Chapter 1

Stratigraphy and Tectonics of the Neogene and Quaternary of the Cauca Basin of Colombia

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Abstract The Cauca River valley is a Cenozoic intermountain basin with a tectonic history characterized by the alternation between compressional and extensional phases. Here, two new radiometric ages of La Paila Formation (10.5 ± 0.4 Ma and 4.4 ± 0.07 Ma Ar/Ar in amphibole) are used as a reference to deduce the tectonic events that occurred in the Miocene – Quaternary interval. The Miocene – Pliocene La Paila Formation is a continental unit deposited during an initial extensional phase under the influence of arc volcanism and a compressional final stage. The overlying units, i.e., the Pleistocene Zarzal Formation and Quaternary deposits, record the compressive tectonic activity that started after the formation of the Panamá Isthmus. The current deformation is registered in the Buga Salient by a series of west–vergent thrust faults that are narrowing the present Cauca River valley. This salient is proposed as the western termination of the Ibagué Fault. The most recent manifestations of this deformation are the folds on Quaternary alluvial fans, which involve Holocene paleosols, and the liquefaction of the deposits of the Zarzal Formation, which affects the overlying Quaternary deposits. On the Western Cordillera, a predominantly transcurrent tectonic style characterizes the recent deformation. It is proposed that the structure of the most recent deformation has occurred due to the indentation of a shallow continental wedge that has been introduced below the Cretaceous basement of the valley.

Keywords: *La Paila Formation age, tectonic inversion, blind thrusts, liquefaction, Quaternary asymmetric folds.*

Resumen El valle del río Cauca es una cuenca intramontana cenozoica con una historia tectónica que alterna entre fases de compresión y de extensión. Dos nuevas edades radiométricas de la Formación La Paila (10,5 ± 0,4 Ma y 4,4 ± 0,07 Ma Ar/Ar en anfíbol) se utilizan como referencia para deducir los eventos tectónicos que ocurrieron durante el intervalo Mioceno–Cuaternario. La Formación La Paila, de edad miocena–pliocena, es una unidad continental depositada durante una fase inicial distensiva bajo influencia de vulcanismo de arco y una etapa final compresiva. Las unidades suprayacentes, Formación Zarzal de edad pleistocena y depósitos del Cuaternario, registran la actividad tectónica compresiva que se inició posterior a la formación del Istmo de Panamá. La deformación actual se registra en la Saliente de Buga por una serie de cabalgamientos de vergencia al oeste que van estrechando el valle actual del río Cauca. Esta saliente se propone como la terminación occidental de la Falla de Ibagué. Las manifestaciones más recientes de esta deformación son pliegues en abanicos aluviales del Cuaternario, los cuales involucran paleosuelos del Holoceno, y licuación de depósitos de la For-

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mación Zarzal, que afecta los depósitos cuaternarios suprayacentes. En la cordillera Occidental, la deformación reciente se caracteriza por un estilo tectónico predominantemente transcurrente. Se propone que la estructura de la deformación actual ha ocurrido por la indentación de una cuña continental superficial que se introduce por debajo del basamento cretácico del valle.
Palabras clave: *edad Formación La Paila, inversión tectónica, cabalgamientos ciegos, licuación, pliegues asimétricos cuaternarios.*

1. Introduction

The main purpose of this chapter is to present a review of the Cenozoic geology of the Cauca Basin, between Popayán y Cartago, and to present some unpublished data in order to show the progress that has been made in understanding the relationships between the sedimentation of a Miocene unit and the more recent tectonic activity in the Cauca valley of Colombia. A sector that currently remains controversial is related to the stress field around the latitude of 4° N (Figure 1).

The Cauca River flows in one of the main intermountain valleys of Colombia (Figure 2). Between the Western and Central Cordilleras, a narrow corridor of tectonic origin causes the river to flow from south to north until reaching the Magdalena valley. Between Jamundí and Cartago, the alluvial floodplain of the valley is gently inclined toward the north due to the episodic overflows of the Cauca River.

In the plain sector called "Plano de Cartago" by Stutzer (1934), the Cauca River is pushed against the Western Cordillera due to the progradation of coalescent alluvial fans from the Central Cordillera as well as to the advance of west–vergent thrusted slices at the "Buga Salient" (López, 2006; López & Audemard, 2011; López et al., 2009a). Around 4° N, the valley reaches its minimum width at the Buga Salient (Figures 1, 2).

The Cauca River valley has been a tectonically active intramountain basin during the Neogene, i.e., at least since 21 Ma (7 anomalies) (e.g., Nivia, 2001), and it is mainly bordered to the west and east by basaltic flows and marine sedimentites of Cretaceous age. Between Buga and Cartago, the basin preserves sedimentary units of Neogene age exposed in the western flank of the Central Cordillera (Figure 3). The history of this basin during the Paleogene has not yet been well established.

The Cali–Patía Basin (Figure 2; sensu Pérez–Tellez, 1980), which is filled with Paleogene sedimentites, is now exposed in a structure that developed under the influence of an oblique tectonic regime (Campbel & Velasco, 1965; Case et al., 1971). The beginning of the current quasi–orthogonal convergence, ca. 26 Ma, gave rise to Andean arc volcanism (Pilger, 1983; Somoza & Ghidella, 2005), which is a conspicuous feature present in the Cauca valley and is characterized by tuffaceous layers and other volcanic deposits. The basement of the Western Cordillera, as well as the sedimentary units in the Cali–Patía Basin, are cross–cut by early Miocene intrusive bodies (diorites, dacites, and andesites; Hubach & Alvarado, 1934). The main parts of the formations included in this basin have alluvial and coastal origins, and according to palynological data, they are of Paleogene age.

Presently, this basin is a syntectonic basin (sensu Einsele, 1992) considering the contemporaneity of tectonics and sedimentation that is characterized by faulting at its margins (López & Moreno–Sánchez, 2005; López et al., 2009a).

The continuity of the Cenozoic units between the Cartago–Buga and Cali–Popayán sectors is not well known. These basins may have been independent sedimentary basins during the Cenozoic or even a part of a larger basin. Some authors (Barrero & Laverde, 1998; Keith et al., 1988; Nivia, 2001; Schwinn, 1969) have assumed that both areas belonged to the same basin; following this reasoning, it is common to find composed stratigraphic columns featuring stacking units from both basins (Table 1).

On the other hand, around a latitude of 4° N, a lateral change in the stress regime defines a transition zone, which is characterized by geodetic measures (Figure 2 Freymueller et al., 1993; Trenkamp et al., 2002), the kinematics of the faults parallel to the mountain ranges (Ego et al., 1995; James, 1985; Toussaint & Restrepo, 1987), volcanic gaps (Hall & Wood, 1985), the paleomagnetism of intrusive bodies (MacDonald et al., 1996), tomography (Taboada et al., 2000), superficial seismicity (Corredor, 2003; Meyer & Mejía, 1995), tectonic deformation (López, 2006; Montes et al., 2003), and paleoseismicity (López et al., 2003; López & Audemard, 2011).

East–west compression and prehistoric earthquakes of Ms ≥ 7 on thrust faults, with a recurrence interval of 6 ky, have been recorded at the Buga Salient, which has been proposed to be the western termination of the Ibagué Fault (López et al., 2003; López, 2006; López & Audemard, 2011). The Ibagué Fault is a Riedel system with left steps between the main right–lateral strike–slip segments; its paleoseismic behavior corresponds to a maximum magnitude of Ms 7 ± 0.1 for a return period of 1300 y and a mean slip–rate velocity of 0.77 mm/y (Montes et al., 2005a, 2005b; Osorio et al., 2008). Evidence from the eastern termination and displacement of the Ibagué Fault was documented by Montes et al. (2003) at the Piedras–Girardot fold belt. Based on the analysis of the shallow seismicity of the Harvard centroid moment tensor (CMT), Corredor (2003) argued that the Ibagué Fault is a transfer zone between two blocks with different seismic behaviors.

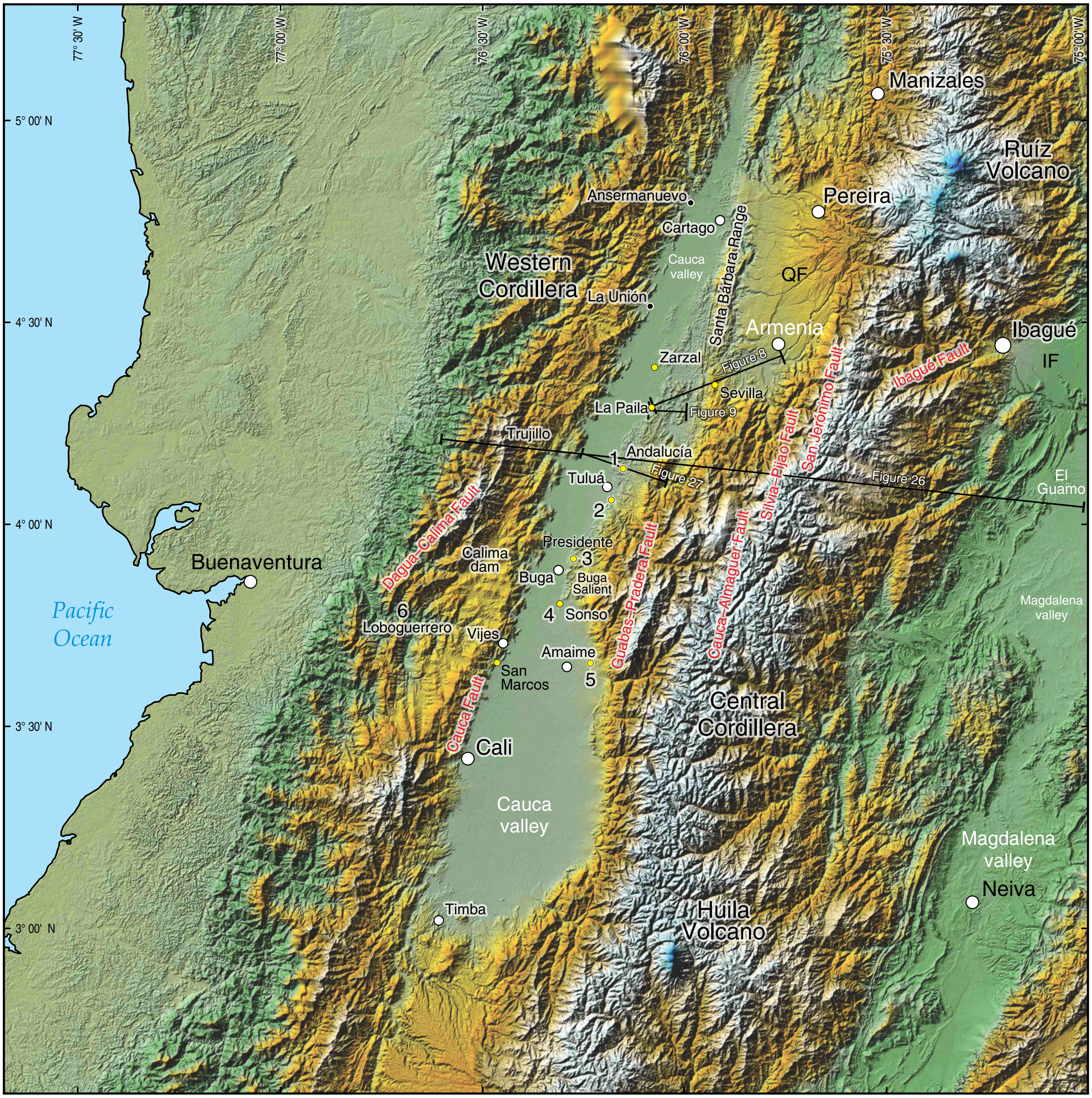

Figure 1. Location of the study area. (QF) Quindío fan; (IF) Ibagué alluvial fan. **(1)** Andalucía Anticline. **(2)** Tuluá. **(3)** Presidente. **(4)** Sonso Anticline. **(5)** Venecia trench. **(6)** Loboguerrero trench.

This analysis focuses on the lithological units cropping out along the western flank of the Central Cordillera, in an elongated N–S area between the towns of Cartago, Buga, and Amaime (Figure 3). These units were referenced by the Servicio Geológico Colombiano (Nivia, 2001) as the Cinta de Piedra, La Paila, and La Pobreza Formations. Some new stratigraphic, structural, and radiometric data were collected, processed, and analyzed by Universidad de Caldas for the Agencia Nacional de Hidrocarburos (ANH) (Contrato 031 de 2008) and presented in an extensive document by López et al. (2009b).

2. Materials and Methods

Five sections were chosen to analyze the characteristics of La Paila Formation (Figure 2). The locations of samples used for petrographic, radiometric, and pollen data, as well as fa-

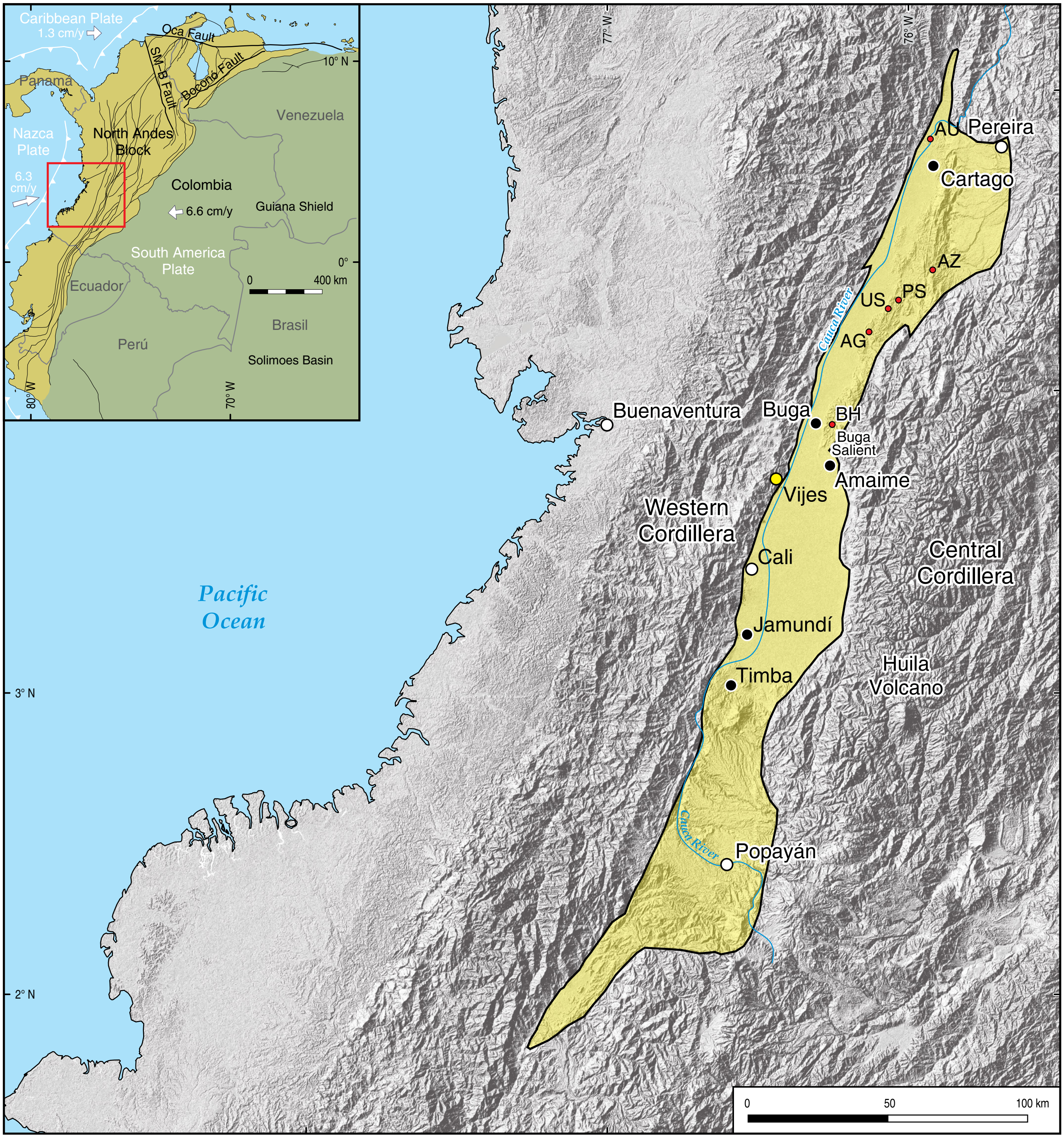

Figure 2. Location of the Cauca Basin. South and north of Vijes, the basin is divided into the Cali–Patía and Buga–Cartago Basins. Upper left: Tectonic map of Colombia and geodesic measurements of displacement by Freymueller et al. (1993). Location of stratigraphic columns and samples: (AZ) Armenia–Zarzal, (PS) La Paila–Sevilla, (US) La Uribe–Sevilla, (AG) Andalucía–Galicia, (BH) Buga–La Habana , (AU) Ansermanuevo–La Unión.

cies analysis, are presented on the stratigraphic columns and geological maps (see López et al., 2009b). Palynological analyses were performed by the Smithsonian Tropical Research Institute, and radiometric analyses of Ar/Ar were performed in the Laboratory of Geochronology of the Sernageomin in Chile.

Table 1. Stratigraphic units in the Cauca Basin according to different authors.

Period	Epoch	van der Hammen (1958) quote to Nelson (1957)	van der Hammen (1958) sensu Nivia (2001)	Schwinn (1969b)	van der Hammen (1958) sensu De Porta (1974)	Hubach & Alvarado (1934) sensu De Porta (1974)	Hubach & Alvarado (1934) sensu Keith et al. (1988)	Aspden (1984)	Keit et al. (1988) (south – Valle del Cauca – north)	Ríos & Aranzazu (1989)	Nivia (2001)
Q	Holocene Pleistocene			Popayán Formation				Jamundí Formation	Popayán Formation; Jamundí Formation; Zarzal Formation	Armenia Formation Zarzal Formation	
Neogene	Pliocene										
Neogene	Miocene	La Paila Formation: Upper La Paila; Lower La Paila	Combia Group: Combia Formation; La Paila Formation Cauca Group – Upper Cauca Formation: Cinta de Piedra Member	Valle Group: Buga Formation; Cartago Formation; Vijes Formation	Galeón Formation La Paila Formation		Piso de Combia Piso de Cinta de Piedra	Vijes Formation	La Paila Formation	La Paila Formation	Valle Group: La Pobreza Formation; La Paila Formation; Cinta de Piedra Formation; Vijes Formation
Paleogene	Oligocene	Upper Cauca Formation	Patía Member Suárez Member		Cauca Group – Upper Cauca Fm.: Cinta de Piedra Mbr.; Patía Member; Suárez Member Middle Cauca Formation: La Rambla Member	Piso de Cinta de Piedra Cauca Group – Conjunto Teteral o superior: Horizonte del Coche; Horizonte Santa Marta	Piso del Cauca – Conjunto Teteral o superior: Horizonte del Coche; Horizonte Santa Barbara	Cauca Group – Ferreira Formation: Cabrera Member; Suarez Member	Cauca Group: Guachinte/ Ferreira Formations; Cinta de Piedra Formation	Cartago Formation: Miravalles Member; Piedras de Moler Member; La Rivera Member	Cauca Group – Ferreira Formation: Cabrera Member; Suárez Member
Paleogene	Eocene	Middle Cauca Formation	Middle Cauca Formation: La Rampla Member; Timba Member Lower Cauca Formation: La Cima Member	Cauca Group: Jamundí Formation; Guachinte Formation; Uribe Formation	Timba Member Lower Cauca Formation: La Cima Member; Ampudia Member	Horizonte Mangó Conjunto de Cali o medio: Horizonte Los Hilos; Horizonte Los Chorros; Horizonte La Salvajilla	Horizonte Mangó Conjunto de Cali o medio: Horizonte Los Hilos; Horizonte Los Chorros; Horizonte La Salvajilla Conjunto Los Confites o inferior	La Rampla Member Guachinte Formation: Los Chorros Member; La Cima Member; Loma Larga Member	Vijes Formation		Guachinte Formation: La Rampla Member; Los Chorros Member; La Cima Member
Paleogene	Paleocene	Lower Cauca Formation Nogales Formation	Ampudia Member Nogales Formation		Nogales Formation	Conjunto Los Confites o inferior		Chimborazo Formation; Confites Member; ? Ampudia Fomation	Chimborazo Formation Basal Quartz		Chimborazo Formation: Loma Larga Member; Confites Member
Cretaceous		Diabase Group	Diabasic Group	Diabase Group Dagua Group	Diabasa Group	Diabásico Group	Faldequera Serie Piso del Espinal Dagua Serie	Volcanic Formation (Espinal Formation) (Cisneros)	Western Cordillera: Espinal Fm.; Volcanic Fm.; Cisneros Fm.; Consolida Fm.; Lázaro Fm.; Ampudia Fm. Central Cordillera: Amaime Fm.; Nogales Fm.; Macizo Ofiolítico de Ginebra Formation	Buga Batholith Amaime Formation	PLOCO

(Q) Quaternary; (Mbr.) Member; (Fm.) Formation; (PLOCO) Spanish acronym for “Provincia Litosférica Oceánica Cretácica Occidental”.

