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**The detrital record of Late-Miocene to Pliocene surface uplift and
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foreland basins**

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ABSTRACT/SUMMARY

A multidisciplinary approach, combining sediment petrographic, palynological and thermochronological techniques, has been used to study the Miocene-Pliocene sedimentary record of the evolution of the Venezuelan Andes. Samples from the Maracaibo (pro-wedge) and Barinas (retro-wedge) foreland basins, proximal to this doubly vergent mountain belt, indicate that fluvial and alluvial-fan sediments of similar composition were shed to both sides of the Venezuelan Andes. Granitic and gneissic detritus was derived from the core of the mountain belt, while sedimentary cover rocks and uplifted foreland basin sediments were recycled on its flanks.

Palynological evidence from the Maracaibo and Barinas basins constrains depositional ages of the studied sections from Late Miocene to Pliocene. The pollen assemblages from the Maracaibo Basin are indicative of mountain vegetation, implying surface elevations of up to 3500-4000 m in the Venezuelan Andes at this time. Detrital apatite fission-track (AFT) data were obtained from both stratigraphic sections. In samples from the Maracaibo basin, the youngest AFT grain-age population has relatively static minimum ages of 5 ± 2 Ma, while for the Barinas basin samples AFT minimum ages are 7 ± 2 Ma. With exception of two samples collected from the Eocene Pagüey Formation and from the very base of the Miocene Parángula Formation, no evidence for resetting and track annealing in apatite due to burial heating in the basins was found. This is supported by rock-eval analyses on organic matter and thermal modeling results. Therefore, for all other samples the detrital AFT ages reflect source area cooling and impose minimum age constraints on sediment deposition.

The main phase of surface uplift, topography and relief generation, and erosional exhumation in the Venezuelan Andes occurred during the Late Miocene to Pliocene. The Neogene evolution of the Venezuelan Andes bears certain similarities with the evolution of the Eastern Cordillera in Colombia, although they are not driven by exactly the same underlying

geodynamic processes. The progressive development of the two mountain belts is seen in the context of collision of the Panama arc with northwestern South America and the closure of the Panama seaway in Miocene times, as well as contemporaneous movement of the Caribbean plate to the east and clock-wise rotation of the Maracaibo block.

Keywords: Venezuelan Andes, apatite fission-track analysis, palynology, exhumation, surface uplift

INTRODUCTION

The Northern Andes in northwestern South America are a complex assemblage of mountain belts, sedimentary basins and reactivated faults, driven by the interaction of the Nazca plate, Caribbean plate, South American plate and Panamá arc (Fig. 1), and modulated by climatic conditions (e.g. Dengo and Covey, 1993; Colletta et al., 1997; Mora et al., 2008, Hoorn et al., 2010; Farris et al., 2011). While the evolution of the Western and Central Cordilleras in Colombia is related to Late Cretaceous arc-terrane accretion (e.g. Case et al., 1990; Dengo and Covey, 1993; Gregory-Wodzicki, 2000; Cediel et al., 2003), the driving factors of the evolution of the Eastern Cordillera in Colombia and the Venezuelan Andes are under discussion. Therefore, the uplift and exhumation histories of these two mountain belts hold important information on the tectonic evolution and possible climatic feedback in this region (e.g. Mora et al., 2008, 2010a, 2010b; Parra et al., 2009a, 2009b, 2010; Bermúdez et al., 2010, 2011, 2013). Of particular interest in this respect are the timing of surface uplift, the creation of high topography, and its relationships with the nature and timing of sedimentation and subsequent thermal history of sedimentary basins flanking the Venezuelan Andes.

The Venezuelan (or Mérida) Andes in northwestern Venezuela result from rotation and oblique convergence between the Maracaibo continental block to the north and the South

American plate to the south (Fig. 1; Case et al., 1990; Colletta et al., 1997; Montes et al., 2005; Pindell and Kennan, 2009). It forms a doubly vergent mountain belt with the pro-wedge facing northwest, related to underthrusting of the Maracaibo Block below South America (Colletta et al., 1997). Convergence started in the late Paleogene and resulted in major surface uplift, evolution of the drainage pattern and exhumation of the Venezuelan Andes during the Late Miocene (Kohn et al., 1984; Hoorn et al., 1995; Bermúdez et al., 2010, 2011, 2013). The growth of the Venezuelan Andes apparently caused the separation of the Maracaibo and Barinas-Apure basins (Guzmán and Fisher, 2006), which previously formed a continuous basin bounded by the northern Andes in Colombia to the NW and W and the Guyana Shield to the SE (Fig. 1).

The pro-wedge Maracaibo foreland basin, flanking the Venezuelan Andes to the north, contains Miocene-Pliocene detrital deposits that are divided into the Palmar, Isnotú and Betijoque formations (Lorente, 1986; James, 2000). These deposits grade from shallow marine mudrocks to fluvial mudrocks, sandstones and conglomerates, derived from erosion of the center and northern flank of the uplifting mountain belt.

The Barinas-Apure basin, here simply referred to as the Barinas basin (Figs. 1 and 2), is the retro-foreland basin on the southern flank of the Venezuelan Andes. This basin connects with the Llanos basin in Colombia to the SW, and forms part of the Orinoco River drainage basin. The Miocene-Pliocene deposits of the Barinas basin include the Parángula and Río Yuca formations. Both formations consist of fluvial mudrocks, sandstones and conglomerates, derived from erosion of the center and southern flank of the Venezuelan Andes. The Miocene-Pliocene history of surface uplift and erosional exhumation of the Venezuelan Andes is thus preserved in these synorogenic sedimentary rocks, which makes them important for understanding the long-term evolution of this mountain belt.

The driving forces and patterns of exhumation of the Venezuelan Andes were

described in a series of previous studies employing bedrock and detrital apatite fission-track (AFT) thermochronology (Kohn et al., 1984; Bermúdez et al., 2010, 2011, 2013). Here, we extend these studies by focusing on the Maracaibo and Barinas basin sediments and incorporating complementary methodologies, including sediment petrography, palynology and organic maturity data. These data were collected from stratigraphic sections in both the pro- and retro-wedge foreland basins, in order to retrieve the exhumation record on both sides of the Venezuelan Andes.

Sediment petrographic analyses on conglomerates in the field and on sandstones in thin sections provide information on source-rock lithologies and sediment provenance. The palynology and thermochronology data provide independent constraints on stratigraphic ages. Rock-Eval analyses of organic matter were performed in order to obtain independent constraints on the thermal history of the sedimentary basins. For these, detailed chrono-stratigraphic data has proven difficult to obtain, mainly because these formations crop out discontinuously, are poor in fossil content and difficult to date with magnetostratigraphy due to the presence of coarse-grained lithologies (Betijoque and Río Yuca formations), or strong secondary magnetization (Parángula Formation; Erikson et al., 2012). Finally, we discuss similarities and differences between the evolution of the Venezuelan Andes and the Eastern Cordillera in Colombia, in the context of the Caribbean geodynamics.

Body of the text:

GEOLOGY OF THE VENEZUELAN ANDES AND ASSOCIATED FORELAND BASINS

Basin formation in northwestern South America started in the late Jurassic, with development of graben systems during Atlantic rifting (Case et al., 1990; Pindell and Kennan, 2009). These grabens were filled with clastic sedimentary rocks of the La Quinta Formation.

Continuous rifting led to development of a passive margin during the Early Cretaceous, in which the La Luna Formation, a calcareous shale unit that is the source rock of 98% of all petroleum reserves in the Maracaibo basin ([Escalona and Mann, 2006](#)), was deposited. The La Luna Formation is overlain by the Upper Cretaceous Colon Formation and the Paleocene Guasare Formation. The tectonic setting of the Maracaibo basin changed from a passive margin to a foreland basin in the late Paleocene, due to the onset of oblique convergence between the Caribbean and South American plates ([Lugo and Mann, 1995](#)). Clastic sediments, derived from the uplifted and eroded northern Colombian Andes, were transported into the Maracaibo basin, resulting in deposition of the Eocene shallow-marine/deltaic Misoa Formation and migration of the basin depocenter to the west. The mainly quartz-arenitic Misoa Formation is one of the two main reservoir rocks of the Maracaibo basin today ([Escalona and Mann, 2006](#)). The reservoir is sealed by low-permeability sediments on top of a regional Late-Eocene/Oligocene unconformity, which indicates uplift and partial erosion of the basin deposits during the Oligocene. Subsidence recommenced in the southern Maracaibo basin in the Early-Middle Miocene, with deposition of the shallow marine clastic La Rosa/Palmar Formation followed by the Upper Miocene fluvial Isnotú Formation and the Pliocene alluvial fan deposits of the Betijoque Formation. The Betijoque Formation can be further divided into the Vichú and Sanalejos members ([Guerrero et al., 2009](#)). Proximal parts of the Palmar, Isnotú and Betijoque formations have been tilted to the north and exposed along the northern flank of the Venezuelan Andes since the Late Pliocene-Pleistocene (Figs 2 and 3A). In total, the pro-wedge foreland basin of the Venezuelan Andes reaches a maximum thickness of about 6 km ([De Toni and Kellogg, 1993](#)).

