AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL073981

Key Points:

- The flat slab beneath Colombia originally extended much farther south than it does today
- Volcanic ages suggest that flattening began at ~9 Ma, with full arc cessation by ~6 Ma
- Modern arc in the south was reestablished after 4 Ma during slab tearing and resteepening

Supporting Information:

- Table S1
- Supporting Information S1

Correspondence to:
L. S. Wagner,
lwagner@carnegiescience.edu

Citation:
Wagner, L. S., J. S. Jaramillo, L. F. Ramírez-Hoyos, G. Monsalve, A. Cardona, and T. W. Becker (2017), Transient slab flattening beneath Colombia, *Geophys. Res. Lett.*, *44*, 6616–6623, doi:10.1002/2017GL073981.

Received 26 APR 2017
Accepted 9 JUN 2017
Accepted article online 14 JUN 2017
Published online 3 JUL 2017

Transient slab flattening beneath Colombia

L. S. Wagner[1], J. S. Jaramillo[2], L. F. Ramírez-Hoyos[2], G. Monsalve[2], A. Cardona[3], and T. W. Becker[4]

[1]Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington, District of Columbia, USA, [2]Departamento de Geociencias y Medio Ambiente, Universidad Nacional de Colombia, Medellin, Colombia, [3]Departamento de Procesos y Energía, Universidad Nacional de Colombia, Medellin, Colombia, [4]Institute for Geophysics and Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA

Abstract Subduction of the Nazca and Caribbean Plates beneath northwestern Colombia is seen in two distinct Wadati Benioff Zones, one associated with a flat slab to the north and one associated with normal subduction south of 5.5°N. The normal subduction region is characterized by an active arc, whereas the flat slab region has no known Holocene volcanism. We analyze volcanic patterns over the past 14 Ma to show that in the mid-Miocene a continuous arc extended up to 7°N, indicating normal subduction of the Nazca Plate all along Colombia's Pacific margin. However, by ~6 Ma, we find a complete cessation of this arc north of 3°N, indicating the presence of a far more laterally extensive flat slab than at present. Volcanism did not resume between 3°N and 6°N until after 4 Ma, consistent with lateral tearing and resteepening of the southern portion of the Colombian flat slab at that time.

1. Introduction

The mid-Miocene to recent history of the northwestern Andes begins with the collision of Panama and associated terranes and the closing of the Central American Seaway [*Duque-Caro*, 1990a, 1990b; *Coates et al.*, 2003, 2004; *Farris et al.*, 2011; *Montes et al.*, 2012a, 2012b, 2015]. This process included the accretion of the westernmost terranes of northwestern Colombia, also known as the Panama-Choco block (Figure 1), and the establishment of subduction of the Nazca Plate west of these newly accreted terranes. The precise location of the suture between the terranes and the NW margin of South America at that time is somewhat inconsistently represented in the literature [e.g., *Cediel et al.*, 2003], but mapping studies such as *Restrepo and Toussaint* [1988] place this margin along the Dabeiba-Pueblo Rico Fault Zone, also known as the Uramita Fault Zone by the stratigraphic studies discussed by *Duque-Caro* [1990a, 1990b], or the Atrato-Uraba Fault Zone [e.g., *Trenkamp et al.*, 2002]. The timing of this accretion is controversial, but the collision may have been underway as early as the early Miocene [*Farris et al.*, 2011] and may have been completed along the northernmost margin as early as 14 Ma [e.g., *Montes et al.*, 2012a, 2012b, 2015]. This is similar to the 12.9–11.8 Ma docking age of the Choco block onto the NW South American Margin proposed by *Duque-Caro* [1990a, 1990b] based on biostratigraphic data. For this study, we focus primarily on the Pacific margin of Colombia, making the age of the accretion of the Choco block and the establishment of Nazca Plate subduction beneath Colombia more significant than the precise age of the final closure of the Central American Seaway.

Our understanding of the evolution of Colombian plate boundaries is limited by uncertainty about the modern geometry of the subducted slabs, and vice versa. There is considerable debate on the geometries of the downgoing Nazca and Caribbean Plates [e.g., *van der Hilst and Mann*, 1994; *Taboada et al.*, 2000; *Corredor*, 2003; *Cortés and Angelier*, 2005; *Zarifi et al.*, 2007; *Vargas and Mann*, 2013; *Bernal-Olaya et al.*, 2015a, 2015b, 2015c; *Syracuse et al.*, 2016; *Chiarabba et al.*, 2016]. The best evidence for the presence of slab material at depth comes from the locations of two distinct, abruptly offset dipping planes of seismicity (Wadati Benioff Zones, WBZs). The location of the WBZ offset (defined by *Vargas and Mann* [2013] as the "Caldas tear") coincides with the location of the subducting inactive Sandra Ridge spreading center [*Lonsdale*, 2005; *Vargas and Mann*, 2013]. The northern WBZ, located >300 km from the trench, extends from 11°N to 5.5°N and includes the region of increased seismic activity known as the Bucaramanga Seismic Nest (Figure 1) [e.g., *Schneider et al.*, 1987; *Frohlich et al.*, 1995; *Zarifi et al.*, 2007; *Prieto et al.*, 2012; *Bernal-Olaya et al.*, 2015a] at ~7°N. The southern WBZ dips at a relatively constant angle of ~45° and directly underlies the modern active Andean arc (Figure 1). Although different interpretations have

