Fracturing of the Panamanian Isthmus during initial collision with South America

David W. Farris[1], Carlos Jaramillo[2], German Bayona[2,3], Sergio A. Restrepo-Moreno[2,4], Camilo Montes[2,3], Agustin Cardona[2,3], Andres Mora[5], Robert J. Speakman[6], Michael D. Glascock[7], and Victor Valencia[8]
[1]Florida State University, Department of Earth, Ocean, and Atmospheric Sciences, Tallahassee, Florida 32306, USA
[2]Smithsonian Tropical Research Institute, Unit 0948, APO AA 34002-0948, USA
[3]Corporación Geológica ARES, Calle 44A N. 53-96 Bogotá, Colombia
[4]University of Florida, Department of Geological Sciences, Gainesville, Florida 32611, USA
[5]Instituto Colombiano del Petroleo, Ecopetrol, Bucaramanga, Colombia
[6]Smithsonian Institution, Museum Conservation Institute, Washington, D.C. 20012, USA
[7]University of Missouri, Archaeometry Laboratory, Columbia, Missouri 65211, USA
[8]University 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, synchroneity 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 shallowing sequences in Panamanian and Colombian bathyal sedimentary basins at 14.8–12.8 Ma (Duque-Caro, 1990; Coates et al., 2004) and folded and thrusted 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).

PANAMA ARC EVOLUTION WITHIN THE CANAL ZONE

The Panama arc formed on the trailing edge of the Caribbean plate at ca. 75–65 Ma (Buchs et al., 2010). Wörner et al. (2009) and Wegner et al. (2011) divide arc activity into a depleted Late Cretaceous–Eocene initial episode and an enriched Miocene arc. Modern magmatism exists only west of the Canal Zone and consists of a <2–3 Ma adakitic suite attributed variously to slab melting (Defant et al., 1992), a slab window (Abratis and Wörner, 2001; Wegner et al., 2011), or subduction erosion (Goss and Kay, 2006).

We report that depleted-type volcanic and plutonic rocks persist until 25 Ma within the central Panama Canal Zone. Older arc rocks are heterogeneous and consist of plutonic and extrusive rocks that range from calc-alkaline to tholeiitic and basaltic to andesitic in composition. These rocks are dominantly hornblende-bearing (Rooney et al., 2010), have a large Ta anomaly, exhibit relative enrichment in fluid-mobile large ion lithophile elements (LILEs) (e.g., Cs, Rb, Ba), and have moderate heavy rare earth element (HREE) concentrations (Fig. 2A; Table DR1 in the GSA Data Repository[1]). Such characteristics are indicative of hydrous mantle-wedge–derived subduction zone magmas (Pearce and Peate, 1995).

Within the Canal Zone, volcanic rocks younger than 24 Ma range from basalt to dacite in composition, but are significantly less hydrous and exclusively tholeiitic. Rock types within the younger group are bimodal with individual units dominated by either silicic tuffs and welded units (Las Cascadas Formation) or basalt to basaltic-andesite lava flows and intrusive sills (Pedro Miguel Formation). Hornblende and other hydrous minerals are absent. In comparison with earlier arc rocks (Bas Obispo Formation and older), Miocene Canal Zone volcanism exhibits low LILEs, higher HREEs and Ti, and a significantly decreased Ta anomaly (Fig. 2A).

Trace element ratios are tracers of volcanic-rock tectonic and mantle environments, and Yb normalization allows one to see through fractionation processes (Pearce and Peate, 1995; Wegner et al., 2011). Welch two-sample t-tests indicate that arc groups identified in Figure 2 have unique element ratio sets, suggesting that the mantle environment changed over time (Table DR2). In the Panama arc, ratios such as La/Yb, Th/Yb, Hf/Yb, and Ta/Yb exhibit an increase and change in slope at 24 Ma (Fig. 2B), with Ta/Yb being the single best discriminator of this change. In rocks younger than 24 Ma, the Ta/Yb ratio is >0.1. Ba/Yb is also effective at discriminating between rocks younger than 24 Ma in the Canal Zone, with younger rocks showing a distinct depletion (Fig. 2C). Conversely, Miocene arc rocks elsewhere in Panama show a progressive increase in Ba/Yb and fluid-mobile elements in general.

