010). The remaining samples are from this study. Abbreviations: HPFC–high-pressure fractional crystallization (involving garnet; Macpherson et al., 2006); LPFC–low-pressure fractional crystallization (involving olivine + clinopyroxene + plagioclase + homblende + titanomagnetite; Castillo et al., 1999). Symbols as in Fig. 5.



Fig. 10. SiO₂ vs. (a) MgO (b) Mg# and (c) K₂O/Na₂O systematics of Maié. Petaguilla and Cerro Patacon mafic and adakitic-like intrusives. Superimposed on all plots are fields of adakites interpreted to have formed via partial melting of various materials and/or experimentally-derived fields representing compositions of melts derived from partial melting of lower crustal materials. In (b), mantle and crustal AFC curves are denoted by circles A, B (mantle) and C (crustal). Mantle AFC curves are from Stern and Kilian (1996) (curve A) and Rapp et al. (1999) (curve B) and the crustal AFC curve is from Stern and Kilian (1996) (curve C). The starting point of curve A (denoted by '1') represents the composition of a 'pure' slab melt as suggested by Stern and Kilian (1996) whereby the starting point of (B) (denoted by '2') represents an experimental metabasaltic or eclogitic composition which is not hybridized with peridotite (i.e., assumes no melt-peridotite interaction) (Rapp et al., 1999). The field of adakites inferred as being derived from subducted oceanic crust is from Wang et al. (2006) whereby the fields for lower crust-derived adakites is from Gao et al. (2004), Wang et al. (2004a,b, 2006) and Xu et al. (2006). The field of experimental metabasaltic and eclogitic melts (1-4 GPa) is from Rapp et al. (1999, 2002) and references therein. The fields in (a) are derived from the same sources cited in (b). In (c), the field of experimental melts derived via melting of mafic lower crustal materials is from Rapp and Watson (1995) and Sen and Dunn (1994). Symbols as in Fig. 5.

an explanation for the origin and 'emplacement' of a thermal source beneath the remnant (i.e., 70-40 Ma Early) Arc and/or CLIP basement which would have been required to facilitate partial melting of lowermost, mafic crust at 30 Ma. This is particularly true if a slab existed beneath Panama at 30 Ma which could have provided an effective physical barrier to a potential heat source. Most geodynamic scenarios agree that the heat source necessary to generate lower crustderived adakites is provided by upwelling asthenosphere beneath the lower crust. Moreover, many different but related mechanisms have been proposed in geodynamic scenarios involving a remnant slab that allows access for upwelling asthenophere to lower crustal materials which could facilitate adakite generation. These include asthenospheric upwelling above an excised slab (i.e., 'slab removal' or 'slab break-off', e.g., Davies and von Blackenburg, 1995; Wortel and Spakman, 2000; Yoshioka and Wortel, 1995) or delaminated, thickened lithosphere (e.g., Hou et al., 2007; Karsli et al., 2010; Kay et al., 1993) or through/above a slab (or asthenophere) window (Calmus et al., 2003; Ickert et al., 2009; Thorkelson and Breitsprecher, 2005) or slab tear (e.g., Lin et al., 2004, 2007; Pallares et al., 2007). We posit a geodynamic scenario for generation of the Majé and Petaquilla

adakitic-like intrusives broadly similar to those described above, i.e., asthenospheric upwelling above a slab tear or window (Fig. 11). It is significant that there exists a west to east regression in the age of adakitic-like magmatism beginning at 30 Ma in Petaquilla, followed by 25 Ma in Cerra Patacon and 19 Ma in Majé, and that all three of these regions define a near horizontal, W-E striking lineament and occur at the same approximate latitude (~8° 50'N-9° 00'N, see Figs. 2, 3). A linear temporal and spatial progression in adakitic-like activity is difficult to reconcile with fractionation (Rooney et al., 2010). We posit that a roughly horizontal slab tear propagated or migrated from west-east (Fig. 11c) similar to the model of Wortel and Spakman (2000) proposed for the Mediterranean–Carpathian region. Such a scenario entailing whole-scale slab removal might also be expected to cause regional scale uplift (see Whattam et al., 2008 and references therein). As we know of no evidence to support large scale uplift at this time and based on the fact that the distribution of Oligocene-Miocene adakitic-like rocks appears to be rather restricted, we further posit that the slab tear was probably relatively deep. With respect to the amphibole-rich mafic enclaves present within the evolved Majé subvolcanic intrusives, we suggest that they likely represent portions of a cumulate segment of lower mafic crust partially digested by ascending adakitic-like intrusives.

It is generally accepted that the basement of Panama comprises a segment of the CLIP and a recent model (Buchs et al., 2010) suggests that the Early (i.e., 70–40 Ma) Arc system was constructed upon the CLIP. We are uncertain thus, whether the partially melted lower mafic crustal material that generated the adaktic-like intrusives, comprised

lower CLIP crust or lowermost EAS crust. We note however, that in a recent study, Hastie et al. (2010) concluded that circa 52 Ma 'Jamaican type adakites' formed via partial melting of metamorphosed CLIP crust that underplated Jamaica in the Late Tertiary. Thus, a similar scenario may be viable for the Panamanian Oligo–Miocene adakitic-like intrusives.

6.4. Tectonic model and reconstructions

6.4.1. Synopsis of the pre-Late Cretaceous tectonic configuration immediately preceding the onset of Panamanian magmatic arc system formation

The Caribbean Plateau or Caribbean Large Igneous Province (CLIP, Hoernle et al., 2002) is widely considered as comprising the bulk of the Caribbean Plate (Fig. 1). According to many researchers, the CLIP represents an enormous section of normal oceanic crust that was thickened via two major pulses of intra-plate magmatism activity at circa 92-88 Ma and 76-72 Ma (e.g., Kerr et al., 2003; Sinton et al., 1998) within the Farallon Plate as it passed above a single plume head of the Galapagos hotspot (e.g., Burke, 1988; Duncan and Hargraves, 1984; Hauff et al., 2000a,b; Sinton et al., 1997, 1998). Other researchers suggest that CLIP formation was the result instead of magmatism that was catalyzed by subduction of an active proto-Caribbean spreading center beneath the 'Great Arc of the Caribbean' (Burke et al., 1978) beginning in the Albian-Aptian and the subsequent development of a slab window (Pindell and Kennan, 2001; Pindell et al., 2006; Serrano et al., 2011). Either way, following its formation, the CLIP was subsequently drawn and 'sandwiched' between the Americas.