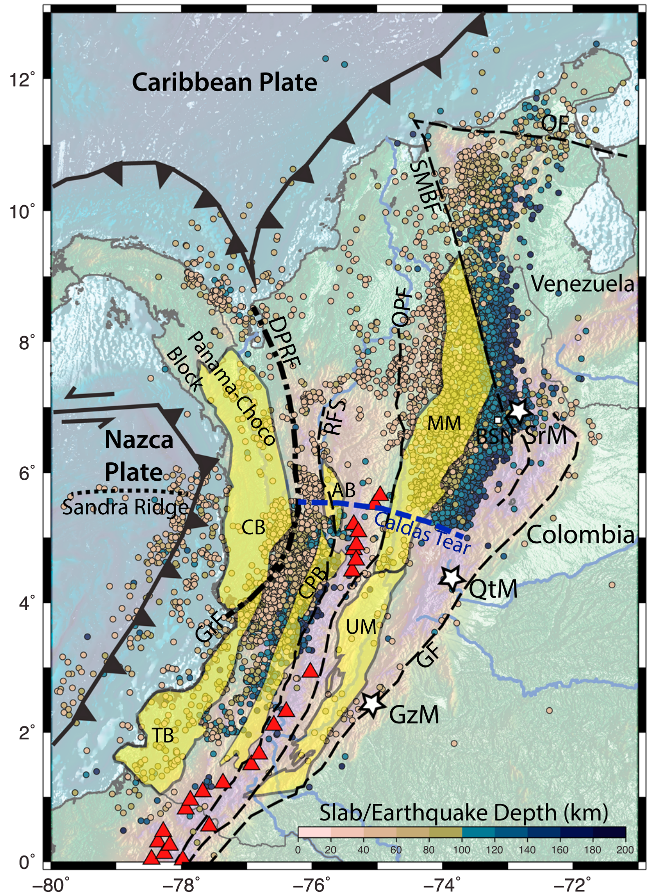

Figure 1. Geologic setting of northwestern South America. Hypocenters plotted as small circles. Plate boundaries are shown with thick black lines. Holocene volcanism (red triangles) from the *Global Volcanism Program* [2013]. Terrane boundaries are indicated by dashed lines. The boundary between the accreted Panama-Choco block is shown with a heavy dash-dotted line. Also shown is the location of the Sandra Ridge [*Lonsdale*, 2005] and Caldas tear. Basins are shown in yellow [*Barrero et al.*, 2012]. Abbreviations: AB: Amaga Basin; CB: Choco Basin; CPB: Cauca-Patia Basin; TB: Tumaco Basin; UM: Upper Magdalena Valley; MM: Middle Magdalena Valley; DPRF: Dabeiba-Puerto Rico Fault: GrF: Garrapatas Fault; RFS: Romeral Fault System; OPF: Otu-Pericos Fault; GF: Guicaramo Fault; SMBF: Santa Marta-Bucaramanga Fault; OF: Oca Fault; GzM: Garzon Massif; QtM: Quetame Massif; and SrM: Santander Massif.

been proposed, tomographic images and seismicity patterns are not conclusive to definitively link the northern WBZ seismicity to either trench, raising questions about whether this WBZ is due to the Caribbean slab, the Nazca slab, or both [*van der Hilst and Mann*, 1994; *Taboada et al.*, 2000; *Cortés and Angelier*, 2005; *Vargas and Mann*, 2013; *Bernal-Olaya et al.*, 2015a; *Chiarabba et al.*, 2016; *Syracuse et al.*, 2016].

Here we present a compilation of volcanic ages and locations that strongly suggest that (a) there was a continuous arc along the entire Pacific margin between 14 and 9 Ma that is attributable to Nazca Plate subduction beneath Colombia, (b) by 6 Ma, the modern flat slab was fully formed and initially extended significantly farther to the south than it does today, and (c) the modern geometry of a flat slab directly adjacent to as steeply dipping slab capable of producing arc volcanism has only existed for the past ~4 Ma. These observations lead to the conclusion that the Nazca Plate comprises at least part of the flat slab north of the Caldas tear, though it is beyond the scope of this paper to define how far to the north the Nazca Plate extends or where the boundary between the Nazca Plate and the Caribbean Plate lies.

2. Data and Methods

We compiled ~125 ages of igneous rocks within Colombia from the Miocene through present day. We searched over standard international literature, theses from Colombian universities, articles in Colombian journals, and internal reports of the Colombian Geological Survey (formerly INGEOMINAS). Only U-Pb, K-Ar, and Ar-Ar ages were included in our compilation; we discarded the fission track ages as they likely represent episodes of heating different from the igneous crystallization. The dated rocks correspond to lava flows, pyroclastic rocks, porphyritic bodies, and plutonic bodies. Although we are aware that Argon ages for plutonic bodies may represent cooling rather than crystallization, the Miocene-Pliocene intrusions are shallow level as they intrude mainly sedimentary rocks [*Gómez et al.*, 2007] and therefore may have experienced fast cooling that almost overlap with magmatic crystallization. There is also the possibility that some of the collected ages correspond to hydrothermal activity contemporaneous with arc volcanism, but we are confident that the general trend of the data should give us a reliable pattern of the evolution of the arc volcanism in Colombia. In supporting information Table S1, we include ages for rocks younger than 14 Ma, along with their errors, methods (including the dated minerals), the type of sampled rock, and references.