---

[1] GSA Data Repository item 2011297, a description of geochemical (INAA and XRF) and geochronologic (U-Th/He) methods, a statistical analysis of the geochemical data, and data tables of the low-temperature thermochronology presented in the paper, 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.

Geology, November 2011; v. 39; no. 11; p. 1007–1010; doi:10.1130/G32237.1; 4 figures; Data Repository item 2011297.

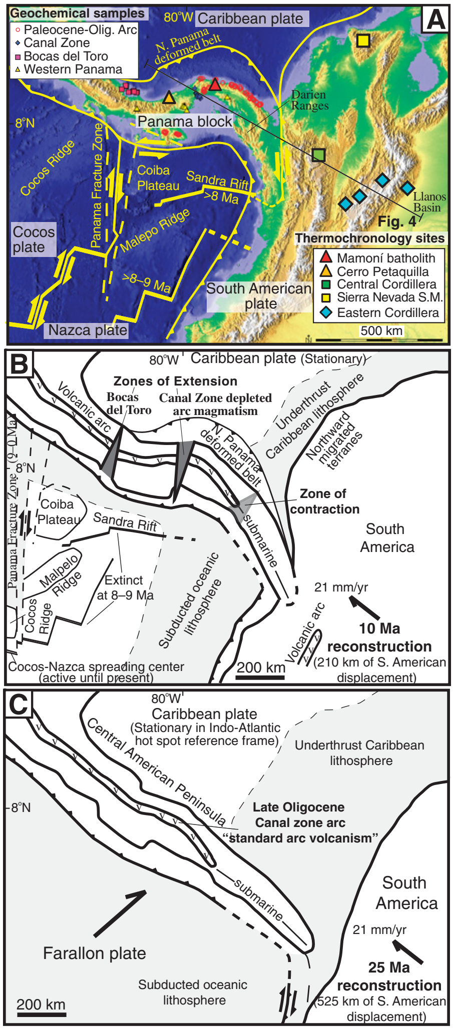

Figure 1. A: Modern tectonic map with location of geochemical samples and low-temperature thermochronology profile sites. S.M.—Santa Marta. B: Tectonic reconstruction at 10 Ma. This is an intermediate step in the collision between South America and Panama. The Panama block has fractured, resulting in two zones of extension (Canal Zone and Bocas del Toro) and one zone of contraction in eastern Panama. Also, the North Panama deformed belt has partially formed and a seaway >200 km wide separates Panama and South America. C: Tectonic reconstruction at 25 Ma. This immediately precedes collision between Panama arc crust and South America. Previously, unmodified Caribbean crust was underthrust beneath South America.

