

Key Points:

- A large geochronological database is used to reconstruct the Neogene sediment dispersal patterns in the western Colombian Andes
- Pulsed growth of the Western and Central cordilleras drove a progressive shift from transverse to longitudinal sediment routing systems
- Inherent segmentation of strike-slip faults and volcanic processes controlled the evolution of sedimentary basins and drainage networks

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

León, S., Faccenna, C., Conrad, E. M., Parra, M., Cárdenas, A. L., & Valencia, V. A. (2025). The role of transpressional tectonics, volcanism, and fluvial processes on the Oligocene to Pliocene evolution of intermontane basins of the western Colombian Andes. *Tectonics*, *44*, e2024TC008461. <https://doi.org/10.1029/2024TC008461>

Received 13 JUN 2024

Accepted 7 MAR 2025

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The Role of Transpressional Tectonics, Volcanism, and Fluvial Processes on the Oligocene to Pliocene Evolution of Intermontane Basins of the Western Colombian Andes

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Abstract We use new and published detrital zircon U-Pb data ($n > 10,000$) from Oligocene-Pliocene strata of intermontane basins of the western Colombian Andes and surrounding regions to study the evolution of sedimentary systems during the transition from arc collision/accretion to subduction. Our database indicates a shift from a compartmentalized basin architecture, locally fed by transverse drainages, toward one with enhanced connectivity and longitudinal sediment dispersal during the Middle-Late Miocene. These events were accompanied by the end of local marine influence on depocenters and the progressive uplift of the flanking Colombian Cordilleras as they became continuous topographic features. Post-Pliocene local and transient disruption of longitudinal rivers was caused by damming and valley-filling, attributed to volcanoclastic flows. We interpret the inherent segmentation of strike-slip faults and their morphological expressions as the primary controls on depocenter evolution during Early-Middle Miocene arc collision/accretion. The subsequent transition to subduction and the tectonic segmentation of the continental margin triggered asymmetrical basin inversion in the western Colombian Andes. The modern rugged morphology in the northern intermontane region is arguably associated with widespread uplift due to upper plate cooling and strengthening by shallow subduction of the Coiba microplate. Conversely, the wide and flat morphology of aggradational basins in the southern intermontane area is interpreted as the result of incomplete inversion and the dominance of strike-slip tectonics. The “normal” subduction of the Malpelo microplate beneath southern Colombia might be linked to a higher heat flow and localized deformation in the intra- and back-arc regions.

1. Introduction

Long-term landscape evolution in active orogenic systems results from the interplay between tectonics, volcanism, and climate. These drivers are jointly modulated by deep-seated and surface processes (Champagnac et al., 2012; Strecker et al., 2007), which operate at different spatiotemporal scales. Disentangling their impacts on mountain building and the evolution of sedimentary basins requires reconstructing the timing and locus of deformation/uplift (Bayona et al., 2008; Finzel et al., 2016). The latter is commonly addressed using thermo-chronological and thermo-kinematic analyses, although these methods are sometimes insensitive to transient episodes of rock uplift (e.g., León et al., 2023). This issue may arise because erosion is not efficient enough to expose cooling ages likely to preserve the signal of uplift/exhumation or because later reheating obliterates preceding cooling events (e.g., Biralvand et al., 2023).

The sedimentary record of intermontane basins is susceptible to changes in the landscape configuration, regardless of the nature of the triggering mechanisms and the spatiotemporal scale at which they operate (e.g., Streit et al., 2017). Depositional settings are primarily controlled by eustasy, crustal deformation, and sediment accumulation rates, while sediment composition is strongly influenced by the nature and erodibility of source areas and the physics of the sedimentary system (Romans et al., 2016; von Eynatten & Dunkl, 2012). The modification of one or several of the parameters above, driven either by changes in the stress regime of crustal deformation, intra-basinal volcanism, or climate-related perturbations of the weathering/erosion patterns, is likely to be preserved in the stratigraphy and provenance of intermontane basins (Caracciolo, 2020).

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The modern landscape of the Colombian Andes (northwestern South America) is characterized by three main cordilleras (Western, Central, and Eastern; Figure 1). These mountain ranges are separated by sedimentary basins filled with Neogene fluvio-deltaic clastic and volcanoclastic deposits. The stratigraphic evolution of such basins was controlled by transpressional regimes associated with interspersed arc-continent collision/accretion and subduction tectonics (León et al., 2018; Montes et al., 2019). Such diverse tectonic configurations resulted in a highly segmented continental margin associated with a complex tectono-magmatic, stratigraphic, and structural evolution (León, Parra et al., 2025; León, Faccenna, et al., 2025; Suter, Sartori, et al., 2008; Wagner et al., 2017), yet defining the interplay among the processes controlling basin evolution remains elusive.

The Neogene sedimentary record of intermontane basins of the Colombian Andes presents an outstanding opportunity to assess the linked roles of tectonic, volcanic, and geomorphological processes on the long-term evolution of sediment dispersal patterns in active orogens. In particular, the prevalence of transpressional tectonics renders the Colombian Andes a key area to study the evolution of sedimentary basins in response to sharp topographic variations and highly asymmetric drainage networks associated with the inherent segmentation of strike-slip fault systems (e.g., Booth-Rea et al., 2004). Here, we assess the Oligocene-Pliocene evolution of source-to-sink systems of the western Colombian Andes as controlled by (a) the topographic growth of the Western and Central Cordilleras, (b) the morpho-structural expression of strike-slip faults during and after arc-collision/accretion, and (c) the history of intra-basinal arc-related volcanism.

2. Geological and Tectonic Background

2.1. Neogene Tectonics of Northwestern South America

The Neogene evolution of the northern Andes resulted from the oblique convergence between the Caribbean, Nazca, and South American plates (Montes et al., 2019). The northeastward drift of the Caribbean plate during most of the Cenozoic led to the Early-Middle Miocene (~20–15 Ma) collision/accretion of the intra-oceanic Central American arc against northwestern South America (León et al., 2018; Montes et al., 2015), subsequently followed by the northward propagation of the subduction of the Nazca plate (González et al., 2023).

After the accretionary episode, a continental arc was established in the Western Colombian Cordillera from ~14 to 12 Ma, which by ~11 Ma migrated ~30 km eastward beneath the intervening Cauca Valley (Figure 1; J. S. Jaramillo et al., 2019). Subsequently, arc magmatism extended eastward, reaching the Eastern Colombian Cordillera (>500 km inland from the trench), and later extinguished as a consequence of slab flattening (Wagner et al., 2017). The onset of flat-slab subduction north of ~5°N is still a matter of debate (Chiarabba et al., 2016), but it seems to shortly postdate the final Middle Miocene collision/accretion of the Central American Arc (León et al., 2018, 2025).

The subducting Nazca plate is locally composed of the Malpelo and Coiba microplates, formed due to Late Miocene spreading (~12–9 Ma) along the Sandra Ridge (McGirr et al., 2020). These microplates subduct beneath northwestern South America with steep (~20–30°; Malpelo) and shallow (~10–15°; Coiba) angles (Sun et al., 2022). The along-strike segmentation of the subduction configuration is thought to be related to a slab tear at ~5°N, namely the Caldas Tear (Figure 1; Vargas & Mann, 2013), which is responsible for a ~250 km right-lateral offset of the deep seismicity and the absence of active volcanism in northern Colombia (Martínez-Jaramillo & Prieto, 2024; Wagner et al., 2017).

Available GPS data indicates that the Coiba and Malpelo microplates obliquely converge to the ENE at an average rate of ~54 mm/yr relative to stable South America (Mora-Páez et al., 2019), which is associated with a partitioned strain regime in the upper plate (Arcila & Muñoz-Martín, 2020; Cortés & Angelier, 2005). The prevalent oblique convergence and the upper-plate structural complexity inherited from a long-lived history of subduction and collision likely exerted a first-order control on basin evolution, which has been poorly explored (e.g., Nie et al., 2012; Zapata, Calderon-Diaz et al., 2023).

In this work, we focus on the intermontane basins of the western Colombian Andes—hereafter referred to as the region comprised by the western part of the Central Cordillera, the Western Cordillera, and the intervening Cauca River—including the Amagá and Cauca-Patía basins (Figure 1). As described below, these basins, and those in the surrounding forearc and intermontane regions, show contrasting stratigraphic and morpho-structural features, which we hypothesize result from distinct Neogene tectonostratigraphic histories.

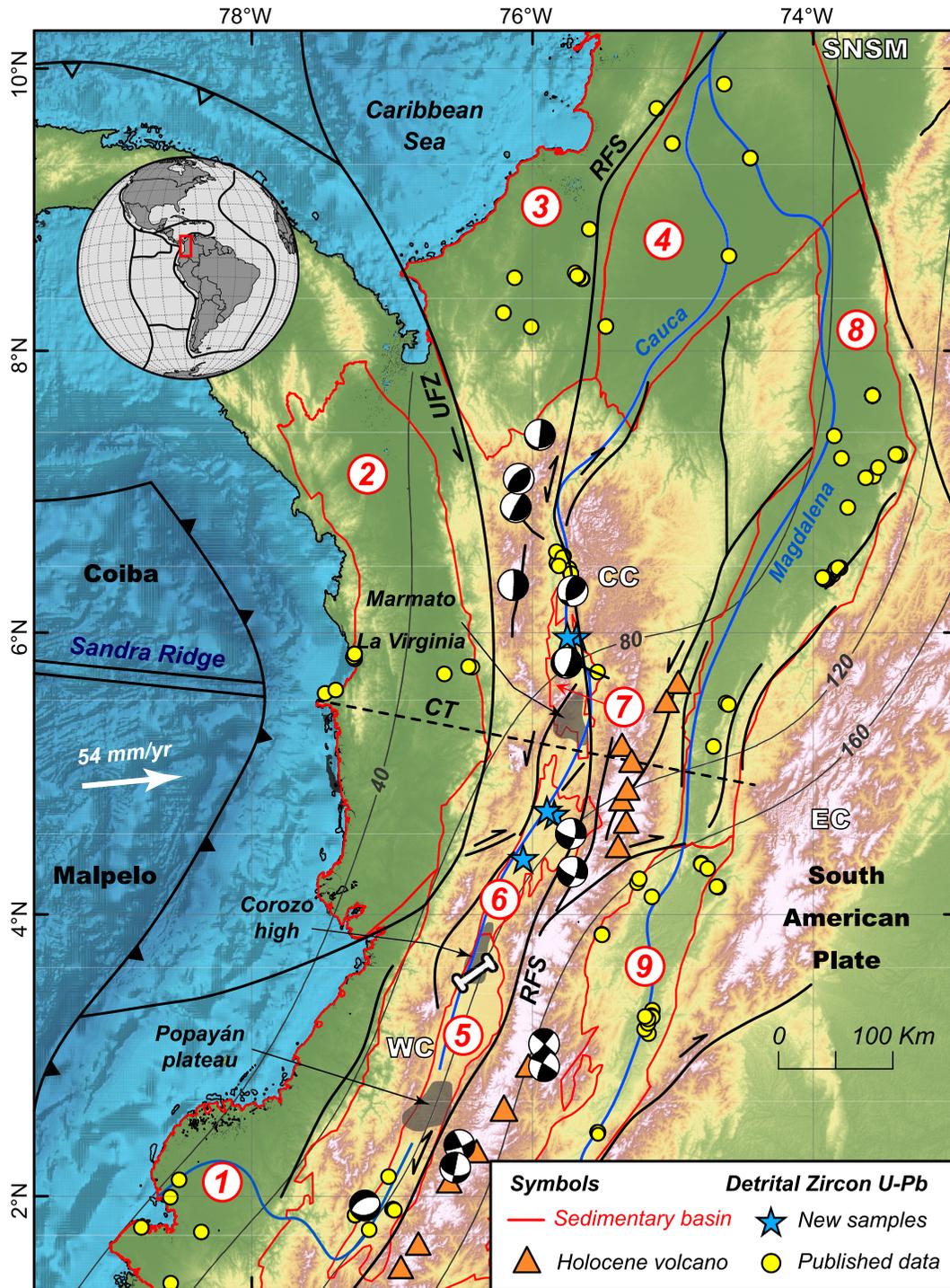


Figure 1. Regional tectonic and morpho-structural map of the Colombian Andes showing the main sedimentary basins discussed in the text and the location of samples analyzed in this work and compiled from previous studies. The main fault structures and focal mechanisms for crustal earthquakes (Dziewonski et al., 1981; Ekström et al., 2012) in the western intermontane region show the variable kinematics of the seismogenic sources. Contours for slab depth (thin gray lines) were taken from the Slab 2.0 Model (Hayes et al., 2018) and convergence vectors (white arrows) from Mora-Páez et al. (2019). The white bar indicates the location of the seismic line shown in Figure 4 (modified from Alfonso et al., 1994). CC, Central Cordillera; EC, Eastern Cordillera; RFS, Romeral Fault System; SNSM, Santa Marta Range; UFZ, Uramita Fault Zone; WC, Western Cordillera. Sedimentary (sub)-basins are 1 = Tumaco, 2 = Atrato, 3 = Sinú-San Jacinto, 4 = Lower Magdalena, 5 = Patía, 6 = Cauca, 7 = Amagá, 8 = Middle Magdalena, 9 = Upper Magdalena.

