Volume 3

Chapter 3

THE GEOLOGY OF COLOMBIA

SERVICIO GEOLÓGICO COLOMBIANO

Construction of the Eastern Cordillera of Colombia: Insights from the Sedimentary Record

https://doi.org/10.32685/pub.esp.37.2019.03
Published online 7 May 2020

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Abstract A continuous, long–lived sedimentary record contains important evidence bearing on the geologic evolution of the Eastern Cordillera in the northern Andes of Colombia. Today, this largely isolated NNE–trending mountain range forms a ca. 1–3 km high topographic barrier separating the Magdalena Valley hinterland basin from the Llanos foreland basin. A Mesozoic – Cenozoic history of marine and nonmarine sedimentation affected the Eastern Cordillera and flanking Magdalena and Llanos provinces during contrasting tectonic regimes. (i) Jurassic to earliest Cretaceous extension led to the development and linkage of extensional sub–basins (commonly half graben features governed by normal faults) in selected regions. (ii) A subsequent phase of postextensional thermal subsidence generated a thermal sag basin across a broader region. (iii) In latest Cretaceous to Paleocene time, initial crustal shortening in the Central Cordillera created a regional flexural basin that was successively broken by the Paleocene – Oligocene emergence of thrust/reverse–fault related uplifts within the Eastern Cordillera partitioning the original regional basin into the Magdalena hinterland basin and Llanos foreland basin. (iv) Major Neogene uplift and establishment of an effective topographic barrier occurred as continued shortening became focused along the bivergent eastern and western flanks of the fold–thrust belt comprising the Eastern Cordillera. Shortening commonly involved contractional reactivation of preexisting normal faults and inversion of pre–foreland basin elements. This geologic history is largely expressed in the clastic sedimentary archives of the Eastern Cordillera, Magdalena Valley Basin, and Llanos Basin. Growth strata and cross–cutting relationships among fold–thrust structures and basin fill provide essential timing constraints for individual structures, particularly when integrated with thermochronological data. Regional stratigraphic correlations and sediment accumulation histories help identify shared and divergent stratigraphic histories during progressive basin compartmentalization. Substantial shifts in sediment provenance, identified through U–Pb geochronology, demonstrate the changes in sediment source regions and paleodrainage patterns during several changes in tectonic conditions.

Keywords: *Eastern Cordillera, fold–thrust belt, foreland basin, provenance, U–Pb geochronology.*

Resumen Un registro sedimentario continuo y prolongado en los Andes del norte alberga evidencia importante sobre la evolución geológica de la cordillera Oriental de Colombia. Actualmente, esta cadena montañosa, en gran medida aislada y de orientación N–NE, forma una barrera topográfica de 1–3 km de altura que separa la cuen-

Citation: Horton, B.K., Parra, M. & Mora, A. 2020. Construction of the Eastern Cordillera of Colombia: Insights from the sedimentary record. In: Gómez, J. & Mateus–Zabala, D. (editors), The Geology of Colombia, Volume 3 Paleogene – Neogene. Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 37, p. 67–88. Bogotá. https://doi.org/10.32685/pub.esp.37.2019.03

ca intramontana del valle del Magdalena de la cuenca de antepaís de los Llanos. La sedimentación marina y continental mesozoica–cenozoica tuvo lugar en la cordillera Oriental y las provincias adyacentes Magdalena y Llanos durante regímenes tectónicos contrastantes. (i) Extensión durante el Jurásico al Cretácico más temprano tuvo como resultado el desarrollo e interconexión de subcuencas extensionales (comúnmente en forma de semigrábenes controlados por fallas normales) en áreas localizadas. (ii) Una fase subsecuente de subsidencia termal posextensional generó una cuenca de subsidencia térmica en una región más amplia. (iii) Durante el Cretácico más tardío al Paleoceno, el inicio del acortamiento cortical en la cordillera Central generó una cuenca flexural regional que fue posteriormente fragmentada en el Paleoceno–Oligoceno tras la emergencia de altos de basamento relacionada con fallas inversas en la cordillera Oriental, subdividiendo la cuenca regional inicial en la cuenca intramontana del Magdalena y la cuenca de antepaís de los Llanos. (iv) Levantamiento neógeno considerable y el establecimiento de una barrera topográfica efectiva ocurrieron en la medida en que el acortamiento persistente fue acomodado de forma bivergente en el cinturón de pliegues y cabalgamientos marginales de los flancos oriental y occidental de la cordillera Oriental. Este acortamiento involucró la reactivación contraccional de antiguas fallas normales y la inversión de segmentos de cuencas de antepaís preexistentes. Esta historia geológica está registrada en gran medida en los archivos sedimentarios de la cordillera Oriental y las cuencas del valle del Magdalena y de los Llanos. Estratos de crecimiento y relaciones de corte entre estructuras de pliegues y cabalgamientos y el relleno sedimentario proporcionan la información esencial para restringir la temporalidad de deformación en estructuras particulares, especialmente cuando se integran con la evidencia termocronológica. Correlaciones estratigráficas e historias regionales de acumulación de sedimentos permiten discriminar entre fases de desarrollo coincidentes y divergentes durante la historia progresiva de fragmentación de la cuenca. Cambios marcados en la procedencia sedimentaria, identificados mediante geocronología U–Pb, demuestran variaciones en las áreas fuente de sedimentos y en los patrones de drenajes ancestrales asociados a cambios en las condiciones tectónicas.

Palabras clave: *cordillera Oriental, cinturón de pliegues y cabalgamientos, cuenca de antepaís, proveniencia, geocronología U–Pb.*

1. Introduction

The Eastern Cordillera of Colombia (Figure 1) forms a major topographic barrier in the northern Andes that profoundly influences climate, erosion, and the delivery of clastic sediment to major rivers and continental–margin deltas, including the Magdalena, Orinoco, and Amazon drainage systems (Hoorn et al., 2010, 2017; Mora et al., 2010a; Anderson et al., 2016). Construction of the Eastern Cordillera also guided the evolution of major sedimentary basins across the northern Andes, including the Magdalena Valley and Llanos Basins, sources of considerable hydrocarbon resources (Morales, 1958; Van Houten & Travis, 1968; Van Houten, 1976; Dengo & Covey, 1993; Cazier et al., 1995; Cooper et al., 1995; Gómez et al., 2003, 2005a, 2005b; Parra et al., 2009a, 2009b; Mora et al., 2010b; Londono et al., 2012).

For several reasons, the Eastern Cordillera is particularly well suited to addressing tectonic issues using the sedimentary record. First, there is a long–duration sediment accumulation history spanning from the Late Jurassic – earliest Cretaceous through Neogene. Second, the associated stratigraphic archives are widely distributed and well preserved over a large segment of the Eastern Cordillera and flanking Magdalena Valley and Llanos provinces (Figure 2). Third, the depositional history in these three sectors involved sedimentation prior to, during, and after upper–crustal deformation.

The extensive temporal and spatial coverage offered by the stratigraphic record affords multiple opportunities to identify whether accumulation of specific stratigraphic intervals in different localities involved pre–, syn–, or post–deformational sedimentation (e.g., Bayona et al., 2008, 2013; Moreno et al., 2011; Parra et al., 2010; 2012; Horton, 2012; Mora et al., 2015). Another key part of the tectonic history involves the issue of when and how the multiple segments of a formerly integrated basin were compartmentalized by upper–crustal structures—specifically, the Magdalena Valley (including the Upper, Middle, and

