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Formation of passive-roof duplexes in the Colombian Subandes and Perú

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ABSTRACT

Passive-roof duplexes are important features for accommodating shortening in active orogens, but their occurrences have been previously demonstrated only with significant subsurface data or after their exhumation. In this study, we describe a series of thin-skinned passive-roof duplexes along the Subandean front in Colombia and compare them with potential analogues in southern Peru. We suggest type localities for this structural style, which display conditions favorable for formation of these structures. It appears that passive-roof duplexes in the Subandean zones are mostly late Miocene features. Our main data for placing temporal and thermokinematic constraints on their development are 25 apatite fission-track (AFT) analyses, including track-length distributions. We show that these areas require high shortening, surface erosion, and downstream sedimentation rates at the time of their formation, as well as two distinct low-friction detachments. These features, which have been previously described by analog models, appear to have been conditioned by a phase of late Miocene topographic growth and denudation in the hinterland and subsequent increase in accommodation as well as sedimentation rates in the foreland.

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INTRODUCTION

Passive-roof duplexes have been identified in field settings since the 1980s (Banks and Warburton, 1986) as stacks of multiple thrust sheets on top of each other where no obvious emergent fault toward the foreland is observed (Fig. 1). Such unique structural features gave rise to the idea that the blind monoclinal front absorbed shortening by a back thrust with a hinterland vergence prompted by the presence of two detachment horizons (Fig. 1). Since the first work suggesting this structural style by Banks and Warburton (1986), it has been proposed that an interaction with surface processes is necessary, such as rapid erosion in the culmination of the structure coeval with rapid syntectonic deposition at the foreland side of the blind deformation front (Fig. 1).

The interaction between structural styles and surface mass transport has been investigated in recent works based on analog modeling (e.g., Baby et al., 1995a; Storti and McClay, 1995; Mugnier et al., 1997) and natural examples (e.g., Horton, 1999; Thiede et al., 2004, 2009). Such interactions have been supported in part by the basic principles of critical taper wedge mechanics for thin-skinned thrust belts (e.g., Davis et al., 1983). For instance, Mugnier et al. (1997) suggested that a thin-skinned thrust belt with one or multiple detachment horizons is narrower in areas of substantial erosion and surface mass transport than in areas where surface erosion is reduced. In such cases, regularly spaced fault-related folds are more typical of zones with less surface transport, whereas passive-roof duplexes are more common in areas with pronounced surface sediment transport. Baby et al. (1995a) demonstrated with analog models and field examples from the Bolivian Andes that a frontal piggyback basin can be associated with a passive-roof duplex on its hinterland side if surface mass transport is combined with efficient sediment storage in the adjacent syncline.

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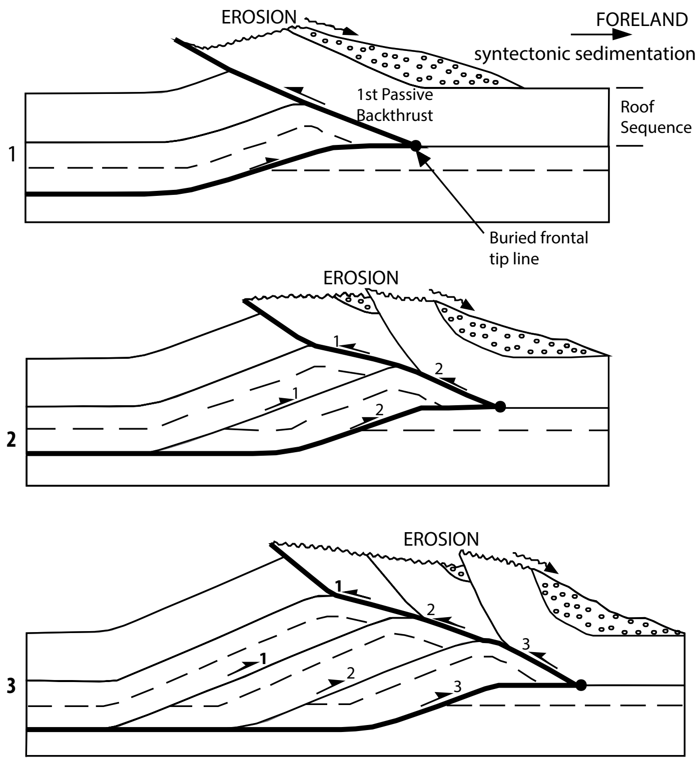

Figure 1. Sketch showing the idealized evolution of a passive-roof duplex structure (after Banks and Warburton, 1986). Since the first documentation of this type of structure, it has been hypothesized that a blind deformation front, bounding a stack of duplexes in its hinterland side, requires erosion of the crestal zone of the structure and deposition at the front for continuous growth. This type of structure was defined as passive-roof duplex by Banks and Warburton (1986).

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Passive-roof duplexes are observed along many Subandean basins north of the Bolivian orocline (Baby et al., 1995b; Gil et al., 2001; Espurt et al., 2011) and in other areas in the world (e.g., Price, 1981; Banks and Warburton, 1986; Morley, 1986; Cooper, 1996, and references therein). However, an interesting question is whether this geometry is always the result of combined efficient erosion and synchronous sediment storage in the adjacent synclines. If this is true, then the timing of intense erosion above the structures should coincide with the timing of passive-roof duplex formation. The lack of detailed information on the timing of deformation and erosion in these structures has been a major obstacle in demonstrating climate-tectonics relationships for these settings. A different approach to understand passive-roof duplexes is focused on the mechanical properties of the deformed materials, especially the need to have two detachment horizons and the frictional conditions of the detachment horizons (Bonini, 2001, 2007; Couzens and Wiltschko, 1996; Couzens-Schultz et al., 2003) as fundamental properties for the presence or absence of passive-roof duplexes.

Due to complex antiformal stacking and intricate dip domains, passive-roof duplex structures are rarely visible with conventional seismic images before intense subsurface drilling (e.g., Price, 1981; Banks and Warburton, 1986; Morley, 1986; Cooper, 1996, and references therein). However, in structural cross sections where they have been documented, they often account for the most significant crustal shortening magnitudes (e.g., Martínez, 2006). In many other cases, surface geology has been used to infer passive-roof duplex structures in the subsurface, but later more complete data showed that their presence is highly unlikely (e.g., cases described in Cooper, 1996). A prediction of these structures based on limited data points from the surface is very useful, especially in light of their importance for crustal shortening balances and hydrocarbon prospects. Field cases documenting the full dynamic behavior suggested by analog modeling are missing.

The latitudinal extent of the Andes encompasses a range of climatic zones, and the high orographic barriers lead to a steep rainfall gradient across the eastern Andes (Bookhagen and Strecker, 2008). The impact of orographic lifting as a rainfall barrier is not likely to change through time (Bookhagen and Burbank, 2010; Insel et al., 2010; Roe, 2005). The zones of high rainfall are characterized by rapid erosion at centennial to millennial and longer time scales (Safran et al., 2005; Bookhagen and Strecker, 2012; Hain et al., 2011).

To test the hypothesis of a linkage between intense surface erosion processes and structural deformation styles, we show two representative balanced cross sections from the Subandean zones in Colombia and compare them with cross sections in similar areas in the Madre de Dios Basin in Peru. We establish the timing of the shortening with the aid of apatite fission-track (AFT) data. We also compare the distribution of the structural styles in two type locations, with the distribution of different lithological controls and climatic zones indicated by a rainfall map averaged over the last decade. Comparing short-term with long-term climatic records is difficult and must be done carefully, but the key underlying atmospheric processes leading to orographic rainfall are not changing (e.g., Galewsky, 2009). Similar comparisons in other areas of the world have led to some important hypotheses and suggestions about orogenic evolution and the coupling of surface and crustal processes (e.g., Thiede et al., 2004, 2009; Burbank et al., 2003). Finally, we constrain the deformation history of the Subandean zones with the available paleoelevation data in adjacent areas to reconstruct a structural scenario.

METHODS

A key question in our work is whether in all cases the analyzed structures are controlled by the same boundary conditions and whether those boundary conditions can be extrapolated to predict similar structures in other areas of the Subandes. To properly assess this question, we first show geologic and structural maps with the distribution of potential detachment horizons as well as thickness maps of the deformed wedge materials. The maps are based on recently published data sets from wells and seismic information from the Colombian Llanos. We then compare those maps from the Subandean Colombian basins with similar maps from the Peruvian and Bolivian Subandean basins.

In addition, four cross sections along the Subandean zones were constructed based on seismic and well information where available. The cross sections are located in the northern Colombian Subandean regions, hereafter referred to as the Piedemonte antiform and the Gibraltar antiform (see Fig. 2 for location). For the Piedemonte cross section, we use the interpretation of Jimenez et al. (2013), whereas for the Gibraltar cross section, we use the interpretation of Mora et al. (2013). The Colombian structural styles are compared with new balanced cross sections in the Madre de Dios Basin in Peru (Fig. 2 for location). Our cross-section locations are in areas where the available data are sufficient to allow interpretation of simi-

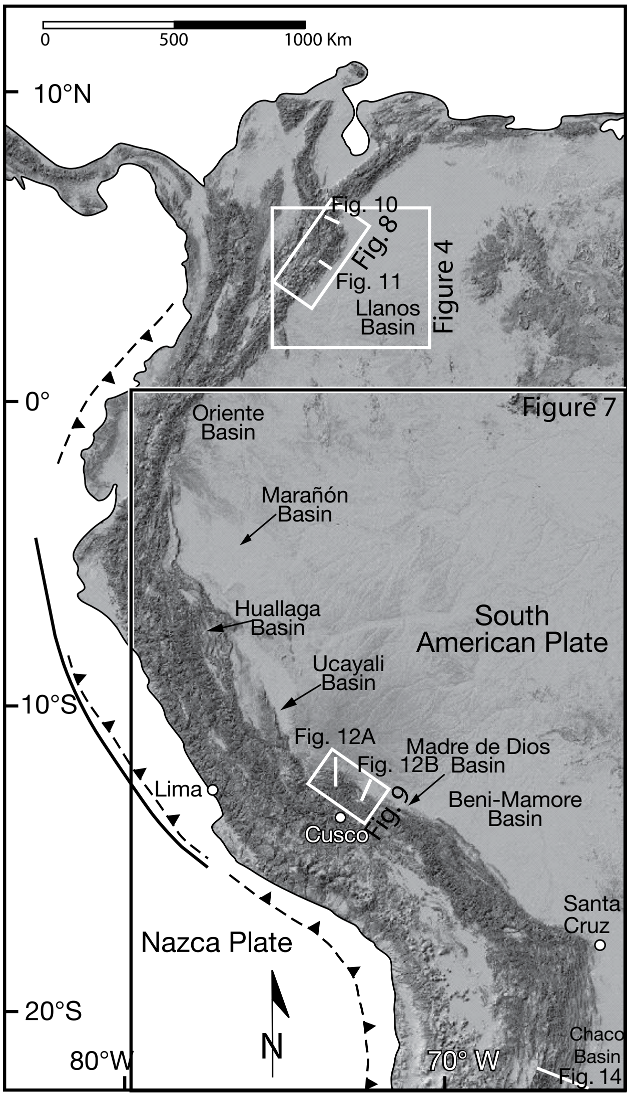

Figure 2. Hillshade view of the central and northern Andes emphasizing topographic relief. White lines indicate locations of cross sections in the Subandean basins shown in the corresponding figures.