Neogene Quaternary

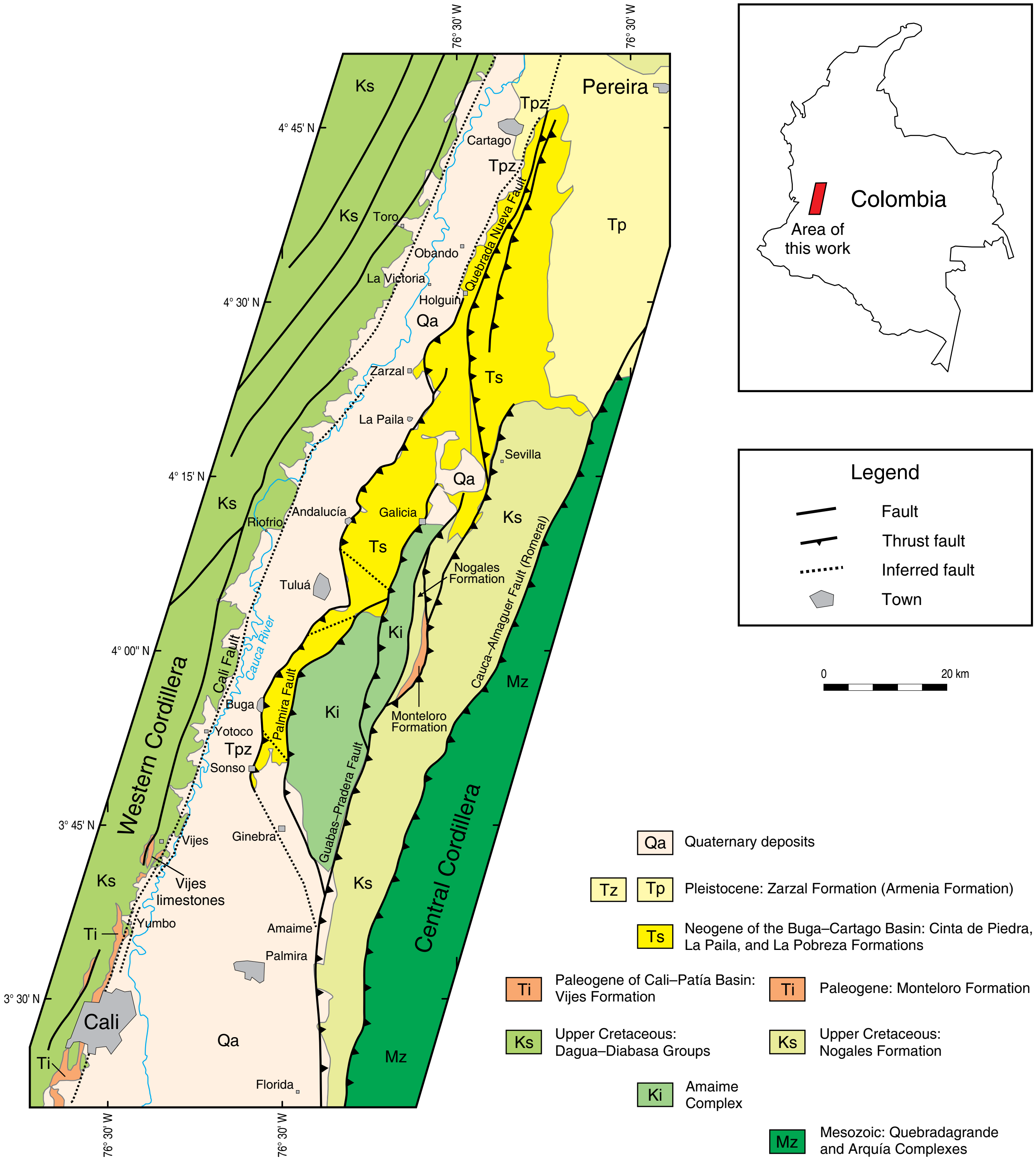

Figure 3. Geological map of the Cauca River valley between Cali and Cartago. In the recent river basin, two relict basins can be identified: the Cali–Patía Basin and the Buga–Cartago Basin. The first is of Paleogene age, and the second is filled with Miocene and Pliocene sedimentites. The Paleogene units of the Cali–Patía Basin include the Chimborazo, Guachinte, Ferrerira, and Calizas de Vijes Formations. The Monteloro Formation is part of the Buga–Cartago Basin. Based on Barrero & Laverde (1998), Nivia et al. (1992), Moreno–Sánchez & Pardo–Trujillo (2003), López (2006), and López et al. (2009a, 2009b).

3. Geology of the Cauca Basin

The Cauca Basin is divided in this work into the Cali–Patía and Buga–Cartago Basins, which are located to the south and north of Vijes, respectively (Figure 2). Here, these units are described chronologically, ranging from the older rocks located in the Central Cordillera to those in the Western Cordillera, and then to the Paleogene rocks in the south in the Cali–Patía Basin through the Neogene rocks to the north in the Buga–Cartago Basin.

3.1. Mesozoic Rocks of the Central Cordillera–Amaime Sector

The basement of the Cauca Basin has a Cretaceous age and correlates to the Amaime–Chaucha Complex (sensu Moreno–Sánchez & Pardo–Trujillo, 2003), which extends from Ecuador (Chaucha Terrane of Litherland & Aspden, 1992) through the Valle del Cauca Department (Amaime Formation of McCourt & Aspden, 1984).

Amaime Formation

The name of the Amaime Formation was proposed by McCourt & Aspden (1984) to designate a set of basic volcanic rocks cropping out at the western flank of the Central Cordillera in the Valle del Cauca Department. This unit consists of a series of massive tholeiitic basalts with abundant layers of pillow lavas. Locally ultramafic lavas have been reported (Spadea et al., 1989). The eastern limit of these volcanics corresponds to the Cauca–Almaguer Fault (Figures 1, 3), which defines the western border of the Arquía schists. The Amaime Formation is cross–cut by granitoids with ages that place them in the middle Cretaceous (Maya, 1992).

Ginebra Ophiolitic Massif

On the western flank of the Central Cordillera, ultramafic rocks are present in an elongated N–S block that is 40 km long and 8 km wide, which is located to the east of the towns of El Cerrito, Ginebra, Buga, San Pedro, Tuluá, and Andalucía. A sequence of peridotites, cumulitic banded gabbros, metabasalts, tuffs, microbreccias, and hyaloclastites were reported by Espinosa–Baquero (1985). According to Ossa–Meza & Concha–Perdomo (2007), the Ginebra Ophiolitic Massif and the Amaime Formation have a genetic relationship in a normal mid–ocean ridge basalt (N–MORB) environment.

Nogales Formation

This unit was defined by Nelson (1957), and it crops out along the Tuluá River and the Nogales Creek in the Tuluá municipality (Figures 1, 3). It is composed of chert, sandstones, and conglomerates. Crustal blocks of similar composition are present to the north and south of the type section and are related to the basalts of the Amaime Formation. Geochemical analyses indicate that the basalts associated with the Nogales Formation are similar to those of the Western Cordillera and likely originated in oceanic plateaus (Kerr et al., 1999).

Nivia (2001) incorporated the Nogales Formation and the Dagua Structural Complex in the PLOCO (the Spanish acronym for "Provincia Litosférica Oceánica Cretácica Occidental"), an entity that presumably developed in an oceanic plateau. He concluded, based on chronologic and paleontological considerations, that the age of this province is younger than the Turonian. Nevertheless, the Nogales Formation is underlain by basalts and has a biochron narrower than those of the other rocks of the PLOCO; therefore, the age defined by ETAYO–SERNA is Campanian (Blau et al., 1995; Etayo–Serna, 1985a; Etayo–Serna & Gaona, 2003; Moreno–Sánchez & Pardo–Trujillo, 2003; Pardo–Trujillo et al., 1993, 2002).

Venus Ultramafic Complex

Vergara (1989) defined a series of ultramafic and mafic rocks exposed in the Morales River, near the towns of Venus and La Moralia (Tuluá municipality), as the Venus Ultramafic Complex. These rocks crop out in an elongated N–S block that is 13 km long and 1.5 km wide and is imbricated between the Amaime and Nogales Formations (Figure 3) close to (1 to 2 km) and east of the Ginebra Ophiolitic Massif. This complex is composed of gabbros, serpentinites, and peridotites.

Buga Batholith

The Buga Batholith crops out in the Buga, San Pedro, and Tuluá municipalities, conforming to the western foothills of the Central Cordillera. The ultramafic rocks and basalts of the Ginebra Ophiolitic Massif are intruded by this body, although their main contact with the basalts is faulted in the eastern region by the Guabas–Pradera Fault (Figure 1). The area of this intrusive contact is invaded by numerous veins and dikes.

The Buga Batholith is a calc–alkaline granitoid (Aspden et al., 1987) whose composition varies from a hornblende quartz diorite to a tonalite with sectors of hornblende diorite present toward the western contacts with the metabasalts of the Ginebra Ophiolitic Massif. This batholith is not foliated, although it presents a banded zone containing abundant mafic xenoliths of basic rocks. Radiometric data indicate that this body was intruded during the Early Cretaceous (Brook, 1984; McCourt et al., 1984a; Toussaint et al., 1978). Nivia et al. (2006) considered this interpretation of the age "problematic"; they assumed that the Upper Cretaceous basalts situated to the east of the Guabas–Pradera Fault must be chronologically equivalent to those situated to the west of the same large structure, where basalts or metabasalts are intruded by a granitoid (dated at 99 ± 4 Ma by whole–rock Rb/Sr analysis; McCourt et al., 1984a).

Porphyritic Andesites

Scattered along the Central Cordillera, dikes and sills that are andesitic to dacitic in composition, with porphyritic textures, follow the main N–S–trending fault lineaments defining the contacts between the metamorphic units. The concordant radiometric age (K/Ar in hornblende and biotite) of 18 ± 1 Ma (Brook, 1984) obtained in the dikes of this series, locally known as La Albania west of Ginebra town, is taken as representative of the age of this intrusion. A younger age (12 ± 1 Ma, K–Ar hornblende age) of a similar dike, located 3–4 km west of La Albania sample, is indicative of more than one period of intrusive activity.

Arquía Complex

A complicated mixture of metamorphic and sedimentary rocks crops out to the east of the Cauca–Almaguer Fault (Romeral Fault in some studies) (Figures 1, 3). These rocks were included in the Arquía Complex by Maya & González (1995). Although it is heterogeneous, this strip of rocks can be followed from the north in Antioquia until reaching the Guayaquil Gulf in Ecuador (Moreno–Sánchez & Pardo–Trujillo, 2003). The Arquía Complex is the most heterolithic series in western Colombia, with igneous, metamorphic, and sedimentary protoliths and complicated structural settings (Hincapié & Moreno–Sánchez, 2001). The main lithologies that have been reported inside this complex are undeformed granitoids (“gneisses” according to some authors), metagabbros, and graphitic and sericitic schists, amphibolites, and quartzites. Locally, sedimentary rock wedges with fossil remnants suggest a Late Cretaceous age (Gómez–Cruz et al., 2002). On the geological map of the northern part of the Cauca valley (de Armas, 1985; McCourt, 1984; McCourt et al., 1984b), three lithological units are recognized as part of this complex: the Bugalagrande Basic Schists, Rosario Amphibolites, and Bolo Azul Metagabbroids.

According to McCourt (1984), the main rock units of the Arquía Complex in the northern sector of the Cauca valley and in the southern part of the Quindío Department were metamorphosed to amphibolite facies under medium–pressure conditions (Barrovian). Southwest of Medellín, the intrusion of the Sinifaná metasedimentites by the “Amagá Stock” suggests that some lithodems of the Arquía Complex could be Paleozoic in age (Pérez, 1967; Restrepo et al., 1991; Vinasco et al., 2006).

The Santa Bárbara Batholith, which is located to the east of Palmira, is frequently cited as a Triassic intrusion that cross–cuts the rocks of the Arquía Complex. Recently, these rocks were included as Paleogene bodies in the Geological Map of Colombia (Gómez et al., 2015), which is consistent with the arguments presented by Restrepo et al. (2009). Radiometric data suggest that a substantial amount of these rocks were metamorphosed or thermally affected around the Early Cretaceous, indicating that the ages of lithologies and their protoliths are not yet well established (Moreno–Sánchez et al., 2008).

Quebradagrande Complex

To the east of the Arquía Complex, in contact with the Silvia–Pijao Fault (Figure 1), the Quebradagrande Complex (Maya & González, 1995) exhibits outcrops of basalts and sedimentary rocks of bimodal origin, i.e., a continental platform origin to the east and a seafloor volcanic arc origin to the west (Gómez–Cruz et al., 1995; Moreno–Sánchez et al., 2008). This complex was given its name based on the Quebradagrande Formation located to the north and west of Medellín by Botero (1963). The age of this complex falls within the Early Cretaceous according to fossils collected around the Manizales, Pácora, San Félix, and Arma towns (Botero & González, 1983; Etayo–Serna, 1985b; Gómez–Cruz et al., 1995). Geological and geochemical data indicate that the rocks of this complex accumulated in a marginal basin close to an island arc (Álvarez, 1995; Moreno–Sánchez & Pardo–Trujillo, 2003; Nivia et al., 2006).

Cajamarca Complex

In the Central Cordillera, the Cajamarca Complex includes the metamorphic lithodems located between the San Jerónimo Fault (Figure 1) to the west and the Otú–Pericos Fault to the east (Maya & González, 1995). It crops out along the eastern border of the Valle del Cauca Department in a NE–SW elongated domain that is 150 km in length.

The Cajamarca and Quebradagrande Complexes are in contact in a sector where the metamorphism of both entities masks their structural relationships, although Maya & González (1995) assumed that the San Jerónimo Fault represents the limit of this metamorphism.

The rocks of the Cajamarca series of Nelson (1962) cropping out in the Ibagué–La Línea highway include the Cajamarca Complex (sensu Maya & González, 1995) and the metamorphic rocks of an area that extends to the north in the Central Cordillera. The most common lithologies in this complex are sericitic schists, greenschists, black schists, quartzites, and slates. Some mylonitic bands have been called “gneisses” by some authors (Barrero & Vesga, 1976). According to radiometric data, the age of the metamorphism in this complex can be set in the Late Jurasic (Blanco–Quintero et al., 2014), in contrast with the previously established age of late Paleozoic (e.g., Vinasco et al., 2006). Both the Arquía and Quebradagrande Complexes are affected by dynamic metamorphism, which is concentrated in narrow elongated areas that are often mapped as regional metamorphic rocks (Gómez–Cruz et al., 1995; Nivia et al., 2006). All of the complexes mentioned in the Central Cordillera are cross–cut by Cenozoic bodies and Neogene hypabyssal intrusions.

3.2. Upper Cretaceous Rocks –Western Cordillera–

There are no reliable data showing the existence of rocks that are older than the Late Cretaceous in the Western Cordillera. The fossils found in this cordillera yield Aptian to Maastrichtian ages (see Nivia, 1996).

Basalts and diabases interbedded with the sedimentary units of the Diabasic Group crop out to the west of the faults bordering the Western Cordillera with the Cauca River valley. Geochemical data indicate that these thick accumulations of submarine basalts were produced in oceanic plateaus (PLOCO in Nivia, 1989, 1994). The "Formación Volcánica" was suggested by Aspden (1984) as a substitute for the Diabasa Group, which would include all basic effusive rocks of the Western Cordillera; on the other hand, the thicker sedimentary bodies that seem to overlie the Diabasa Group (Barrero, 1979) were included in the Dagua Group by Nelson (1957) (Figure 3).

Barrero (1979) divided the Dagua Group into the Espinal Formation and the Cisneros Formation. The former constitutes cherts, black shales, sandstones, and some limestones; the latter constitutes metasedimentary rocks such as metacherts, phyllites, and slates. The fossils found in the Diabasic and Dagua Groups point to a Late Cretaceous age (Nivia, 1996).

Gabbros and ultrabasites are related to the effusive basic rocks (e.g., Bolívar Ultramafic Complex) that represent ophiolitic suites produced during the obduction of oceanic crust (Nivia, 1994). Additionally, the Western Cordillera is cross–cut by small igneous intrusions of intermediate composition with ages ranging between the Late Cretaceous and Cenozoic. Geochronological and geochemical data suggest that these rocks are linked to a Caribbean Plate origin (Kerr et al., 1997).

3.3. Cenozoic Rocks –Cali–Patía Basin–

A succession of Cenozoic sedimentary rocks is defined in the literature by its exploitable coal seal outcrops ranging from Vijes in the north to Popayán in the south. In a broad sense, these rocks belong to the Patía Sub–basin (sensu Barrero & Laverde, 1998) (Figure 2).

The sedimentary sequences in the Cali–Patía Basin (Figure 2) pre–date movements that formed some of the present mountain range structures; for that reason, they can be classified as pre–tectonic. This basin began as a larger syntectonic basin that was in communication with the Pacific Ocean and received sediments from the emerging orographic structures in the east. The reef limestones of the Vijes Formation (Figure 3) and submarine levels of the Guachinte (Leona horizon) and Ferreira Formations (San Francisco horizon) clearly show that the sea flooded a broad part of what now constitutes the Western Cordillera during the Oligocene (Dueñas et al., 2000; Nelson, 1957).

The main part of the formations included in this basin, which were deposited in coastal and/or fluvial environments, can be dated to the Paleogene according to pollen data. The earliest basin where the Paleogene sediments accumulated (and are now exposed in a structure of tectonic origin) was most likely developed under more oblique tectonic conditions than currently exist.

Paleogene and Neogene Units of the Buga–Cartago Basin

The tectonic structure that preserves the Cenozoic (Paleogene? – Miocene) sedimentary units exposed in the western flank of the Central Cordillera between Buga and Cartago is named the Buga–Cartago Basin in this chapter (Figure 2). In this basin, the Servicio Geológico Colombiano (McCourt, 1984; Nivia, 2001) defined its formations as follows: the Cinta de Piedra at the base, La Paila in the middle, and La Pobreza at the top (Figure 3; Table 1). The Monteloro Formation (Moreno–Sánchez & Pardo–Trujillo, 2003), which is also cited as the "intervalo clástico rojo", is a succession of Paleogene conglomerates and red beds that paraconformably overlies the sedimentites of the Nogales Formation (Pardo–Trujillo et al., 1993, 2002) and should be equivalent to the graywackes and conglomerates cropping out to the SW of Sevilla town, which Nelson (1957) included in the Upper Cauca Formation. The age suggested by Moreno–Sánchez & Pardo–Trujillo (2003) is Paleogene, but no biostratigraphic data have been presented.

The Cauca Group (Table 1; ex Piso del Cauca from Hubach & Alvarado, 1934) was proposed by van der Hammen (1958) to have three formations: the Lower Cauca, Middle Cauca, and Upper Cauca (Table 1). This unit unconformably overlies the Nogales Formation or the Diabasic Group and underlies the volcanic materials of the "Combia Group". The correlation chart of the "Graben Interandino Cauca–Patía" (Cauca–Patía Interandean Graben) presented by Nivia (2001) included the Nogales Formation in the Cauca Group located in the column of van der Hammen (1960) (Table 1). This correlation seems to be a reiterated mistake of the date because in the original document of van der Hammen (1958 (wrongly cited as 1960)), the Nogales Formation is outside the Cauca Group. van der Hammen (1958), in agreement with Stutzer (1934), correlated the Vijes Formation (limestones of Oligocene age) with the Middle Cauca Formation.

Schwinn (1969) identified three main Cenozoic sedimentary units in the Cauca valley, namely, the Cauca Group at the base, followed by the Vijes Formation and the Valle Group toward the top (Table 1; Buga–Cartago Basin in this work). In the Stratigraphic Lexicon, De Porta (1974) followed the proposal of Schwinn (1969) to define the sedimentites to the south of Vijes town as the Cauca Group and those to the north of it as the Valle Group. Schwinn (1969) stated that none of the type localities of the Cauca Group, which crop out to the south of Vijes and Buga in the Cauca Basin, exhibit equivalence with those of the Valle Group.

The age of the Cauca Group is Eocene according to microflora (pollen). The Vijes Formation is excluded from the Cauca Group according to a paleontological review performed by the Intercol staff (Schwinn, 1969). Aspden (1984) and Schwinn (1969) mistakenly concluded that the Vijes Formation represented a marine remnant of the Miocene; nevertheless, Nivia (2001) maintained the correlation of the Vijes Formation in accordance with them (Table 1).

Underlying the limestones of the Vijes Formation are the conglomerates ("Conglomerados de Vijes") of the Vijes Formation, which were included by Hubach & Alvarado (1934) in the Cinta de Piedra Formation. Although the name "Cinta de Piedra" originally comes from the "Piso Cinta de Piedra" that crops out to the west of Jamundí town, van der Hammen (1958) proposed the serranía de Santa Bárbara as the type locality NE of Zarzal town (the "NW" in the original is an error), and included it as a member of the Upper Cauca with the type localities of the other two members (Patía and Suárez) to the south of the Cauca Department.

The Neogene

The conglomerates described as the "Cinta de Piedra" in the serranía de Santa Bárbara by van der Hammen (1958) were included in the Cartago Formation by Schwinn (1969), who proposed the Valley Group based on the Intercol geologist nomenclature (Schwinn, 1969) and recognized two units, i.e., the Cartago Formation and the Buga Formation (Table 1).

In the Cartago Formation, Ríos & Aranzazu (1989) recognized three members (Table 1); the basal La Ribera Member is characterized by conglomeratic, coarse, and medium sandstones with high quartz contents. The middle Piedras de Moler Member is characterized by lithic sandstones of medium to fine grain size and green to gray color, and the upper Miravalles Member is characterized by sequences of conglomerates and coarse to medium sandstones. The lack of volcanoclastic deposits in the Cartago Formation is a distinctive feature. Therefore, the basal contact of the Cartago Formation (Cinta de Piedra Formation (sic)) was observed by Keith et al. (1988) to overlie the Buga Batholith and the Amaime Formation to the east of Tuluá and Bugalagrande. The upper contact of the Cartago Formation was described by Schwinn (1969) as the Buga Formation. According to Ríos & Aranzazu (1989), the age of the lower part of the Cartago Formation is early Oligocene; this age is based on palynological data analyzed by Bioss (1988) from the Piedras de Moler Member (Table 1).