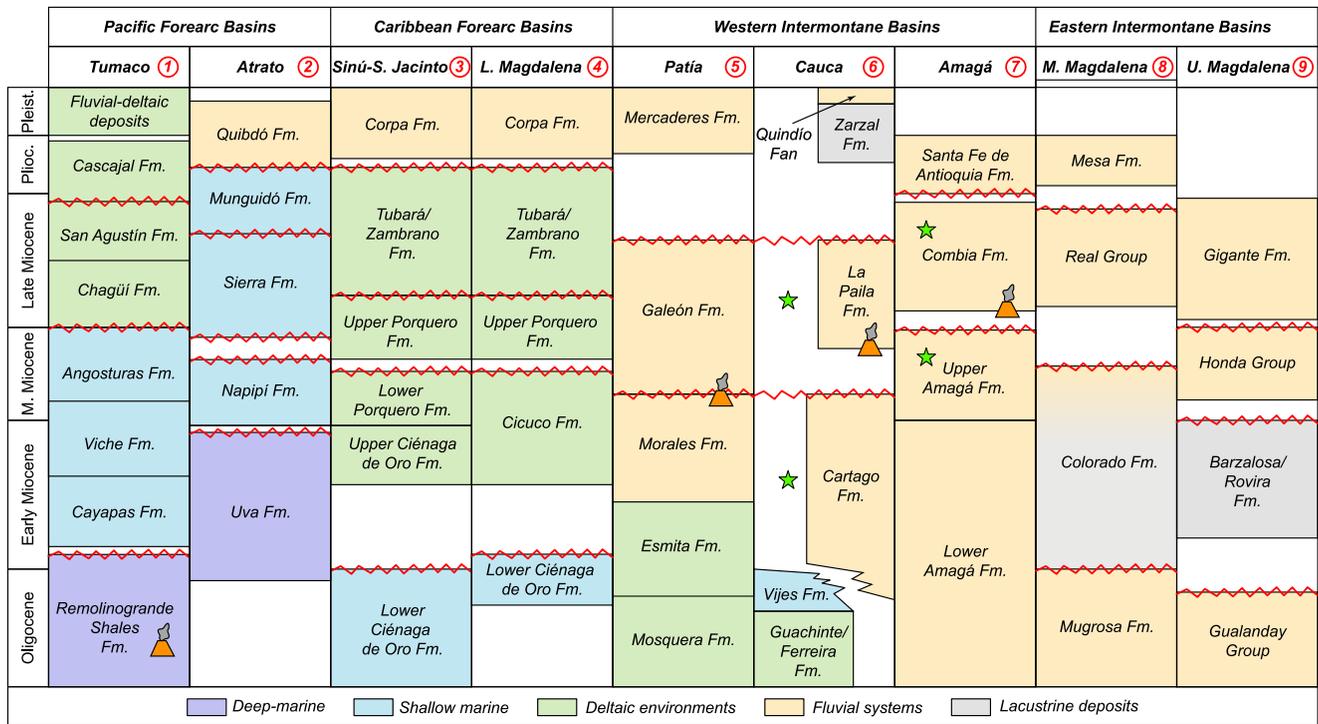


Figure 2. Simplified stratigraphic chart for intermontane and forearc basins of the Colombian Andes showing the dominant sedimentary environments, the onset of post-collisional intra-basinal volcanism, and the stratigraphic units sampled in this work (green stars). Red lines indicate stratigraphic unconformities. Numbers are as in Figure 1. Sources: (1; Borrero et al., 2012; Pardo-Trujillo, Echeverri, et al., 2020), (2; Duque-Caro, 1990; León, Parra et al., 2025; León, Faccenna, et al., 2025), (3; Celis et al., 2023; J. A. Mora et al., 2018), (4; Mora-Bohórquez, Oncken, et al., 2017; J. A. Mora et al., 2018), (5; Echeverri et al., 2015; Gallego-Ríos et al., 2020; Orrego et al., 1996; Ruiz, 2002), (6; Alfonso et al., 1994; López & Toro-Toro, 2020; Neuwerth, 2009), (7; Cárdenas et al., 2023; Lara et al., 2018; Pardo-Trujillo et al., 2023; Silva-Tamayo et al., 2008, 2020; Zapata, Jaramillo-Ríos et al., 2023), (8; Caballero et al., 2013; Cooper et al., 1995; E. Gómez, Jordan, Allmendinger, Hegarty, & Kelley, 2005; Reyes-Harker et al., 2015), and (9; Anderson et al., 2016; Montes et al., 2021; Zapata, Calderon-Diaz et al., 2023), and references therein.

2.2. Forearc and Intermontane Basins of the Colombian Andes

In the southern forearc region, the onshore Tumaco basin extends from the Pacific coast to the western flank of the Western Cordillera (Figure 1; Borrero et al., 2012). There, up to 8 km-thick Eocene to Pleistocene marine to fluvial-deltaic volcanoclastic rocks (Figure 2) unconformably overlie Cretaceous basement units and are thought to represent the sedimentary record of long-lived arc magmatism and tectonically-driven uplift of the southernmost Western Cordillera (Echeverri et al., 2015; Pardo-Trujillo, Echeverri, et al., 2020).

Farther to the north, the Atrato forearc basin comprises an up to 10 km-thick sequence of marine to fluvial strata (Duque-Caro, 1990), flanked to the east by the western flank of the Western Cordillera and to the west by the coastal Baudó Range (Figures 1 and 2). Paleocene-Oligocene volcanoclastic deposits of the Atrato basin are interpreted as accumulated in an intra-oceanic setting during the pre-collisional history of the Central American Arc (Duque-Caro, 1990). Younger Oligocene to Pliocene strata record the progressive shallowing of accumulation settings and pulsed changes in the source area configuration, driven by the transition from collision/accretion to subduction of the Nazca plate (León, Parra et al., 2025; León, Faccenna, et al., 2025).

Eocene-Oligocene marine to fluvial rocks of the forearc Sinú-San Jacinto and Lower Magdalena basins (Figures 1 and 2) are exposed in the Caribbean coastal plains and unconformably overlie Cretaceous and older rocks forming the basement of the northernmost Central and Western Cordilleras (Celis et al., 2023; J. A. Mora et al., 2018). The Romeral Fault System (RFS) separates the Sinú-San Jacinto basins from the Lower Magdalena basin, which is fault-bounded to the east by the Santa Marta Range (Figure 1). Stratigraphic and structural constraints suggest that the Cenozoic basin evolution in the Caribbean forearc region resulted from the oblique convergence and subsequent southeastward subduction of the Caribbean plate (Montes et al., 2010; Mora-Bohórquez, Oncken, et al., 2017).

Along the eastern intermontane region, the Middle and Upper Magdalena basins lie between the Eastern and Central Cordilleras (Figure 1). Such basins are mainly composed of middle Eocene to Pliocene fluvial and lacustrine deposits unconformably overlying Paleocene and older basement rocks (Figure 2; Reyes-Harker et al., 2015 and references therein). This Cenozoic stratigraphic record is interpreted to preserve the impacts of the pulsed growth of the cordilleras, including the early collision-driven uplift in the Central Cordillera (Gómez, Jordan, Allmendinger, Hegarty, & Kelley, 2005; Horton et al., 2015; León, Monsalve, & Bustamante, 2021; Parra et al., 2012).

To the west, the Amagá and Cauca-Patía basins, separated at $\sim 4.5^{\circ}\text{N}$ in the vicinity of the Marmato-La Virginia region, lie between the western slope of the Central Cordillera and the eastern slope of the Western Cordillera. These basins are flanked by the Cauca-Cali Fault System (CCF) to the west and the RFS to the east (Figure 1), and comprise shallow-marine to fluvial deposits spanning from the Eocene-Oligocene to the Pliocene (Figure 2; Gallego-Ríos et al., 2020; López & Toro-Toro, 2020; Silva-Tamayo et al., 2020; and references therein). Sedimentary rocks rest unconformably on top of and are fault-bounded with Cretaceous and older basement rocks (Grosse, 1926). The latter are mostly arc-related units tectonically juxtaposed along the RFS, which represents a Cretaceous-Paleocene suture zone along which Caribbean-derived oceanic terranes accreted to the continental paleomargin (Villagómez et al., 2011).

Scarce structural and seismological data indicate that the RFS comprises a series of east-dipping reverse faults, which show contrasting left-lateral and right-lateral kinematics north of $\sim 5^{\circ}\text{N}$ and south of 4°N , respectively (Ego et al., 1995; MacDonald et al., 1996). Such a kinematic change is thought to be compensated by N–S-oriented compression to the west of the fault system at $\sim 4.5^{\circ}\text{N}$ (Ego et al., 1995). Nevertheless, field observations and available earthquake focal mechanisms indicate that the RFS also shows extensional kinematics and local changes in the strike-slip sense of motion, which might be the product of local fault geometry, strain partitioning, and/or structural overprinting (Figures 1 and 4; e.g., Sierra et al., 2012; Taboada et al., 2000). On the other hand, the CCF (eastern flank of the Western Cordillera; Figure 1) mainly comprises east-dipping reverse faults with sinistral strike-slip components (Figure 4), interpreted as former extensional structures, inverted during the Early or the Late Miocene (Alfonso et al., 1994). Recent work on the neotectonics of the region and new field observations highlight the local influence of extensional tectonics (Figure 4; López & Toro-Toro, 2020; Suter, Neuwerth, et al., 2008).

3. Stratigraphy and Structure of Intermontane Basins of the Western Colombian Andes

We summarize the stratigraphy and structural configuration of intermontane basins exposed along the Cauca River from available (bio)stratigraphic constraints and new field observations gathered during sampling campaigns. The stratigraphic framework and compositional constraints from siliciclastic rocks are used to reconstruct source-to-sink systems and compare them with surrounding intermontane and forearc basins.

3.1. Amagá Basin

The Amagá basin extends from the Marmato-La Virginia region at $\sim 4.5^{\circ}\text{N}$ up to $\sim 7^{\circ}\text{N}$ following an NNW-SSE trend. It is characterized by a relatively high local relief associated with a moderate to deeply incised canyon carved by the Cauca River (Figures 1 and 4). The basin comprises an up to ~ 1.4 km thick Oligocene-Middle Miocene sedimentary pile represented by coal-bearing siliciclastic rocks (Figures 2 and 3), which unconformably overlie or are in faulted contact with Cretaceous and older (meta)sedimentary and plutonic units of both the Central and Western Cordilleras (Silva-Tamayo et al., 2020).

Available palynological and provenance constraints (i.e., detrital zircon U-Pb and fission-track ages) suggest that, toward the base, the Amagá basin comprises Late Oligocene-Early Miocene organic matter- and quartz-rich strata accumulated in fluvio-deltaic settings dominated by meandering river systems (Figure 2; Cárdenas et al., 2023; Lara et al., 2018; Montes et al., 2015; Pardo-Trujillo et al., 2023; Piedrahita et al., 2017; Silva-Tamayo et al., 2008). These rocks are overlain by compositionally immature sediments with high contents of lithic fragments and unstable minerals, for which detrital zircon U-Pb and fission-track data indicate a depositional age between ~ 18 and ~ 11 Ma (Lara et al., 2018; Montes et al., 2015; Piedrahita et al., 2017). Middle-Upper Miocene strata are interpreted to represent a transition from meandering to braided fluvial systems coeval with a period of increased sedimentation rates (Silva-Tamayo et al., 2020 and references therein).

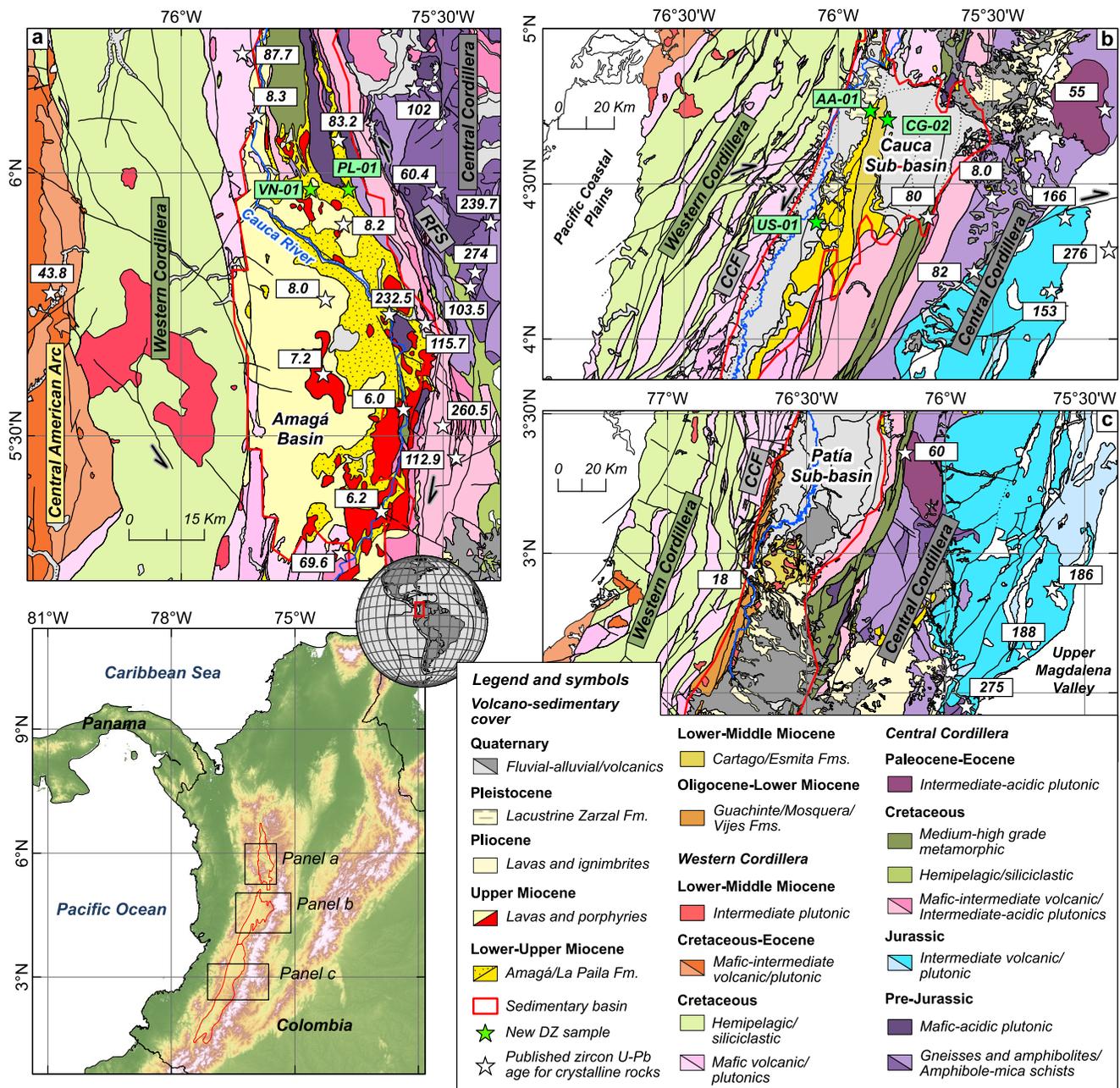


Figure 3. Geological map of the Amagá basin (a), and the Cauca (b) and Patía (c) sub-basins, modified from Gómez-Tapias et al. (2017). White stars indicate the location of samples from crystalline rocks (i.e., potential source areas and intra-basin subvolcanic units) with available zircon U-Pb ages (provided in Ma in the white rectangles). Data compiled from Rodríguez-Corcho et al. (2022) and sources therein. CCF, Cauca-Cali Fault System; RFS, Romeral Fault System.