Fig. 11. Cartoon depicting the fundamental change in the tectonic and tectonomagmatic regimes prior to (a) 40 Ma and after (b, c) 30 Ma. (a) Lavas and extrusive of the Early Arc system formed essentially by mantle wedge flux melting above the dehydrating Farallon slab circa 70–40 Ma. Subsequently, indentor–Early Arc system collision at ~40 Ma effectively shut down the EAS and possibly steepened the Farallon slab. By 30 Ma (b) a subhorizontal slab tear developed beneath the vicinity of Petaquilla. Partial melting of lowermost mafic arc crust generated a small volume of adaktic-like intrusives. As the slab tear propagated from west to east (c), ALI were subsequently generated in the same fashion in Cerro Patacon at 25 Ma and Majé at 19 Ma. Thick red arrows indicate asthenosphere flow; the thick blue arrow indicates effect of slab pull which is accentuated by proliferation of slab tear. Model of slab tear propagation is based on Wortel and Spakman (2000).

A prevailing tectonic model for incipient generation of the Central American Arc system (i.e., the EAS) entails collision in the Late Cretaceous of the northern segment of the CLIP with the 'Great Arc' (Burke et al., 1978) of the Caribbean (i.e., Greater Antilles Arc system) as illustrated by Hoernle et al. (2002) (based on Burke, 1988; Duncan and Hargraves, 1984; Pindell and Barrett, 1990) which extended along the southern Pacific margin of the proto-Caribbean region (Burke, 1988; Pindell and Barrett, 1990). An apt tectonic analog for this geodynamic scenario may be the collision of the massive $(1.9 \times 10^6 \text{ km}^2 \text{ and } \sim 35 \text{ km thick})$ Ontong Java Plateau (OJP) with the south-dipping Solomon Arc to the east of present-day Papua-New Guinea in the Neogene (Petterson et al., 1999). Initial 'soft-docking' and attempted but failed subduction of the OJP circa 25-20 Ma resulted in slab-breakoff and 'hard docking' of the plateau with the subduction zone at 20-15 Ma, a subduction polarity reversal by ~12 Ma and ultimately the re-establishment of arc volcanism soon thereafter above



the newly reconfigured subduction zone. Similarly, due to the 'unsubductable' nature of the buoyant and anomalously thick (up to 21 km) Caribbean plateau, its attempted subduction upon arrival at the trench failed; subsequent jamming of the subduction system instigated a subduction jump and an induced subduction nucleation event to the rear of the southern segment of the CLIP, which ultimately led to construction of the EAS along the southern perimeter of the CLIP.

6.4.2. Synopsis of our current understanding of Panamanian magmatic arc system formation

A synopsis of the tectonic and tectonomagmatic evolution of the Panamanian magmatic arc system as we now understand it is provided below. In addition to our new geochemical and geochronological data of the Oligo-Miocene adakitic-like intrusives recovered from Petaquilla and Majé, these points need to be taken into consideration when contemplating updated models for the evolution of the Panamanian magmatic arc system. (1) A Late Cretaceous-Middle Eocene subductionrelated, magmatic arc (i.e., the EAS) was constructed along the southern edge of the Caribbean Plate (i.e., CLIP) between ~75 and 40 Ma (Fig. 14). This arc system extended (at least) from present-day southern Panama in the Sona-Azuero peninsulas to the present-day San Blas range/ Chagres–Bayano region in eastern Panama (Buchs et al., 2010). (2) The plutonic root of the EAS was partially exhumed between ~47 and 42 Ma (Montes et al., 2012). (3) For reasons that are poorly understood, left-lateral offset of the originally contiguous EAS which formerly extended from the Sona-Azuero peninsulas to the San Blas range in the Chagres-Bayano region took place between 40 and 30 Ma resulting in a > 200 km displacement (Fig. 2) (Lissinna, 2005). (4) Arc activity was essentially shutdown between ~40 and 20 Ma apart from sporadic 30-26 Ma predominantly adakitic-like arc-related plutonism in western Panama, the Panama Canal Basin and Majé (eastern Panama) (Rooney et al., 2010; this study); and extensional arc activity between 28 and 18 Ma in the Panama Canal Basin (see below) (Farris et al., 2011; Montes et al., 2012) and rare localized arc activity to the south of the Panama Canal Basin in the Pearl Islands and Bahia Piña at 21-18 Ma (Lissinna, 2005). Furthermore, the interval at 38-28 Ma is accompanied by northverging folding (Montes et al., 2012) and post-orogenic, partially terrestrial sedimentation (e.g., Gatuncillo Formation, Woodring, 1957). (4) Collision of the easternmost segment of the remnant EAS with South America is followed by formation of an extensional magmatic arc within the Panama Canal Basin (Farris et al., 2011) at 27-24 Ma followed soon thereafter by reestablishment of arc construction (i.e., of the LAS) some 75 km to the south of the former spreading axis of the remnant EAS (Lissinna, 2005; Montes et al., 2012).

Fig. 12. Plate tectonic reconstructions of the 70–20 Ma evolution of the Central America region (modified from Hoernle et al., 2002 and based on the models of Burke, 1988; Duncan and Hargraves, 1984; Pindell and Barrett, 1990; and aspects of models/reconstructions of Kerr and Tarney, 2005: Farris et al., 2011: Montes et al., 2012). Thick grav arrows represent relative plate motion vectors. CLIP was generated circa 95-75 Ma within the Farallon Plate as it passed over the Galapagos Hot Spot (GHS). (a) Subsequent to collision of the CLIP with the Greater Antilles Arc (GAA) system circa 75–70 Ma, a subduction jump of same polarity to the rear of the CLIP catalyzes inception of the Early Arc system (EAS) which (b) continues to operate 'normally' until an indentor begins to collide with the easternmost segment of the EAS at ~45 Ma. One possible candidate for the indentor is the Gorgona Plateau which has been proposed as having collided with the proto-Andean subduction zone in northwestern South America in the middle Eocene (Kerr and Tarney, 2005). Whatever the nature of the indentor, evidence of its existence may effectively have been erased (i.e., subducted); nevertheless, we posit that (c) its collision with the EAS effectively shuts the EAS down by ~38 Ma. 40 Ma also marks the approximate timing of initial left-lateral offset of the EAS (Lissinna, 2005). Effects of this collision may also have led to a steepening of the subducting Farallon slab, and ultimately (d) slab break-off and an interval of adakitic-like intrusive activity above the torn slab between \sim 30 and 19 Ma (see Fig. 11). As well, 28 Ma marks the inferred timing of collision of Panama with eastern South America which initiates oroclinal bending of the isthmus and an interval of localized extensional arc volcanism with the Panama Canal Basin. (e) Subsequent to final slab breakoff by ~20 Ma, production of the Later Arc system (LAS) is initiated above a NE-dipping subduction system some 75 km to the south of the remnant EAS (Lissinna, 2005; Montes et al., 2012). Other abbreviations: ChB-Chortis Block; CLIP-Caribbean Large Igneous Province; GAA-Greater Antilles Arc; LAA - Lesser Antilles. Arc; SA-South America.

