Landscape evolution within a retreating volcanic arc, Costa Rica, Central America

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ABSTRACT

Subduction of hotspot-thickened seafloor profoundly affects convergent margin tectonics, strongly affecting upper plate structure, volcanism, and landscape evolution. In southern Central America, low-angle subduction of the Cocos Ridge and seamount domain largely controls landscape evolution in the volcanic arc. Field mapping, stratigraphic correlation, and $^{40}Ar/^{39}Ar$ geochronology for late Cenozoic volcanic rocks of central Costa Rica provide new insights into the geomorphic response of volcanic arc landscapes to changes in subduction parameters (slab thickness, roughness, dip). Late Neogene volcanism was focused primarily along the now-extinct Cordillera de Aguacate. Quaternary migration of the magmatic front shifted volcanism northeastward to the Caribbean slope, creating a new topographic divide and forming the Valle Central basin. Stream capture across the paleo–Aguacate divide led to drainage reversal toward the Pacific slope and deep incision of reorganized fluvial networks. Pleistocene caldera activity generated silicic ash flows that buried the Valle Central and descended the Tárcoles gorge to the Orotina debris fan at the coast. Growth of the modern Cordillera Central accentuated relief along the new divide, establishing the Valle Central as a Pacific slope drainage basin. Arc migration, relocation of the Pacific-Caribbean drainage divide, and formation of the Valle Central basin resulted from slab shallowing as irregular, hotspot-thickened crust entered the subduction zone. The geomorphic evolution of volcanic arc landscapes is thus highly sensitive to changes in subducting plate character.

Keywords: Costa Rica, volcanic arc, subduction, landscape evolution, geochronology.

INTRODUCTION

The subduction of irregular, hotspot-thickened seafloor profoundly affects the tectonic evolution of convergent margins (e.g., von Huene et al., 2000). As thickened crust enters the subduction zone, the downgoing slab shallows due to increased buoyancy, strongly impacting upper plate structure, kinematics, and volcanism (Kolarsky et al., 1995). Along the southern Middle America margin (Fig. 1A), late Cenozoic subduction of thickened seafloor led to pronounced changes within the subduction system of Costa Rica. Offshore, the Cocos plate has several sharp segment boundaries (Barckhausen et al., 2001), including the trace of the Cocos-Nazca-Pacific triple junction and an abrupt morphologic break between rough and smooth seafloor domains. Rough seafloor to the southeast contains the Cocos Ridge and seamounts, products of crustal thickening at the Galapagos hotspot (Werner et al., 1999). Near orthogonal convergence at >9 cm/yr localizes these features along the margin, producing diverse effects from the trench to the volcanic arc.

Along-strike variations in Cocos plate thickness (Fig. 1A) coincide with sharp differences in slab dip and subduction-zone seismicity (Protti et al., 1995). Subducting seafloor roughness generates tectonic erosion and subsidence of the offshore margin wedge (Ranero and von Huene, 2000; Vannuchi et al., 2001). Onshore, broad uplift and shortening affect the forearc inboard of the Cocos Ridge (Gardner et al., 1992; Kolarsky et al., 1995), whereas localized block uplift occurs above shorter-wavelength seamounts (Fisher et al., 1998; Gardner et al., 2001). The thickened slab also generates transpression along a deformation front across the volcanic arc (Marshall et al., 2000). Variations in subducting crust, ocean sediments, and fluid flux are linked to differences in magma chemistry along the arc (Carr et al., 1990; Kussmaul et al., 1994; Patino et al., 2000).