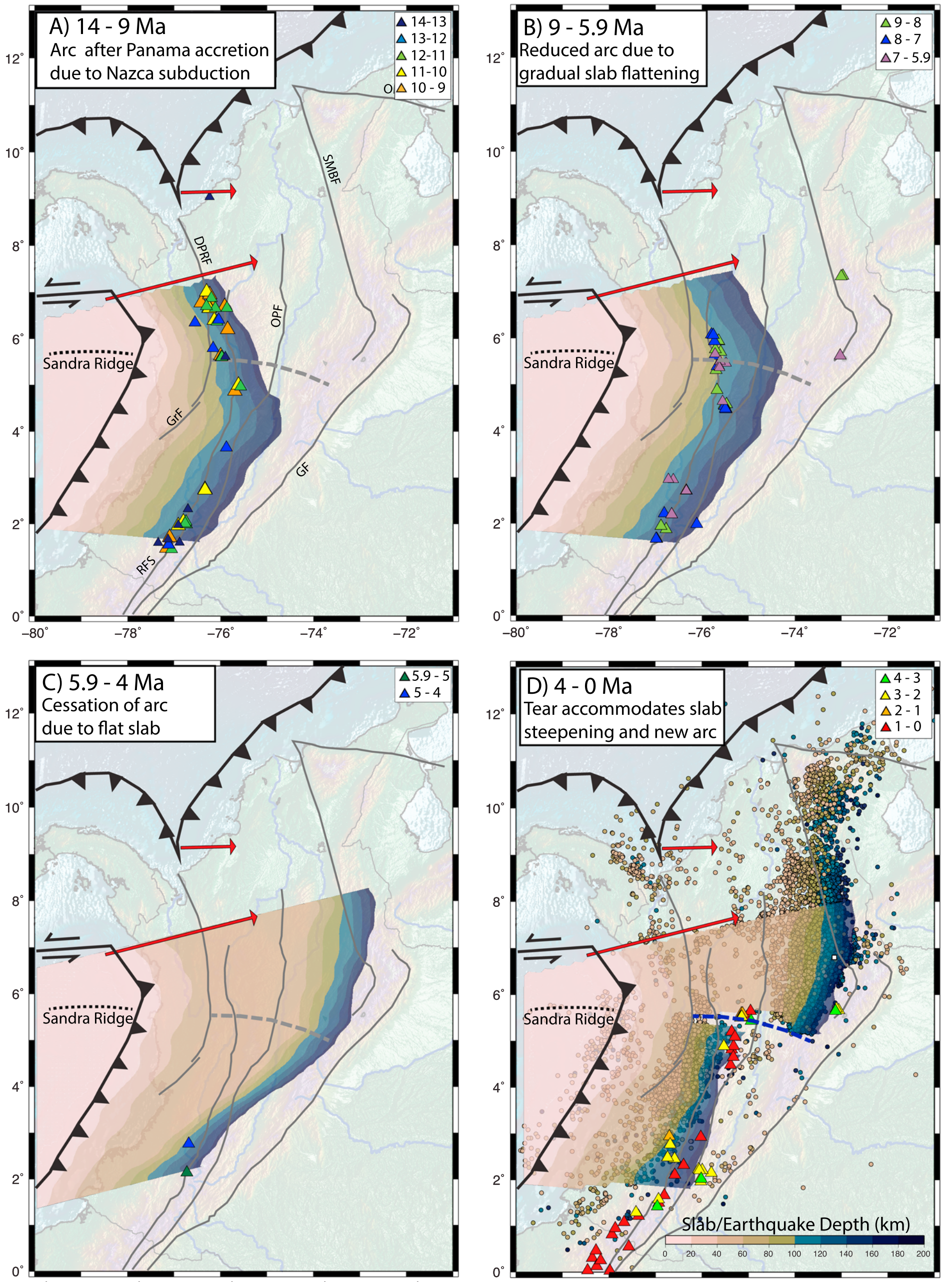

Figure 2. Temporal evolution of volcanism and proposed slab geometry in northwestern Colombia. Grey lines indicate terrane boundaries (see Figure 1). Plate boundaries are from *Trenkamp et al*. [2002]. Location of Sandra Ridge is from *Lonsdale* [2005]. Holocene volcanism is from the *Global Volcanism Program* [2013]. Convergence vectors relative to stable South America (in red) are from *DeMets et al*. [2010].

3. Results

We plot volcanism across Colombia in 1 Ma increments, beginning after the recently proposed accretion date of Panama of ~14 Ma [*Montes et al*., 2012a, 2012b, 2015]. From 14 to 9 Ma, evidence for volcanism exists almost exclusively along the modern western Cordillera in a nearly continuous arc from ~7°N to 1.5°N. The full extent of the arc is visible as of 12 Ma, with earlier volcanism less evenly distributed along the arc. The northernmost cluster of volcanism during this time is located near the latitude of the offshore transform plate boundary between the Panama block and the Nazca Plate [*Trenkamp et al*., 2002] (Figure 2a). Notably, the arc between 12 and 9 Ma is fairly consistently linear and crosses seamlessly the margin of the accreted Panama-Choco block and the modern location of the Caldas tear.

Beginning at 9 Ma, the northern extent of the arc moves to the south, and the amount of observed volcanism decreases (Figure 2b). During this time period, all volcanism is east of the accreted terranes, and the arc is continuous across the location of the modern Caldas tear, still extending significantly farther north than the modern arc despite its reduced northward extent. Note that the gap in observed volcanism between 3°N and 4.5°N may be due to negative sampling bias due to the difficulty of obtaining samples in this region of Colombia. Volcanism south of 3°N continues apparently unabated throughout the time period addressed in this study. Between 5.9 and 4 Ma, volcanism is only present in this southernmost portion of our study area in the western Cordillera (south of 3°N). Given the abundance of samples from bracketing time periods, this cessation of arc volcanism farther to the north is unlikely to be due to sampling bias alone. At ~3.8 and 3.5 Ma, we have the first evidence of volcanism north of 3°N, located at the southernmost edge of the modern flat slab and the northernmost extent of the modern arc, respectively. Beginning at 3 Ma, volcanism resumes along the length of the arc south of the Caldas tear, establishing the geometry of the modern arc.

4. Discussion

The cessation and/or migration of arc volcanism are perhaps the most consistent features of modern flat slabs [e.g., *Dickinson and Snyder*, 1978; *Jordan and Allmendinger*, 1986; *Gutscher et al.*, 2000; *Kay and Mpodozis*, 2002]. The cause of this cessation is believed to be due to the pinching out of asthenospheric corner flow above the subducting plate, which results in a dramatic decrease in temperature [e.g., *English et al.*, 2003], as witnessed by unusually low heat flow measurements above modern flat slabs [*Henry and Pollack*, 1988]. While the causes of flat slab subduction itself are not fully understood, we expect that an anomalous (with respect to typical oceanic plate) buoyancy of the downgoing plate plays an important, if not sufficient, role [e.g., *van Hunen et al.*, 2004; *Espurt et al.*, 2008; *Manea et al.*, 2012; *Martinod et al.*, 2013; *Taramón et al.*, 2015; *Huangfu et al.*, 2016; *Hu et al.*, 2016]. This anomalous buoyancy can be due to a combination of plate age and the presence of overthickened oceanic crust, e.g., due to aseismic ridge tracks or oceanic plateaus. Recent work in Peru has suggested that once the buoyant anomaly is removed, the presence of other factors that contribute to flat slab formation (e.g., overriding plate motion, trench rollback, and suction due to the thickness of the overriding lithosphere) may not be not sufficient to maintain a flat slab geometry [*Antonijevic et al.*, 2015].