Upper Miocene volcano-sedimentary and subvolcanic rocks, mafic to intermediate in composition, both unconformably overlie and intrude on Oligocene-Middle Miocene strata of the Amagá basin (Figures 2 and 3; J. S. Jaramillo et al., 2019). Volcano-sedimentary rocks are interpreted as associated with debris flows and braided fluvial systems (Weber et al., 2020). Intrusive and sub-volcanic units are related to continental arc magmatism with a highly heterogeneous history of fractionation and crustal assimilation (J. S. Jaramillo et al., 2019; Villalba et al., 2023), and have yielded zircon U-Pb ages between 11 and 5 Ma (Zapata, Jaramillo-Ríos et al., 2023 and references therein).

The youngest siliciclastic deposits of the Amagá basin are represented by Pliocene coarse-grained deposits that unconformably overlie the Cretaceous intrusive rocks of the Western Cordillera and younger strata. These rocks,

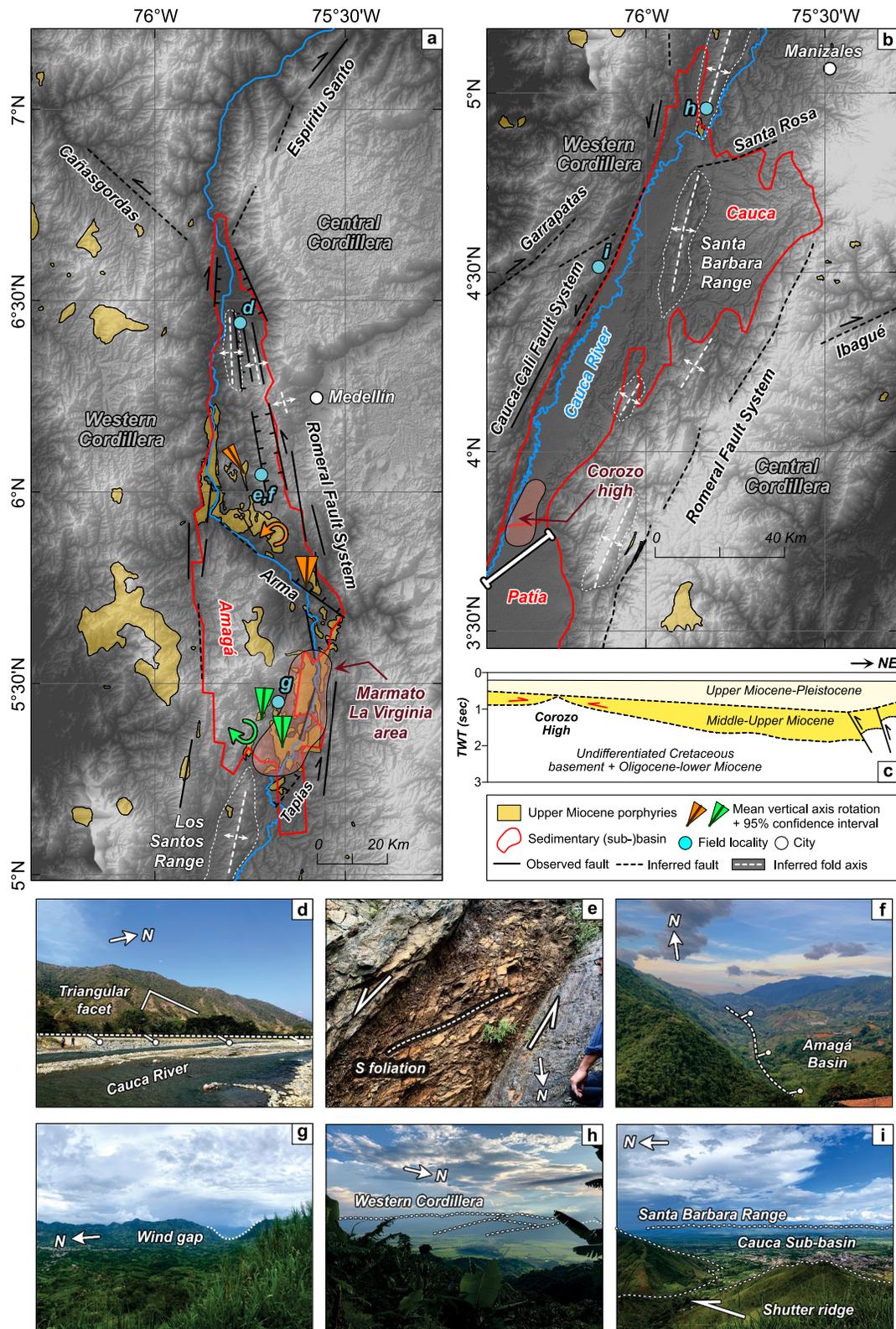


Figure 4.

for which a Maximum Depositional Age (MDA) of ~ 5 Ma has been estimated from detrital zircon U-Pb data (Lara et al., 2018), are interpreted as deposited in high-energy braided fluvial systems during a period of limited accommodation space and relatively high sedimentation rates (Silva-Tamayo et al., 2020).

Morphological and structural features of the Amagá basin suggest the existence of *en-echelon* narrow anticline and fault structures, whose NW-oriented axes are sub-parallel to the primary fault systems (e.g., RFS; Figure 4). Field data have shown the existence of inverse fault structures along which Cretaceous volcano-sedimentary rocks thrust over Neogene strata (Grosse, 1926). New field observations gathered during our sampling campaigns and previous constraints indicate the presence of young oblique NW-SE and NE-SW-oriented structures with extensional kinematics (e.g., Arma and Tapias Faults; Figure 4; Suter, Sartori, et al., 2008).

Available paleomagnetic data for Miocene strata of the southernmost Amagá basin suggest the existence of at least two deformational episodes related to the development of intra-basinal morpho-structural expressions (Sierra et al., 2012). A pre-Late Miocene event was seemingly contemporaneous with the opening of the southernmost Amagá basin and minor clockwise block rotation. This episode was overprinted by post-Late Miocene thrust-faulting and folding of Middle-Upper Miocene sediments, accompanied by counterclockwise ($\sim 30^\circ$) rotations of Upper Miocene subvolcanic rocks of the central part of the Amagá basin (Figure 4; MacDonald et al., 1996; Sierra et al., 2012).

3.2. Cauca-Patía Basin

This basin extends from the Cartago region at $\sim 4.5^\circ\text{N}$ to the south, up to the headwaters of the Patía River, and is characterized by a relatively flat morphology associated with the Cauca River Valley that reaches its maximum width (~ 45 km) at $\sim 3.2^\circ\text{N}$ (Figure 1). This basin is divided into the Cauca and Patía sub-basins to the north and south of the Corozo high ($\sim 3.8^\circ\text{N}$; Figures 1 and 4; Alfonso et al., 1994), which represents a positive gravity anomaly that separates two regions with contrasting stratigraphic records (Gallego-Ríos et al., 2020; López & Toro-Toro, 2020).

3.2.1. Cauca Sub-Basin

The infill of the Cauca sub-basin is represented by an up to ~ 3 km-thick sedimentary succession interpreted as marine to fluvial deposits spanning the Oligocene to the Pleistocene, which forms an angular unconformity with underlying Cretaceous volcano-sedimentary rocks of the Western and Central Cordilleras (Figures 2 and 3; Alfonso et al., 1994 and references therein).

Basal conglomerates and mudstones unconformably overlie Cretaceous basement rocks in the southwestern region of the Cauca sub-basin and are interpreted as syn-tectonic fluvial deposits (Alfonso et al., 1994). These rocks are unconformably overlain by Oligocene coal-bearing, quartz-rich sandstones, and mudstones, which are thought to have accumulated coevally with transtensional deformation in marine to fluvial-deltaic settings, influenced by local incursions of the Pacific Ocean as indicated by the presence of corals, foraminifera, bivalves, calcareous algae and gastropods (Dueñas et al., 2000). Neogene sediments are represented, toward the base, by Lower-Middle Miocene fluvial coarse-grained strata showing an upward decrease in compositional maturity (i.e., shift from quartz- to lithic-rich compositions; López & Toro-Toro, 2020).

Middle-Upper Miocene deposits overlie in angular unconformity Oligocene-Middle Miocene strata and represent the first record of nearby volcanic activity (Figure 2), as indicated by the abundant volcanoclastic material (López & Toro-Toro, 2020). These rocks are composed of fine- to coarse-grained volcanic-rich deposits, interlayered with vitreous and crystal tuffs, interpreted as accumulated in fluvial and lacustrine environments near arc-related volcanoes (D. Sanín et al., 2016). Available seismic reflection data show that Middle-Upper Miocene sediments onlap onto underlying strata and basement rocks at the Corozo high (Figure 4), indicating that this structural high was active since at least the Middle Miocene and played a primary role in basin geometry and

Figure 4. Morpho-structural map of the Amagá (a) and Cauca-Patía (b) basins showing the trace and the kinematics (when observed in the field) of the main fault structures in the study area, primary topographic features, and the distribution of Upper Miocene porphyritic rocks. Paleomagnetic data from MacDonald (1980) and MacDonald et al. (1996) indicate relative clockwise (green) and counterclockwise (orange) vertical axis rotations of subvolcanic rocks. (c) Seismic section near the Corozo high (location indicated by the white bar in panel b) showing the onlap termination of La Paila Fm. (modified from Alfonso et al., 1994). Panels (d–i) are field photographs showing some of the observed morphological and structural expressions of the structures drawn in panels (a, b).

filling history (Alfonso et al., 1994). Pliocene-Pleistocene diatomites and volcanic-rich fine-to medium-grained rocks unconformably overlie Middle-Upper Miocene volcanoclastic sediments (Figure 2) and are interpreted as syn-tectonic deposits, accumulated in lacustrine and braided-fluvial systems between the Pliocene (~2.8 Ma) and Pleistocene (~0.5 Ma; Neuwerth, 2009; Suter, Neuwerth, et al., 2008).

Available structural observations from the eastern part of the Cauca sub-basin suggest the existence of east-dipping reverse faults along the western flank of the Central Cordillera (Figures 3b and 4b) and fault-related folding linked to high-angle structures with an important horizontal slip component affecting Middle-Upper Miocene strata (Alfonso et al., 1994; López & Toro-Toro, 2020). However, as mentioned above, field observations and earthquake focal mechanisms also indicate local extensional kinematics (Figure 1; Suter, Sartori, et al., 2008 and references therein). Along the western flank of the Cauca sub-basin, the eastern slope of the Western Cordillera is controlled by high-angle, east-dipping fault structures with dominant left-lateral kinematics, which locally include normal dip-slip components (Figure 4; Suter, Neuwerth, et al., 2008).

Morphologically, the Cauca sub-basin comprises NE-trending anticline structures associated with discontinuous areas of positive relief (e.g., Los Santos and Santa Bárbara Ranges) and minor oblique NE-SW-oriented faults, which lack evident morphological expressions (Figure 4). Conversely, the CCF, on the basin's western edge, is linked to fragmented NE-SW-oriented shutter ridges (Figure 4). Other syn- to post-depositional features indicative of recent tectonic activity in the Cauca sub-basin are found in Pleistocene to Quaternary deposits, and include clastic dykes, and liquefaction, water escape, fold, and fault structures (López & Toro-Toro, 2020; Neuwerth et al., 2006).

3.2.2. Patía Sub-Basin

The Patía sub-basin comprises an up to ~4.7 km thick Eocene-Oligocene to Pliocene sedimentary succession that shifts from marine to terrestrial settings and records the contribution of Miocene to recent subduction-related volcanism (Echeverri et al., 2015; Gallego-Ríos et al., 2020). These rocks were unconformably deposited on top of Mesozoic volcano-sedimentary rocks forming the basement of the Central Cordillera and accreted terranes of the Western Cordillera (Ruiz, 2002).

Eocene-Oligocene coal-bearing strata represent the oldest record in the Patía sub-basin. It comprises fine-to coarse-grained sandstones and conglomerates, with abundant quartz and metamorphic and sedimentary lithic fragments, which are interpreted as accumulated in a tide-influenced deltaic setting (Figures 2 and 3; Orrego et al., 1996; Ruiz, 2002). Overlying Lower Miocene strata show an upward shift from fossil-rich mudstones to cross-stratified and wavy-laminated sandstones and conglomerates, interpreted as accumulated in fluvial channels and floodplains in tide-influenced nearshore settings. These rocks show a relative increase in the abundance of unstable detrital components, such as amphibole, feldspar, and biotite, as well as volcanic, and sedimentary lithics compared to the underlying unit (Gallego-Ríos et al., 2020; Orrego et al., 1996; Ruiz, 2002). Lower-Middle Miocene mudstones and sandstones, containing abundant mafic-ultramafic minerals, such as olivine, pyroxene, and spinel, conformably overlie younger deposits and are thought to have been accumulated in fluvial channels, alluvial plains, and swamps in a braider river system (Gallego-Ríos et al., 2020).

Middle-Upper Miocene strata show a dramatic shift toward volcanic-rich compositions, related to a peak of arc-related volcanism in southwestern Colombia (Echeverri et al., 2015). These rocks are interpreted as deposited in proximal braided rivers with volcanoclastic input originating from surrounding active volcanoes and exhumed Lower Miocene and Cretaceous subvolcanic rocks along the Central and Western Cordilleras (Gallego-Ríos et al., 2020). Middle-Upper Miocene strata are unconformably overlain by Pliocene to Pleistocene volcanoclastic deposits, up to ~200 m thick (Ruiz, 2002). These rocks, mostly rhyolitic in composition, are related to massive ignimbrites thought to be part of a short-lived episode of intense magmatic activity in southern Colombia (Kroonenberg et al., 1981; M. J. Sanín, Cardona, et al., 2022). Such volcanic deposits are associated with local low-relief surfaces (e.g., Popayán plateau; Figure 1) that seemingly filled former inter-cordilleran depressions (Pérez-Consuegra, Ott, et al., 2021).