6.4.3. EAS shutdown at 40 Ma: possible tectonic causes

As explained in Section 6.4.1, collision of the northern periphery of the CLIP with the Greater Antilles Arc system in the Late Cretaceous instigated a subduction jump to the rear of the CLIP and consequent EAS formation upon the southern perimeter of the CLIP by ~73 Ma (Buchs et al., 2010). Traditionally, only this solitary plateau (i.e., the CLIP) has been considered as relevant in the origin and consequent tectonic evolution of the Central America Arc System. Kerr and Tarney (2005) however, proposed the existence of another plateau and its collision at ~40 Ma with the proto-Andean subduction zone along the northwestern margin of the South American Plate (as shown by the 'indentor' on Fig. 12). The 40 Ma timing of this proposed collision is significant as it coincides with the initial timing of left-lateral offset of the older Panamanian arc system (i.e., the EAS) (Lissinna, 2005), EAS shutdown at 38 Ma and isthmus-scale northverging folding soon thereafter at 38–28 Ma (Montes et al., 2012).

The proposed second plateau is termed the Gorgona Plateau by Kerr and Tarney (2005) and is posited to comprise Gorgona Island (Fig. 1) off the southwestern coast of Colombia and some accreted plateau terranes along western South America. Main lines of evidence cited for distinction of Gorgona Plateau lavas from those of the Caribbean Plateau by Kerr and Tarney (2005) is three-fold and based on paleomagnetic, isotopic and geochronological evidence. Paleomagnetic data (MacDonald et al., 1997) indicates formation at two distinct paleolatitudes (i.e., of the CLIP and the Gorgona Plateau) whereby isotopic data demonstrates that Gorgona Island plateau rocks are more depleted than CLIP rocks. A weighted mean age of 91.4 + 0.4 Ma for CLIP basalts from western Colombia (Kerr et al., 2003; Sinton et al., 1998), Hispaniola (Sinton et al., 1998), Costa Rica (Hauff et al., 1997; Sinton et al., 1997), Curacao and the DSDP Leg 15 Caribbean Sea (Sinton et al., 1998) slightly predates an age of 88.9 + 1.2 Ma obtained on Gorgona rocks (Sinton et al., 1998).

As explained by Kerr and Tarney (2005), if the similarly aged Gorgona Plateau did indeed form at a much lower latitude (26–30°) than the Caribbean Plateau and collided ~45 m.y. later than the Caribbean Plateau, this implies that the colliding Gorgona Plateau would have been much denser and more susceptible to subduction than the Caribbean Plateau which apparently began to partially subduct <10 m.y. after its formation. Hence, much evidence for the existence of the Gorgona Plateau could effectively have been erased. Regardless of the exact nature of the 'indentor' (Fig. 12) (e.g., whether it was the Gorgona Plateau or another plateau), based on structural and geochronological data that demonstrate that exhumation of the EAS circa 47–42 Ma was followed by deformation manifest as northwest-verging folding between 38 and 28 Ma, it is probable that a sizeable body collided with the EAS~45–40 Ma which caused its shutdown soon thereafter.

6.4.4. Significance of intrusive, predominantly adakitic-like activity at 30–19 Ma and LAS establishment soon thereafter

Arc-related magmatism at 30–26 Ma resulted predominately in the production of mid-crustal, intermediate intrusive bodies in western Panama as recorded by the circa 30–26 Ma Petaquilla batholith (Kesler, 1978; Kessler et al., 1977; Speidel and Faure, 1996; this paper) and the ~30 Ma El Baru plutonics (Drummond et al., 1995). Fundamentally, we have illustrated that that 30–26 Ma intrusive-activity at Petaquilla is adakitic-like, similar to that at Cerro Patacon of the Panama Canal Basin in central Panama at 25 Ma (Rooney et al., 2010) and Majé in eastern Panama at 19 Ma. The combined geochemical and radiometric age data suggest that these adakitic-like intrusives formed by partial melting of lowermost, mafic arc crust above a subhorizontal slab tear that propagated from west (Petaquilla) to east (Majé) between 30 and Ma. We suggest that establishment of the LAS after 20 Ma occurred at a new NE-dipping subduction system which nucleated to the rear (south) of the EAS subsequent to slab removal by ~20 Ma,

7. Conclusions

- 1. As documented recently by others (Montes et al., 2012) evidence of Panamanian magmatic arc activity is essentially absent at 40–28 Ma. This interval coincides with left-lateral offset of the originally contiguous 70–40 Ma EAS beginning about 40 Ma and which was followed by a period of intense deformation as recorded by EAS components at 38–30 Ma. We posit these features to be the result of collision of an 'indentor' (probably an oceanic plateau and possibly the Gorgona Plateau) with the eastern segment of the EAS at or just before ~40 Ma (see Kerr and Tarney, 2005). This collision resulted in a temporary shutdown of the Panamanian magmatic arc system and cessation of major arc activity until after 20 Ma.
- 2. The Majé subvolcanic igneous complex situated to the east of the Panama Canal Basin predominantly comprises mafic-nodule-bearing intrusives of andesitic composition (diorites) but ranges from basalt through dacite. Zircons from a Majé diorite yield a mean ²⁰⁶Pb/²³⁸U LAM-ICP-MS age of 18.9.0 + 0.4 Ma. Granodiorites of the Petaquilla batholith in western Panama yield 206 Pb/ 238 U ages of 29.0 + 0.7, -0.6 Ma, 28.5 + 0.7, -0.5 Ma, 28.3 + 0.5, -0.4 Ma and 26.2 + 0.5, -0.5 Ma0.9 Ma. The 30–26 Ma Petaguilla and 20 Ma Maié intrusive suites are compositionally similar to a subvolcanic suite of 25 Ma, adakiticlike andesitic intrusives from Cerro Patacon, Panama Canal Basin. These adakitic-like intrusives from Petaquilla, Cerro Patacon and Majé are compositionally distinct from other 70-5 Ma Panamanian magmatic arc lavas and intrusives. Petaquilla granodiorites and Majé subvolcanic andesites and dacites yield adakitic-like major and trace element abundances (e.g., >15 wt.% Al₂O3, >3.5 wt.% Na₂O, >400 ppm Sr, <1.9 ppm Yb, <18 ppm Y, Sr/Y that range to >120) and strongly fractionated REE patterns similar to the subvolcanic, adakitic-like andesites at Cerro Patacon.
- 3. A recent study of the Cerra Patacon adakitic-like intrusives concluded that they are the result of fractionation of water-saturated arc magmas in the lower crust. Geochemical data for the Majé subvolcanic intrusives however, is inconsistent with either low-pressure or high-pressure fractional crystallization (LPSC, HPFC) but is similar to that of adakites derived from partial melting of lower, mafic crust. Fractionation is also difficult to reconcile with the west to east regression in ages (30–20 Ma) of the Oligo-Miocene adakitic-like intrusives in Panama which define a roughly horizontal, W–E striking lineament. We suggest this pattern to be the result of a subhorizontal slab tear that propagated from west to east beginning beneath Petaquilla at 30 Ma and terminating beneath Majé at 19 Ma. The Panamanian adakitic-like intrusives were generated via partial melting of lower, mafic crust above this migrating slab tear.
- 4. Establishment of a new NE-dipping subduction system and the Later Arc system after 20 Ma some 75 km to the rear (south) of the EAS was realized subsequent to slab removal and the production of Oligo-Miocene adakitic-like intrusives.