Miocene-Pliocene flexural subsidence was caused by crustal loading of the rising Venezuelan Andes, which resulted from oblique collision of the Maracaibo block with the South American plate ([De Toni and Kellogg, 1993](#)). This change in regional plate kinematics

may have been driven by collision of the Panama Arc with the northern Andes in Colombia (Kohn et al., 1984; Colletta et al., 1997), resulting in clockwise rotation of the Maracaibo block and the Santa Marta massif (Fig. 1; Montes et al., 2005, 2010).

The Barinas basin is limited to the southeast by the Guyana shield, to the west by the Eastern Cordillera of the Colombian Andes, and to the northeast by the El Baúl Arch (Fig. 1). During the Late Cretaceous and Eocene, the Barinas basin was connected to the Maracaibo basin (Zambrano et al., 1972; Roure et al., 1997; James 2000; Guzmán and Fisher, 2006). Middle Eocene marine clastic sediments of the Gobernador and Pagüey formations reach a thickness of up to 1 km in the Barinas basin. In contrast to most parts of the Maracaibo basin, the central part of the Barinas basin was affected by subsidence during the Oligocene, leading to deposition of the Carbonera Formation. This formation is not preserved in the proximal basin, where units are generally tilted to the south and exposed along the southern flank of the Venezuelan Andes today (Fig. 3B). Here, the Eocene Pagüey Formation is unconformably overlain by the Miocene fluvial Parángula Formation, which in turn is (unconformably?) overlain by the Late Miocene to Pliocene fluvial Río Yuca Formation. In contrast to the relatively deep northern pro-wedge foreland basin, the southern retro-wedge foreland basin reaches a maximum thickness of only 2-3 km (De Toni and Kellogg, 1993; Chacín et al., 2005; Jácome and Chacín, 2008).

SAMPLE COLLECTION

Maracaibo basin

On the northern flank of the Venezuelan Andes, two complementary sections were mapped and sampled along the Río Hoyos and Río Vichú, north of the city of Betijoque, in the state of Trujillo (Figs 2 and 3A). The combined sections record about 2700 m of continuous stratigraphy, entirely in the Pliocene Betijoque Formation (Fig. 4).

Seven sandstone samples were collected along the Río Hoyos and Río Vichú sections for petrographic thin-section analysis (RH2, RH3, RH9, RH17, RV2, RV3, and RV6). In addition, 52 palynological samples were collected from mudrock deposits along the Río Hoyos section (CH74 to CH 125; Fig. 4), and two samples of organic material were collected for Rock-Eval analyses (RV1, RV3; Fig. 4). A total of seven samples, ~5-15 kg each, were collected from medium to coarse-grained sandstones of the Betijoque Formation for detrital apatite fission-track (AFT) analysis. Three samples (H2, H9 and H11) were collected along the Río Hoyos section, and four samples (V33, V90, V95 and V97) were collected along the Río Vichú section (Fig. 4).

Barinas basin

The entire section of the Upper Miocene-Pliocene Parángula and Río Yuca formations was studied along the Parángula River to the west and south of the town of Barinitas, on the southern flank of the Venezuelan Andes (Figs. 2 and 3B). The total thickness of the Neogene section we studied is about 2700 m. Eleven sandstone samples were collected for petrographic thin section analysis (PAS2, PAS6, PAS10, PAS13, PAS20, PAS24, PAS28, PAS29, PAS35, PAS41, and PAS42, Figs. 5 and 9). A total of 73 palynological samples were collected from mudrock deposits (CH1-CH73, Fig. 5), while two samples of organic material were collected for Rock-Eval analyses (CH51(1), CH52(2); Fig. 5). For AFT analysis, samples were collected from the Eocene Pagüey Formation (PAN-3), the Parángula Formation (PAN-1, TPG-1, TPG-2), and the Río Yuca Formation (TPMY-2, TPMY-3, TPMY-4, TPMY-5, TPMY-7 and TPMY-8) along the Parángula River section (Fig. 5).

METHODS

Sediment petrography

Stratigraphic logs and descriptions of conglomerate petrography are based on our field observations. In the Maracaibo basin section, we performed clast counts over a 3600-cm² surface area directly on the conglomerate outcrops. Only pebbles were counted that had a minimum size of 3 cm along their long axis, distinguishing granite, gneiss, amphibolite quartzite, sandstone and mudstone clasts. Percentages were calculated from the total clast counts (about 50 counts per location), normalized to 100 percent. No pebble counts were performed in the Barinas basin section because of the lack of conglomerates.

Thin sections of sandstone samples were point-counted at 10 – 100× magnification using a BX41 Olympus polarizing microscope; over 300 points were counted per thin section.

We acknowledge that grain-size may bias the results (Garzanti et al., 2007) but because the samples showed at least moderate sorting, this bias is considered small. Therefore we distinguished mono- and polycrystalline (>3 subgrains) quartz, feldspar (K-feldspar and plagioclase), mica (muscovite, biotite and chlorite), sedimentary lithic grains (chert, sandstone, siltstone, mudstone and carbonate clasts), metamorphic lithic grains (phyllite, mica schist, gneiss), igneous lithic grains (granite), other grains, calcite cement, iron oxide cement, matrix and porosity (primary and secondary). The values of mono- and polycrystalline quartz were combined to calculate total quartz for representation in a Quartz-Feldspar-Lithic grains (QFL) diagram (Folk, 1965). The feldspar component is calculated by combining K-feldspar and plagioclase. Lithic grains were combined for calculating the rock-fragment component.

Palynology

The palynological analysis was aimed at better constraining the depositional age of the Betijoque and Río Yuca formations. For this reason, particular attention was paid to the presence of biostratigraphic markers as defined for the Caribbean ([Germeraad et al., 1968](#); [Lorente, 1986](#); [Muller et al., 1987](#)), the Andes ([Hooghiemstra, 1984](#); [Torres-Torres, 2006](#)) and the Llanos basin ([Jaramillo et al., 2011](#)). The most productive samples from the Betijoque Formation were collected from a one meter thick series of grey laminated clays (at 1620 m in our section) that represent a channel infill in a sequence of otherwise braided fluvial deposits. This bed was sampled at every 10 centimeters and all samples were processed. The samples from the Río Yuca Formation were collected from very organic-rich clay beds that occur in the middle part of the formation. The palynological slides were rich in fine, black and dark-brown colored organic matter; nevertheless, pollen densities were very low. Out of 31 samples from the Río Yuca Formation that were chosen for processing, 25 samples contained pollen but only 6 slides produced sufficient pollen for analysis (above 50 grains per sample). The palynological assemblage was dominated by reworked pollen species. For this reason the palynological results are represented in table format, and not in the usual graphical manner. The positions of all samples are indicated in the stratigraphic columns in Figs. 4 and 5.

Palynological processing followed standard procedures at the department of Paleoecology and Landscape Ecology at the University of Amsterdam. For each sample one cm³ of material was taken. Organic-rich clays and silts were treated with a 10% sodium pyrophosphate (Na₄P₂O₇·10H₂O) solution and sieved over 250 µm mesh size. At the end of the process bromoform with a density of 2.0 g/cm³ was used to separate the organic and inorganic fractions, and the organic residue was mounted in glycerin and sealed with paraffin.

The sporomorph content of each slide was counted applying morphogeneric names,

but in some cases affinities with modern taxa was indicated. All taxonomic references and age ranges (based on [Jaramillo et al. 2011](#)) are listed in the supplementary data to this manuscript. For this work we consulted [González-Guzmán \(1967\)](#), [Germeraad et al. \(1968\)](#), [Hooghiemstra \(1984\)](#), [Muller et al. \(1987\)](#), [Lorente \(1986\)](#), [Jaramillo and Rueda \(2008\)](#) and [Jaramillo et al. \(2011\)](#).

Detrital thermochronology

Detrital apatites were extracted from sandstone samples using sieving, heavy-liquid, and magnetic separation techniques. During mounting, 500-800 grains were randomly distributed on the mounts in order to avoid sampling bias during counting, given the variety of grains in a detrital sample with respect to their cooling age and uranium content. Apatite aliquots were mounted in epoxy resin and polished to expose internal grain surfaces. The apatite grain mounts were etched for 20 seconds in 5.5 M HNO₃ at 21°C. The samples were irradiated together with Fish Canyon Tuff and Durango apatite age standards and IRMM-540 uranium glass dosimeters at the well-thermalized Orphée reactor, Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.

Randomly selected grains were counted dry at 1250× magnification using an Olympus BH-2 microscope. Our goal was to date about 100 grains per sample, to achieve the required level of statistical adequacy for provenance studies ([Vermeesch, 2004](#)). However, it was not possible to find this number of countable grains in all samples because of inclusions, dislocations and poor apatite quality caused by intense tropical weathering. Observed fission-track grain-age distributions were analyzed for obtaining central ages ([Galbraith and Laslett, 1993](#)) and decomposed into major grain-age components or peak ages, using binomial peak-fitting as described in [Stewart and Brandon \(2004\)](#). The obtained AFT peak ages can be related to certain source areas in the Venezuelan Andes by comparison with published

bedrock AFT ages ([Kohn et al., 1984](#); [Bermúdez et al., 2010, 2011](#)).