Structural constraints suggest that the Patía sub-basin mainly comprises west-verging thrust faults to the east, minor east- and west-dipping thrusts to the west, and associated folding involving Cretaceous basement rocks and Eocene-Oligocene to Middle-Upper Miocene strata (Sierra & Marín-Cerón, 2011). However, some east-dipping structures along the eastern slope of the Western Cordillera (i.e., CCF) and the western flank of the Central

Cordillera (i.e., RFS) show evidence of sinistral strike-slip kinematics and localized extension (Paris et al., 2000; Suter, Neuwerth, et al., 2008). The existence of a Late Miocene to Pliocene unconformity and the presence of fault and fold structures affecting Pliocene to Pleistocene volcanoclastic rocks provide evidence for the most recent deformation phase in the Patía sub-basin (Orrego & Paris, 1996).

4. Potential Sediment Sources: Geology of the Colombian Central and Western Cordilleras

In the following paragraphs, we recall the main geochronological and compositional characteristics of the Central and Western Cordilleras basement rocks. This information is used to evaluate the provenance of the Neogene strata of the intermontane basins.

The Central Cordillera of Colombia is chiefly composed of a Jurassic and older (meta)sedimentary and (meta)igneous basement, associated with Jurassic to Eocene arc-related magmatic and sedimentary rocks (Blanco-Quintero et al., 2014; Bustamante et al., 2016; Bustamante, Cardona, et al., 2017; Cochrane et al., 2014; J. S. Jaramillo et al., 2017; Zapata et al., 2019). Metamorphic units include low-to high-grade rocks derived from mafic, acidic, and pelitic protoliths that yield zircon U-Pb ages between ~480 and ~160 Ma (see a summary in León et al., 2019). Magmatic units comprise arc-related mafic to acidic plutonic and volcanic rocks with zircon U-Pb ages ranging from ~280 to ~50 Ma (Cardona et al., 2018; Duque-Trujillo et al., 2019; Restrepo et al., 2021; Spikings et al., 2015; and references therein). Pre-Cretaceous (meta)sedimentary rocks are primarily pelitic in composition and were sourced by basement units of the Central Cordillera and the Amazonian craton. Accordingly, they include detrital zircon U-Pb ages between >2,000 and ~160–100 Ma (i.e., primary or reworked zircons from source areas), with ubiquitous ~1,200–1,000 Ma, ~600–480 Ma, and ~300–200 Ma age peaks (Avellaneda-Jiménez et al., 2020; Bustamante, Archanjo, et al., 2017; J. S. Jaramillo et al., 2017; Martens et al., 2012; Zapata et al., 2019).

Together, the units mentioned above are the product of the protracted convergence of oceanic (Pacific) plates and the western continental margin of Gondwana and preserve the imprints of extensional and compressional regimes associated with subduction and collisional tectonics (Avellaneda-Jiménez et al., 2022; Cardona et al., 2020; Martens et al., 2014; Restrepo et al., 2021; Spikings et al., 2015; Zapata et al., 2019).

The Colombian Western Cordillera is composed of Cretaceous to Eocene plateau- and island arc-related rocks overlain by Cretaceous-Paleocene to Pliocene syn- to post-collisional strata (Cardona et al., 2018; Pardo-Trujillo, Cardona, et al., 2020). Mafic to intermediate volcanic and volcanoclastic rocks, intruded by gabbros and diorites, form the basement of the cordillera and, together, yield zircon U-Pb ages ranging from ~100 to ~34 Ma (Barbosa-Espitia et al., 2019; Cardona et al., 2018; Villagómez et al., 2011; Weber et al., 2015; and references therein). Magmatic mafic rocks with plateau-like geochemical affinity are part of the Caribbean Large Igneous Province (CLIP; Kerr et al., 1997; Villagómez et al., 2011).

Subduction-related rocks belong to two island arc systems, the Ecuadorian-Colombian-Leeward Antilles Arc (ECLA; ~100–80 Ma; e.g., Seyler et al., 2021) and the Central American Arc (~100–34 Ma; León, Avellaneda-Jiménez et al., 2024 and sources therein). The latter is only exposed along the western flank of the Western Cordillera, sutured to the ECLA along the Uramita Fault Zone (UFZ; León et al., 2018), and represents a key provenance marker for Neogene strata since it is the only known crystalline unit in the Colombian Andes with zircon U-Pb ages between 50 and 40 Ma (Montes et al., 2015 and references therein).

Cretaceous-Paleocene hemipelagic and terrigenous strata, exposed along the Western Cordillera, are characterized by detrital ages clustered around ~1,200–1,000 Ma, ~600–400 Ma, ~300–200 Ma, and ~100–70 Ma and have been interpreted as accumulated during and shortly after the collision of the ECLA against northwestern South America (Botero-García et al., 2023; León et al., 2018; Pardo-Trujillo, Cardona, et al., 2020).

As mentioned above, subduction of the Nazca plate beneath northwestern South America propagated northward, together with the associated continental arc, during and after the collision/accretion of the Central American Arc (i.e., migration of the triple junction point between the Nazca, Caribbean, and South American plates; González et al., 2023; Montes et al., 2019). The magmatic record of the above includes Oligocene-Lower Miocene (~30–18 Ma) intermediate intrusive rocks exposed along the southern segment of the Western Cordillera (Figure 3; Botello et al., 2024 and sources therein). These rocks represent primary provenance proxies for the Neogene erosion/uplift of the southern segment of the Western Cordillera.

5. Data and Methods

We combine new and published detrital zircon U-Pb data from Neogene rocks of intermontane basins of the western Colombian Andes to (semi)quantitatively assess their provenance (see sample location in Figure 1 and Table S1 in Supporting Information S1). Five new samples were collected in the Amagá basin and the Cauca sub-basin, from which we obtained 538 individual zircon ages (see the results in the Table S2 in Supporting Information S1). Available data for these basins ($n = 2,021$) was compiled from Lara et al. (2018), Montes et al. (2015), and Zapata et al. (2020). New field observations and sampling were restricted to the Amagá and Cauca sub-basins since the area comprised by the Patia sub-basin was inaccessible due to sociopolitical unrest.

Additionally, we compiled published detrital zircon U-Pb ages from Neogene rocks of sedimentary basins surrounding the Central and Western Cordilleras, including the Middle and Upper Magdalena intermontane basins ($n = 4,637$; Anderson et al., 2016; Caballero et al., 2013; B. K. Horton et al., 2015; Montes et al., 2021; Nie et al., 2012; Rodríguez-Corcho et al., 2022; Zapata, Calderon-Diaz et al., 2023; and sources therein), and the Lower Magdalena, Sinú-San Jacinto, Atrato, and Tumaco forearc basins ($n = 3,025$; Echeverri et al., 2015; León, Avellaneda-Jiménez et al., 2024; León, Parra, et al., 2024; Montes et al., 2015; Osorio-Granada et al., 2020). These data sets are used for comparison, as they have proven valuable in identifying episodes of uplift/erosion of the Central and Western Cordilleras and are, therefore, important for our regional approach. Information for the new and published samples and the geochronological data are provided in Tables S1–S3 in Supporting Information S1.

New geochronological analyses were conducted at the Radiogenic Isotope and Geochronology Lab at Washington State University. Zircon concentrates were obtained by standard procedures, including crushing, sieving, hydraulic sorting in a Wilfley water table, magnetic separation, and precipitation in heavy liquids. Grains were mounted alone with Plešovice, Temora-1, and 91,500 standards in epoxy resin discs and polished until exposure to crystal surfaces. Zircon U-Pb ages were measured using an Analyte G2 193 excimer laser ablation system coupled with a Thermo-Finnigan Element 2 single collector inductively coupled plasma mass spectrometer. Analyses were performed following the analytical procedures of Chang et al. (2006). Laser spot size and repetition rate were 30 μm and 10 Hz, respectively. Each analysis consisted of a 10s blank measurement of the He and Ar carrier gases, followed by 250 sweeps through masses ^{202}Hg , $^{204}\text{Pb} + \text{Hg}$, ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , ^{235}U , and ^{238}U , taking 30s.

Unknown and quality control zircons (Temora-1 and 91,500) were interspersed with analyses of external calibration standards (Plešovice; Sláma et al., 2008). The ^{207}Pb method of Williams (1998) was used for common Pb correction; data reduction was conducted using the Iolite software (Woodhead & Hergt, 2005) and drawn using the package IsoplotR (Vermeesch, 2018b). The Table S2 in Supporting Information S1 reports zircon U-Pb data with associated 2σ uncertainties. Individual ages with analytical errors over 10% and those exceeding 15% of discordance (for zircons over 400 Ma) were excluded from further processing and interpretations. Maximum depositional ages for newly analyzed samples were estimated using the *Maximum Likelihood Age* algorithm (MLA; Vermeesch, 2021).

6. Detrital Geochronology of Oligocene-Pliocene Strata

6.1. New Geochronological Constraints From the Amagá Basin and the Cauca Sub-Basin

Two samples from the Amagá basin were analyzed for detrital zircon U-Pb geochronology. A total of 108 individual ages were obtained from sample VN-01 (Upper Amagá Fm.), which cluster around Mesoproterozoic ($\sim 1,400$ – $1,000$ Ma, 13%), Neoproterozoic (~ 800 – 550 Ma, 10%), Late Cretaceous (~ 100 – 70 Ma, 24%), Eocene (~ 45 – 34 Ma, 24%), and Oligocene-Miocene (~ 23 – 19 Ma, 16%) age peaks; with a MDA of 19.4 ± 0.4 Ma (Figure 5a). From sample PL-01 (Combia Fm.), a total of 101 zircon grains were dated, which mostly yielded Jurassic (~ 160 – 149 Ma, 14%), Late Cretaceous (~ 90 – 70 Ma, 8%), Late Miocene (~ 11 – 6 Ma, 32%), and Pliocene (~ 5 Ma, 22%) individual U-Pb ages, and suggest a MDA of 5.2 ± 0.1 Ma (Figure 5a).

We selected three samples from the Cauca sub-basin for geochronological analyses. From sample US-01 (Cartago Fm.), we obtained a total of 110 individual zircon U-Pb ages, which yield Neo-Mesoproterozoic ($\sim 1,100$ – 600 Ma, 7%), Permian-Triassic (~ 280 – 230 Ma, 12%), Late Cretaceous (~ 100 – 80 Ma, 44%), and Paleocene (~ 60 – 56 Ma, 28%) age peaks (Figure 5b). A total of 110 zircon grains from sample CG-02 (Cartago Fm.) were analyzed and yielded individual ages that cluster around Neo-Mesoproterozoic ($\sim 1,000$ – 600 Ma, 15%), Permian-

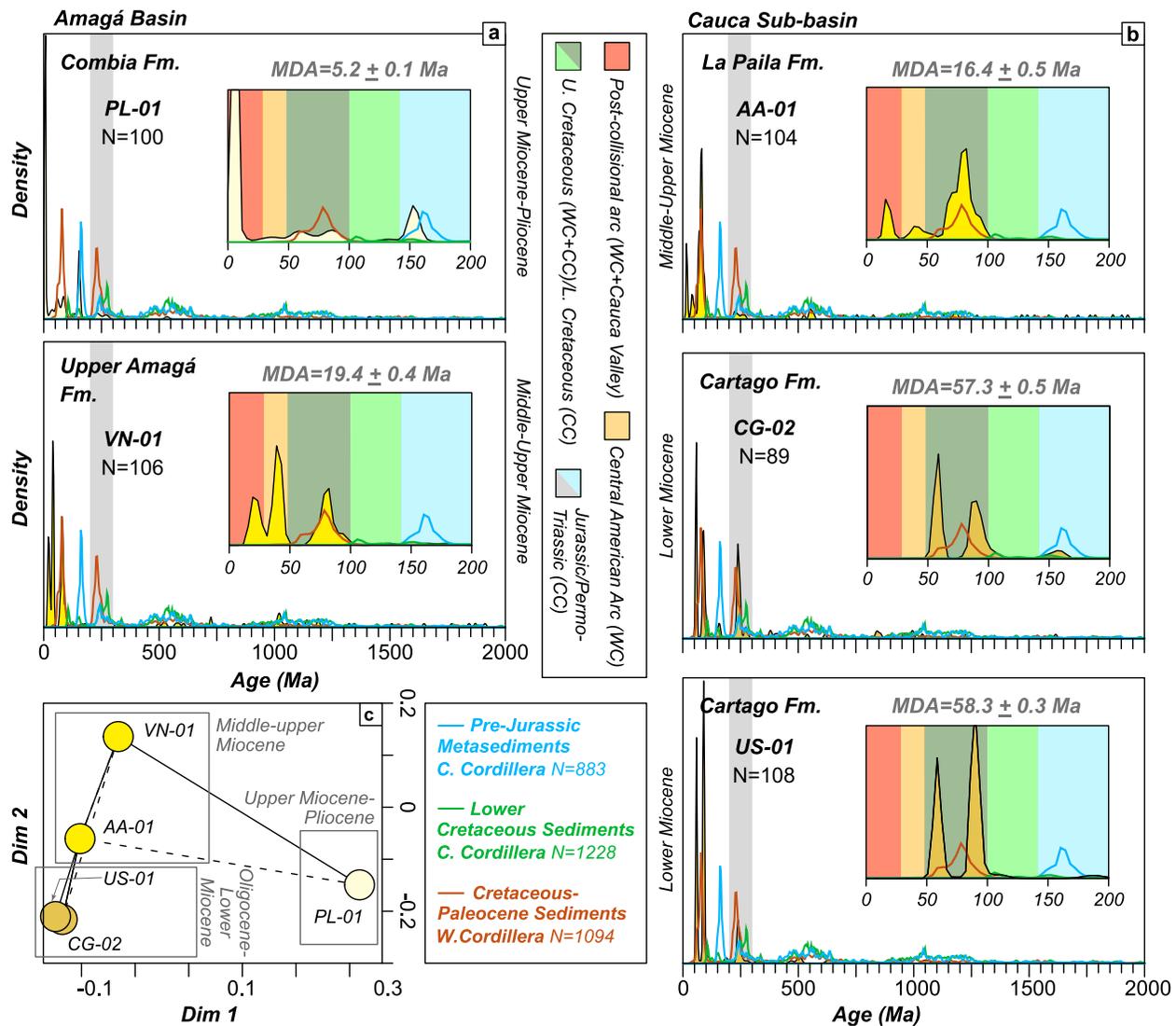


Figure 5. Summary of the new detrital geochronological data from Neogene samples of the Amagá (a) and Cauca-Patía (b) basins, as depicted by Kernel Density Estimates (KDE). (c) Classical multi-dimensional scaling plot showing dissimilarity between analyzed samples. The similarity was estimated using the Kolmogorov-Smirnov statistic that measures the maximum vertical distance between cumulative age distributions (Vermeesch, 2018a). Colored polygons in the background show the age ranges for crystalline rocks found in potential source regions, which are used to track their contribution to Neogene strata. Data from pre-Jurassic, Lower Cretaceous, and Upper Cretaceous-Paleocene (meta)sedimentary rocks of the Central (CC) and Western Cordilleras (WC) are included for comparison (Botero-García et al., 2023; León et al., 2018, 2023; Pardo-Trujillo, Cardona, et al., 2020; and sources therein). MDA, Maximum Depositional Age.