Supplementary data related to this article can be found online at doi:10.1016/j.lithos.2012.02.017.

Acknowledgments

This study was made possible by ACP (Panama Canal Authority) contract SAA-199520-KRP and the U.S. National Science Foundation (NSF) grant 0966884 (OISE, EAR, DRL), and Mr. Mark Tupper, NSF EAR 0824299. Access to field areas and collection permits were granted by Ministerio de Industria y Comercio. Minera Panamá is thanked for providing core samples from Petaquilla. Federerico Moreno and the Department of Geological Sciences, University of Florida, are thanked for the CL images. Ed. A.C. Kerr, E. Gazel and an anonymous reviewer are thanked for their detailed and insightful comments. J.K. Kim is acknowledged for insightful comments which improved aspects of data presentation.

Appendix A



Fig. A1. Representative CL images of dated zircons from this study.



Fig. A2. Total alkali-silica (TAS) (Le Bas et al., 1986) classification of (a) Later Arc volcanic and intrusives and (b) Middle Arc system intrusives of the Panamanian magmatic arc system. Later Arc system east samples are from this study (Majé), Rooney et al. (2010) (Cerro Patacon), Wörner et al., 2009; and Farris et al. (2011) (Canal) and Lissina (Bahia Piña and Pearl Islands); Later Arc system west samples are from the Central Cordillera (Wörner et al., 2009); Middle Arc system samples are from this study (Petaquilla), Kessler et al., 1977 (Petaquilla), and Drummond et al., 1995 (El Baru). The shaded fields in (a, b) encompass volcanic and intrusive rocks of the Sona-Azuero and Chagres–Bayano Arcs of the Early Arc system (EAS, Wörner et al., 2009). All samples here have been normalized on an anhydrous, volatile-free basis and the databases used here are the ones used in subsequent geochemical plots unless indicated otherwise.

References

- Adamek, S., Frohlich, C., Pennington Wayne, D., 1988. Seismicity of the Caribbean-Nazca boundary; constraints on microplate tectonics of the Panama region. Journal of Geophysical Research 93, 2053–2075.
- Aguillón-Robles, A., Caimus, T., Bellon, H., Maury, R.C., Cotton, J., Bourgois, J., Michaud, F., 2001. Late Miocene adakites and Nb-enriched basalts from Vizcaino Peninsula, Mexico: indicators of East Pacific Rise subduction below southern Baja California. Geology 29, 531–534.
- Anonymous, 1969. Porphyry copper mineralization at Cerro Petaquilla, Province of Colon, Panama. Projecto Minero Panama, Naciones Unidas, 3 (87 pp.).
- Anonymous, 1972. Geologia general de las regions oriental y occidental. Projecto Minero Panama, Fase II, Informe tecnico, Naciones Unidas, New York. (54 pp.).
- Atherton, M.P., Petford, N., 1993. Generation of sodium-rich magmas from newly underplated basaltic crust. Nature 362, 144–146.
- Bandy, O.L., Casey, R.E., 1973. Reflector horizons and paleobathymetric history, eastern Panama. Geological Society of America Bulletin 84, 3081–3086.
- Barnes, C.G., Petersen, S.W., Kistler, R.W., Murray, R., Kays, M.A., 1996. Source and tectonic implications of tonalite-trondhjemite magmatism in the Klamath Mountains. Contributions to Mineralogy and Petrology 123, 40–60.
- Baumgartner, P.O., Flores, K., Bandini, A.N., Girault, F., Cruz, D., 2008. Upper Triassic to Cretaceous radiolaria from Nicaragua and Northern Costa Rica. The Mesquito Composite Oceanic Terrane: Ofioliti, 33, pp. 1–19.
- Bourdon, E., Eissen, J.P., Monzier, M., Robin, C., Martin, H., Cotton, J., Hall, M.L., 2002. Adakite-like lavas from Antisana volcano (Ecuador): evidence for slab melt metasomatism beneath the Andean Northern Volcanic Zone. Journal of Petrology 43, 199–217.
- Bowin, C.L., 1976. Caribbean gravity field and plate tectonics. Geological Society of America Special Paper, 169, p. 79.
- Buchs, D.M., Baumgartner, P.O., Baumgartner-Mora, C., Bandini, A.N., Jackett, S.J., Diserens, M.O., Stucki, J., 2009. Late Cretaceous to Miocene seamount accretion and mélange formation in the Osa and Burica Peninsulas (Southern Costa Rica): episodic growth of a convergent margin. In: James, K.H., Lorente, M.A., Pindell, J.L. (Eds.), The Origin and Evolution of the Caribbean Plate: Geological Society of London Special Publications, 328, pp. 411–456.
- Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Baumgartner-Mora, C., Ulianov, A., 2010. Late Cretaceous arc development on the SW margin of the Caribbean Plate: insights from the Golfito (Costa Rica) and Azuero (Panama) complexes. Geochemistry, Geophysics, Geosystems 11, Q07S24. doi:10.1029/2009GC002901.
- Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Ulianov, A., 2011. Oceanic intraplate volcanoes exposed: example from seamounts accreted in Panama. Geology 39, 335–338. Purko K. 1098. Totenic avaluation of the Corbhean Accret Panama. Geology 39, 335–338.
- Burke, K., 1988. Tectonic evolution of the Caribbean. Annual Review of Earth and Planetary Science 16, 201–230.