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lar structural styles. For instance, dip domains show broad antiforms with significant structural relief (~6 km), and the space needs to be filled with structures that feed slip to the west. In Gibraltar and Piedemonte, well data show that there are actually multiple stacks, which create the structural relief in the antiform. Based on the stratigraphy that crops out, all of the structures selected can be interpreted to varying degrees as thin skinned (Fig. 2). In the Colombian examples, the timing of the main deformation events was established using AFT ages and modeling as a proxy for exhumation from maximum paleotemperatures close to 120 °C (assuming that erosion is directly related to deformation by enhancing relief and slope). With this information, we try to assess whether all of the Colombian type locations feature similar timing and kinematics of deformation. We present new data (11 samples) from the Gibraltar region, in addition to previously published data (14 samples; Mora et al., 2010a) for the Piedemonte area (see Fig. 2 for location).

AFT analyses were performed by Paul O'Sullivan of Apatite to Zircon, Inc. The etching protocol was 5.5 *M* HNO_3 for 20 s at 21 °C, and tracks were measured at 1600× under transmitted and reflected light. U determination for the Piedemonte samples utilized the external detector method, and for the Gibraltar sample, it was performed using the laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) method, both as summarized by Donelick et al. (2005).

Thermal history modeling incorporating both multikinetic AFT and vitrinite data was performed using HeFTy (Ketcham, 2005). AFT modeling used either etch figure lengths (Dpar; Burtner et al., 1994) or Cl content as the kinetic variable, depending on their respective ability to segregate age populations as evaluated using the chi-squared test. For all models, at least two and sometimes three kinetic populations were simultaneously fitted. Track lengths were modeled with *c*-axis projection to incorporate track-angle information. Modeling utilized the Ketcham et al. (2007b) annealing calibration and *c*-axis projection based on Ketcham et al. (2007a). Vitrinite data calculations utilized the Easy %Ro model of Sweeney and Burnham (1990). Initial thermal path constraints were placed based on stratigraphic information with preceding unroofing and present-day mean annual surface temperature. Intermediate constraints describing postdepositional burial and unroofing were added as needed to allow simultaneous fitting of low-annealing-resistance and high-annealing-resistance AFT populations (e.g., Mora et al., 2010a); in all cases, the smallest number of constraints was used that allowed fitting of the data. Intermediate nodes on time-temperature paths were generated using the "gradual" option in HeFTy, and in various cases maximum heating or cooling rates of 5 °C/m.y. to 10 °C/m.y. were used to avoid geologically unreasonable paths. In addition, we present rainfall climatology based on 13 yr of Tropical Rainfall Measurement Mission (TRMM) data. We carefully calibrated these data to mean annual rainfall rates using previously described methods (Bookhagen and Strecker, 2008; Bookhagen and Burbank, 2010). High rainfall rates are linked to orographic rainfall processes at steep mountain ranges with high relief (e.g., Roe, 2005; Bookhagen and Burbank, 2010). Past spatial rainfall patterns may have somewhat changed due to changing atmospheric boundary conditions, but the overall rainfall gradient and associated spatial pattern of erosion are likely to remain similar (Bookhagen and Strecker, 2012). Exhumation data from the Himalaya and other analogous places (e.g., Thiede et al., 2004) suggest that threshold elevations for orographic rainfall do not change much through time, and hence that rainfall likely remains roughly stationary, and long-term exhumation is focused in those areas. In addition, in the northern Andes, the few paleoclimate data available (Kaandorp et al., 2005), the presence of high biodiversity since the late Miocene (Hoorn et al., 2010), and the Amazon paleodrainage conditions and paleogeography (Mora et al., 2010c) suggest that the present-day humid conditions and a high-elevation Andean rain shadow have been in place since the mid-Miocene at least.

RESULTS

Basin configuration in the northern and tropical Subandes related to passive roof duplexes

It is evident from the review of the structural styles of the Andean foreland fold-and-thrust belts conducted by Kley et al. (1999) that not many passive-roof duplex structures had been documented in the Andean foreland belts at that time. More recent publications (Hermoza et al., 2005; Gil et al., 2001; Kley et al., 1999; Ramos et al., 2002; Kozlowski et al., 2005; Echavarria et al., 2003; Espurt et al., 2008, 2011; Mora et al., 2006, 2010a, 2010b, 2010c) have shown almost no new documented passive-roof duplex structures in the outer parts of the Subandean belts, with the notable exception of those mostly located north of the Bolivian orocline. Oil companies have studied these cases mostly because of the exploratory efforts (Dunn et al., 1995). However, oil exploration has been intense south of the Bolivian orocline over the past 10 yr as well (e.g., Kozlowski et al., 2005). These reviews and our data suggest that actual thin-skinned passive-roof duplex structures are concentrated north of the Bolivian orocline and close to the equator. For instance, south of 17°S, despite the presence of thin-skinned tectonics, there are no passive-roof duplexes. The only exceptions are those in the Neuquén foothills (Zamora-Valcarce et al., 2006; Dicarlo and Cristallini, 2007), which are mostly thick-skinned passive-roof duplexes, with presumably different boundary conditions that we do not discuss here.

In the following, we review existing data and present new data that may favor the presence of passive-roof duplex styles in very specific parts of the northern and central Andes, which will be the focus of our analysis in the discussion part of this manuscript.

Llanos–Eastern Foothills of Colombia

The Eastern foothills of Colombia represent the deformed belt adjacent to the Eastern Cordillera inversion orogen, and the Llanos Basin is the foreland east of the Eastern foothills. Intense exploratory efforts in the Llanos–Eastern foothills basin of Colombia have included the analysis of nearly 625,000 palynomorph occurrences from over 6700 palynological samples gathered from 70 wells and surface sections. These data enabled the creation of a unique pollen-based zonation scheme that was used to establish the chronological framework in the Llanos Basin (Jaramillo et al., 2011). The chronology provided by the pollen zonation in the Llanos–Eastern foothills basins of Colombia allowed us to determine that the Upper Miocene–Pliocene units, carefully controlled in wells, are thicker than the rest of the Cenozoic record, and therefore late Miocene–Pliocene depositional rates were faster than during other Cenozoic times (Fig. 3). Based on the same pollen zonation and the dense grid of wells and seismic data, thickness changes and pinch-outs can be documented with confidence. Potential detachment horizons mapped in the Llanos Basin are the Upper Cretaceous shales of the Chipaque-Gachetá Formations and the early Oligocene C8 member of the Carbonera Formation. The mapping suggests rapid thinning and pinch out of potential detachments close to the deformation front (Fig. 4; Table DR1[1]). Structural assessments supported on a dense grid of two-dimensional (2-D) and three-dimensional (3-D) seismic data allowed

[1]GSA Data Repository Item 2014334, Tables DR1, DR2, and DR3, and explanations, is available at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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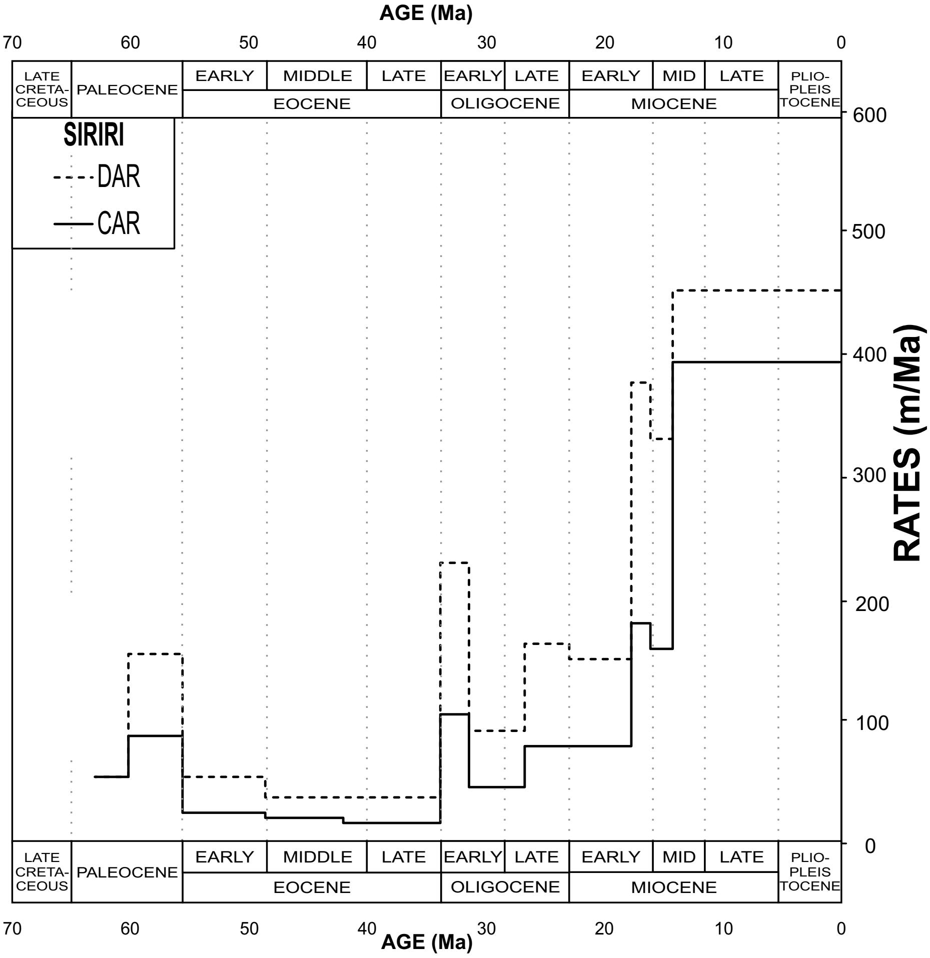

Figure 3. Cenozoic sediment accumulation rates based on both compacted (CAR) and decompacted (DAR) thickness from the Gibraltar area (northernmost square in Fig. 2).

us also to document the different structural styles along strike. All of these data sets revealed a changing behavior along the Llanos–Eastern foothills.

