Pleistocene to Present North Andean “escape”

Obi Egbue*, James Kellogg

Department of Earth and Ocean Sciences, University of South Carolina, USA

**Abstract**

This study compiles 20 published field geologic estimates of displacement rates for the northern Andes, such as displaced glacial moraines and offset pyroclastic flow, and compares them to published Global Positioning System (GPS) measurements. Dated displacements compiled in this study were obtained from the Gulf of Guayaquil, Pallatanga, Chingual-la So, and Cayambe-Afiliadores-Sibundoy fault systems in Ecuador and southern Colombia and the Boconó fault system in Venezuela. Right-lateral slip estimates on the individual fault segments range from 2 mm/a to 10 mm/a. The mean estimated geologic slip rate for the last 86,000 years is 7.6 mm/a. This estimate is very similar to the GPS measurements of Present day motion at the 2 sigma level. Published GPS results suggest that a large part of the northern Andes is “escaping” to the northeast relative to stable South America at a rate of 6±2 mm/a. The GPS displacement rates of seven sites in Venezuela, Colombia, and Ecuador are statistically identical at the 95% confidence level. Four geologic estimates indicate that slip rates of 4 to 10 mm/a continued back to 1.8 Ma. No geologic slip estimates have been reported for Ecuador prior to that time period. The relative northeastward motion of increased coupling between the obliquely subducting Nazca plate and the overriding South American plate due to the subduction of the Carnegie Ridge at the Ecuador–Colombia trench. If this is correct, the slip estimates for the North Andes suggest that the Carnegie Ridge arrived at the trench prior to 1.8 Ma. In the Eastern Cordillera of Colombia, strike-slip crustal earthquakes reflect slip partitioning on high angle faults located above crustal detachment ramps across a 200 km wide zone. Intermediate depth mantle earthquakes indicate that brittle shearing extends to the base of the lithosphere.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

Northwestern South America is a broad convergent plate boundary zone characterized by active seismicity, a volcanic arc, subduction, and an on-going arc–continent collision. The North Andes is bounded by the Colombian–Ecuador trench and the Panama block to the west, the South Caribbean deformed belt to the north, and the Boconó fault and East Andean fault zones to the east (Pennington, 1981; Kellogg and Vega, 1995). Cenozoic deformation in this broad zone has been produced by the converging Nazca, South American, and Caribbean plates, and the Panama microplate (Kellogg and Bonini, 1982). Geodetic measurements using GPS from the Central and South American (CASA) GPS project show that the Nazca oceanic plate is rapidly converging with stable South America (Freymueller et al., 1993; Trenkamp et al., 2002). The convergence direction is slightly oblique to the Colombia–Ecuador trench (Fig. 1). The aseismic Carnegie Ridge, produced by the passage of the Nazca plate over the Galapagos hotspot, is being subducted in the Ecuador–Colombia trench. CASA measurements also suggest that a large part of the northern Andes is “escaping” to the northeast relative to stable South America at a rate of 6±2 mm/a. The relative northeastward motion of the northern Andes is also demonstrated by earthquake focal mechanism solutions (Fig. 2) as well as numerous geologic field measurements of dated offset glacial features and pyroclastic flow. Tapponnier et al. (1982), using plane indentation experiments on unilaterally confined blocks of plasticine were able to model intracrustal deformation and the evolution of strike-slip faults due to the collision of India and Asia. The faults that develop, allow the “escape” of the detached block in the direction of the free boundary. Proposed driving mechanisms for the “escape” of the North Andes include subduction of the Caribbean plate, collision with the Panama arc, rapid oblique subduction of the Nazca plate, and the subduction of the aseismic Carnegie Ridge at the Ecuador–Colombia trench. The geologic history of the “escape” might therefore shed light on the driving mechanisms. If subduction of the Carnegie Ridge is an important factor as has been proposed (Lonsdale, 1978; Pennington, 1981; Gutscher et al., 1999; Witt et al., 2006), then the initiation of northeastward displacement could indicate when the Ridge arrived at the trench.

