Oceanic intraplate volcanoes exposed: Example from seamounts accreted in Panama

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ABSTRACT

Two Paleogene ocean islands are exposed in the Azuero Peninsula, west Panama, within sequences accreted in the early-Middle Eocene. A multidisciplinary approach involving lithologic mapping, paleontological age determinations, and petrological study allows reconstruction of the stratigraphy and magmatic evolution of one of these intraplate oceanic volcanoes. From base to top, the volcano's structure comprises submarine basaltic lava flows locally interlayered with hemipelagic sediments, basaltic breccias, shallow-water limestones, and subaerial basaltic lava. Gabbros and basaltic dikes were emplaced along a rift zone of the island. Geochemical trends of basaltic lavas include decreased Mg# {[Mg/(Mg + Fe)] * 100} and, with time, increased incompatible element contents thought to be representative of many poorly documented intraplate volcanoes in the Pacific. Our results show that, in addition to deep drilling, the roots of oceanic islands can be explored through studies of accreted and subaerially exhumed oceanic sequences.

INTRODUCTION

Oceanic intraplate volcanoes are common but poorly understood features (Staudigel and Clague, 2010). The evolution of larger volcanic edifices is generally subdivided into four stages: (1) an alkalic submarine preshield stage; (2) a main tholeiitic submarine-subaerial shield stage; (3) a subaerial alkalic postshield stage; and (4) a strongly alkalic posterosional stage that occurs after a volcanic hiatus of 1.5–10 m.y. (Clague and Dalrymple, 1987; Staudigel and Clague, 2010). Successive modes of volcanic development can be explained by changing conditions of mantle melting and magma ascent as volcanoes start forming above hotspots and are progressively isolated from their main mantle sources due to lithospheric drift (e.g., Morgan, 1971; Clague and Dixon, 2000; Koppers and Watts, 2010). Although this evolutionary model is in agreement with superficial observations of variously aged volcanic edifices along the Hawaiian-Emperor volcano chain, supporting observations from volcanic chains elsewhere or single edifices are limited because intraplate volcanoes either undergo rapid subsidence (e.g., Pacific islands), or deep erosion (e.g., Atlantic islands) fails to expose extended rock sequences. The internal anatomy of intraplate oceanic volcanoes has been deduced from exposures of deeply eroded islands, geophysical inversions, dive observations, and drilling (e.g., Staudigel and Schmincke, 1984; Kauahikaua et al., 2000; Garcia and Davis, 2001; Garcia et al., 2007). Development modes of Pacific intraplate oceanic volcanoes remain a matter of key multidisciplinary interest, but access is needed to their interiors to better understand their origins and development.

Circum-Pacific accretionary complexes contain numerous occurrences of oceanic basalts, some of which are interpreted as ancient fragments of ocean islands on the basis of their geochemistry and nature of associated sediments (e.g., Xenophontos and Osozawa, 2004; Dickinson, 2008; Buchs et al., 2009). However, accreted ocean islands are generally considered to have undergone intense dismemberment that limits characterization of their formation in the oceans. We present here new tectonostratigraphic, petrologic, and geochemical data from accreted oceanic islands exposed on the Pacific margin of Panama. Our results allow reconstruction of the anatomy and volcanic development of a large accreted ocean island, and show that some accreted oceanic basalts afford a new opportunity for the study of oceanic intraplate volcanoes.

BACKGROUND AND METHOD

The outer forearc of south Central America exposes accretionary complexes uplifted due to shallow subduction of the Cocos Ridge and topographically rough Cocos and Nazca plates (Sak et al., 2009) (Fig. 1). Late Cretaceous to Tertiary accreted seamounts and ocean islands have been recognized at five sites along the margin, which includes some parts of the Azuero Peninsula (west Panama) (Hauff et al., 2000; Hoernle et al., 2002; Hoernle and Hauff, 2007).