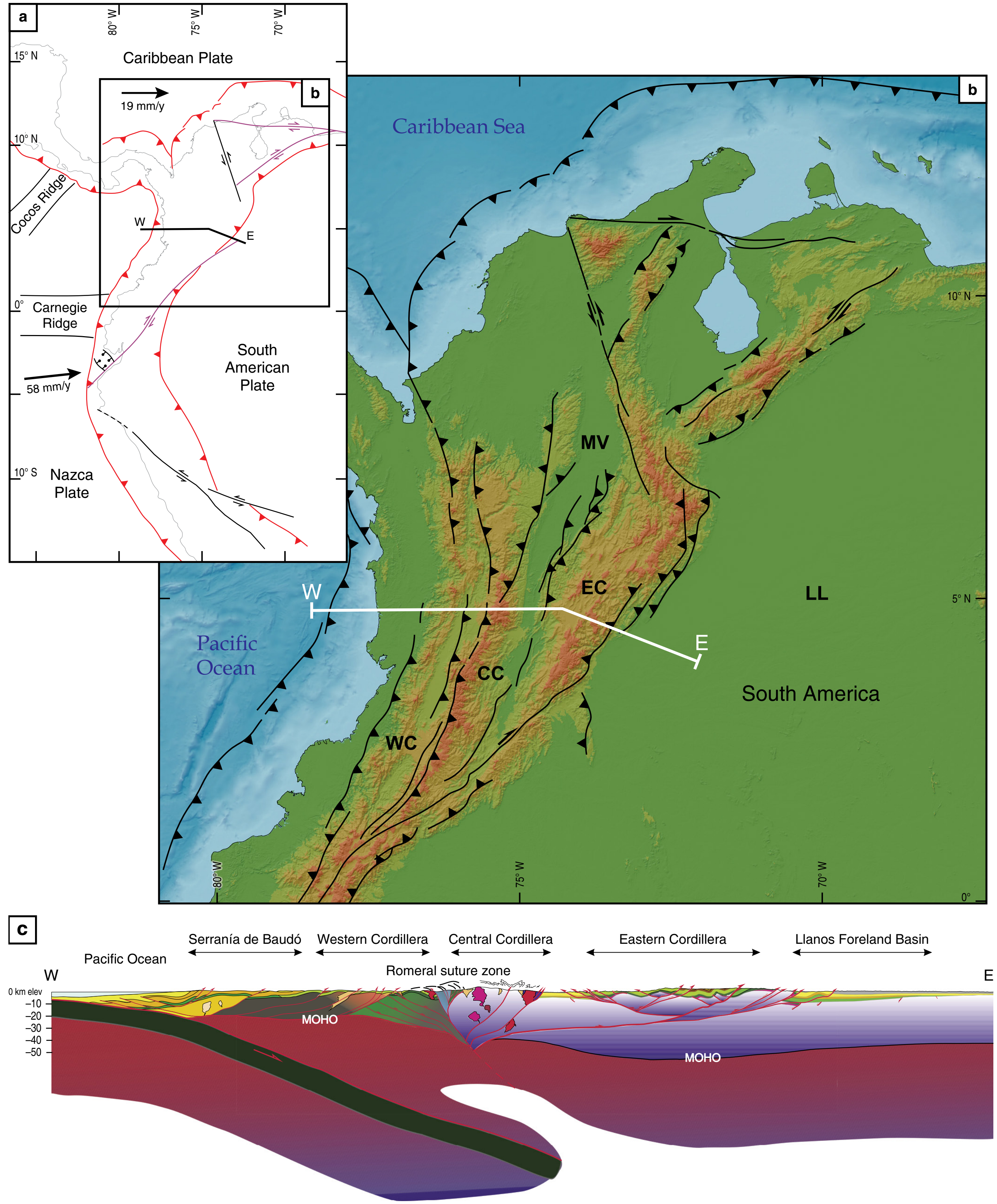

Figure 1. (a) Tectonic map of northwestern South America (from Veloza et al., 2012) showing major structures, plate boundaries, and plate velocities relative to a stable South American Plate (MORVEL–2010 plate model of DeMets et al., 2010). **(b)** Shaded relief map (after Mora et al., 2006) and **(c)** cross section (after Restrepo–Pace et al., 2004) of the northern Andes of Colombia, showing the subduction zone, and various tectonomorphic provinces: (WC) Western Cordillera; (CC) Central Cordillera; (MV) Magdalena Valley; (EC) Eastern Cordillera; (LL) Llanos foreland basin.

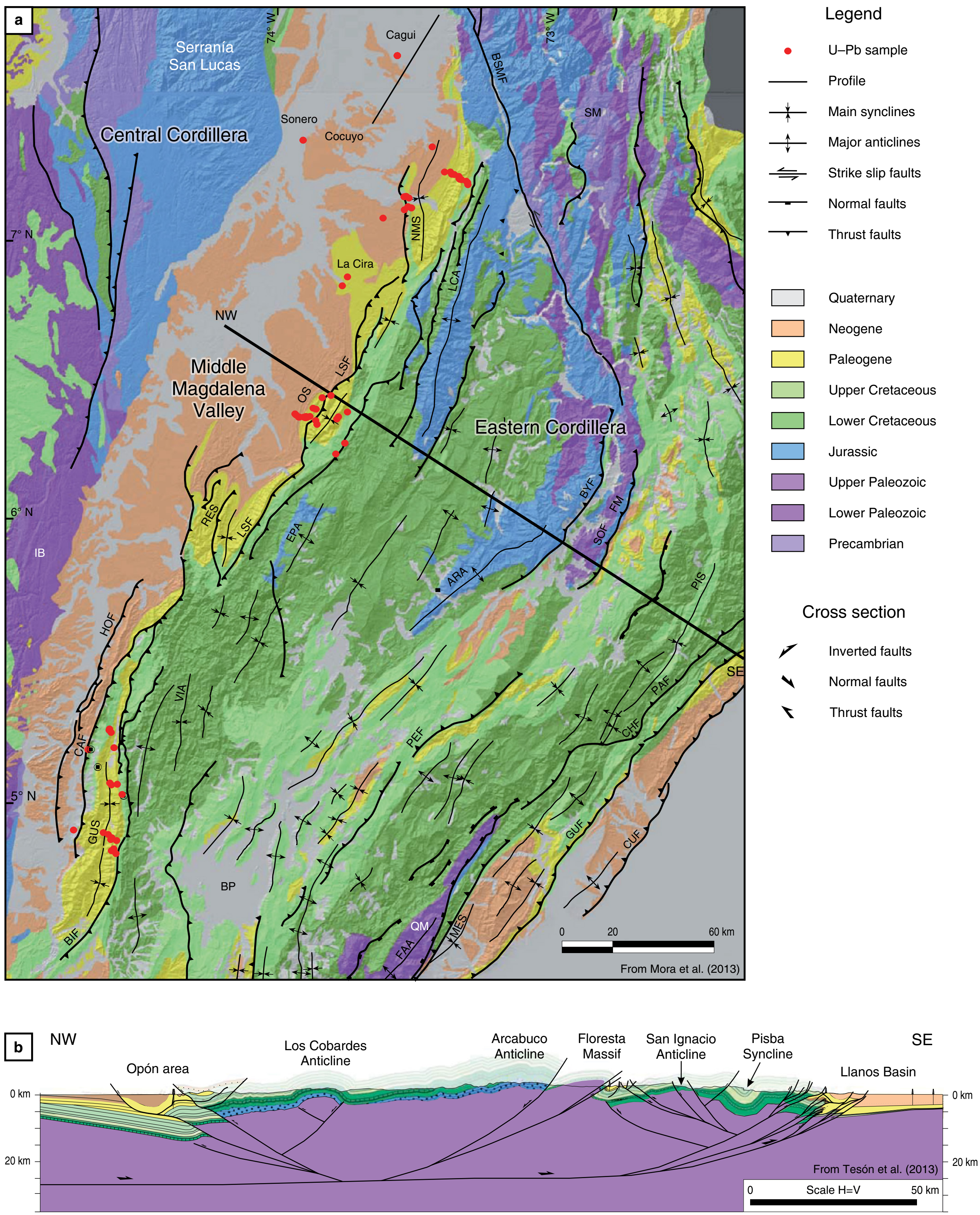
a
Serranía San Lucas
Central Cordillera
74° W
73° W
Cagui
Sonero
Cocuyo
La Cira
BSMF
SM
NMS
LCA
7° N
NW
LSF
OS
Middle Magdalena Valley
Eastern Cordillera
BYF
FM
SOF
RES
LSF
EPA
ARA
PIS
6° N
IB
HOF
VIA
PAF
SE
CHF
PEF
CAF
5° N
GUS
GUF
CUF
BP
QM
MES
FAA
BIF
0 20 60 km
From Mora et al. (2013)
Legend
U–Pb sample
Profile
Main synclines
Major anticlines
Strike slip faults
Normal faults
Thrust faults
Quaternary
Neogene
Paleogene
Upper Cretaceous
Lower Cretaceous
Jurassic
Upper Paleozoic
Lower Paleozoic
Precambrian
Cross section
Inverted faults
Normal faults
Thrust faults
b
NW
Opón area
Los Cobardes Anticline
Arcabuco Anticline
Floresta Massif
San Ignacio Anticline
Pisba Syncline
SE
Llanos Basin
0 km
20 km
0 km
20 km
From Tesón et al. (2013)
0 Scale H=V 50 km

Figure 2. (a) Regional geologic map (Mora et al., 2015) and **(b)** cross section (Caballero et al., 2013b; Tesón et al., 2013) of the Central Cordillera, Magdalena Valley, Eastern Cordillera, and Llanos Basin. (BSMF) Bucaramanga–Santa Marta Fault; (SM) Santander Massif; (NMS) Nuevo Mundo Syncline; (LCA) Los Cobardes Anticline; (OS) Opón Syncline; (LSF) La Salina Fault; (IB) Ibagué Batholith; (RES) Ermitaño Syncline; (EPA) El Peñon Anticline; (ARA) Arcabuco Anticline; (BYF) Boyacá Fault; (SOF) Soapaga Fault; (FM) Floresta Massif; (HOF) Honda Fault; (PIS) Pisba Syncline; (CAF) Cambao Fault; (VIA) Villeta Anticlinorium; (PEF) Pesca Fault; (CHF) Chámeza Fault; (PAF) Pajarito Fault; (GUS) Guaduas Syncline; (BIF) Bituima Fault; (BP) Bogotá Plateau; (GUF) Guaicáramo Fault; (CUF) Cusiana Fault; (FAA) Farallones Anticline; (QM) Quetame Massif; (MES) Medina Syncline.

Lower Magdalena Valley basins), axial Eastern Cordillera (including the Floresta Basin), and the Eastern Cordillera foothills and Llanos Basin.

The utility of sediment provenance studies in tectonic and paleogeographic reconstructions has been demonstrated clearly in the consideration of the Mesozoic – Cenozoic evolution of the Eastern Cordillera (e.g., Bayona et al., 2008; Horton et al., 2010a, 2010b, 2015; Nie et al., 2010, 2012; Saylor et al., 2011, 2013; Bande et al., 2012; Ramírez–Arias et al., 2012; Caballero et al., 2013a, 2013b; Silva et al., 2013; Reyes–Harker et al., 2015). The application of techniques such as detrital zircon U–Pb geochronology is enabled by distinctive detrital signatures, owing to considerable contrasts in the geologic column for the Eastern Cordillera relative to the Central Cordillera and distal eastern craton (Guiana Shield). From the Cretaceous – Cenozoic stratigraphic successions of the Eastern Cordillera and flanking Magdalena Valley and Llanos provinces, one can extract not only the erosional history but also the broader consequences of uplift and exhumation.

The motivation here is to highlight the stratigraphic framework and sediment provenance records from the Eastern Cordillera, flanking Magdalena Valley, and Llanos Basins in an attempt to discern the generalized pattern of deformation, exhumation, and sediment delivery associated with construction of the Eastern Cordillera. We further emphasize that the stratigraphic record is but one component of a complete regional tectonic analysis. A critical complementary method involves low–temperature thermochronology, which offers the ability to understand the time–temperature history of rock materials, which reflects exhumational processes in relationship to tectonic and climatic mechanisms. In the case of the Eastern Cordillera, the combination of extensive sedimentary cover and selected crystalline basement massifs offers excellent opportunities to illuminate the evolution of crustal structures and sedimentary basins, including tectonic inversion of precursor structural and stratigraphic heterogeneities during Andean mountain building.