This study provides the first compilation of published geologic estimates of displacements with reliable ages from the entire East Andean frontal fault zone. The results include 20 geologic estimates obtained from transverse faults underlying the pull-apart basin in the Lechuza depression, on Puna Island, and from the Zambapala Fault.
Zone, both in the Gulf of Guayaquil, as well as from the Pallantanga and Chingual-la Soñafe faults in Ecuador, the Cayambe-Afliladores-Sibundoy fault in southern Colombia, and the Boconó fault system in northwestern Venezuela. These estimates were compared with the Present day displacement rate for the North Andes determined from CASA GPS measurements. The results were then used to make inferences regarding the driving forces for the northeastward "escape" of the North Andes as well as to attempt to explain the lack of geologic measurements of northeastward strike-slip motion in the Eastern Cordillera of Colombia.

1.1. GPS results for the North Andes

Space geodetic studies are now the primary method of studying the kinematics of plate boundary zones on land, because, since space geodetic measurements are in a global reference frame, they can be used to measure motions within the boundary zones as well as relative global motions of plate interiors (Stein and Sella, 2002). These measurements include coseismic, postseismic, and interseismic deformations associated with plate motion and crustal deformation at the plate boundaries. The demonstrated repeatability of horizontal position estimates for regional GPS networks is in the order of 1–5 mm (Jaldeha et al., 1996; Segall and Davis, 1997). The CASA GPS project measured plate motions and crustal deformation of the Nazca, Cocos, Caribbean, and South American plates. Fig. 1 includes velocity vectors from geodetic measurements conducted in the field from 1991 to 1998 in Venezuela, Colombia, and Ecuador (Trenkamp et al., 2002). The data was analyzed using GIPSY OASIS and GIPSY OASIS II software. Deformation vectors in the northern Andes reflect strain associated with convergence at the broad Nazca–South American plate boundary, Caribbean–South American plate boundary, and Panama arc–South America boundary. GPS measurements are consistent with rapid active subduction (58 ± 2 mm/a) of the oceanic Nazca plate and the Carnegie aseismic ridge at the Ecuador–Colombia trench beneath stable South America (Trenkamp et al., 2002). Approximately 50% of the Nazca–South America convergence is locked at the subduction interface, causing elastic strain in the overriding plate.

Fig. 1. Structural map of the North Andes. Numbers are the locations of geological displacement estimates (Table 2). CASA station GPS velocity vectors relative to stable South America are shown with 95% confidence error ellipses (Trenkamp et al., 2002). The Galapagos vector (GALA) has been relocated so that it is visible on this map. AUFZ: Atrato-Uraba fault zone; CASF: Cayambe-Afliladores-Sibundoy fault; CSF: Chingual-la Soñafe fault; DGM: Dolores Guayaquil megashear; EAFZ: East Andean Frontal fault zone; ESF: Espiritu Santo fault; SAFZ: Sub-Andean Frontal fault zone; SMBF: Santa Marta-Bucaramanga fault.
viscoelastic relaxation associated with the rupture zone of the 1979 (Mw 8.2) trench earthquake (White et al., 2003), and permanent deformation associated with the Panama collision (Trenkamp et al., 2002). For a complete list of the GPS vectors and their velocities, please refer to Table 2 in Trenkamp et al. (2002).