Here we show that changes in slab thickness, roughness, and dip also profoundly affect the geomorphic and stratigraphic evolution of the volcanic arc. The late Neogene onset of Cocos Ridge subduction (Kolarsky et al., 1995) shut off volcanism in the Cordillera de Talamanca of southern Costa Rica (Fig. 1A). However, shallow subduction of moderately thickened crust on the ridge flank initiated retreat of the volcanic arc in central Costa Rica. Arc migration from the Cordillera de Aguacate to the Cordillera Central (Fig. 1B) produced a landscape of overlapping volcanic ranges and intervening depositional basins. The progress of arc migration is recorded within the volcanic stratigraphy of the Valle Central basin and Orotina debris fan (Fig. 1B). We link these sections through $^{40}Ar/^{39}Ar$ dating and stratigraphic correlation, then develop a chronology for geomorphic evolution of central Costa Rica, demonstrating that volcanic arc landscapes are highly sensitive to changes in subducting plate character.

GEOCHRONOLOGY AND VOLCANIC STRATIGRAPHY

Prior to this study, isotopic ages for late Cenozoic volcanic rocks of central Costa Rica were based primarily on K/Ar analyses (Alvarado et al., 1993). We report 20 new $^{40}Ar/^{39}Ar$ ages (Table 1; Appendix DR-A[1]) that greatly improve age limits on these rocks, and present these ages along with new interpretations of regional stratigraphy and landscape evolution.

Aguacate Group

Grifo Alto Formation. The Cordillera de Aguacate (Fig. 1B) consists of extinct Neogene to Quaternary volcanic remnants composed of basaltic to andesitic lavas, tuffs, and lahar deposits (Dengo, 1962; Denyer and Arias, 1991). Two ages for lava flows of the Grifo Alto Formation (Fig. 2, 19 and 20) confirm late Neogene activity (5.5–5.0 Ma) within the Aguacate Range prior to arc retreat.

Tivives Formation. Along the Pacific piedmont of the Aguacate Range (Fig. 1B), a >100-m-thick sequence of interbedded lahar deposits, ash flows, and volcaniclastic sediments (Tivives Formation; Madrigal, 1970) forms the 25-km-wide Orotina debris fan. Seven ages for juvenile phenocrysts of plagioclase and biotite from lahar matrices, a welded tuff, and a pumice-rich sand unit (Fig. 2, 12–18) establish that the Tivives Formation is Pleistocene (1.7–1.1 Ma), and not Miocene–Pliocene, as previously mapped (Madrigal, 1970). Abundant euhedral phenocrysts and intact pumice fragments within ash-rich matrices strongly suggest a pyroclastic origin for

[1]GSA Data Repository item 2003057, Appendix DR-A, analytical methods and $^{40}Ar/^{39}Ar$ dating results, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