2. Materials and Methods

This chapter draws upon published work that informs the understanding of the geologic history of the Eastern Cordillera and its margins, with emphasis on the sedimentary record. Structural geologic relationships, stratigraphic nomenclature, and basic geochronologic constraints largely derive from long efforts of the Servicio Geológico Colombiano (Gómez et al., 2015a, 2015b, 2015c, 2017, and references therein). Further advances have been motivated by the research efforts of Ecopetrol and the Instituto Colombiano del Petróleo (Mora, 2015 and references therein), which emphasized integrated structural, stratigraphic, and thermochronometric approaches to understanding the evolution of petroleum systems.

Many studies have explored detrital zircon U–Pb geochronology, and low–temperature (fission–track and (U–Th)/He) geochronology in Colombia, with several comprehensive approaches for selected regions (e.g., Horton et al., 2010a, 2015; Mora et al., 2010b, 2015; Parra et al., 2010, 2012; Bayona et al., 2012, 2013; Ramírez–Arias et al., 2012; Caballero et al., 2013a, 2013b; Silva et al., 2013; Reyes–Harker et al., 2015). Rather than an exhaustive synthesis of all published results bearing on the sedimentary and tectonic evolution of the Eastern Cordillera, we highlight key observations from selected representative zones that contain the type sections of several important stratigraphic units.

3. Results

3.1. Geologic Background

The Eastern Cordillera is the manifestation of Cenozoic retroarc shortening and transpressional deformation in the northernmost Andes of northwestern South America (Figure 1). This distinctive, nearly isolated mountain range is composed of series of fold–thrust structures and transpressional strike–slip faults. The NNE–trending Eastern Cordillera and its immediate margins have accommodated 50–150 km of horizontal shortening and up to 50 km of right–lateral strike–slip displacement (Colletta et al., 1990; Dengo & Covey, 1993; Cooper et al., 1995; Roeder & Chamberlain, 1995; Toro et al., 2004; Mora et al., 2006, 2008, 2013; Acosta et al., 2007; Tesón et al., 2013). This deformation of principally Cenozoic age has been accomplished during east–dipping subduction beneath northwestern South America of an oceanic slab defined by the modern Nazca Plate and precursor Farallon Plate (Pennington, 1981; van der Hilst & Mann, 1994; Lonsdale, 2005; Wagner et al., 2017). Consideration of the structural relief between the Eastern Cordillera and the flanking Magdalena Valley to the west and the Llanos Basin to the east indicates that Cretaceous units have been elevated up to ca. 8 km above regional levels. Associated surface uplift in the Eastern Cordillera has generated a ca. 100–250 km wide by ca. 500 km long range of ca. 1.5–3 km average elevation.

The structural architecture of the Eastern Cordillera is one of a bivergent fold–thrust belt defined by sharp eastern and western mountain fronts against flanking sedimentary basins (Figure 2). This contractional range contains a relatively uniform distribution of NNE–striking thrust/reverse faults, with a prominent west–directed fault system along the western front (Magdalena Valley) and east–directed fault system along the eastern front (Llanos Basin) (Casero et al., 1997; Corredor, 2003; Restrepo–Pace et al., 2004; Mora et al., 2006, 2010b; Sánchez et al., 2012; Wolaver et al., 2015). Individual structures accommodate several kilometers of dip–slip reverse displacement, with locally important dextral strike–slip offset. Although most structures have a thin–skinned ramp–flat geometry above regional decollements within the Cretaceous stratigraphic succession, there are several thrust/reverse faults involving crystalline basement rocks. The spatial association of such basement–involved structures with Jurassic – lowermost Cretaceous synextensional sub–basins suggests a common pattern of normal fault reactivation and basin inversion during later contraction (e.g., Cooper et al., 1995; Branquet et al., 2002; Cortés et al., 2006; Kammer & Sánchez, 2006; Mora et al., 2006, 2009).

The Eastern Cordillera is dominated by exposures of Mesozoic – Cenozoic sedimentary rocks with localized basement massifs (Bürgl, 1967; Julivert, 1970; Gómez et al., 2015a, 2015b). The relative proportions of the various geologic units exposed across the ca. 100 000 km^2 surface area are as follows (in order of decreasing abundance): Upper Cretaceous (50%), Lower Cretaceous (30%), Cenozoic (10%), Jurassic (10%), basement (10%). Jurassic to Neogene sedimentary rocks of mixed marine and nonmarine origin are comprised of mostly clastic facies with limited carbonate (estimated 60% mudrock, 30% sandstone, 10% conglomerate).

The Mesozoic – Cenozoic record reflects a combination of regionally extensive and locally restricted stratigraphic units. The three major basin elements include (from west to east): (i) the Magdalena Valley, a NNE–trending longitudinal basin situated between the Central and Eastern Cordilleras and commonly divided into the Upper, Middle, and Lower Magdalena Valleys; (ii) basin fill now exposed in the axial Eastern Cordillera notably the Floresta Basin (and Bogotá/Altiplano Basin); and (iii) the Llanos Basin, on the eastern cratonic flank of the Eastern Cordillera.

A complex but discernible evolution is preserved within the stratigraphic record, in which these three sectors were either joined together as a single integrated basin or structurally partitioned by upper–crustal structures. The broad sedimentary history involves three principal phases: (i) Middle or Late Jurassic to early Early Cretaceous extension with the growth and coalescence of extensional sub–basins across the Eastern Cordillera; (ii) Late Early Cretaceous to Late Cretaceous development of a single regionally integrated postextensional sag basin spanning the Eastern Cordillera, Magdalena Valley, and Llanos regions; and (iii) Latest Cretaceous – Cenozoic evolution of shortening–related basins in foreland, hinterland, and intermontane settings associated with the progressive growth of the Andean fold–thrust belt.

Multiple tectonic provinces may have acted as sources of clastic sediment to the Eastern Cordillera and its neighboring regions. Potential source areas include: (i) eastern cratonic zones of crystalline basement in the distal Llanos Basin and Guiana Shield; (ii) western zones of the Andean magmatic arc and its substrate; and (iii) the retroarc fold–thrust belt forming the Eastern Cordillera, including its pre–Devonian basement substrate. These morphostructural zones exhibit distinctive geologic units that lend themselves to discrimination through various geochronological and geochemical techniques (Cardona et al., 2010; Horton et al., 2010b, 2015; Nie et al., 2012; Saylor et al., 2013).

3.2. Stratigraphic Framework

The stratigraphic framework for the Eastern Cordillera must be considered along with that of the flanking hinterland and foreland provinces. It is instructive to emphasize the geologic records of three basin sectors—the Magdalena Valley, axial Eastern Cordillera, and Llanos Basin—and the shared versus divergent components of their stratigraphic histories (Figure 3). Here we review the principal stratigraphic units and briefly outline regional stratigraphic correlations and growth strata relationships.

The Magdalena, Eastern Cordillera, and Llanos regions share a similar crystalline basement that is regarded as the westernmost segments of South American continent crust, of Mesoproterozoic to early Paleozoic age, with accreted oceanic materials of late Mesozoic to Cenozoic age defining regions farther west (Aspden & McCourt, 1986; Forero, 1990; Taboada et al., 2000; Cediel et al., 2003; Restrepo–Pace et al., 2004; Cordani et al., 2005; Ordóñez–Carmona et al., 2006; Ibañez–Mejia et al., 2011; Montes et al., 2012; Saylor et al., 2012a).

Paleozoic sedimentary rocks of marine origin are locally preserved, but generally absent from most sectors of the Eastern Cordillera and its peripheral regions, which are dominated by Mesozoic – Cenozoic clastic basin fill. In several localized regions, crystalline basement is capped by coarse–grained nonmarine deposits, commonly sandstone and conglomerate and associated volcaniclastic components, of Middle/Late Jurassic to Early Cretaceous age (Girón Group). These extensional sub–basins are overlain by a more regionally extensive Lower Cretaceous marine succession of clastic and subordinate carbonate facies that directly rests upon isolated Jurassic deposits or crystalline basement. Upsection, an Upper Cretaceous to Cenozoic clastic succession chronicles the transition from marine to nonmarine deposition and rapid accumula-