1.2. Seismicity

Fig. 3 shows focal mechanism solutions for earthquakes with Mw $> 4$ from 1979 to 2008 (Ekström et al., 2005). Focal mechanisms in the northern Andes are generally bimodal, showing NW–SE and ENE–WSW maximum compressive stress directions (Ego et al., 1996; Corredor, 2003; Cortés and Angelier, 2005). The NW–SE compression has been associated with Caribbean–South American convergence and Panama–South America collision (Kellogg and Vega, 1995; Taboada et al., 2000; Trenkamp et al., 2002; Colmenares and Zoback, 2003; Corredor, 2003), and the ENE–WSW compression has been ascribed to Nazca–South America convergence at the Colombia–Ecuador trench (Ego et al., 1996; Trenkamp et al., 2002; Colmenares and Zoback, 2003; Corredor, 2003). Many of the earthquakes with strike-slip solutions (black and white in Fig. 3) are compatible with northeast-trending right-lateral displacement along the East Andean Frontal fault system including the Bocón fault zone in Venezuela, the Eastern Cordillera in Colombia, and the Gulf of Guayaquil, Pallatanga, Chingual-La Soña, and Cayambe-Añasco fault systems in Ecuador and southern Colombia. Only in the Eastern Cordillera of Colombia are these earthquakes not associated with any major mapped fault trace. As in other strike-slip fault zones, most of these earthquakes occurred in the crust, from 15 to 40 km depth. The two largest earthquakes occurred at a depth of 15 km in the brittle upper crust, June 6, 1994 in the Central Cordillera of Colombia and May 24, 2008 east of Bogota. A cluster of mantle earthquakes known as the Bucaramanga nest (Pennington et al., 1979) occurs at a depth of 163±10 km. Although these earthquakes are not primarily caused by North Andean escape, they may represent a maximum thickness for the overriding North Andean block. Three strike-slip earthquakes also occurred in the mantle at depths of 57 km, 67 km, and 96 km. These three intermediate depth mantle earthquakes are not associated with subducting slabs, and they suggest that the East Andean
frontal fault zone extends to the base of the lithosphere. Brittle failure may be induced by rapid vertical movements associated with ongoing compressional orogenesis. The crustal earthquakes reflect slip partitioning on high angle faults located above crustal detachment ramps. The dexial northeast-trending shear follows a broad 200 km wide zone of weakness associated with Mesozoic rift basins. Surface displacement in the Eastern Cordillera of Colombia is obscured by rapid NW–SE permanent shortening and uplift associated with the on-going Panama Arc–South America collision. Stevens et al. (2002) show that continental strike-slip faults are often broad zones up to 350 km wide.

2. Geologic slip estimates

The geologic estimates of right-lateral displacement for the North Andes used in this paper are from published work and have been estimated from a broad spectrum of geologic evidence all across the North Andes (Table 2). To be considered reliable, a displacement estimate must have a well constrained age estimate associated with it.

The estimates include offset drainage features like post-glacial strike-slip movement, offset glacial moraines, offset pyroclastic flow and lahar, and estimates of slip necessary to produce some pull-apart basins in the northern Andes. These measurements have been conducted in the field and in some instances from detailed aerial photographs and radar imagery. Other displacement estimates without well constrained age estimates have been excluded from this study.

2.1. Boconó fault