We compared the location and style of the comprehensive cross sections from Martínez (2006), Mora et al. (2010a), Egbue and Kellogg (2012), and Jimenez et al. (2013) with a published isopach map of the basin (Fig. 5), and it can be readily detected that in the Llanos–Eastern foothill basin, structures that can be interpreted as passive-roof duplexes are located in the precise zone of maximum thickness of the Cenozoic cover (Fig. 5). To reinforce this assessment, it is worth stressing that structures not drilled or not imaged at least with 2-D seismic data are rare in the foothills of the Colombian Llanos–Eastern foothills basins. Southward, the Llanos–Eastern foothills basin depocenter has an along-strike continuation with a much thinner foreland basin fill, already referred to by Mora et al. (2010c) as the Vaupes swell (Fig. 6). In the Oriente Basin of Ecuador, we refer to the study by Baby et al. (2013), where the basin fill is evidently much thinner than in the Llanos–Eastern foothills basins in Colombia, and duplex structures are also absent.

Peruvian and Bolivian Subandes

As known since the work of Mathalone and Montoya (1995), the geometry of the Cenozoic and Mesozoic sedimentary basin fill in the Peruvian Subandes is highly variable but rarely as thick as in the depocenters of the Llanos Basin of Colombia (e.g., Hermoza et al., 2005; Espurt et al., 2008). In this area, more careful assessments have to be made if the presence or absence of passive-roof duplexes is to be interpreted. A notable exception is the Madre de Dios Basin. In that area, the depth to basement is controlled by wells and can be mapped with the help of 2-D seismic information. Well reports in addition to data from geological maps show that the Neogene thickness is higher than in other basins, such as the Ucayali, Huallaga, and Santiago Basins, and that Neogene units in Madre de Dios are thicker than the other sedimentary units. In most of the Peruvian and Bolivian Subandes, the presence of Silurian to Devonian shales, which can act as detachment horizons, has been documented. To analyze this in more detail, we present a refined version of the Mathalone and Montoya (1995) and Sheffels (1995) maps of the Paleozoic subcrop, also expanded to Bolivia with seismic data (Fig. 7). This map shows that in most of the Peruvian basins, it is possible to find areas with potential detachments but with restricted lateral continuity due to the presence of basement highs such as those present in the Ucayali Basin.

If we make a first-order comparison of map patterns, we find that the foothills in Colombia resemble the structural style of the Madre de Dios Basin (Figs. 8 and 9). In map view, it is evident that both areas feature an arcuate basement uplift with significant topographic relief adjacent to low-elevation Tertiary synclines (Figs. 8 and 9). Published works show that this association is not present in the Caguan-Putumayo deformation front in Colombia (e.g., Casero et al., 1997), the Ecuadorian Andes (Baby et al., 2013), nor in the Peruvian Ucayali, Huallaga, or Santiago Basins (Gil et al., 2001), where the frontal faults are either emergent basement faults in the first cases or blind basement monoclines in the Huallaga and Santiago Basins.

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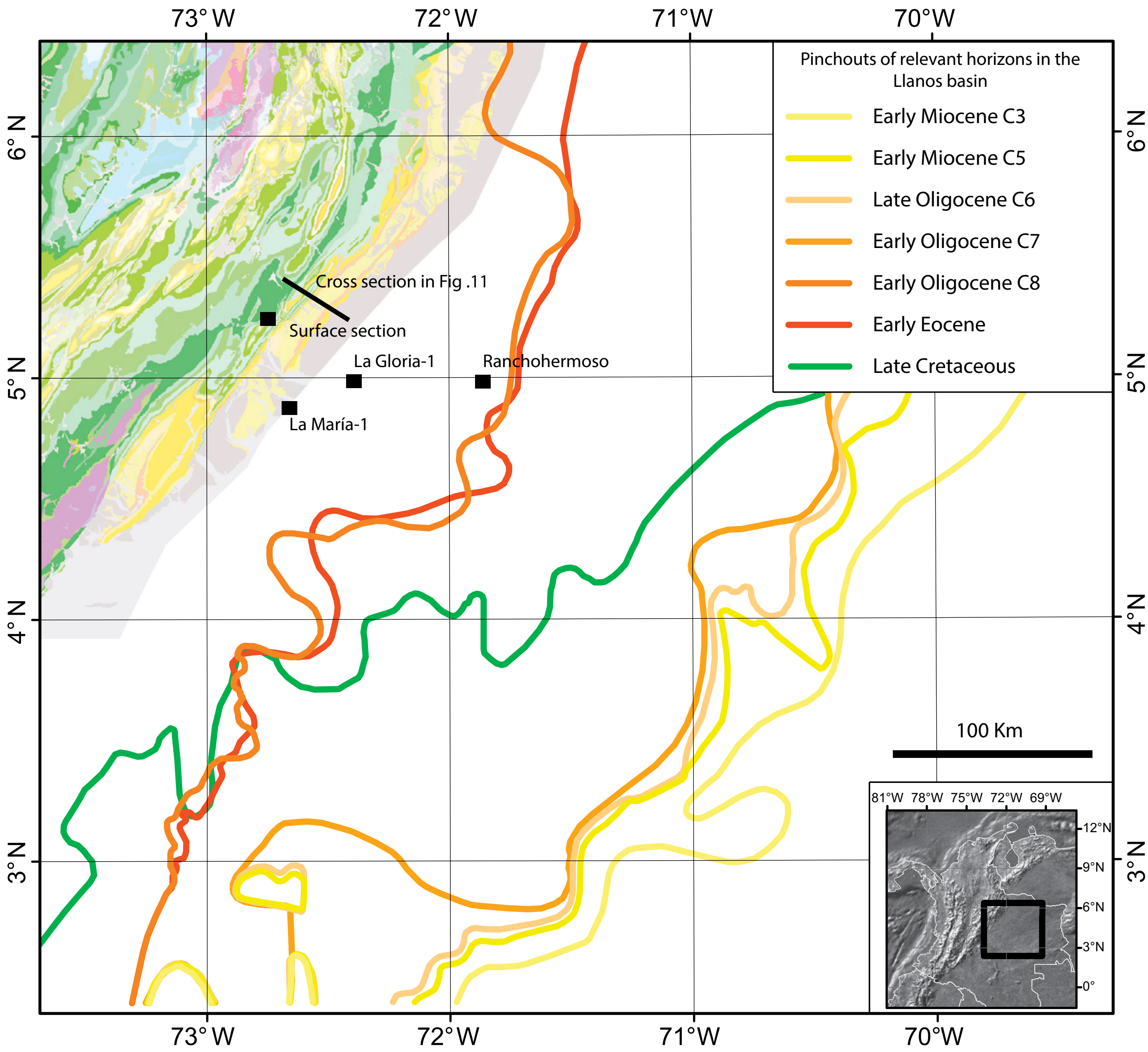

Figure 4. Map of subsurface pinch-outs of the different units in the Llanos foreland basin. The relevant shaly units as detachment levels correspond to the Late Cretaceous and the early Oligocene C8 units. The pinch out of the units coeval with the detachment levels occurs between 100 and a maximum of 300 km away from the deformation front. However, these horizons lose about one quarter of their thickness and most of their shaly levels some tens of kilometers away from the deformation front (Table DR3 [see text footnote 1]). The pinch-out distance is similar to the northern Bolivian Bení Basin (Fig. 7), but at least half of the same distance in the Chaco Basin. The colored map to the west corresponds to the uplifted Cordillera Oriental folded belt. The rock units exposed at the surface in that region are: Paleozoic or older (red and purple), Jurassic (blue), Cretaceous (green), and Tertiary (yellow).

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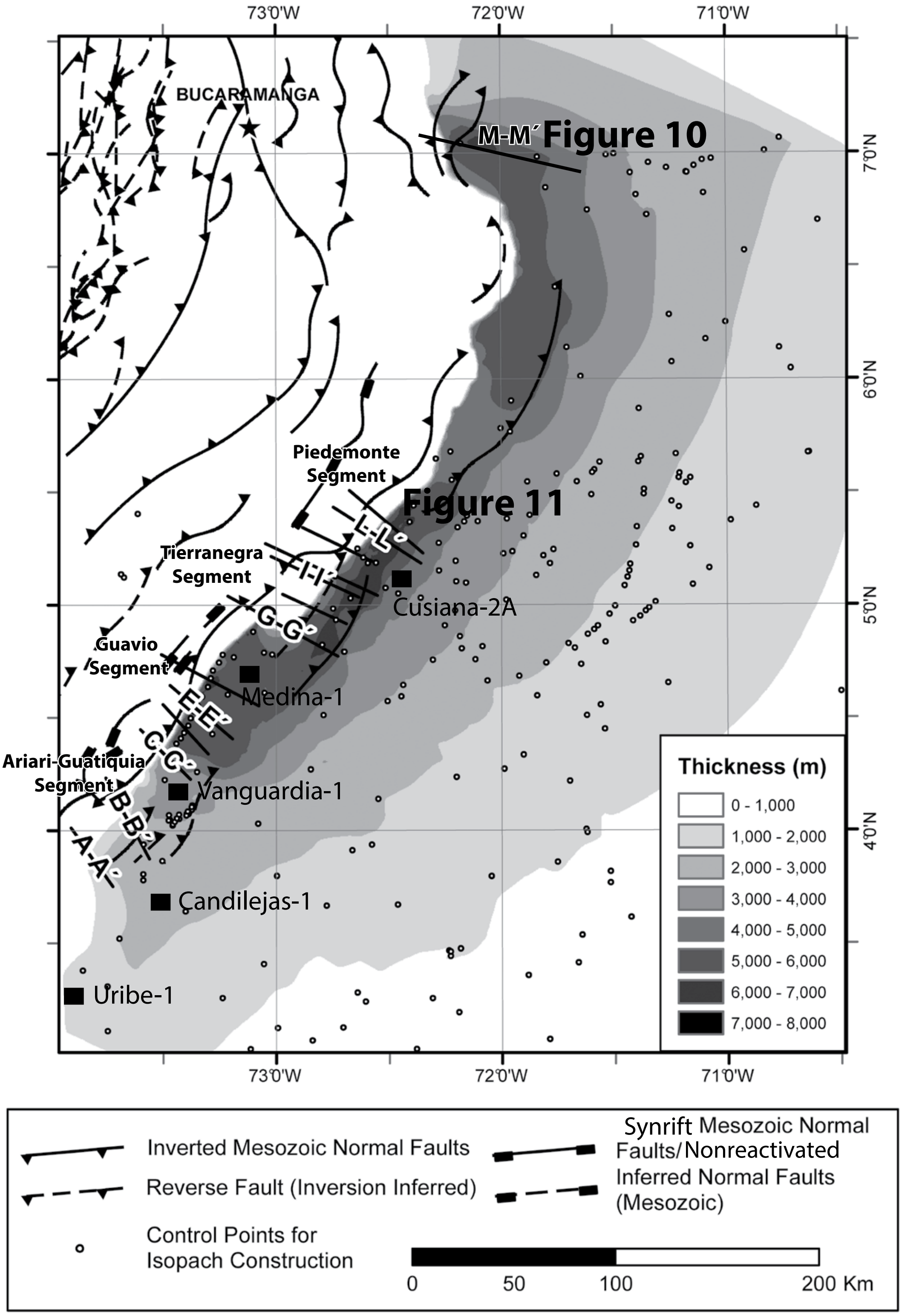

Figure 5. Isopach map of the Cenozoic units in the Llanos Basin. The cross section traces correspond with those in Jimenez et al. (2013). Notice the location of cross sections in Figures 10 (M-M′) and 11 (L-L′) in the areas with thickest Cenozoic fill, where the cross sections by Martínez (2006) and Egbue and Kellogg (2012) are also located. The duplex style of deformation has been only documented in areas north of cross section L-L′. The black squares and names correspond with the northernmost wells used by Casero et al. (1997) for the correlations that we show in Figure 6.