- Burke, K., Fox, P.J., Sengor, M.C., 1978. Buoyant ocean floor and the origin of the Caribbean. Journal of Geophysical Research 83, 3949–3954.
- Calmus, T., Aguillón-Robles, A., Maury, R.C., Bellon, H., Benoit, M., Cotten, J., Bourgois, J., Michaud, F., 2003. Spatial and temporal evolution of basalts and magnesian andesites ("bajaites") from Baja California, Mexico: the role of slab melts. Lithos 66, 77–105.
- Camacho, E., Hutton, W., Pacheco, J.F., 2010. A new look at evidence for a Wadati–Benioff zone and active convergence at the north Panama deformed belt. Bulletin of the Seismological Society of America 100, 343–348.
- Castillo, P.R., Janney, P.E., Solidum, R.U., 1999. Petrology and geochemistry of Camiguin island, southern Philippines: insights to the source of adakites and other lavas in a complex arc setting. Contributions to Mineralogy and Petrology 134, 33–51.
- Chung, S.L., Liu, D., Ji, J., Chu, M.F., Lee, H.Y., Wen, D.J., Lo, C.H., Lee, T.Y., Qian, Q., Zhang, Q., 2003. Adakites from continental collision zones: melting of thickened lower crust beneath southern Tibet. Geology 31, 1021–1024.
- Coates, A.G., Collins, L.S., Aubry, M.-P., Berggren, W.A., 2004. The Geology of the Darien, Panama, and the late Miocene–Pliocene collision of the Panama arc with northwestern South America. Geological Society of America Bulletin 116, 1327–1344.
- Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. Atlas of zircon textures. Reviews in Mineralogy and Geochemistry 53, 469–500.
- Davies, J.H., von Blackenburg, F., 1995. Slab break-off: a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. Earth and Planetary Science Letters 129, 85–102.
- De Boer, J.Z., Defant, M.J., Stewart, R.H., Bellon, H., 1991. Evidence for active subduction below western Panama. Geology 19, 649–652.
- Defant, M.J., Drummond, M.S., 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347, 662–665.
- Defant, M.J., Kepezhinskas, P., 2001. Evidence suggests slab melting in arc magmas. EOS Transactions 82, 65–69.
- Defant, M.J., Clark, L.F., Stewart, R.H., Drummond, M.S., de Boer, J.Z., Maury, R.C., Bellon, H., Jackson, T.E., Restrepo, J.F., 1991a. Andesite and dacite genesis via contrasting processes: the geology and geochemistry of El Valle volcano, Panama. Contributions to Mineralogy and Petrology 106, 309–324.
- Defant, M.J., Richerson, P.M., Deboer, J.Z., Stewart, R.H., Maury, R.C., Bellon, H., Drummond, M.S., Feigenson, M.D., Jackson, T.E., 1991b. Dacite genesis via both slab melting and differentiation-petrogenesis of La-Yeguada volcanic complex, Panama. Journal of Petrology 32, 1101–1142.
- Defant, M.J., Jackson, T.E., Drummond, M.S., deBoer, J.Z., Bellon, H., Feigenson, M.D., Maury, R.C., Stewart, R.H., 1992. The geochemistry of young volcanism throughout western Panama and southeastern Costa Rica: an overview. Journal of the Geological Society of London 149, 569–579.
- Defant, M.J., Xu, J.F., Kepezhinskas, P., Wang, Q., Zhang, Q., Xiao, L., 2002. Adakites: some variations on a theme. Acta Petrologica Sinica 18, 129–142.
- Dengo, G., 1985. Mid America: tectonic setting for the Pacific margin from southern Mexico to northwestern Colombia. In: Nairn, A.E.M., Stehli, F.G. (Eds.), The Ocean Basins and Margins, 7. Plenum-Press, pp. 123–180.
- Di Marco, G., Baumgartner, P.O., Channell, J.E.T., 1995. Late Cretaceous–early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama. In: Mann, P. (Ed.), Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America: Geological Society of America Special Paper, 295, pp. 1–27.
- Drummond, M.S., Bordelon, M., de Boer, J.Z., Defant, M.J., Bellon, H., Feigenson, M.D., 1995. Igneous petrogenesis and tectonic setting of plutonic and volcanic rocks of the Cordillera de Talamanca, Costa Rica-Panama, Central American arc. American Journal of Science 295, 875–919.
- Drummond, M.S., Defant, M.J., Kepezhinskas, P.K., 1996. The petrogenesis of slab derived trondhjemite-tonalite-dacite/adakite magmas. Transactions of the Royal Society of Edinburg Earth Sciences 87, 205–216.
- Duncan, R.A., Hargraves, R.B., 1984. Plate tectonic evolution of the Caribbean region in the mantle reference frame. Geological Society of America Memoir 162, 81–93.
- Duque-Caro, H., 1990. The Choco Block in the northwestern corner of South America; structural, tectonostratigraphic, and paleogeographic implications. Journal of South American Earth Sciences 3, 71–84.
- Farris, D.W., Jaramillo, Carlos, Bayona, German, Restrepo-Moreno, Sergio A., Montes, Camilo, Cardona, Agustin, Mora, Andres, Speakman, Robert J., Glascock, Michael D., Valencia, Victor, 2011. Fracturing of the Panamanian Isthmus during initial collision with South America. Geology 39, 1007–1010. doi:10.1130/G32237.1.
- Feeley, T.C., Hacker, M.D., 1995. Intracrustal derivation of Na-rich andesite and dacite magmas: an example from Volcan Ollagüe. Andean Central Volcanic Zone. Journal of Geology 103, 213–225.
- Ferenčić, A., 1970. Porphyry copper mineralization in Panama. Mineralium Deposita 5, 383–389.
- Gao, S., Rudnick, R.L., Yuan, H.L., Liu, X.M., Liu, X.M., Liu, Y.S., Xu, W.L., Ling, W.L., Ayers, J., Wang, X.C., Wang, Q.H., 2004. Recycling lower continental crust in the North China Craton. Nature 432, 892–897.
- Gao, Y.F., Hou, Z.Q., Kamber, B.Z., Wei, R.H., Meng, X.S., Zhao, R., 2007. Adakite-like porphyries from the southern Tibetan continental collision zones: evidence for slab melt metasomatism. Contributions to Mineralogy and Petrology 153, 105–120.
- Gao, J., Klemd, R., Long, L.L., Xiong, X.M., Qian, Q., 2009. Adakitic signature formed by fractional crystallization: an interpretation for the Neo-Proterozoic metaplagiogranites of the NE Jiangxi ophiolitic melange belt, South China. Lithos 110, 277–293.
- Garrison, J.M., Davidson, J.P., 2003. Dubious case for slab melting in the northern volcanic zone of the Andes. Geology 31, 565–568.
- Gazel, E., Carr, M.J., Hoernle, K., Feigenson, M.D., Hauff, F., Szymanski, D., van den Bogaard, P., 2009. The Galapagos-OIB signature in southern Central America:

mantle re-fertilization by arc-hotspot interaction. Geochemistry, Geophysics, Geosystems (G3), Q02S11. doi:10.1029/2008GC002246.