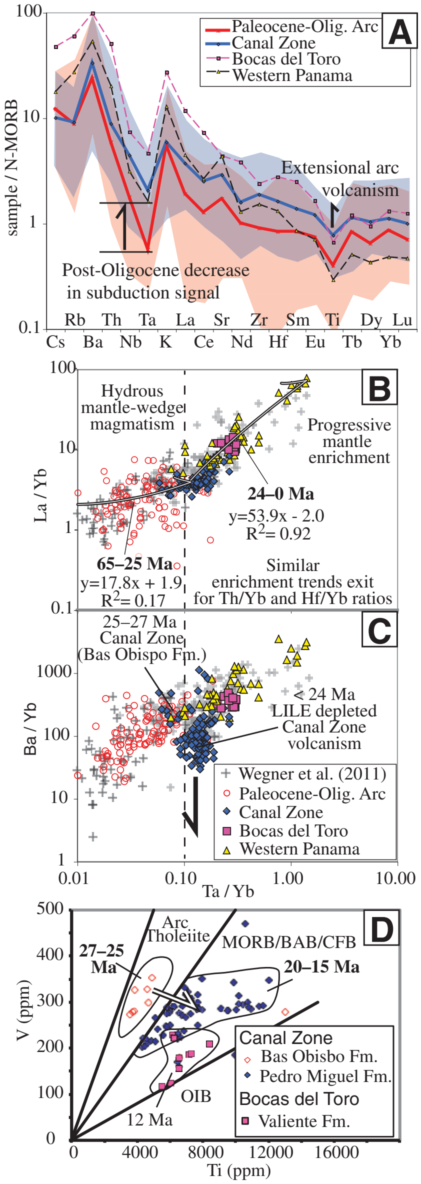

Figure 2. Instrumental neutron activation analysis (INAA) trace element geochemistry from the Panama arc (see Table DR1). A: Averaged trace element geochemistry from different temporal and spatial groups of Panama arc rocks. Shaded red/blue fields indicate the full data range for early arc and Canal Zone, respectively. N-MORB—normal mid-oceanic-ridge basalt. B: La/Yb versus Ta/Yb with individual samples plotted. Regressions through the early and youngest arc groups intersect at Ta/Yb = 0.1. In Canal Zone rocks, this boundary is crossed at 23–25 Ma and corresponds to a permanent change in arc chemistry. C: Ba/Yb versus Ta/Yb with individual samples. Canal Zone volcanic rocks have sharply lower Ba/Yb ratios indicative of general large ion lithophile element (LILE) depletion. D: Shervais (1982) tectonic discrimination diagram. Canal Zone volcanic formations (Fm.) transition from arc tholeiites to extensional products after 25 Ma. Rocks from Bocas del Toro also plot in the extensional field. MORB—mid-oceanic-ridge basalt; BAB—backarc basin; CFB—continental flood basalt.

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% K_2O at 52 wt% SiO_2. In terms of rock type, they consist of glassy basaltic to andesitic blocky 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),

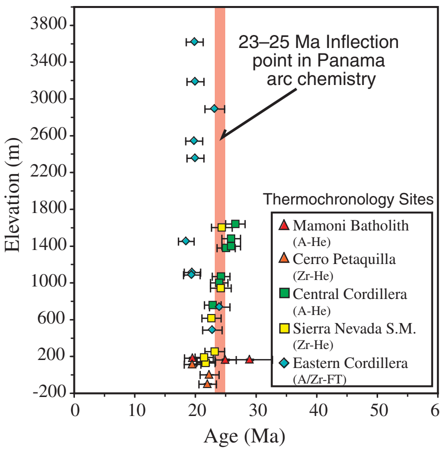

Figure 3. Low-temperature thermochronology from Panama and inboard South America (see Tables DR3 and DR4 [see footnote 1]). Ages shown are (U-Th)/He and fission-track dates from apatite and zircon sampled on vertical profiles through igneous intrusive suites. S.M.—Santa Marta. Cooling ages coincide with the Panama arc chemistry inflection point at 23–25 Ma.

the Colombian Central Cordillera (Restrepo-Moreno et al., 2009), and the Sierra Nevada de Santa Marta (Cardona et al., 2011), and from sedimentary sequences in Colombia's Eastern Cordillera (Mora et al., 2010). Igneous suite crystallization ages vary, but all are Eocene and older except for Petaquilla in Panama (Early Oligocene; Kesler et al., 1977). Different locations experienced varying subsequent levels of exhumation, and so the 25 Ma event is manifested by different thermochronometers at different locations. Cooling during this episode translates to exhumation rates of 0.6–0.8 km/m.y. (Fig. 3). This exhumation pulse correlates with the arc geochemical change in Panama and the onset of localized extensional magmatism.