The Azuero Peninsula includes a composite igneous basement unconformably overlain by Middle Eocene and younger forearc sediments (Kolarsky et al., 1995). Autochthonous rocks from the basement comprise Late Cretaceous to Eocene sequences of the South Central American arc and its basement (Buchs et al., 2010). Exotic rocks from the igneous basement are restricted to the southwest corner of the peninsula, broadly on the southwest side of the left-lateral Azuero-Soná fault zone, and form the Azuero Accretionary Complex, which is the focus of this study (Fig. 2). Exotic igneous rocks

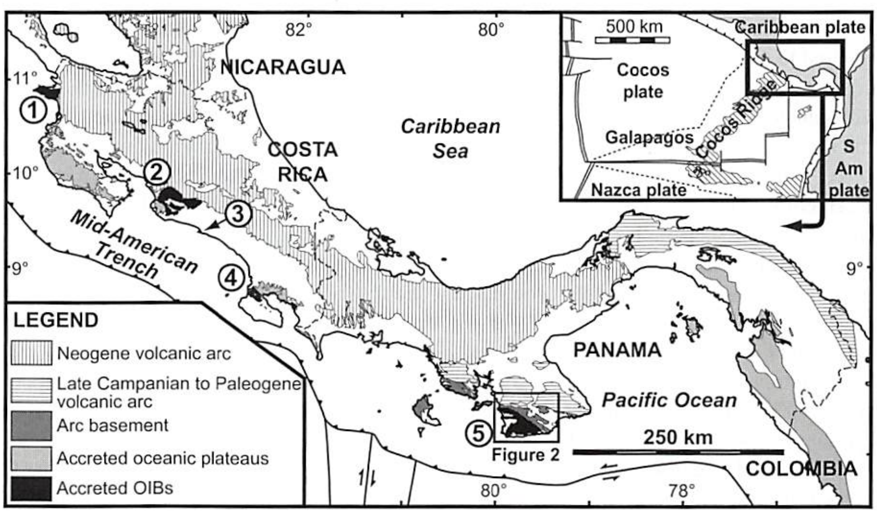

Figure 1. Tectonic setting and simplified geologic map of studied area (modified from Buchs et al., 2009). Numbers show locations of south Central American accretionary complexes containing fragments of seamounts and oceanic islands: 1—Santa Rosa; 2—Tulín; 3—Quepos; 4—Osa; 5—Azuero. S Am—South American; OIB—oceanic island basalt.