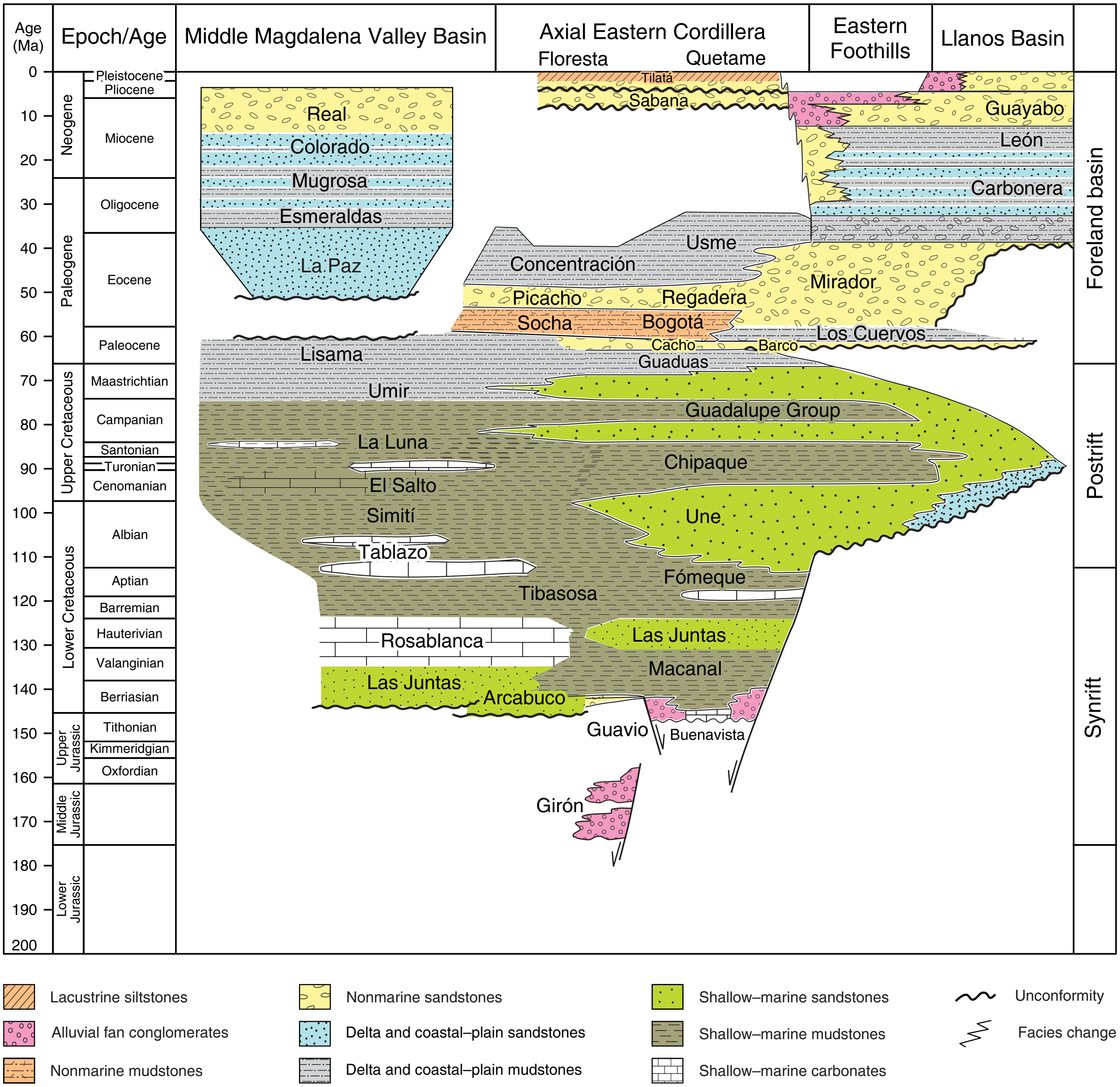

Figure 3. Cross–strike (west–east) geologic column for the Eastern Cordillera and flanking Magdalena Valley and Llanos Basins (after Mora et al., 2006; Parra et al., 2009a, 2009b).

tion during Andean shortening and flexural subsidence. Age control is provided by Cretaceous marine invertebrate fossils (Etayo–Serna et al., 1983; Etayo–Serna & Laverde–Montaño, 1985) and ubiquitous preservation of fossil pollen (palynomorph) assemblages that provide age resolution within several million years for Cenozoic basin fill across Colombia (e.g., Jaramillo et al., 2009, 2011). Further age control is provided by isotopic ages for selected volcanic horizons and syndepositional volcanogenic zircons (e.g., Gómez et al., 2003, 2005a, 2005b; Bayona et al., 2012; Saylor et al., 2012b; Gómez et al., 2015c; Anderson et al., 2016).

The Upper Cretaceous – Cenozoic stratigraphic intervals within the Magdalena Valley Basin, axial Eastern Cordillera, and Llanos Basin define broad upward coarsening packages (Figure 4) with some internal variability that makes lithostratigraphic correlations difficult. The sediment provenance characteristics (discussed in a following section) provide additional constraints on potential correlations, and prove instrumental in

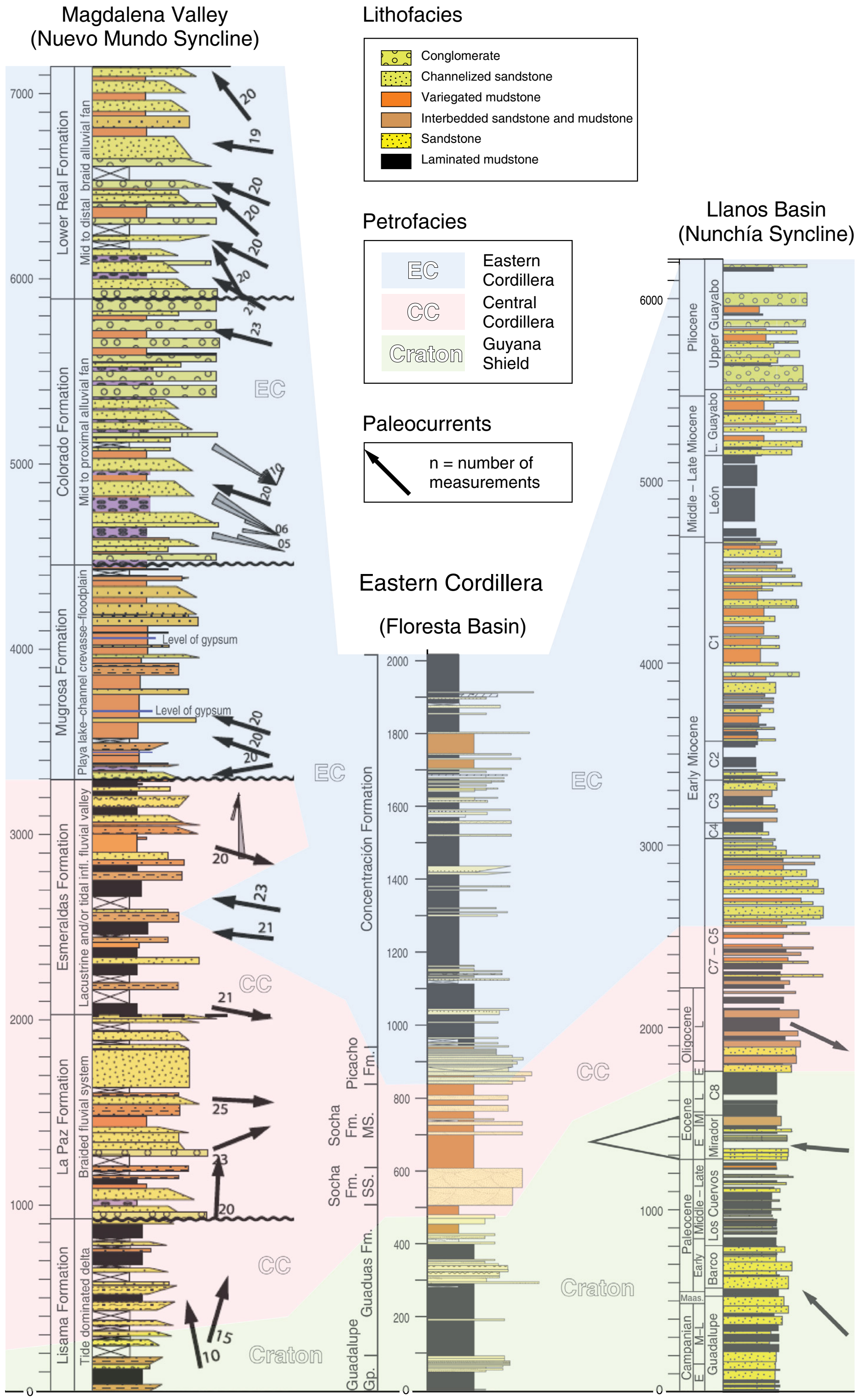

Figure 4. Measured stratigraphic sections and approximate chronostratigraphic correlations for the Middle Magdalena Valley (Caballero et al., 2013a), axial Eastern Cordillera (Saylor et al., 2011), and Llanos basins (Parra et al., 2010).

assessing sediment source regions and overall "petrofacies" of different levels of the Cretaceous – Cenozoic successions.

Widespread sandstone facies of Campanian, Maastrichtian, and early Paleocene age (including the Guadalupe Group, Guaduas Formation, Barco Formation, and Lisama Formation) are distributed across the Eastern Cordillera and its margins. These deposits are routinely correlated across broad regions, show a general axial northward transport, and appear to be principally derived from cratonic sources, with limited input from the emerging Eastern Cordillera (Bayona et al., 2008, 2012; Saylor et al., 2011; Silva et al., 2013; Vallejo et al., 2017). In contrast, the overlying mid–Paleocene through Quaternary panels show significant variability among the three basin systems, which are considered individually.

In the Magdalena Valley, the ca. 7000 m thick Cenozoic succession consists of alternating distal fluvial, proximal fluvial, alluvial fan, and limited lacustrine facies organized into an alternating upward coarsening and fining packages (Morales, 1958; Van Houten, 1976; Gómez et al., 2003, 2005b; Caballero et al., 2010, 2013a; Horton et al., 2010b, 2015; Nie et al., 2010, 2012; Moreno et al., 2011). At the base, the Maastrichtian – lower Paleocene Umir and Lisama Formations contain the transition from marine to nonmarine sedimentation. These organic–rich shale and sandstone are overlain by the upper Paleocene to middle Eocene La Paz Formation, which represents a major clastic wedge of sandstone and conglomerate derived from early Andean sources to the west. This panel is abruptly capped by a fine–grained late Eocene – lowermost Oligocene interval (Esmeralda Formation) representative of mud–dominated overbank fluvial and lacustrine deposition. This is capped, in turn, by a thick upward coarsening panel of sandstone and conglomerate in alternating channel–belt fluvial and alluvial fan deposits of Oligocene to Quaternary age (Mugrosa, Colorado, and Real Formations).