In the case of Colombia, we present evidence of a continuous arc from at least 1.5°N to 7°N following the accretion of the Panama-Choco block. While there are uncertainties about the precise age of this accretion, both earlier estimates based on biostratigraphy placing the accretion age at ~13–12 Ma [*Duque-Caro*, 1990a, 1990b] and more recent work based on detrital zircons that estimate the closure of the Central American Seaway at between 15 and 13 Ma [*Montes et al.*, 2015] are broadly consistent with these results. The nearly linear trend of volcanism from this time period crosses the boundary between the newly accreted terranes and proto-Colombia without any observed offset. This is consistent with the Panama-Choco block being very near in its modern position by 12 Ma and that the subduction responsible for this arc is the subduction of the Nazca Plate and not the subduction between the Panama-Choco block and NW South America. Also noteworthy is that we find no evidence for different volcanic activity across the modern location of the Caldas tear prior to 3.5 Ma (Figures 2a, 2b, and 3a). This indicates that the plate subducting north of this offset today is the same plate that is subducting south of this offset, in contradiction to earlier studies suggesting that the offset represents the boundary between two separate plates [e.g., *van der Hilst and Mann*, 1994; *Taboada et al.*, 2000; *Corredor*, 2003; *Cortés and Angelier*, 2005; *Vargas and Mann*, 2013; *Sanchez-Rojas and Palma*, 2014; *Bernal-Olaya et al.*, 2015a; *Idárraga-García et al.*, 2016]. This does not preclude the existence of a Caribbean flat slab farther to the north nor does define the modern boundary between the Caribbean Plate and Nazca Plate at depth. It does, however, suggest that the Pacific Plate was subducting as far north as 7°N by 12 Ma, producing arc volcanism at that latitude as recently as 9 Ma. The fate of this northernmost subducted material is not well constrained by this study, but if South America passed over this segment of the subducting plate parallel to the modern convergence direction, the northern margin of the Nazca Plate would intersect the modern WBZ at ~8°N (Figure 2d).

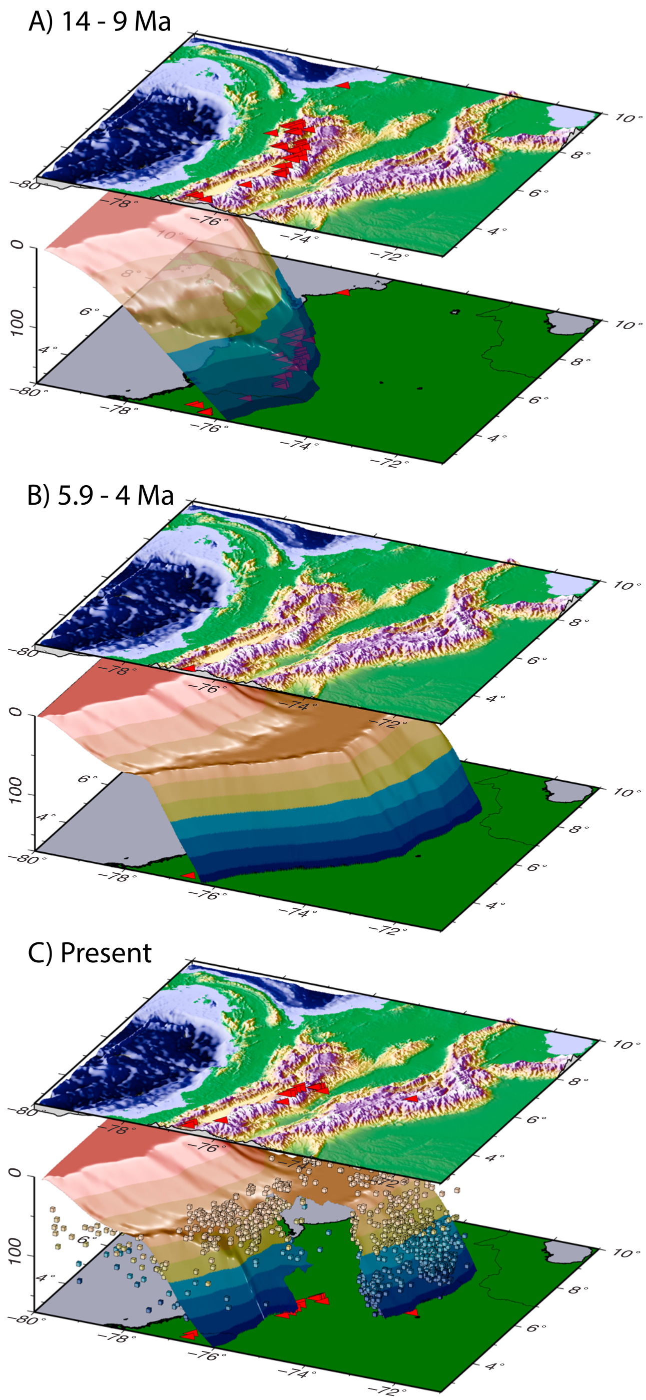

Figure 3. Three-dimensional gridded view of proposed slab geometries over time.