Triassic (~280–230 Ma, 28%), Late Cretaceous (~100–80 Ma, 25%), and Paleocene (~60–56 Ma, 19%) age peaks (Figure 5b). For samples US-01 and CG-02, Paleocene (~57 Ma) maximum depositional ages were estimated, which, however, strongly differ from available biostratigraphic constraints that robustly indicate Oligocene-Lower Miocene deposition (López & Toro-Toro, 2020).

We dated a total of 109 zircon grains from sample AA-01 (La Paila Fm.), which yielded individual ages clustered in Paleoproterozoic (~2,700–1,600 Ma, 13%), Meso-Neoproterozoic (~1,500–550 Ma, 22%), Late Cretaceous (~100–68 Ma, 41%), and Miocene (~19–16 Ma, 9%) age peaks (Figure 5b). A MDA of 16.4 ± 0.5 Ma was estimated for sample AA-01, which agrees with available (bio)stratigraphic and geochronological constraints assigning a Middle Miocene age (ANH-Universidad de Caldas, 2008; López & Toro-Toro, 2020).

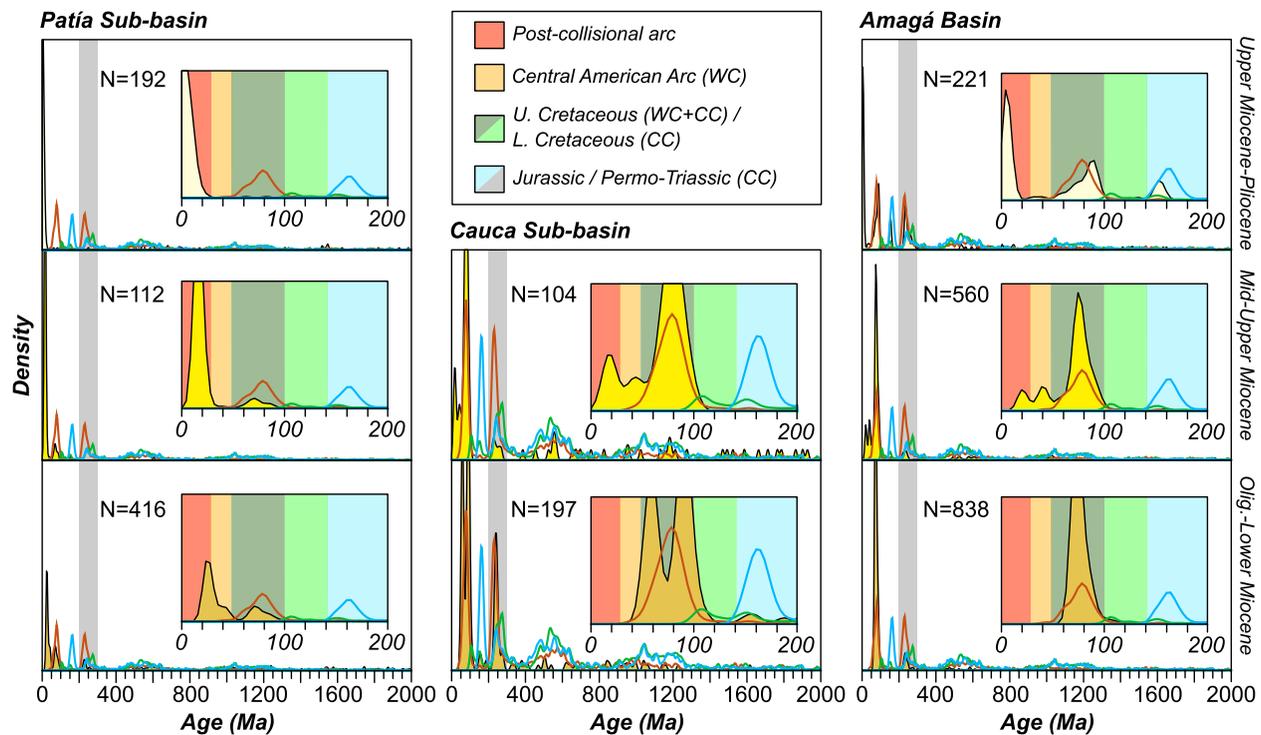


Figure 6. Summary of the published detrital geochronological data from Oligocene-Pliocene strata from the western Colombian Andes intermontane basins, as depicted by Kernel Density Estimates (KDE). Data from Paleozoic to recent crystalline units and pre-Jurassic, Lower Cretaceous, and Upper Cretaceous-Paleocene (meta)sedimentary rocks of the Central and Western Cordilleras, are included for comparison and colored as in Figure 5.

6.2. Interpretation of New and Available Detrital Zircon U-Pb Data of Intermontane Basins in the Western Colombian Andes

Published detrital zircon U-Pb ages for Oligocene-Lower Miocene strata of the Amagá basin are mostly represented by Meso-Neoproterozoic (1,500–550 Ma, <11%), Cambrian-Carboniferous (~500–300 Ma, <10%), Permian-Triassic (~280–200 Ma, <14%), and Late Cretaceous (~100–70 Ma, 66%–100%) individual ages (Figure 6; Lara et al., 2018; Montes et al., 2015; Zapata et al., 2020). Available geochronological constraints for Middle-Upper Miocene strata indicate the dominance of Meso-Neoproterozoic (~1,500–550 Ma, <28%), Permian-Triassic (~300–200 Ma, <13%), and Late Cretaceous (~100–70 Ma, 25%–91%) age peaks. Nevertheless, published data indicate the presence of abundant Eocene (~45–30 Ma, <7%) and Miocene (~20–13 Ma, <9%) detrital zircon U-Pb ages, which are absent in underlying strata (Figure 6; Lara et al., 2018; Montes et al., 2015).

The data above indicate a dominant contribution to Oligocene-Lower Miocene strata from sources to the east, in the Central Cordillera (Lara et al., 2018), as also supported by NNW-directed paleocurrents (Silva-Tamayo et al., 2008). The prevalence of ultra-stable and stable detrital components, including garnet and plutonic and metamorphic lithics, is consistent with the erosion of intermediate-acidic plutonic and metamorphic rocks forming the basement of the Central Cordillera (Silva-Tamayo et al., 2008).

Importantly, Oligocene-Lower Miocene strata of the Amagá basin contain few Early Cretaceous-Jurassic detrital zircon ages (~2%), which are abundant in Lower Cretaceous and older (meta)sedimentary rocks of the Central Cordillera (up to ~20%; Figure 6). This suggests that the contribution from easterly sources was dominantly represented by Upper Cretaceous and Permian-Triassic (meta)igneous rocks (i.e., mid-crustal levels), rather than by Lower Cretaceous and older volcanoclastic and (meta)sedimentary units (i.e., upper crustal levels). This interpretation is consistent with the available thermo-kinematic modeling showing that during the Oligocene-Early Miocene, Late Cretaceous intrusives were being exhumed at moderately rapid rates after a prolonged period of erosion and tectonic quiescence that would have deeply eroded shallower crustal rocks (Zapata et al., 2021). The (meta)sedimentary cover was an essential source for older, Lower-Upper Cretaceous and

Paleocene, fluvial-lacustrine deposits of foreland and intermontane basins farther inland (e.g., Eastern Cordillera and Upper Magdalena basins; León et al., 2023 and references therein).

Middle Eocene (~40 Ma) detrital zircon fission-track ages yielded by Oligocene-Lower Miocene strata of the Amagá basin resemble those found in Cretaceous-Paleocene rocks of the Western Cordillera, indicating additional contribution from the latter (Piedrahita et al., 2017; Zapata et al., 2020). Thus, the reworking of quartz-rich Cretaceous-Paleocene strata, as a consequence of moderate-rapid erosion/exhumation of the Western Cordillera during the Oligocene (León et al., 2018), seemingly contributed to the high quartz content of sandstones from the Amagá basin.

New geochronological data from Oligocene-Lower Miocene rocks of the Cauca sub-basin show significant differences when compared with coeval strata accumulated to the north in the Amagá basin. For instance, rocks from the Cauca sub-basin show more abundant Paleocene-Eocene (~62–55 Ma) and Permian-Triassic (~300–200) and less abundant Late Cretaceous (~100–70 Ma) detrital zircon U-Pb ages (Figure 6). This finding reflects a relatively higher contribution from Paleocene-Eocene arc-related intrusives of the Central Cordillera and their Triassic and older host-rocks, which are exposed only toward the central segment of the mountain range (Figure 3). Minor contribution from westerly sources into the Cauca sub-basin is arguably indicated by the presence of detrital zircon ages between ~80 and 70 Ma (<1%), which are particularly abundant, in Cretaceous-Paleocene strata of the Western Cordillera (~10%; Figure 6). Alternatively, Late Cretaceous (~80–70 Ma) detrital zircons would have been derived from the Central Cordillera.

Oligocene-Lower Miocene strata of the Patía sub-basin also show a contrasting provenance when compared with the Cauca and Amagá (sub-)basins. The most striking difference is the appearance of Eocene-Early Miocene (~48–20 Ma) detrital zircon U-Pb ages, particularly ~30–21 Ma ages (up to ~25%), which are absent in coeval units farther to the north (Figure 6). These data suggest that Eocene-Early Miocene arc-related rocks of the Western Cordillera (Figure 3) were essential sediment sources. This interpretation is consistent with the similarity between the detrital age distributions of Oligocene-Lower Miocene strata and westerly Cretaceous-Paleocene sediments, as depicted by the abundance of ~80–70 Ma detrital zircons in the Patía sub-basin (Figure 6). Furthermore, the high abundance of olivine, pyroxene, and spinel, common in Cretaceous mafic-ultramafic rocks of the Western Cordillera, also point to the latter as an important source area (Gallego-Ríos et al., 2020). Provenance from the Central Cordillera is arguably suggested by the moderate-high abundance of Permian-Triassic (~300–200 Ma) and Neoproterozoic-Cambrian (~650–500 Ma), and minor Cretaceous (~100–70 Ma) detrital ages. Alternatively, Neoproterozoic-Paleozoic zircons could also indicate the reworking of the Cretaceous-Paleocene strata of the Western Cordillera (Figure 6).

Significant changes in the intermontane sediment routing systems during the Middle Miocene occurred at basin and regional scales in the western Colombian Andes. The appearance of Eocene-Miocene (~45–14 Ma) detrital ages in Middle Miocene strata of the Cauca and Amagá (sub-)basins, absent in underlying rocks (Figure 6), indicate the onset of sediment contribution of the Central American and post-collisional arcs, exposed along the axis and western flank of the Western Cordillera (Lara et al., 2018; Montes et al., 2015). The enhanced sediment contribution from this region is also indicated by: (a) The remarkable similarity between the detrital age distribution of Middle Miocene rocks and Cretaceous-Paleocene strata (Figures 5 and 6) and (b) the sharp shift from quartz- to lithic-rich sandstone compositions (López & Toro-Toro, 2020; Silva-Tamayo et al., 2008).

Sedimentary and volcanic lithic fragments shed into the Amagá and Cauca (sub-)basins during the Middle Miocene are interpreted as mainly derived from the Western Cordillera, given the apparent lack of an extensive volcano-sedimentary cover in the Central Cordillera during the Neogene. Instead, rocks exposed at or close to the surface were mostly represented by crystalline units of deeper crustal levels (Zapata et al., 2021). Moreover, if the Central Cordillera were the primary source, the prediction would be a change from lithic- to quartz-rich compositions due to the progressive unroofing of the source area (i.e., dissected orogen; Dickinson, 1985). However, petrographic constraints indicate an opposite trend, showing a shift in sediment composition from quartz- to lithic-rich during the Middle Miocene, which is here interpreted to likely indicate the contribution from a less dissected orogenic source, such as the nascent Western Cordillera.

During the latest Miocene to Pliocene, extensive intra-basinal volcanism is recorded by the widespread accumulation of volcanoclastic rocks with abundant ~6–2 Ma detrital zircons (Figure 6). Increased fluvial connectivity is suggested by the sharp increase in the abundance of Early Cretaceous and Jurassic (~160–140 Ma) detrital

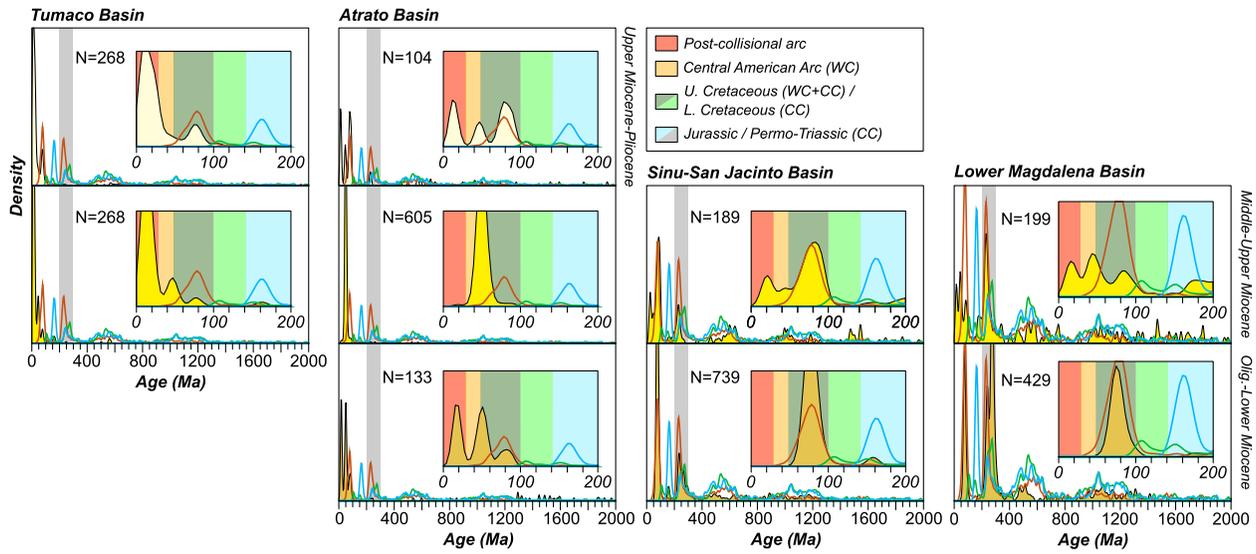


Figure 7. Summary of the published detrital geochronological data from Oligocene-Pliocene strata from forearc basins of the Colombian Andes, as depicted by Kernel Density Estimates (KDE). Data from Paleozoic to Recent crystalline units and pre-Jurassic, Lower Cretaceous, and Upper Cretaceous-Paleocene (meta)sedimentary rocks of the Central and Western Cordilleras, are included for comparison and colored as in Figure 5.

zircons in Upper Miocene-Pliocene strata of the Amagá basin, which were likely derived from acidic-intermediate rocks exposed along the Central Cordillera farther to the south (Figure 3; i.e., northern Ibagué Batholith; Restrepo et al., 2021 and references therein). We tentatively interpret these Jurassic detrital zircons as sourced from distal rather than proximal sources such as Lower Cretaceous (Central Cordillera) or Cretaceous-Paleocene strata (Western Cordillera). If the latter were the primary sources of Early Cretaceous-Late Jurassic zircons, one would also expect to find similar detrital ages in older (i.e., Oligocene-Middle Miocene) strata, which is not the case (Figure 6). Moreover, available thermochronological data have been used to identify a post-Late Miocene (<10 Ma) pulse of rapid cooling/exhumation of Upper Jurassic crystalline rocks, which could have prompted its contribution to intermontane sedimentary basins (Villagómez & Spikings, 2013; Zapata, Calderon-Diaz et al., 2023).