In the axial Eastern Cordillera, the Floresta Basin and smaller satellite sub–basins contain a partial stratigraphic record (ca. 2000 m total thickness) that spans from the Upper Cretaceous through Oligocene (Bayona et al., 2010; Saylor et al., 2011; Ochoa et al., 2012; Silva et al., 2013). The Maastrichtian – lower Paleocene Guadalupe Group and Guaduas Formation (ca. 500 m thick) are part of a regionally extensive sandy interval that contains the final marine to nonmarine transition in the region, similar to the Magdalena Valley Basin. This diagnostic part of the section is commonly defined by resistant, well–exposed sandstones that can be correlated across the Eastern Cordillera, albeit with variable stratigraphic names (Cacho and Barco Formations). In the axial Eastern Cordillera, including the Floresta Basin (and Bogotá/Altiplano Basin), these sandstones are capped by a mixed collection of fluvial and lacustrine sandstone, mudstone, and subordinate conglomerate, comprising the Paleocene Socha (Bogotá) Formation, lower – middle Eocene Picacho (Regadera) Formation, and upper Eocene – Oligocene Concentración (Usme) Formation. These units are broadly organized into a generally upward fining panel ca. 1500 m in thickness. The lack of Miocene and younger deposits is considered to reflect a history of nondeposition during Andean uplift, rather than deposition and subsequent erosional removal.

On the eastern flank of the Eastern Cordillera, exposed stratigraphic panels in the proximal (western) segments of the Llanos Basin attain ca. 6000 m in total thickness and provide access to Cretaceous – Cenozoic depositional histories (Parra et al., 2009a, 2009b, 2010; Bande et al., 2012). The regionally extensive Upper Cretaceous – lower Paleocene section (Guadalupe Group, and Barco and Los Cuervos Formations) represents protracted pre–Andean marine accumulation (up to 1500 m) during post–extensional thermal subsidence. Progressively diminished accommodation resulted in a relatively thin (100–200 m) but diagnostic middle – upper Eocene unit, the fluvial to coastal marine Mirador Formation (Jaramillo et al., 2009, 2011). Capping the Mirador Formation is a ca. 4500 m thick Oligocene – Quaternary upward coarsening succession representative of a classic distal to proximal evolution of a foreland basin. This interval is best exposed along the deformation front, including the Nazareth Syncline (Medina Basin) and Nunchía Syncline adjacent to the Guaicáramo and Yopal thrust faults, respectively (Parra et al., 2009a, 2010; Bande et al., 2012). In many ways, the Oligocene – Quaternary deposits of the proximal Llanos foreland can be considered as a mirror image of the western flank of the Eastern Cordillera and the comparable and contemporaneous upward coarsening succession of the Magdalena Valley Basin.

Evaluation of potential regional lithostratigraphic correlations for Mesozoic – Cenozoic units reveals contrasting situations, in which Cretaceous – Paleocene units show clear laterally continuous facies, yet Eocene and younger units show greater variability. Multiple stratigraphic levels of the largely marine Cretaceous succession have been correlated across the Eastern Cordillera and flanking Magdalena and Llanos basins, on the basis of comparable lithology, lithofacies assemblages, depositional conditions, and marine fossil assemblages (Morales, 1958; Bürgl, 1961; Etayo–Serna & Laverde–Montaño, 1985; Cooper et al., 1995; Mora et al., 2010c; Gómez et al., 2015a, 2015b). The upper levels of this interval uniformly show regional–scale upward coarsening and a shift to nonmarine conditions. These Maastrichtian – Paleocene stratigraphic units are correlated regionally across the Eastern Cordillera and adjacent basin sectors, and represent large fluvial systems characterized by generally northward longitudinal transport within a broad early Andean foreland basin system (Villamil, 1999; Gómez et al., 2005a, 2005b; Caballero et al., 2013b; Silva et al., 2013). This stratigraphic continuity contrasts sharply with the Eocene depositional record, for which regional correlation proves challenging. A significant hiatus, the Middle Magdalena Valley unconformity, can be linked to structural activity along a series of local fault–related uplifts (Gómez et al., 2003, 2005b; Moreno et al., 2011; Parra et al., 2012). Although many earlier studies inferred a long (ca. 20 my) early – middle Eocene hiatus across the Eastern Cordillera, (e.g., Dengo & Covey, 1993; Cooper et al., 1995; Villamil, 1999), recent, higher–resolution palynological studies demonstrate continuous sedimentation, albeit at a reduced rate (e.g., Jaramillo et al., 2009, 2011). Stratigraphic contrasts in lithofacies, deposystems, and thicknesses suggest that structural partitioning of the early Andean foreland basin was underway during the Eocene. Nevertheless, the common occurrence of relatively fine–grained uppermost Eocene – lower Oligocene successions (Figure 4) (Parra et al., 2010; Saylor et al., 2011; Ochoa et al., 2012) may suggest a regional–scale reduction in exhumation and flexural accommodation, conceivably related to a transient reduction in the pace of orogenesis in the northern Andes (Gómez et al., 2003; Londono et al., 2012; Mora et al., 2013; Horton, 2018a), similar to large segments of the southern Andes (e.g., Horton & Fuentes, 2016; Horton, 2018b). Importantly, the lack of regionally correlative stratigraphic units points to a late Eocene to Quaternary evolution of compartmentalized basins across the Magdalena, Eastern Cordillera, and Llanos Basin sectors, with strongly contrasting depositional conditions, sediment dispersal, and accumulation.

Stratigraphic correlations are further supported by a series of localities reported to contain growth strata. In contractional systems, growth strata are characterized by an upsection reduction in stratal dip, thinning of individual beds or bed packages toward the structure, and common internal angular unconformities (e.g., Riba, 1976; Perez & Horton, 2014). In Colombia, the recognition of growth strata in surface and subsurface datasets is critical to assessing basin evolution in relationship with upper–crustal structures (e.g., Julivert, 1963, Corredor, 2003; Gómez et al., 2003, 2005a; Restrepo–Pace et al., 2004; Cortés et al., 2006; Parra et al., 2010, 2012; Mora et al., 2013). These features are unambiguous indicators of fault activity, and with sufficient stratigraphic age control, provide a direct means of dating deformation. Although growth strata are commonly elusive within the fold–thrust belt interiors, as reported for most of Eastern Cordillera (Mora et al., 2015), key examples in Colombia include: (i) upper Paleocene – Eocene growth strata in the Magdalena Valley and along the Magdalena–Eastern Cordillera transition zone (Gómez et al., 2003; Restrepo–Pace et al., 2004; Parra et al., 2012; Sánchez et al., 2012); (ii) isolated Paleogene examples within the Eastern Cordillera (Julivert, 1963; Gómez et al., 2005a; Bayona et al., 2010); and (iii) Oligocene – Pliocene growth strata along the eastern Andean deformation front and proximal zone of the Llanos foreland basin (Corredor, 2003; Cortés et al., 2006; Bayona et al., 2008; Parra et al., 2010; Mora et al., 2013).

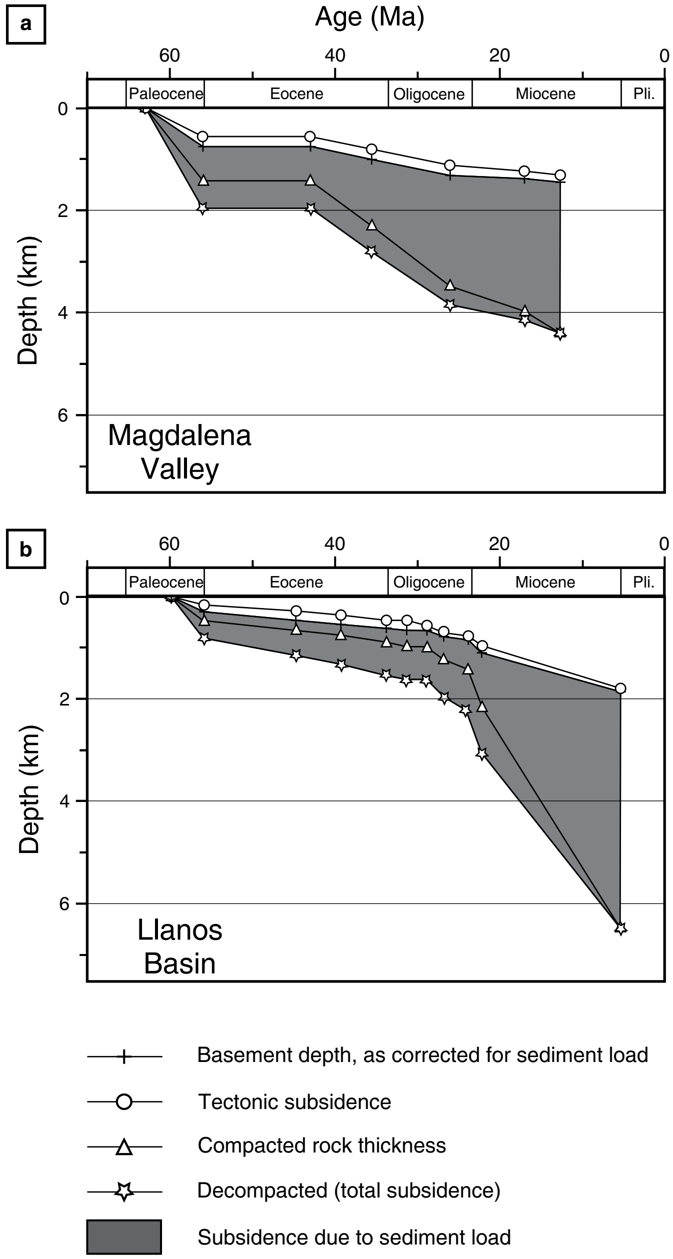

Figure 5. Sediment accumulation plots for **(a)** the Middle Magdalena Valley Basin and **(b)** Llanos Basin (Parra et al., 2010).