Five reliable slip rate measurements for the Boconó fault have been used and they range in values from 2 mm/a to 10 mm/a. The Boconó fault (Fig 1) is the best developed strike-slip fault in northern Venezuela. It was first described by Rod (1956), as forming part of a major system of faults in northern Venezuela, the Oca, El-Pilar, and Boconó faults. It extends along the axis of the Venezuelan Andes from the Tachira depression near San Cristobal to a point near the Caribbean Sea west of Puerto Cabello in the northeast (Rod, 1956, Giegengack et al., 1976). Since the pioneering work of Rod, several
authors have made estimates of slip rates along the Boconó fault (Schubert and Sifontes, 1970; Schubert and Henneberg, 1975; Giegengack et al., 1976; Schubert, 1980; Soulas et al., 1986; Audemard et al., 1999). They have described displacement of lateral moraines, offset drainage and stratigraphic features, and seismic slip evidence. The most recent age for displacement along the fault is about 10,000 BP, based on radiocarbon dating of displaced moraines. Schubert and Sifontes (1970) estimated a displacement rate of about 6 mm/a for the Boconó fault based on measurements of post-glacial right-lateral strike-slip displacement on detailed topographic maps. Giegengack et al. (1976) reported offsets on the order of 100 m. They conclude that since the event that displaced these moraines occurred after the formation of those features and the fact that no stratigraphically younger moraines have been identified, the moraines must have been deposited during Mucubaji time, about 15±2 ka (Salgado-Laboriau et al., 1977), the Late Pleistocene. The displacement rates along the segment have varied from 40 m in the northern strand to 85 m for glacial moraines dated at 13,000 BP northeast of Mérida (Audemard et al., 1999). The displacement rates along the segment are about 15±2 km in the area of Laguna Mucubaji examined during the 1976 field works, Ego et al. (1996) determined a long term slip rate for the Chingual-la Soña fault of 8±2 mm/a for the offset pyroclastic flow and a short term slip rate of 6±2 mm/a for the offset of the younger lahars. The Ecuadorian segment has been described as the Chingual-la Soña fault (Ego et al., 1996). The CASF extends about 270 km from northern Ecuador to southern Colombia along the Sub-Andean zone, and its surface expression is represented by one or more parallel fault traces striking NNE to NE (Tibaldi et al., 2007). Local names such as Algeciras, Suaza, Garzon, Pitalito, and Altamira have been given to several related faults in southwest Colombia with similar strikes as the CASF. The name Algeciras Fault System has been used by Velandia et al. (2005), to minimize confusion and preserve the genetic relationship between these faults. Using stereoscopic aerial photos and geological-structural field data on offset geomorphic features, Tibaldi et al. (2007) estimated slip rates for both the Colombian and Ecuadorian segments of the CASF from measurements of dated offset geologic deposits and landforms for two different time spans: Late Pleistocene–Holocene and Holocene. Slip rates were also computed for the same time span along different segments of the fault system with multiple measurements along each segment. Offset land forms were also measured with calibration points based on dated displaced deposits. These methods are useful in areas where collecting samples for absolute dating such as radiocarbon is difficult or impossible: the time span involved in the CASF displacement is larger than the 40 ka range for 14C and outcrops showing faulted buried paleosols are rare in this area. In the northern segment (Colombia), the right-lateral components of slip cluster into three groups, 9±3 mm/a, 8±2 mm/a, and 7±2 mm/a, and the Ecuadorian segment has a mean slip rate of 8±2 mm/a. From an offset pyroclastic flow (37.22±0.63 ka BP) and lahar (8.6±0.6 ka BP) of the Soche lava flow, Ego et al. (1996) determined a long term slip rate for the Chingual-la Soña fault of 8±2 mm/a for the offset pyroclastic flow and a short term slip rate of 6±2 mm/a for the offset of the younger lahar.

