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Chapter 8

Holocene Lahar Deposits Associated with the Eruptive Activity of Cerro Machín Volcano, Colombia: Impact on Landscape and Associated Potential Hazards

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Abstract Cerro Machín Volcano is an active volcano (4° 29' N; 75° 23' W) located in the central part of the Colombian Andes (Tolima Department, Colombia). Lahars are one of the greatest hazards associated with Cerro Machín Volcano. Approximately 300 000 people live in lowlands around the volcano. This added to the explosive potential, chemical composition, magnitude of its eruptions, and distribution of its deposits make Cerro Machín one of the most dangerous volcanoes in Colombia. Volcanic risk management of Cerro Machín requires a balance of science, education, risk reduction, and disaster management, which are all critical to the safety, well–being, and quality of life of the population living around the volcano.

The highly explosive eruptions that have occurred in the last 10 000 years have generated thick sequences of pyroclastic fall and pyroclastic density current deposits, which have filled the valleys of rivers and streams within a 15 km radius of the volcano. The interaction of pyroclastic material with water generates large lahars that flow for distances greater than 100 km along the Coello and Magdalena Rivers channels. The distribution and total extension of the lahar deposits allow us to identify three deposition areas: proximal, intermediate, and distal. I identified six lahar units between the towns of Carmen de Bulira and Nariño, located 42 and 113 km from the volcano, respectively. Four units were defined as being dominated by hyperconcentrated flow deposits and two by debris flow deposits. The former are associated with pumice pyroclastic flows, while the latter are associated with block and ash pyroclastic flows. The lahars from Cerro Machín had a key role in the configuration of the regional landscape of a particularly important sector of Tolima Department. The lahar deposits dammed and changed the course of the Coello and Magdalena Rivers, forming terraces and large coalescent fans, El Guamo and El Espinal. Dam breakouts originated lahars. Hyperconcentrated flow deposits (dated 9130–8540 y BP; 4360 ± 105 y BP; 3618–3186 y BP; 1200 ± 105 y BP) and debris flow deposits (dated ca. 2500 y BP and <1200 y BP) cover an area of approximately 1074 km^2 (equivalent to a volume of 22.5 km^3). Numerous towns, such as Payandé, Valle de San Juan, Gualanday, San Luis, El Guamo, El Espinal, Chicoral, Flandes, and Coello in the Tolima Department and Girardot and Nariño in the Cundinamarca Department, have been built on these lahar deposits. The inhabitants of

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these towns are mostly unaware of the volcanic origin of their territory because Cerro Machín erupted 900 years ago, and no historical activity is known.

Keywords: *Colombian Andes, Cerro Machín Volcano, lahars, debris flows, hyperconcentrated flows, volcaniclastic, fans, Plinian eruptions.*

Resumen El Volcán Cerro Machín es un volcán activo (4° 29' N; 75° 23' W) localizado en la parte central de los Andes colombianos (departamento del Tolima, Colombia). Los lahares son una de las mayores amenazas asociadas al Volcán Cerro Machín. Aproximadamente, 300 000 personas viven en las tierras bajas alrededor del volcán. Esto sumado al potencial explosivo, la composición química, la magnitud de sus erupciones y distribución de sus depósitos hacen del Cerro Machín uno de los volcanes más peligrosos en Colombia. La gestión del riesgo volcánico del Cerro Machín requiere un balance entre ciencia, educación, reducción del riesgo y manejo de desastres, los cuales son todos cruciales para la seguridad, bienestar y calidad de vida de la población que vive alrededor del volcán.