Rock-Eval analysis

Rock-Eval analyses of organic matter were performed by F. Baudin at Université Pierre and Marie Curie in Paris, France, using an Oil Show Analyzer and following the procedure described by [Espitalié et al. \(1986\)](#). The organic carbon composition of a sedimentary rock can be used as a proxy for the maximum temperature experienced during burial. This method requires heating of about 100 mg of sample material to volatilize the organic carbon contained in the sample and to expel petroleum. The amount of petroleum expelled increases with an increasing hydrogen to carbon ratio (H/C). The results are plotted in a Rock-Eval Tmax (°C) versus Hydrogen Index (HI) graph; the Hydrogen Index is defined as $HI = (S2/TOC) \times 100$ ([Espitalié et al., 1977](#)), where TOC is the percentage of Total Organic Carbon, and S2 is the residual petroleum potential produced at Tmax, which is dependent on the type of kerogen, this could be to explain the different paths obtained when plotting Tmax versus HI. Samples that plot within the immature field on the left of the graph indicate that maximum burial temperature conditions remained below the oil window. This coincides with part of the AFT partial annealing zone (~60-120°C).

RESULTS

Sedimentology and sedimentary petrography

Maracaibo basin

Because of limited accessibility and poor outcrop conditions, fieldwork focused on the upper part of the Vichú Member and most of the Sanalejos Member of the Betijoque Formation (Fig. 4). For most of the section the strata strike and dip consistently at about 330/35 NW. However, at the top of the section the strata rapidly become sub-horizontal (Fig.

3A). While the upper part of the Vichú Member contains several meter-thick alternating fine sandstone and mudrock deposits, the Sanalejos Member is marked in general by 1 to 2 m thick, mainly matrix supported polymict conglomerate beds, alternating with sandstone and mudrock layers (Fig. 6). Conglomerate clasts of the Sanalejos Member include gneiss, granite, amphibolite, sandstone, mudrock and vein-quartz pebbles, with granite decreasing upsection (see pebble count diagrams in Fig. 4).

Point-counting results of the sub-lithic and lithic arenites (between 14% and 52% of lithic grains) of the Betijoque Formation are reported in Table 1 and shown in Figure 7A. No obvious upsection trend within the Betijoque Formation is detectable in the framework petrologic composition. Lithic grains observed in thin sections include metamorphic (mica schist, gneiss, and metasedimentary grains), sedimentary and plutonic lithic grains, as well as polyquartz grains. Samples from the Vichú member and the base of the Sanalejos member contain mainly crystalline lithoclasts, with the proportion of sedimentary lithoclasts increasing upsection (Fig. 7B).

Barinas basin

The studied section starts near the unconformable contact of the Eocene Pagüey Formation with the overlying Parángula Formation. The strata of the Pagüey Formation are gently folded in an anticline, the southern limb of which dips 140/37. The Parángula Formation has dips 135/44 near the contact, but the dip angles increase to ~60°SE up-section (Fig. 3B). The direct contact between the Pagüey Formation and the Parángula Formation is not exposed, but the difference in lithology between the shallow marine, thin-bedded quartz-rich sandstones of the Pagüey Formation and the red fluvial sand- and mudstones of the Parángula Formation, as well as the slight change in strike and dip of the sedimentary layers is apparent. The contact between the Parángula Formation and the overlying Río Yuca

Formation is not exposed along the Parángula River either, which is consistent with the observations of [Erikson et al. \(2012\)](#), but a lithologic change from the red sandstone of the Parángula Formation to several dm to m thick, beige, mudrock and fine- to coarse-grained sandstone of the Río Yuca Formation is observed in the field (Fig. 8C and D). From about the middle of the Río Yuca Formation upsection, matrix-supported polymict conglomerate layers appear (Fig. 8E and F). These layers are more frequent toward the top of the section. Similar to the Betijoque Formation in the Maracaibo basin, the conglomerates include gneiss, granite, sandstone, and vein-quartz clasts (Fig. 8A and B).

Thin-section analysis and point counting show that the sandstones of the Parángula and Río Yuca formations are mostly relatively quartz-rich lithic sandstones (Fig. 9A). The two samples from the Parángula Formation (PAS6-2 and PAS10) have much higher quartz concentrations than the samples from the Río Yuca Formation and contain only sedimentary lithoclasts (Table 1B). The observed lithic grains in the Río Yuca Formation include granitic and gneissic basement rock fragments, as well as sedimentary lithic grains (Fig. 9B, C and D)

Palynology

Maracaibo basin

Only two samples (Supplementary Table 1A) from the Betijoque Formation produced acceptable quantities of pollen; palynological results should thus be regarded with some caution.

Samples CH100 and CH105 from the middle part of the section (locations RH18 and RH19 in Fig. 4A, Table 2A) contain *Cyatheacidites annulatus* and *Lanagiopollis crassa*. The latter has a reliable Last Appearance Date of 4.77 Ma, suggesting an Late Miocene to Pliocene age ([Jaramillo et al., 2011](#)). Key markers such as *Grimsdalea magnaclavata* and *Crassoretitriletes vanraadshooveni* (both <3.4 Ma), *E. mcneilly* (< 1.56 Ma), *Myrica* (Late

Pliocene) and *Alnus* (Middle Pleistocene) are absent (Fig. 10). In addition, taxa such as affinity (aff.) *Valeriana*, *Ericipites* sp., *Foveotrilletes* cf. *ornatus* (aff. *Huperzia*) point at a páramo vegetation, which is characteristic of altitudes between 3500 - 4000 m (e.g., Hooghiemstra 1984; van't Veer and Hooghiemstra, 2000; Rull, 2006).

The palynological assemblage further contains fern spores such as *Kuylisporites waterbolkii* (*Cyathea horrida*) and *Nijssenosporites* sp. (aff. *Pityrogramma*) and pollen such as *Clavinaaperturites microclavatus* (*Hedyosmum*), aff. *Symplocos* (Apocynaceae), aff. *Draba*, and *Podocarpidites* sp. All these taxa are typical for the Andean forest at 2300-3000 m elevation (e.g. see Hooghiemstra 1984; van't Veer and Hooghiemstra, 2000; Rull, 2006). In contrast, humid tropical lowland taxa were almost absent from the palynological assemblage.

The low pollen numbers may be related to the depositional environment in which the sediments were formed. Palynological sampling in braided-fluvial to alluvial-fan sediments is challenging as silt and clay, the fractions in which pollen are generally found, are rare. Another factor hampering the palynological research in these kinds of depositional environments is the damage caused to the pollen wall by repetitive oxidizing conditions.

Barinas basin

The pollen assemblage contained biostratigraphically significant taxa such as *Cyatheacidites annulatus*, *Grimsdalea magnaclavata*, *Crassoretitrites vanraadshooveni*, *Psilastephanocolpites evansii*, *Striasyncolpites zwaardii*, *Echitricolporites spinosus*, and *Fenestrites spinosus*. Based on the presence of *C. annulatus*, *G. magnaclavata* and *C. vanraadshooveni*, the age is estimated as ranging from 7.15 to 3.4 Ma (Late Miocene-early Late Pliocene). The absence of *E. mcneilly* (<1.56 Ma), *Myrica* (first occurrence Late Pliocene) and *Alnus* (first occurrence Middle Pleistocene) further supports this age estimate.

We also found that a significant proportion of the pollen assemblage was composed of *Lanagiopollis crassa* and occurrences of dinoflagellates and inner (organic) linings of foraminifers. Dinoflagellate cysts are few and poorly preserved in the samples from the Río Yuca Formation in the Barinas basin section. *Polysphaeridium* spp. is the most frequent, followed by *Spiniferites* spp. Rare or single occurrences include *Areoligera* sp., *Homotryblum* sp. and a questionable specimen of *Diphyes colligerum*. The *Polysphaeridium* specimens bear numerous slender processes, which is more typical for the “older” types, particularly for the Eocene-Oligocene types. The combined presence of *Homotryblum*, *Areoligera* and the questionable specimen of *Diphyes colligerum*, would indicate an Eocene age (Brinkhuis and Biffi, 1993; Bujak and Mudge, 1994; Powell, 1992; Zevenboom, 1995), but the poor preservation and the scattered occurrences suggest reworking.

The presence of pollen taxa such as *Spinozonocolpites* sp., *Spirosyncolpites spiralis*, *Annutriporites iversenii*, *Retibrevitricolpites* sp. and *Cicatricosisporites dorongensis*, among others, suggests reworking from pre-Miocene units and in particular of the Eocene-Oligocene formations. In addition, the occurrence of elaterate pollen also indicates reworking from Cretaceous sediments. The palynological data are listed in Supplementary Table 1; some of the most characteristic taxa are illustrated in Figure 11.