The first volcanic indication of a shallowing of the subducted Pacific Plate begins at 9 Ma at which time there is a noticeable change in the pattern of arc volcanism (Figure 2b). The amount of volcanism is reduced, and there is a subtle eastward shift of the main arc and evidence for volcanic activity in the Eastern Cordillera. These observations are consistent with the gradual formation of a flat slab between 9 and 5.9 Ma [e.g., *Jordan and Allmendinger*, 1986; *Kay and Mpodozis*, 2002]. *Chiarabba et al*. [2016] use paleoconvergence rates and modern WBZ geometry to calculate the age of the beginning of flattening and propose that this process began at ~10 Ma. Given that volcanism at the surface will require some amount of time to respond to changes in subducting slab geometry, this suggestion is consistent with our observations and proposed slab history.

By 5.9 Ma, the full cessation of arc volcanism north of 2–3°N suggests a pervasive flat slab extending from ~3°N to the northern margin of the subducting Nazca Plate at 7°N (Figures 2c and 3b). The eastward extent of the flat slab south of the modern WBZ offset is unknown, but we propose that the eastern margin of the flat slab aligned itself with the Eastern Cordillera, much as the modern flat slab continues to do today. We propose this geometry because the eastern limit of the flat slab could be due to the presence of thicker lithosphere along and east of the Eastern Cordillera that hinders the farther eastward horizontal advance of the flat slab [e.g., *Yarce et al*., 2014; *Blanco et al*., 2017]. This geometry is also the simplest geometry that connects the ongoing active volcanism (and therefore ongoing normal subduction) at 3°N to the broadest portion of the modern flat slab just north of 5.5°N (Figure 3b).

The cause of the formation of such a broad flat slab is not constrained by this study. It has been proposed that the northern portion of the flat slab is supported in part by a completely subducted buoyant oceanic feature that may also contribute to the increased seismicity of the Bucaramanga Nest [*Chiarabba et al*., 2016]. Buoyancy may also have been provided in part by the very young age of the ocean lithosphere along both sides of the Sandra Ridge [*Lonsdale*, 2005]. At the time of the formation of the flat slab, the Sandra Ridge had only just ceased to produce new oceanic crust along its flanks. The buoyancy from this young plate on both sides of the Sandra Ridge may have facilitated the initial formation of the broader flat slab geometry we propose existed from 5.9 to 4 Ma. It is possible that as the age of the oceanic plate on either side of the Sandra Ridge increased over time (today, the youngest plate being subducted adjacent to the Ridge is ~9 Ma), this buoyancy was reduced. The preservation of the flat slab north of the Sandra Ridge may be due to the subducted buoyant feature proposed by *Chiarabba et al*. [2016]. The flat slab farther south, however, has no such buoyant feature. The Sandra Ridge may have provided a zone of weakness along which the southern flat slab, once gravitationally unstable, could fail.

The first evidence from the volcanic record of the failure of the southern extension of the Colombian flat slab occurs only after 4 Ma (Figures 2d and 3c). Volcanism begins slowly along the location of the modern arc with only one known sample north of 3°N at 3.5 Ma and with only few more between 2 and 3 Ma. We propose that beginning at ~4 Ma, the southern portion of the flat slab became gravitationally unstable and began to sink, tearing away from the persistent flat slab to the north along a preexisting zone of weakness (the Sandra Ridge). This resulted in volcanism first to the east where the tear began (at 3.8 Ma) and then along the northernmost edge of the modern arc (at 3.5 Ma). Vigorous mantle shearing through the tear would be consistent with the inference of along-slab flow by *Porritt et al*. [2014] based on analysis of azimuthal seismic anisotropy. By 1–2 Ma, volcanism along the modern Pacific arc was likely fully established. This suggests an ~2 Ma time frame for the reestablishment of arc volcanism after the resumption of normal subduction.

The presence and failure of a southern extension of the Colombian flat slab has to our knowledge not previously been postulated but is supported by the volcanic data presented here. This finding provides numerous testable hypotheses about the effects of flat subduction, and flat slab failure, on the overriding plate. For example, continental crust overlying flat slab subduction regions typically experience compressive stresses and associated deformation [e.g., *Gutscher et al*., 2000; *Ramos and Folguera*, 2009; *Finzel et al*., 2011]. A comprehensive analysis of all literature associated with this type of deformation is beyond the scope of this paper. However, a preliminary review of existing work on crystalline massifs located in the Eastern Cordillera (Figure 1), including the Santander Massif located along the modern flat slab, the Quetame Massif just south of the Caldas tear [*Shagam et al*., 1984; *Mora et al*., 2008, 2015; *Parra et al*., 2009; *Sánchez et al*., 2012; *van der Lelij et al*., 2016], and the Garzón Massif at the southernmost extent of our proposed southern flat slab extension [*Villagómez and Spikings*, 2013; *Anderson et al*., 2016], shows evidence of fast cooling and exhumation between 10.6 Ma and 3 Ma, with fast cooling focusing between 3 Ma and 6 Ma. Very limited thermochronological data from the central and western Cordilleras also suggest fast cooling between 10.6 Ma and 4 Ma [*Villagómez and Spikings*, 2013; *Restrepo-Moreno et al*., 2015]. Similarly, there is significant evidence of upper Miocene-Pliocene deformation of sedimentary basins located both north (e.g., Middle Magdalena, Amagá, and Choco Basins) and south (e.g., Upper Magdalena, Cauca-Patia, and Tumaco Basins) of the Caldas tear (Figure 1) [*Howe*, 1974; *Barrero et al*., 2012; *Barbosa-Espitia et al*., 2013]. This is consistent with the presence of similar tectonic forces (e.g., flat slab) at work on both sides of the modern Caldas tear during this time period. More work is needed to evaluate the possible tectonic effects of flat slab failure on the overriding plate.