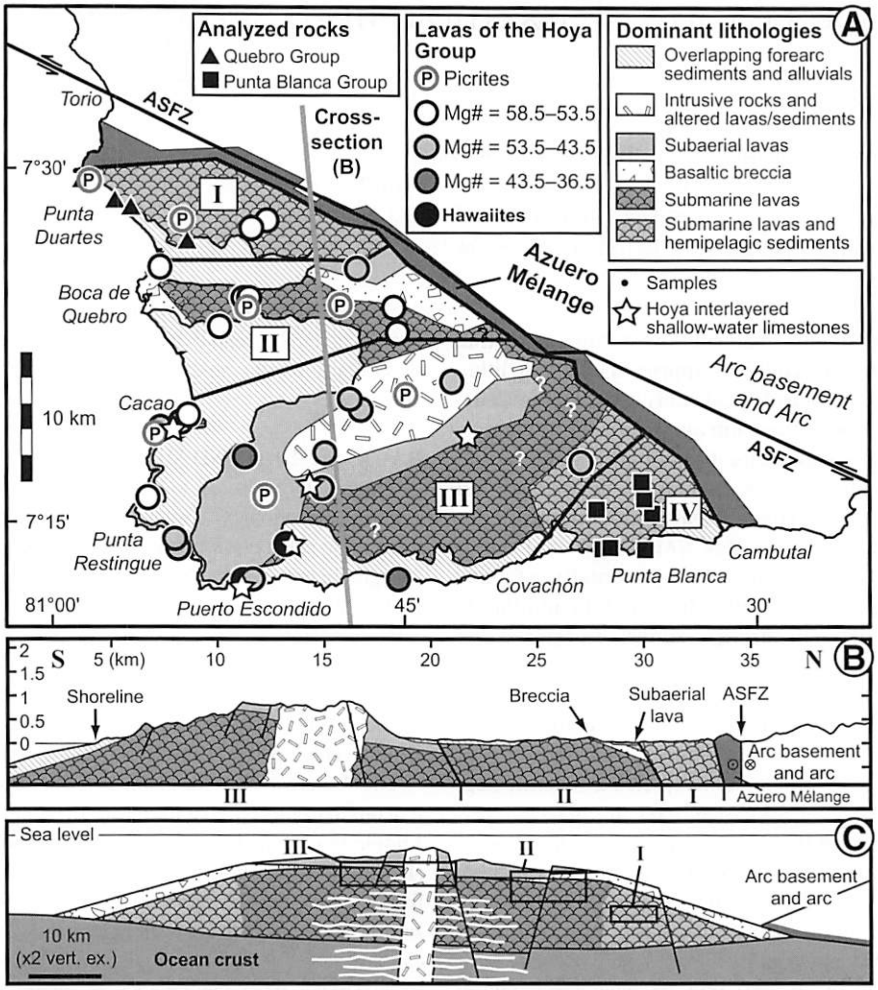

Figure 2. Geological map and structure of Azuero Accretionary Complex, with reconstruction of accreted Hoya Island. A: Geologic map of complex with location of analyzed igneous samples and geochemical variations of Hoya group. ASFZ—Azuero-Soná fracture zone (Kolarsky et al., 1995); I–IV—accreted rock stacks (see text). B: Cross section through accreted stacks of Hoya Island. C: Reconstructed structure of Hoya Island, assuming basal sequences are similar to those of Hawaii (basal sequences after Garcia et al., 2007).

from the Azuero Peninsula have previously been considered to represent a highly heterogeneous, disorganized assemblage of accreted Pacific ocean islands, seamounts, and aseismic ridges, on the basis of geochemical characteristics and $^{40}Ar/^{39}Ar$ radiometric dating (Hoernle et al., 2002; Hoernle and Hauff, 2007). In contrast, our results show that the complex comprises large stacks of oceanic seamounts and/or islands, and coherently preserves an exceptional occurrence of a Pacific intraplate volcano.

Our results integrate three months of geologic mapping and field observations, extended sampling of igneous and sedimentary rocks, morphological observation via satellite imagery, geochemical analysis of igneous rocks, and recent biochronologic determinations. Due to tropical vegetation and weathering, our field observations and sampling were restricted to well-exposed road cuts, riverbeds, and shorelines at low tide. Distribution of boulder lithologies in watersheds was used as a complement to outcrop observations to define major lithologic zonations. Analyzed samples were taken in situ (analytical procedure in Buchs et al., 2010). Although reconstructions are limited at subkilometer scales by scattered outcrop, lack of stratigraphic markers, and lateral discontinuity of rock assemblages, our data nevertheless permit reconstruction of kilometer-sized patterns that are the focus of this study.

RESULTS

Five types of lithology have been mapped in the Azuero Accretionary Complex: (1) submarine massive and pillowed lava flows with minor occurrences of hemipelagic calcareous sediments and hyaloclastites; (2) submarine sheeted lava flows and scarce pillow lavas, locally capped by shallow-water limestones; (3) clastic deposits comprising basaltic breccias infrequently crosscut by basaltic dikes; (4) subaerial massive lava flows locally deposited on top of shallow-water limestones and clastic deposits; and (5) large gabbroic intrusions and dense dike networks crosscutting both submarine and subaerial sequences (Fig. 2; Figs. DR1 and DR2 in the GSA Data Repository[1]). Igneous rocks form >90% of the complex.