Also indicative of Andean orogenesis at this time are changing patterns of erosion and deposition inboard of the Panama block. In the Eastern Cordillera, Middle Eocene continental deposition covered broad areas. By Late Oligocene, the Eastern Cordillera underwent exhumation and erosion (Mora et al., 2010) coupled with synorogenic deposition on its eastern and 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 lull, 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 lull, 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 (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

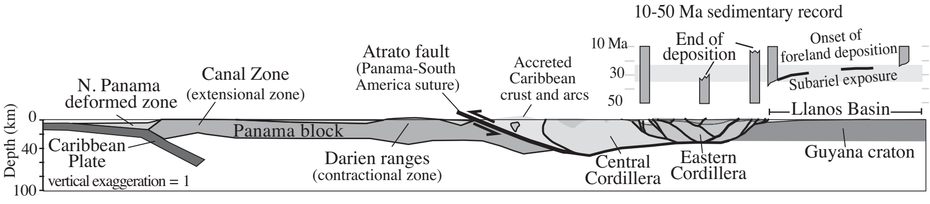

Figure 4. Modern cross section through Panama and South America. Location is shown in Figure 1A. Gray bars indicate sedimentary depositional history. Panama and the northern Andes form a bivergent orogen, with the N. Panama deformed belt and Llanos Basin forming opposing thrust belts. Exhumation and eastward Llanos Basin propagation is synchronous with Panama arc geochemical change and is interpreted to result from accretion of Panama arc crust to South America at 23–25 Ma.

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 unsubductability, 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 exhumation 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 (PCP) was supported by National Science Foundation (NSF) PIRE grant 0966884 (OISE, EAR, DRL). Funding also came from NSF grant DEB-0733725, the Smithsonian Institution, the Panama Canal Authority, Mr. Mark Tupper, the National Geographic, SENACYT, and Ricardo Perez SA. Thanks go to the Panama Canal Authority, Ministerio de Industria y Comercio, Odebretch, and to the Kuna Congress and Nation for access and logistical help.

REFERENCES CITED

Abratis, M., and Wörner, G., 2001, Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm: Geology, v. 29, p. 127–130, doi: 10.1130/0091-7613(2001)029<0127:RCSWFA>2.0.CO;2.

Bayona, C., Cortes, M., Jaramillo, C., Ojeda, G., Aristizabal, J.J., and Reyes, A., 2008, An integrated analysis of an orogen–sedimentary basin pair: Latest Cretaceous–Cenozoic evolution of the linked Eastern Cordillera orogen and the Llanos foreland basin of Colombia: Geological Society of America Bulletin, v. 120, p. 1171–1197, doi: 10.1130/B26187.1.

Buchs, D.M., Arculus, R., Baumgartner, P.O., Baumgartner-Mora, C., and 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, 2010: Geochemistry, Geophysics, Geosystems, v. 11, Q07S24.

Cardona, A., Valencia, V., Weber, M., Dique, J., Montes, C., Ojeda, G., Reiners, P., Domaniz, K., and Villagomez, D., 2011, Transient Cenozoic tectonic stages in the southern margin of the Caribbean plate: U-Th/He thermochronological constraints from Eocene plutonic rocks in the Santa Marta Massif and Serranía de Jarara, northern Colombia: Geologica Acta (in press).

Coates, A.G., Aubry, M.-P., Berggren, W.A., and Collins, L.S., 2003, Early Neogene history of the Central American arc from Bocas del Toro, western Panama: Geological Society of America Bulletin, v. 115, p. 271–287, doi: 10.1130/0016-7606(2003)115<0271:ENHOTC>2.0.CO;2.

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 collision of the Panama arc with northwestern South America: Geological Society of America Bulletin, v. 116, p. 1327–1344, doi: 10.1130/B25275.1.

Defant, M.J., Jackson, T.E., Drummond, M.S., de Boer, J.Z., Bellon, H., Feigenson, M.D., Maury, R.C., and Stewart, R.H., 1992, The geochemistry of young volcanism throughout western Panama and southeastern Costa Rica: An overview: The Geological Society of London Journal, v. 149, p. 569–579, doi: 10.1144/gsjgs.149.4.0569.