2.3. Pallatanga fault

The Pallatanga fault (Fig. 1) is part of the Dolores Guayaquil megashear. It marks the southern end of the East Andean Front Fault Zone east of the Gulf of Guayaquil in Ecuador (Winter and Lavenu, 1989; Winter et al., 1993) and extends about 200 km across the Western Cordillera of central Ecuador up to the foot of Chimborazo volcano, following the entrenched valley of the Rio Pangor. In northern Ecuador, the Pallantanga fault crosses to the eastern side of the Andean Cordillera and is called the Chingual–la Soña fault (Tibaldi and Ferrari, 1992; Ego et al., 1996). Morphological evidence for right-lateral slip is

Table 2

<table>
<thead>
<tr>
<th>#</th>
<th>Displacement (m)</th>
<th>Age</th>
<th>Displacement rate (mm/a)</th>
<th>Fault/region</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60–100</td>
<td>13 ka BP</td>
<td>∼4–8</td>
<td>Boconó fault</td>
<td>Soulas et al. (1986)</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>10,575 ± 165 BP</td>
<td>∼9–10</td>
<td>Boconó fault</td>
<td>Giegengack et al. (1976)</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>1.5 ± 2 ka BP</td>
<td>2.0–3.0</td>
<td>Boconó fault</td>
<td>Audemard et al. (1999)</td>
</tr>
<tr>
<td>4</td>
<td>85–100</td>
<td>1.5 ± 2 ka BP</td>
<td>5.0–7.7</td>
<td>Boconó fault</td>
<td>Schubert and Sifontes (1970)</td>
</tr>
<tr>
<td>5</td>
<td>69</td>
<td>10.7 ka BP</td>
<td>∼6</td>
<td>Boconó fault</td>
<td>Schubert (1980)</td>
</tr>
<tr>
<td>6</td>
<td>7000–9000</td>
<td>1.8 Ma (7)</td>
<td>3.5</td>
<td>Cayambe-Afladores-Sibundoy Fault (Colombian segment)</td>
<td>Tibaldi et al. (2007)</td>
</tr>
<tr>
<td>7</td>
<td>132 ± 27</td>
<td>14–16 ka BP</td>
<td>8.9 ± 3</td>
<td>Cayambe-Afladores-Sibundoy Fault (Ecuadorian segment)</td>
<td>Tibaldi et al. (2007)</td>
</tr>
<tr>
<td>8</td>
<td>233 ± 24</td>
<td>27–32 ka BP</td>
<td>8.0 ± 2</td>
<td>Cayambe-Afladores-Sibundoy Fault (Ecuadorian segment)</td>
<td>Tibaldi et al. (2007)</td>
</tr>
<tr>
<td>9</td>
<td>331 ± 29</td>
<td>40–46 ka BP</td>
<td>7.4 ± 2</td>
<td>Cayambe-Afladores-Sibundoy Fault (Ecuadorian segment)</td>
<td>Tibaldi et al. (2007)</td>
</tr>
<tr>
<td>10</td>
<td>630 ± 70</td>
<td>75–86 ka BP</td>
<td>8.0 ± 2</td>
<td>Cayambe-Afladores-Sibundoy Fault (Ecuadorian segment)</td>
<td>Tibaldi et al. (2007)</td>
</tr>
<tr>
<td>11</td>
<td>36–64</td>
<td>8600 ± 60 BP</td>
<td>6 ± 2</td>
<td>Chingual-la Soña fault</td>
<td>Ego et al. (1996)</td>
</tr>
<tr>
<td>13</td>
<td>30–60</td>
<td>11–12 ka BP</td>
<td>4.0 ± 1.0</td>
<td>Pallatanga fault</td>
<td>Winter and Lavenu (1989)</td>
</tr>
<tr>
<td>15</td>
<td>590 ± 65</td>
<td>120–135 ka BP</td>
<td>4.4–6.6 mm</td>
<td>Pallatanga fault</td>
<td>Winter and Lavenu (1989)</td>
</tr>
<tr>
<td>16</td>
<td>27 ± 11</td>
<td>4–7 ka BP</td>
<td>2.6–6</td>
<td>Pallatanga fault</td>
<td>Winter and Lavenu (1989)</td>
</tr>
<tr>
<td>17</td>
<td>41.5 ± 4</td>
<td>10–13 ka BP</td>
<td>2.9–5</td>
<td>Pallatanga fault</td>
<td>Winter and Lavenu (1989)</td>
</tr>
<tr>
<td>18</td>
<td>35–40</td>
<td>5–6 ka BP</td>
<td>5.8–8</td>
<td>Gulf of Guayaquil</td>
<td>Dumont et al. (2005a)</td>
</tr>
<tr>
<td>19</td>
<td>2900 ± 200</td>
<td>440 or 550 ka BP</td>
<td>5.3–6.6</td>
<td>Gulf of Guayaquil</td>
<td>Dumont et al. (2005b)</td>
</tr>
<tr>
<td>20</td>
<td>13,500–20,000</td>
<td>1.6–1.8 Ma</td>
<td>9.9 ± 3</td>
<td>Gulf of Guayaquil</td>
<td>Witt et al. (2006); Witt and Bourgois (2009)</td>
</tr>
</tbody>
</table>

Please cite this article as: Egbe, O., Kellogg, J., Pleistocene to Present North Andean “escape”, Tectonophysics (2010), doi:10.1016/j.tecto.2010.04.021
Winter et al. (1993), reported short term offsets of 27 ± 11 m and 41 ± 4 m, and long term offsets of 590 ± 65 m and 960 ± 70 m based on topographic measurements of offset morphological features such as tributaries of Rio Pangor and intervening ridges. Assuming that slip on the fault has been continuous over several thousands of years and punctuated by major glacial events which formed coeval topographic features, Winter et al. (1993) estimated that these displacements have corresponding ages of 4–7 ka BP and 10–13 ka BP, and 120–135 ka BP and 240–250 ka BP respectively. Glacial structures of the last glacial maximum estimated to be about 10,000 BP to 12,000 BP have also been offset by about 30–60 m (Winter and Lavenu, 1989) giving a slip rate of 4 ± 1 mm/a.