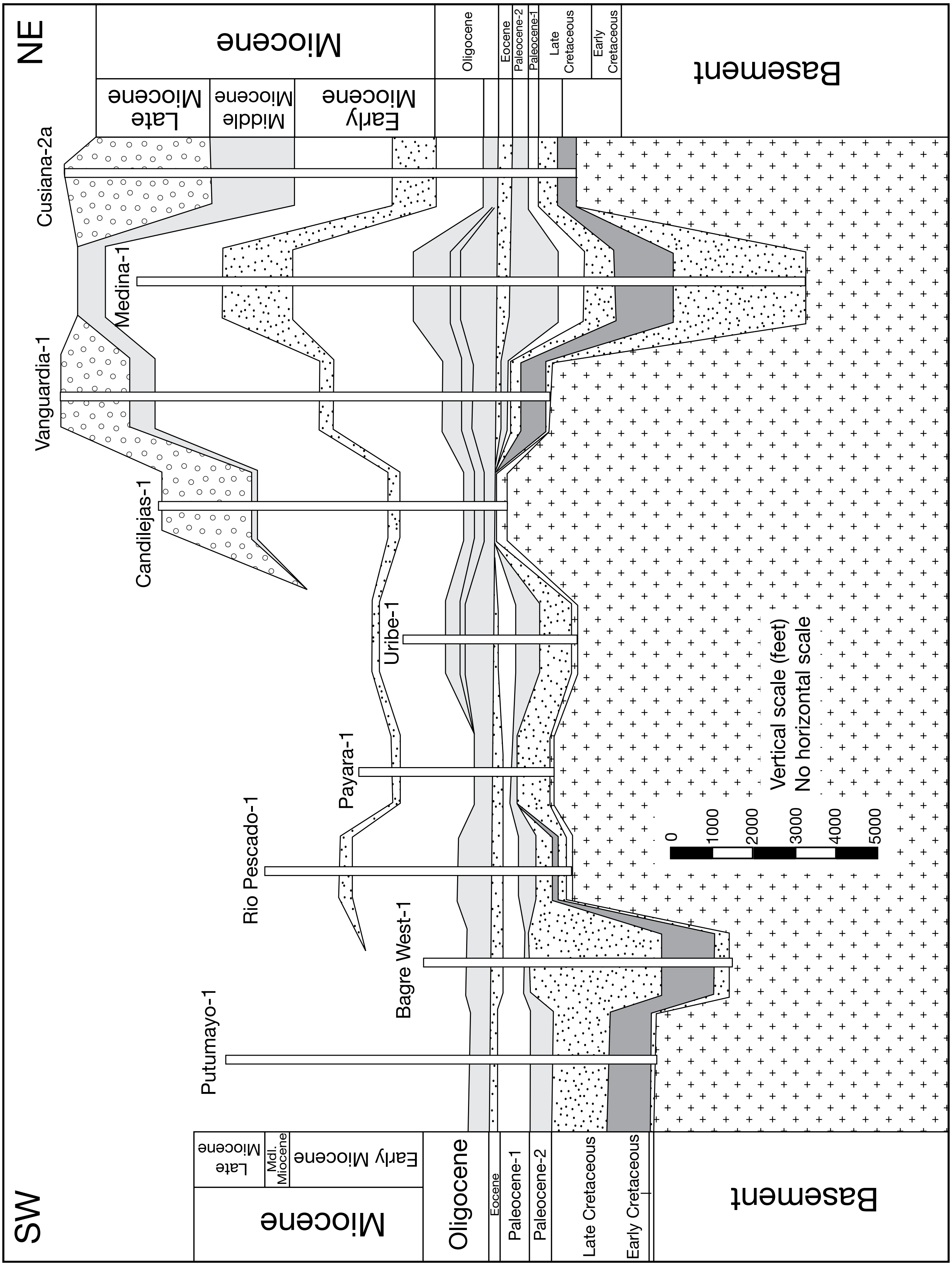

Figure 6. Correlation of wells at the proximal part of the Llanos Basin and lateral equivalents (modified after Casero et al., 1997). The southernmost well (Putumayo-1) is located right in the border with Ecuador and therefore technically is representative of the Ecuadorian Oriente Basin. Notice that the sedimentary units there are still much thinner (by ~5000 ft [1524 m]) than in the Medina-1 well area.

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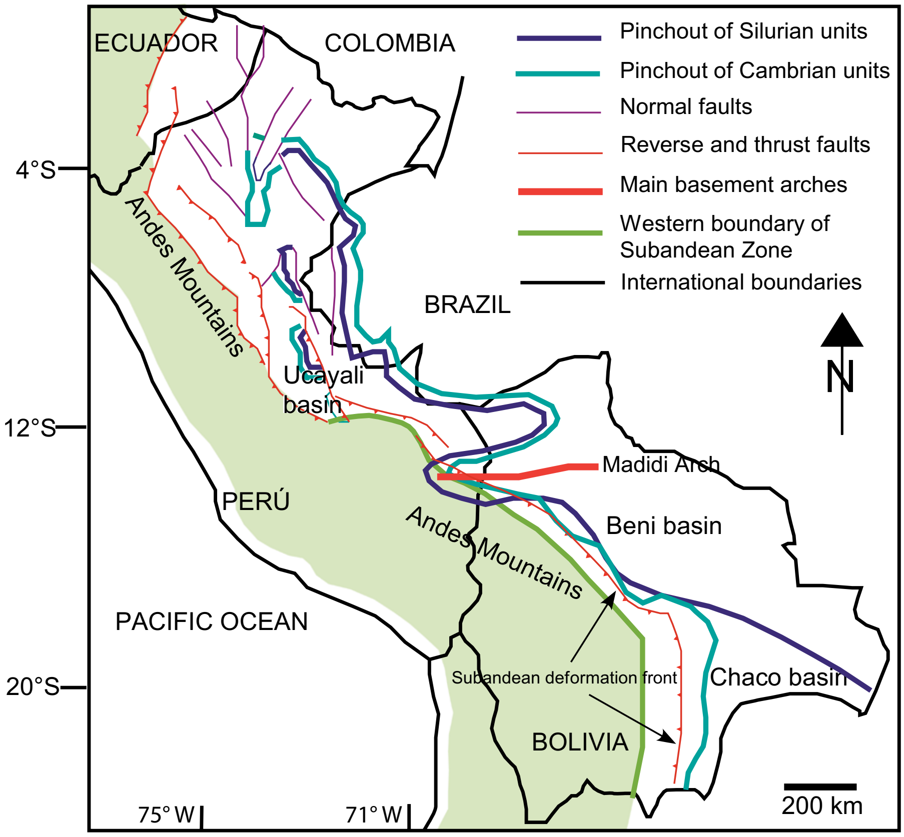

Figure 7. Tectonic sketch from Ecuador to Bolivia comparing the main structural features of those provinces and the pinch-out of the Paleozoic units in the foreland basins. Figures was produced based on recent subsurface data and previous maps by Mathalone and Montoya (1995). See Figure 2 for location.

The data so far presented appear to show that the Madre de Dios and Colombian Eastern foothills seem to have sufficient thicknesses of synkinematic deposits and potential detachment horizons that may favor the presence of passive-roof duplexes. In the following section, we use our results to test if the kinematics and evolution of the structures and associated basins also favor the localized presence of this type of structure. We first describe the kinematics of the structures in the different cross sections from north to south.

Description of the Different Antiformal Structures: Timing and Structure

Gibraltar Antiform

This structure is located in the northernmost Eastern foothills (Fig. 2), and its most frontal structure is a monocline with no obvious east-vergent emergent fault. Based on the presence of similar structures along strike, seismic data, one exploratory well (Villamil et al., 2004), structural relief, and the principles of dip domains, we deduced that this structure is an antiformal stack (cross section in Fig. 10). Following this interpretation, the structure could have grown as a passive-roof duplex bounded to the west by the "Los Deseos syncline" and with basal detachments in the Paleozoic sequence and an intra-Cenozoic upper detachment (Fig. 10). The frontal monocline folds are of Miocene age but also contain younger sedimentary units, and therefore the structures that produced that monocline should be in part younger or coeval compared to the youngest rock units. AFT data from this area show (Fig. 10; Table DR2 [see footnote 1]) that the Upper Eocene units in the El Indio anticline were the uppermost units reaching temperatures higher than those required for the apatite fission tracks to be completely reset (e.g., sample 606-11 in Fig. 10). Following this interpretation, AFT ages much younger than the stratigraphic age have been found in the Upper Eocene units and samples from lower units, all of them passing the χ^2 test. By contrast, the overlying units do not pass the χ^2 test and have AFT ages that are much older than the Oligocene stratigraphic age of the unit. AFT ages in the late Eocene units and the underlying formations are around 3.77 ± 0.62 Ma (sample 606-07 in Table DR2 [see footnote 1]) and 5.34 ± 0.89 Ma (sample 606-11 in Table DR2 [see footnote 1]). Modeling of these samples using HeFTy (Ketcham, 2005) corroborates a late Miocene onset of denudation (Fig. 10). Combining these data with assumptions about the geothermal gradient (20–25 °C/km) and an AFT total annealing temperature of ~120 °C (Ketcham et al., 2007b), AFT ages indicate that the Eocene units were exhumed from maximum paleotemperatures of ~120 °C and depths of at least 4–6 km starting in the late Miocene. Provided that the elevation difference in the Gibraltar antiformal stack of the late Eocene units above the regional level measured in the adjacent foreland is ~6 km and characterized by late Miocene or younger deposition, it seems that the most important shortening deforming the Gibraltar antiformal stack should have occurred during the last 6 m.y.