5. Conclusions

The volcanic patterns presented here indicate the presence of a normally subducting plate along the Pacific coast of Colombia between 14 and 9 Ma that extended from at least 1.5°N to 7°N. The linear geometry of the volcanic arc throughout much of this time period strongly suggests that the accretion of the Panama-Choco block was largely complete and Nazca Plate subduction well established along Colombia's Pacific margin by 12 Ma, consistent with previous estimates from biostratigraphy and detritial zircons [*Duque-Caro*, 1990a, 1990b; *Montes et al*., 2012a, 2012b, 2015] The cessation of arc volcanism north of 2–3°N between 5.9 and 4 Ma suggests a pervasive flat slab during that time along most of the Colombian Pacific margin. The resumption of volcanism between 3 and 4 Ma along the location of the modern arc to the south indicates that the tearing of the slab along the Sandra ridge and the development of the modern slab geometry began at that time. We speculate that this transition between slab flattening and resteepening may be reflected in the overriding plate deformation history, and further analysis of the complex subduction history along Colombia's Pacific margin may yield general insights into slab-overriding plate coupling.

Acknowledgments
Figures were made using Generic Mapping Tools (GMT) software [*Wessel and Smith*, 1991]. T.W.B. was partially supported by NASA under OSP 201601412-001. The Colombian science foundation, COLCIENCIAS, is acknowledged for the support to J.S. Jaramillo, L.F. Ramírez-Hoyos, and A. Cardona through grants 50491 and 51686. The data compiled for this paper can be found in supporting information Table S1. We would like to thank the reviewers of an earlier version of this manuscript, Paul Mann and James Kellogg, for constructive comments that improved our presentation.

References

Anderson, V. J., B. K. Horton, J. E. Saylor, A. Mora, E. Tesón, D. O. Breecker, and R. A. Ketcham (2016), Andean topographic growth and basement uplift in southern Colombia: Implications for the evolution of the Magdalena, Orinoco, and Amazon River systems, *Geosphere*, *12*(4), 1235–1256.

Antonijevic, S. K., L. S. Wagner, A. Kumar, S. L. Beck, M. D. Long, G. Zandt, H. Tavera, and C. Condori (2015), The role of ridges in the formation and longevity of flat slabs, *Nature*, *524*, 212–215.

Barbosa-Espitia, A. A., S. A. Restrepo-Moreno, A. Pardo, J. A. Osorio, and D. Ochoa (2013), Uplift and exhumation of the southernmost segment of the western Cordillera (Colombia) and development of the neighboring Tumaco Basin, *Geol. Soc. Am. Abstr. Programs*, *45*(7), 548.

Barrero, C., A. Pardo, C. M. Jaramillo, J. A. Osorio, A. Cardona, A. Flores, S. Echeverri, S. Rosero, J. García, and H. Castillo (2012), Tectonostratigraphy of the Cenozoic Tumaco forearc basin (Colombian Pacific) and its relationship with the northern Andes orogenic build up, *J. S. Am. Earth Sci.*, *39*, 75–92.

Bernal-Olaya, R., P. Mann, and C. A. Vargas (2015a), Earthquake, tomographic, seismic reflection, and gravity evidence for a shallowly dipping subduction zone beneath the Caribbean Margin of Northwestern Colombia, in *Petroleum Geology and Potential of the Colombian Caribbean Margin*, edited by C. Bartolini and P. Mann, *AAPG Mem.*, 118, 247–270.

Bernal-Olaya, R., J. Sanchez, P. Mann, and M. Murphy (2015b), Along-strike crustal thickness variations of the subducting Caribbean plate produces two distinctive styles of thrusting in the offshore South Caribbean deformed belt, Colombia, in *Petroleum Geology and Potential of the Colombian Caribbean Margin*, edited by C. Bartolini and P. Mann, *AAPG Mem.*, *108*, 295–322.

Bernal-Olaya, R., P. Mann, and A. Escalona (2015c), Cenozoic tectonostratigraphic evolution of the lower Magdalena Basin, Colombia: An example of an under-to overfilled forearc basin, in *Petroleum Geology and Potential of the Colombian Caribbean Margin*, edited by C. Bartolini and P. Mann, *AAPG Mem.*, 118, 345–398.

Blanco, J. F., C. A. Vargas, and G. Monsalve (2017), Lithospheric thickness estimation beneath northwestern South America from an *S*-wave receiver function analysis, *Geochem. Geophys. Geosyst.*, *18*, 1376–1387, doi:10.1002/2016GC006785.

Cediel, F., R. P. Shaw, and C. Cáceres (2003), Tectonic assembly of the northern Andean block, in *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics*, edited by C. Bartolini, R.T. Buffler, and J. Blickwede, *AAPG Mem.*, 79, 815–848.

Chiarabba, C., P. De Gori, C. Faccenna, F. Speranza, D. Seccia, V. Dionicio, and G. A. Prieto (2016), Subduction system and flat slab beneath the Eastern Cordillera of Colombia, *Geochem. Geophys. Geosyst.*, *17*, 16–27, doi:10.1002/2015GC006048.

Coates, A. G., M. P. Aubry, W. A. Berggren, L. S. Collins, and M. Kunk (2003), The central American arc from Bocas del Toro, western Panama, *Geol. Soc. Am. Bull.*, *115*, 271–287.

Coates, A. G., L. S. Collins, M. P. Aubre, and W. A. Berggren (2004), The geology of the Darien, Panama, and the late Miocene-Pliocene collision of the Panama arc with northwestern South America, *Geol. Soc. Am. Bull.*, *116*, 1327–1344.

Corredor, F. (2003), Seismic strain rates and distributed continental deformation in the northern Andes and three-dimensional seismotectonics of northwestern South America, *Tectonophysics*, *372*(3), 147–166.

Cortés, M., and J. Angelier (2005), Current states of stress in the northern Andes as indicated by focal mechanisms of earthquakes, *Tectonophysics*, *403*(1), 29–58.

DeMets, C., R. G. Gordon, and D. F. Argus (2010), Geologically current plate motions, *Geophys. J. Int.*, *181*(1), 1–80.

Dickinson, W. R., and W. S. Snyder (1978), Plate tectonics of the Laramide orogeny, *GSA Mem.*, *151*, 355–366.