2.4. Dolores Guayaquil megashear (Gulf of Guayaquil-Tumbes Basin)

Witt et al. (2006) propose that the northward drift of the North Andean block created space for the tectonic evolution of the Gulf of Guayaquil area as a trailing edge “pull-apart” basin. Using industry seismic data and well logs, Witt et al. (2006) and Witt and Bourgois (2009) estimate 13.5 to 20 km of extensional lengthening from beginning Pleistocene (1.8 Ma) to Present time. The resulting displacement rate is 10 ± 3 mm/a. The Zambapala Fault Zone is located in Puna, a 50 km long, 25 km wide island off the Guayas estuary and the Gulf of Guayaquil. The Zambapala Fault Zone has a similar strike, and connects with the Pallatanga fault in the northeast (Deniaud et al., 1999). It runs along the Zambapala Cordillera which is characterized by a morphology of pull-apart basins and Quaternary uplift (Dumont et al., 2005b). Based on offset drainage in the vicinity of the fault, Dumont et al. (2005a) reported 35–40 m of displacement dated at 5–6 ka BP and based on this, calculated a displacement rate of 6–8 mm/a for the Zambapala Fault Zone. Also radar imagery analysis of two transverse faults underlying the Lechuza depression, a pull-apart basin, shows evidence of 2900 ± 200 m of displacement since Marine Isotope Stage (M.I.S.) 11 or 13 (440 ka or 550 ka), resulting in a mean displacement rate of 5–7 mm/a (Dumont et al., 2005b).

3. Results and discussion

Fig. 4 shows the displacement rates for the major North Andean strike-slip faults discussed in the previous section. The four graphs show the Present day slip rate from GPS results and the geological estimates of displacement for the last 20,000 years (Fig. 4a), 90,000 years (Fig. 4b), 600,000 years (Fig. 4c), and 2 Ma (Fig. 4d). From these, mean displacement rates of 6 mm/a, 8 mm/a, 6 mm/a, and 10 mm/a were obtained for the last 20,000, 90,000, 600,000, and 2 million years respectively. These estimated mean slip rates for the middle to late Pleistocene are all consistent with Present day GPS measurements (6 ± 2 mm/a) at the 95% confidence level, suggesting that the rate of “escape” for the North Andes has remained fairly constant for the last 1.8 Ma. Since most of the displacements referred in this paper were measured on individual faults, which may represent a fraction of the overall displacement in a fault zone, it is possible that our slip rate is an underestimation, and the true slip rates are probably closer to the higher estimated values. As discussed earlier, GPS results (Fig. 2a) and seismicity (Fig. 3) also indicate that shear strain is distributed across a broad zone. The measurements shown in Fig. 4 suggest that maximum slip rates of about 8 mm/a may have been reached between 20,000 and 90,000 years ago and 10 mm/a between 0.6 and 2 Ma.
There also appears to be a correlation between the rate of displacement on the faults and the obliquity of the fault and the trench to the Nazca–South America convergence direction. The highest strain rates are measured on the Cayambe-Afladiases-Sibundoy fault system (7–8 mm/a) and the Dolores Guayaquil megasearch (10 mm/a), the fault systems oriented closest to the convergence direction. The lowest displacement rates (3–5 mm/a) are measured on the Pallatanga fault system in Ecuador, the fault system oriented most orthogonal to the convergence direction.

As discussed previously in this paper, the dated slip estimates for the Boconó fault zone in the Mérida Andes of Venezuela are for only the last 15,000 years, except for one less reliable estimate based on the age of formation of three pull-apart basins (Schubert, 1980). Based primarily on the analysis of radar satellite and Digital Elevation Model imagery, complemented by structural fieldwork, Backé et al. (2006) described two stages of regional deformation during the Neogene–Quaternary: 1) Mio-Pliocene NW–SE compression followed by 2) strike-slip shearing along the Boconó, Burbusay and Valera faults. They propose that the wrenching started at some point between the Pliocene and the Quaternary.

3.1. Panama arc collision

Several mechanisms have been proposed for the northeastward “escape” of the North Andes. Pindell and Dewey (1982) proposed that the collision of Panama with northwestern Colombia is driving the escape of the North Andes. The Panama arc arrived at the North Andean margin about 12 Ma, and the GPS results show a Present day collision rate of approximately 30 mm/a (Trenkamp et al., 2002). The collision has been linked by geometry and timing to basin inversion, crustal shortening and thickening, and uplift of the Eastern Cordillera of Colombia (Taboada, et al., 2000). Total shortening in the Eastern Cordillera has been estimated from volume-balanced geologic profiles as 68 to 180 km (Colletta et al., 1990; Dengo and Covey, 1993; Kellogg and Duque, 1994; Cooper et al., 1995). The timing of uplift of the Eastern Cordillera determined by climatic and apatite fission track studies suggests that most of the shortening occurred in the last 6 Ma (Van der Hammen, 1957; Wijninga, 1996; Gregory-Wodzicki, 2000; Mora, 2007). At the present rate of collision, this would require that most of the Panama–South America convergence has gone into permanent deformation and mountain building in the last 6 Ma. The fact that none of the reliable dated slip estimates for the Boconó fault zone in the Venezuelan Andes are older than 15,000 BP suggests that the primary driving mechanism for the displacement on the Boconó fault is younger than the Panama–North Andes collision. Furthermore, because the Panama–North Andes suture zone is located in northwestern Colombia, although the collision may partially account for the “escape” in northern Colombia and Venezuela, the collision could not explain northeastward “escape” in southern Colombia and Ecuador, and so cannot be the sole driving force behind the northeastward displacement of the North Andes.