The type locality of the Buga Formation was defined in the road cut parallel to the Guadalajara River east of Buga town (Valle del Cauca Department). It is composed of thick levels of lenticular conglomerates comprising pebbles of mainly igneous basic rocks, tonalities, quartz, chert, and metamorphic rocks. In the upper part, there are pieces of carbonized and petrified wood and some green–blue to green–brown claystone pebbles, which are usually carbonaceous, sandy, and locally calcareous.

Schwinn (1969) found equivalence between the Buga and La Paila Formations (sensu van der Hammen, 1958), and he assigned a middle Miocene age to the sedimentites cropping out in the Guadalajara road cut section. "La Paila Formation" was used for the first time in 1955 in an unpublished document of Keizer, H.W. Nelson, and T. H. van der Hammen (in van der Hammen, 1958). Later, Nelson (1957, 47) used the name "La Paila Formation" for the first time in a scientific article (recommendations in North American Commission on Stratigraphic Nomenclature, 2005) and divided it into two entities (Table 1): the Lower La Paila (with reworked tuffs; 200 m in thickness) and the Upper La Paila (with conglomerates, sandstones, and muddy sandstones; 400 m in thickness), indicating a Miocene age; in addition, this author suggested a syntectonic sedimentation origin for the Upper La Paila. De Porta (1974) returned to the proposal of Schwinn (1969) to define the sedimentites cropping out in the north of the basin as the Valley Group.

McCourt (1984) reported two outcrop sections of La Paila Formation: The Uribe–Sevilla section, which has a basal tuffaceous member, and the Guadalajara section, which has an upper conglomeratic member. In addition, he proposed that La Pobreza Formation to the north of Sevilla is a unit of local extension that unconformably overlies the Cinta de Piedra Formation and is covered by the ashes of the Armenia Formation. However, Keith et al. (1988) established that La Pobreza Formation (sensu McCourt et al., 1985) should be included in La Paila Formation (sensu van der Hammen, 1958) considering that in both units, the basal contact is erosive, the lithological characteristics are similar, and the environment of deposition is a humid alluvial fan.

Regardless, Nivia (2001) keeps the subdivisions defined by McCourt (1984) for the Cenozoic units in the Cauca valley (Table 1). He defined La Pobreza Formation as unconformably overlying the Cinta de Piedra Formation, although this contradicts a previous statement that La Pobreza Formation clearly unconformably overlies La Paila Formation (Nivia et al., 1992). In this same region, La Paila Formation unconformably overlies the Cretaceous basalts of the Amaime Formation.

van der Hammen (1958) defined the type locality of the Zarzal Formation to the E and NE of Zarzal town. This unit is composed of a succession of diatomites, claystones, and sandy tuffs unconformably overlying La Paila Formation. According to Nelson (1957), this lacustrine formation suffered only small dislocation effects and unconformably overlies the Upper La Paila sedimentites. The Zarzal Formation is mapped in the geological map of the Cauca valley (Nivia et al., 1992) in the northern part of the valley between the towns of Zarzal and Cartago. Cardona & Ortíz (1994) found the lacustrine sedimentites of the Zarzal Formation interfingered with the volcaniclastic sediments of the Quindío alluvial fan or the Armenia Formation (sensu McCourt, 1984); for that reason, they proposed maintaining the same nomenclature for both units. Afterwards, Suter et al. (2008a) found the Zarzal Formation on both sides of the serranía de Santa Barbara, and López et al. (2009a) reported a southern outcrop near the town of Presidente north of Buga. The Zarzal Formation contains an important volcanic phase whose age has traditionally been assigned to the late Miocene (Murcia, 1982; van Houten & Travis, 1968), although its interfingering with the volcaniclastic deposits of the Armenia Formation suggests a younger age. This was corroborated by Neuwerth et al. (2006) based on the presence of *Alnus* pollen in this unit.

The presence of the *Alnus* pollen in the Zarzal Formation indicates that at least its upper part is Pliocene in age (Suter et al., 2008a, 2008b). *Alnus* are trees of boreal origin whose arrival to Colombia has been dated to close to 1 Ma (Hooghiemstra, 1994a, 1994b; Hooghiemstra & Cleef, 1995; Hooghiemstra & Sarmiento, 1991; Hooghiemstra et al., 2006; van der Hammen & Hooghiemstra, 1997).

Although the area of Presidente was interpreted by Nivia (2001) as belonging to La Paila Formation, the more detailed analysis of these deposits indicates that the diatomites, tuffs, and lacustrine deposits, which mainly comprise clays with well–preserved fossil plants, are better correlated with the Zarzal Formation. In La Paila Formation, diatomite layers have never been reported. These deposits are overlain by gravels (López et al., 2009a).

On the other hand, in the analysis of the prospectivity of hydrocarbons in the Cauca Basin, Hincapié et al. (2009) summarized the main geological processes and distribution of unconformities along the Cauca Basin (Figure 4). They stated that the Chimborazo, Ferreira, Mosquera, Cinta de Piedra, and Guachinte Formations are potential reservoirs, while the volcaniclastic deposits, such as the Galeón and La Paila Formations, may be seals.

4. Tectonic Setting

The western margin of the Cauca River valley corresponds to a series of rectilinear staircased faults (Cali–Patía Fault) in contact with the alluvial plain that exhibit strike–slip displacement (Figure 5). Along the foothills of the Western Cordillera, the Cali Fault was mapped by McCourt et al. (1984a), and geophysical analyses performed by Bermúdez et al. (1985) confirmed that this fault borders Upper Cretaceous rocks. Based on the reverse faulting identified in the contact between the Vijes Formation and the basement, Alfonso et al. (1994) included this fault in the Tertiary fold and thrust belt defining the border with the Bolívar Ultramafic Complex and the Roldanillo and Santana Faults in Nivia (2001). Toward the axis of the Western Cordillera, the Dagua–Calima Fault defined by Barrero (1979) is in contact with a massive sequence of basalts comprising the eastern portion of the Western Cordillera. This fault was trenched by Woodward–Clyde Consultants (1983) and attributed to a sinistral component (Woodward–Clyde Consultants, 1983).

The eastern margin of the Cauca River valley, which is located between Vijes and Cartago, is more complex than the western margin (Figures 1, 3). To the east of Buga, Hubach & Alvarado (1934) described a frontal fault where Neogene sedimentites (La Paila and Zarzal Formations) are compressed against the ultramafic rocks, granitoids (Buga Batholith), and diabase rocks of the Amaime Formation (McCourt et al., 1985).

The main faults separating the lithological units on the western side of the Central Cordillera (Figures 1, 5) have a general NS orientation and are named the San Jerónimo, Silvia–Pijao, and Cauca–Almaguer Faults (sensu Maya & Gonzalez, 1995). These faults have been included in the Romeral Fault System, although they exhibit no relationship with the original denomination of Grosse (1926) of a segment of the fault cropping out in the Romeral ridge in the Antioquia Department.

Toward the west of the Cauca–Almaguer Fault, in the foothills of the Central Cordillera, there are other NNE–trending structures, such as the Guabas–Pradera, Palmira–Buga, and La Ribera–Galicia Faults. The Guabas–Pradera Fault was originally defined by de Armas (1985). This fault borders the western side of the volcanic Amaime Formation, which is in contact with the Neogene units. Alfonso et al. (1994) defined this fault as a west–vergent fault uplifting the "basement" core in the hanging wall. Moreno–Sánchez & Pardo–Trujillo (2003) defined an east–vergent fault at the western border of the sedimentites of the Nogales Formation (Figure 3). The Palmira–Buga and La Ribera–Galicia Faults, which were originally defined by Alfonso et al. (1994), form the western border of the Ginebra Ophiolitic Massif (Nivia, 2001).

In comparison with other basins in Colombia, the subsurface structure in the northern sector of the Cauca River valley is poorly understood. Only two seismic profiles have been performed by Ecopetrol in the northern part of the "Cauca Basin" between Yotoco and Cali (Figure 6; see Barrero & Laverde, 1998). Barrero & Laverde (1998) interpreted the imbricate west–vergent faults and folds parallel to the main frontal ranges, as well as the lesser degree of back thrusting in the Cauca Basin (between Cali and Cartago), which also passively deformed the Cenozoic section.

5. Results

This chapter summarizes the stratigraphic, geomorphic, and tectonic features of La Paila Formation in the western foothills of the Central Cordillera.

5.1. Facies and Age of La Paila Formation

La Paila Formation is characterized by polymictic conglomerates of massive to clast–supported gravel interbedded with

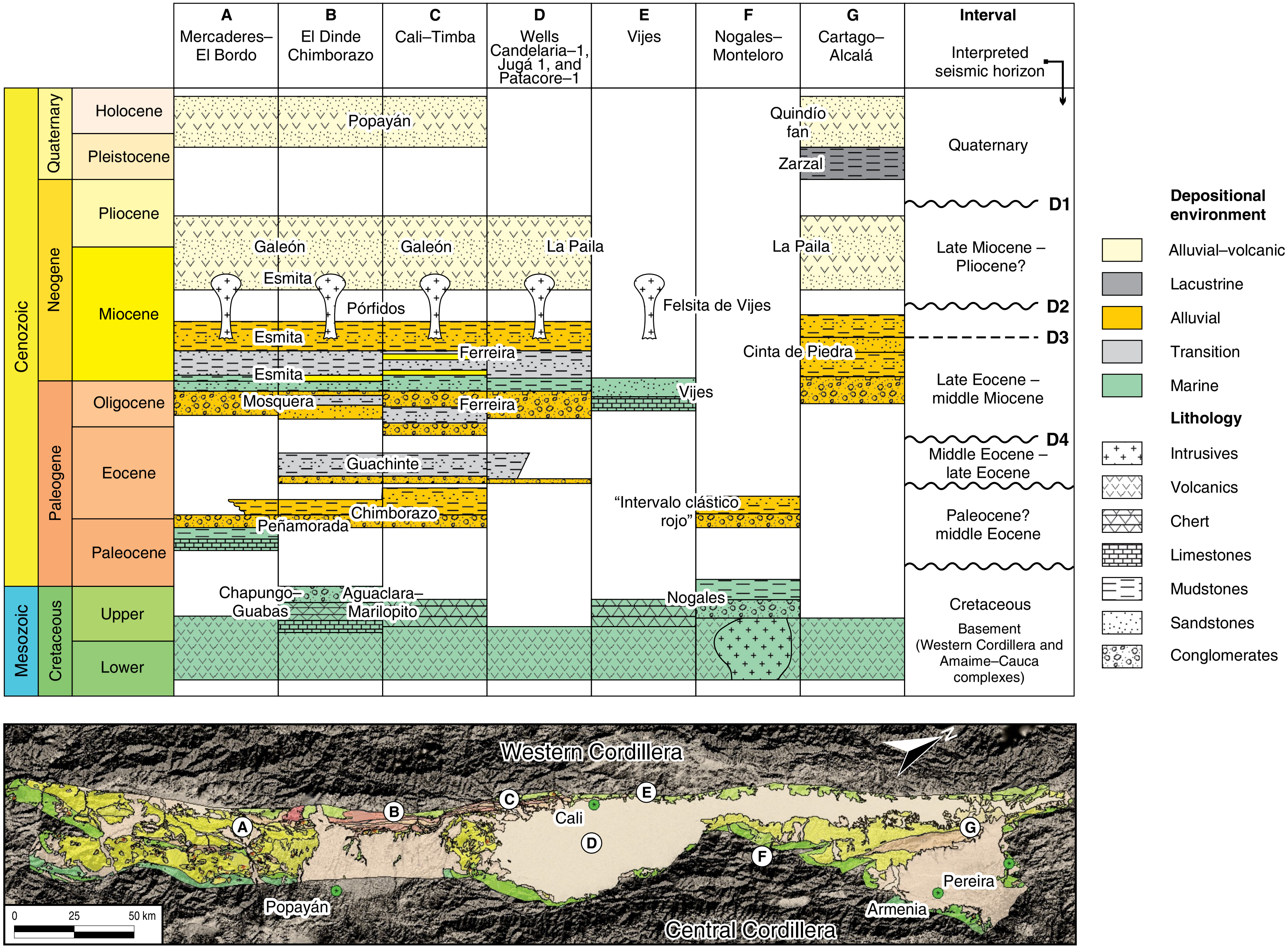

Figure 4. Chronostratigraphic sketch of the Cauca Basin with the regional unconformities (D1–D4) proposed from the correlation between seismic and surface geology data. After Hincapié et al (2009).

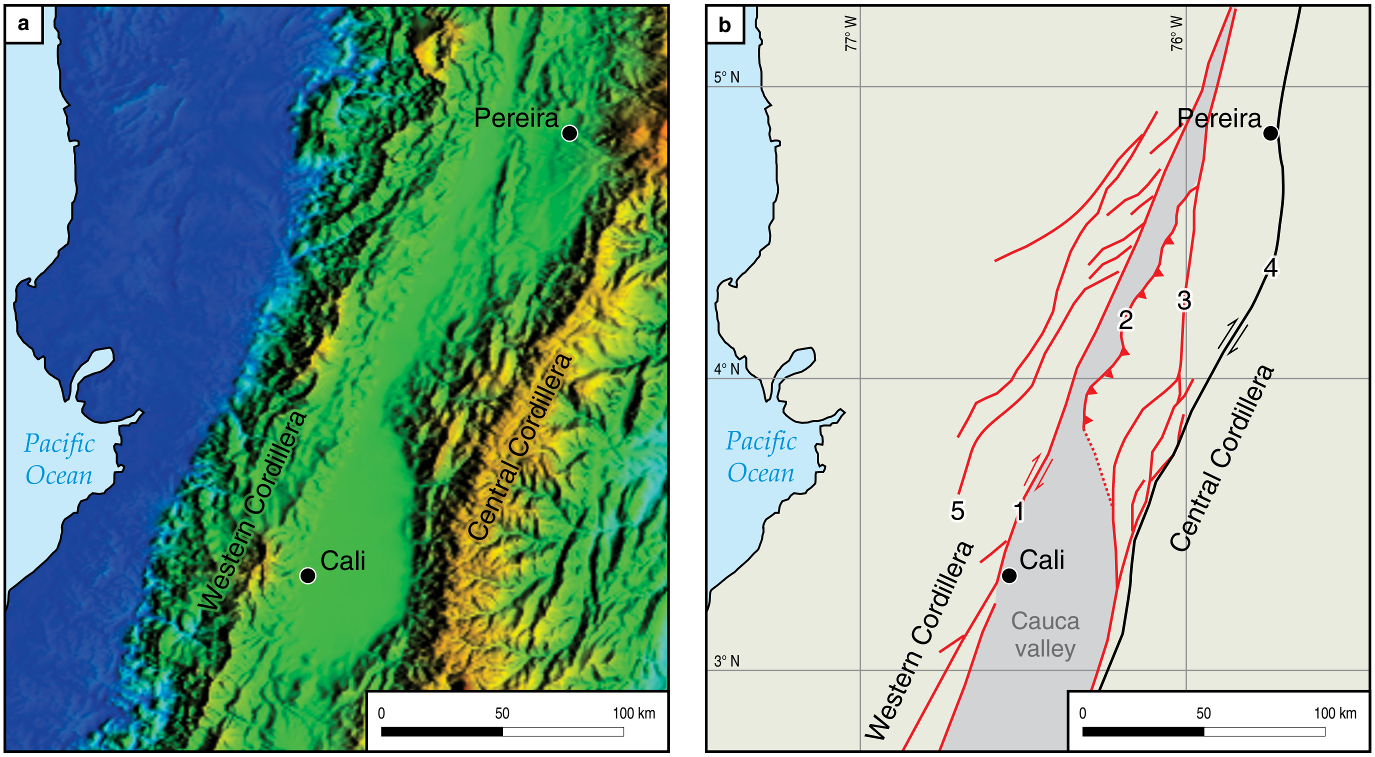

Figure 5. (a) Digital elevation model (DEM) generated with light from the east (elevation 60º–azimuth 100) highlighting the main geologic structures of the Cauca River valley. **(b)** The main structures are the (1) Cauca–Patía Fault, also known as the Cali Fault; (2) Buga–La Paila thrust fault (after López, 2006); (3) Quebrada Nueva Fault; (4) Silvia–Pijao Fault; (5) Dagua–Calima Fault. Modified from López et al. (2009b).

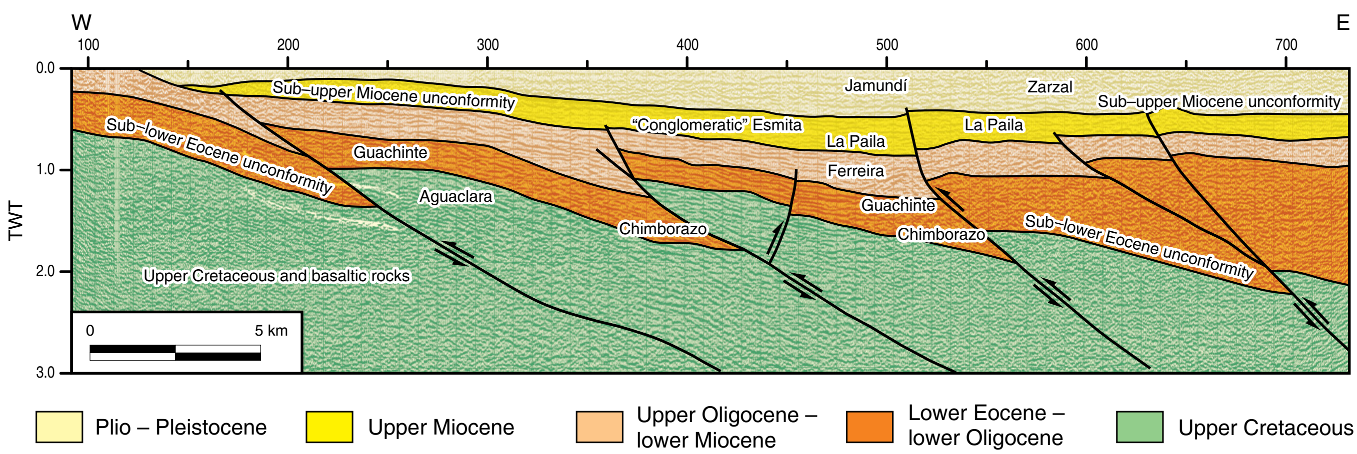

Figure 6. Interpretation of the structure and regional unconformities of the Cauca Basin in the seismic profile VC–79–10, located to the east of Cali, near Palmira. After Barrero & Laverde (1998).

fine– to medium–grained and locally conglomeratic sandstones. Toward the top of the Armenia–Zarzal section (AZ in Figure 2), layers of mudstones and tuffaceous sandstones are interbedded with polymictic clast–supported and roughly imbricated conglomerates (see Appendix 12, 13 in López et al., 2009b).

Tuffaceous material was identified near La Uribe in La Paila–Sevilla and Armenia–Zarzal sections (PS and AZ in Figure 2; see Appendix 9–13 in López et al., 2009b). These tuffs are fine– to lapilli–grained, crystalline and vitreous, gray, cream and white, and sometimes massive, exhibiting normal to reverse gradation, trough cross bedding and undulated stratification.

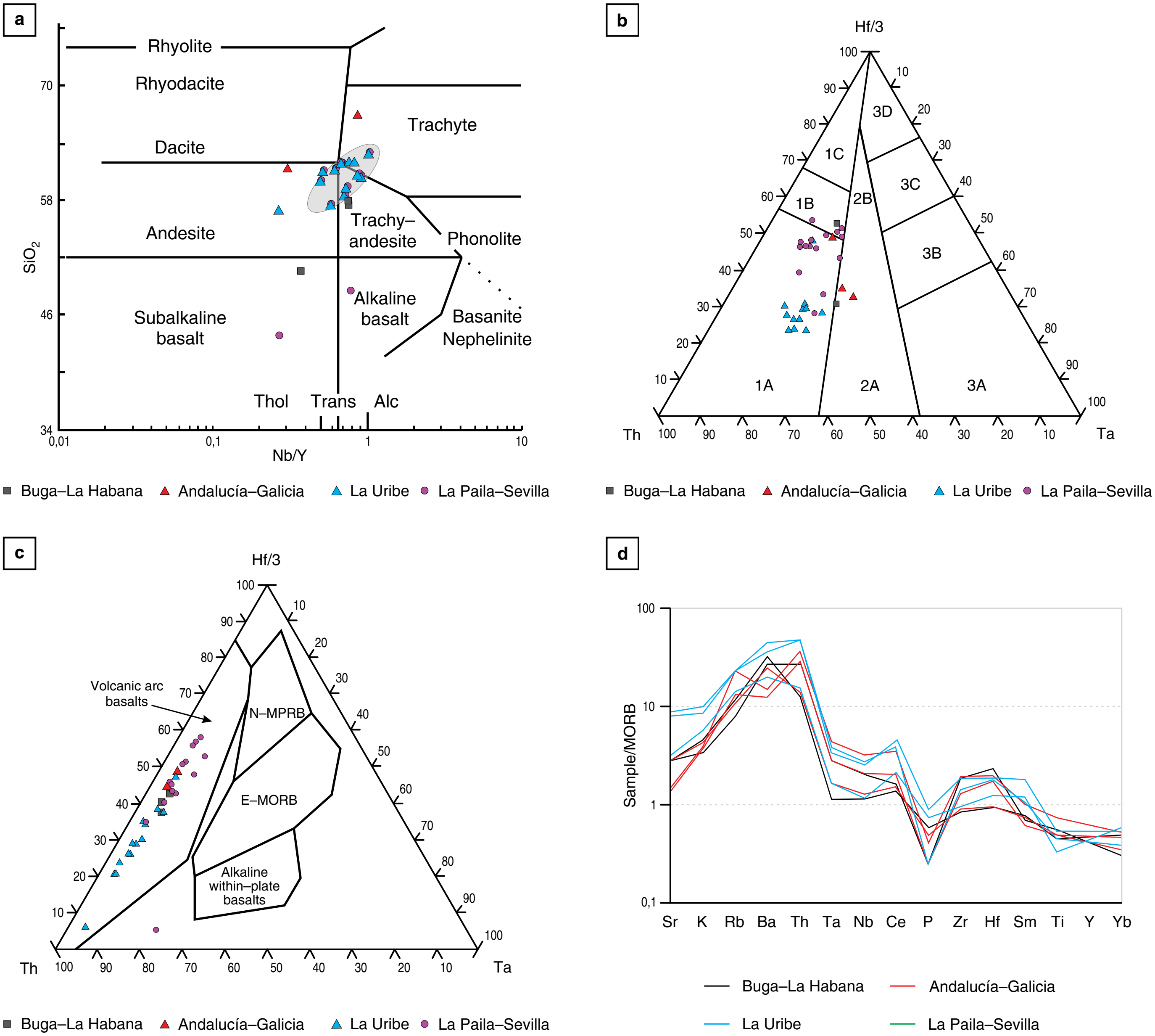

Figure 7. Geochemical classification of rocks of La Paila Formation. **(a)** SiO_2 vs. Nb/Y diagram of Winchester & Floyd (1977). **(b)** Tectonic discrimination diagram of Cabanis & Lecolle (1989). **(c)** Tectonic discrimination diagram of Wood (1980). **(d)** Multielement diagram of La Paila Formation tuffs. Location of samples indicated in Figure 2. Modified from López et al. (2009b).