Piedemonte Antiform

The Piedemonte antiform in Colombia (Fig. 11; Martínez, 2006) exhibits a structure that was constrained in this cross section (from Jimenez et al., 2013) with three wells and seismic data using a precise projection of the trajectories to the cross-section plane. Well data also included dipmeter and recorded formational tops (Fig. 11). From the cross-section balancing, the mechanism of growth of this structure can be interpreted during part of its evolution as a passive-roof duplex. The three horses under the Piedemonte antiform fed slip east to the Yopal fault and probably back toward the west as a passive-roof structure before the Guaicaramo fault moved.

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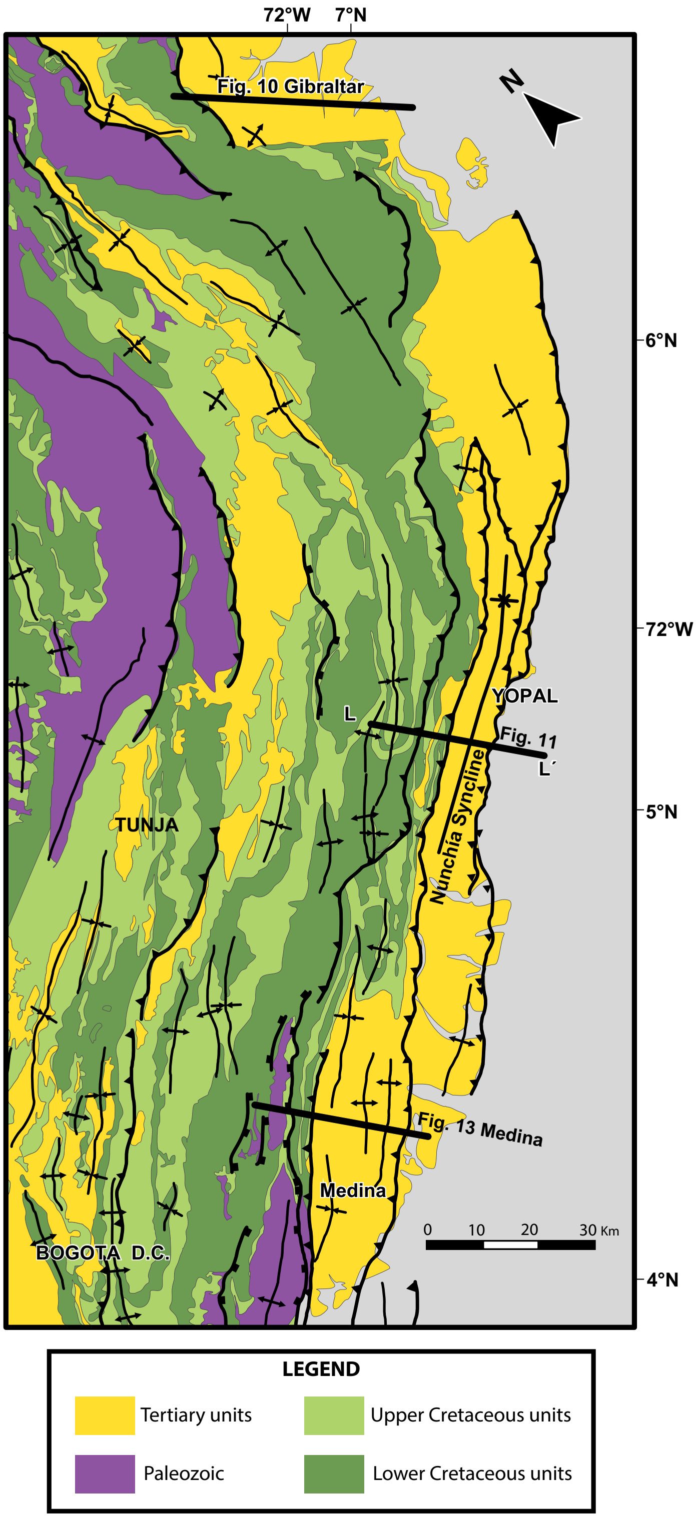

Figure 8. Generalized map of the Eastern foothills of the Colombian Eastern Cordillera.

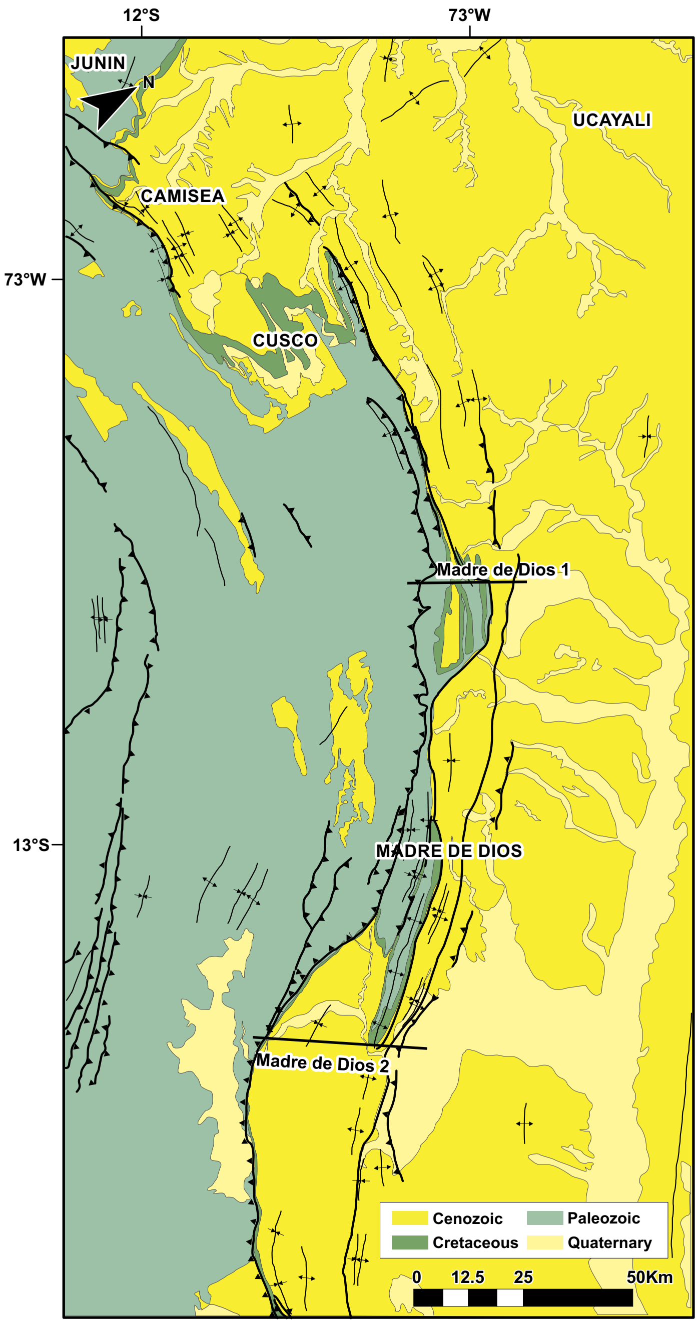

Figure 9. Generalized map of the foothills of the Peruvian Andes in the Madre de Dios Basin. Notice the presence of an arcuate shape in the basement salient with narrow marginal synclines involving Tertiary rocks here and in the Eastern foothills of the Colombian Eastern Cordillera.

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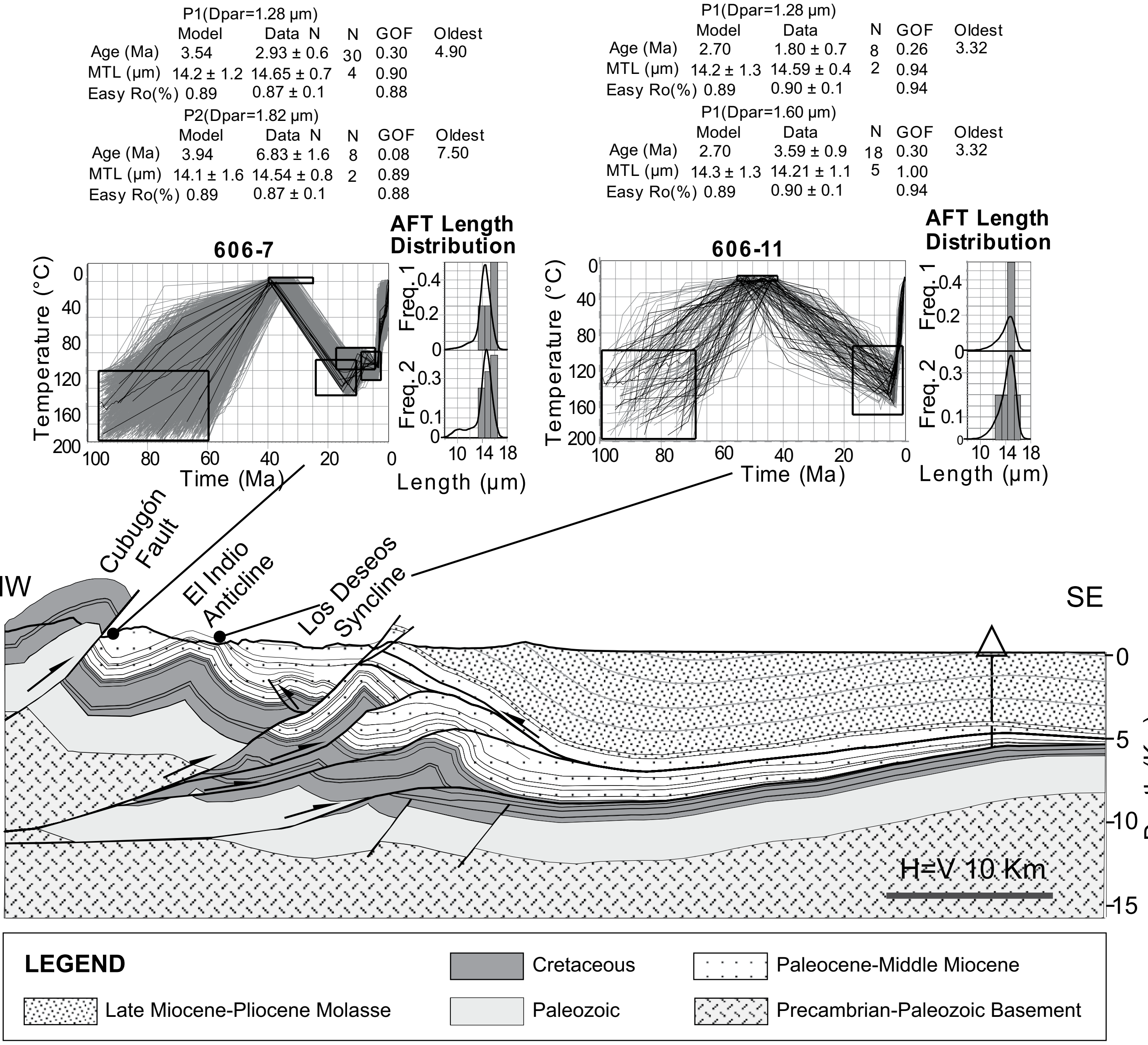