6.3. Overview of Published Provenance Constraints of Forearc and Eastern Intermontane Basins

6.3.1. Forearc Basins of the Pacific Region

Our compiled data set demonstrates that the Atrato forearc basin was sourced mainly from the Western Cordillera, as suggested by the high content of middle Eocene to Early Miocene (~45–18 Ma) detrital zircon ages (Figure 7), which, as mentioned above, are exclusive to this region (León, Parra et al., 2025; León, Faccenna, et al., 2025). Additional evidence for this is the abundance of sedimentary and volcanic lithics and unstable minerals such as amphibole, pyroxene, and feldspar, suggesting a provenance from magmatic and siliciclastic proximal sources (León, Parra et al., 2025; León, Faccenna, et al., 2025). Contributions from other domains farther inland (e.g., Central Cordillera) are unlikely because the northern segment of the Western Cordillera represented a local topographic barrier at least since the Oligocene-Early Miocene (Zapata et al., 2020). Importantly, detrital zircons with ages ca. 30–17 Ma found in Oligocene-Lower Miocene strata of the Atrato basin (Figure 7) were likely sourced from nearby volcanically active regions of the Central American Arc before or during its collision with the continental paleomargin (León, Parra et al., 2025; León, Faccenna, et al., 2025). Conversely, as mentioned above, Oligocene-Early Miocene detrital zircons (~30–21 Ma) found in coeval rocks of the Patía sub-basin were probably derived from the post-collisional continental arc, which was located in the southernmost Western Cordillera (Botello et al., 2024).

A significant change in the source area configuration in the Atrato basin is indicated by a dramatic decrease in the abundance of detrital zircons older than 100 Ma in Middle-Upper Miocene rocks compared to Oligocene-Lower Miocene strata (Figure 7). This shift is interpreted as driven by the local uplift of the northwestern flank of the Western Cordillera that is composed chiefly of Eocene-Oligocene magmatic rocks, disconnecting the basin with

source areas further east (León, Parra et al., 2025; León, Faccenna, et al., 2025). Continuous uplift in the Pacific forearc region drove basin inversion, enhanced recycling of older strata during the Upper Miocene-Pliocene, and the establishment of longitudinal routing systems, which caused an increase in the abundance of intra-basinal sedimentary lithic components and the re-appearance of detrital U-Pb ages older than 100 Ma (Figure 7; León et al., 2018; León, Avellaneda-Jiménez et al., 2024; León, Parra, et al., 2024). On the other hand, the near disappearance of detrital zircons younger than ~28 Ma in the Atrato basin is arguably a consequence of the vanishing of magmatism in the easternmost Central American Arc and its final cessation by ca. 16 Ma (Buchs et al., 2019).

6.3.2. Forearc Basins of the Caribbean Region

Oligocene-Lower Miocene rocks from the Sinú-San Jacinto basin show abundant Cretaceous and Permian-Triassic detrital U-Pb ages (Figure 7) and high contents of heavy minerals indicative of low-to medium-grade metamorphic and ultramafic-mafic igneous sources (Montes et al., 2015; Osorio-Granada et al., 2020). This characteristic, together with south-to-north paleocurrents, suggests provenance from the northernmost Central and Western Cordilleras and local uplifts within the adjacent Lower Magdalena basin (Celis et al., 2023; Mora-Bohórquez, Ibañez-Mejía et al., 2017; Osorio-Granada et al., 2020).

Similarly, coeval strata from the Lower Magdalena basin were chiefly sourced by the northern Central Cordillera, local intra-basinal highs, and the Santa Marta Range, as indicated by abundant Permian-Triassic, Upper Cretaceous, and Paleocene-early Eocene detrital U-Pb ages (Figure 7; Montes et al., 2015; Mora-Bohórquez et al., 2020; J. A. Mora et al., 2018). The prevalence of such proximal sources is also supported by the abundance of unstable granitic, basaltic, and gneissic lithics in coarse-grained deposits, accompanied by high contents of unstable minerals, including amphiboles, pyroxenes, micas, and feldspar (Piraquive et al., 2017). Notably, the relatively low abundance of Jurassic detrital zircons in Oligocene-Lower Miocene rocks of the Lower Magdalena basin, which are more abundant in the Upper and Middle Magdalena basins (Figure 7), supports the previously suggested disconnection between both depocenters (Horton et al., 2015; Mora-Bohórquez et al., 2020).

The appearance of middle Eocene and younger (~45–15 Ma) detrital ages in Middle-Upper Miocene strata of both the Sinú-San Jacinto and Lower Magdalena basins represents a significant change in the provenance signal, associated with the first sediment input from the Central American Arc (Figure 7; Montes et al., 2015). The relative increase in the content of epidote-group minerals, amphibole, and pyroxene, akin to mafic-intermediate magmatic sources (Garzanti & Andò, 2007), supports such an interpretation.

6.3.3. Eastern Intermontane Basins

The Middle and Upper Magdalena intermontane basins received continuous input from the Central Cordillera during the Oligocene-Early Miocene given the ubiquitous presence of Jurassic and Permian-Triassic detrital zircon ages (Figure 8) and the high abundance of plutonic and metamorphic lithic fragments in Oligocene to Lower Miocene strata (A. Mora et al., 2013; Reyes-Harker et al., 2015; Zapata, Calderon-Diaz et al., 2023). Notably, the Middle and Upper Magdalena basins also received detritus from the growing Eastern Cordillera and intra-basinal highs, whose contribution was seemingly more substantial toward the east (Bayona et al., 2021; Gómez, Jordan, Allmendinger, & Cardozo, 2005). Evidence for this is the high content of sedimentary lithics (i.e., limestones, quartz-rich sandstones, and siltstones) similar to the Jurassic-Cretaceous strata of the Eastern Cordillera, and the abundance of Proterozoic zircons (particularly those older than 900 Ma; Figure 8), which are common in the latter (Bayona et al., 2021; Caballero et al., 2013). Significantly, the prevalence of lacustrine settings and the intermittency of fluvial input during the Early Miocene along the Upper and Middle Magdalena basins indicate that these depocenters were isolated (Zapata, Calderon-Diaz et al., 2023 and references therein).

A notable change in the sediment provenance of easterly intermontane basins is associated with increased contribution from late Eocene to Miocene volcanic sources during the Middle-Late Miocene (Montes et al., 2021). This variation is shown by the appearance of detrital ages younger than ~50 Ma (Figure 8), including those ~50–40 Ma zircons that are exclusive to the accreted Central American Arc, and the dramatic increase in the abundance of volcanic lithic fragments (Anderson et al., 2016; Zapata, Calderon-Diaz et al., 2023). Such a change in sediment composition is interpreted as related to the establishment of transversal drainage systems crossing the Central Cordillera, communicating the Western Cordillera and the Cauca intermontane region with the Middle and Upper Magdalena basins (Montes et al., 2021; Zapata, Calderon-Diaz et al., 2023).

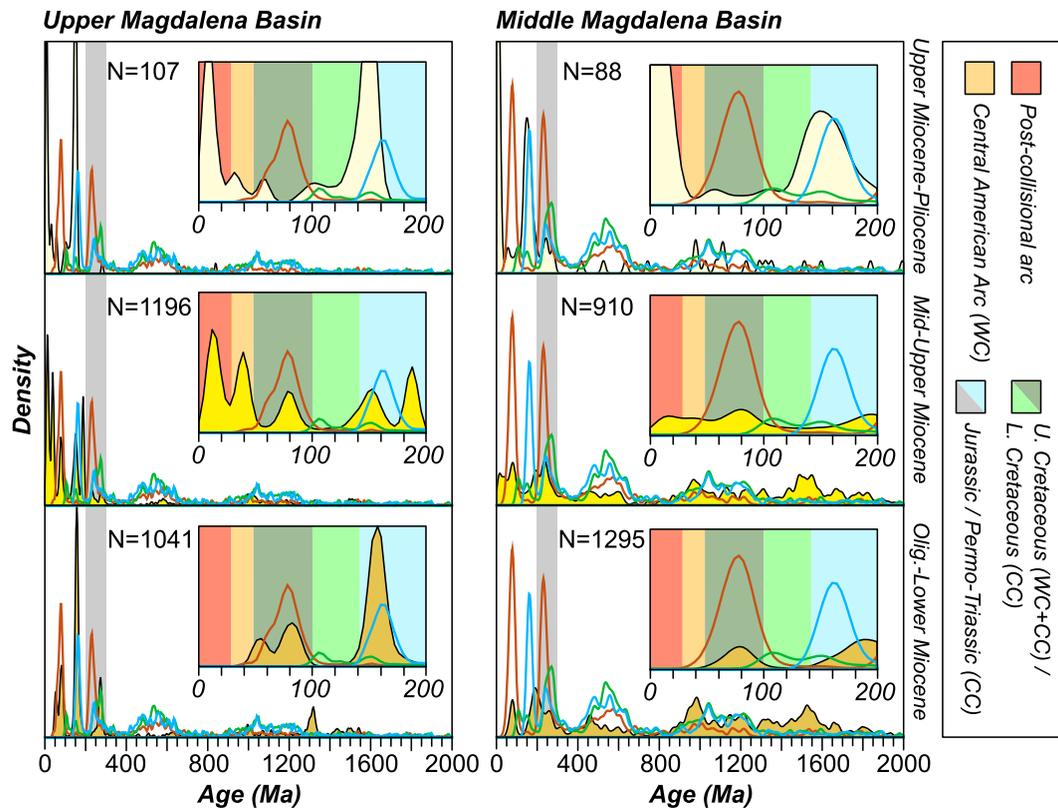


Figure 8. Summary of the published detrital geochronological data from Oligocene-Pliocene strata from eastern Colombian Andes intermontane basins, as depicted by Kernel Density Estimates (KDE). Data from Paleozoic to Recent crystalline units and pre-Jurassic, Lower Cretaceous, and Upper Cretaceous-Paleocene (meta)sedimentary rocks of the Central and Western Cordilleras are included for comparison and colored as in Figure 5.

The observed increase in the abundance of Early Cretaceous-Jurassic zircons in Middle-Upper Miocene strata of the Lower Magdalena basin (Figure 8), which were found in coeval and older Oligocene-Lower Miocene rocks of the Upper and Middle Magdalena basins, might suggest enhanced axial sediment transport. Alternatively, the relative increase in the abundance of Jurassic detrital U-Pb ages in Middle-Upper Miocene strata of the Lower Magdalena basin could be attributed to a transient and local acceleration of erosion/exhumation rates along the western side of the Santa Marta Range (Piraquive et al., 2017).

Zircon U-Pb data show a dramatic increase in the abundance of Middle-Late Miocene and Jurassic detrital ages in Upper Miocene-Pliocene strata of the Upper and Middle Magdalena basins (Figure 8), accompanied by a shift toward a volcanic-rich composition of siliciclastic rocks (Anderson et al., 2016). This event was probably associated with the installation of the volcanic arc in the axis of the Central Cordillera (Wagner et al., 2017) and enhanced northward (i.e., longitudinal) dispersal of sediments derived from Jurassic arc-related rocks forming the basement of the southern Central and Eastern Cordilleras. The latter were being rapidly exhumed/eroded according to available thermochronological data (Anderson et al., 2016; Pérez-Consuegra, Hoke, et al., 2021; Villagómez & Spikings, 2013; Zapata, Calderon-Diaz et al., 2023).