They are composed of amphiboles, feldspar, quartz, and biotite in a fine vitreous matrix and form tabular strata of decimetric to metric thicknesses interstratified with paleosols. The volcanic natures (andesitic) of many of the conglomerate clasts and ignimbrite layers are distinctive features of La Paila Formation. Facies analysis allowed us to identify the alternations of volcanic and sedimentary processes with periods of "low or null volcanic activity" (López et al., 2009b).

In La Uribe–Sevilla section (US in Figure 2), tuff layers contain abundant remains of the fern *Thelypteris* subg. *Meniscium* (Monilophyta) (Sanín et al., 2016), and some of them contain freshwater mollusks.

Samples of tuffaceous material with radiometric ages and shales that underwent palynological analysis are located in the stratigraphic columns presented by López et al. (2009b). In the Armenia–Zarzal section (AZ in Figure 2), the amphiboles of La Paila Formation yield two radiometric ages (Ar/Ar) with plateau ages of 10.5 ± 0.4 Ma (sample AZ–9–1, with coordinates 4.39° N–75.92° W) and 4.4 ± 0.07 Ma (sample AZ–1–1c, with coordinates 4.42° N–75.87° W).

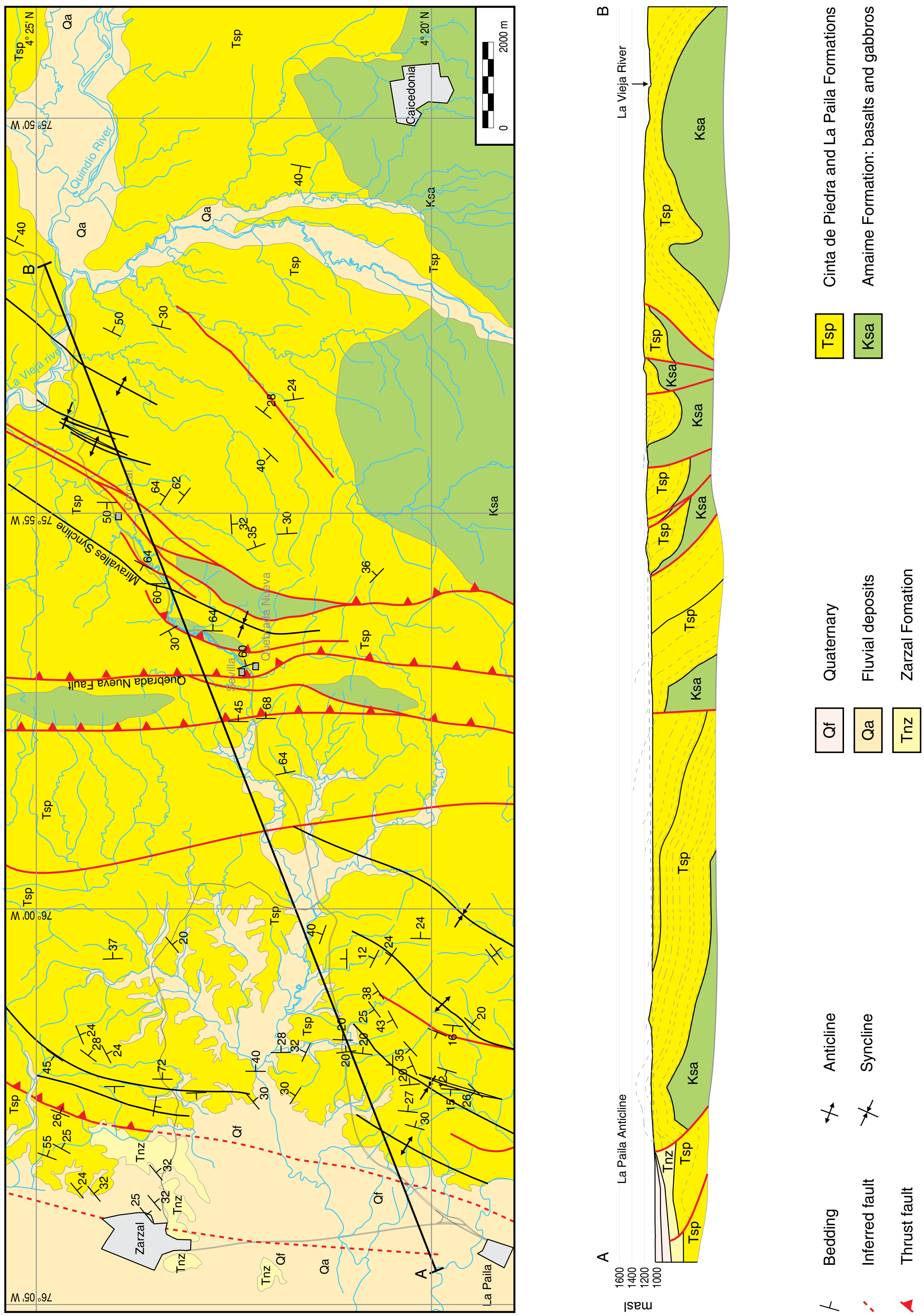

Figure 8. Map and geological section of the Armenia–Zarzal section (AZ in Figure 2). Depths of the basement are hypothetical. Based on McCourt et al. (1984a), Nivia et al. (1992), and López et al. (2009b).

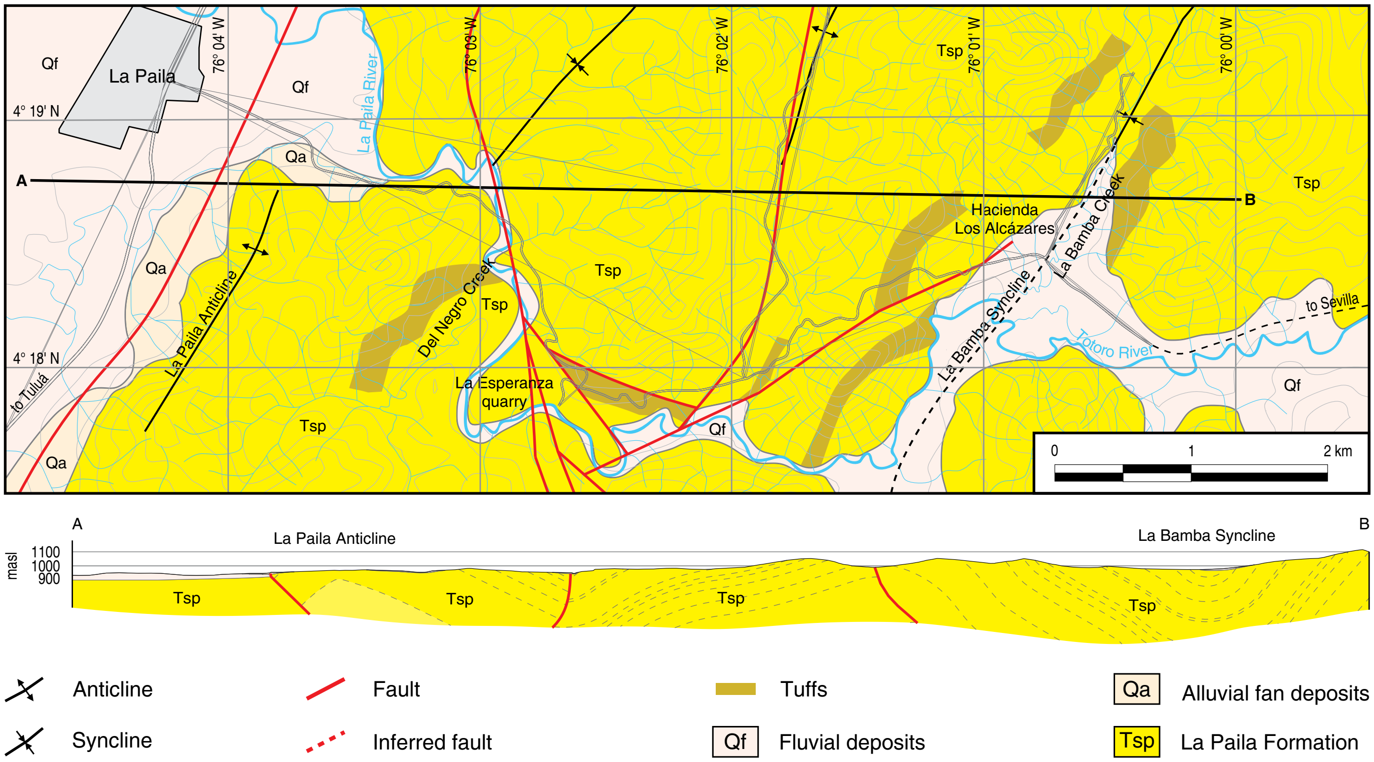

Figure 9. Map and geological section between the towns of La Paila and Sevilla (PS in Figure 2). Based on McCourt et al (1985), Nivia et al. (1992), and López et al. (2009b).

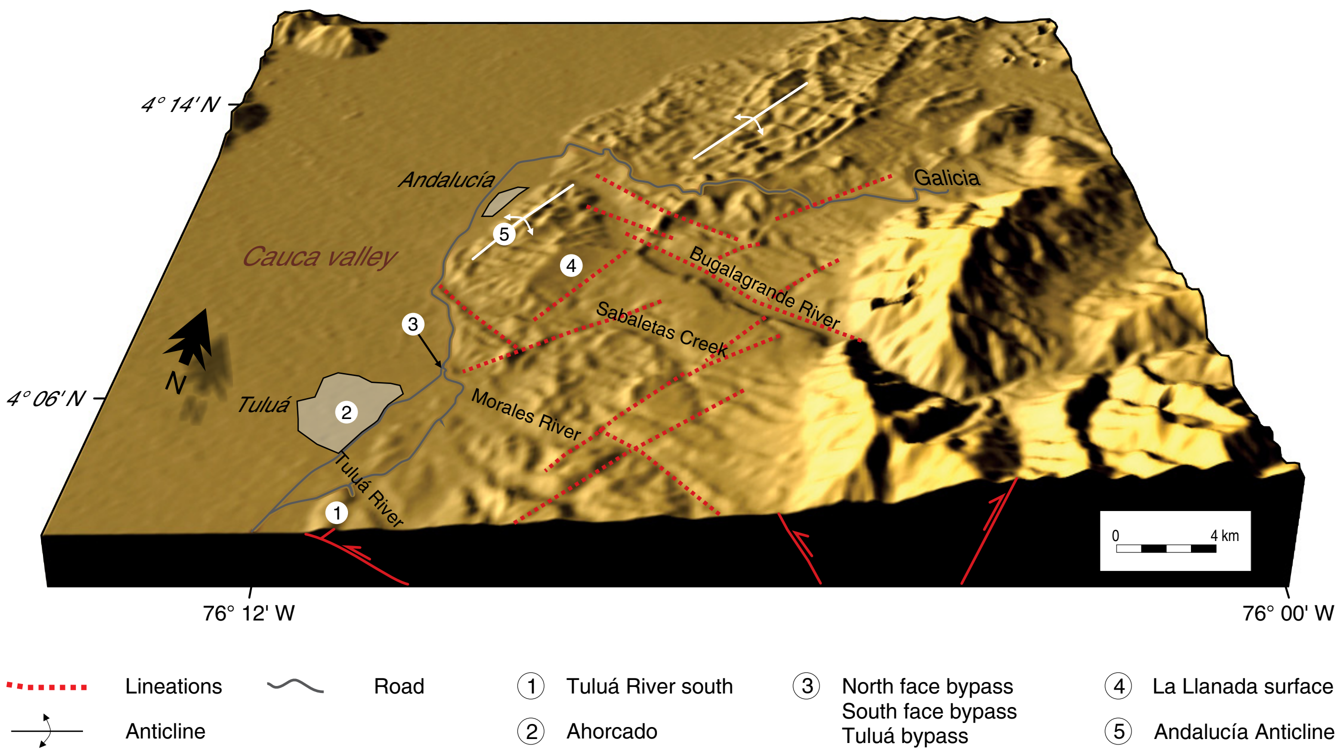

Figure 10. Digital elevation model (DEM) with location of the sites with the most recent tectonic deformation on the alluvial fans between Tuluá and Andalucía. Reverse faults are not drawn in plain view. Enclosed numbers in circles are the locations mentioned in this work. The relief is exaggerated 15 times. Modified from López (2006).

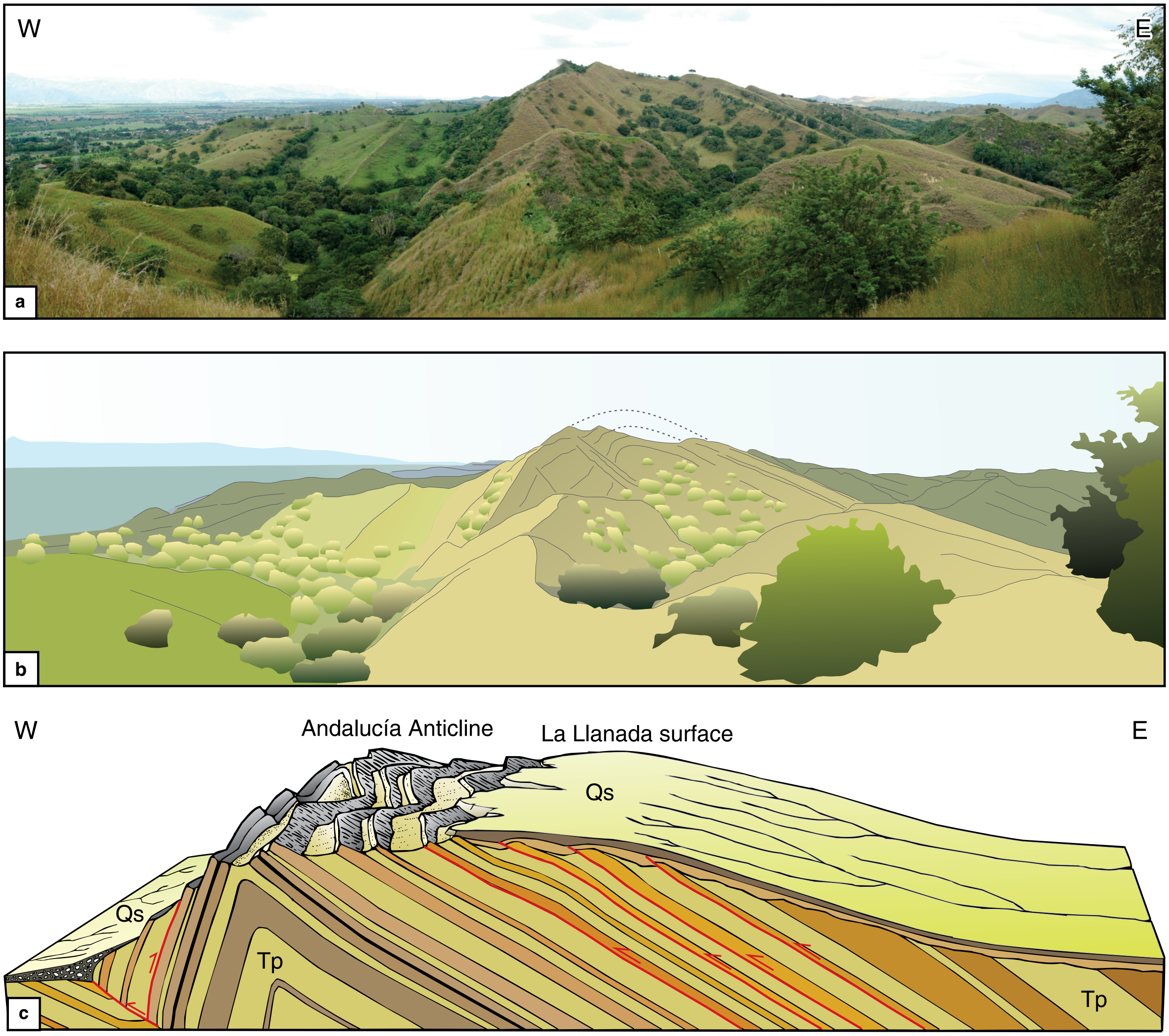

Figure 11. (a) View of the Andalucía Anticline from the south (4° 8' 22.92'' N – 76° 10' 11.99'' W). **(b)** Interpretative drawing. **(c)** Simplified sketch of the flexural scarp of the western foothills of the Central Cordillera, which is actually in the process of erosion. It represents the western limb of the Andalucía Anticline (not to scale). Modified from López (2006).

The geochemical analyses of the rocks in different stratigraphic sections of La Paila Formation (López et al., 2009b) classify them as tholeiitic–transitional– and alkaline–transitional–series rocks on the Winchester & Floyd (1977) diagram (Figure 7a). The diagram of Cabanis & Lecolle (1989) indicates that the rocks of La Paila Formation come from a volcanic arc with calc–alkaline affinity and a tholeiitic primitive arc (Figure 7b). In addition, on the tectonic environment discrimination diagram of Wood (1980), it plots within the orogenic, transitional, and intracontinental domains (Figure 7c). Their rare earth element and multielement distribution patterns show that La Paila Formation tuffs developed in a calc–alkaline continental volcanic arc related to subduction processes in an active continental margin (Figure 7d).

5.2. Tectonic Relationships

Figures 1 and 2 show the main sections presented in this chapter, in which the tectonic structures forming before and after La Paila Formation have been determined.

In the eastern part of the Armenia–Zarzal section (AZ in Figure 2, Figure 8), an anticline exposes an inlier of Cretaceous basement capped by La Paila deposits (Figure 8). High–angle faults crop out in the center of the section, and low–angle thrust

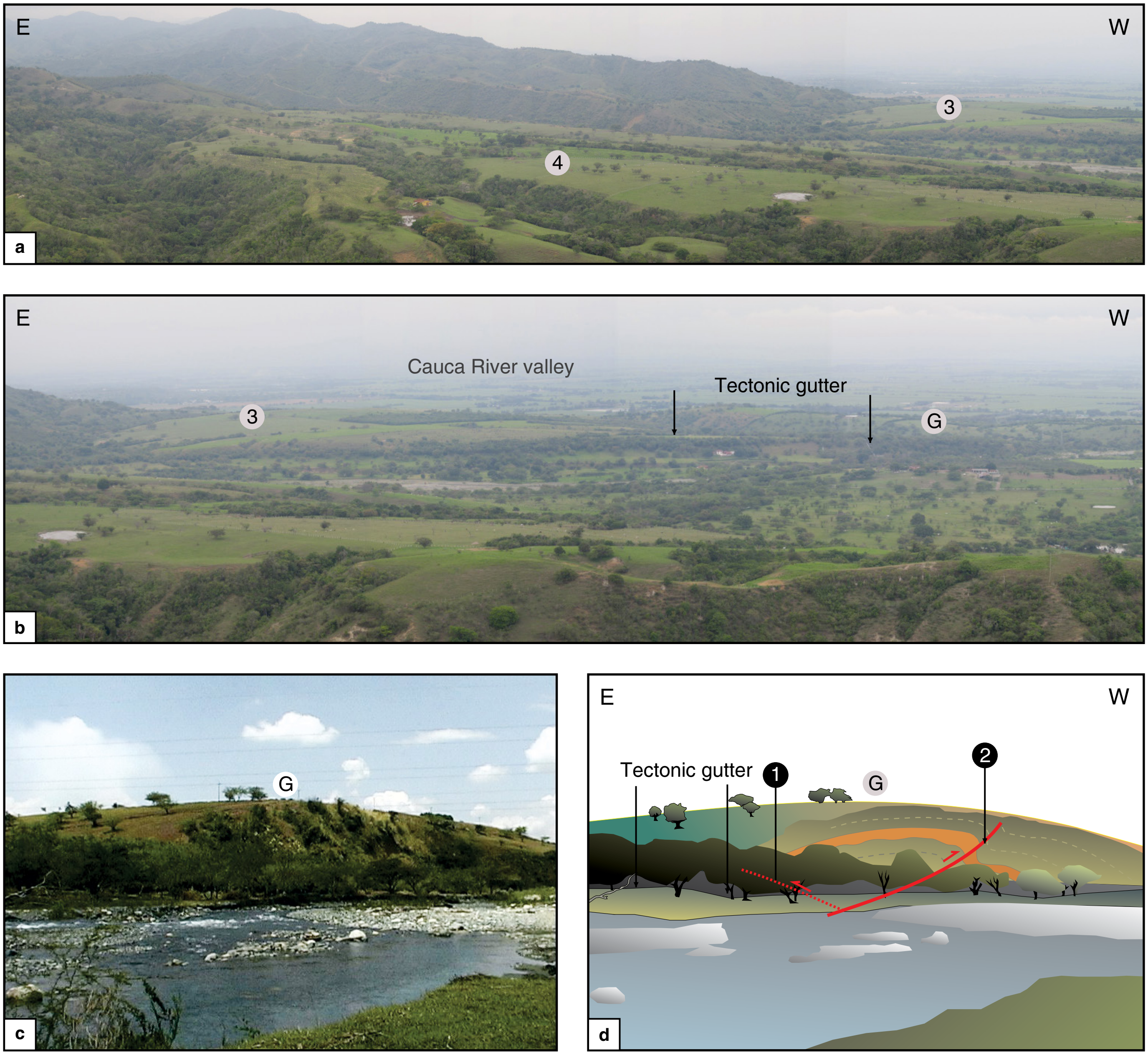

Figure 12. (a, b) View toward the south of the Tuluá alluvial fan. Warping of the surface is indicated by 3, 4, and G. **(c)** Close up of the pressure ridge (G) on the southern margin of the Tuluá River (1 in Figure 10; 4° 3' 36.88'' N – 76° 11' 28.3'' W). **(d)** Interpretative sketch. A tectonic gutter (channel) is developed in front of the antithetic fault. Modified from López & Audemard (2011).

faults have been interpreted toward the west. Near the old Sevilla railroad station, an ENE fault was measured, with horizontal striations affecting calcrete horizons. To the north of this area, an ENE fault is inferred based on the east concave shape of the NNE folds.