Other components of the palynological assemblage, such as *Bombacacidites* (Bombacaceae), *Retitrescolpites? irregularis* (*Amanoa*) and *Mauritiidites* (*Mauritia* palm), point at the existence of tropical lowland vegetation. In addition, the presence of diverse taxa typical for the Andean forest such as *Podocarpidites* (*Podocarpus*) and *Clavainaperturites microclavatus* (*Hedyosmum*), and some páramo taxa like *Foveotriletes* cf. *ornatus* type (aff. *Huperzia*) and *Nijssenosporites* sp. (aff. *Pityrogramma*) indicate the existence of a montane vegetation. The assemblage is low in spores and thus ferns must not have formed a significant part in the paleovegetation.

Finally, the abundance of clay beds rich in fossil leaves offers good perspectives for a reconstruction of the local flora at the time of deposition. Fragments of palm leaves and Melastomataceae suggest that the local vegetation was of humid, tropical character. Further investigation and sampling could yield valuable new data on the Late Miocene-early Late Pliocene climate in this region.

Detrital thermochronology

Maracaibo basin

A total of 444 individual apatite grains from the seven sandstone samples collected in the field were dated with the fission-track method. All samples fail the χ^2 test, indicating that they are characterized by multiple age components or peaks. Consequently, apatite grains are interpreted as being derived from multiple sources. The age range of dated grains and binomial fitted peaks of all seven samples are reported in Table 2. Probability density plots of all seven samples are shown in Figure 12. All samples from the Betijoque Formation except sample V95 contain Late Miocene to Early Pliocene age components, with a peak age ranging between 4 and 8 Ma. All samples further contain apatites with mid-Late Miocene cooling ages (age components of 10 to 18 Ma), which are the youngest ages in sample V95. In addition, Eocene to Early Miocene age components can be discriminated in several samples, while sample H9 also shows a minor Jurassic age component (Table 2). Only few track lengths could be measured in these samples; where more than 10 lengths could be measured these vary between 12.2 and 13.1 μm (Table 2).

Barinas basin

Well over 900 individual apatite grains were dated for the samples of the Barinas basin. The age range of the dated grains and binomial fitted peaks are reported in Table 2.

With the exception of samples PAN-1, PAN-3 and TPG-2, which yielded very low numbers of countable grains, all samples failed the χ^2 test and are thus characterized by multiple grain-age components, indicating that grains were derived from several different sources. Probability density plots with best-fit peak ages are shown in Figure 13. Sample PAN-3 from the Eocene Pagüey Formation was of very poor quality and only 5 grains could be dated from this sample, which give a Late Miocene-Early Pliocene central age (6.4 ± 1.8 Ma). This result is similar to the 5.0 ± 1.0 Ma central age determined from 25 grains of sample PAN-1, from the very base of the Parángula Formation. Samples TPG-1 and TPG-2, stratigraphically higher up in the Parángula Formation, have central ages younger than their supposedly early Miocene depositional age. Sample TPG-1 from the Parángula Formation and all samples from the Río Yuca Formation show Late Miocene age components of about 11-9 Ma, and most samples also have an Early to Middle Miocene peak of about 22 to 15 Ma. Oligocene and older age peaks are only present in samples TPG-1, TPMY-5, TPMY-4 and TPMY-7 (Table 2). Sample TPMY-8 from near the top of the studied section has young peak age of 4.6 ± 0.9 , comparable to detrital AFT ages in samples from the Maracaibo basin (Table 2) and *in-situ* bedrock AFT ages in the present-day Santo Domingo River catchment (Bermúdez et al., 2010; 2013). Reasonable numbers of track lengths could be measured in 6 samples and, like for the Maracaibo basin samples, mean track lengths vary between 12.2 and 13.3 μm (Table 2).

Rock-Eval analysis

The Rock-Eval analyses of organic matter of samples RV1 and RV3 from the Maracaibo Basin indicate significant percentages of total organic carbon (TOC) levels, in the range of coal (Baudin et al., 2007). Both samples plot below the field of hydrocarbon maturation in the Rock-Eval Tmax ($^{\circ}\text{C}$) diagram shown in Figure 14. The other samples

collected from the Betijoque Formation did not contain sufficient organic material for successful analysis (Table 3).

Two samples from the middle of the Río Yuca Formation in the Barinas basin (Table 3) show TOC levels of 0.95 (CH52-1) and 4.74% (CH52-2). Figure 14 shows that both samples plot in the immature field, indicating that maximum burial temperatures in the Río Yuca Formation were below the temperatures needed for hydrocarbon maturation and therefore below the temperature required for total annealing of fission tracks in apatite.

DISCUSSION

Maracaibo basin

Sediment provenance

Sandstone petrography and pebble lithologies are good indicators of sediment provenance. During the Miocene-Pliocene, the southern part of the Maracaibo basin, which is the pro-side of the Venezuelan Andes, received detritus derived from the crystalline core of the mountain belt via a paleo-drainage system that must have resembled the present-day drainage, as shown by gneiss and granite lithic grains in the sandstones, and gneiss, granite and amphibolite pebbles in the conglomerates (Figs. 6A and B). The variety of granitic pebbles observed in the field includes micro-granular and epi-granular granite with large feldspars and/or hornblende. Further petrographic work on these clasts is needed to relate them more closely to Mesozoic, Paleozoic and Proterozoic crystalline rocks currently exposed in the core of the mountain belt. Beside the crystalline fragments, sedimentary lithic grains are common. The appearance of sedimentary rock fragments is an indication of sediment recycling, particularly during the deposition of the Betijoque Formation. The recycled sedimentary lithic grains have three possible sources: A) Mesozoic and Paleozoic sedimentary cover of the Venezuelan Andes, B) Eocene shallow marine deposits, such as the

Palmar Formation, and C) recycling of poorly consolidated Middle to Late Miocene foreland basin deposits.

Implications of palynological results

The depositional ages of Mio-Pliocene sedimentary rocks in the Maracaibo basin have hitherto not been well constrained. Our palynological analyses provide some age constraints, suggesting a maximum age of 7 Ma and a minimum age of 4.77 Ma for the middle of the studied Betijoque Formation section; a Late Miocene-Early Pliocene age appears most likely. Significantly, the palynological spectrum includes taxa that are representative for the “páramo”, a type of Andean vegetation that is characteristic for altitudes between 3500 - 4000 m (cf. Hooghiemstra 1984; van’t Veer and Hooghiemstra, 2000; Rull, 2006). Such taxa are known in the Colombian Andes only from the Middle Pleistocene onwards (see Hooghiemstra, 1984; Torres-Torres, 2006 and references herein). In contrast, the presence of these taxa in our samples confirms that the Venezuelan Andes had already gained a considerable altitude of at least 3500 - 4000 m when the Betijoque Formation was deposited in the Late Miocene-Pliocene. In addition, the presence of an assemblage of spores and pollen typical for Andean forest taxa (2300-3000 m altitude; cf. Hooghiemstra 1984; van’t Veer and Hooghiemstra, 2000; [Rull, 2006](#)) are further evidence that - at the time of deposition - the vegetation in the source area was distributed following an altitudinal zonation.

Detrital thermochronology

The detrital AFT ages in the pro-wedge foreland basin (Table 2) correspond closely to the bedrock ages in the orogen published by [Kohn et al. \(1984\)](#) and Bermúdez et al. (2010, 2011). Apatites with 10-15 Ma and 24-35 Ma cooling ages are encountered in the Trujillo and Caparo blocks, located toward the northeast and southwest extremities of the Venezuelan

Andes, respectively (Figure 2; Bermúdez et al., 2010).

Given the location of our sections in the Maracaibo basin, the most likely source for these apatites would be the Trujillo block (Figure 2), although the Caparo source region could have been much closer to the section in Early Pliocene times than it is now, given the documented 30-80 km right-lateral slip on the Boconó Fault since ~5 Ma ([Schubert, 1982](#); [Audemard and Audemard, 2002](#)). The youngest peak ages at around 6 ± 2 Ma are close to *in-situ* ages encountered within the central Sierra La Culata, El Carmen and Sierra Nevada blocks and therefore record the rapid exhumation of these central blocks of the orogen in Late Miocene – Early Pliocene times ([Kohn et al., 1984](#); Bermúdez et al., 2010, 2011).

In addition to the biostratigraphic information presented in this paper, detrital AFT ages provide an independent estimate for the maximum depositional age, as the youngest grains or peak age in a detrital age spectrum should be equal to or older than the depositional age ([Kowallis et al., 1986](#); [Bernet and Garver, 2005](#)). In case of volcanic deposits, the AFT age is equal to the depositional age, because of very rapid cooling following eruption. However, no volcanic detritus has been observed in the Betijoque, Parángula and Río Yuca formations. Therefore, the youngest peak provides an upper limit to the depositional age, given a certain lag time.

