Fracturing of the Panamanian Isthmus during initial collision with South America

David W. Farris, Carlos Jaramillo, German Bayona, Sergio A. Restrepo-Moreno, Camilo Montes, Agustin Cardona, Andres Mora, Robert J. Speakman, Michael D. Glascock and Victor Valencia

Geology published online 4 October 2011; doi: 10.1130/G32237.1

Advance online articles have been peer reviewed and accepted for publication but have not yet appeared in the paper journal (edited, typeset versions may be posted when available prior to final publication). Advance online articles are citable and establish publication priority; they are indexed by GeoRef from initial publication. Citations to Advance online articles must include the digital object identifier (DOIs) and date of initial publication.

© Geological Society of America
Fracturing of the Panamanian Isthmus during initial collision with South America

David W. Farris1, Carlos Jaramillo2, German Bayona2,3, Sergio A. Restrepo-Moreno2,4, Camilo Montes2,3, Agustín Cardona2,3, Andres Mora5, Robert J. Speakman6, Michael D. Glascock7, and Victor Valencia8

1Florida State University, Department of Earth, Ocean, and Atmospheric Sciences, Tallahassee, Florida 32306, USA
2Smithsonian Tropical Research Institute, Unit 0948, APO AA 34002-0948, USA
3Corporación Geológica ARES, Calle 44A N. 53-96 Bogotá, Colombia
4University of Florida, Department of Geological Sciences, Gainesville, Florida 32611, USA
5Instituto Colombiano del Petroleo, Ecopetrol, Bucaramanga, Colombia
6Smithsonian Institution, Museum Conservation Institute, Washington, D.C. 20012, USA
7University of Missouri, Archaeometry Laboratory, Columbia, Missouri 65211, USA
8University of Arizona, Department of Geosciences, Tucson, Arizona 85721, USA

ABSTRACT

Tectonic collision between South America and Panama began at 23–25 Ma. The collision is significant because it ultimately led to development of the Panamanian Isthmus, which in turn had wide-ranging oceanic, climatic, biologic, and tectonic implications. Within the Panama Canal Zone, volcanic activity transitioned from hydrous mantle–wedge–derived arc magmatism to localized extensional arc magmatism at 24 Ma, and overall marks a permanent change in arc evolution. We interpret the arc geochemical change to result from fracturing of the Panama block during initial collision with South America. Fracturing of the Panama block led to localized crustal extension, normal faulting, sedimentary basin formation, and extensional magmatism in the Canal Basin and Bocas del Toro. Synchronous with this change, both Panama and inboard South America experienced a broad episode of exhumation indicated by (U-Th)/He and fission-track thermochronology coupled with changing geographic patterns of sedimentary deposition in the Colombian Eastern Cordillera and Llanos Basin. Such observations allow for construction of a new tectonic model of the South America–Panama collision, northern Andes uplift and Panama orocline formation. Finally, synchrony of Panama arc chemical changes and linked uplift indicates that onset of collision and Isthmus formation began earlier than commonly assumed.

INTRODUCTION

The Isthmus of Panama fully separated the Caribbean Sea and Pacific Ocean by 3–3.5 Ma (Keigwin, 1978; O’Dea et al., 2007) and is inferred to result from collision between South America and the Panama block (Trenkamp et al., 2002; Coates et al., 2004) (Fig. 1). However, this closure date is based on evolutionary divergence of marine organisms and therefore must be a minimum age. Other evidence on when Isthmus formation began comes from shallow-sequences in Panamanian and Colombian bathyal sedimentary basins at 14.8–12.8 Ma (Dague-Caro, 1990; Coates et al., 2004) and folded and thrustsed Upper Miocene strata in eastern Panama (Mann and Kolarsky, 1995). These observations document that significant contraction in eastern Panama occurred since the Middle Miocene, but do not put a firm limit on when or how the collision between South America and the Panama block initiated. We suggest that collision initiated at 23–25 Ma when South America first impinged upon Panama arc crust as observed by distinct Panama arc chemical changes, broad exhumation of the northern Andes and Panama, and extensive foreland deposition in the distal Llanos Basin of Colombia (Fig. 1).
Canal Zone rocks also show the 24 Ma transition on the V versus Ti tectonic discrimination diagram of Shervais (1982) (Fig. 2D). Bas Obispo Formation rocks plot within the arc tholeiite field, whereas younger Pedro Miguel Formation rocks fall within the backarc basin field. Las Cascadas Formation rocks are too silicic, and thus are not plotted. The V versus Ti diagram is sensitive to changes in source oxygen fugacity, and coupled with the decrease in Ba/Yb and loss of hydrous minerals suggests a significant drying out of the mantle source after 25 Ma.