In the Armenia–Zarzal section, the high angles of the structures seem to be a consequence of strike–slip movement inside an embryonic flower structure, although the rotation of thrust sheets (originally of lower angles) has caused the progressive steepening of the cut–off angles of the faults.

The main structures found in La Paila–Sevilla section (PS in Figure 2, Figure 9) are a syncline developed to the east of a west–vergent fault, a NNW fault with a horse tail structure controlling the course of La Paila River and La Paila Anticline toward the west of an east–dipping fault. Near La Esperanza quarry, a NNE strike–slip fault without surficial expression was measured. The presence of volcanic material in this section (Figure 9) contradicts the idea that the volcanism of this formation is basal.

East of Andalucía town, on the border between the recent alluvial plain and the lower foothills, is the Andalucía Anti-

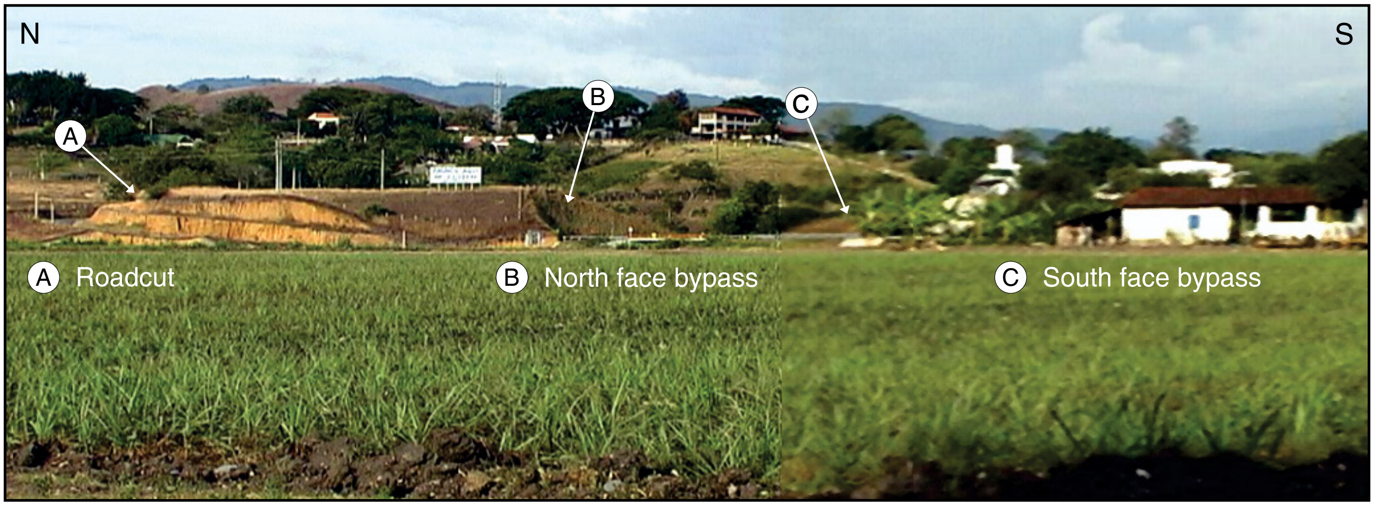

Figure 13. Morphological aspect of the pressure ridge cut by the Tuluá bypass ("Oreja Tuluá") located at the west end of the Morales River bend to the east of the town of Tuluá (3 in Figure 10; 4° 6' 1.35'' N – 76° 10' 26.93'' W). Letters indicate the locations of the outcrops of east–dipping faults. Modified from López & Audemard (2011).

cline (1 in Figure 1, 5 in Figure 10). This anticline affects La Paila Formation, which is unconformably overlain by Quaternary deposits. The surface of these deposits (named La Llanada surface) is softly warped and inclined toward the main frontal range, with a visible counterscarp to the east of the present axis of the Andalucía Anticline (Figure 11).

The gentle warping of the Quaternary deposits (Qs) as well as the concavity of the surface toward the east indicates the reactivation of the fold–propagation fault that generated the Andalucía Anticline and a piggy–back basin, which is currently present as a flexure fault (4 in Figure 10, Figure 11). Flexural slip has occurred along the underlying bedding planes of La Paila Formation (Tp) and broken through the Quaternary deposits, as shown by López (2006) and López & Audemard (2011) in the stratigraphic record at Tuluá.

Between Andalucía and Tuluá (2 in Figure 1), active blind thrust faulting has been documented based on the application of geomorphic criteria (Ollarves et al., 2006). Drainage and landform anomalies, such as a series of east– and/or west–facing scarps, shape the landscape of the Tuluá region (1, 2, and 3 in Figure 10; Figures 12, 13). On the southern margin of the Tuluá River, the warping of the alluvial fan surface is related to an outcrop of a high–angle west–dipping fault (1 in Figure 10, G in Figure 12).

East of Tuluá town, a road bypassing the main highway between Cali and Cartago cuts a lower NS–trending, west–facing scarp (3 in Figure 10, Figure 13), thus revealing imbricate east–dipping faults overlying Holocene paleosols. This evidence was analyzed by López & Audemard (2011), who concluded that these faults can generate earthquakes of magnitude 7.0 Mw with return periods of 5–6 ky BP. To the south of this area, the "Variante Tuluá–S" growth strata and west– and east–dipping thrust faults are directly related (Figure 14). In this area, an unconsolidated Quaternary sequence comprises, from bottom to top, g: clast–supported gravels unconformably overlying La Paila Formation; Sp: cross–stratified coarse sandy–pebbly sands; Sm: coarse sandy–pebbly horizon, brown–orange in color; Sv: coarse to fine sands with volcanic material, gray in color; and A: organic soil horizon, the most recent accumulation, black in color. Sp thickens at the foot of the faults and thins at the fold hinge or hanging wall, while Sm thickens in the back limb of the fold (Figure 14).

In addition, on the southern margin of the Tuluá River, a high–angle west–dipping fault crops out (1 in Figure 12d), and an east–dipping fault (2 in Figure 12d) is inferred on the southern margin of the Tuluá alluvial fan.

The high angle of the west–dipping fault should be a consequence of the youngest west–dipping blind fault growing in the alluvial plain.

Continuing to the south, north of Buga and near Presidente town (3 in Figure 1), east of the Cali–Cartago highway, crops out the Zarzal Formation, which is affected by a series of NE conjugate reverse faults that have reached recent alluvial deposits (Figure 15). In addition, metric–scale clastic dikes (cd in Figure 15) of clayey material perturb the gravel and sandstone beds, causing important changes in the thicknesses of the soft layers. The western fault (fault A) dips toward the east and overturns the deposits including paleosols. Faults B, C, D, and E are antithetic of fault A. Thrust faults allow us to infer the NW–SE main stress (sigma 1) in this area (López, 2008; López & Moreno–Sánchez, 2009).

On the other hand, normal faults were observed propagating into the harder (sandstone) beds and disappearing into the lower softer (clayey) beds near the Cartago–Ansermanuevo motorway (López, 2006). An important feature is that the underlying layers do not exhibit deformation (Ac in Figure 16). These struc-

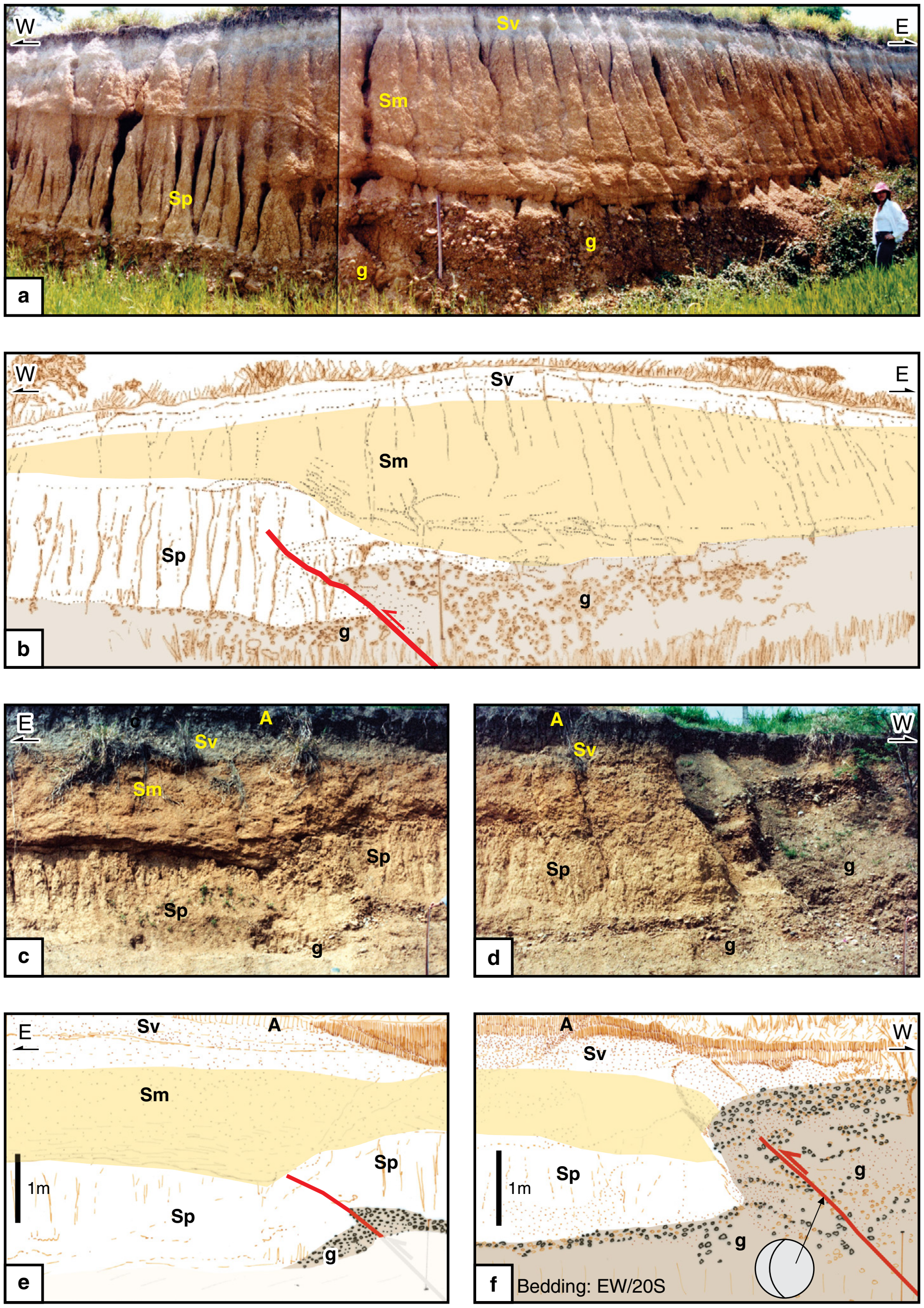

Figure 14. Growth strata in Quaternary alluvial deposits on the Tuluá motorway (3 in Figure 10; 4° 5' 51.49'' N – 76° 11' 28.36'' W). **(a, b)** View of the north face of the Tuluá motorway. **(b)** Interpretative sketch showing an east–dipping fault offsetting and bending unconsolidated Quaternary deposits. **(c, d)** View of the south face of the Tuluá motorway. **(e, f)** Interpretative sketches showing two west–dipping faults. The two–letter codes represent different lithofacies. Modified from López & Audemard (2011).

tures correspond to typical graded faults usually associated with seismites (sensu Seilacher, 1969, 1991).

A conspicuous feature in the landscape of the Buga Salient, on the eastern side of the Cali–Cartago highway, is the Sonso Anticline (4 in Figure 1). Near Sonso town in El Vínculo quarry (Figure 17), a west–vergent NNE fold involves the units of La Paila Formation and is unconformably overlain by Quaternary deposits. These deposits are softly warped and develop a pronounced west–facing scarp at the latitude of Sonso (Figure 17). This fold was excavated in El Vínculo quarry, where the main structures (Figures 17, 18) that affect La Paila Formation and shape the western foothills of the Central Cordillera were documented by López & Moreno–Sánchez (2005). Some beds of La Paila Formation (Tp4–Tp8 in Figure

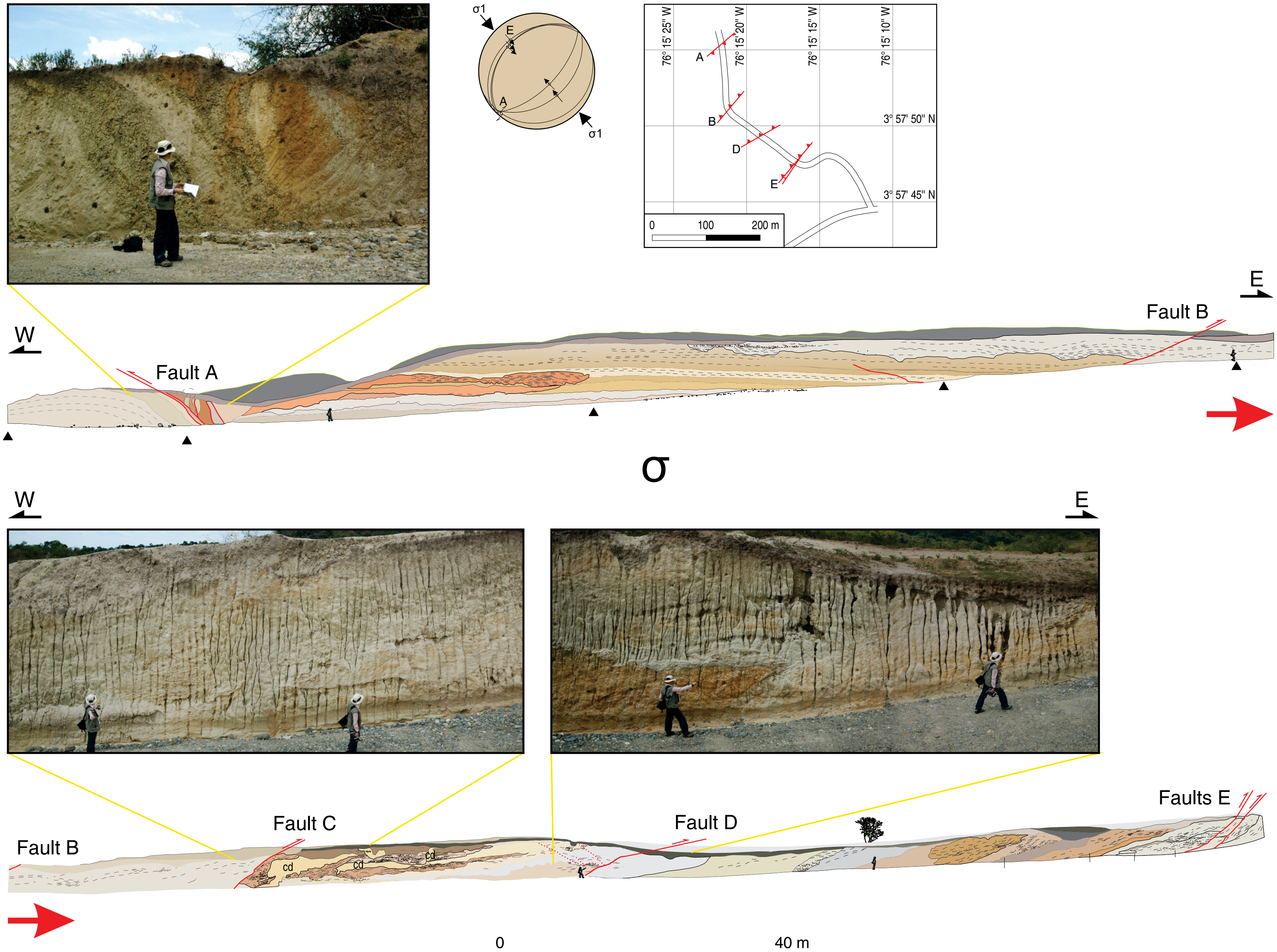

Figure 15. Near the town of Presidente (3° 58' 10.81'' N – 76° 15' 9.07'' W). Imbricated east–vergent faults affecting the Pleistocene Zarzal Formation. Liquefaction features and metric–scale clastic dikes (cd) crossing conglomerates are coeval with faulting. Modified from López et al. (2009a).

Neogene
Quaternary

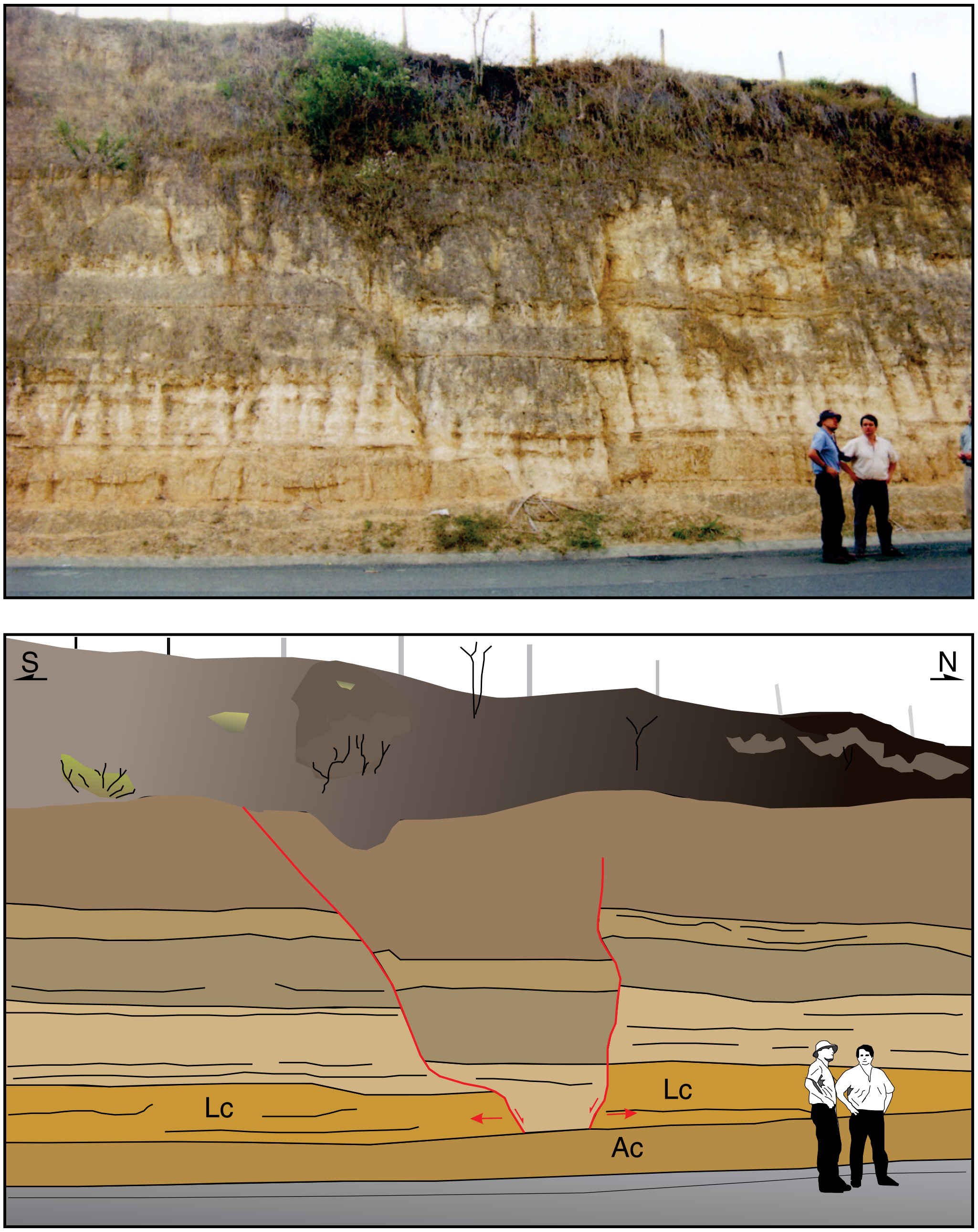

Figure 16. Example of plastic deformation in outcrops along the Cauca valley in the Zarzal Formation (between the towns of Ansermanuevo and La Unión) along the Panorama motorway (AU in Figure 2). Lower conglomeratic sands (Ac) are the rigid substrate on which finer deposits (muds) underwent liquefaction (Lc). After López (2006).