Duque-Caro, H. (1990a), The Chocó block in the northwestern corner of South America: Structural, tectonostratigraphic, and paleogeographic implications, *J. S. Am. Earth Sci.*, *3*, 71–84.

Duque-Caro, H. (1990b), Neogene stratigraphy, paleoceanography and paleobiogeography in northwest South America and the evolution of the Panama seaway, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *77*, 203–234.

English, J. M., S. T. Johnston, and K. Wang (2003), Thermal modeling of the Laramide orogeny: Testing the flat-slab subduction hypothesis, *Earth Planet. Sci. Lett.*, *214*, 619–632.

Espurt, N., F. Funiciello, J. Martinod, B. Guillaume, V. Regard, C. Faccenna, and S. Brusset (2008), Flat subduction dynamics and deformation of the South American plate: Insights from analog modeling, *Tectonics*, *27*, TC3011, doi:10.1029/2007TC002175.

Farris, D. W., et al. (2011), Fracturing of the Panamanian Isthmus during initial collision with South America, *Geology*, *39*(11), 1007–1010, doi:10.1130/G32237.1.

Finzel, E. S., J. Top, K. D. Ridgway, and E. Enkelmann (2011), Upper plate proxies for flat-slab subduction processes in southern Alaska, *Earth Planet. Sci. Lett.*, *303*, 348–360.

Frohlich, C., K. Kadinsky-Cade, and S. D. Davis (1995), A reexamination of the Bucaramanga, Colombia, earthquake nest, *Bull. Seismol. Soc. Am.*, *85*(6), 1622–1634.

Global Volcanism Program (2013), *Volcanoes of the World*, vol. 4.5.0, edited by E. Venzke, Smithsonian Institution, Downloaded 8 Sept 2016, doi:10.5479/si.GVP.VOTW4-2013.

Gómez, J., et al. (2007), Geological map of Colombia, scale 1:1′000.000, 2 sheets. INGEOMINAS, Project Geological Map of Colombia, Bogotá, Colombia. [Available at http://www2.sgc.gov.co/getattachment/Geologia/Mapageologico-de-colombia/GMC_2007_1000K.pdf.aspx.]

Gutscher, M. A., W. Spakman, H. Bijwaard, and E. R. Engdahl (2000), Geodynamics of flat subduction: Seismicity and tomographic constrains from the Andean margin, *Tectonics*, *19*, 814–833, doi:10.1029/1999TC001152.

Henry, S. G., and H. N. Pollack (1988), Terrestrial heat flow above the Andean subduction zone in Bolivia and Peru, *J. Geophys. Res.*, *93*(B12), 15,153–15,162, doi:10.1029/JB093iB12p15153.

Howe, M. (1974), Non-marine Neiva Formation (Pliocene), Upper Magdalena Valley, Colombia, regional tectonism, *Geol. Soc. Am. Bull.*, *85*, 1031–1042.

Hu, J., L. Liu, A. Hermosillo, and Q. Zhou (2016), Simulation of late Cenozoic South American flat-slab subduction using geodynamic models with data assimilation, *Earth Planet. Sci. Lett.*, *438*, 1–13, doi:10.1016/j.espl.2016.01.011.

Huangfu, P., Y. Wang, P. A. Cawood, Z.-H. Li, W. Fan, and T. V. Gerya (2016), Thermomechanical controls of flat subduction: Insights from numerical modeling, *Gondwana Res.*, *40*, 170–183.

Idárraga-García, J., J. M. Kendall, and C. A. Vargas (2016), Shear wave anisotropy in northwestern South America and its link to the Caribbean and Nazca subduction geodynamics, *Geochem. Geophys. Geosyst.*, *17*, 3655–3673, doi:10.1002/2016GC006323.

Jordan, T. E., and R. W. Allmendinger (1986), The Sierras Pampeanas of Argentina: A modern analogue of Rocky Mountain foreland deformation, *Am. J. Sci.*, *286*, 737–764.

Kay, S. M., and C. Mpodozis (2002), Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab, *J. S. Am. Earth Sci.*, *15*, 37–57.

Lonsdale, P. (2005), Creation of the Cocos and Nazca plates by fission of the Farallon plate, *Tectonophysics*, *404*(3), 237–264.

Manea, V. C., M. Perez-Gussinye, and M. Manea (2012), Chilean flat slab subduction controlled by overriding plate thickness and trench rollback, *Geology*, *40*(1), 35–38, doi:10.1130/G32543.

Martinod, J., B. Guillaume, N. Espurt, C. Faccenna, F. Funiciello, and V. Regard (2013), Effect of aseismic ridge subduction on slab geometry and overriding plate deformation: Insights from analogue modeling, *Tectonophysics*, *588*, 39–55.

Montes, C., G. Bayona, A. Cardona, D. M. Buchs, C. A. Silva, S. Morón, and V. Valencia (2012a), Arc continent collision and orocline formation: Closing of the Central American Seaway, *J. Geophys. Res.*, *117*, B04105, doi:10.1029/2011JB008959.

Montes, C., et al. (2012b), Evidence for middle Eocene and younger land emergence in central Panama: Implications for Isthmus closure, *Geol. Soc. Am. Bull.*, *124*(5–6), 780–799, doi:10.1130/B30528.1.

Montes, C., et al. (2015), Middle Miocene closure of the Central American Seaway, *Science*, *348*, 226–229.

Mora, A., M. Parra, G. Rodriguez-Forero, V. Blanco, N. Moreno, V. Caballero, D. Stockli, I. Duddy, and B. Ghorbal (2015), What drives orogenic asymmetry in the northern Andes?: A case study from the apex of the northern Andean orocline, in *Petroleum Geology and Potential of the Colombian Caribbean Margin*, edited by C. Bartolini and P. Mann, *AAPG Mem.*, 108, 547–586.

Mora, A., M. Parra, M. R. Strecker, E. R. Sobel, H. Hooghiemstra, V. Torres, and J. Vallejo-Jaramillo (2008), Climatic forcing of asymmetric orogenic evolution in the Eastern Cordillera of Colombia, *GSA Bull.*, *120*(7), 930–949.