However, this relation only holds if fission tracks in apatite were not reset after deposition because of burial heating, while a partial reset could alter the source-area information. In our section there is no clear trend of increasing AFT (central or peak) ages with depth (Figures 15A and B), as expected when AFT ages record source-area exhumation without thermal resetting ([van der Beek et al., 2006](#)). A slight decrease in central ages below 2200 m depth of the section we sampled could indicate the onset of partial annealing in deeper samples (Fig. 15B). However, the Hydrogen Index/Rock-Eval Tmax values of both samples plot below the temperature range needed for hydrocarbon formation ([Espitalié et al.,](#)

1977), and the AFT total annealing zone. Therefore, AFT ages were likely not significantly reset in our samples and the youngest peak ages can be used as maximum values for depositional ages. These youngest-peak ages cluster around 6 ± 2 Ma for most samples.

The fact that the sampled rocks were not sufficiently heated to significantly anneal fission tracks in apatite is not surprising. While paleo-geothermal gradients within the Maracaibo basin are not well constrained, it has been shown that foreland basins in general tend to be relatively cool, with typical thermal gradients of 15-25 °C/km ([Ravenhurst et al., 1994](#); [Allen and Allen, 2005](#); [Coutand et al., 2006](#)), because of rapid sedimentation and infiltration of meteoric water. Assuming a mean surface temperature of 20 °C and a thermal gradient of 20 °C/km even the most deeply buried samples ($2.7 \text{ km} \times 20^\circ\text{C/km} + 20^\circ\text{C} = 74^\circ\text{C}$) in our sections would not have exceeded 75 °C and therefore have hardly experienced the onset of partial annealing. Therefore, samples V97 and V95 of the Betijoque Formation indicate a maximum Early Pliocene depositional age for the base of the section we studied (Fig. 3, Table 2).

Barinas basin

Sediment provenance

As in the Maracaibo basin, the Mio-Pliocene Barinas basin received erosional detritus from the crystalline core of the mountain belt, as shown by gneiss and granite lithic grains in the sandstones (Fig. 9). The appearance of sedimentary lithic grains is an indication of sediment recycling, particularly during deposition of the Parángula Formation where no other lithic grains were observed. The recycled sedimentary rock fragments have three possible sources: A) Mesozoic and Paleozoic sedimentary cover rocks of the Venezuelan Andes, B) Eocene shallow marine deposits, such as the fine-grained Pagüey Formation or C) in the upper Rio Yuca Formation sedimentary clasts derived from the Middle to Late Miocene

sedimentary deposits. However, such grains were not found, are these deposits are in many places only poorly consolidated and disintegrate easily during recycling.

Implications of palynological results

The analysis of pollen can also give information on sediment recycling by the appearance of recycled palynomorphs in younger sediments. Our pollen analyses of upper Río Yuca Formation samples show abundant mature (dark brown) Eocene-Oligocene pollen and dinoflagellates, a clear indication for the recycling of Eocene sediments of the Pagüey Formation. Despite the recycling of older pollen, the presence of biostratigraphic marker species form a clear indication of the Late Miocene-Early Pliocene depositional age ($<7.15 - 3.40$ Ma) of the formation. In contrast to the Maracaibo basin, no pollen species indicative of high-altitude vegetation were encountered; the samples rather record the low-lying tropical forest environment of the depositional site

Detrital thermochronology

Similar to the Maracaibo basin, the detrital AFT ages in the Barinas basin correspond closely to the published bedrock AFT ages of the Venezuelan Andes ([Kohn et al., 1984](#); [Bermúdez et al., 2010](#), [2011](#)). The data are also broadly consistent with those presented by [Erikson et al. \(2012\)](#) from two locations located along the same section. Their samples have similar central ages than ours ($11.2 - 12.7$ Ma) but contain only a single grain-age component, because too few grains (6 to 20) were analyzed to fully characterize the age spectrum. Our samples generally contain significantly more grains, rendering recognition of different age components more effective, except for samples PAN-1, PAN-3 and TPG-2. Apatites belonging to components with 16-35 Ma peak ages are probably derived from the Trujillo or Caparo blocks. The 9-11 Ma age peak apatites were probably derived from the

Sierra Nevada and Sierra La Culata blocks, because in these areas Middle-Late Miocene AFT ages are encountered today (Bermúdez et al., 2010, [2011](#)). The youngest peak ages at around 5 Ma, detected only in one sample (TPMY8) for Río Yuca Formation, should reflect exhumation of the Santo Domingo gneiss on the southern flank of the Venezuelan Andes (Fig. 2 in Bermúdez et al., 2010); this 5 Ma peak age is also present in the modern Santo Domingo River sediments (Fig. 2; [Bermúdez et al., 2013](#)).

Rock Eval analyses of sample CH52 from the Río Yuca Formation (Fig. 14) show that burial heating of the sandstones of this formation was insufficient for hydrocarbon formation. Therefore, AFT ages were not reset in samples of the Río Yuca Formation. While the paleothermal gradient within the Barinas basin is not known, we can make the same estimate as for the Maracaibo basin. Using a typical foreland-basin average thermal gradient of 20°C/km and a surface temperature of 20°C, even the most deeply buried samples at about 2.7-3 km paleodepth of the section we studied have hardly experienced partial annealing, residing at temperature of less than 75-80°C for less than 10 Myr ([Reiners and Brandon, 2006](#)).

In order to better constrain the burial and exhumation history, we generated inverse models in order to study convergence of AFT data (ages, track lengths and kinetic indicators) and thermal maturity available data ([Erikson et al., 2012](#)) of the geological formations, using the HeFTy program of [Ketcham \(2005\)](#) with the following model parameters: we assumed that rocks were initially exhumed between 15-11 Ma, buried in the foreland basin between ~10 to 5 Ma, held at peak temperatures between 60-140°C for an interval of ~5 My, and exhumed to the surface between 3-1 Ma and the present. The modeling results of the best-constrained samples (e.g., TPG-1, TPMY-5, TPMY-4) suggest a maximum burial temperature between not exceeding 90°C, and probably around 75°C, between ~6 and ~1 Ma (Fig. 16); predicted vitrinite reflectance values between 0.57-0.62 (using the Easy-Ro model; Sweeney and Burnham, 1990). This finding is consistent with vitrinite reflectance values of

0.56-0.67 for samples from the Río Yuca Formation reported by [Erikson et al. \(2012\)](#), as well as with their thermal modeling of an AFT sample from the base of this formation, which shows peak burial temperatures of $\sim 80^{\circ}\text{C}$. Therefore, a maximum Middle – Late Miocene depositional age (< 12 Ma) for the Parángula Formation can be discerned from sample TPG-2, in the lower part of the studied section (Fig. 5, Table 2) and which has a single age population of 14 ± 3 Ma (assuming short lag times between exhumation and deposition on the order of ~ 2 My). [Erikson et al. \(2012\)](#) reached a similar conclusion for the maximum age of these deposits. The AFT ages of samples PAN-3 and PAN-1 provide evidence for exhumation-driven cooling of the Pagüey Formation and the lower part of the Parángula Formation starting at about 6-5 Ma. Therefore, apatite fission tracks in the Pagüey Formation were totally reset and the observed AFT cooling ages provide information about the timing of exhumation of this formation. Unfortunately no track-lengths data are available for time-temperature history modeling of these samples.

The static peaks observed in the detrital samples from both foreland-basin sections (Fig. 15) imply episodic exhumation of the central tectonic blocks in the Venezuelan Andes (cf. Bermúdez et al. 2010, [2011](#)). A static peak is an age peak that remains fairly constant up-section in the stratigraphic record, which means the lag time increases (e.g. Garver and Brandon, 1994a, 1994b). In contrast, continuous exhumation would provide a “moving” peak, which becomes younger upsection (e.g. Garver and Brandon, 1994a, 1994b). While one could argue that deposition of the Betijoque Formation was very rapid ($\sim 3\text{--}1.5$ Ma), the Parángula and Río Yuca formations represent up to 10 Ma of deposition, a sufficient time span to discriminate a moving from a static AFT age peak (e.g., van der [Beek et al., 2006](#)).

Interestingly, the youngest age peak in the Barinas basin samples tends to be 3-5 Myr older than the youngest age peak of the Maracaibo basin samples. While this difference is probably partly due to the older sedimentary record in the Barinas basin, it also appears in

samples that should have similar Early Pliocene apparent cooling ages. Unfortunately, the lack of precise depositional ages of the sampled sandstone units in both basins prohibits a more detailed comparison.

Neogene surface uplift and exhumation of the Venezuelan Andes in comparison to the Eastern Cordillera of Colombia

The development of the Northern Andes has attracted significant attention in recent years. It has long been recognized that the formation of the Western and Central Cordillera in Colombia and Ecuador are related to the accretion of oceanic terranes during the Late Cretaceous to Paleocene (e.g. Case et al., 1990; [Dengo and Covey, 1993](#); [Gregory-Wodzicki, 2000](#); [Gómez et al., 2005](#); [Jaillard et al., 2009](#)). Within the Eastern Cordillera of Colombia, Cretaceous quartzose sandstones and mudrocks are widely exposed, and to a lesser extent Jurassic graben conglomerates and Paleocene to Eocene non-marine sandstones. Paleogene sediments are derived from the erosion of the Central Cordillera to the west and were deposited prior to uplift of the Eastern Cordillera along reactivated former graben structures (e.g., [Dengo and Covey, 1993](#); [Corredor, 2003](#); [Mora et al., 2009, 2010b](#); [Horton et al., 2010b](#)).