19), mainly mudstones and sandstones, are in angular unconformity in the southern flank of the structure, and the top of the lower sequences is a paraconformity (Figure 19); therefore, the erosive surface could correspond to a seventh–order or greater surface bounding, which represents the sedimentary response to a pulse of tectonic activity along the basin–margin fault (sensu Miall, 1996; Catuneanu et al., 2011). Associated with this folding, a series of minor (mainly reverse) faults (1 to 7 in Figure 19) cut through the beds of La Paila Formation represented in this place by layers Tp1 to Tp11 in Figure 19. Some of the normal faults are perpendicular to the main reverse faults and have developed at the hinge of the anticline (Figure 17).

The structure shown in Figure 20 suggests two different phases of activity; originally, this structure began as a half–graben. The main structures described by López & Moreno–Sánchez (2005) in El Vínculo quarry are summarized in Figure 21. All of these structures indicate that their tectonic activity was simultaneous during the accumulation of the sedimentites of La Paila Formation.

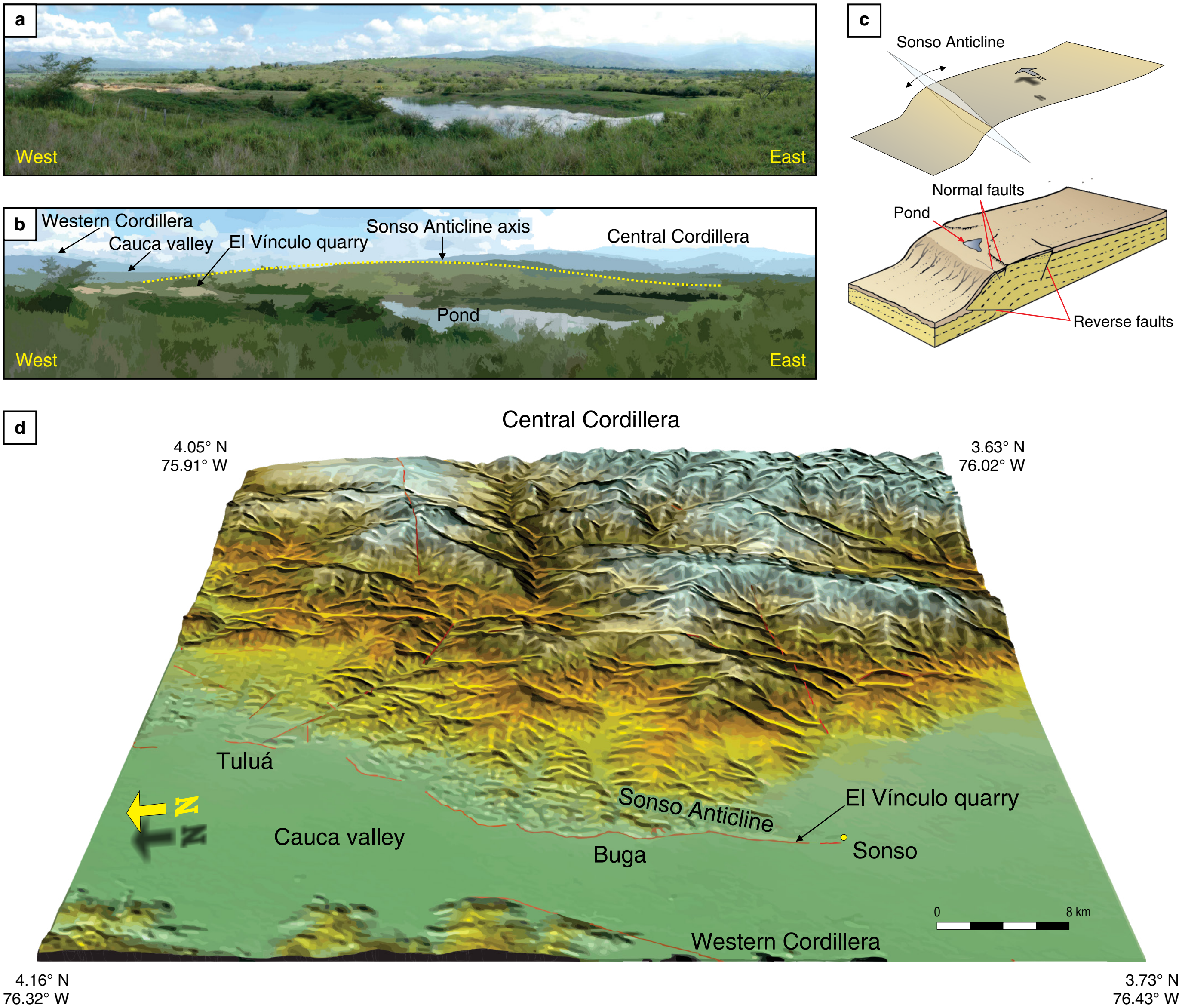

Figure 17. Buga Salient sector. **(a)** The Sonso Anticline seen in the northerly direction (3° 48' 5.95'' N – 76° 18' 9.57'' W). **(b)** Sketch of (a) showing the bulging of the Sonso Anticline. **(c)** Schematic drawing of the Sonso Anticline with the main faults. Reverse faults are parallel to the fold axis, and normal faults have developed on the area of greater stretching on the hinge. **(d)** STRM model of the Buga Salient with the main regional structures drawn. Modified from López & Moreno–Sánchez (2005).

One of the main features found in El Vínculo quarry is a NS west–dipping normal fault that has been reactivated as a reverse fault (Figure 22). The normal faults perpendicular to the main reverse faults, which are parallel to the orientation of the minimum stress, are interpreted as moment–bending faults.

At the southern tip of the Buga Salient (Figure 1), two discontinuous NW–SE scarps appear between the Amaime River and Sonso town (i.e., the Honda Creek and La Novillera scarps) (Figures 23, 24). The Honda Creek scarp extends from the Amaime River to the Santa Elena Aqueduct. Woodward–Clyde Consultants (1983) trenched the southernmost culmination of this scarp (Figures 23, 24). The Venecia trench (5 in Figure 1, T in Figure 23, and Figure 24) was reinterpreted by López & Audemard (2011). Two debris flows were separated by an offset paleosol, and colluvial material was deposited at the foot of the scarp. They suggested that folding of the paleosols and debris flows was generated by surficial thrust faults. The age of the surficial paleosol (1) was established by Woodward–Clyde Consultants (1983) as 2 ky, and the folded paleosol (2) was dated using ^{14}C to 6320 y (Figure 24). The most recent offset

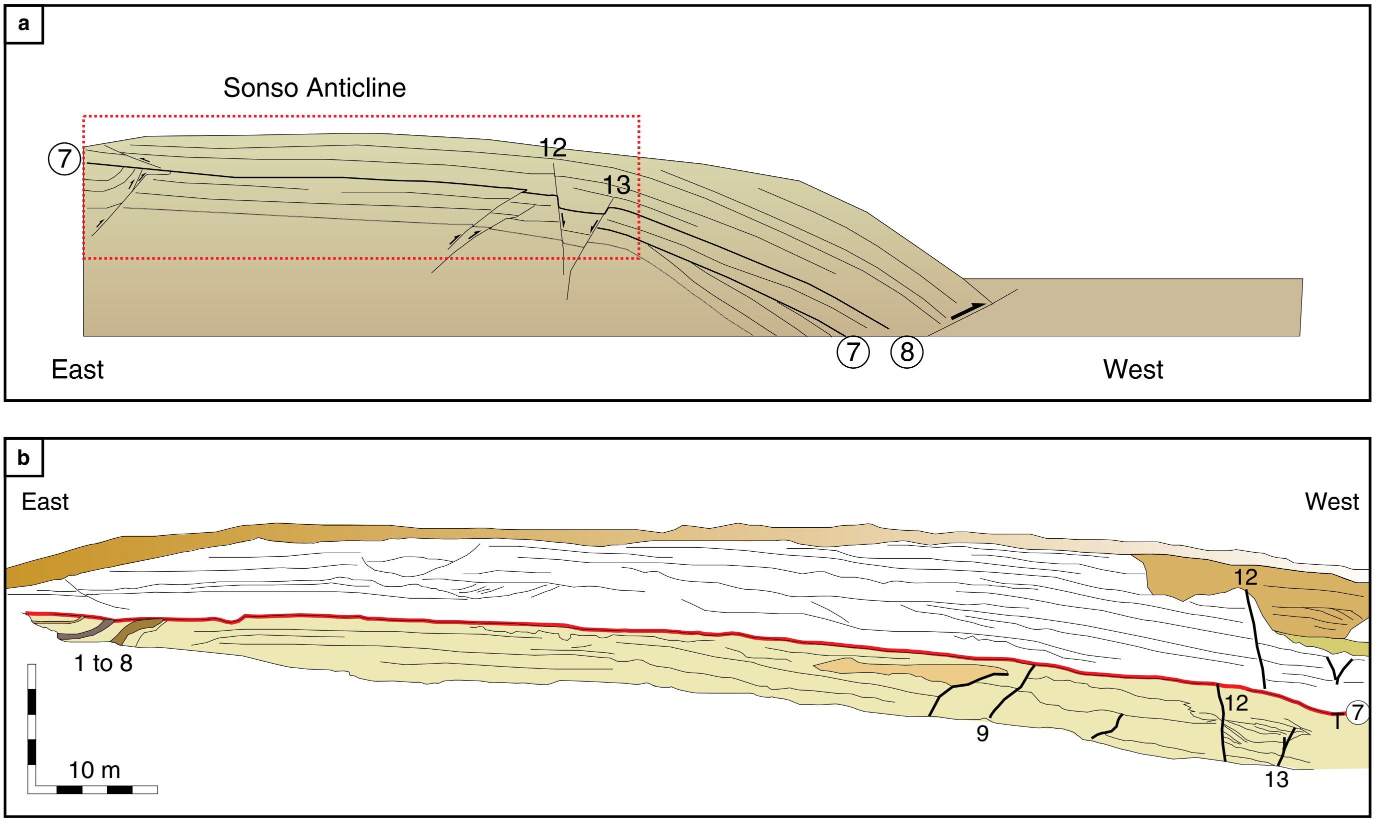

Figure 18. (a) Sonso Anticline as it appears in El Vínculo quarry (3° 48' 23.02'' N – 76° 18' 22.02'' W). **(b)** Details of the sector indicated in the red box up. The positions of normal faults with respect to the main flexure of the anticline are highlighted (normal faults 12 and 13). Reverse faults are distributed throughout the structure (numbers 1 to 8 and 9). Seventh– and eighth–order bounding surfaces (numbers enclosed in circles) fossilize some faults and folds. Red line follows a manmade terrace. Modified from López & Moreno–Sánchez (2005).

of the fault was calculated at 1 m, the previous offset was 1.75 m, and the slip rate was 0.2–1.0 mm/y. The position of the fault plane was suggested based on the folding of the debris flows, paleosol, and present soil.

In addition, a regional structure shaping the landscape of the Western Cordillera (6 in Figure 1) is the Dagua–Calima Fault, which exhibits outstanding triangular facets on the western side of the Calima Dam (Figure 25). Woodward–Clyde Consultants (1983) identified the Loboguerrero Fault, which is related to this structure, in a trench near the town of the same name (6 in Figure 1). The authors suggested a sinistral component based on the apparent offset of a small ridge and the horizontal slickensides measured at the trench. The secondary faults, along with the main fault, evolve to a negative flower structure. These faults cut through at least five paleosols (2, 4, 5, 6, 7 in Figure 25), although none touches the surface of the terrain (Figure 25).

6. Discussion

La Paila Formation is a continental unit whose lower and middle parts were deposited in an extensional tectonic regime, and it is thicker in the eastern part than it is in the western part. Radiometric age dating indicates that this unit was deposited between the middle Miocene and Pliocene and that it can be correlated with the Honda Group in the Upper Magdalena Valley. The volcanism in La Paila Formation was proximal, as indicated by the presence of pyroclastic flows and tuffaceous material.

The deposits dated at 10.4 Ma come from a predominantly lacustrine environment, suggesting that the accommodation space at that time was enhanced. A restricted accommodation space existed at 4.27 Ma, when conglomeratic deposits were dominant; however, volcanic activity seems to be ubiquitous.

During the initial stages of deposition of La Paila Formation, the tectonic regime was extensional. The reverse structures present at El Vínculo quarry indicate that tectonic inversion affected the final stage of the deposition of La Paila Formation (Pliocene – Pleistocene). Some normal faults in El Vínculo quarry were reactivated in a compressional state of stress. The out–of–sequence thrusts observed in the stratigraphic record, e.g., in the lowest foothills, affected Quaternary deposits and even Holocene paleosols. These conclusions contradict those of Barrero & Laverde (1998).

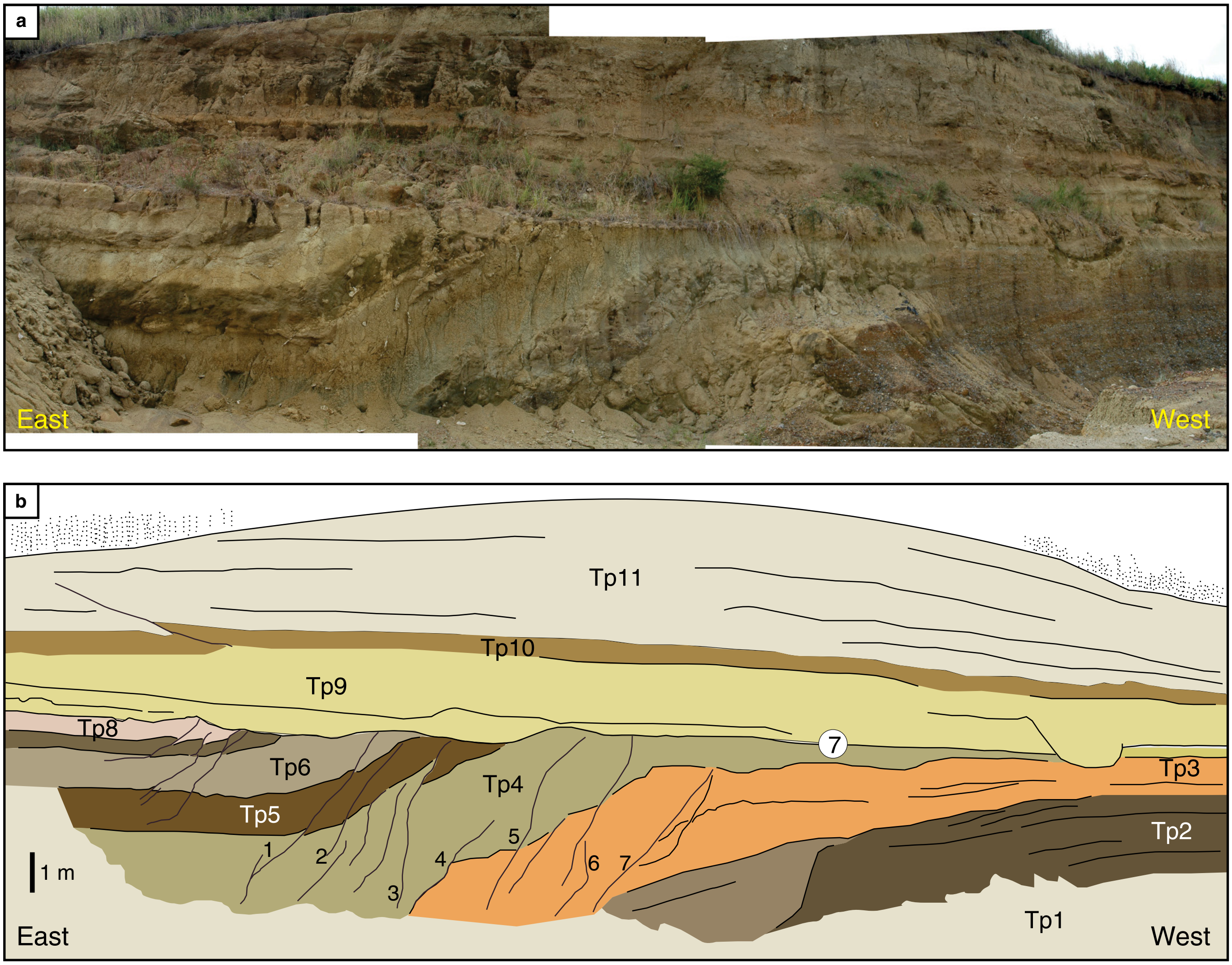

Figure 19. Details of Figure 18. **(a)** Eastern side of El Vínculo quarry (3° 48' 23.45'' N – 76° 18' 21.59'' W). **(b)** Interpretative sketch of (a); two–letter and number codes (Tp1 to Tp11) correspond to beds of La Paila Formation, 7 is an erosion surface within La Paila Formation on which a terrace was built due to quarry activities. Modified from López & Moreno–Sánchez (2005).

Reverse faulting and sedimentation are documented at two localities. In the Tuluá region, an alluvial fan was formed by the coeval activity of west–vergent faults and backthrust faults, generating La Variante Tuluá growth strata. In addition, Holocene paleosols were affected by backthrust faults (López, 2006; López & Audemard, 2011).

Between Sonso and Amaime, the alluvial surface was affected by a reverse west–vergent fault that produced a NW west–facing scarp. The folding of these deposits and paleosols was documented in a trench by Woodward–Clyde Consultants (1983).

More recent tectonic activity (post–La Paila Formation) was generated by compression. In the Andalucía Anticline, the Quaternary deposits of La Llanada surface accumulated in a piggyback basin developed at the back limb of the fault–propagation fold. The west–facing flexural scarp is the forward part of the fault that generates the anticline.

Although the area around the town of Presidente was interpreted by Nivia (2001) as belonging to La Paila Formation, the analysis of these deposits led to the identification of diatomites, tuffs, and lacustrine deposits mainly comprising clays with well–preserved fossil plants. These deposits, in places overlain by Quaternary gravels, are better correlated to the Zarzal Formation. In La Paila Formation, diatomite layers have never been reported. The Zarzal Formation was deposited during the Pleistocene (Suter et al., 2008a). The main tectonic structures reported in this unit in the western part of the Cauca valley are normal faults associated with liquefaction (López, 2006; Neuwerth et al., 2006). However, in Presidente, this unit is faulted and deformed by compressive events that affect the Quaternary deposits, and it also exhibits liquefaction features. Clastic dikes are good indicators of coseismic liquefaction (e.g., Audemard & de Santis, 1991;

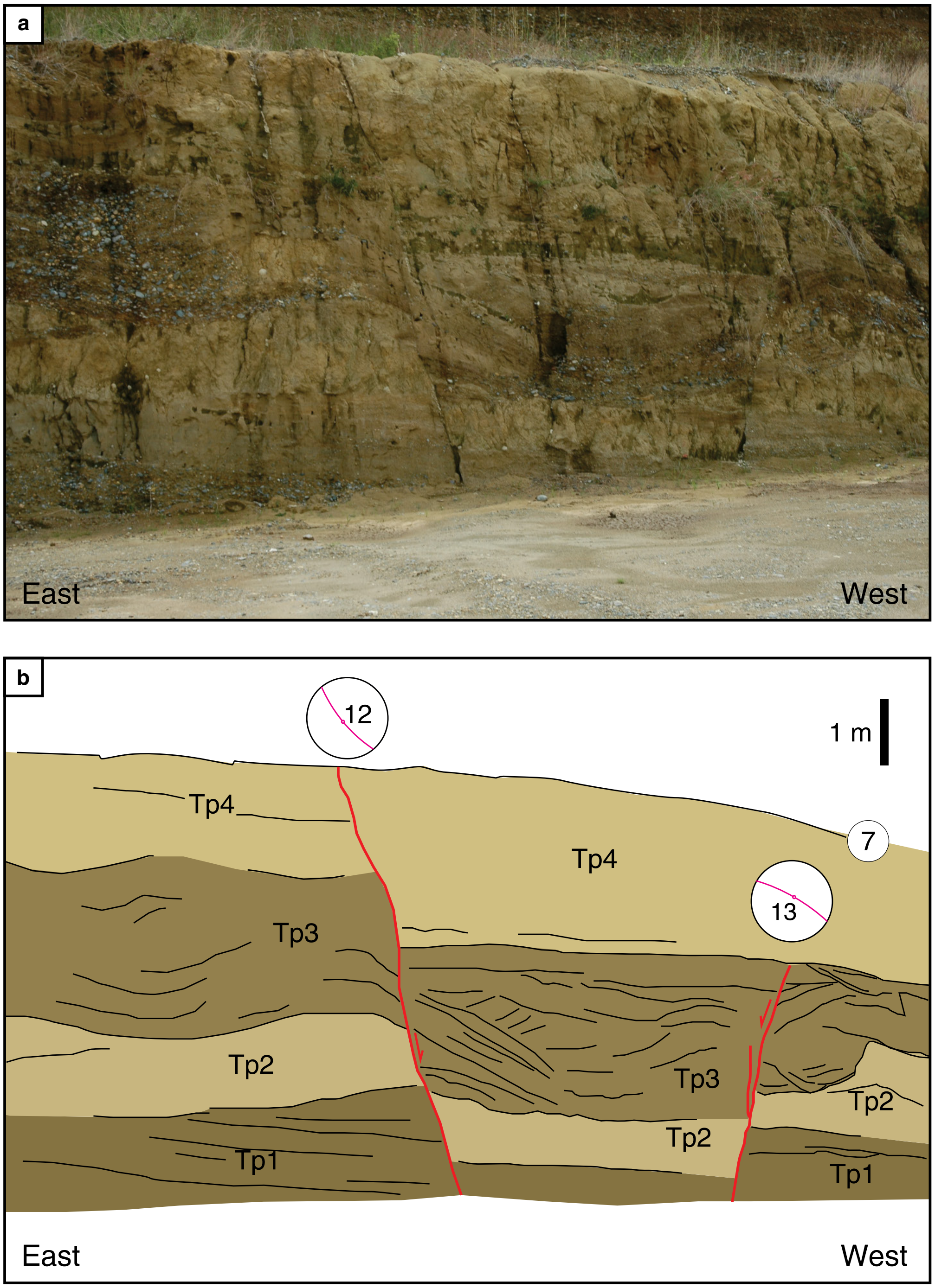

Figure 20. Details of Figure 18. **(a)** Western side of El Vínculo quarry (3° 48' 36.43'' N – 76° 18' 25.37'' W). **(b)** Interpretative sketch of (a); graben in La Paila Formation (Tp1 to Tp4), an ancient erosive surface fossilizing normal fault 13. Fault 12 is younger than this surface. The upper surface is a terrace constructed by quarrying over a claystone level whose base coincides with a seventh–order surface bounding (number 7 enclosed in a circle). Modified from López & Moreno–Sánchez (2005).