Las erupciones altamente explosivas ocurridas en los últimos 10 000 años generaron sucesiones espesas de depósitos de caída piroclástica y de corrientes de densidad piroclástica, que llenaron los valles de los ríos y quebradas en un radio de 15 km del volcán. La interacción de material piroclástico con agua generó grandes lahares que fluyeron por distancias mayores a 100 km a lo largo de los canales de los ríos Coello y Magdalena. La distribución y extensión total de los depósitos de lahar permiten identificar tres áreas de depósito: proximal, intermedia y distal. Se identificaron seis unidades de lahar entre las poblaciones de Carmen de Bulira y Nariño, localizadas a 42 y 113 km del volcán, respectivamente. Cuatro unidades fueron definidas como dominadas por depósitos de flujo hiperconcentrado y dos por depósitos de flujo de escombros. Los primeros están asociados con flujos piroclásticos pumíticos, mientras los últimos están asociados con flujos piroclásticos de bloques y ceniza. Los lahares del Cerro Machín tuvieron un papel clave en la configuración del paisaje regional de un sector muy importante del departamento del Tolima. Los depósitos de lahar represaron y cambiaron el curso de los ríos Coello y Magdalena, formando terrazas y grandes abanicos coalescentes, El Guamo y El Espinal. La ruptura de los represamientos originó lahares. Depósitos de flujo hiperconcentrado (datados en 9130–8540 años antes del presente; 4360 ± 105 años antes del presente; 3618–3186 años antes del presente y 1200 ± 105 años antes del presente) y depósitos de flujo de escombros (datados en ca. 2500 años antes del presente y <1200 años antes del presente) cubren un área de aproximadamente 1074 km^2 (equivalente a un volumen de 22,5 km^3). Numerosas poblaciones, tales como Payandé, Valle de San Juan, Gualanday, San Luis, El Guamo, El Espinal, Chicoral, Flandes y Coello en el departamento del Tolima y Girardot y Nariño en el departamento de Cundinamarca, están construidas sobre estos depósitos de lahar. Los habitantes de estas poblaciones, en su mayoría, desconocen el origen volcánico de su territorio, debido a que el Cerro Machín hizo erupción hace 900 años, y no se conoce ninguna actividad histórica.

Palabras clave: *Andes colombianos, Volcán Cerro Machín, lahares, flujos de escombros, flujos hiperconcentrados, volcanoclástico, abanicos, erupciones plinianas.*

1. Introduction

The main purpose of this chapter is to publicize the studies of lahar deposits associated with the highly explosive eruptions of the Cerro Machín Volcano (CMV) as well as the nature and role of the CMV in the geological formation of part of Tolima Department and its associated hazards.

Lahars are associated with volcanic eruptions and other processes in mountainous volcanic regions. They are generated when large masses of water mix with existing sediments on the slopes of volcanoes. Lahars are saturated with water, and the interactions between the liquid and solids influence their behavior and distinguish them from other volcano–related phenomena. The rock fragments transported by lahars make them particularly destructive; the abundant liquid allows them to flow along gentle slopes and to flood distant areas. People in these areas normally do not recognize this danger or anticipate the destructive power of lahars (Vallance & Iverson, 2015), as unfortunately occurred in Colombia with the eruption of Nevado del Ruiz Volcano (NRV) on 13 November 1985, that caused the destruction of Armero in the Tolima Department and had disastrous effects on populated areas of the Villamaría and Chinchiná municipalities in Caldas Department (Pierson et al., 1990).

The study area is located in the Tolima Department and part of the Cundinamarca Department (distal region located to the SE of the CMV) and includes the land along the banks of the Coello and Magdalena Rivers, including El Guamo and El Espinal Fans (Figure 1).

Because this chapter is a review, it presents an update on the state–of–the–art studies on lahars associated with the CMV, which originate from the interaction of pyroclastic density current deposits (pyroclastic flows and pyroclastic surges) and water. The large distribution of CMV lahar deposits and their excellent outcrops, unlike other active Colombian volcanoes of similar eruptive styles, have allowed pioneering studies (Cortés, 2001a, 2001b), complementary studies (Hernández & Sánchez, 2012; Hurtado & Murcia, 2003; Murcia et al., 2008), and follow–up studies, which are all presented here. These studies provide excellent examples and overviews of the significant dynamics and geomorphological changes associated with highly explosive eruptive processes.

This chapter presents information about the origin of the CMV lahar deposits, such as their type, age, distribution, and minimum volume, as well as important knowledge about the eruptive history, hazard assessment, and volcanic risk of the CMV. This chapter is relevant because Colombia, as was demonstrated by the lahars generated by the eruption of the NRV in 1985 (the most catastrophic lahars in global history), is a classic example of how lahars can damage and destroy communities downstream of volcanoes, independent of the mechanism that generates them. NRV lahars caused by the interaction between hot pyroclastic flows or surges and glacial ice and snow at the summit of the volcano destroyed more than 5000 homes and killed more than 23 000 people. A total of approximately 9×10^7 m^3 of lahar slurry was transported to depositional areas up to 104 km from the source area, and the initial volumes of individual lahars increased up to 4 times with distance from the summit (Pierson et al., 1990). Vallance & Iverson (2015), in addition to presenting examples of historical lahars with different origins, highlighted the importance of considering prehistoric studies that reveal the potential for even greater disasters. An important and iconic example of a prehistoric lahar is the 3.8 km^3 Osceola mudflow from Mount Rainier, USA (5600 years ago), transformed from an enormous debris avalanche within a few kilometers of its source. The inundated area is now populated by hundreds of thousands of people (Crandell, 1971; Vallance & Pringle, 2008; Vallance & Scott, 1997).