7. Discussion

Overall, our new and available detrital zircon U-Pb data from forearc basins and intermontane basins of the Colombian Andes points to the Central Cordillera as the main sediment source area, and suggests limited basinal connectivity during the Oligocene-Early Miocene (Figures 9 and 10). These characteristics are related to the prevalence of an immature relief in the Western and Eastern Cordilleras, whose pulsed growth was accompanied by an increasing sediment contribution to intermontane basins (Figure 9) and a progressive shift from transverse to longitudinal sediment routing systems (Figure 10). In the following sections, we combine stratigraphic and

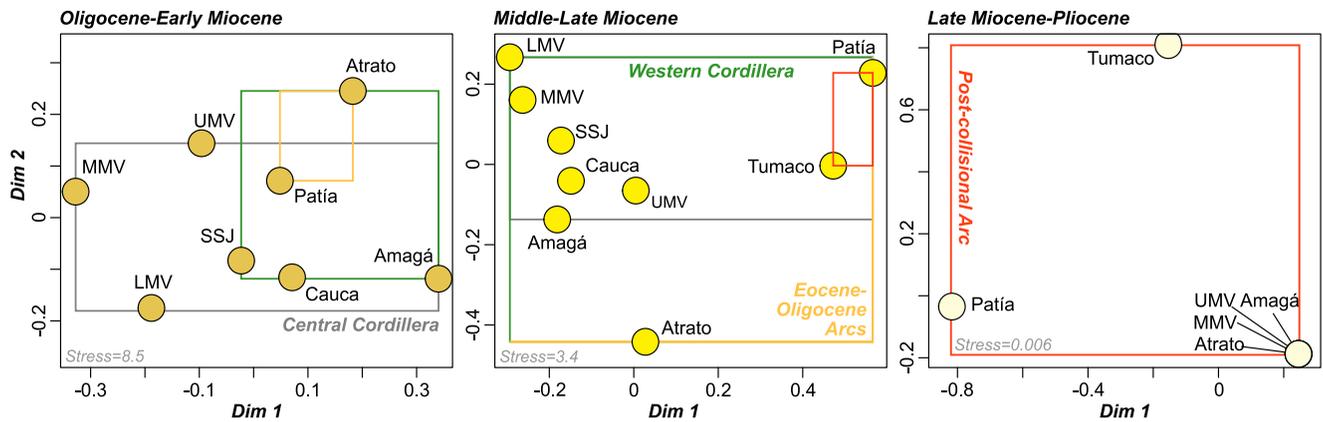


Figure 9. Non-metric Multi-dimensional Scaling (MDS) plots summarizing our new and published detrital zircon U-Pb data from Neogene rocks of the forearc and intermontane basins of the Colombian Andes. Similarity was estimated using the Kolmogorov-Smirnoff statistic that measures the maximum vertical distance between cumulative age distributions (Vermeesch, 2018a). The more distant the samples are, the larger their dissimilarity in the distribution of detrital zircon U-Pb ages (Vermeesch, 2013). The estimated large stress values (e.g., >1) indicate poor goodness of fit of the non-metric MDS, which might be due to significant variations in sample sizes. However, the petrographic and geochronological data discussed in Section 6 provide semi-quantitative evidence supporting the inter-basin dissimilarity observed in the MDS plots. Colored rectangles enclose basins showing a dominant provenance from the Central Cordillera (gray rectangle), the Western Cordillera (green rectangle), the accreted Central American Arc (yellow rectangle), the post-collisional (i.e., post-Early Miocene) continental arc (red rectangle), or a combination of the above. See the progressive increase in the contribution from sources of the Western Cordillera and the post-collisional magmatic arc since the Middle-Upper Miocene. LMV, Lower Magdalena basin; MMV, Middle Magdalena basin; SSJ, Sinú-San Jacinto basin; UMV, Upper Magdalena basin.

provenance constraints to reconstruct the regional paleogeography. Then, we interpret the observed changes in the source-to-sink systems in the regional tectono-magmatic setting.

7.1. Neogene Paleogeography of the Colombian Andes

Extensive work on the stratigraphy of forearc basins of the Pacific region has demonstrated the prevalence of marine-deltaic accumulation settings during most of the Neogene (Borrero et al., 2012; Duque-Caro, 1990; León, Parra, et al., 2024; Pardo-Trujillo, Echeverri, et al., 2020; and references therein). Depocenters were chiefly sourced from local uplifts of the Western Cordillera and intra-basinal highs through short transverse drainage systems (e.g., Osorio-Granada et al., 2017). The fragmented topography of the Western Cordillera during the Oligocene-Early Miocene was associated with a heterogeneous sediment contribution into adjacent basins and local incursions of the Pacific Ocean that reached the westernmost intermontane region (Figure 10). Forearc basins in the Caribbean were also dominated by marine-deltaic settings during the Oligocene-Early Miocene and were locally disrupted by intra-basinal uplifts (Figure 10; Celis et al., 2023; Mora-Bohórquez et al., 2020). Distal fine-grained facies represented the external (seaward) areas. In contrast, the inland region of the forearc basins comprised coarse-grained deposits sourced from the northern segments of the Central and the nascent Western Cordilleras to the south and the Santa Marta Range to the east (e.g., Mora-Bohórquez et al., 2020; Piraquive et al., 2017).

The nearly continuous positive relief of the Central Cordillera ensured the predominance of continental settings in the intermontane basins. In the western Colombian Andes, the intermontane region was dominantly characterized by fluvial (i.e., meandering, braided rivers) settings, which, to the south (e.g., Cauca and Patía sub-basins), locally transitioned to deltaic and shallow-marine conditions due to the influence of westerly marine incursions during the Oligocene-Early Miocene (Figure 10; e.g., Dueñas et al., 2000; Gallego-Ríos et al., 2020). Such marine incursions were linked to the lack of continuous topography along the proto-Western Cordillera, as opposed to a well-established and more continuous Central Cordillera. Oligocene-Lower Miocene sediments were mainly shed through transverse river systems and locally dispersed by immature longitudinal drainages, which were seemingly connected to forearc basins of the western Caribbean region (Figure 10; e.g., Celis et al., 2023).

Basin connectivity and longitudinal sediment dispersal were even more limited or absent in the eastern intermontane region during the Oligocene-Early Miocene, as suggested by the prevalence of disconnected lacustrine systems in the Upper and Middle Magdalena basins (Caballero et al., 2013; Zapata, Calderon-Diaz et al., 2023), which could have been isolated from the Caribbean region (Figure 10; J. A. Mora et al., 2018). Such lake systems

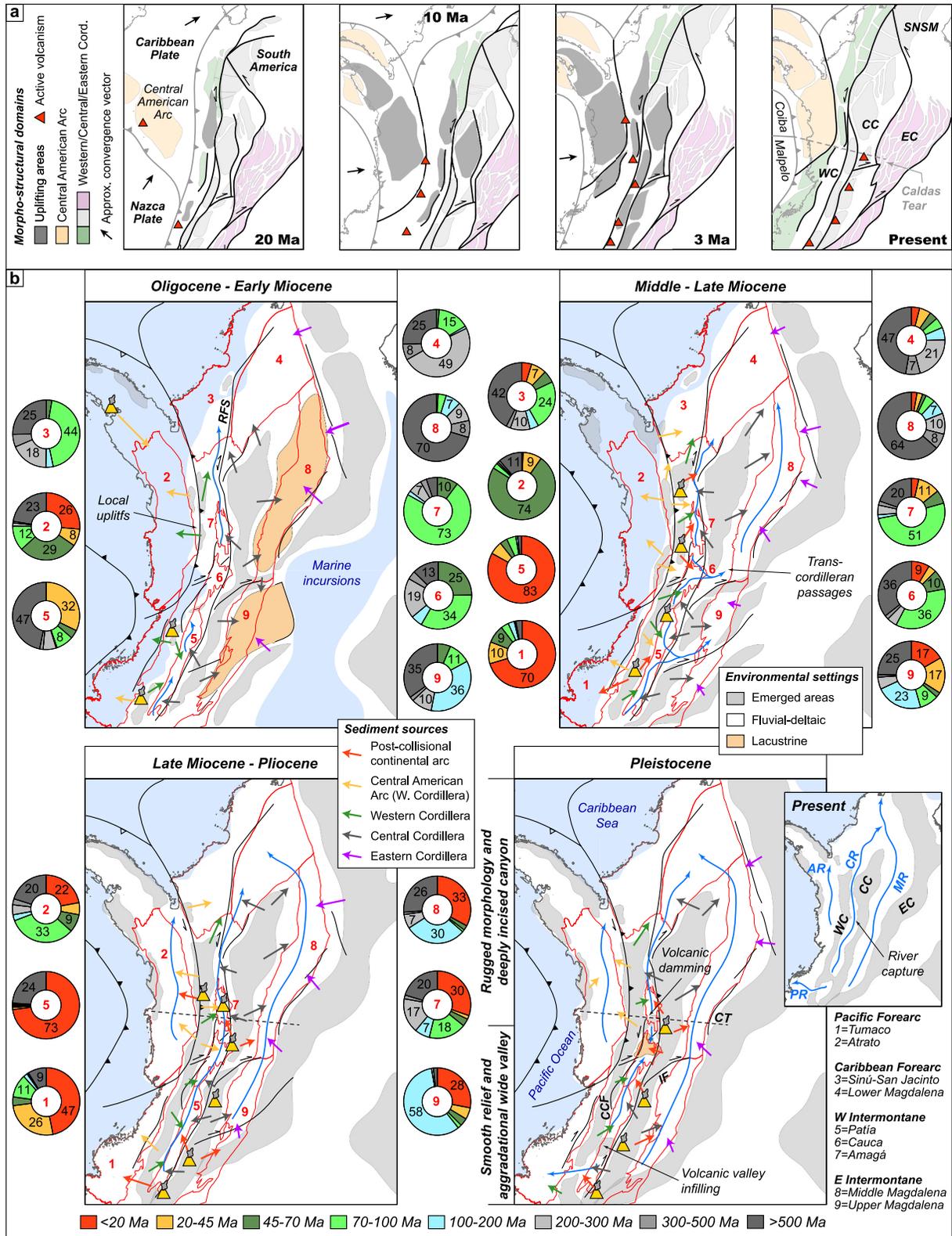


Figure 10.

were enclosed by the positive topography of the Central Cordillera to the west, the Eastern Cordillera to the east, and local intra-basinal highs, which together served as the primary sediment sources (Caballero et al., 2013; Gómez, Jordan, Allmendinger, & Cardozo, 2005; Parra et al., 2010; Reyes-Harker et al., 2015).

The dramatic change in the provenance signal of forearc and intermontane basins, associated with the onset of widespread sediment contribution from the western flank of the Western Cordillera (Figures 9 and 10), was concurrent with a regional Middle-Upper Miocene paleogeographic reorganization. The latter is associated with the continentalization of sedimentary environments, enhanced longitudinal fluvial connectivity, and the creation of trans-cordilleran sediment routing systems (Figure 10; Montes et al., 2021; Zapata, Calderon-Diaz et al., 2023). Such transverse drainage systems across today's Central and Eastern Cordilleras allowed biotic exchange between the western Colombian Andes and the Amazonian region, as indicated by available sedimentological and paleontological constraints (Montes et al., 2021 and references therein).

The final establishment of fully terrestrial conditions in the western intermontane region was accompanied by a relative reduction in the accommodation space and an increase in the sedimentation rates due to the ongoing uplift of the surrounding cordilleras and increased volcanic activity in the post-collisional arc (Lara et al., 2018; León et al., 2018; Pardo-Trujillo, Echeverri, et al., 2020; Silva-Tamayo et al., 2020). In the Pacific forearc basins, the uplift of the northwestern flank of the Western Cordillera was coeval with the shallowing of sedimentary environments from deep-to shallow-marine and nearshore settings, and the transient disconnection between forearc depocenters and mountainous regions farther inland (Figure 10; Borrero et al., 2012; Duque-Caro, 1990; León, Parra, et al., 2024). Similarly, in the Caribbean region, mountain growth in the surrounding cordilleras caused the progradation of deltaic systems and enhanced fluvial connectivity with intermontane valleys (Figure 10; J. A. Mora et al., 2018).

During the latest Miocene-Pliocene, protracted uplift across the Colombian Andes finally led to the establishment of major longitudinal drainages in the intermontane regions, similar to today's Cauca and Magdalena rivers (Figure 10). This drainage rearrangement was driven by an enhanced topographic continuity along the Western Cordillera, and the progressive closure of trans-cordilleran passages across the Central Cordillera, accomplished by the Early Pleistocene (M. J. Sanín, Mejía-Franco et al., 2022). Widespread uplift, accompanied by tectonically-driven basin inversion, caused the final continentalization of depositional systems in the forearc region by the Late Pliocene (León, Parra et al., 2025; León, Faccenna, et al., 2025; Pardo-Trujillo, Echeverri, et al., 2020).

The transition from marine to fluvial settings in the Pacific region of the northwestern Andes, as driven by the growth of the Western Cordillera and the uplift of the coastal Baudó Range, led to the establishment of the longitudinal Atrato River (León, Parra et al., 2025; León, Faccenna, et al., 2025; León, Monsalve, Jaramillo, et al., 2021). However, the southern Pacific Region (e.g., Tumaco Basin) remained characterized by transverse drainages due to the absence of coast-parallel positive relief areas. Consequently, the Tumaco basin has been characterized by deltaic and estuarine systems since the latest Miocene-Pliocene (Pardo-Trujillo, Echeverri, et al., 2020).

Significant changes in the drainage network during the latest Pliocene-Pleistocene were associated with the volcanic damming of the longitudinal river system in the western intermontane region (e.g., proto-Cauca River, at $\sim 4.5\text{--}5^\circ\text{N}$, present coordinates) and the establishment of local and transient lacustrine settings (Figure 10; D. Jaramillo et al., 2017; Pérez-Consuegra, Ott, et al., 2021; M. J. Sanín, Cardona, et al., 2022; Suter, Neuwerth, et al., 2008). Farther to the south ($\sim 2.5\text{--}3^\circ\text{N}$, present coordinates), the eruption of large volumes of Pliocene-Pleistocene acidic ignimbrites filled the intermontane valley in between the Central and Western Cordilleras (M. J. Sanín, Cardona, et al., 2022). Such volcanic damming/filling of axial drainages was concurrent with transient basin disconnection and regional changes in the sediment routing systems as indicated by available

Figure 10. Schematic diagrams summarizing the interpreted evolution of Neogene source-to-sink systems in the western Colombian Andes. (a) Palinspastic reconstruction modified from (Montes et al., 2019) showing the relative block motions and the propagation of the continental magmatic arc during the transition from the collision/accretion of the Central American arc to the subduction of the Nazca plate. These maps provide a simplified paleo-tectonic framework for interpreting basin evolution illustrated in panel (b). This panel shows the primary sedimentary environments and the configuration of source areas, interpreted from our data set and available stratigraphic constraints. As mentioned in the text, we focused on the western Colombian Andes, but hinterland and foreland regions located farther to the east are shown for comparison (Montes et al., 2019, 2021; Reyes-Harker et al., 2015; Zapata, Calderon-Diaz et al., 2023; and references therein). The modern coastline of northwestern South America (thin light-gray line) is shown in all figures for reference. CCF, Cauca-Cali Fault System; CT, Caldas Tear; IF, Ibagué Fault; RFS, Romeral Fault System.

paleocurrent and geomorphological data (Pérez-Consuegra, Ott, et al., 2021; Suter, Neuwerth, et al., 2008). Subsequent fluvial processes, such as headward erosion and river capture, led to the establishment of the modern physiographic configuration during the Middle-Late Pleistocene (Figure 10; D. Jaramillo et al., 2017).