Figure 10. Results of thermal history modeling using HeFTy (top) from the Gibraltar antiformal stack and balanced structural cross section (bottom). See text for description of modeling techniques. Multiple kinetic populations were modeled, as indicated by the number of track length histograms; summary information for selected populations is indicated as "P1" for the first (lowest annealing resistance) population, "P2" for the second, etc. "*N*" indicates number of age grains or track lengths in each population, and "GOF" indicates goodness of fit of each data component. "Oldest" indicates oldest modeled track remaining. Darker paths represent good fits to the data, and lighter ones are statistically acceptable. MTL—mean track length. For more details, see Ketcham (2005). The apatite fission-track (AFT) length modeling combined with crosscutting relationships show late Miocene onset of deformation in the antiformal stack.

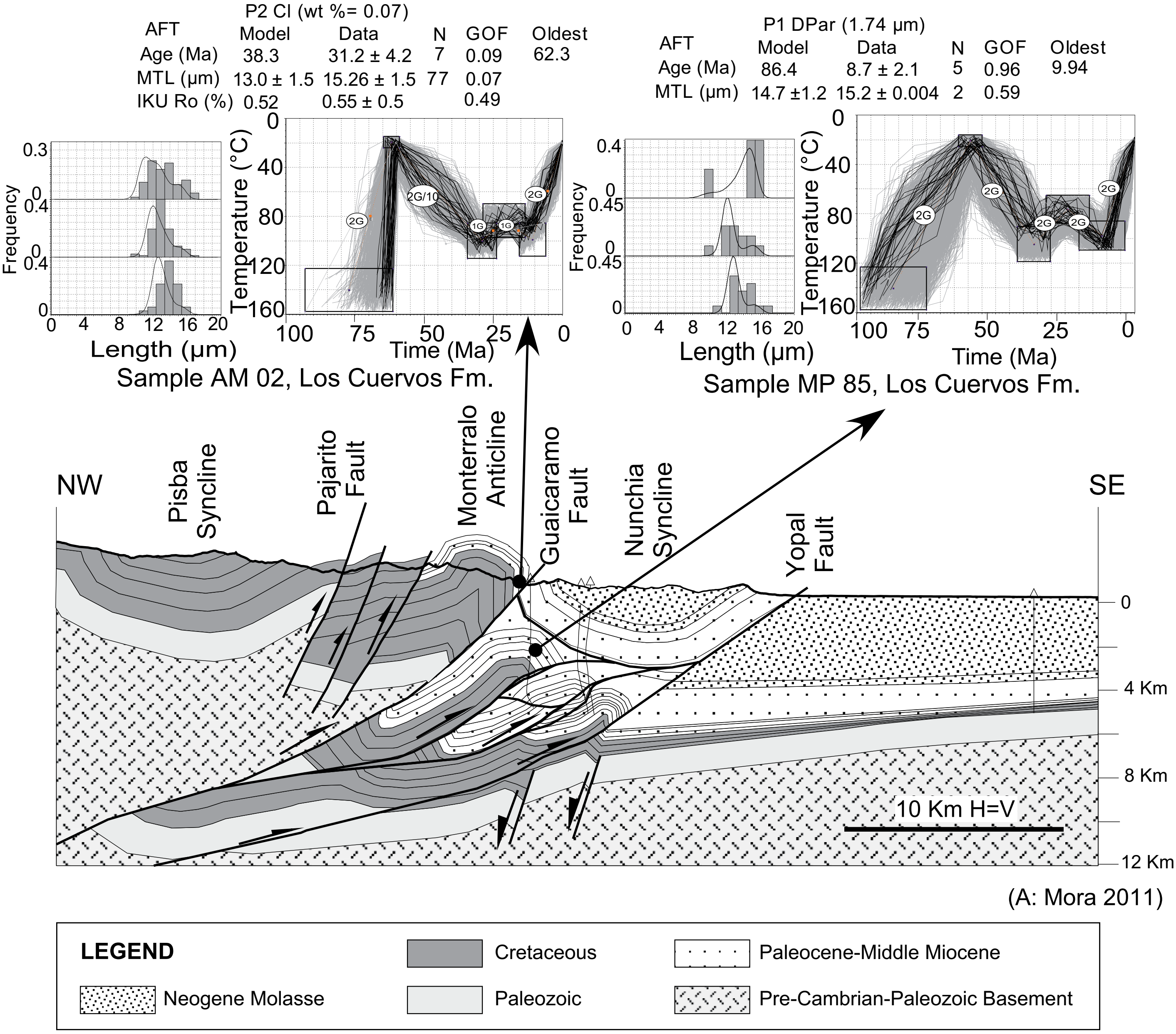

Figure 11. Results of apatite fission-track (AFT) length modeling from the Piedemonte antiformal stack (top) and balanced structural cross section (bottom; modified after Mora et al., 2010a). See Figure 10 caption for details of modeling. AFT length modeling combined with crosscutting relationships show late Miocene onset of deformation in the antiformal stack. Cl—chlorine content; IKU—Ro kinetic model; MTL—mean track length.

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We interpret a basal detachment horizon in the Paleozoic sequence and a roof thrust in the Cenozoic (Upper Eocene) shaly units. Similar to the Gibraltar area, a post–late Miocene timing of deformation can be deduced from crosscutting relationships in the cross section. The Yopal fault, at the easternmost portion of the structure, cuts through a footwall ramp in the Upper Miocene flat-lying foreland sedimentary units. The AFT data from this area have already been presented in Mora et al. (2010a) and confirm this hypothesis. AFT data from Eocene units in the Monterralo anticline, the uppermost anticline of the stack, yield AFT ages clearly younger than the stratigraphic age of the Upper Eocene units that crop out (Fig. 11; Table DR3 [see footnote 1]). All of the AFT ages from samples located stratigraphically below the Upper Eocene formations cluster around late Miocene, with the notable exception of the Paleocene samples (AM-2 and MP-85). This may confirm a late Miocene or younger important cooling event. In addition, modeling of the Paleocene samples (AM-2 and MP-85) suggests that the uppermost stacks of the Piedemonte antiformal stack underwent their most severe cooling (from temperatures of ~100 °C) after the late Miocene (Fig. 11). Importantly, the structure of the Monterralo anticline, with the Guaicaramo breakthrough fault to the east, shows a very late out-of-sequence rupture, which may suggest that AFT samples coming from that structure (e.g., AM-2; see Fig. 4) are actually dating the activity of this horse and not the activity of the lower horses. However, sample MP-85 is from the lower El Morro stack and shows similar cooling histories (Fig. 11). This indicates that the onset of cooling in Monterralo was not independent and decoupled from onset of cooling in the lower stacks (compare samples MP-85 and AM-02 in Fig. 11).

A Geometrical Comparison with the Peruvian Madre de Dios Basin

In Colombia, thin-skinned deformation in the frontal synclines adjacent to the main basement highs has been documented widely with 3-D seismic surveys in the Colombian foothills (see a representative cross section in Fig. 11; for cross sections in the same area, see Martínez, 2006; Mora et al., 2010a; Egbue and Kellogg,(2012; Jimenez et al., 2013). In Colombia, the structural relief of these thin-skinned synclines, as well as the dip of the western limb, responds to the presence of thin-skinned duplex stacks at the central parts of the arcuate basement uplift (Figs. 8 and 11). In the Colombian foothills, it has been suggested that the presence of an arcuate basement uplift adjacent to a narrow thin-skinned deformation front is related to the presence of inverted basement-involved normal faults, which focus the contractional basement deformation and structural relief (Mora et al., 2006; Moreno et al., 2013). A narrow front with synclines, such as the Punquiri syncline, involving mostly Tertiary rocks, is also present in the Madre de Dios Basin (Fig. 9). Based only on the aforementioned analogue behaviors, we propose the presence of thin-skinned duplexes similar to those in the Colombian foothills in the frontal synclines of our cross sections in Figure 12. We hypothesize that, in this case, inversion faults would also dictate that basement-involved deformation concentrates shortening, whereas the thin-skinned front is narrow. Based on these assumptions, we constructed our cross sections in Figure 12.