The surface-uplift history of the Eastern Cordillera is still a matter of debate ([Horton et al., 2010b](#)). While [Bayona et al. \(2008, 2013\)](#) provide sedimentological evidence for five episodes of deformation during the evolution of the Eastern Cordillera, other authors prefer a more continuous deformation history, with migration of the deformation front toward the east. Most authors agree that early deformation in the area of the Eastern Cordillera may have started in the Late Cretaceous (subsidence and foreland basin formation), but was definitely underway in mid-late Eocene to Late Oligocene times (e.g., [Corredor, 2003](#); [Horton et al. 2010a, 2010b](#); [Mora et al. 2010a, 2010b](#); [Parra et al., 2010](#); [Ochoa et al., 2012](#)), with onset of

surface uplift in the axial zone (26-23 Ma; [Horton et al., 2010b](#)). Structural and geochronologic data from detrital zircon from both sides and across the Eastern Cordillera imply that the major phase of surface uplift and associated erosional exhumation started in the Late Oligocene to Early Miocene (e.g; [Horton et al., 2010a, 2010b](#); [Nie et al., 2010](#)). Mora et al. (2010c) suggested that plate deformation had started well before the Late Miocene in the Colombian Eastern Cordillera, but no evidence for high paleoelevation exists before the Late Miocene. Based on pollen data by van der Hammen et al. (1973) and Hooghiemstra et al. (2006), Mora et al. (2010c) favor surface uplift of the Colombian Eastern Cordillera toward present-day elevations between 15 and 3 Ma. Bedrock AFT data from the eastern flank range from 1-3 Ma across the Quetame massif (Mora et al., 2008; Parra et al., 2009a, 2009b) and other parts of the Eastern Cordillera (Mora et al., 2010b), while the deposition of thick Miocene-Pliocene sediments in the foreland basin to the east of the Eastern Cordillera (e.g. [Gómez et al., 2005](#); [Bayona et al. 2008, 2013](#); Parra et al., 2009b, 2010; [Horton et al. 2010b](#)) demonstrates Late Miocene to Pleistocene accelerated erosional exhumation and possible surface uplift of the Eastern Cordillera. Gregory-Wodzicki (2000) proposed that from the Middle Miocene through the Early Pliocene, the Eastern Cordillera only reached about 40% of its present-day mean elevation and that surface uplift between 5-2 Ma brought the mountain belt to its current elevation. This timing coincides with the final closure of the Panama isthmus and the end of the collision of the Panama arc with northwestern South America (Bartoli et al., 2005; [Farris et al. 2011](#)).

As shown by the detrital AFT data of the present study and the published bedrock and detrital AFT data from the Venezuelan Andes ([Shagam et al., 1984](#); [Kohn et al., 1984](#); [Bermúdez et al., 2010, 2011, 2013](#)), the main phase of exhumation in the Venezuelan Andes started in the Middle-Late Miocene and continued into the Pliocene. The palynological data presented here provide evidence that the mountain belt had reached its present-day elevation

during the Late Miocene to Pliocene, apparently somewhat earlier than the Colombian Eastern Cordillera. The clockwise rotation of the Maracaibo block and the collision of the Panama Arc with northwestern South America are regarded as the driving forces responsible for the surface uplift of the individual tectonic blocks that make up the Venezuelan Andes (Bermúdez et al., 2010, [2011](#), [2013](#)). Therefore, the evolution of the Eastern Cordillera and the Venezuelan Andes are more or less contemporaneous but not driven by exactly the same underlying geodynamic processes. While both ranges are doubly vergent, thick-skinned orogenic wedges that have similar modern mean elevations, the Eastern Cordillera is roughly twice as wide as the Venezuelan Andes (~100 km). The Eastern Cordillera is more or less N-S oriented, while the Venezuelan Andes are largely NE-SW oriented. The Venezuelan Andes contain their highest relief in the central zone along the Boconó strike-slip fault. The axial zone of the Eastern Cordillera, in contrast, is the high plateau of the Sabana de Bogotá with much less relief ([Mora et al., 2008](#)). An interesting difference between the two mountain belts is that exposure of crystalline basement rocks is much more widespread in the Venezuelan Andes than in the Eastern Cordillera. In addition, the Venezuelan Andes appear more symmetric in deformation style and bedrock exposure than the asymmetric Eastern Cordillera ([Mora et al. 2008](#)). The link between both orogens, the Santander Massif and the Santa Marta-Bucaramanga fault (SBF; Fig. 1) represent key elements to understand the evolution of this area, because they correspond to the NE termination of the "classical" Colombian/Ecuadorian Andes with the Western, Central and Eastern Cordilleras and the seemingly independent Venezuelan Andes.

It still needs to be determined how the surface uplift of the Eastern Cordillera in Colombia and the Venezuelan Andes influenced the local and regional climate. It is obvious from the bedrock AFT data that Pliocene erosional exhumation is focused on the currently relatively wet eastern flank of the Eastern Cordillera, where 1-3 Ma cooling ages are

observed ([Mora et al., 2008, 2010b](#); [Parra et al., 2009a, 2009b](#)), while such young AFT cooling ages in the Venezuelan Andes have so far only been observed in outcrops of the relatively dry central zone along the Boconó strike slip fault ([Kohn et al., 1984](#); [Bermúdez et al., 2010](#)). Therefore, it has been proposed that Pliocene exhumation of the Venezuelan Andes is principally controlled by tectonics ([Bermúdez et al., 2013](#)), while climate could have a larger role in driving exhumation of the Colombian Eastern Cordillera ([Mora et al., 2008](#)).

CONCLUSIONS

Sediment petrographic, palynologic and thermochronologic evidence from the pro- and retro-wedge foreland basins of the Venezuelan Andes lead us to the following conclusions:

1. The sediment petrography indicates erosion of crystalline (granitic and gneissic) bedrock in the core of the mountain belt, as well as recycling of sedimentary cover units on its flanks, at least since the Late Miocene. The basins on both sides of the orogen received sediments of roughly similar composition, which are characterized by a coarsening upward trend.
2. Contrary to previous estimates, the fluvial Parángula Formation in the Barinas basin appears to be of Middle-Late Miocene age, based on our AFT and pollen data, instead of Oligocene-Middle Miocene.
3. Rock-Eval analyses of organic matter from the Betijoque and Río Yuca formations indicate that these units were not sufficiently heated for kerogen production. Therefore, the burial temperatures were insufficient for resetting of fission tracks in apatite. As a consequence, the detrital AFT age patterns from the apparently unreset samples mainly reflect source rock cooling.

4. Reset AFT ages of 6-5 Ma of samples from the Eocene Pagüey Formation and the very base of the Parángula Formation indicate exhumational cooling on the southern flank of the Venezuelan Andes in the latest Miocene. This is consistent with the observation of sediment recycling of Eocene sedimentary rocks and an increasing number of sedimentary rock fragments upsection in the Barinas basin.

5. The detrital AFT data presented in this work show relatively static minimum ages in each sample at about 5 ± 2 Ma in the Pliocene Maracaibo basin sediments and about 7 ± 2 Ma in the Mio-Pliocene Barinas basin sediments. These data are consistent with the bedrock AFT ages in the Venezuelan Andes of Kohn et al. (1984) and Bermúdez et al. (2010, 2011) and suggest rapid episodic exhumation of different fault-bounded blocks within this mountain belt.

6. The palynological data show that the Venezuelan Andes had reached their present-day elevation (3500-4000 m) by the Late Miocene – Pliocene. In addition, the recycling of older pollen supports the notion of sediment recycling based on petrography.

7. The main phase of surface uplift, creation of important topography and relief, and erosional exhumation in the Venezuelan Andes occurred during the Late Miocene to Pliocene. Therefore the evolution of the Eastern Cordillera in Colombia and the Venezuelan Andes were not fully contemporaneous. The two mountain belts are considerably different in size, structure and exhumation history.

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CONFLICT OF INTEREST

No conflict of interest declared.

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Tables

Table 1A Point-counting results of the Maracaibo basin section samples

Sample	Mono qtz	Poly qtz	Feldspar	L Sed.	L Ign.	L Meta.	Mica	Other	Calcite cement	Hematite cement	Matrix	Porosity	Total
RV2	81	63	27	5	35	24	20	8	64	0	0	7	334
RV3	79	38	18	5	55	46	25	2	49	0	2	9	328
RV6	84	7	18	43	17	4	58	16	0	9	70	15	341
RH2	74	51	30	32	32	41	43	1	0	5	1	0	310
RH3	57	34	16	19	20	81	52	1	0	22	29	12	343
RH9	104	22	35	10	12	5	36	1	0	32	60	11	328
RH17	72	9	25	75	6	11	83	1	0	6	0	36	324

Note: qtz = quartz, L. Sed. = sedimentary lithic grains, L. Ign. = igneous lithic grains, L. Meta. = metamorphic lithic grains. Mica includes muscovite, biotite and chlorite.