7.2. Effects of Morpho-Structural Overprinting on Basin Architecture and Drainage Network

Stratigraphic, structural, and sedimentological constraints suggest that two major episodes shaped basin evolution in the intermontane region of the western Colombian Andes, seemingly controlled by the kinematics and morphological expression of strike-slip structures. The first episode, during the Oligocene-Early Miocene, was characterized by the prevalence of transverse over longitudinal sediment routing systems, limited topographic growth, and strong basin compartmentalization. A second Middle-Late Miocene event was accompanied by the full development of the Colombian Cordilleras, asymmetric basin inversion, and the progressive establishment of longitudinal fluvial systems. We provide a tectonic interpretation of this two-step evolutionary scenario below.

The RFS has a nearly continuous trace following an NNE trend from southern Colombia up to $\sim 5^{\circ}\text{N}$, shifting to the NNW up to $\sim 7^{\circ}\text{N}$. Along its trace, the RFS partially overlaps with the discontinuous CCF, and together, these structures represent the external limits of the intermontane basins of the western Colombian Andes (Figures 1 and 4). Intra-basinal, NE-SW- and NW-SE-oriented oblique faults spatially correlate with important structural features or sharp changes in the topography that isolate different (sub-)basins. For instance, the NW-SE-trending Cañasgordas and Arma faults, and the NE-oriented Espíritu Santo Fault, coincide with the narrowing of the Cauca Valley and delimitate the main depocenter of the Amagá basin (Figure 4). Farther to the south, the Corozo high, which separates the Cauca and Patía sub-basins, is associated with lateral thickness variations and onlapping stratigraphic relationships (Alfonso et al., 1994), and also delimitates regions with contrasting provenance during the Oligocene-Middle Miocene (Figure 10b).

The relationship between fault activity and basin opening during the Oligocene-Miocene is supported by paleomagnetic data suggesting that oblique fault structures (e.g., Tapias Fault; Figure 4), would have been active during sediment deposition and were related to local extension (Sierra et al., 2012). Local changes in crustal thickness due to vertical deformation along intra-basinal faults would also explain the heterogeneous patterns of assimilation and fractionation of Miocene-Pliocene magmatic rocks emplaced along the intermontane region (J. S. Jaramillo et al., 2019; Villalba et al., 2023; Weber et al., 2020). We interpret strike-slip morpho-structural features as the primary control of the formation of disconnected depocenters during the Oligocene-Early Miocene. This interpretation is consistent with analog and numerical modeling experiments, showing that partially overlapping sub-parallel strike-slip structures (e.g., CCF and RFS) shape basin geometry and that oblique faults locally accommodate crustal extensional/compression (i.e., thinning/thickening) and, therefore, control the connectivity of depocenters (e.g., Conrad et al., 2023; Smit et al., 2008; van Wijk et al., 2017).

A second tectonic episode was related to Middle-Late Miocene thrust-faulting and folding of Neogene strata in the Amagá basin, associated with the formation of anticline structures (Figure 4), counterclockwise rotation of subvolcanic rocks, and local basin closure (MacDonald et al., 1996; Sierra et al., 2012). This event was accompanied by the uplift of the Central and Western Cordilleras (León et al., 2018; Pérez-Consuegra et al., 2022), and the closure of seaways communicating the intermontane region with the Pacific Ocean (Figure 10). Such a deformational episode resulted in the modern topographic configuration of the northern intermontane region, represented by a rugged relief carved by the incision of the Cauca River (Pérez-Consuegra et al., 2022). Compressional features are not common in the southern intermontane region, except for local intra-basinal uplifts interpreted as positive flower structures, which disrupt the characteristic wide and flat morphology of the area (Suter, Sartori, et al., 2008), flanked to the west by strike-slip morpho-structural features (e.g., shutter ridges; Figure 4). We presume that, as opposed to the Amagá basin, the southern intermontane region is characterized by sedimentation rates exceeding uplift/incision rates, resulting in an aggradational system and a flat-lying topography (e.g., Streit et al., 2017).

The evolution of the western intermontane region of the Colombian Andes occurred during the Miocene transition from arc-collision to subduction. Tectonic reconstructions and geological observations in Colombia and Panama suggest that the initial accretion/collision of the Central American Arc occurred during the Oligocene-Early Miocene (Figure 10a; González et al., 2023; Montes et al., 2019; and references therein). Nevertheless, a growing body of evidence indicates that Oligocene-Early Miocene upper-plate deformation and subsequent uplift was scarce. This evidence includes the prevalence of deep-intermediate marine settings with little terrestrial input

in the forearc region, the limited topographic growth of the Western Cordillera (León, Parra et al., 2025; León, Faccenna, et al., 2025), and the opening of the here discussed transtensional intermontane basins.

We consider the above features to support the recently proposed soft-collision (i.e., accretionary) scenario, in which the oceanic terrane was initially (partially) subducted beneath the overriding plate, and did not trigger widespread deformation/uplift (León, Parra et al., 2025; León, Faccenna, et al., 2025). Instead, the initial oblique accretion of the Central American Arc would have been associated with a highly partitioned strain regime in the upper plate that allowed the opening of narrow forearc and intramontane basins. The final accretion of the island arc during the Middle-Late Miocene (~15–13 Ma), and the subsequent transition to subduction, drove widespread basin inversion and topographic uplift in the northwestern Colombian Andes (León et al., 2018; León, Monsalve, Jaramillo, et al., 2021; León, Parra, et al., 2024; and references therein). The virtual lack of compressional deformation during the initial approach of the Central American arc encourages revisiting the dynamics of island arc-continent interactions and their role in the upper-plate deformational record.

Shortly after the tectonic shift from collision/accretion to subduction, the Colombian Pacific margin was segmented along-strike due to the contrasting geometries of the subducting Coiba and Malpelo microplates (i.e., formerly Nazca plate before ~12 Ma; McGirr et al., 2020). Such a tectonic segmentation drove asymmetric basin inversion and the development of contrasting morpho-structural styles along the western intermontane region. The inversion of sedimentary basins in the northern intermontane area was concomitant with orogen-scale uplift across the northern Colombian Andes (e.g., León et al., 2018; Parra et al., 2009; Pérez-Consuegra et al., 2022). This scenario was likely related to effective crustal stress transmission associated with the flat subduction of the Coiba microplate since the Late Miocene (Chiarabba et al., 2016). Widespread deformation is thought to result from lithospheric cooling and thermal strengthening of the upper plate due to the progressive removal of the underlying mantle wedge and magmatic cessation during slab flattening (Gutscher et al., 2000; Horton et al., 2022; Liu et al., 2022).

Less effective compression and limited basin inversion in the southern intermontane region since the Middle-Late Miocene would have been linked to the “normal” or steep subduction of the Malpelo microplate. This setting would have triggered focused and not widespread crustal deformation, related to lateral strength variations due to ongoing arc magmatism and higher thermal gradients in the intra- and back-arc regions (Pons et al., 2023; Seymour et al., 2020). Evidence for this is the Late Miocene accelerated exhumation/uplift of inland tectonic domains, virtually focused along the southern segments of the Central and Eastern Cordilleras (Anderson et al., 2016; Pérez-Consuegra, Hoke, et al., 2021; Zapata, Calderon-Diaz et al., 2023).

As mentioned above (Section 7.1), the uplift of the Colombian Cordilleras during the Middle-Late Miocene was accompanied by the formation of trans-cordilleran passages communicating the western and eastern intermontane regions (Figure 10), which played a fundamental role in the biogeographic history of the Colombian Andes (M. J. Sanín, Mejía-Franco et al., 2022). Such trans-cordilleran passages would have formed due to focused slip along strike-slip faults (e.g., Ibagué Fault) and structural entrainment of transverse drainages and enhanced incision (e.g., Conrad et al., 2023). Nevertheless, a mechanism for closing such trans-cordilleran passages during the Pleistocene (M. J. Sanín, Mejía-Franco et al., 2022) has yet to be found. We speculate that such an episode could have been caused by a shift in fault slip kinematics related to either regional or local changes in block motions, or by tectonically-driven orogen-scale uplift that obliterated the imprints of local structures (e.g., Landgraf et al., 2013). However, as discussed below, volcanism also contributed to the topographic development of the Colombian Cordilleras and the closure of intermontane and trans-cordilleran depressions.

7.3. The Role of Volcanism in Basin Infilling and Morphological Segmentation

Available biostratigraphic data provide strong evidence for the occurrence of a crucial drainage reorganization during the latest Pliocene-Pleistocene, related to the damming of the Cauca River and the accumulation of lacustrine deposits around ~4.5–5°N (Figure 10b; D. Jaramillo et al., 2017; López & Toro-Toro, 2020). These deposits overlie in angular unconformity Middle-Upper Miocene strata of the Cauca sub-basin, lying on the flanks of positive relief structures such as the Santa Barbara Range (e.g., Quindío Fan; López & Toro-Toro, 2020). Thus, the creation of lacustrine settings post-dates the main phase of deformation and is somewhat related to the rapid accumulation of volcanoclastic fans and the subsequent damming of the recently established longitudinal river (Suter, Neuwerth, et al., 2008). This scenario demonstrates the importance of volcanic processes as first-order controls on the regional drainage network and the evolution of intermontane basins.

Geomorphological and petrological data indicate the presence of thick Pliocene-Pleistocene volcanoclastic rocks in the southernmost Patía sub-basin and the surrounding Central and Western Cordilleras, associated with dissected low-relief surfaces (Kroonenberg et al., 1981; Pérez-Consuegra, Ott, et al., 2021; M. J. Sanín, Cardona, et al., 2022). Such morphological features are interpreted as related to the emplacement of large volumes of ignimbrites that filled the southernmost inter-montane depression and former topographic gaps of the Central Cordillera (Figure 10b). Subsequent incision of volcanic deposits and river capture processes led to the establishment of the modern fluvial network (Pérez-Consuegra, Ott, et al., 2021).

The shift from flat-lying to rugged morphology in the Cauca River at $\sim 4.5\text{--}5^\circ\text{N}$ coincides with the appearance of widespread Late Miocene sub-volcanic rocks, associated with prominent cone-shaped morphological features disrupting the narrow valleys formed by Neogene strata (Figure 4a; e.g., Weber et al., 2020). These basaltic-andesitic porphyries are absent farther to the south, where coeval volcanoclastic units are chiefly composed of stratified rocks, such as tuffs, and tuffaceous sandstones and conglomerates (López & Toro-Toro, 2020). We suggest that spatially heterogeneous erodibility due to the local presence of Late Miocene porphyritic rocks and volcanoclastic deposits in the northern Cauca Valley contributed to its incised canyon-like morphology. On the contrary, the lack of significant erodibility variations in the southern Cauca Valley and limited intra-basinal uplift/erosion facilitated the prevalence of the observed flat-lying morphology. Hence, lithological features of magmatic rocks, along with the spatial extent of surface volcanic activity, jointly contributed to the most recent evolution of sediment routing systems of intermontane basins in the western Colombian Andes, as observed in other orogenic and anorogenic settings (e.g., Scharf et al., 2013).

8. Conclusions

New and available detrital zircon U-Pb data, together with sedimentological constraints from Oligocene to Pleistocene strata of intermontane basins of the western Colombian Andes and field observations suggest a transition from transverse to longitudinal sediment dispersal in response to the pulsed growth of the Central and Western Cordilleras. The latter remained a discontinuous topographic feature until the Middle-Late Miocene, allowing marine incursions to influence depositional systems in the intermontane and Pacific forearc regions.

The dominance of localized provenance and strong basin compartmentalization during the Oligocene-Middle Miocene was related to a highly partitioned strain regime due to the soft collision/accretion of the Central American Arc. The kinematics, inherent segmentation, and morphological expression of strike-slip fault systems seemingly controlled basin architecture and connectivity. These structures also provided paths for creating trans-cordilleran passages that allowed sediment exchange between the western and the eastern intermontane regions.

The shift from collision/accretion to subduction during the Late Miocene and subsequent tectonic segmentation of the Colombian Pacific margin was accompanied by the asymmetric inversion of intermontane basins. Crustal thermal strengthening above the flat slab region enhanced lateral stress transmission, resulting in more effective basin inversion and widespread uplift in the northern part of the intermontane basins of the Western Colombian Andes. Conversely, lateral strength variations in the upper plate above the steep slab region, due to locally increased geothermal gradients in the intra- and back-arc region, resulted in localized and not widespread uplift/deformation, and limited inversion of intermontane basins south of $\sim 4.5^\circ\text{N}$.

The tectonic transition to subduction triggered surface uplift along the Western Cordillera and the Pacific forearc regions, prompting intermontane basin connectivity and the onset of longitudinal sediment routing systems. The progressive development of longitudinal rivers was interrupted by volcanic activity, which drove the damming and filling of intermontane depressions. These phenomena caused transient and permanent disconnection between depocenters in the central-northern and southernmost areas of the intermontane region, respectively. Subsequent processes of river capture of the western Colombian Andes led to the establishment of the modern fluvial network.

Our reconstruction of the Oligocene to present-day intermontane source-to-sink systems in a regional paleogeographic framework allowed us to demonstrate the joint contribution of volcanic processes and tectonically-driven landscape modifications to the history of sediment routing patterns and basin connectivity. We showed how accretionary and subduction-related tectonics, mixed with significant topographic variations due to the segmentation of strike-slip faults and magmatic activity, shaped the modern physiography of the Colombian Andes.

Data Availability Statement

All the supporting data used in this work can be found in the Tables S1–S3 in Supporting Information S1 or downloaded from <https://doi.org/10.6084/m9.figshare.26031346>.

Acknowledgments

S. León is grateful to the Alexander von Humboldt Foundation (Georg Forster Fellowship). We thank the GFZ (PoF-Expedition 2024; TectonoTropics) and the BMBF (ESkolA project) for supporting fieldwork. E. Conrad was partially supported by NSF EAR-1925939. Thorough comments by R. Ondrak on an early version of this manuscript are acknowledged. We thank reviewers Sarah George and Cristian Vallejo and editors Laura Giambiagi and Djordje Grujic for their thorough comments and suggestions. Open Access funding enabled and organized by Projekt DEAL.

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