In the Colombian foothills, significant stacking of duplexes has been observed and documented with multiple wells and 3-D seismic surveys. Stacking is exclusively observed in areas where the horizons in the axis of the frontal Nunchía syncline are structurally higher than the coeval units in the foreland (see Fig. 8; cross sections in Fig. 11; for cross sections in the same area, see also Martínez, 2006; Mora et al., 2010b; Egbue and Kellogg, 2012; Jimenez et al., 2013). On the other hand, it is not associated with the foreland-dipping limb on the hinterland side of the frontal syncline in cases where the syncline was at almost the same regional level as the undeformed foreland (Fig. 13). In such cases, a simple basement wedge without stacked duplexes has been documented in most of Colombia, except for the Gibraltar region (cross section in Fig. 10). Only in our northern Madre de Dios section (Figs. 9 and 12) have the units in the central part of the syncline been significantly uplifted above the regional level in the foreland. This is

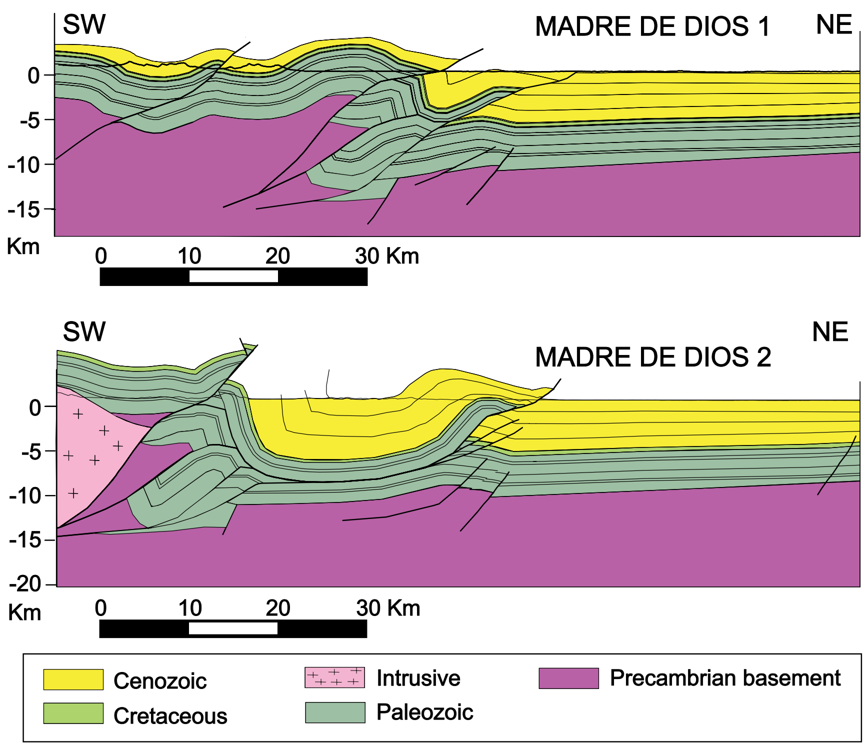

Figure 12. (A) Cross section Madre de Dios 1. (B) Cross section Madre de Dios 2. See Figure 9 for location. Notice the interpreted normal fault below the duplex stacks in both cross sections, which is similar to the case in the cross sections in Colombia (Figs. 10 and 11).

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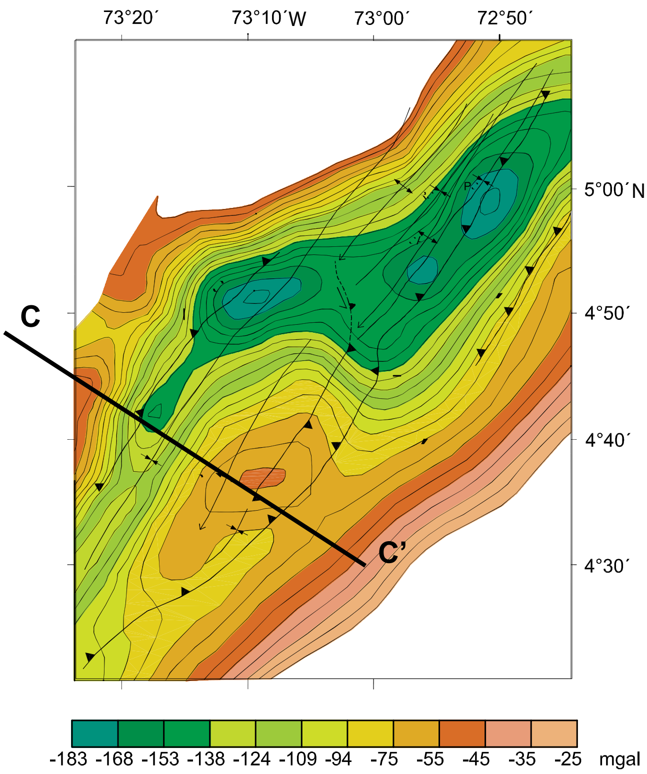
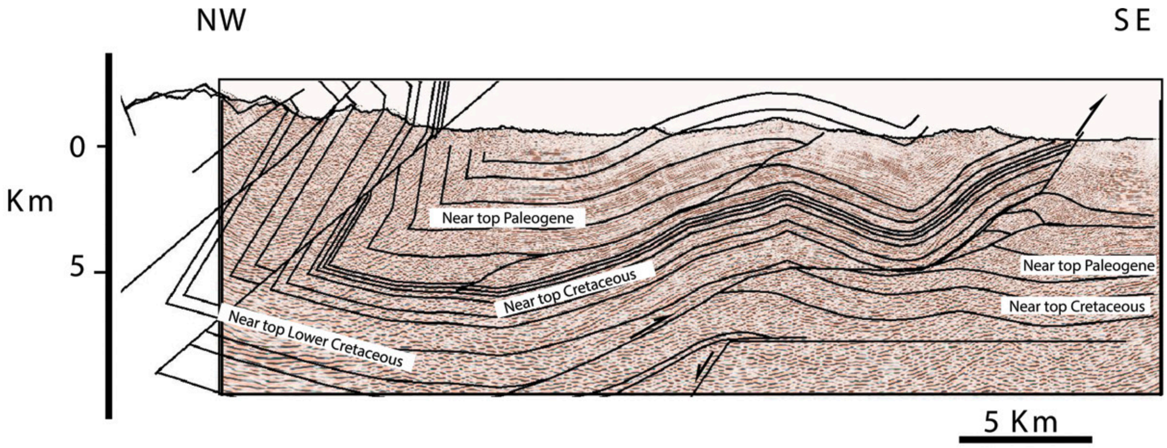


Figure 13. (Top) Gravimetric map of the Medina syncline area (see location of the Medina syncline in Fig. 5). The map depicts the variations in Bouguer anomaly in mGal (modified from Mora et al., 2006). Gravimetric lows are in green colors; orange and red colors show gravimetric highs. (Bottom) Interpreted and uninterpreted seismic lines in the same area. While the gravimetric map and the presence of a much thinner sequence in the undeformed foreland to the east (as shown by numerous wells) compared to the surface thicknesses to the west suggest a buried normal fault below the anticline, the frontal part of the seismic line suggests a hanging-wall flat involving significant thin-skinned shortening. Mora et al. (2010b) and Moreno et al. (2013) suggest that the apparent contradiction can be solved with a bypass thin-skinned structure. Notice that the regional level in the syncline and the foreland is the same, and no antiformal stacks or duplexes are present in the western limb of the syncline. Figure is after Moreno et al. (2013). See text for discussion.



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not the case in our southern Madre de Dios cross section (Figs. 9 and 12). Therefore, our thin-skinned stacked interpretation may be too optimistic in terms of thin-skinned deformation in our southern Madre de Dios section, and instead a simple and single basement wedge is also possible.

In addition, crosscutting relationships together with limited exhumation data (Mora et al., 2010c) show that the youngest Neogene units are folded and faulted, and the structures are late Neogene in age (Figs. 9 and 12). Presumably, high Neogene sedimentation rates were coeval with the structural growth and active denudation of the areas with the main structural relief in the antiformal stacks discussed here.

DISCUSSION

Previous studies suggest that the structural style of passive-roof duplexes requires rapid erosion rates often associated with steep climatic gradients (Baby et al., 1995a). Furthermore, a thick sedimentary cover with low-basal-friction detachment horizons and fast deformation rates are additional conditions (Bonini, 2001, 2007; Couzens and Wiltschko, 1996; Couzens-Schultz et al., 2003). Probably the most important feature in the mechanical stratigraphy is the lithology of the detachment horizons, which exerts a primary control on the basal shear strength of the wedge (Koyi, 1995, 1997). In the following sections, we analyze the interactions between these preexistent conditions and the basin evolution, surface processes, and the structural styles in our type locations.

From the data presented here, in the Colombian Eastern foothills, passive-roof duplexes appear to be associated with the documented presence of two detachment horizons and mostly are late Miocene features formed during times of peak depositional rates in the deepest parts of the proximal foredeep regions. Similar conditions appear to be present in the Madre de Dios Basin.

If our hypothesis holds, then the absence of passive-roof duplex structures south of 17°S, in the Bolivian Chaco Basin, where high Neogene sedimentation and surface processes were also documented (see Fig. 2 for location of the basin), is remarkable. For example, the foreland basin record in southern Bolivia reveals a 10-fold increase in sedimentation rate with the onset of Yecua Formation deposition at 12.4 Ma. A decrease in $\delta^{18}O$ of pedogenic carbonate from these strata is interpreted to indicate increased rainout caused by growing topography (e.g., Mulch et al., 2010; Uba et al., 2009). This leads to a significant change in precipitation-induced erosion in the south.

However, in this context, it is worth mentioning that the most significant finding of our refined map is the extended Paleozoic subcrop in Bolivia, based on subsurface data not available to Sheffels (1995). This allows correlation between the width of the Bolivian Subandes and the pinch-out of the Silurian units (Fig. 7). The observation strongly argues for a causal relationship. McQuarrie et al. (2008) suggested a relationship between the width of the Subandean zones in Bolivia and the precipitation north and south of this region. While this factor may potentially exert an influence, the Paleozoic basin seems to have a more straightforward effect. Thus, the broader Chaco Basin to the south may have been less favorable for the development of passive-roof duplexes and more conducive to the deformation front advance to the east (Fig. 14), since the Paleozoic basin is much broader here compared with the areas north of the Bolivian orocline.

In the areas of the Madre de Dios Basin where we made our cross sections, the pinch-out of the Paleozoic detachments is not as close to the deformation front as in the Beni Basin north of the Bolivian orocline. We speculate that the narrow deformation front could be controlled by the presence of normal faults below the frontal structures as in the Colombian foothills (compare cross sections in Figs. 10, 11, and 12 as well as Fig. 13).

Climatic Control

An important component of the processes at work in a growing wedge is overcoming gravitational forces (Mitra and Boyer, 1986; Hilley and Strecker, 2004). Erosion is an instrumental mechanism for reducing gravity (Mugnier et al., 1997; Baby et al., 1995a; Koyi et al., 2000; Hilley and Strecker, 2004; Hoth et al., 2006), and the main process driving erosion and mass transport in tropical regions is rainfall. It is thus notable that the Madre de Dios, Camisea, Gibraltar, and Piedemonte areas are close to regions with annual precipitations higher than 4 m/yr, and all are close to the present-day topographic front of the Andes, characterized by high topographic relief (Fig. 15; Bookhagen and Strecker, 2008). Recent publications have shown that it is likely that present-day humid conditions have existed since at least the late Miocene (Kaandorp et al., 2005), with precipitation concentrated in the Andean topographic front as long as topography higher than 2 km existed (Hain et al., 2011). The paleoelevation data available in Peru (Picard et al., 2008; Saylor and Horton, 2014) and Colombia (Hooghiemstra et al., 2006) are derived from areas to the west and adjacent to all of the localities studied in this paper. The data show that elevations close to present-day topographic elevations and higher than 2 km were reached by the early to middle Miocene (Picard et al., 2008) west of the Madre de Dios section in the Eastern Cordillera, toward the middle to late Miocene in the Eastern Cordillera west of the Ucayali Basin (Picard et al., 2008), and between the late Miocene and Pliocene in the Colombian Eastern Cordillera west of the Piedemonte area (Hooghiemstra et al., 2006).