3.2. Carnegie ridge collision

Pennington (1981) and Gutscher et al. (1999) proposed that the arrival of the aseismic Carnegie Ridge at the Ecuador–Colombian trench initiated the “escape”, while Kellogg and Mohriak (2001) proposed that the rapid oblique subduction of the Nazca plate and the Carnegie Ridge may together be driving the northeastward “escape”. Elastic modeling of observed horizontal displacements in the Ecuador forearc is consistent with partial locking in the subduction zone and partial transfer of motion to the overriding South American plate (Trenkamp et al., 2002; White et al., 2003). Gutscher et al. (1999) and Bourdon et al. (2003) noted an apparent shallowing in the subduction of the Nazca plate in northwestern Ecuador based on the distribution of hypocenters obtained from a local seismic network as well as the nearly complete absence of intermediate depth seismicity between 2.5° N and 1° S. Gutscher et al. (1999) and Bourdon et al. (2003) hypothesized that this shallow subduction zone was the subducted extension of the Carnegie Ridge. Pennington (1981), Gutscher et al. (1999), Kellogg and Mohriak (2001), and Trenkamp et al. (2002) proposed that the subduction of the thick buoyant crust of the Carnegie Ridge resulted in increased coupling with the overriding South American plate. Scholz and Small (1997) proposed that even the subduction of a large seamount would increase the normal stress across the subduction interface, thereby increasing seismic coupling. The result is a large increase in the recurrence intervals of earthquakes, up to twice as long as normal. The inferred continuation of the Paleo-Carnegie Ridge beyond the trench (Gutscher et al., 1999) has a northeast orientation and is compatible with the displacement direction of the North Andes. GPS measurements of east-northeast rapid subduction (58±2 mm/a) of the Nazca plate and Carnegie Ridge under South America at the Ecuador trench are also consistent with the northeastward displacement of the North Andes (Trenkamp et al., 2002).

3.3. Mechanical model

Mechanically we propose that stable South America (Guyana shield) is acting as a rigid buttress for the margin-normal component of Nazca–South America convergence, while the margin-parallel component of the Nazca–South America convergence is driving the North Andes northeastward toward the relatively free Caribbean–North Andes boundary (Fig. 5). For extrusion tectonics to occur, the block being impinged on cannot be bilaterally confined (Tappoolling et al., 1982). The escape direction is always toward the free boundary, which in the northern Andes is towards the Caribbean. In fact, at the Caribbean–North Andes boundary in Venezuela, the Caribbean is moving eastward at 20 mm/a relative to stable South America, even faster than the North Andes, and hence assisting with the “escape”. Also, due to the east–west convergence of the rigid South American backstop and the rigid Panama arc indenter, the relatively ductile sediments of the inverted basin of the Colombian Eastern Cordillera are compressed as in a vice.