3.3. Sediment Accumulation

The history of basin development along the flanks and interior of the Eastern Cordillera is contained in the lithofacies patterns, accumulation histories, and shifts in sediment provenance. Sediment accumulation histories for the Magdalena Valley and Llanos foreland register periods of rapid, thrust–induced subsidence and possible spatial variations in a cross–strike (east–west) direction (Gómez et al., 2005b; Bayona et al., 2008; Parra et al., 2009a; Saeid et al., 2017; Horton, 2018a). Sufficient age control from basin fill in the Middle Magdalena Valley (Guaduas Syncline; Gómez et al., 2005a) and western Llanos Basin (Medina Basin; Parra et al., 2010) enables a geohistory analysis that accounts for incremental sediment compaction. This analysis yields the Cenozoic history of subsidence, depicted in time–depth plots (Figure 5), and allows for discrimination of tectonic subsidence and subsidence due to sediment loading.

Although both the Magdalena Valley Basin and Llanos foreland basin show sustained rapid subsidence, they experienced relatively abrupt increases in accommodation at different moments in their Cenozoic histories. In the Magdalena Valley, a

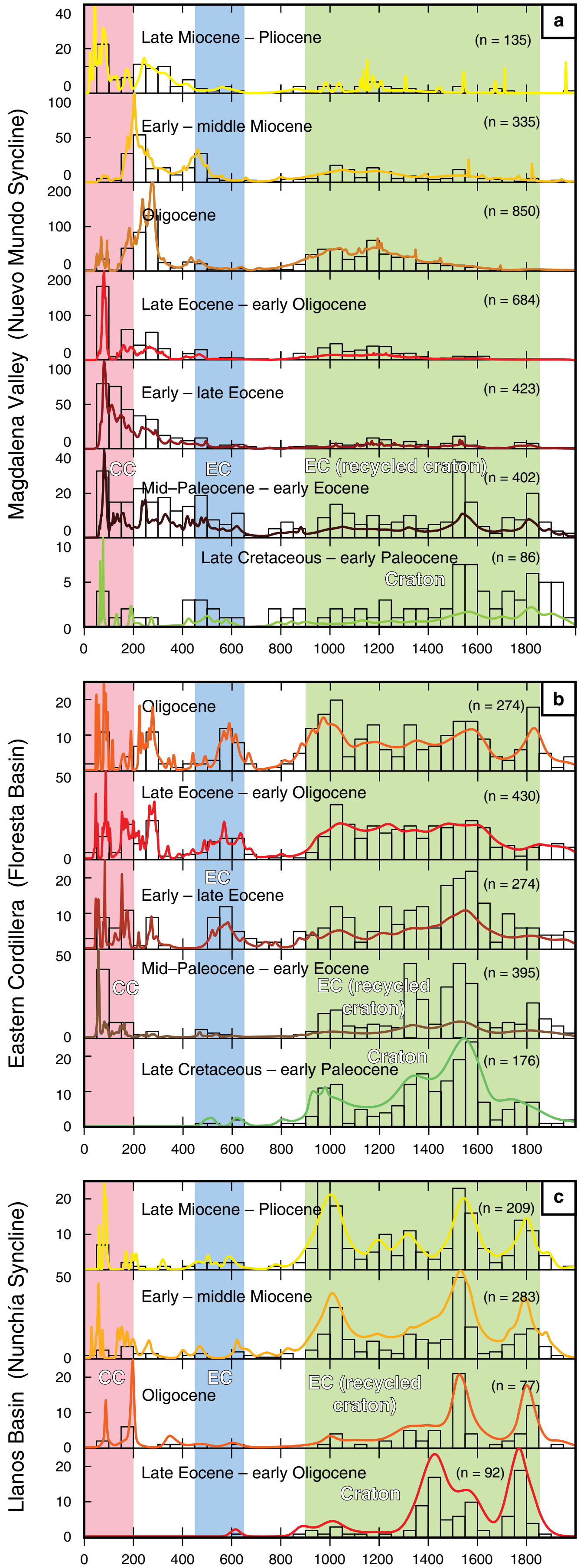

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Figure 6. Comparative plots of detrital zircon U–Pb age distributions for latest Cretaceous – Cenozoic basin fill of the **(a)** Middle Magdalena Valley Basin (Nuevo Mundo Syncline; Horton et al., 2015), **(b)** axial Eastern Cordillera (Floresta Basin; Saylor et al., 2011), and **(c)** Llanos Basin (Yopal/Nunchía Syncline; Bande et al., 2012). Bold white text labels identify the initial craton provenance followed by the first appearance of detritus from the Central Cordillera (CC), Eastern Cordillera (EC), and recycled cratonic detritus from the Eastern Cordillera.

multi–phase history involves rapid Paleocene accumulation followed by sharply diminished accommodation, then a renewed rapid period of accumulation commencing at about 45–40 Ma. The early record probably reflects initial flexural subsidence due to Paleocene shortening and crustal thickening in the Central Cordillera followed by limited early Eocene accumulation above growing basement–involved structures in the Magdalena Valley. It is important to note that other local zones on the flanks of these basement highs in the Magdalena Valley likely underwent rapid subsidence during the early Eocene, suggesting significant spatial variability in accommodation. Subsequent to this record, an inflection point at 45–40 Ma in the sediment accumulation curve suggests that considerable flexural accommodation was underway by middle to late Eocene time. This subsidence, however, was likely generated by shortening within the Eastern Cordillera, suggesting that the Magdalena Valley had transformed from a proximal foreland basin into an intermontane hinterland basin.

In the Llanos Basin, a more straightforward sediment accumulation history is revealed in which continuous Paleocene – Eocene accommodation is replaced by rapid accommodation in Oligocene time, as shown by a ca. 30 Ma inflection point. The ca. 10–15 my difference in the onset of rapid subsidence between the Magdalena Valley and Llanos Basin is attributed to patterns of fold–thrust deformation across the Eastern Cordillera. The timing constraints are consistent with an overall eastward advance of upper–crustal shortening, which is compatible with low–temperature thermochronological records (mentioned below) in suggesting early Andean exhumational cooling in western sectors followed by late Andean exhumation near the eastern deformation front (Mora et al., 2008, 2010a, 2015; Parra et al., 2009b, 2010; Saylor et al., 2012b).

3.4. Sediment Provenance

U–Pb geochronological data are fundamental to assessing the sediment sources and paleodrainage patterns in Colombia. Several major shifts in sediment provenance can be linked to the tectonic evolution of the Eastern Cordillera and its peripheral regions. During the Mesozoic, sediment was overwhelmingly derived from eastern sources of the Guiana Shield, including possible minor sources that are now buried beneath Cenozoic fill of the Llanos Basin. The ages of these cratonic crystalline basement rocks span the late Paleoproterozoic to early Neoproterozoic (Teixeira et al., 1989; Horton et al., 2010b; Cardona et al., 2010, and references therein). Detrital zircon U–Pb geochronological results for Upper Cretaceous deposits show comparable age populations, concentrated at 900–2000 Ma (Figure 6). The lack of significant Phanerozoic grains indicates very limited erosional input from the present–day Central or Eastern Cordilleras. These results confirm a pre–Andean extensional to post–extensional landscape involving west–directed sediment dispersal from cratonic sources uniformly across all three basin sectors—the Llanos Basin, Eastern Cordillera, and Magdalena Valley—as interpreted by many previous studies on the basis of lateral facies changes, thickness trends, and paleocurrents (Toussaint & Restrepo, 1994; Cazier et al., 1995; Cooper et al., 1995; Villamil, 1999; Sarmiento–Rojas et al., 2006).

A major reversal in sedimentary polarity archived by sediment provenance signatures within Upper Cretaceous – Cenozoic basin fill points to the initial effects of Andean orogenesis. The initial delivery of detritus from the Central Cordillera is evidenced by the first appearance of Mesozoic – Cenozoic age populations that must originate in the Andean magmatic arc. Paleogene deposits across the region record the arrival of a significant population of 50–200 Ma grains emblematic of Andean igneous materials from the Central Cordillera (McCourt et al., 1984; Aspden et al., 1987; Villagómez et al., 2011; Villagómez & Spikings, 2013). Although this first appearance of Andean detritus can be identified in all three basin sectors, it occurred at different moments in their respective sedimentary histories. Whereas the reversal in sediment dispersal occurred in the Paleocene in the Magdalena Valley and axial Eastern Cordillera (Lisama, La Paz, Socha Formations; Figure 6a, 6b), it was delayed until the Oligocene for the Llanos Basin (Carbonera Formation; Figure 6c). This delay is consistent with the pattern of flexural loading inferred from the sediment accumulation histories (Figure 5), in which the Magdalena Valley experienced rapid flexural accommodation prior to the Llanos Basin.

Following the initial delivery of Andean sediment, diverse provenance patterns characterize the three basin sectors during their independent evolution from Eocene to present (Figure 6). (i) In the west, the Magdalena Valley underwent a complex alternating history of Eastern Cordillera versus Western Cordillera detrital input (Nie et al., 2010, 2012; Caballero et al., 2013b; Silva et al., 2013), prior to establishment of a throughgoing Magdalena River in late Miocene time (Horton et al., 2015). This pattern (Figure 6a) is revealed by Eocene to Pliocene alternations between Andean arc (<200 Ma) signals from the Central Cordillera and two signals from the Eastern Cordillera: a late Neoproterozoic – early Paleozoic (650–450 Ma) population from local basement and a recycled cratonic (900–1800 Ma) population derived from ubiquitous Cretaceous Eastern Cordillera strata originally derived from cratonic sources (Horton et al., 2010a, 2010b, 2015). (ii) In contrast, the axial Eastern Cordillera was fed mostly by local sources within the fold–thrust belt, with limited input of Andean arc detritus (Bayona et al., 2010, 2012; Saylor et al., 2011; Silva et al., 2013). This pattern (Figure 6b) is reflected in Eocene – Oligocene strata by the dominance of Eastern Cordillera signatures. Although a minor signal from the Central Cordillera arc (<200 Ma) persists, the dominant populations are diagnostic of the Eastern Cordillera (the aforementioned 650–450 Ma and recycled 900–1800 Ma populations). (iii) In the east, the Llanos Basin was dominated by erosional input from the Eastern Cordillera, with very limited delivery of arc detritus (Horton et al., 2010a, 2010b; Bande et al., 2012). This pattern (Figure 6c) is attributed to exhumation within the Eastern Cordillera of not only Cretaceous strata, which provided recycled cratonic populations (900–1800 Ma), but also Cenozoic basin fill, which provided the restricted amounts of Andean arc (<200 Ma) material.