The sequences are characterized by very low metamorphic conditions consistent with shallow accretion of the complex. Secondary mineral assemblages reflect oceanic hydrothermal alteration and include epidote, calcite, zeolites, and serpentine. Except in the close vicinity of intrusives, alteration of igneous rocks is generally low, with pristine mineral assemblages and moderate alteration of interstitial glass and olivine (Fig. DR3).

Frequent faulting at the outcrop scale and folding of overlapping forearc sediments indicate partial dismemberment of the sequences during accretion and later tectonics. Precise characterization of the structural arrangement of the complex is beyond the scope of this paper; however, we observed that accreted sequences generally dip 0°–45° northeast and exposures lack ductile deformation and evidence for overturned position. Accreted sequences are separated from the autochthonous igneous basement by a kilometer-thick layer of deformed igneous rocks and sediments named the Azuero mélange (after Buchs et al., 2010). Structural fabric of the mélange is clearly distinct from the accretionary complex, with local occurrence of ductile deformation (Figs. DR1 and DR2).

Igneous rock types are predominantly tholeiitic and alkali basalt and/or gabbro. The composition of these rocks defines three distinct magmatic groups, named here Hoya, Quebro, and Punta Blanca (Figs. 2 and 3; Fig. DR4) (for location of analyzed samples and geochemical results, see Tables DR1–DR3). Each group has a typical oceanic island basalt (OIB)–like signature with plume affinities on a Zr/Y versus Nb/Y plot, primitive mantle normalized (N) $(La/Sm)_N$ >1.2 and $(Sm/Yb)_N$ >2.0, and TiO_2 contents >2.5 wt%. In terms of incompatible element contents (e.g., light rare earth elements, Ti) the Quebro and Hoya groups are distinct from other South American forearc igneous complexes, whereas the Punta Blanca group exhibits some similarities to the Tulín Formation, which represents an accreted ocean island in Costa Rica (Arias, 2003) (Figs. 3B and 3C). Hoya basalts have higher $(La/Yb)_N$ with decreasing Mg# (Fig. 3D). The Hoya group also includes hawaiite and picrite lava flows with chemical affinities similar to those of

[1]GSA Data Repository item 2011112, Table DR1 (list of samples), Table DR2 (XRF analyses), and Figures DR1–DR4, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