Parra, M., A. Mora, E. R. Sobel, M. R. Strecker, and R. Gonzalez (2009), Episodic orogenic-front migration in the northern Andes: Constraints from low-temperature thermochronology in the Eastern Cordillera, Colombia, *Tectonics*, *28*, TC4004, doi:10.1029/2008TC002423.

Porritt, R. W., T. W. Becker, and G. Monsalve (2014), Seismic anisotropy and slab dynamics from *SKS* splitting recorded in Colombia, *Geophys. Res. Lett.*, *41*, 8775–8783, doi:10.1002/2014GL061958.

Prieto, G. A., G. C. Beroza, S. A. Barrett, G. A. López, and M. Florez (2012), Earthquake nests as natural laboratories for the study of intermediate-depth earthquake mechanics, *Tectonophysics*, *570*, 42–56.

Restrepo, J., and J. Toussaint (1988), Terranes and continental accretion in the Colombian Andes, *Episodes*, *11*, 189–193.

Restrepo-Moreno, S. A., C. Vinasco, D. A. Foster, S. Noriega, M. Bernet, M. I. Marín-Ceron, M. Bermudez, and M. Botero (2015), Cenozoic accretion and morpho-tectonic response in the northern Andes (Colombia) through low-temperature thermochronology analyses/modeling, *Geol. Soc. Am. Abstr. Programs*, *47*(7), 675.

Ramos, V. A., and A. Folguera (2009), Andean flat slab subduction through time, in *Ancient Orogens and Modern Analogues*, edited by B. Murphy, *Geol. Soc. Spec. Publ.*, 327, 31–54.

Sánchez, J., B. K. Horton, E. Tesón, A. Mora, R. A. Ketcham, and D. F. Stockli (2012), Kinematic evolution of Andean fold-thrust structures along the boundary between the Eastern Cordillera and Middle Magdalena Valley Basin, Colombia, *Tectonics*, *31*, TC3008, doi:10.1029/2011TC003089.

Sanchez-Rojas, J., and M. Palma (2014), Crustal density structure in northwestern South America derived from analysis and 3-D modeling of gravity and seismicity data, *Tectonophysics*, *634*, 97–115.

Schneider, J. F., W. D. Pennington, and R. Meyer (1987), Microseismicity and focal mechanisms of the intermediate depth Bucaramanga Nest, Colombia, *J. Geophys. Res.*, *92*(B13), 13,913–13,926, doi:10.1029/JB092iB13p13913.

Shagam, R., B. P. Kohn, P. O. Banks, L. E. Dasch, R. Vargas, G. I. Rodriguez, and N. Pimentel (1984), Tectonic implications of Cretaceous-Pliocene fission-track ages from rocks of the circum-Maracaibo Basin region of western Venezuela and Eastern Colombia, in The *Caribbean-South American Plate Boundary and Regional Tectonics*, edited by W. E. Bonini, R. B. Hargraves, and R. Shagam, *Mem. Geol. Soc. Am.*, *162*, 385–412.

Syracuse, E. M., M. Maceira, G. A. Prieto, H. Zhang, and C. J. Ammon (2016), Multiple plates subducting beneath Colombia, as illuminated by seismicity and velocity from the joint inversion of seismic and gravity data, *Earth Planet. Sci. Lett.*, *444*, 139–149.

Taboada, A., L. A. Rivera, A. Fuenzalida, A. Cisternas, H. Philip, H. Bijwaard, and C. Rivera (2000), Geodynamics of the northern Andes: Subductions and intracontinental deformation (Colombia), *Tectonics*, *19*(5), 787–813, doi:10.1029/2000TC900004.

Taramón, J. M., J. Rodríguez-González, A. M. Negredo, and M. I. Billen (2015), Influence of cratonic lithosphere on the formation and evolution of flat slabs: Insights from 3-D time-dependent modeling, *Geochem. Geophys. Geosyst.*, *16*, 2933–2948, doi:10.1002/2015GC005940.

Trenkamp, R., J. N. Kellogg, J. T. Freymueller, and H. P. Mora (2002), Wide plate margin deformation, southern central America and northwestern South America, CASA GPS observations, *J. S. Am. Earth Sci.*, *15*, 157–171.

van der Hilst, R., and P. Mann (1994), Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America, *Geology*, *22*(5), 451–454.

van der Lelij, R., R. Spikings, and A. Mora (2016), Thermochronology and tectonics of the Mérida Andes and the Santander Massif, NW South America, *Lithos*, *248*, 220–239.

van Hunen, J., A. P. van den Berg, and N. J. Vlaar (2004), Various mechanisms to induce present-day shallow flat subduction and implications for the younger Earth: A numerical parameter study, *Phys. Earth Planet. Inter.*, *146*, 179–194.

Vargas, C. A., and P. Mann (2013), Tearing and breaking off of subducted slabs as the result of collision of the Panama arc indenter with northwestern South America, *Bull. Seismol. Soc. Am.*, *103*(3), 2025–2046.

Villagómez, D., and R. A. Spikings (2013), Thermochronology and tectonics of the central and western cordilleras of Colombia: Early Cretaceous–Tertiary evolution of the northern Andes, *Lithos*, *160–161*, 228–249.

Wessel, P., and W. H. F. Smith (1991), Free software helps map and display data, *Eos Trans. AGU*, *72*, 441.

Yarce, J., G. Monsalve, T. W. Becker, A. Cardona, E. Poveda, D. Alvira, and O. Ordoñez-Carmona (2014), Seismological observations in northwestern South America: Evidence for two subduction segments, contrasting crustal thicknesses and upper mantle flow, *Tectonophysics*, *637*, 57–67.

Zarifi, Z., J. Havskov, and A. Hanyga (2007), An insight into the Bucaramanga nest, *Tectonophysics*, *443*(1), 93–105.