Duque-Caro, H., 1990, Neogene stratigraphy, paleoceanography and paleobiogeography in northwest South America and the evolution of the Panama Seaway: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 77, p. 203–234, doi: 10.1016/0031-0182(90)90178-A.

Ewart, A., Collerson, K.D., Regelous, J.I., Wendt, J.I., and Niu, Y., 1998, Geochemical evolution within the Tonga-Kermadec-Lau arc-back-arc systems: The role of varying mantle wedge composition in space and time: Journal of Petrology, v. 39, p. 331–368, doi: 10.1093/petrology/39.3.331.

Gomez, E., Jordan, T.E., Allmendinger, R.W., and Cardozo, N., 2005, Development of the Colombian foreland-basin system as a consequence of diachronous exhumation of the northern Andes: Geological Society of America Bulletin, v. 117, p. 1272–1292, doi: 10.1130/B25456.1.

Goss, A.R., and Kay, S.M., 2006, Steep REE patterns and enriched Pb isotopes in southern Central American arc magmas: Evidence for forearc subduction erosion?: Geochemistry, Geophysics, Geosystems, v. 7, Q05016, 20 p.

Johnston, S.T., 2001, The Great Alaskan Terrane Wreck: Reconciliation of paleomagnetic and geologic data in the northern Cordillera: Earth and Planetary Science Letters, v. 193, p. 259–272, doi: 10.1016/S0012-821X(01)00516-7.

Keigwin, L.D., 1978, Pliocene closing of the Isthmus of Panama, based on biostratigraphic evidence from nearby Pacific Ocean and Caribbean Sea cores: Geology, v. 6, p. 630–634, doi: 10.1130/0091-7613(1978)6<630:PCOTIO>2.0.CO;2.

Kesler, S.E., Sutter, J.F., Issigonis, M.J., Jones, L.M., and Walker, R.L., 1977, Evolution of porphyry copper mineralization in an oceanic island arc, Panama: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 72, p. 1142–1153, doi: 10.2113/gsecongeo.72.6.1142.

Kirby, M.X., Jones, D.S., and MacFadden, B.J., 2008, Lower Miocene stratigraphy along the Panama Canal and its bearing on the Central American Peninsula: PLoS ONE, v. 3, no. 7, p. e2791, doi: 10.1371/journal.pone.0002791.

Lin, P.-N., Stern, R.J., and Bloomer, S.H., 1989, Shoshonitic volcanism in the northern Mariana arc: Journal of Geophysical Research, v. 94, no. B4, p. 4497–4514, doi: 10.1029/JB094iB04p04497.

Lonsdale, P., 2005, Creation of the Cocos and Nazca plates by fission of the Farallon plate: Tectonophysics, v. 404, p. 237–264, doi: 10.1016/j.tecto.2005.05.011.

Lutton, R.J., and Banks, D.C., 1970, Study of clay shale slopes along the Panama Canal, Report 1: U.S. Army Engineer Waterways Experiment Station Technical Report S-70-9, 326 p.

Mann, P., and Kolarsky, R.A., 1995, East Panama deformed belt: Structure, age, and neotectonic significance, *in* Mann, P., ed., Geologic and tectonic development of the Caribbean plate boundary in southern Central America: Geological Society of America Special Paper 295, p. 111–130.

Mora, A., 2010, Tectonic history of the Andes and sub-Andean zones: Implications for the development of the Amazon drainage basin, *in* Hoorn, C., and Wesselingh, F.P., eds., Amazonia, landscape and species evolution: A look into the past: Blackwell Publishing, p. 38–60.

Mora, A., Horton, B., Mesa, A., Rubiano, J., Ketchman, R., Parra, M., Blanco, V., García, D., and Stockli, D., 2010, Migration of Cenozoic deformation in the Eastern Cordillera of Colombia interpreted from fission track results and structural relationships: Implications for petroleum systems: American Association of Petroleum Geologists Bulletin, v. 94, p. 1543–1580, doi: 10.1306/01051009111.