Table 1B Point-counting results of the Barinas basin section samples

Sample	Mono qtz	Poly qtz	Feldspar	L Sed.	L Ign.	L Meta.	Mica	Other	Calcite cement	Hematite cement	Matrix	Porosity	Total
PAS6-2	218	2	0	17	0	0	1	0	0	14	44	65	361
PAS-10	204	5	0	31	0	0	0	0	0	74	6	16	336
PAS-13	91	59	87	10	28	1	9	1	27	0	19	6	338
PAS-20	44	79	31	29	91	18	14	1	0	0	0	0	307
PAS-24	142	20	24	16	8	3	16	0	100	6	2	28	365
PAS-28	109	32	81	31	31	12	38	1	0	1	1	0	337
PAS-29	114	28	27	52	44	9	39	1	0	2	0	0	316
PAS-35	124	29	8	39	4	3	1	1	134	0	0	4	347
PAS-41	116	83	21	22	9	1	9	1	67	0	0	31	360
PAS-42	99	17	51	2	10	0	33	1	0	0	65	53	331

Note: Samples PAS6-2 and PAS10 belong to the Parángula Formation, all other samples were collected from the Rio Yuca Formation.

Table 2 Detrital apatite fission-track results of the Maracaibo and Barinas basins, Venezuela

Sample	Stratigraphic depth (m)	<i>n</i>	Age range (Ma)	P1 (Ma)	P2 (Ma)	P3 (Ma)	P4 (Ma)	P5 (Ma)	Central age $\pm 1\sigma$ (Ma)	MTL $\pm$ SE (μ m)	SD (μ m)	Dpar $\pm$ SD (μ m)
Maracaibo												
H02	1075	102	2.2-39.7	6.2 $\pm$ 0.7 85.3%	17.2 $\pm$ 3.0 14.7%	-	-	-	7.8 $\pm$ 1.0	12.90 $\pm$ 0.31 (16)	1.23	1.79 $\pm$ 0.41
H09	1425	79	2.6-161.6	4.5 $\pm$ 2.7 23.4%	10.0 $\pm$ 2.7 41.4%	23.7 $\pm$ 4.5 18.9%	38.7 $\pm$ 6.9 15.1%	163.6 $\pm$ 125 1.3%	15.3 $\pm$ 3.1			
H11	1810	100	3.4-67.0	8.2 $\pm$ 1.9 27.9%	15.4 $\pm$ 2.2 59.2%	33.8 $\pm$ 7.4 12.9%	-	-	15.4 $\pm$ 1.9	12.19 $\pm$ 0.34 (27)	1.76	1.70 $\pm$ 0.22
V33	1900	49	3.9-49.3	5.1 $\pm$ 1.2 16.2%	11.1 $\pm$ 1.1 81.0%	41.8 $\pm$ 36.5 2.7%	-	-	10.4 $\pm$ 1.3	13.08 $\pm$ 0.25 (26)	1.30	2.95 $\pm$ 0.45
V90	2160	40	2.5-67.9	4.4 $\pm$ 1.0 27.9%	18.3 $\pm$ 4.6 54.5%	40.5 $\pm$ 28.8 17.6%	-	-	16.6 $\pm$ 4.3	9.16 (01)	-	1.34
V95	2425	50	3.5-61.3	12.0 $\pm$ 1.9 85.7%	28.1 $\pm$ 19.8 14.3%	-	-	-	13.8 $\pm$ 2.0	9.79 $\pm$ 0.002 (02)	0.003	1.35 $\pm$ 0.20
V97	2700	24	4.4-29.3	7.0 $\pm$ 1.6 92.9%	18.7 $\pm$ 25.4 7.1%	-	-	-	7.3 $\pm$ 1.4	12.70 $\pm$ 1.56 (03)	2.71	2.85 $\pm$ 0.39
Barinas												
TPMY7	0	40	4.8-100.0	10.3 $\pm$ 1.5 97.4%	96.9 $\pm$ 74.3 2.6%	-	-	-	12.2 $\pm$ 2.8	12.88 $\pm$ 0.25 (22)	1.17	1.99 $\pm$ 0.25
TPMY8	60	100	2.2-34.4	4.6 $\pm$ 0.9 42.0%	9.1 $\pm$ 2.1 54.8%	19.9 $\pm$ 22.6 3.2%	-	-	7.3 $\pm$ 0.8	12.96 $\pm$ 0.38 (16)	1.53	1.52 $\pm$ 0.15
TPMY2	650	100	3.8-35.0	11.6 $\pm$ 2.2 78.2%	16.1 $\pm$ 7.9 21.8%	-	-	-	12.6 $\pm$ 1.4	-	-	-
TPMY3	860	103	4.2-76.4	11.1 $\pm$ 1.4 56.2%	22.1 $\pm$ 3.3 43.8%	-	-	-	15.6 $\pm$ 1.6	13.31 $\pm$ 0.41 (12)	1.43	1.66 $\pm$ 0.17
TPMY4	1260	364	2.9-120.8	9.5 $\pm$ 1.2 33.0%	15.9 $\pm$ 1.8 52.2%	32.7 $\pm$ 5.2 14.8%	-	-	15.6 $\pm$ 1.1	12.52 $\pm$ 0.15 (62)	1.22	2.84 $\pm$ 0.46
TPMY5	1700	120	4.9-29.6	9.4 $\pm$ 2.3 38.0%	13.3 $\pm$ 2.4 58.3%	24.8 $\pm$ 6.8 3.7%	-	-	12.2 $\pm$ 1.3	12.29 $\pm$ 0.15 (48)	1.05	1.78 $\pm$ 0.20
TPG1	2450	100	3.5-54.6	9.6 $\pm$ 0.9 79.5%	18.7 $\pm$ 4.0 19.6%	53.0 $\pm$ 42.8 0.9%	-	-	11.4 $\pm$ 1.1	12.16 $\pm$ 0.18 (60)	1.38	1.68 $\pm$ 0.20
TPG2	2550	10	7.5-41.6	-	-	-	-	-	14.2 $\pm$ 3.3	-	-	-
PAN 1	2650	25	3.4 – 12.1	-	-	-	-	-	5.0 $\pm$ 1.0	-	-	-
PAN 3	Pagüey Fm.	5	1.9 – 9.5	-	-	-	-	-	6.4 $\pm$ 1.8	-	-	-

Note: n = total number of grains counted; binomial fitted peak ages are given ± 2 SE. No peaks were fitted for sample TPG2 because of the low grain count. Also given is the percentage of grains in a specific peak. All samples were counted at 1250x dry (100x objective, 1.25 tube factor, 10 oculars) by M. A. Bermudez using a zeta (IRMM 540) of 288.66 ± 5.32 (± 1 SE).

Table 3. Results of Carbonate content (CaCO₃) and Rock-Eval analysis

Sample	CaCO ₃ (%)	Tmax (°C)	S1 (mg/g)	S2 (mg/g)	TOC (%)	Ctot LECO (%) 1	Ctot LECO (%) 2	Corg LECO (%)	HI (OSA) mg HC/g TOC	HI (LECO) mg HC/g TOC
Maracaibo										
RH3	NA	NA	0.0	0.0	0.1	0.1	0.1	NA	NA	NA
RH5	NA	NA	0.0	0.0	0.0	0.0	0.0	NA	NA	NA
RV1	NA	400.0	3.2	16.5	51.0	50.9	53.3	NA	32.0	32.0
RV3	0.0	397.0	11.3	100.3	37.4	46.1	48.5	46.1	268.0	212.0
Barinas										
CH52(1)	NA	424	1.20	0.11	0.95	0.97	1.0	-	12	11
CH52(2)	38.5	389	0.88	0.41	4.74	8.9	9.3	4.51	9	9
PS39	NA	NA	0.78	0.06	0.07	0.0	0.0			

Note: NA indicates measure not available; Tmax is the maximum temperature; S1 indicates hydrocarbons concentration (gas and oil) present in the rock; S2 indicates the amount of hydrocarbon produced from kerogen cracking. TOC is the weighted concentration of Carbon Organic Total expressed in percentage; Ctot 1 and 2 correspond to the two measures of the weighted total carbon in percentage; Corg is the content of carbon organic; HI (OSA) and HI (LECO) are measures of the Hydrogen Index.

Figure legends

Fig. 1 Major tectonic features of northern South America (after Colmenares and Zoback, 2003). Topography and bathymetry is based on GeoMapApp developed by the IEDA database group at Columbia University's Lamont-Doherty Earth Observatory (see <http://www.geomapapp.org>) square shows location of Fig. 2.