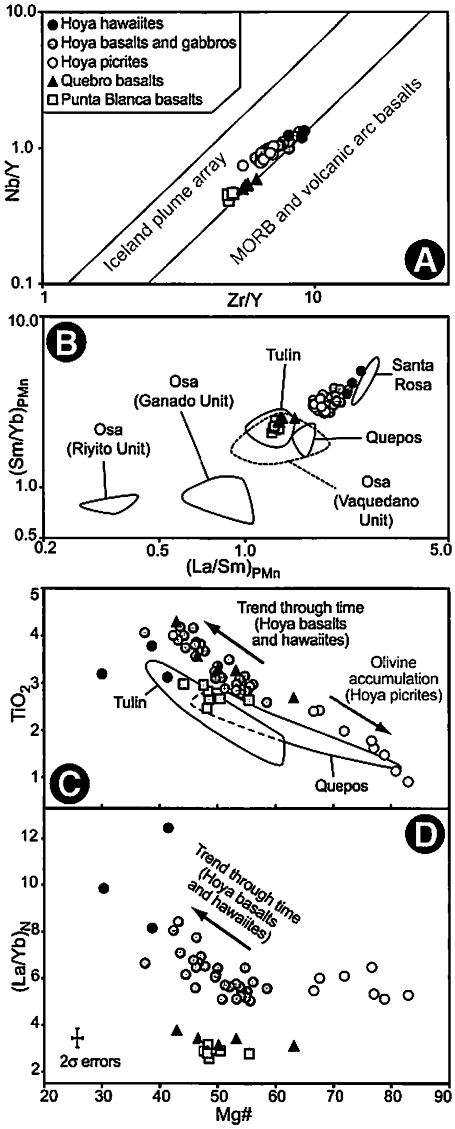

Figure 3. Geochemistry of oceanic island basalt (OIB) in Azuero Accretionary Complex. A: Zr/Y vs. Nb/Y plot (after Fitton et al., 1997). B: Primitive mantle normalized (N) $(La/Sm)_N$ vs. $(Sm/Yb)_N$ plot also showing compositions of OIB that belong to other mid-American accretionary complexes displayed in Figure 1 (data from Hauff et al., 2000; Hoernle et al., 2002; Arias, 2003; Buchs, 2008; Geldmacher et al., 2008). C: Mg# vs. TiO_2 plot. D: Mg# vs. $(La/Yb)_N$ plot.

other igneous rocks of the group (Fig. 3). The hawaiites are more enriched in highly incompatible element contents than basaltic rocks with lower Mg# and TiO_2. We interpret olivine-clinopyroxene resorption textures and Mg-rich compositions to indicate that the picrites of the Hoya group were mostly formed by olivine and clinopyroxene accumulation in a basaltic melt. Large pebbles of foid monzosyenite were found in canyons that crosscut gabbroic intrusives of the Hoya group, and probably belong to the same magmatic series of this group.

Magmatic groups are spatially well organized and their distribution correlates to lithologic arrangements (Fig. 2A). The Quebro group is a submarine volcanic sequence, whereas the Hoya and Punta Blanca groups are an assemblage of submarine, subaerial, and intrusive rocks. The more magnesian Hoya samples are generally of submarine emplacement, whereas the less magnesian lava samples (including hawaiites) were mostly erupted subaerially. Picritic lava flows of the Hoya group are locally interlayered with lavas of the Quebro group, indicating these two groups were emplaced contemporaneously.

ACCRETED OCEAN ISLANDS IN WEST PANAMA

Composition of the igneous rocks, occurrence of shallow-water carbonates devoid of terrigenous input in the volcanic sequences, and lack of thick turbiditic or pelagic sediment deposits interlayered between volcanic sequences are evidence for preservation of accreted ocean islands in the Azuero Peninsula (Hoernle et al., 2002; Hoernle and Hauff, 2007; this study). Based on our results that outline well-organized spatial distribution of lithologies at the scale of the complex and consistent compositions of igneous rocks relative to other accreted OIB in Central America, we propose that the Azuero Accretionary Complex includes two distinct ancient ocean islands. The first island is named Hoya Island, and is exposed in the area defined by occurrence of the Quebro and Hoya groups. The second island is exposed in an area defined by occurrence of the Punta Blanca group (Fig. 2).

We tentatively define four distinct kilometer-sized stacks of accreted rocks (i.e., stacks I, II, III, and IV) separated by fault zones on the basis of our lithologic mapping and field observations (Figs. 2A and 2B). Although this subdivision may be refined by further data, it is important to note that alternate interpretations of the structures would have no effect on the observed lithologic and geochemical arrangement of the complex on a map view (Fig. 2A), and therefore is independent from our ocean island definition and reconstruction of the magmatic evolution of Hoya Island (see following).

The age of formation of accreted islands can be defined based on existing $^{40}Ar/^{39}Ar$ radiometric dating of igneous rocks, and biochronologic ages from interlayered sediments and overlapping forearc sediments. Published $^{40}Ar/^{39}Ar$ ages range from 63 to 21 Ma for the Hoya group and from 66 to 33 Ma for the Punta Blanca group (Hoernle et al., 2002). We believe that some of these ages do not date the formation of the igneous rocks, because OIB ages are locally younger than Middle Eocene overlapping forearc sediments (Kolarsky et al., 1995), and are also locally inconsistent with Paleocene to early-Middle Eocene ages of interlayered shallow-water limestones (Baumgartner-Mora et al., 2008) (Figs. DR2E and DR2F). Radiometric data by Hoernle et al. (2002) show evidence for Ar loss, with segmented ^{39}Ar step-heating plateaus. Consequently, we propose that the Azuero Accretionary Complex underwent Ar loss during tectonic events, and $^{40}Ar/^{39}Ar$ ages represent minimal ages of formation of the OIB, as already suggested for some accreted OIB in Costa Rica (Buchs et al., 2009). This interpretation is in good agreement with Paleocene to early-Middle Eocene ages of formation of the ocean islands in the Azuero Peninsula, supported by stratigraphic and biochronologic data (Kolarsky et al., 1995; Baumgartner-Mora et al., 2008). Deposition of overlapping forearc sediments in the Middle Eocene and formation ages of the islands indicate that accretion occurred in the early-Middle Eocene.