Due to the importance of the CMV and its risk to the country, this chapter contributes to the "Apropiación Social de Conocimiento Geocientífico" project of Servicio Geológico Colombiano (SGC) that seeks to reduce the high existing vulnerability and to communities who are knowledgeable about their territory and therefore more resilient. CMV represents a significant challenge to volcanic risk management in Colombia. Knowledge of the risk is the first step towards its reduction.

2. Methodology

Because this is a revision and follow–up study, it was necessary to begin with a compilation of the geological studies that have been carried out on the lahars of the CMV. In the main study that was updated and synthesized in this chapter, a photogeological analysis was carried out, and several phases of fieldwork were performed, including the identification of the transition zone between pyroclastic density currents and lahars, transport zones without deposition, and transport zones with deposition. The fieldwork focused on the latter, which corresponded to large extensions in the distal area SE of the CMV in the Tolima and Cundinamarca Departments (Figure 1). A total of 209 field stations were established, excluding those from complementary studies that have contributed and validated the initial proposal.

The sequence of the occurrence and deposition of the CMV lahar deposits was proposed based on the geological mapping (1:25 000) and stratigraphy of the lahar units that form the terraces located along the banks of the Coello and Magdalena Rivers and the existing fans in the study zone (Cortés, 2001a, 2001b). Specifically, detailed stratigraphic columns were surveyed, and ^{14}C dating on 5 carbon samples and soil samples were performed at University of Arizona (Table 1). Conventional sedimentological terminology is used to define the different particle sizes that form the units: clay, silt, sand, and gravel. Estimates of lahar volumes were obtained by multiplying the deposit area by the estimated average deposit thickness.

3. Cerro Machín Volcano (CMV)

The CMV is an active volcano in Colombia and is part of the northern volcanic segment of the Colombian Andes, which results from the subduction of the Nazca Plate beneath the South American Plate. It is located on the eastern side of the Central Cordillera of Colombia (4° 29' N; 75° 23' W) at 2750 masl, 17 km NW of the city of Ibagué, 35 km NE of the city of Armenia, and 150 km SW of the city of Bogotá (Figure 1).

The Machín Volcano is known as the CMV; the nickname "Cerro" is due to its low elevation (2750 masl) and because it is surrounded by much higher mountains; additionally, it is not clearly recognized as an active volcano. It formed on meta-