Canal Zone volcanic units are interbedded within well-dated Canal Basin sedimentary rocks. Sr isotope dating places the depositional contact of the terrestrial volcanic Las Cascadas Formation and the overlying marine sedimentary Culebra Formation at 23 Ma (Kirby et al., 2008). Rooney et al. (2010) reported an Ar/Ar age of Bas Obispo Formation equivalents (Cerro Patacon) to be 25.37 ± 0.13 Ma. Geochemical data (Ta/Yb ratios >0.1) indicate that the Las Cascadas Formation is the first younger arc unit within the Canal Zone and so the transition is constrained to 25–23 Ma.

Canal Zone arc chemistry change also coincides with formation of the Canal Basin. The basin is shallow and oriented perpendicular to the axis of the Isthmus. It is important because it preserves unique Miocene terrestrial and marine fossil assemblages (Kirby et al., 2008). Both sedimentary and volcanic units within the basin are cut by a pervasive orthorhombic fault set. In general, earlier faults have normal movement and are cut by later strike-slip faults related or synthetic to the active right-lateral Pedro Miguel fault (Rockwell et al., 2010). The largest normal faults are parallel to the Canal Basin axis and have drill core–constrained vertical offsets of >100 m on individual faults (Lutton and Banks, 1970).

Another volcanic sequence of note is from Bocas del Toro (Fig. 1A). This group shares geochemical characteristics of Canal Zone rocks with moderate enrichment in compatible elements such as HREEs and Ti; however, they are distinct with strongly enriched LILEs and shoshonitic, with >4 wt% K2O at 52 wt% SiO2. In terms of rock type, they consist of glassy basaltic to andesitic lava flows interbedded with marine sandstones cut by normal faults and range in age from 12 to 8 Ma (Coates et al., 2003). This group also plots within an extensional tectonic environment (Fig. 2D).

**EXHUMATION AND CHANGING DEPOSITIONAL PATTERNS**

Exhumation and changing depositional patterns in the northern Andes and Panama are synchronous with geochemical changes in the Panama arc. Apatite-zircon (U-Th)/He and fission-track thermochronology collected from the Colombian northern Andes and Panama indicate a broad exhumation pulse at 22–28 Ma, with most data near 25 Ma (Fig. 3). Onset and intensity of this event was derived from vertical sample profiles collected through igneous suites in Panama (Mamoni and Petaquilla),...
western flanks (Gomez et al., 2005; Parra et al., 2009). Also at this time, the Llanos Basin propagated over 200 km to the east, reflecting onset of Eastern Cordillera deformation (Bayona et al., 2008; Parra et al., 2009) (Fig. 4).

**DISCUSSION**

Overall, our goal is to link geochemical changes in the Panama arc with synchronous exhumation in Panama and the northern Andes using a tectonic model that explains both. Unit-based observations indicate that at 23–25 Ma the Panama arc experienced permanent geochemical change. Two related events occur at this time: (1) progressive mantle enrichment (e.g., La/Yb, Ta/Yb) that affects all younger arc rocks, and (2) localized extensional arc magmatism. A linear regression fit ($R^2 = 0.92$) through the younger arc rocks suggests an enriched mantle source mixed into the subarc environment beginning at 25 Ma.

The enrichment event is compatible with the Wegner et al. (2011) division of arc activity into a depleted Late Cretaceous through Eocene initial arc, an Oligocene Iull, and an enriched Miocene arc. However, Canal Zone observations sharply delineate the boundary between the initial and Miocene arc episodes and show that magmatism continues throughout the Oligocene, although at a lower volumetric level. Throughout the Iull, arc magmatism retains a strong subduction signal and geochemical characteristics similar to the earlier magmatic peak.