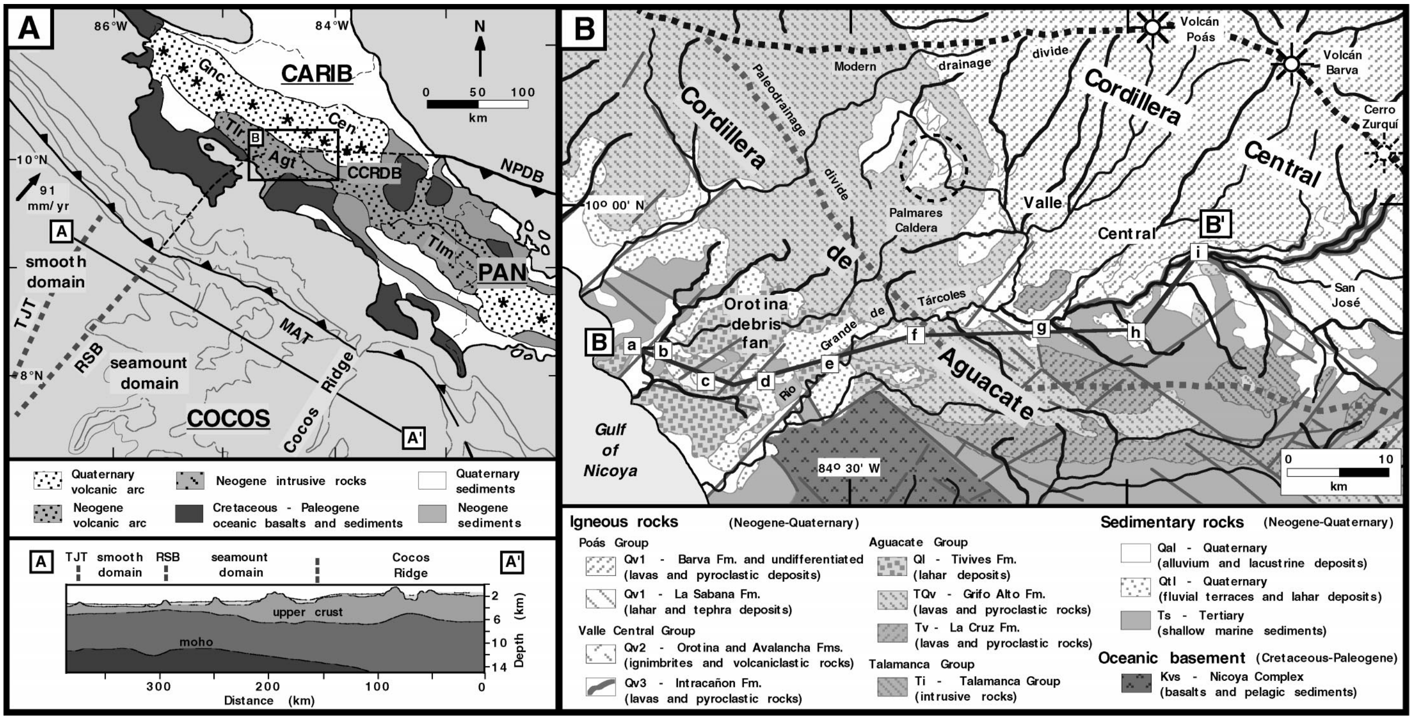

Figure 1. A: Tectonic features of Costa Rican Pacific margin. Asterisks are active volcanoes. Volcanic cordilleras: Gnc, Guanacaste; Cen, Central; Tlr, Tilarán; Agt, Aguacate; Tlm, Talamanca. Tectonic plates: CARIB, Caribbean; COCOS, Cocos; PAN, Panama block. Tectonic boundaries: MAT, Middle America Trench; TJT, triple junction trace (Cocos-Nazca-Pacific); RSB, rough-smooth boundary; CCRDB, Central Costa Rica deformed belt; NPDB, North Panama deformed belt. Cross section A-A′ shows along-strike variations in Cocos plate thickness and roughness (modified from von Huene et al., 2000). Bathymetric contour interval is 1000 m. B: Geology of central Costa Rican volcanic arc. Locations of stratigraphic columns (Fig. 2) are shown by letters (in squares) along line B-B′. Modern river network is shown as black lines. Pacific-Caribbean drainage divide is shown as heavy dashed lines (black, modern divide; gray, paleodivide). Quaternary volcanoes are shown as circles with spokes (solid, active; dashed, extinct). Extinct caldera is outlined by dashed circle. Active faults are shown as light gray lines. Geology is based on Madrigal (1970), Denyer and Arias (1991), and our field mapping.

the lahars. This interpretation is supported by nearly identical ages for an inset tuff (Fig. 2, 17) and two lahar samples (Fig. 2, 15 and 16). The Tivives Formation is interpreted here as a series of eruption-generated debris flows that descended from the volcanic arc onto the coastal lowland. Buried paleosols, abrupt textural changes, and interbedded fluvial sediments (Fig. 2) occur between separate flow units dated as 1.7 Ma (Puente Agres), 1.4 Ma (Jesús María), and 1.1 Ma (Bajamar and El Tigre).