O'Dea, A., Jackson, J.B.C., Fortunato, H., Smith, J.T., D'Croz, L., Johnson, K.G., and Todd, J.A., 2007, Environmental change preceded Caribbean extinction by 2 million years: Proceedings of the National Academy of Sciences of the United States of America, v. 104, no. 13, p. 5501–5506, doi: 10.1073/pnas.0610947104.

Oldow, J.S., Bally, A.W., and Ave Lallemant, H.G., 1990, Transpression, orogenic float, and lithospheric balance: Geology, v. 18, p. 991–994, doi: 10.1130/0091-7613(1990)018<0991:TOFALB>2.3.CO;2.

Parra, M., Mora, A., Jaramillo, C., Strecker, M.R., Sobel, E.R., Quiroz, L., Rueda, M., and Torres, V., 2009, Orogenic wedge advance in the northern Andes: Evidence from the Oligo-Miocene sedimentary record of the Medina Basin, Eastern Cordillera, Colombia: Geological Society of America Bulletin, v. 121, p. 780–800, doi: 10.1130/B26257.1.

Pearce, J.A., and Peate, D.W., 1995, Tectonic implications of the composition of volcanic arc magmas: Annual Review of Earth and Planetary Sciences, v. 23, p. 251–285, doi: 10.1146/annurev.ea.23.050195.001343.

Restrepo-Moreno, S.A., Foster, D.A., Stockli, D.F., and Parra-Sanchez, L.N., 2009, Long-term erosion and exhumation of the Altiplano Antioqueño, northern Andes (Colombia) from apatite (U-Th)/He thermochronology: Earth and Planetary Science Letters, v. 278, p. 1–12.

Rockwell, T.K., Bennett, R.A., Gath, E., and Franceschi, P., 2010, Unhinging an indenter: A new tectonic model for the internal deformation of Panama: Tectonics, v. 29, TC4027, doi: 10.1029/2009TC002571.

Rooney, T.O., Franceschi, P., and Hall, C.M., 2010, Water-saturated magmas in the Panama Canal region: A precursor to adakite-like magma generation?: Contributions to Mineralogy and Petrology, v. 161, p. 373–388, doi: 10.1007/s00410-010-0537-8.

Shervais, J.W., 1982, Ti-V plots and the petrogenesis of modern and ophiolitic lavas: Earth and Planetary Science Letters, v. 59, p. 101–118, doi: 10.1016/0012-821X(82)90120-0.

Silver, E.A., Reed, D.L., Tagudin, J.E., and Heil, D.J., 1990, Implications of the north and south Panama thrust belts for the origin of the Panama orocline: Tectonics, v. 9, p. 261–281, doi: 10.1029/TC009i002p00261.

Silver, P.G., Russo, R.M., and Lithgow-Bertelloni, C., 1998, Coupling of South American and African plate motion and plate deformation: Science, v. 279, p. 60–63, doi: 10.1126/science.279.5347.60.

Trenkamp, R., Kelloggg, J.N., Freymueller, J.T., and Mora, H.P., 2002, Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations: Journal of South American Earth Sciences, v. 15, p. 157–171, doi: 10.1016/S0895-9811(02)00018-4.

Wegner, W., Wörner, G., Harmon, S.H., and Jicha, B.R., 2011, Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times: Geological Society of America Bulletin, v. 123, p. 703–724, doi: 10.1130/B30109.1.

Wörner, G., Harmon, R.S., and Wegner, W., 2009, Geochemical evolution of igneous rock and changing magma sources during the evolution and closure of the Central American Landbridge, *in* Mahlburg Kay, S., and Ramos, V., eds., Backbone of the Americas: Geological Society of America Memoirs, v. 204, p. 183–196.

Manuscript received 8 March 2011
Revised manuscript received 19 May 2011
Manuscript accepted 24 May 2011

Printed in USA