One significant difference between the arc chemistry presented here and that of previous workers is the identification of localized extensional magmatism in the Canal Zone and Bocas del Toro. Within the Canal Zone, this interpretation is supported by sharp decreases in fluid-mobile elements, tectonic discrimination diagrams, and flattened REE curves. Onset of extensional Canal Zone volcanism is also associated with extensive normal faulting and basin formation. Our preferred model is extension-induced decompression melting of the subarc asthenosphere, in which high degrees of shallow partial melting caused fluid and LILE depletion in Canal Zone rocks. Strong LILE enrichments with similar Yb concentrations at Bocas del Toro are explainable by low degrees of decompression melting in compositionally similar asthenosphere (Fig. 2). Similar variations within extensional arcs have been observed in the northern Marianas (Lin et al., 1989).

The standard interpretation of extensional arc magmatism is trench rollback–coupled backarc extension and trenchward arc migration (Ewart et al., 1998). However, in the Panama arc we propose an alternative interpretation. First, a transition to backarc magmatism would create a continuous belt of extensional volcanism parallel to the arc. In contrast, extensional magmatism is observed only in the Canal Zone and Bocas del Toro. Second, dominant normal faults within the Canal Zone are perpendicular to the arc, whereas backarc faulting should be arc-parallel. Third, Canal Basin formation is synchronous with the onset of extensional arc magmatism at 24 Ma, and is also arc-perpendicular. Thus, our interpretation is that the Panama block underwent localized arc-perpendicular extension. One mechanism is that during Panama orocline formation (Silver et al., 1990) the Isthmus fractured. Basic geometric reconstructions (Fig. 1B) of the Panama orocline can be accomplished with two localized zones of extension (Canal Zone and Bocas del Toro) and one zone of contraction (Darien Ranges). This method can accommodate crustal-scale bending by brittle processes and is potentially widespread in the geologic record as the accretion of ribbon continents is an important mechanism of crustal growth (Johnston, 2001).

The opposed geometry of the two extensional zones can explain age/chemical variations in that Bocas del Toro is in an extensional zone “tip” whereas the Canal Zone is in a “mouth.” Volcanism at an extensional zone tip should be younger and result from less mantle melting, with which observations are consistent.

Exhumation in Panama and the northern Andes is synchronous with onset of Canal Zone extensional magmatism shortly after 25 Ma. Our preferred explanation is the onset of collision between South America and Panama arc crust. Collision with South America is the dominant explanation for the Panama orocline formation (Silver et al., 1990) and can also explain the localized zones of extension within the Panama arc. Other influences for exhumation and arc change include a 25–30 Ma westward increase in South American plate motion (no-net-torque reference frame; Silver et al., 1998) and/or the 23 Ma fissioning of the Farallon plate (Lonsdale, 2005). The motion of South America is almost certainly the driver of broad Andean tectonic trends, and the 23 Ma exhumation event is observed throughout western South America (Mora, 2010). However, inboard of Panama, the Central/Western Cordilleras are deflected northward, and the width of the Colombian orogenic belt is almost twice that farther south in Ecuador, suggesting a causative
relationship. Overall, our preferred interpretation is that South America surged westward at the end of the Oligocene and collided with Panama arc crust. Due to arc crust subductability, the Panama block detached from the Caribbean plate and was thrust over it, leading to the formation of the North Panama deformed belt. The North Panama deformed belt and Llanos Basin form opposite verging fold-and-thrust belts occurring ~500 km on either side of the Panama–South America suture (the Atrato fault; Trenkamp et al., 2002) (Fig. 4). Between the bivergent thrust belts, heterogeneous basement blocks exhibit near-synchronous extension at 23–25 Ma, suggestive of a regional detachment at depth. Bivergent orogenic float (Oldow et al., 1990) could produce such widespread exhumation. Finally, we propose that the semirigid beam of Panama arc crust fractured and underwent rotation in response to collision with South America, leading to the observed zones of extensional magmatism.

ACKNOWLEDGMENTS

This contribution to the Panama Canal Project (CP) was supported by National Science Foundation (NSF) PIRE grant DEB-0733725, the Smithsonian Institution, the Panama Canal Authority, Mr. Mark Coates, A.G., Collins, L.S., Aubry, M.P., and Berggren, W.A., 2004, The geology of the Darien, Panama, and the late Miocene–Pliocene evolution of the Panama arc with northwestern South America: Geological Society of America Bulletin, v. 116, p. 1327–1344, doi: 10.1130/B25275.1.


Received manuscript revised 8 March 2011
Revised manuscript received 19 May 2011
Manuscript accepted 24 May 2011
Printed in USA

Geology, published online on 4 October 2011 as doi:10.1130/G32237.1