3.4. Timing of Carnegie Ridge collision and North Andean “escape”

Gutscher et al. (1999), based on examination of the basement uplift signal along a trench-parallel transect, and adakite volcanism along the Ecuador arc, proposed that the ridge reached the trench and has been colliding with South America for at least 2 Ma and most likely for the last 8 Ma. Subsequently, Garrison and Davidson (2003) among others, documented that adakites in the Andes can be explained by the state of equilibrium that exist between the mantle wedge derived arc magma and the thickened garnet-bearing continental crust and therefore do not require melting of subducted oceanic slabs. Pedoja (2003) and Cantalamessa and Di Celma (2004), based on analyses of marine terrace uplift independently postulated that ridge subduction began at the Pliocene–Pleistocene boundary (1.8 Ma). Lonsdale and KIttgord (1978) proposed that the Carnegie Ridge arrived at the trench about 1 Ma, based on interpretation of magnetic anomalies and bathymetry of the Cocos and Nazca plates. They concluded that the Malpelo, Cocos, and Carnegie Ridges were formed by a hot spot that originated about 20 to 22 Ma. Isotopic and geochemical similarities and paleomagnetic latitudes suggest that the Caribbean Large Igneous Province (139–69 Ma) may have been formed by melting in the Galapagos mantle plume (Duncan and Margraves, 1984; Hoernle, et al., 2004). If this is true, the Galapagos hot spot may have undergone a quiescent phase prior to reactivation about 20 to 22 Ma.

Please cite this article as: Egbue, O., Kellogg, J., Pleistocene to Present North Andean “escape”, Tectonophysics (2010), doi:10.1016/j. tecto.2010.04.021
3.5. Eastern Cordillera

The Eastern Cordillera of Colombia is a NE-trending fold belt bounded by the Llanos foreland basin to the east and the Magdalena Valley basins to the west (Julivert, 1970; Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995). It has been interpreted as a Cretaceous extensional basin that was inverted during the Cenozoic (Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995; Mora et al., 2006. Most of the structures in the Eastern Cordillera are related to NE–SW-trending thrust faults. The lack of a clearly defined northeast-trending strike-slip fault zone in the Eastern Cordillera of Colombia may be because the rapid range-normal permanent shortening and uplift obscures the strike-slip signal. We estimate the average range-normal shortening rate for the Eastern Cordillera over the last 6 Ma as approximately 20 to 30 mm/a. This is 3 to 5 times greater than the Present range-parallel “escape”, and the total shortening of 120 to 180 km is 15 to 20 times greater than the largest dated measurements of northeastward strike-slip displacement. Despite the lack of evidence of clear surface displacement in the Eastern Cordillera, both earthquake focal mechanisms discussed earlier and the GPS measurements indicate northeastward displacement consistent with “escape.”

3.6. Other examples of slip partitioning and oblique oceanic plate and ridge subduction

The margin-parallel displacement of a block or sliver of the overriding plate above a subduction zone is not unique to the North Andes. McCaffrey (1996) has shown that about half of all modern subduction zones have mobile forearc blocks. Slip partitioning into margin-parallel and margin-normal components within the overriding plate at oblique subduction zones frequently results in lithospheric blocks being detached from the overriding plate. The forearc blocks are strained by plate coupling and are displaced relative to the overriding plate (McCaffrey, 2002). Sumatra is a classic example of the slip partitioning process, where the Australian plate is subducting obliquely 35°–50° relative to the normal to the Java trench beneath the Eurasian margin of southwest Sumatra. Using rigid-body rotations to describe the motions of forearc blocks and calculating surface deformation with elastic halfspace dislocations, McCaffrey (2002), estimated a velocity of 13.7 ± 6.9 mm/a WNW close to the Sumatra fault. The oblique subduction of the aseismic Cocos Ridge at the Mid-America Trench may also be driving the detachment of the Panama arc from the Caribbean plate as well as driving Panama’s eastward collision with South America.

4. Conclusions

If subduction of the Carnegie Ridge is the driving mechanism for the northeastward displacement of the North Andes, then the initiation of the “escape” could indicate when the ridge arrived at the trench. The compilation of geologic estimates presented in this paper suggests that the North Andean “escape” has been occurring for the last 1.8 Ma. If increased coupling, resulting from the subduction of the Carnegie Ridge beneath the South American plate, is driving the northeastward “escape” of the North Andes, the Carnegie Ridge must have reached the trench at least 1.8 Ma. Well dated evidence for earlier northeastward displacement of the northern Andes has not yet been reported. Since the East Andean fault zone passes near the cities of Quito, Bogota, and Merida, the on-going northeastward slip of the northern Andes poses a continued seismic risk for the populations of these cities.

Acknowledgements

This study was supported by the University of South Carolina and a grant from BP Colombia. The authors are grateful to Robert Trenkamp for his input and suggestions, as well as Editor Mian Liu, and the
anonymous reviewers whose comments and recommendation improved the quality of the original manuscript.

References