STRATIGRAPHY AND VOLCANIC DEVELOPMENT OF HOYA ISLAND

Accreted stacks of Hoya Island crop out over ~900 km², dominating much of the exposed Azuero Accretionary Complex. Lithologies in stacks I to III and their spatial distributions support a stratigraphic model of the island prior to accretion broadly similar to that of Hawaiian volcanoes (Fig. 2C). Intrusives in stack III are interpreted to have been emplaced along a rift zone during formation of the island. Stack I contains interlayered hemipelagic sediments that suggest lower rates of lava deposition. We interpret this stack as part of the deepest flanks of the island, which became accreted prior to stacks II and III.

Magmatic evolution of the island can be reconstructed using correlation of Mg# of the Hoya group with stratigraphic patterns in stacks II and III, which show higher Mg# in association with older submarine lavas (Fig. 2). This approach allows definition of the secular trends shown in Figures 3C and 3D. We propose that three volcanic stages are recorded in accreted sequences of the island. The first stage is represented by submarine-subaerial tholeiitic and alkali basalts characterized by decreased Mg# and increased $(La/Yb)_N$ with time. The second stage corresponds to emplacement of subaerial hawaiite, with lower Mg# and higher $(La/Yb)_N$. A third possible volcanic stage is supported by strongly alkalic foid monzosyenite. This magmatic evolution is interpreted to result from lesser partial melting of the source, and more effective mineral segregation in rising magmas during waning of volcanism. The occurrence of two distinct geochemical groups in stack I (i.e., Quebro and Hoya groups) may denote the formation of two coalescent volcanoes in the island, and points toward a heterogeneous mantle source.

DISCUSSION AND CONCLUSIONS

Good preservation and overall exposure of Hoya Island provide a valuable opportunity to reconstruct the volcanic development of a Pacific intraplate oceanic volcano. Although detailed petrologic study of Hoya Island is beyond the aim of this paper, the magmatic evolution of the island (based on lithologic mapping and geochemical analyses) is in good agreement with that generally expected for intraplate volcanoes, with: (1) a submarine and/or subaerial shield or Hoya basalt stage with increased $(La/Yb)_N$ and reduced Mg# through time; (2) a subaerial postshield or Hoya hawaiite stage; and (3) a subaerial(?) posterosional or Hoya foid monzosyenite stage. The occurrence of this magmatic evolution in an accreted oceanic island is significant; previously, this evolutionary pattern has been documented for few oceanic islands and seamounts (e.g., Garcia et al., 2007; Konter et al., 2009). Broadly similar schemes of magmatic evolution between distinct intraplate oceanic volcanoes likely reflect the overall similarity of fundamental parameters controlling intraplate oceanic volcanism, such as overall magma flux, evolving hydrothermal circulation during volcanic growth, and lithospheric cooling during magmatic waning (Clague and Dixon, 2000; Staudigel and Clague, 2010). These remain to be studied in detail among a larger population of volcanoes.

Our study shows that a combination of lithologic observations and geochemical analysis permits reconstruction of the development of some accreted ocean islands. Numerous accretionary complexes are exposed in the world, and it is anticipated the study of more of these complexes will offer a new mode of exploration of intraplate oceanic volcanism.

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