Thus, the timing of the passive-roof duplex structures in the Subandes documented here is in all cases later or at least synchronous with the time when the adjacent Eastern Cordilleras reached more than 2 km of elevation. It is therefore likely that the Eastern Cordilleras formed orographic barriers, which coexisted at the same time as the deformation in the Subandean zones. In addition, Mora et al. (2010c) suggests that this situation led to more pronounced late Miocene erosion rates in the eastern front of the Andes and increasing sedimentation rates in the adjacent foredeep

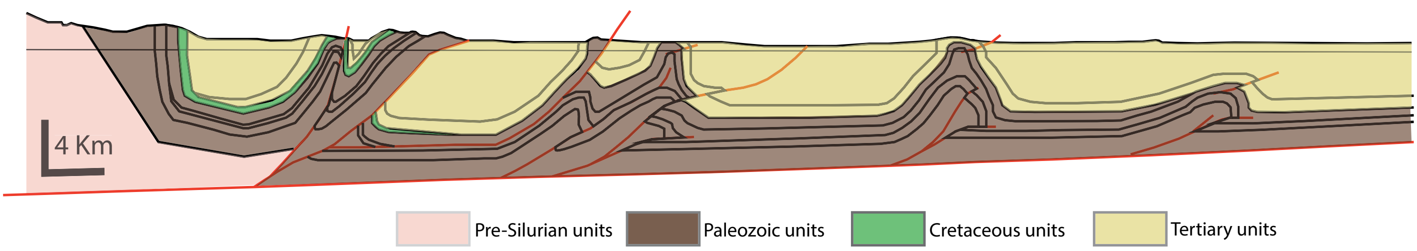

Figure 14. Simplified version of the cross section by Echavarria et al. (2003) from the Chaco Basin (see location in Fig. 2, and discussion in the text). Notice the absence of active or passive-roof duplexes and the much broader deformation area.

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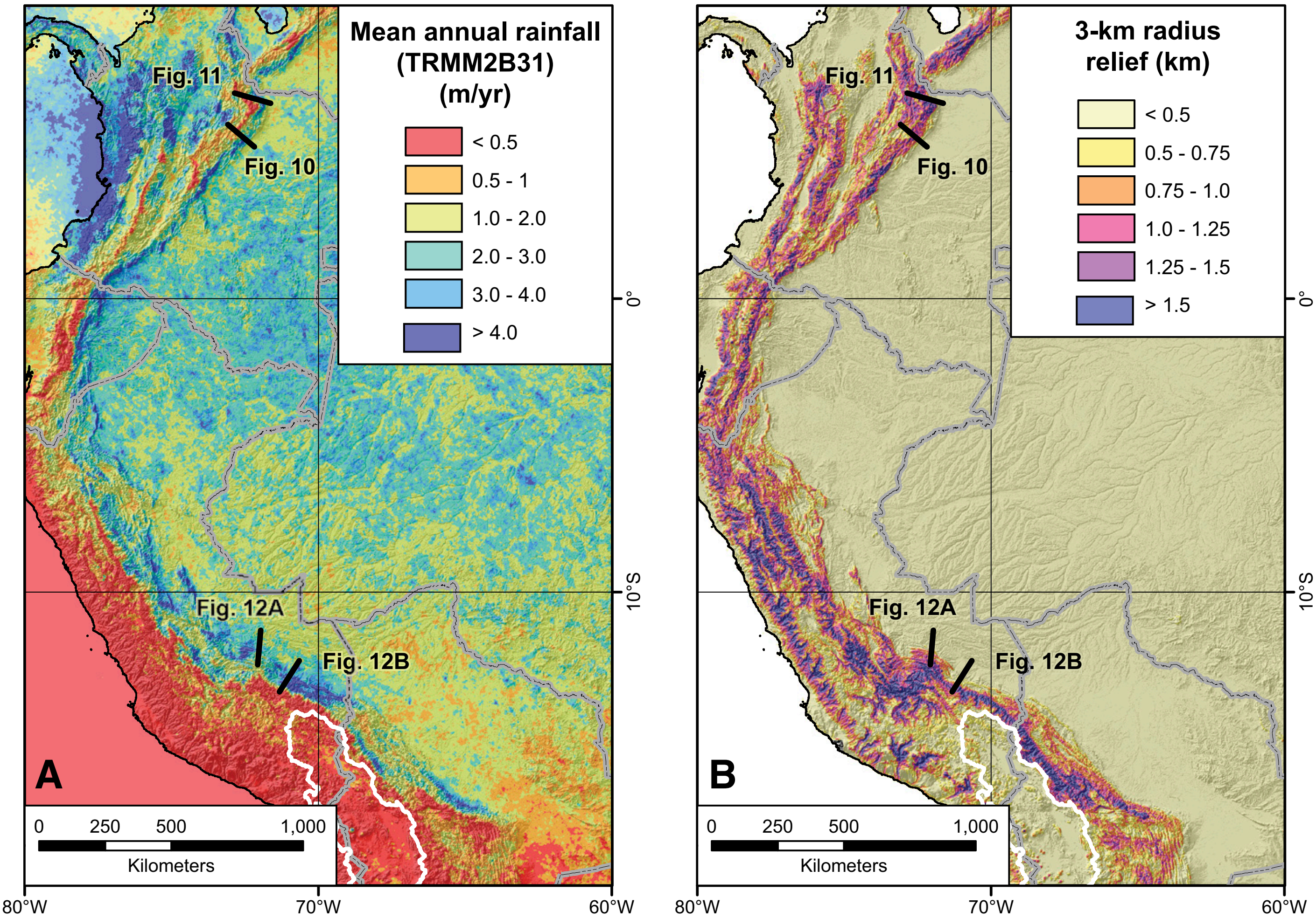

Figure 15. (A) Tropical Rainfall Measurement Mission (TRMM) map of the northern and central Andes. TRMM data are based on product TRMM 2B31 with previously described processing and calibration steps (Bookhagen and Strecker, 2008; Bookhagen and Burbank, 2010). Data show mean annual rainfall rates averaged over 13 yr (1998–2010). International borders are in gray, and the northern part of the internally drained Altiplano-Puna Plateau is shown in white. Note the high rainfall amount along the eastern Andes at orographic barriers. (B) Calculated relief for the northern Andes. Notice the presence of an abrupt topographic change from Andean front to the foothill regions in the Colombian as well as in the Peruvian foothill areas.

(see also Roddaz et al., 2010). Thus, with such a climatic regime similar to that observed today, it appears that the surface processes could have conditioned the Subandean belt's structural growth. We hypothesize that, as suggested by Baby et al. (1995a), Mugnier et al. (1997), and others, based on analog modeling, the passive-roof duplex style was partly conditioned by intense erosion and mass removal of the growing structures and rapid sedimentation in the adjacent foredeep. Additional accommodation space generation could have been facilitated by higher elevations in the hinterland, but also the basin should have had a thick crust that allowed the foreland lithosphere to be flexed under the orogenic loads. We therefore propose that more humid climatic zones in the topographic front adjacent to the Subandean zones north of the Bolivian orocline facilitated the generation of a structural style of passive-roof duplexes in thin-skinned belts such as Madre de Dios, Piedemonte, and Gibraltar.

However, we reiterate that the pinch-out of the detachment units along very short distances in the foreland direction in the Colombian Llanos Basin is much narrower. These are areas where the Subandes have passive-roof duplex structures in a narrow foothill belt, compared with the southern Bolivian Subandes, where these structures do not exist, and the foothill belt is much broader. This documents a primary lithostratigraphic control that was in place before the Neogene influence of the surface processes. We speculate that, as documented in the Colombian foothills (Moreno et al., 2013; Fig. 13), the presence of pre-Andean Cretaceous normal faults in the subsurface below the stacks would also act as rigid obstacles in the Madre de Dios Basin, impeding the advance of the deformation front, as has been suggested in analog models by Schedl and Wiltschko (1987).

Following the analogue models, a final element required for passive-roof duplex formation is the presence of fast shortening rates (Bonini, 2001, 2007; Couzens and Wiltschko, 1996; Couzens-Schultz et al., 2003). The documented passive-roof duplex structures were shortened by 20 km (e.g., Piedemonte; Martínez, 2006; Mora et al., 2010a) in less than 10 m.y., suggesting rates of shortening of at least 2 mm/yr. Other data sets suggest that these values imply peak Cenozoic shortening rates in the Andean orogen as a whole (Echavarria et al., 2003; Oncken et al., 2006; Mora et al., 2008, 2010c; Uba et al., 2009; Espurt et al. 2011). It has been recently documented that faster Neogene to recent deformation rates in the Colombian foothills were focused in the foothill regions (Mora et al., 2013). Thus, our data suggest that migration of deformation toward the previously undeformed deformation fronts implies that they occurred during the maximum rates of shortening.

CONCLUSION

Passive-roof duplexes are important structures that can accommodate large structural shortening amounts and have therefore significant implications for orogen evolution. In the Andes, several passive-roof duplexes have been documented, and we have compiled and reevaluated these data, but also added new age constraints. Our analysis suggests that passive-roof duplex structures along the eastern Andes appear to have only formed in areas with a relatively narrow range of tectonic and climatic boundary conditions. These are constrained by a combination of pre-orogenic structures, lithological and mechanical behavior, foreland crust able to flex under the orogenic load, and high surface mass transport rates (erosion rates) often associated with high rainfall amounts. All of these conditions are met in the Andes north of 17°S. We document the presence of two detachment horizons in our type locations, deposited much earlier than the timing of passive-roof duplex formation. However, initiation of passive-roof duplexes only occurred when threshold elevations were reached in the hinterland to promote orographic rainfall processes with documented higher erosion rates and higher shortening rates at the deformation front. This occurred coeval and interrelated with the maximum amount of overburden in the undeformed foreland regions adjacent to the deformed areas. Therefore, we suggest that thin-skinned passive-roof duplexes potentially only occur in areas where all boundary conditions are met. Previous descriptions of passive-roof duplexes based only on limited surface data may need to be revised, and associated crustal shortening assessments may need to be adjusted, because of their potentially large overestimation. The conditions mentioned here should be assessed when the presence of stacked duplex structures is interpreted in foothill prospects where limited seismic or surface geology data are available.

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