Galli & Ferreli, 1995; Papadopoulos & Lefkopoulos, 1993; Obermeier, 1996; Winslow, 1983). Rodriguez–Pascua (1997) suggests that clastic dikes cross–cutting conglomerates can be generated by M > 7.5 earthquakes.

West–vergent faults and their backthrusts induced the asymmetric folding of Quaternary deposits, and they also override the Holocene paleosols in some places. This suggests that the thrust faults are west–vergent and have developed a thin–skinned fold and thrust belt, producing subtle morphological evidence of the development of blind faults. This evidence contradicts the observations of Alfonso et al. (1994), who described thick–skinned folds that were active

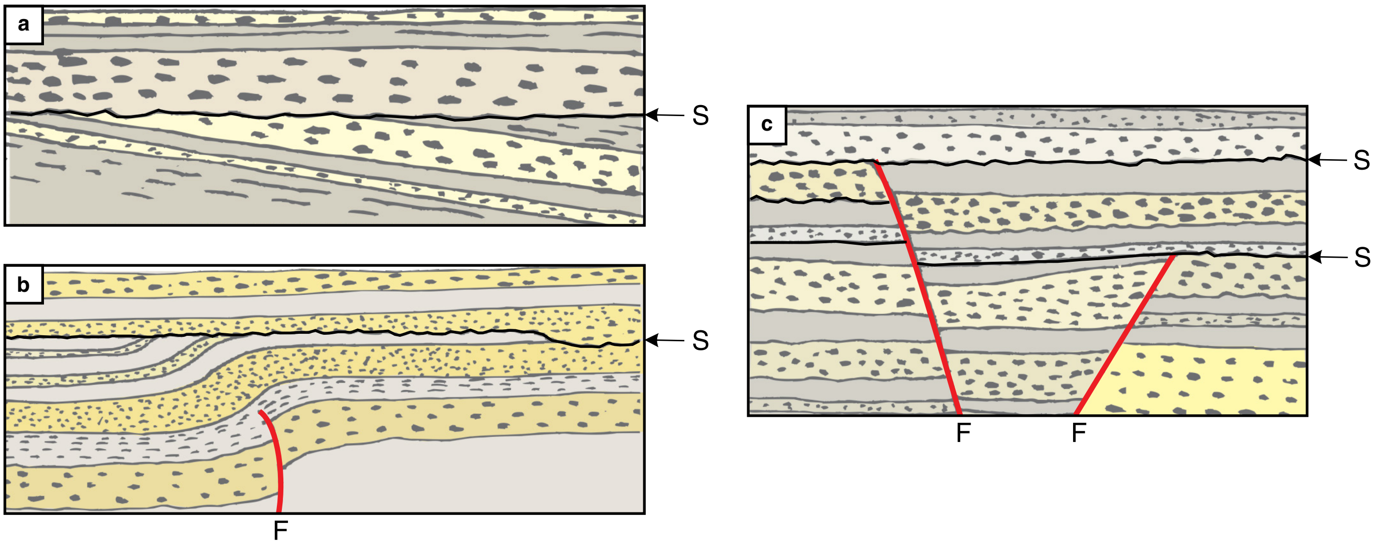

Figure 21. Main structures in El Vínculo quarry. Different–order bounding surfaces (s). **(a)** Discordant strata corresponding to an eighth–order surface. **(b)** Fossilized fold under an eighth–order surface that locally produces a paraconformity. **(c)** Normal diachronic faults and bounding surfaces. (S) erosive surface; (F) fault. Modified from López (2006).

during the Tertiary and have been inactive ever since. In the lower foothills, in contact with the alluvial plain in the Tuluá sector, superficial levels of detachments have been inferred. The evidence suggests that the western foothills of the Central Cordillera were developed by different tectonic events. Despite the small number of faults and sampling sites, these data provide insights into the recent tectonic history and thus the paleoseismicity of the region. The measured fault planes were dated (between 18 and 6 ky BP) using the ^{14}C analyses of overriding paleosols (López & Audemard, 2011; Woodward–Clyde Consultants, 1983) and stratigraphic criteria in El Vínculo quarry (López & Moreno–Sánchez, 2005).

Applying structural deformation models (e.g., Crowell, 1982; Harding & Lowell, 1979; Wilcox et al., 1973) indicate that the compression at the Buga Salient may indicate future surficial ruptures transverse to the Central Cordillera, probably associated with the ENE right–lateral strike–slip Ibagué Fault (Montes et al., 2005a). This observation would be consistent with that of Corredor (2003), who argued that this fault is a regional transfer zone. Compared with the structures observed at the eastward termination of the Ibagué Fault and at the Piedras–Girardot fold and thrust belt (e.g., Montes et al., 2003), the structures at the Buga Salient seem to be in an embryonic stage of development.

In addition, to the west of the Buga Salient, Sonso Lake has developed at the narrowest site of the valley. This is due to the increased subsidence that is probably related to the weight of the thrust sheets that control the morphology of this part of the valley. Consequently, the sinuosity pattern of the Cauca River changes, as described by López (2006) and López et al. (2009a), in accordance with the concepts of Schumm et al. (2002).

A very different structural style is observed in the Western Cordillera. The trench established at the Loboguerrero Fault by Woodward–Clyde Consultants (1983) reveals that a negative flower structure is developing along a NNE strike–slip fault related to the Dagua–Calima Fault. In addition, the main structure that borders the Cauca valley on the eastern side of the Western Cordillera presents features of strike–slip offset, and its morphological expression is parallel to NNE faults, some of which have horizontal slickensides, as reported by López et al. (2009a) at variante San Marcos.

The evidence summarized here supports the hypothesis that the active structures of the Cauca valley and the Central Cordillera are a consequence of the indentation of a continental wedge below the Cauca valley (e.g., Meissner et al., 1976). A composite transverse section is presented in Figure 26, which extends from the Pacific plain through the Western and Central Cordilleras up to the Magdalena valley at the latitude of El Guamo (see Figure 1 for location). This conceptual model connects the main data presented here (Figure 27) with the regional geological data of the Servicio Geológico Colombiano, as well as the data described by Meissner et al. (1976). One of the arguments that supports the existence of a continental wedge is based on the crustal density data interpreted as part of the "Proyecto Cooperativo Internacional – Nariño" study (Meissner et al., 1977).

These data suggest that a low–density indentation of continental crust exists below the Cauca valley. In this model, the Upper Cretaceous basement ("Western Cordillera") is

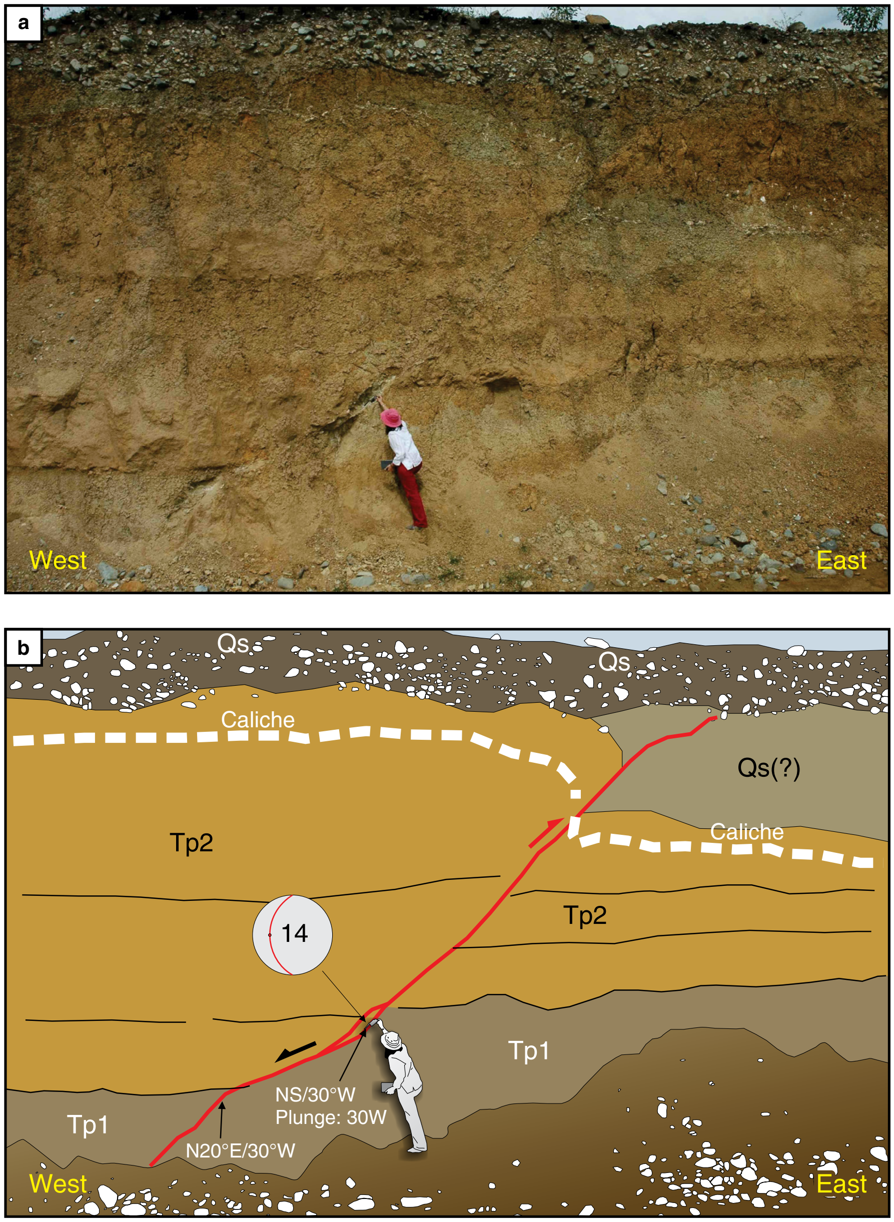

Figure 22. Detail of Figure 18. **(a)** Western side of El Vínculo quarry (3° 48' 36.66'' N – 76° 18' 26.64'' W). **(b)** Interpretative drawing of (a); the two–letter and number codes are for sedimentary strata of La Paila Formation. Normal fault is reactivated as a reverse fault. In the lower part of the fault, the displacement levels of La Paila Formation appear normal, while in the upper part, the displacement of calcrete levels indicates the reverse characteristic of the most recent fault. The Quaternary conglomerate level (Qs) is apparently not displaced; however, the Qs (?) levels are affected. After López (2006).

being detached from the continental basement (of Precambrian to Paleozoic and locally Mesozoic age). From this model, it is inferred that at a regional level, this basement is being thrust below the Cauca valley. The structure above the wedge is an effect of the compressive stress due to this indentation, as has been documented in the recent structures between Sonso and Tuluá. The growth strata directly related to the west–vergent faults and their backthrusts have developed over a superficial wedge that behaves as a subcritical Coulomb wedge.

The radiometric ages of La Paila Formation indicated that the reactivation of normal faults occurred after the Pliocene. Before this time, the sedimentation of this unit occurred in an extensional regime with the input of volcanic activity. According to the data in El Vínculo quarry, two cycles of tectonic quiescence and at least two cycles of faulting controlled the

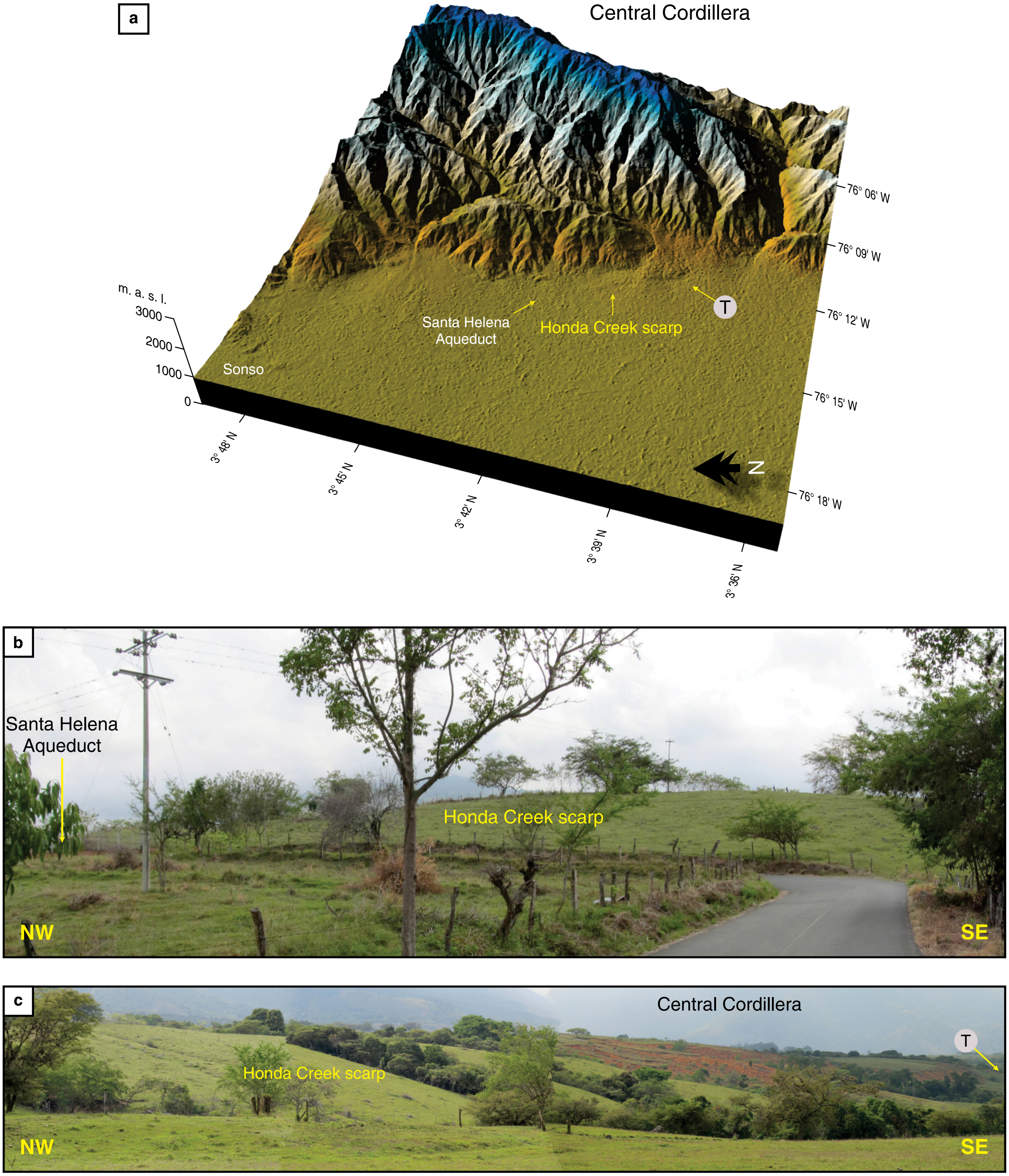

Figure 23. (a) Digital elevation model between Sonso in the north and Amaime in the south, with the location of the subtle Honda Creek NW–SE trending scarp. The relief is exaggerated 5 times. **(b, c)** View of the Honda Creek NW–SE trending scarp, taken from the Ginebra–Santa Elena Aqueduct roadcut toward the east (3° 39' 37.28'' N – 76° 13' 15.19'' W) (b) View of the NW tip of the scarp at the aqueduct (3° 39' 42.01'' N – 76° 13' 9.14'' W) (c) View of the SE prolongation of the scarp. (T) Location of the Venecia trench (3° 38' 42.1'' N – 76° 12' 41.76'' W).

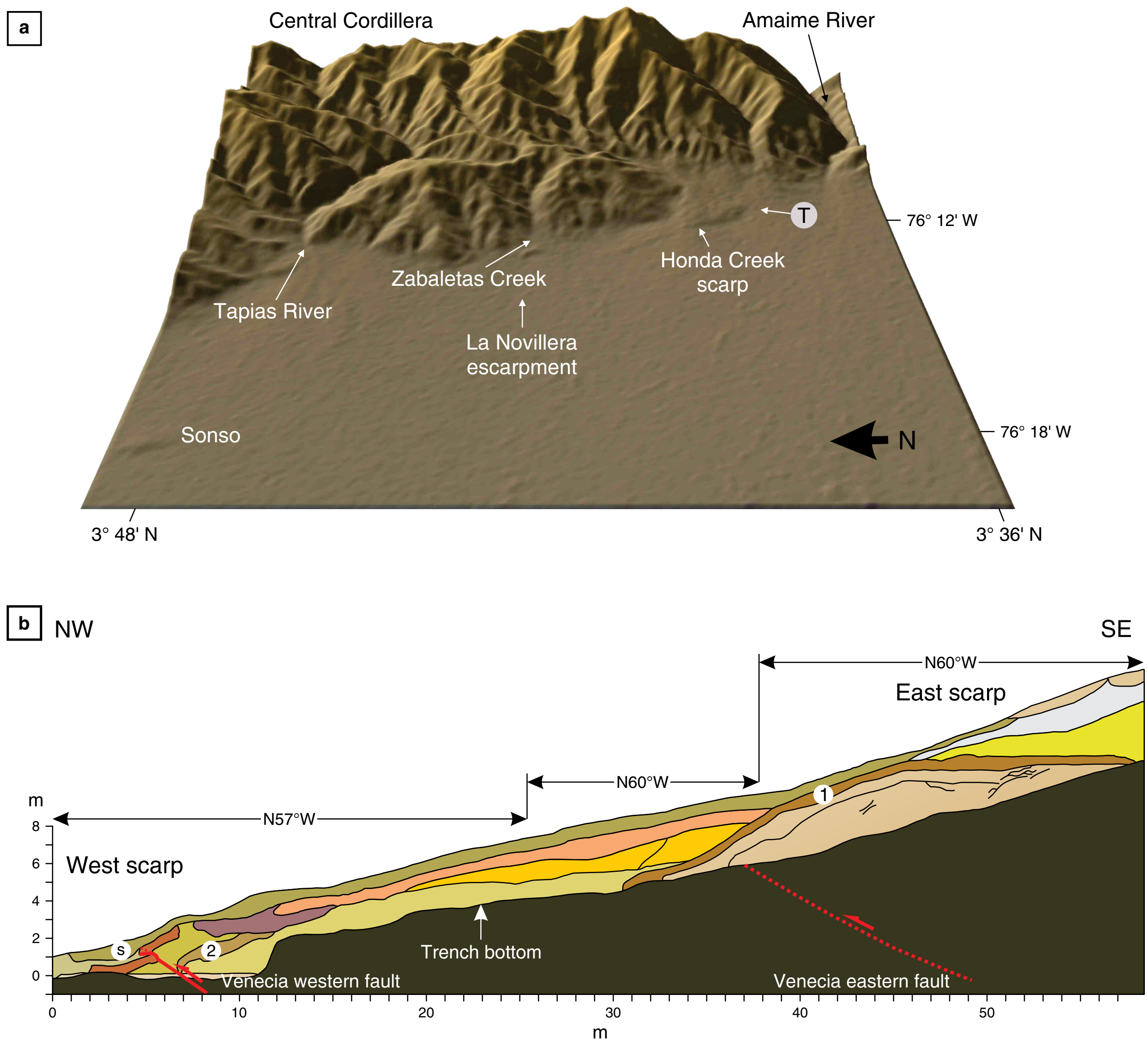

Figure 24. (a) Digital elevation model of the Sonso–Amaime sector. The relief is exaggerated 10 times. The escarpments that make up the lateral ramp of the thrust front are highlighted. Note the Honda Creek and Novillera scarps. (T) Location of the trench (3° 38' 42.1'' N – 76° 12' 41.76'' W) presented below. **(b)** Venecia trench log (modified from I. Mesa and W. Page of Woodward–Clyde Consultants, 1983). The present soil (s) has a vertical separation of 1 m relative to the lowest scarp. Folding was produced by two west–vergent thrust faults. Offset calculated over the dip of 2 m. Numbers 1 and 2 are paleosols. Modified from López (2006).

deposition of the fluvial sequences of La Paila Formation, which was characterized by the presence of paraconformities and progressive unconformities. After that time, the recent period of tectonic inversion most likely began.

Barrero & Laverde (1998) proposed that La Paila Formation was formed by the accretion of the Panamá Isthmus. However, the age of the unconformity between La Paila and Zarzal Formations falls in the Pliocene (Figure 28). This suggests that most of this unit was developed in an extensional environment without the effects of collision. The effects of compression are only detectable at the end of the deposition of La Paila Formation. Radiometric data indicate that the age of this formation extends into the Pliocene. This is in agreement with the age of the formation of the Isthmus of 2.8 Ma (e.g., O'Dea et al., 2016).