Valle Central Group

Intracañon Formation. The Intracañon Formation (Williams, 1952) consists of a 100–300-m-thick volcanic sequence observed only in canyons, quarries, and wells in the Valle Central (Fig. 1B). These deposits include a lower member (Belén) of andesite lavas, ash-flow tuffs, and lacustrine beds; a discontinuous middle unit (Puente Mulas) of densely welded ignimbrites; and an upper member (Linda Vista) of andesite breccias and dense lava flows (Echandi, 1981; Denyer and Arias, 1991). Geochemical data (Kussmaul et al., 1994) show that these K-rich andesites differ from the basaltic andesites of the Aguacate Group. The Intracañon Formation is interpreted as a product of distinct magma sources that developed northeast of the Aguacate Range beneath the modern Valle Central. This shift in magmatism may reflect slab shallowing (e.g., Gutscher et al., 2000) and the onset of arc migration. Isotopic ages for both the Intracañon and Tivives Formations (Fig. 2, 9–18) suggest that arc retreat was underway by 0.8 Ma, and may have begun as early as 1.7 Ma. Intracañon Formation lavas created a topographic barrier to rivers on the Caribbean slope of the Aguacate highlands. Interbedded lacustrine silts (Fig. 2) indicate drainage disruption and ponding as growth of this new divide isolated a proto–Valle Central basin.

Avalancha Formation. The Avalancha Formation (Williams, 1952) consists of 25 km^3 of silicic ash-flow tuffs that overlie the Intracañon Formation and form a 500 km^2 tableland within the Valle Central (Fig. 1B). These deposits include a lower member (Nuestro Amo) of densely welded block and ash flows; a middle unit (Electriona) of columnar ignimbrites; and an upper member (La Caja) of partially welded ash and pumice flow tuffs (Echandi, 1981; Denyer and Arias, 1991). These pyroclastic flows are interpreted here as products of caldera eruptions along the flank of the Aguacate Range (e.g., Palmares Caldera, Fig.1B) or within the active cordillera (e.g., Volcán Barva; W. Pérez, 2001, personal commun.). The Electriona Member ignimbrites were dated at three locations (Fig. 2, 5–7). A fourth age (Fig. 2, 8) was determined for an underlying white ash and pumice marker bed found throughout the Valle Central. These ages show significant statistical overlap with ages for underlying Intracañon Formation lavas (Fig. 2, 9–10), suggesting a rapid transition between these units.

Orotina Formation. A sequence of ash-flow tuffs and volcaniclastic sediments (Orotina Formation; Madrigal, 1970) overlies lahar deposits of the Orotina debris fan (Fig. 1B). A resistant ryhodacite welded tuff (Snake Flow Member) forms meandering ridges that outline paleoriver channels across the debris fan surface. The Orotina Formation (Fig. 2, 1–4) was dated using three Snake Flow samples and a fourth from a pervasive white ash horizon identical to the Valle Central marker bed. The Snake Flow tuff can be traced from the Orotina debris fan, up the Río Tárcoles gorge, and into the Valle Central (Fig. 1B), where it merges with the Electriona Member ignimbrites of the Avalancha Formation (Fig. 2). Ages for this unit from both the Valle Central (Fig. 2, 5–7) and Orotina fan (Fig. 2, 1–3) are statistically indistinguishable, although separate flow branches on the Orotina fan may represent discrete events. Previous authors