- Gazel, E., Hoernle, K., Carr, M., Herzberg, C., Saginor, van den Bogaard, P., Folkmar, H., Feigenson, M., Swisher III, C., 2011. Plume-subduction interaction in southern Central America: mantle upwelling and slab melting. Lithos 121, 117–134.
- Gehrels, G., Valencia, V., Pullen, A., 2006. Detrital zircon geochronology by laserablation multi-collector ICPMS at the Arizona Laserchron Center. The Paleontological Society Papers 12, 67–76.
- Gehrels, G.E., Valencia, V., Ruiz, J., 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of U–Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry. Geochemistry, Geophysics, Geosystems 9, Q03017. doi:10.1029/2007GC001805.
- Gill, J.B., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag. (390 pp.).
- Grove, T.L., Elkin-Tanton, L.T., Parman, S.W., Chatterjee, N., Müntener, O., Gaetani, G.A., 2003. Fractional crystallization and mantle-melting controls on calc-alkaline differentiation trends. Contributions to Mineralogy and Petrology 145, 515–533.
- Hastie, A.R., Kerr, A.C., McDonald, I., Mitchell, S.F., Pearce, J.A., Millar, I.L., Barfod, D., Mark, D.F., 2010. Geochronology, geochemistry and petrogenesis of ryhodacite lavas in eastern Jamaica: a new adakite subgroup analogous to early Archaen continental crust? Chemical Geology 276, 344–359.
- Hauff, F., Hoernle, K., Schmincke, H.-U., Werner, R., 1997. A mid Cretaceous origin for the Galápagos hotspot: volcanological, petrological and geochemical evidence from Costa Rican oceanic crustal segments. Geologische Rundschau 86, 141–155.
- Hauff, F., Hoernle, K., Tilton, G., Graham, D.W., Kerr, A.C., 2000a. Large volume recycling of oceanic lithosphere over short time scales: geochemical constraints from the Caribbean Large Igneous Province. Earth and Planetary Science Letters 174, 247–263.
- Hauff, F., Hoernle, K., van den Bogaard, P., Alvarado, G.E., Garbe-Schonberg, C.D., 2000b. Age and geochemistry of basaltic complexes in western Costa Rica: contributions to the geotectonic evolution of Central America. Geochemistry, Geophysics, Geosystems 1 (Paper number 1999GC000020).
- Hidalgo, P.J., Vogel, T.A., Rooney, T.O., Currier, R.M., Layer, P.W., 2012. Origin of silicic volcanism in the Panamanian arc: evidence for a two-stage fractionation process at El Valle volcano. Contributions to Mineralogy and Petrology 162 (6), 1115–1138.
- Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., Garbe-Schanberg, D., 2002. Missing history (16–71 Ma) of the Galapagos hotspot: implications for the tectonic and biological evolution of the Americas. Geology 30, 795–798.
- Hoernle, K., Hauff, F., van den Bogaard, P., 2004. 70 m.y. history (139–69 Ma) for the Caribbean large igneous province. Geology 32, 697–700.
- Hoernle, K., Abt, D.L., Fischer, K.M., Nichols, H., Hauff, F., Abers, G.A., van den Bogaard, P., Heydolph, K., Alvarado, G., Protti, M., Strauch, W., 2008. Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. Nature 451, 1094–1097.
- Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and metamorphic petrogenesis. Reviews in Mineralogy and Geochemistry, vol. 53. Mineralogical Society of America, Washington, pp. 27–62.
- Hou, M.L., Jiang, Y.H., Jiang, S.Y., Ling, H.F., Zhao, K.D., 2007. Contrasting origin of Late Mesozoic adakitic granitoids from the northwestern Jiaodong Peninsula, east China: implications for crustal thickening to delamination. Geological Magazine 144, 619–631.
- Huang, F., Li, S., Dong, F., He, Y., Chen, F., 2008. High-Mg adakitic rocks in the Dabie orogen, central China: implications for foundering mechanism of lower continental crust. Chemical Geology 255, 1–13.
- Ickert, R.B., Thorkelson, D.J., Marshall, D.D., Ullrich, D., 2009. Eocene adaktic volcanism in southern British Columbia: Remelting of arc basalt above a slab window. Lithos 464, 164–185.
- Johnson, K., Barnes, C.G., Miller, C.A., 1997. Petrology, geochemistry, and genesis of high-Al tonalite and trondhjemites of the Cornucopia stock, Blue Mountains, Northeastern Oregon. Journal of Petrology 38, 1585–1611.
- Jordan, T.H., 1975. The present-day motions of the Caribbean plate. Journal of Geophysical Research 80, 4433–4867.
- Karsli, O., Dokuz, A., Uysal, I., Aydin, F., Kandemir, R., Wijbrans, 2010. Generation of the Early Cenozoic adakitic volcanism by partial melting of mafic lower crust, Eastern Turkey: implications for crustal thickening to delamination. Lithos 114, 109–120.
- Kay, R.W., 1978. Aleutian magnesian andesites; melts from subducted Pacific Ocean crust. Journal of Volcanology and Geothermal Research 4, 117–132.
- Kay, R.W., Kay, S.M., 2002. Andean adakites: there ways to make them. Acta Petrologica Sinica 18, 303–311.
- Kay, S.M., Ramos, A., Marquez, M., 1993. Evidence in Cerro Pampa volcanic rocks of slab melting prior to ridge trench collision in southern SouthAmerica. Journal of Geology 101, 703–714.
- Kellogg, J.N., Vega, V., 1995. Tectonic development of Panama, Costa Rica, and the Colombian Andes; constraints from Global Positioning System geodetic studies and gravity. In: Mann, P. (Ed.), Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America: Geological Society of America Special Paper, 295, pp. 75–90.
- Kepezhinskas, P.K., Defant, M.J., Drummond, M., 1995. Na metasomatism in the island arc mantle by slab melt-peridotite interaction: evidence from mantle interaction evidence from mantle xenoliths in the north Kamchatka arc. Journal of Petrology 36, 1505–1527.
- Kerr, A.C., Tarney, J., 2005. Tectonic evolution of the Caribbean and northwestern South America: the case for accretion of two Late Cretaceous oceanic plateaus. Geology 33, 269–272. doi:10.1130/G21109.1.
- Kerr, A.C., White, R.V., Thompson, P.M.E., Tarney, J., Saunders, A.D., 2003. No oceanic plateau-no Caribbean Plate? The seminal role of an oceanic plateau in Caribbean

Plate evolution. In: Bartolini, C., Bufler, R.T., Blickwede, J. (Eds.), The Circum-gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation and Plate Tectonics: AAPG Memoir, 79, pp. 126–168.