Palynomorphs analyzed by the Smithsonian (Anexo 5 in López et al., 2009a) contain, among others, *Myrica*, which was found in samples dated at 4.27 Ma (Anexo 23 in López et al., 2009b). *Myrica* is an immigrant taxon associated with boreal flora (Hooghiemstra, 1994b; Hooghiemstra et al., 2006); accordingly, the distribution of this taxon can be extended to this age. The dis-

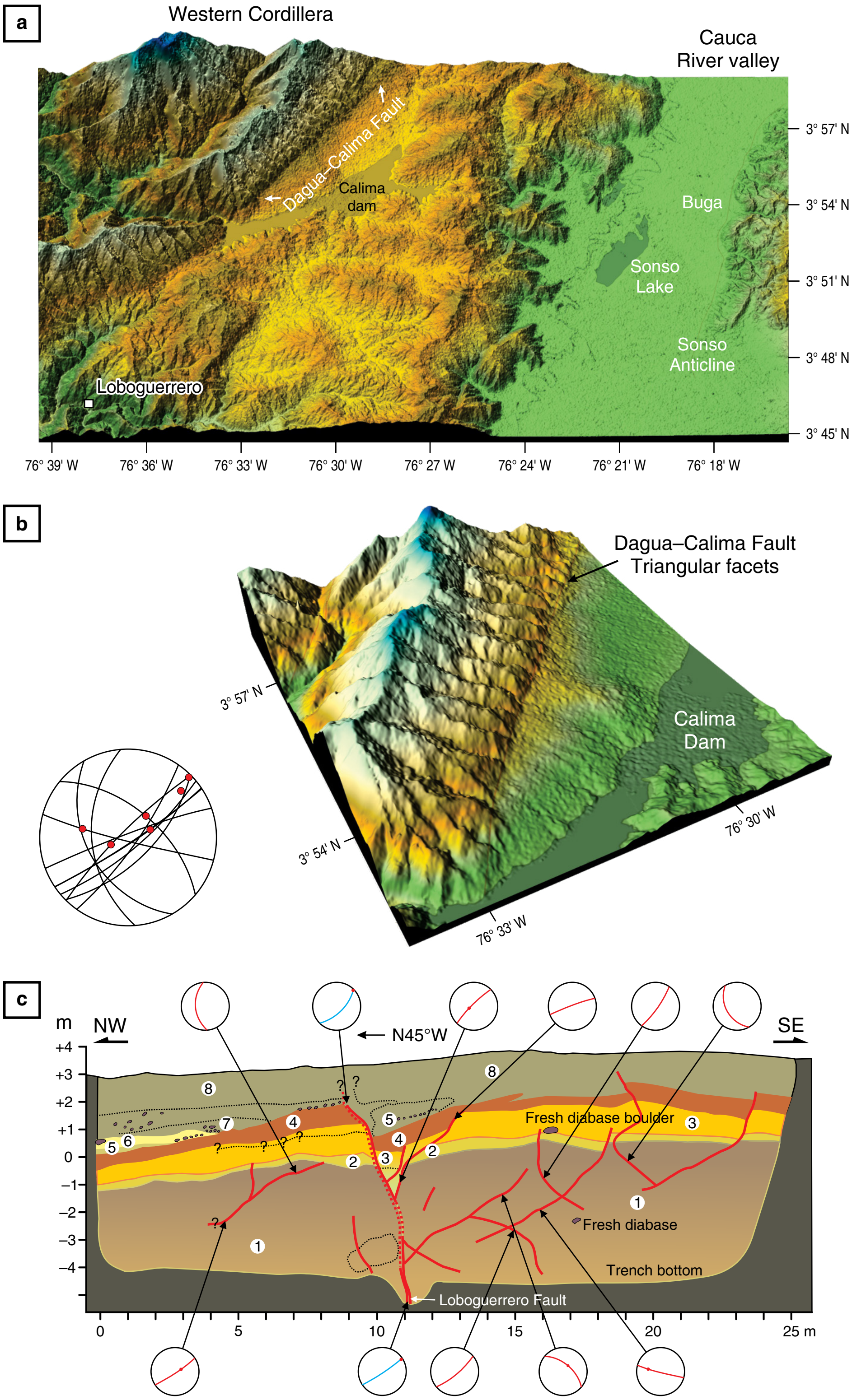

Figure 25. Morphological and stratigraphic evidences of tectonic deformation in Western Cordillera. **(a)**, **(b)** Digital elevation models (made from the NASA Shuttle Radar Topography Mission (SRTM) DEM version 1 (https://dds.cr.usgs.gov/srtm/version1/South_America/)) of Loboguerrero (vertical exaggeration 4 times) and Dagua–Calima Fault (vertical exaggeration 6 times) respectively. **(c)** Loboguerrero trench log (modified from Londoño and West of Woodward–Clyde Consultants, 1983). **(1)** Clays with clasts of fresh diabase. **(2)**, **(4)**, **(5)**, **(6)**, **(7)** Paleosols. **(3)** Silt with angular diabase clasts. **(8)** Organic soil. The main fault at the center of the trench has horizontal striations. Secondary structures are extensive structures. Modified from López (2006).

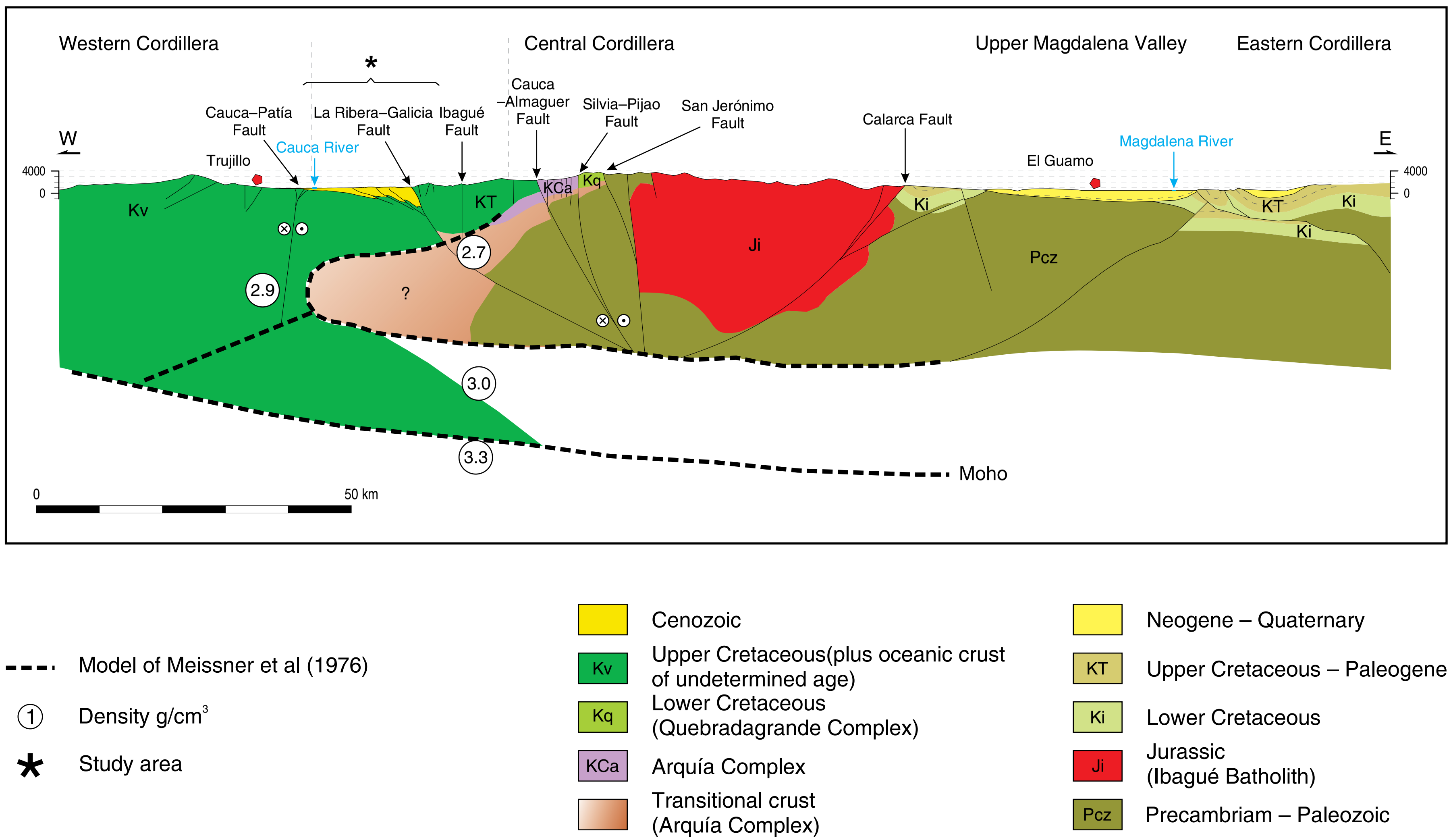

Figure 26. Geological section between the Trujillo (east of the Western Cordillera) and Guamo regions (in the Upper Magdalena Valley). The geology of the Cauca valley and the eastern flank of the Central Cordillera is based on Nivia (2001) and data from López (2006). The geology of the Magdalena valley is modified from Butler & Schamel (1988). The structure of the crust at the latitude of Buenaventura is based on the gravimetric profile of Meissner et al. (1976). See Figure 1 for the location of the section. Modified from López (2006).

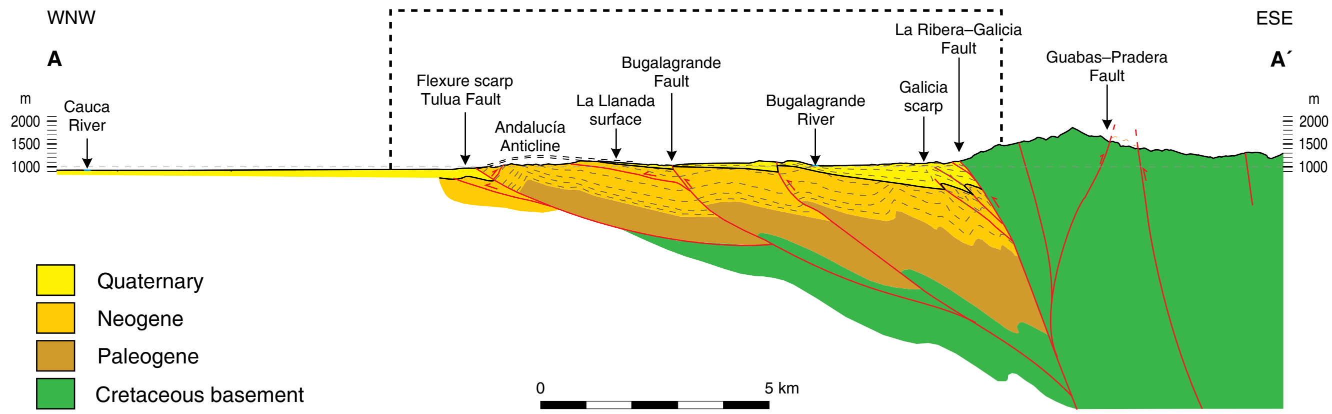

Figure 27. AA' cross section in the N80°W trough of the Cauca valley and the Central Cordillera, between Bugalagrande in the north and Tuluá in the south. Note the development of piggy–back basins where the Quaternary sediments from the main mountain front are deposited. The detachment of the west–vergent faults is reconstructed from a structure that controls the main frontal mountain range. The topographic profile is based on 25–m contour lines. See Figure 1 for the location of the section. Modified from López (2006).

tribution of immigrant plants can be compared with the arrival of mamifers to South America (Figure 29; Marshall, 1981; Marshall et al., 1982). Furthermore, La Paila Formation can be established as a unit of interest to complement the studies of the Bogotá High Plain in the Miocene – Pliocene interval (Figure 29).

7. Conclusions

Based on the stratigraphic relationships between the lithological units cropping out in the Cauca Basin, the following conclusions can be drawn, which are illustrated in a chronostratigraphic map (Figure 28):

- In the area of the Buga–Cartago Basin, the term "Cinta de Piedra" does not apply because its type locality is located far to the south of the Cali–Patía Basin.
- The term "Cinta de Piedra" was extensively used in the Cauca Basin in an epoch when lithological continuity was presumed between the conglomerates of the Cali–Patía and Buga–Cartago Basins. However, none of the Cenozoic units of the Cali–Patía Basin crops out in the Buga–Cartago Basin. The use of the term "Cinta de Piedra" for the serranía de Santa Bárbara (Cartago–Buga Basin), despite its previous application to the Jamundí conglomerates, is a reason for its abandonment according to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005) because of its homonymy. Instead, the term "Cartago Formation" should be used in the Buga–Cartago Basin.
- The Vijes limestones (Vijes Formation) have an Oligocene age and represent the northern prolongation of the Cali–Patía Basin. These limestones (including the Vijes conglomerates) overlie the volcanic rocks of the Diabasic Group.
- La Pobreza Formation should be abolished because of its homonymy with La Paila Formation.
- Both the terms "Buga Formation" and "La Paila Formation" have been used to partially describe the same sedimentites.
- The lower part of La Paila Formation is equivalent to the top of the Cartago Formation (as described in the Guadalajara River section).
- The Cartago Formation and, in some cases, the Monteloro Formation, unconformably overlie the Amaime and Nogales Formations of Cretaceous age.
- In the Buga–Cartago Basin, the beds that define the limits or contacts between formations have not yet been defined.

In the western foothills of the Central Cordillera, most of the recent reverse faults break pre–existing folds, both towards the orogen and towards the basin. Growth strata of the alluvial fan in Tuluá indicate synthectonic deposition of quaternary sediments.

Out–of–sequence thrust faults generate asymmetric folds in Quaternary deposits, some of these faults are normal fault inversions. These evidences, together with the position of the unconformities observed in El Vinculo quarry, indicate that the last stage of deposition of La Paila Formation occurred under a compressive regime, after the Pliocene.

The structures documented in the Buga Salient between Andalucía in the north and Amaime in the south support the current maximum E–W compression. This last phase of deformation created the main folds in the region, forming the Andalucía and Sonso Anticlines and reactivating some of the older normal faults.

Unfortunately, many of the outcrops presented here, including those that provide stratigraphic evidence of tectonic activity, have disappeared due to erosion, weathering, and mainly quar-

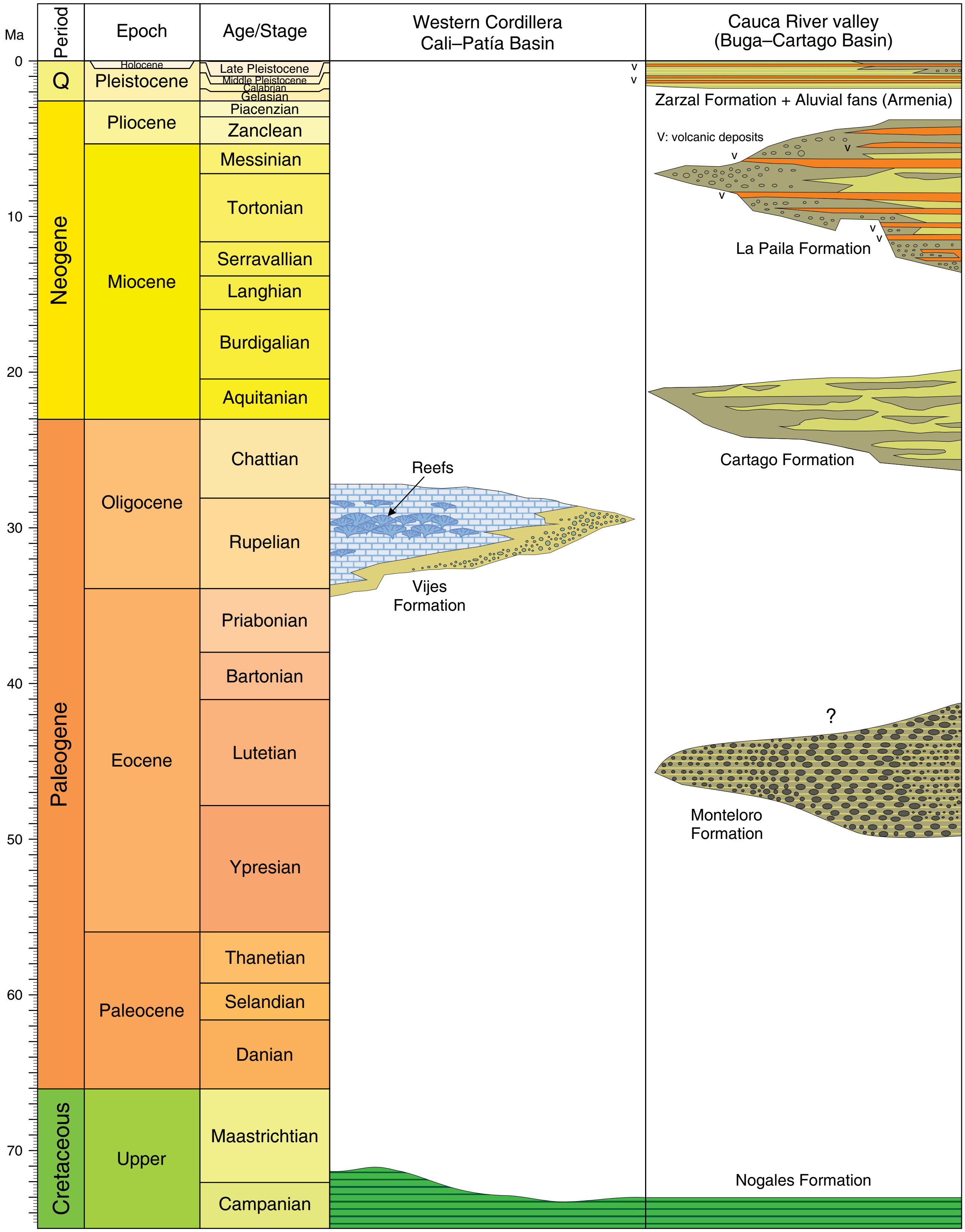

Figure 28. Chronostratigraphic chart of the northern part of the Cali–Patía Basin and the Buga–Cartago Basin. Time scale sensu Cohen et al. (2013; updated 2017/2).

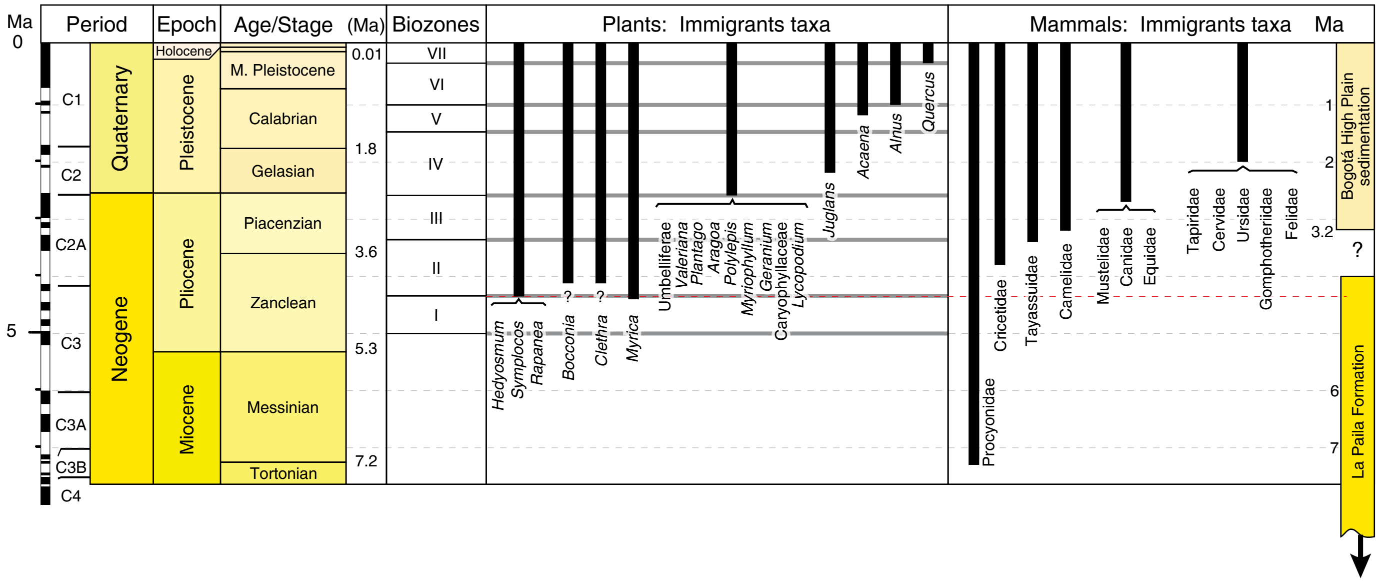

Figure 29. Chart of the distribution of Neogene and Quaternary immigrant plants and mammifers at the age of La Paila Formation. Data from Marshall (1981), Hooghiemstra (1994b), Hooghiemstra et al. (2006), and López et al. (2009b).

rying. Despite the small number of faults and sampling sites, these data provide insights into the recent tectonic history and thus the paleoseismicity of the Cauca valley.

From a paleoseismic point of view, the Cauca valley is susceptible to suffering the impacts of M > 7.5 earthquakes on thrust faults. The investigation of how much stress has been released or is accumulating on the Cauca valley and its relationship with the E–W right–lateral strike–slip system is necessary when applying all of the available techniques.

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Explanation of Acronyms, Abbreviations, and Symbols:

BP	Before present
ca.	About
PLOCO	The spanish acronym for “Provincia Litosférica Oceánica Cretácica Occidental”
SGC	Servicio Geológico Colombiano

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