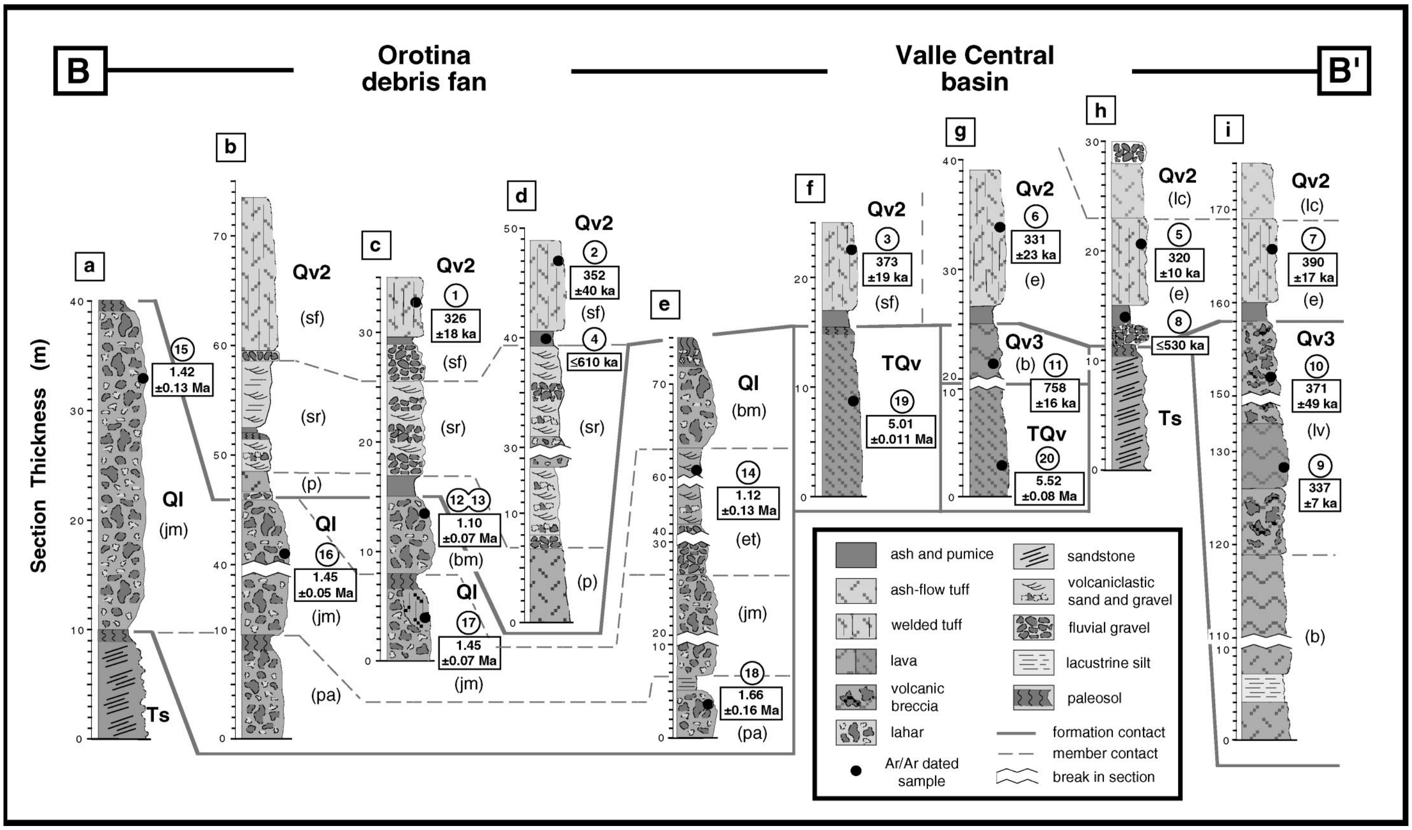

Figure 2. Stratigraphic columns for Orotina debris fan and Valle Central basin along line B-B′ (Fig. 1). Correlations between columns are shown by gray lines (solid, formation contact; dashed, member contact). ^{40}Ar/^{39}Ar ages (in boxes) are shown next to sample locations (solid black circles). Sample numbers (in circles) refer to Table 1. Formations (in bold): Qv2, Avalancha and Orotina; Qv3, Intracañon; Ql, Tivives; TQv, Grifo Alto; Ts, undifferentiated Tertiary sediments. Members (in parentheses): lc, La Caja; e, Electriona; sf, Snake Flow; sr, Santa Rita; p, Pozón; lv, Linda Vista; b, Belén; bm, Bajamar; et, El Tigre; jm, Jesús María; pa, Puente Agres.

tentatively correlated the Valle Central ash flows with those of the Orotina fan (Dengo, 1962; Madrigal, 1970; Denyer and Arias, 1991). Detailed field mapping and the ^{40}Ar/^{39}Ar ages of this study confirm that correlation.