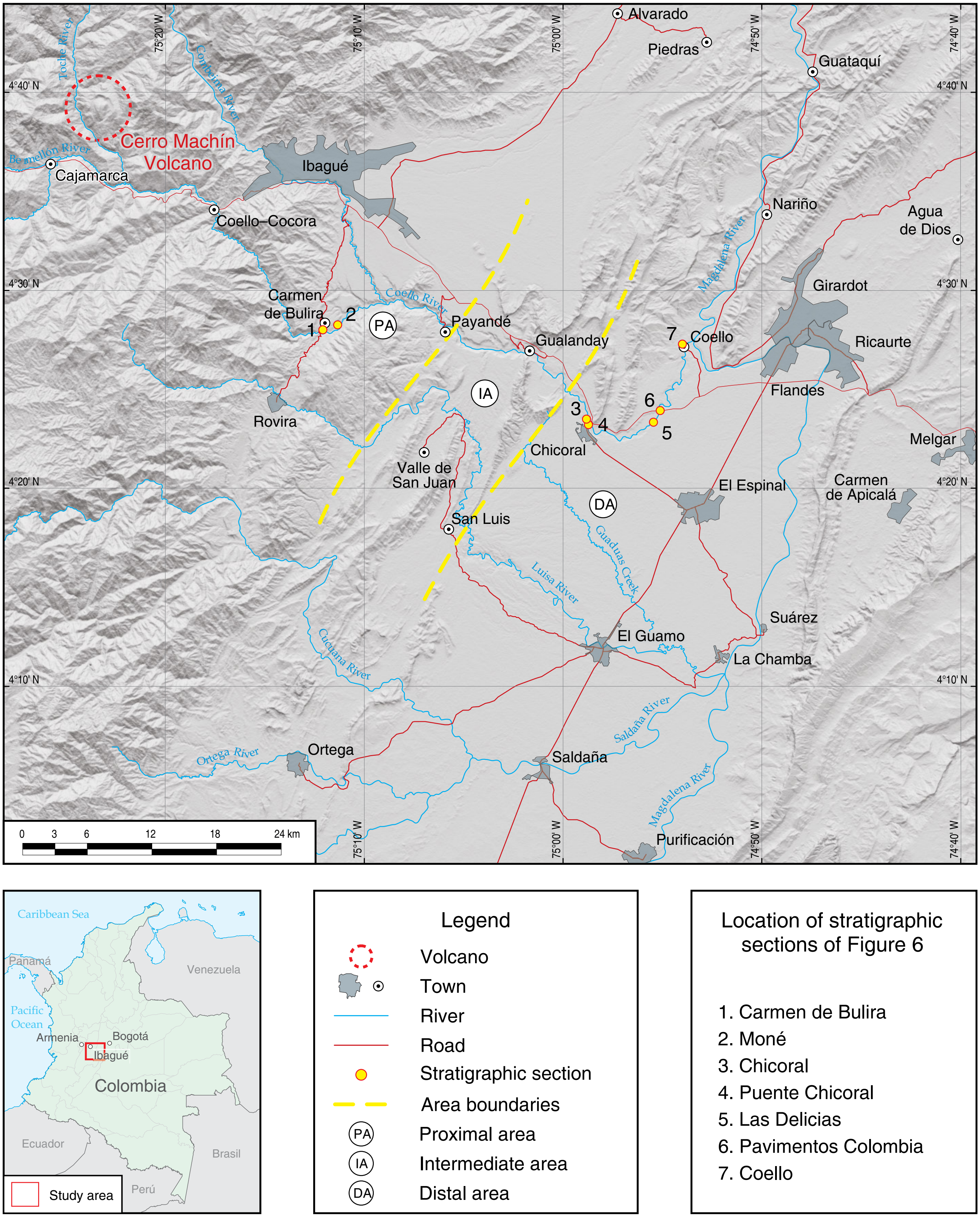

Figure 1. Location map of the CMV, the main population centers and drainage network in the study area. The Coello River, which is formed by the union of the Toche and Bermellón Rivers, and the Luisa and Saldaña Rivers are important tributaries of the Magdalena River, which is the largest river in the Andean region of Colombia.

Table 1. Radiocarbon dates of lahar deposits of CMV.

Sample	Age (y BP)	Sample type	Location*		Eruptive unit	Laboratory
			Latitude N	Longitude W		
JGP–06–3	1640 ± 45	Paleosol	4° 18’ 15”	75° 12’ 16”	Top DFD2	University of Arizona
JGP–06–1	2505 ± 65	Paleosol	4° 18’ 14”t	75° 12’ 18”	Below DFD_2	University of Arizona
JGP-78–3–1[a]	3618–3136	Charcoal	4° 05’ 40”	74° 51’ 59”	$HCFD_1$	University of Arizona
JGP–85	4360 ± 105	Charcoal	4° 03’ 07”	74° 53’ 38”	$HCFD_2$	University of Arizona
JGP–63–3–1[a]	9130–8540	Charcoal	4° 13’ 19”	74° 57’ 41”	$HCFD_3$	University of Arizona

*WGS84 reference system.

[a] Samples analyzed by accelerator mass spectrometry (AMS). Calibrated age range.

morphic rocks (quartz–sericitic schists, green schists, phyllites, quartzites, and some strips of marbles) of the Cajamarca Complex (Maya & González, 1995) that form the basement of the Colombian Central Cordillera. It is a typical pyroclastic–dome ring volcanic complex (Gómez et al., 2016; Monsalve et al., 2019) and has a crater approximately 2.4 km in diameter that opens towards the SW, with dacitic lava domes in the interior (Figure 2a–c) that exhibit discrete fumarolic activity.