The power of provenance applications in Colombia is enabled by the distinctive morphostructural zones of the northern Andes, which have diagnostic geochronological signatures that can be identified in the stratigraphic record (Cardona et al., 2010; Horton et al., 2010b, 2015; Nie et al., 2010, 2012; Saylor et al., 2011, 2013). When integrated with considerations of regional stratigraphic continuity and the timing of basin compartmentalization, the provenance record provides a robust understanding of the spatial and temporal evolution of the Eastern Cordillera. These first–order constraints from the stratigraphic record can be augmented by higher resolution studies that seek to assess changes in climate and absolute elevation (Guerrero, 1997; Mora et al., 2008; Anderson et al., 2015) and the exhumational history of individual structures from thermochronological data (Mora et al., 2008, 2013, 2015; Parra et al., 2009b, 2010, 2012; Saylor et al., 2012b; Almendral et al., 2015).

3.5. Low–Temperature Thermochronometry

Thrust–induced rock uplift histories in the Eastern Colombia have been diagnosed through multi–method fission track and (U–Th)/He thermochronometry assisted by vitrinite reflectance data (see Mora et al., 2015 and references therein). Analytical results from multiple samples provide the basis for 1–D time–temperature histories extracted through thermal modeling (e.g., HeFTy software; Ketcham, 2005). Mineral cooling ages and thermal modeling of thermally reset Mesozoic to Paleogene strata and their underlying basement rocks along a cross–strike transect from the Magdalena Valley to the Llanos Basin reveal a diachronous inception of fold–thrust belt development (Figure 7).

First, Paleocene – early Eocene onset of thrusting along the western margin of the Eastern Cordillera and in basement highs beneath the Magdalena Valley reveal the extent of a relict Paleocene thrust–belt associated with arc collision and early

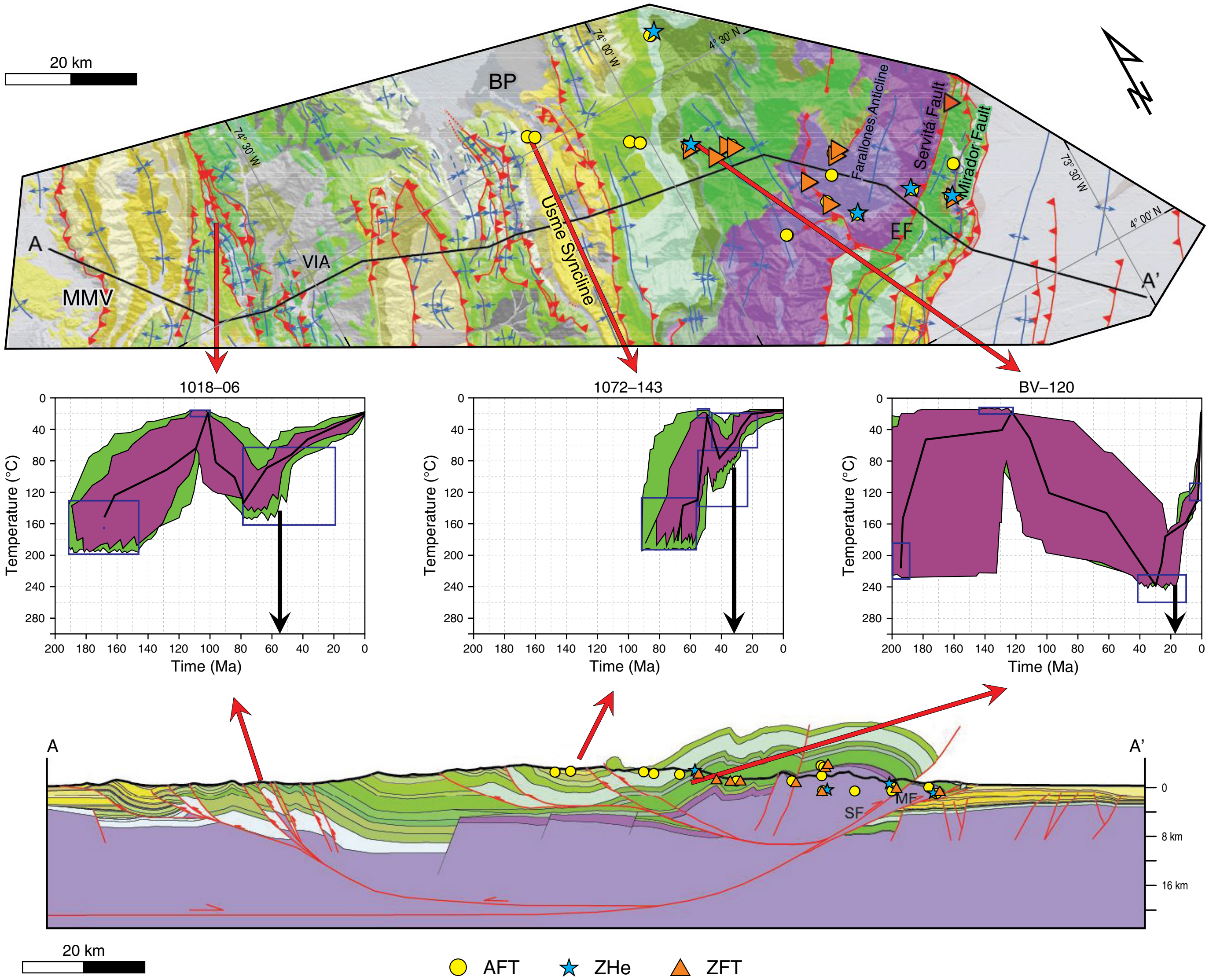

Figure 7. Geologic map (above) and structural cross section (below) at the latitude of Bogotá (4° N, after Mora et al., 2015) showing geologic context for three representative 1D thermal models constructed using multiple thermochronometers with HeFTy software (Ketcham, 2005). The time–temperature (t–T) paths show good (purple) and acceptable (green) thermal histories that fit the observed data. (MMV) Middle Magdalena Basin; (VIA) Villeta Anticlinorium; (BP) Bogotá Plateau; (EF) Eastern Foothills.

shortening in the Western and Central Cordilleras (Parra et al., 2012, Caballero et al., 2013b). An eastward advance of thrusting induced cooling and rock exhumation at 40–35 Ma in the axial Eastern Cordillera (Parra et al., 2009b; Mora et al., 2010b; Ramírez–Arias et al., 2012; Saylor et al., 2012b) and ca. 10 my later, at 30–25 Ma along the eastern margin of the Eastern Cordillera (Parra et al., 2009b; Horton et al., 2010a; Mora et al., 2010b; Bande et al., 2012; Ramírez–Arias et al., 2012; Mora et al., 2015). Remarkably, in all three of these regions, cooling associated with rock exhumation was associated with contractional reactivation of major ancestral normal faults (active during Mesozoic extension) and coincide with major shifts in sediment delivery and accommodation revealed by provenance and facies distributions.

3.6. Discussion

The preceding synthesis of sedimentary datasets and representative thermochronometric data provides a foundation for a generalized reconstruction of the Mesozoic – Cenozoic history of the Eastern Cordillera and adjacent regions in the Magdalena Valley and Llanos Basin of Colombia. A multi–step two–dimensional cross–sectional reconstruction shows an east–west profile of evolving basin configurations from Late Jurassic to present. We consider and incorporate elements from many similar regional reconstructions depicted by previous authors (e.g., Restrepo–Pace et al., 2004; Bayona et al., 2008, 2013; Horton et al., 2010b, 2015; Mora et al., 2010b, 2013, 2015; Bande et al., 2012; Caballero et al., 2013a, 2013b; Wolaver et