LATE CENOZOIC LANDSCAPE EVOLUTION

Stratigraphic correlation (Fig. 2), isotopic ages (Table 1), and interpretations of volcanic units allow us to reconstruct late Cenozoic landscape evolution in central Costa Rica (Fig. 3A). During the late Neogene (Fig. 3B), calc-alkaline volcanism (Aguacate Group) formed the Cordillera de Aguacate and created a Pacific-Caribbean drainage divide. After an apparent Pliocene lull in volcanism, a series of eruption-generated lahars (Tivives Formation) descended from the volcanic arc to the Pacific coast (Fig. 3C), forming the Orotina debris fan (1.7–1.1 Ma). By the early to middle Pleistocene (Fig. 3D), the volcanic front had expanded into the backarc with eruption of andesite lavas and tuffs (Intracañon Formation) northeast of the Aguacate Range (0.8–0.3 Ma). This shift in volcanism created a new drainage divide that ponded Caribbean slope rivers and formed a proto–Valle Central basin. Stream capture across the Aguacate divide redirected drainage networks toward the Pacific coast. A steeper gradient and shorter distance to coastal base level led to deep incision of the Río Tárcoles gorge through the Aguacate Range (Fig 1B). Mid-Pleistocene caldera activity (Fig. 3E) generated silicic ash flows (0.4–0.3 Ma) that buried the Valle Central (Avalancha Formation) and descended the gorge to the Orotina debris fan at the coast (Orotina Formation). Paleoriver channels are now preserved across the fan surface beneath sinuous ridges of welded tuff. By the late Pleistocene (Fig. 3F), the Cordillera Central had developed with eruption of basaltic andesite lavas and pyroclastic debris (Poás Group). Growth of these volcanoes accentuated relief along the new divide, establishing the Valle Central as a Pacific slope drainage basin. Headward elaboration of river networks resulted in deep incision along fault-controlled canyons within the Quaternary volcanic fill.

CONCLUSIONS

Late Cenozoic landscape evolution within the Costa Rican volcanic arc has been strongly influenced by low-angle subduction of the Cocos Ridge and seamount domain. Migration of the magmatic front from the Cordillera de Aguacate to the Cordillera Central resulted in relocation of the Pacific-Caribbean drainage divide, formation of the Valle Central basin, and reorganization of fluvial networks. Along other convergent margins, episodes of arc retreat have been linked to a decrease in subduction angle (e.g., Ferrari et al., 1999; Gutscher et al., 2000; Kay and Mpodozis, 2001). We suggest that arc migration and the consequent sequence of landscape evolution in central Costa Rica resulted from slab shallowing as irregular, hotspot-thickened oceanic crust propagated down the subduction zone. Arc retreat occurred only onshore of moderately thickened crust of the seamount domain (Fig. 3A). Directly inboard of the Cocos Ridge, volcanism has shut off and rapid uplift maintains the drainage divide along the Talamanca mountain crest. This new landscape evolution model for the Costa Rican arc illustrates the sensitivity of volcanic arc geomorphology to changes in subducting plate character.