The eruptive history of the CMV in the Holocene has been characterized by extended periods of quiescence (i.e., centuries), between which large eruptions (Volcanic Explosivity Index [VEI] of 5) occurred, which generated huge eruptive columns (mainly Plinian), pyroclastic fall, and pyroclastic density currents (pyroclastic flows and pyroclastic surges) and emplacement and destruction by lava domes (Aguilar & Piedrahita, 2017; Arango & Castañeda, 2012; Cepeda et al., 1996a; Méndez, 2001, 2002; Laeger et al., 2013; Murcia et al., 2010; Piedrahita et al., 2018; Rueda, 2000, 2005). After the eruptions, lahars were generated (Cortés, 2001a, 2001b; Cortés et al., 2006; Hernández & Sánchez, 2012; Hurtado & Murcia, 2003; Murcia et al., 2008) and descended through the main drainages of the volcano and its area of influence, blocking or damming them and leaving large terraces and fans as evidence of their impacts over large areas.

Because of its great explosive potential, its chemical composition (dacitic), the magnitude of its eruptions, the large distribution of its deposits, and the important population and existing infrastructure in its area of influence, the CMV is known as one of the most dangerous volcanoes in Colombia.

3.1. Previous Studies on Lahars Associated with the CMV

Based on photointerpretation with some field control, Soeters (1976) discussed the geomorphological development of the region between Ibagué and Girardot and referred to volcanic activity as a contributing factor. Cepeda et al. (1996a, 1996b) compiled the pre–1995 studies on the CMV, recording information on the type of volcano, current activity, tephrostratigraphy, volcanic surveillance, and potential eruptive activity. They classified the volcano as a pyroclastic ring–type (ash tuff ring) volcano and recognized the relationship between the deposits of El Espinal Fan (Figure 3) and upstream volcanic activity, referring to the fan as the volcanic–detrital Gualanday–Espinal plain. Núñez (2001) associated the formation of El Guamo and El Espinal Alluvial Fans with volcanic sources in the Central Cordillera. This study did not recognize significant differences in the stratigraphy and lithology; hence, the author considered everything as a single unit. As a pioneering study on the lahar deposits of the CMV, Cortés (2001a, 2001b) provided detailed descriptions of six units of lahar deposits (four corresponded to hyperconcentrated flow facies, and two corresponded to debris flow facies), presented ^{14}C data, and attributed the formation of El Guamo and El Espinal Alluvial Fans to these deposits. This grouping was carried out according to fieldwork on the characterization of units based on their composition, distribution, stratigraphy, and morphology. Méndez et al. (2002) described the potential volcanic hazard of the CMV and presented historical eruptive scenarios in detail, including a compilation of ^{14}C data from different types of deposits and the potential eruptive scenario and risk zone for each type of volcanic event that may occur in future eruptions. The potential eruptive scenario considers the basin of the Coello River, which will control the majority of the pyroclastic flows and surges via narrow (200 m) and deep (150 m) valleys with strong waters that favor the formation of lahars. Ingeominas (2003) presented information about the CMV in relation to “Túnel de La Línea” project and detailed future eruptive scenarios and their effects with a special emphasis on the Ibagué–Armenia road. Deposits associated with the CMV lahars filled the valleys of the drainage basin of the Coello River, and they overflowed and invaded other drainage basins, such as those of the Luisa, Guaduas, Cucuana, and Saldaña Rivers. Hurtado & Murcia (2003) and Murcia et al. (2008) studied in detail and characterized the Chicoral Debris Flow Deposit (DFD_2), which is one of the units proposed by Cortés (2001a, 2001b), and made important contributions related to the estimation of the peak discharge, mobility, and flow speed of the events that formed this unit. Additionally, they