- Kesler, S.E., 1978. Metallogenesis of the Caribbean region. Journal of the Geological Society of London 135, 429–441.
- Kessler, S.É., Sutter, J.F., Issigonis, M.J., Jones, L.M., Walker, R.L., 1977. Evolution of copper porphyry mineralization in an oceanic island arc: Panama. Economic Geology 72, 1142–1153.
- Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on total alkali-silica diagram. Journal of Petrology 27, 745–750.
- Lin, J.Y., Hsu, S.K., Sibuet, J.C., 2004. Melting features along the Ryukyu slab tear, beneath the southwestern Okinawa Trough. Geophysical Research Letters 31 (L19607). doi:10.1029/2004GL020862.
- Lin, J.-Y., Sibuet, J.-C., Lee, C.S., Hsu, S.-K., Klingelhoefer, F., 2007. Origin of the southern Okinawa Trough volcanism from detailed seismic tomography. Journal of Geophysical Research 112, B08308. doi:10.1029/2006JB004703.
- Lissinna, B., 2005. A profile through the Central American Landbridge in western Panama: 115 Ma interplay between the Galápagos Hotspot and the Central American Subduction Zone. Ph.D. thesis, 102 pp., Christian-Albrechts University, Kiel, Germany.
- Lonsdale, P., 2005. Creation of the Cocos and Nazca plates by fissuring of the Farallon plate. Tectonophysics 404, 237–264.
- Lowrie, A., Stewart, J.L., Stewart, R.H., Van Andel, T.J., McRaney, L., 1982. Location of the eastern boundary of the Cocos plate during the Miocene. Marine Geology 45, 261–279.
- Ludwig, K.R., 2003a. Isoplot/EX version 3.0, a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication. .
- Ludwig, K.R., 2003b. User's Manual for Isoplot 3.00. Berkeley Geochronology Center, Berkeley, CA. (70 pp.).
- Ludwig, K.R., Mundil, R., 2003. Extracting reliable U–Pb ages and errors from complex populations of zircons from Phanerozoic tuffs. Geochimica et Cosmochimica Acta 66, 463. doi:10.1016/S0016-7037(01)00786-4.
- MacDonald, W.D., Estrada, J.J., Humberto, G., 1997. Paleoplate affiliations of volcanic accretionary terranes of the northern Andes. Geological Society of America Abstracts with Programs, 29, no. 6, p. 245.
- Macpherson, C.G., Dreher, S.T., Thirwall, M.F., 2006. Adakites without slab melting: high pressure differentiation of island arc magma, Mindanao, the Philippines. Earth and Planetary Science Letters 243, 581–593.
- Martin, H., Smith, R.H., Rapp, R., Moyen, J.F., Champion, D., 2005. An overview of adakite, tonalite-trondhjemite-granodiorite (TTG), and sanitoid: relationships and some implications for crustal evolution. Lithos 79, 1–24.
- Molnar, P., Sykes, L.R., 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. Geological Society of America Bulletin 80, 1639–1684.
- Montes, C., Cardona, A., McFadden, R., Morón, S.E., Silva, C.A., Restrepo-Moreno, S., Ramírez, D.A., Hoyos, N., Wilson, J., Farris, D., Bayona, G.A., Jaramillo, C.A., Valencia, V., Bryan, J., Flores, J.A., 2012. Evidence for middle Eocene and younger land emergence in central Panama: implications for lsthmus closure. Geological Society of America Bulletin. doi:10.1130/B30528.1.
- Moore, G.F., Sender, K.L., 1995. Fracture zone collision along the south Panama margin. In: Mann, P. (Ed.), Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America: Geological Society of America Special Paper, 295, pp. 201–212.
- Muir, R.J., Weaver, S.D., Bradshaw, J.D., Eby, G.N., Evans, J.A., 1995. Geochemistry of the Cretaceous Separation Point batholith, New Zealand: granitoid magmas formed by melting of mafic lithosphere. Journal of the Geological Society of London 152, 689–701.
- Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary meteorites. Geochimica et Cosmochimica Acta 38, 757–777.
- Nelson, C.E., 1995. Porphyry copper deposits of southern Central America. Arizona Geological Society Digest 20, 553–565.
- Pallares, C., Maury, R.C., Bellon, H., Royer, J.-Y., Calmus, T., Aguillón-Robles, A., Cotten, J., Benoit, M., Michaus, Bourgois, J., 2007. Slab-tearing following ridge-trench collision: Evidence from Miocene volcanism in Baja California, México. Journal of Volcanology and Geothermal Research 161, 95–117.
- Peacock, S.M., Rushmer, T., Thompson, A.B., 1994. Partial melting of subducting oceanic crust. Earth and Planetary Science Letters 121, 227–244.
- Peccerillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. Contributions to Mineralogy and Petrology 58, 63–81.
- Petford, N., Atherton, M., 1996. Na-rich partial melts from newly underplated basaltic crust: the Cordillera Blanca Batholith, Peru. Journal of Petrology 37, 1491–1521.
- Petterson, M.G., Babbs, T., Neal, C.R., Mahoney, J.J., Saunders, A.D., Duncan, R.A., Tolia, D., Magu, R., Qopoto, C., Mahoa, H., Natogga, D., 1999. Geological-tectonic framework of Solomon Islands, SW Pacific: crustal accretion and growth within an intra-oceanic setting. Tectonophysics 301, 35–60.
- Pidgeon, R.T., Furfaro, D., Kennedy, A.K., Nemchin, A.A., Broswijk, W., 1994. Calibration of zircon standards for the Curtin SHRIMP II. 8th International Conference on Geochronology, Cosmochronology, and Isotope Geology, U.S. Geological Survey Abstracts 1107, p. 251.
- Pindell, J.L., Barrett, S.F., 1990. Geological evolution f the Caribbean region: a plate tectonic perspective. In: Dengo, G., Case, J.E. (Eds.), The Geology of North America Volume H. Geological Society of America, The Caribbean Region, Boulder, Colorado, pp. 405–432.
- Pindell, J., Kennan, L., 2001. Kinematic evolution of the Gulf of Mexico and Caribbean. Transactions, Petroleum Systems of Deep-water Basins: Global and Gulf of Mexico

Experience. GCSSEPM 21st Annual Foundation Bob F. Perkins Research Conference, Houston, Texas, pp. 193–220.