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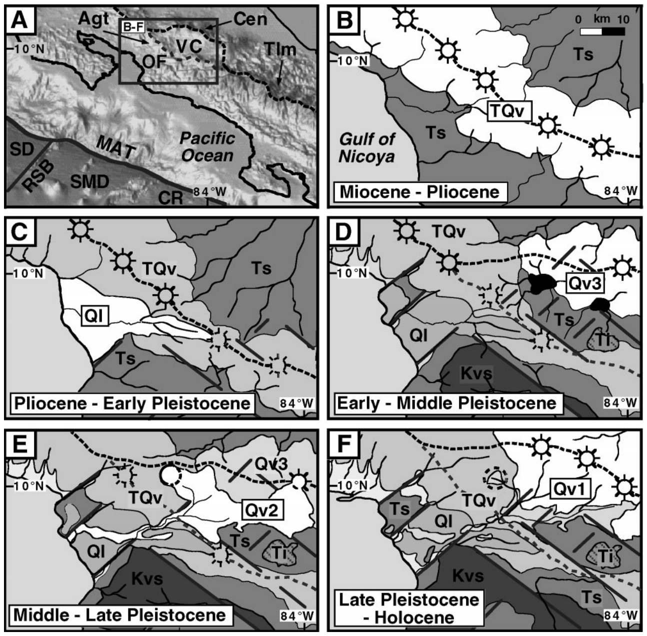

Figure 3. Late Cenozoic landscape evolution of central Costa Rican volcanic arc. A: Digital elevation model of modern landscape. Dashed lines indicate Pacific-Caribbean drainage divide (black, active divide; gray, paleodivide). VC, Valle Central; OF, Orotina debris fan; Cen, Cordillera Central; Agt, Cordillera de Aguacate; Tlm, Cordillera de Talamanca; MAT, Middle America Trench; RSB, rough-smooth boundary; SD, smooth domain; SMD, seamount domain; CR, Cocos Ridge. B–F: Sequential geologic maps (units shown in white were deposited during that time interval). Solid lines are faults; circles with spokes are volcanoes (dashed where extinct). Formations: Ts, Tertiary sediments; TQv, Grifo Alto; Ql, Tivives; Qv3, Intracañon; Qv2, Avalancha and Orotina; Qv1, Poás Group; Ti, Talamanca Group; Kvs, Nicoya Complex.

TABLE 1. $^{40}Ar/^{39}Ar$ AGE RESULTS

Sample*	Rock type†	Age§
Orotina Formation (Valle Central Group)		
1	Welded tuff (p)	326 ± 18 ka#
2	Welded tuff (p)	352 ± 40 ka
3	Welded tuff (p)	373 ± 19 ka
4	Ash (b)	*664 ± 109 ka*
Avalancha Formation (Valle Central Group)		
5	Welded tuff (b)	320 ± 10 ka#
6	Welded tuff (p)	331 ± 23 ka
7	Welded tuff(p)	390 ± 17 ka
8	Ash (b)	*597 ± 54 ka*
Intracañon Formation (Valle Central Group)		
9	Andesite (gm)	337 ± 7 ka
10	Andesite (gm)	371 ± 49 ka
11	Andesite (gm)	758 ± 16 ka
Tivives Formation (Aguacate Group)		
12	Lahar (b)	*909 ± 53 ka*
13	Lahar (p)	1.10 ± 0.07 Ma
14	Pumice sand (p)	1.12 ± 0.13 Ma
15	Lahar (b)	1.42 ± 0.13 Ma
16	Lahar (p)	1.45 ± 0.05 Ma
17	Welded tuff (b)	1.45 ± 0.07 Ma
18	Lahar (p)	1.66 ± 0.16 Ma
Grifo Alto Formation (Aguacate Group)		
19	Andesite (gm)	5.01 ± 0.11 Ma#
20	Trachyte (p)	5.52 ± 0.08 Ma

Note: Methods and analytical data are presented in Marshall (2000) and Appendix DR-A (see text footnote one).

*See Figure 2 for stratigraphic context of sample and Figure 1B for location.

†Analyzed phases indicated in parentheses, where p = plagioclase, b = biotite, gm = groundmass.

§Isochron ages are reported, unless otherwise indicated; values in italics reflect mean square of weighted deviates > 2.5.

#Plateau age.

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