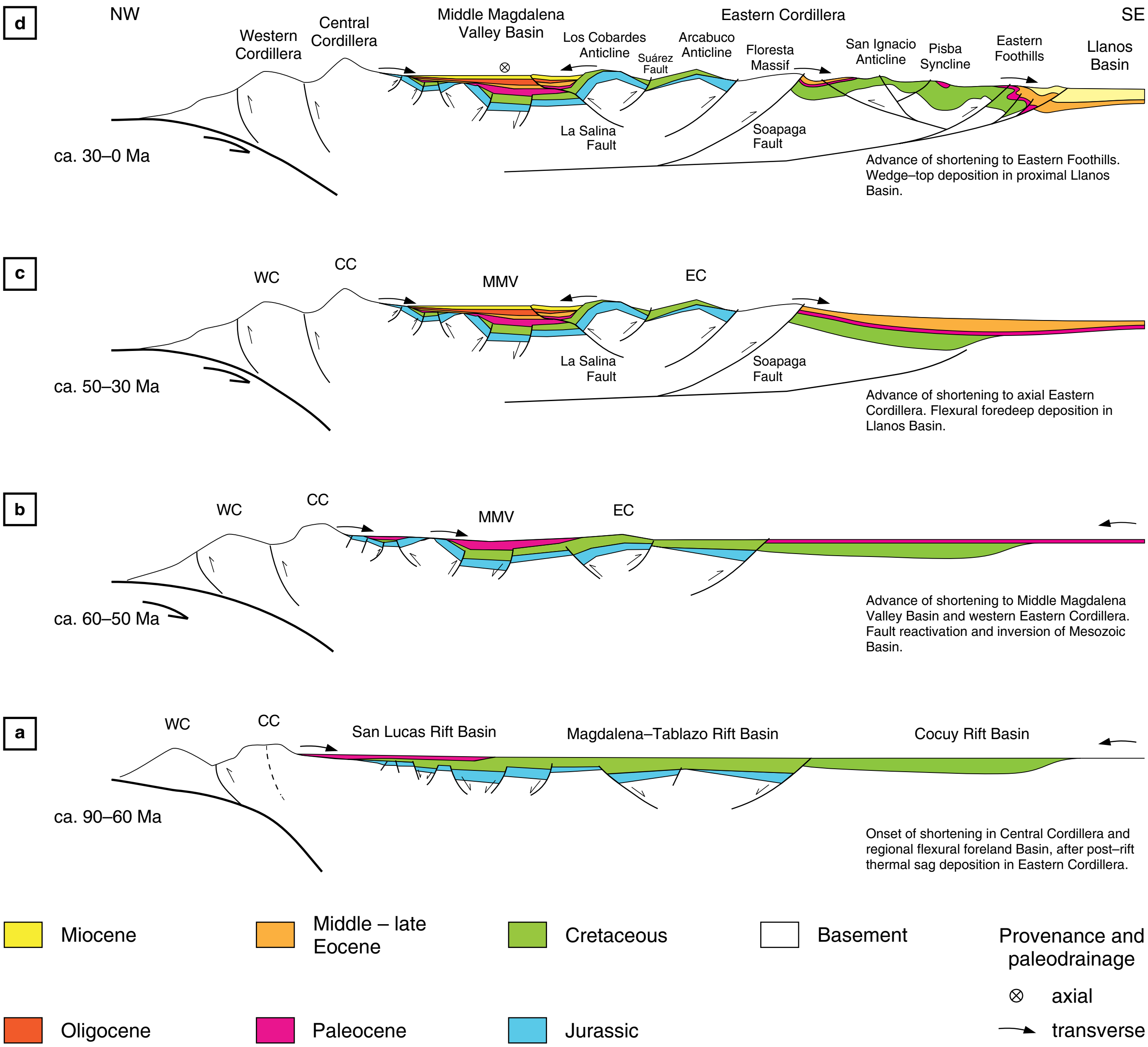

Figure 8. Highly schematic reconstruction of Cretaceous – Cenozoic basin evolution, with emphasis on the structural and topographic development of the Eastern Cordillera (after Horton et al., 2010b and Caballero et al., 2013b). **(a)** Late Cretaceous, **(b)** Maastrichtian – Paleocene, **(c)** Eocene – Oligocene, **(d)** Miocene – Quaternary. (WC) Western Cordillera; (CC) Central Cordillera; (MMV) Middle Magdalena Basin; (EC) Eastern Cordillera.

al., 2015). In drafting these reconstructions, we relied heavily on the three datasets summarized above: (i) the regional stratigraphic framework; stratigraphic correlations, and depositional conditions; (ii) sediment accumulation histories; and (iii) sediment provenance constraints principally from detrital zircon U–Pb geochronology.

During the Late Jurassic – earliest Cretaceous, a series of newly formed normal faults guided the generation of individual extensional sub–basins with half–graben geometries. Progressive east–west extension in backarc regions was accommodated by the linkage of normal faults and the coalescence of sub–basins into larger extensional basins. Basin evolution was largely governed by two major extensional basins, the Tablazo–Magdalena and Cocuy basins, occupying the Magdalena Valley and Eastern Cordillera provinces, respectively (Cooper et al., 1995; Sarmiento–Rojas et al., 2006). Sedimentation during upper–crustal extension consisted of initial, locally source nonmarine facies (Girón Group) followed by regional accommodation with widespread marine conditions.

The Late Cretaceous history (Figure 8a) involved a shift to a neutral tectonic regime in which basin subsidence was no longer controlled by individual faults, but was governed by regional postextensional cooling of lithosphere and associated thermal subsidence. The dominant sediment source regions throughout Jurassic – Cretaceous basin evolution were situated to the east, in the Guiana Shield. Clastic detritus derived from cratonic crystalline basement (900–1800 Ma) was transported westward to principally marine deposystems.

The Maastrichtian – Paleocene (Figure 8b) marked the initial topographic emergence of the Colombian Andes and a fundamental reorganization of paleodrainage systems in northwestern South America (Horton, 2018a). The abrupt reversal in sedimentary polarity from west–directed to east–directed drainage coincided with the appearance of detritus from the Andean magmatic arc (<200 Ma zircons from the Central Cordillera; Figure 6), accelerated accumulation rates in the Magdalena Valley (Figure 5), and a regional shift from marine to nonmarine conditions (Figure 4). This episode marks the first major Andean shortening, crustal loading, and flexural subsidence in Colombia, with reverse/thrust faulting limited to the Central Cordillera, and locally, to the Magdalena Valley, as suggested by Paleocene – early Eocene cooling. The reversal in sedimentary polarity appears to have been time transgressive, with a Maastrichtian – early Paleocene age in the Magdalena Valley and Eastern Cordillera, ca. 30 my prior to the reversal in the Llanos region. This dynamic pattern, as reflected in three sedimentary "petrofacies" indicative of direct input from either the Central Cordillera, Eastern Cordillera, or craton (Figure 4) requires the eastward advance of an effective drainage axis separating western (Andean) from eastern (cratonic) contributors of sediment (Silva et al., 2013; Reyes–Harker et al., 2015).

During Eocene – Oligocene time (Figure 8c), the regionally contiguous foreland basin system that spanned from the Magdalena to Llanos provinces was partitioned by a series of fault–related uplifts within the Eastern Cordillera. These structures commonly include former normal faults reactivated during Andean shortening, inducing basin inversion and severing the topographic and depositional continuity among the Magdalena, Eastern Cordillera, and Llanos basins. Evidence for this phase of basin compartmentalization comes from the progressively greater contributions of detritus from the Eastern Cordillera, in the form of Eastern Cordillera basement (450–650 Ma) and recycled cratonic (900–1800 Ma) grains from the thick widespread cover succession spanning the Eastern Cordillera (Figure 6). Although this period marks the initiation of the Magdalena Valley as a hinterland basin, the axial Eastern Cordillera persisted as a low subsiding region, with an intermontane basin system (Floresta Basin) with potential minor depositional links with the Llanos foreland basin farther east.

The final Miocene to Quaternary phase (Figure 8d) reflects the final establishment of the Eastern Cordillera in the form observed today. By the end of the Paleogene, substantial shortening had ceased in the Central Cordillera, yet the range persisted as an intermittent sedimentary source to the Magdalena Valley. Full emergence of the Eastern Cordillera led to the termination of subsidence in its axial zone (Floresta Basin) and the establishment of elevated topography that served as an orographic barrier and dominated sediment delivery to the Llanos Basin. This stage in the evolution of the northern Andes also coincides with accelerated accumulation rates in the Llanos Basin (Figure 5), attributable to shortening and crustal loading within the Eastern Cordillera.

The proposed reconstruction (Figure 8) focuses on the construction of the Eastern Cordillera of Colombia, from the perspective of the sedimentary record and supportive thermochronometric data, and their utility as an archive of tectonic processes associated with contractional mountain building. However, important along–strike variations are expressed in the northern Andes, such that the Ecuadorian Andes to the south experienced substantially lower degrees of shortening, thrust–front advance, and basin compartmentalization (Aleman & Ramos, 2000; Ruiz, 2002; Baby et al., 2004; Vallejo, 2007; Horton, 2018a). Within a broader, continental–scale framework, the issues discussed here have further implications for the evolution of major paleodrainage systems in South America, including the Magdalena, Orinoco, and Amazon river systems (Hoorn et al., 2010, 2017; Mora et al., 2010a; Horton et al., 2015; Anderson et al., 2016).

4. Conclusions

The tectonic history of the Eastern Cordillera in the northern Andes of Colombia is largely contained in the clastic sedimentary record preserved in three principal regions (from west to east): the Magdalena Valley Basin, the Eastern Cordillera (notably axial basins such as the Floresta Basin), and the Llanos Basin. We find several critical elements in the long–lived stratigraphic record of Colombia. These include: (i) stratigraphic correlations and deposystems, (ii) sediment accumulation histories, and (iii) sediment provenance. These three elements are represented by observational and laboratory–generated data that are similarly retrievable from many sedimentary basins in tectonically active regions.

A Mesozoic – Cenozoic history of marine and nonmarine sedimentation affected the Eastern Cordillera and flanking Magdalena Valley Basin and Llanos Basin during contrasting tectonic regimes. (i) Jurassic to earliest Cretaceous extension led to the development and linkage of extensional sub–basins (commonly half graben features governed by normal faults) in selected regions. (ii) A subsequent phase of postextensional thermal subsidence generated a thermal sag basin across a broader region. (iii) In latest Cretaceous to Paleocene time, initial crustal shortening in the Central Cordillera created a regional flexural basin that was successively broken by the Paleocene – Oligocene emergence of thrust/reverse–fault related uplifts within the Eastern Cordillera and the partitioning of the original regional basin into the Magdalena hinterland basin and Llanos foreland basin. (iv) Major Neogene uplift and establishment of an effective topographic barrier occurred as continued shortening (commonly involved contractional reactivation of preexisting normal faults) became focused along the bivergent eastern and western flanks of the fold–thrust belt comprising the Eastern Cordillera. Fundamentally, (i) regional stratigraphic correlations, (ii) sediment accumulation histories, (iii) sediment provenance data, and (iv) supporting thermochronometric data help identify shared and divergent stratigraphic histories during progressive basin compartmentalization, changes in sediment source regions, and the evolution of paleodrainage patterns during changing tectonic regimes.

Acknowledgments

This research was supported by a collaborative research agreement between Ecopetrol's, Instituto Colombiano del Petróleo (ICP), and the University of Texas at Austin, within the framework of ICP project "Cronología de la deformación en las cuencas subandinas". Additional support was provided by U.S. National Science Foundation grants EAR–1019857 and EAR–1338694, and FAPESP (São Paulo Research Foundation) grant 2013/03265–5. We thank Cristian VALLEJO and the editorial board for helpful comments that improved the presentation.

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