- Pindell, J., Kennan, L., Stanek, K.P., Maresh, W.V., Draper, G., 2006. Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved. Geologica Acta 4, 303–341.
- Prouteau, G., Scaillet, B., Pichavant, M., Maury, R.C., 2001. Evidence for mantle metasomatism by hydrous silicic melts derived from subducted oceanic crust. Nature 410, 197–200. Rapp, R.P., Watson, E.B., 1995. Dehydration melting of metabasalt at 8–32 kbar: implications
- for continental growth and crust-mantle recycling. Journal of Petrology 36, 881–931. Rapp, R.P., Shimizu, N., Norman, M.D., Applegate, G.S., 1999. Reaction between slab
- derived melts and peridotite in the mantle wedge: experimental constraints at 3.8 GPa. Chemical Geology 160, 335–356.
- Rapp, R.P., Xiao, L., Shimizu, N., 2002. Experimental constraints on the origin of potassium-rich adakites in east China. Acta Petrologica Sinica 18, 293–311.
- Rooney, T.O., Franceschi, P., Hall, C., 2010. Water saturated magmas in the Panama Canal region—a precursor to adakite-like magma generation? Contributions to Mineralogy and Petrology 161, 373–388.
- Rubatto, D., 2002. Zircon trace element geochemistry: distribution coefficients and the link between U–Pb ages and metamorphism. Chemical Geology 184, 123–138.
- Sajona, F.G., Naury, R.C., Pubellier, M., Leterrier, J., Bellon, H., Cotton, J., 2000. Magmatic source enrichment by slab-derived melts in a young post-collision setting, central Mindanao (Philippines). Lithos 54, 173–206.
- Sen, C., Dunn, T., 1994. Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: implications for the origin of adakites. Contributions to Mineralogy and Petrology 117, 394–409.
- Serrano, L, Ferrari, L, López Martínez, M., Petrone, C.M., Jaramillo, C., 2011. An integrative geologic, geochronologic, and geochemical study of the Gorgona Plateau: implications for the formation of the Caribbean Large Igneous Province. Earth and Planetary Science Letters 309, 324–336.
- Silver, E.A., Reed, D.L., Tagudin, J.E., Heil, D.J., 1990. Implications of the north and south Panama thrust belts for the origin of the Panama orocline. Tectonics 9, 261–281.
- Silver, E.A., Galewsky, J., McIntosh, K.D., 1995. Variation in structure, style, and driving mechanism of adjoining segments of the North Panama deformed belt. Geological Society of America Special Paper 295, 225–233.
- Sinton, C.W., Duncan, R.A., Denyer, P., 1997. Nicoya Peninsula, Costa Rica: a single suite of Caribbean oceanic plateau magmas. Journal of Geophysical Research 102, 15507–15520.
- Sinton, C.W., Duncan, R.A., Storey, M., Lewis, J., Estrada, J.J., 1998. An oceanic flood basalt province at the core of the Caribbean plate. Earth and Planetary Science Letters 155, 222–235.
- Sorensen, S.S., Grossman, J.N., 1989. Enrichment of trace elements in garnet amphibolites from a paleo-subduction zone: Catalina schist, southern California. Geochemica et Cosmochimica Acta 53, 3155–3177.
- Speidel, F., Faure, S., 1996. Surface geology of Botija and Petaquilla deposits. (Panamá, Internal Report, 36 pp.).
- Speidel, F., Faure, S., Smith, M.T., McArthur, G.F., 2001. Exploration and discovery at the Petaquilla copper–gold concession, Panama. Society of Economic Geologists SP8 (14 pp.).
- Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters 26, 207–221.
- Stern, C.R., Kilian, R., 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Austral Volcanic Zone. Contributions to Mineralogy and Petrology 123, 263–281.
- Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins: Geological Society of London Special Publication, vol. 42, pp. 313–345.
- Thorkelson, D.J., Breitsprecher, K., 2005. Partia melting of slab window margins: genesis of adakitic and non-adakitic magmas. Lithos 79 (1–2), 25–41.

- Tournon, J., Seyler, M., Astorga, A., 1995. Les peridotites du Rio San Juan (Nicaragua et Costa Rica); jalons possibles d'une suture ultrabasique E-W en Amerique Centrale meridionale. Comptes Rendus de l'Academie des Sciences 320, 757–764.
- Valencia, V.A., Ruiz, J., Barra, F., Gehrels, G.E., Ducea, M.N., Titley, S., Ochoa-Landín, L., 2005. U–Pb zircon and Re–Os molybdenite geochronology from La Caridad porphyry copper deposit: insights from the duration of magmatism and mineralization in the Nacozari district, Sonora, Mexico. Mineralium Deposita 40, 175–191.
- Wang, Q., Xu, J.F., Zhao, Z.H., Bao, Z.W., Xu, W., Xiong, X.L., 2004a. Cretaceous high potassium intrusive rocks in the Yueshan–Hongzhen area of east China: adakites in an extensional tectonic regime within a continent. Geochemical Journal 38, 417–434.
- Wang, Q., Zhao, Z.H., Bao, Z.W., Xu, J.F., Liu, W., Li, C.F., et al., 2004b. Geochemistry and petrogenesis of the Tongshankou and Yinzu adakitic intrusive rocks and the associated porphyry copper–molybdenum mineralization in southeast Hubei, east China. Resource Geology 54, 137–152.
- Wang, Q., Xu, J.F., Jian, P., Bao, Z.W., Zhao, Z.H., Li, C.F., Xiong, X.L., Ma, J.L., 2006. Petrogenesis of adakitic porphyries in an extensional tectonic setting, Dexing, South China: implications for the genesis of porphyry copper mineralization. Journal of Petrology 47, 119–144.
- Wegner, W., Wörner, G., Harmon, R.S., Jicha, B.R., 2011. Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times. Geological Society of America Bulletin 123, 703–724. doi:10.1130/B30109.1.
- Westbrook, G.K., Hardy, N.C., Heath, R.P., 1995. Structure and tectonics of the Panama-Nazca Plate boundary. In: Mann, P. (Ed.), Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America: Geological Society of America Special Paper, 295, pp. 91–109.
- Whattam, S.A., Malpas, J., Ali, J.R., Smith, I.E.M., 2008. New SW Pacific tectonic model: cyclical intraoceanic magmatic arc construction and near coeval emplacement along the Australia–Pacific margin in the Cenozoic. Geochemistry, Geophysics, Geosystems 9. doi:10.1029/2007GC001710.
- Wolters, B., 1986. Seismicity and tectonics of southern Central America and adjacent regions with special attention to the surroundings of Panama. Tectonophysics 128, 21–23 (27-46).
- Woodring, W.P., 1957. Geology and description of Tertiary mollusks (gastropods; trochidae to Turritellidae). Geology and paleontology of Canal Zone and adjoining parts of Panama. U.S. Geological Survey Professional Paper, 306-A, p. 145.
- Wörner, G., Harmon, R., Wegner, W., 2009. Geochemical evolution of igneous rock and changing magma sources during the formation and closure of the Central American land bridge of Panama. In: Kay, S.M., Ramos Victor, A., Dickinson, W.R. (Eds.), Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir, 204, pp. 183–196.
- Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean– Carpathian region. Science 290, 1910–1917.
- Xiong, X.L., Li, X.H., Xu, J.F., Li, W.X., Zhao, Z.H., Wang, Q., 2003. Extremely high-Na adakite-like magmas derived from alkali-rich basaltic underplate: the late Cretaceous Zhantang andesites in the Huichang Basin, SE China. Geochemical Journal 37, 233–252.
- Xu, J.F., Shinjio, R., Defant, M.J., Wang, Q., Rapp, R.P., 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust? Geology 12, 1111–1114.
- Xu, W.L., Wang, Q.H., Wang, D.Y., Guo, J.H., Pei, F.P., 2006. Mesozoic adakitic rocks from the Xuzhou–Suzhou area, eastern China: evidence for partial melting of delaminated lower continental crust. Journal of Asian Earth Sciences 27, 454–464.
- Yoshioka, S., Wortel, M.J.R., 1995. Three-dimensional numerical modeling of detachment of subducted lithosphere. Journal of Geophysical Research 100, 20,223–20,244.