Fig. 2 42° clockwise rotated geologic map of the study area in the Venezuelan Andes (modified after Hackley et al., 2005), indicating the locations of *in-situ* AFT data (Kohn et al., 1984; Bermúdez et al., 2010), modern river AFT samples (locations from Bermúdez et al., 2013; blue stars), new synorogenic detrital AFT (red hexagons) and palynology (black circles) samples in the Maracaibo and Barinas basins for this study. White and blue numbers are *in-situ* AFT ages, and detrital AFT age populations, respectively. Upper left inset shows major fault systems and delimited tectonic blocks of the Venezuelan Andes as defined by Bermúdez et al. (2010): CATB, Cerro Azul Thrust; CB, Caparo; EB, Escalante; ECB, El

Carmen; SLCB, Sierra La Culata; SNB, Sierra Nevada; and TB, Trujillo blocks. Faults abbreviations correspond to: VFS Valera fault system; BFS Boconó fault system; CSAFS Central-Sur Andino fault system; CFS Caparo fault system; BurF Burbusay fault; NWFTB and SEFTB are North-Western and South-Eastern Fold-Thrust Belts, respectively.

Fig. 3 A) Line drawing of seismic section of the southern part of the Maracaibo basin and the northern flank of the Venezuelan Andes, showing approximate sample locations along the Río Hoyos and Río Vichú sections. The seismic profile was provided by Petróleos de Venezuela, SA. B) Line drawing of seismic section of the Barinas basin showing sample locations along the Parángula River section near Barinitas on the southern flank of the Venezuelan Andes. The seismic profile was modified from Henriques-Casas (2004). Vertical scale is in TWT (s) for profile AA' and in km for BB' (0 km corresponds to sea level).

Fig. 4 Generalized stratigraphic section of the Betijoque Formation from the Maracaibo basin on the northern flank of the Venezuelan Andes; Stratigraphic positions of samples collected for different analysis (sandstone petrography, palinology, apatite fission-track analysis) are indicated. Samples for Rock-Eval analysis are highlighted in dark-gray. Pebble counts are presented from 4 locations.

Fig. 5 Generalized stratigraphic section of the Parángula and Río Yuca formations from the Barinas basin on the southern flank of the Venezuelan Andes. Stratigraphic positions of samples collected for different analysis (sandstone petrography, palinology, apatite fission-track analysis) are indicated. Samples for Rock-Eval analysis are highlighted in dark-gray.

Fig. 6 Outcrop photos from the Maracaibo basin sections. A) Conglomeratic layers at outcrop

location RH2 in the lower part of the Betijoque Formation. B) Close-up of matrix-supported polymict conglomerate at location RH3. C) Sandstone layer with cross-lamination and climbing ripples at location RH9.

Fig. 7 Triangular plots showing normalized point-count data of the Betijoque Formation. (A) QFL plot; Q is total quartzose grains; F is total feldspar grains; L is total unstable lithic fragments; (B) Lithic grains plot showing plutonic lithic fragments, metamorphic lithic fragments, and sedimentary lithic fragments.

Fig. 8 Outcrop photos from the Barinas basin section. A) Location PAS8 in the Parángula Formation, showing this overbank mudstone and channel sandstones. B) Location PAS6 in the Parángula Formation. Black arrows mark angular unconformity with overlying Quaternary conglomerates and soil layers. C) Massive layers medium grained sandstone of the Río Yuca Formation at location PAS 24. D) Massive layers of channel sandstones in the Río Yuca Formation at location PAS 28. Note the erosive contact shown with black arrow. E) Conglomerate layer with sand lenses in the upper part of the Río Yuca Formation, location PAS29. F) Conglomeratic deposits in gray, quartz-rich sandstone at location PAS 20 of the upper Río Yuca Formation.

Fig. 9 Triangular plots showing normalized point count data of the Parángula and Río Yuca formations. (A) QFL plot; Q is total quartzose grains; F is total feldspar grains; L is total unstable lithic fragment; (B) Lithic grains plot showing plutonic lithic fragments, metamorphic lithic fragments, and sedimentary lithic fragments. (C) Example of a granite lithic grain (PAS20). (D) Example of a mica schist lithic grain (PAS 20).

Fig. 10 Characteristic pollen and spores from the Betijoque Formation (Maracaibo Basin).

The sample code is indicated after the taxonomic name: 1. *Podocarpidites* sp. (Bet 105.1), 2. *Monoporopollenites annulatus* (Bet 105.2), 3. *Clavainaperturites microclavatus* (Bet 105.2), 4. aff. *Valeriana* (Bet 105.2), 5. aff. *Symplocos* (Bet 105.2), 6. *Spirosyncolpites spiralis* (Bet 105.2), 7. *Echitricolporites spinosus*, 8. *Ericipites* sp., 9. *Verrucatotriletes* cf. *bullatus* (Bet 105), 10a & b. *Retitriletes* sp. (105.2), 11. *Cyatheacidites annulatus* (Bet 105.1), 12. *Cingulasporites laevigatus* (Bet 105.1), 13a & b. *Foveotriletes* cf. *ornatus* (Bet 105.1), 14. indeterminate trilete spore (Bet 105.1), 15. *Psilatriteles lobatus* (Bet 105.2), 16. *Nijssenosporites fossulatus* (Bet 105.1), 17. *Nijssenosporites* sp., fragment of characteristic ridges (Bet 105.1) and 18. *Matonisporites mulleri* (Bet 105.2).

Fig. 11 Characteristic pollen, spores and dinoflagellates in the Río Yuca Formation (Barinas Basin).

The sample code is indicated after the taxonomic name: 1. *Bombacacidites brevis* (CH 40.2), 2. *Psilaperiporites robustus* (CH 26), 3. *Glencopollis curvimuratus* (CH 40.2), 4a. *Crototricolpites* sp., 4b. Detail of sculpture (CH 40.2), 5. *Retibrevitricolpites* sp. (CH 40.2), 6. *Cyclusphaera scabrata* (CH 40.2), 7. *Lanagiopollis crassa* (CH 40.2), 8. *Lanagiopollis crassa* (CH 40.2), 9. *Nijssenosporites* sp. (CH 40.2), 10. *Cicatricosisporites dorongensis* (CH 40.2), 11. *Spiniferites* sp. (CH 38), 12. *Lingulodinium machaerophorum*? (CH 40.2), 13. *Spiniferites* sp. (CH 50.1), 14. indeterminate dinoflagellate (CH 40.2) and 15. foraminifer lining (CH 44).

Fig. 12 Detrital AFT results of samples from the Maracaibo basin on the northern flank of the Venezuelan Andes. The observed grain-age distributions are shown as histograms and as probability-density functions (continuous black lines). Also shown are the binomial best-fit solutions, with 2 to 4 peaks. In terms of stratigraphic position the histograms should be read

down the left hand side and then down the right hand side.

Fig. 13 Detrital AFT results of samples from the Barinas basin on the southern flank of the Venezuelan Andes. The observed grain-age distributions are shown as histograms and as probability-density functions (continuous black lines). Also shown are the binomial best-fit solutions, with 1 to 3 peaks. In terms of stratigraphic position the histograms should be read down the left hand side and then down the right hand side.

Fig. 14 Hydrogen Index (HI) versus Maximum Temperature (Tmax) plot for samples RV1 and RV2 from the Betijoque Formation, Maracaibo basin, and for sample CHS2 from the Río Yuca formation, Barinas basin. None of the samples were sufficiently heated during burial to allow kerogen maturation.

Fig. 15 Upsection variation of AFT ages in the Maracaibo and Barinas basins. A) Peak ages plotted against stratigraphic depth for each age population (P_i). B) Central ages plotted against stratigraphic depth. Independent constraints on stratigraphic ages are indicated.

Fig. 16 Time-temperature (t-T) history of sample TPMY-5 as reconstructed using the AFT data (central age, track-length distribution and kinetic indicator Dpar) and HeFTy inversion code (Ketcham, 2005). Thick black and blue lines represent overall best-fit thermal history, and weighted mean t-T path; purple and green ranges show thermal histories that provide a “good” and “acceptable” fit to the data, respectively, as defined by Ketcham (2005). Fit to track-length distribution is shown in the track-length histogram to the right.

Supporting information legends

Fig. 1 see <http://www.geomapapp.org>

Fig. 10 see supplementary data

Fig 11 see supplementary data

Supplementary data

Taxonomic references for all palynomorphs; age ranges for the pollen and spores based on Jaramillo et al. 2011.

Figure 1. Bermudez et al.

Figure 2. Bermúdez et al.

Figure 3. Bermúdez et al.

Rio Hoyos - Rio Vichu section

Figure 4. Bermudez et al.

Figure 5. Bermudez et al.

Figure 6. Bermudez et al.

Figure 7. Bermudez et al.

Figure 8. Bermudez et al.

Figure 9. Bermudez et al.

Figure 10. Bermudez et al.

Figure 11. Bermudez et al.

Figure 12. Bermudez et al.

Figure 13 Bermudez et al.

Figure 14 Bermudez et al.

Figure 15. Bermúdez et al.

Fig. 16 Bermúdez et al.