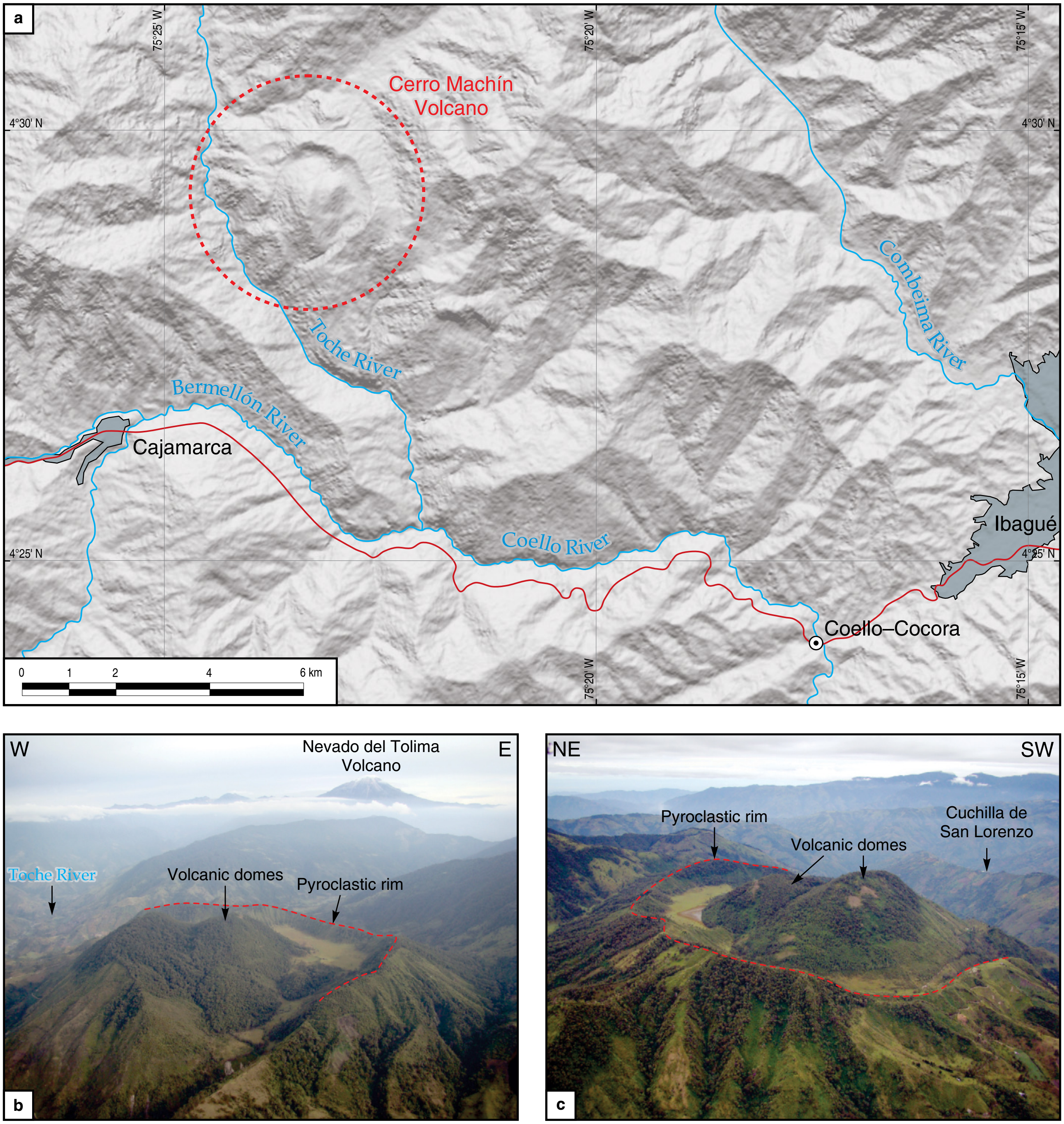

Figure 2. (a) Locations of the CMV, the Toche, Bermellón, and Coello Rivers, the population center of Cajamarca and part of the city of Ibagué. Image taken from Google Earth. **(b)** and **(c)** Aerial views of the CMV, which is a pyroclastic–dome complex ring volcano. Note the existing opening of the pyroclastic ring. (b) View from the south with the Nevado del Tolima Volcano in the background. (c) View from the NW with the cuchilla de San Lorenzo to the right. (Courtesy of the SGC– Observatorio Vulcanológico y Sismológico de Manizales).

discussed the implications of the CMV hazard. Hernández & Sánchez (2012) performed facies analysis of the lahar deposits in the CMV outcrops in the Gualanday–Coello section of the Ibagué–Bogotá relief road, which was built in 2010 and longitudinally and transversely cuts complete sequences deposited for 14 km along the Coello River. The authors performed a detailed study of the rheological changes in the lahars during downstream conveyance along the Coello River in 5 important

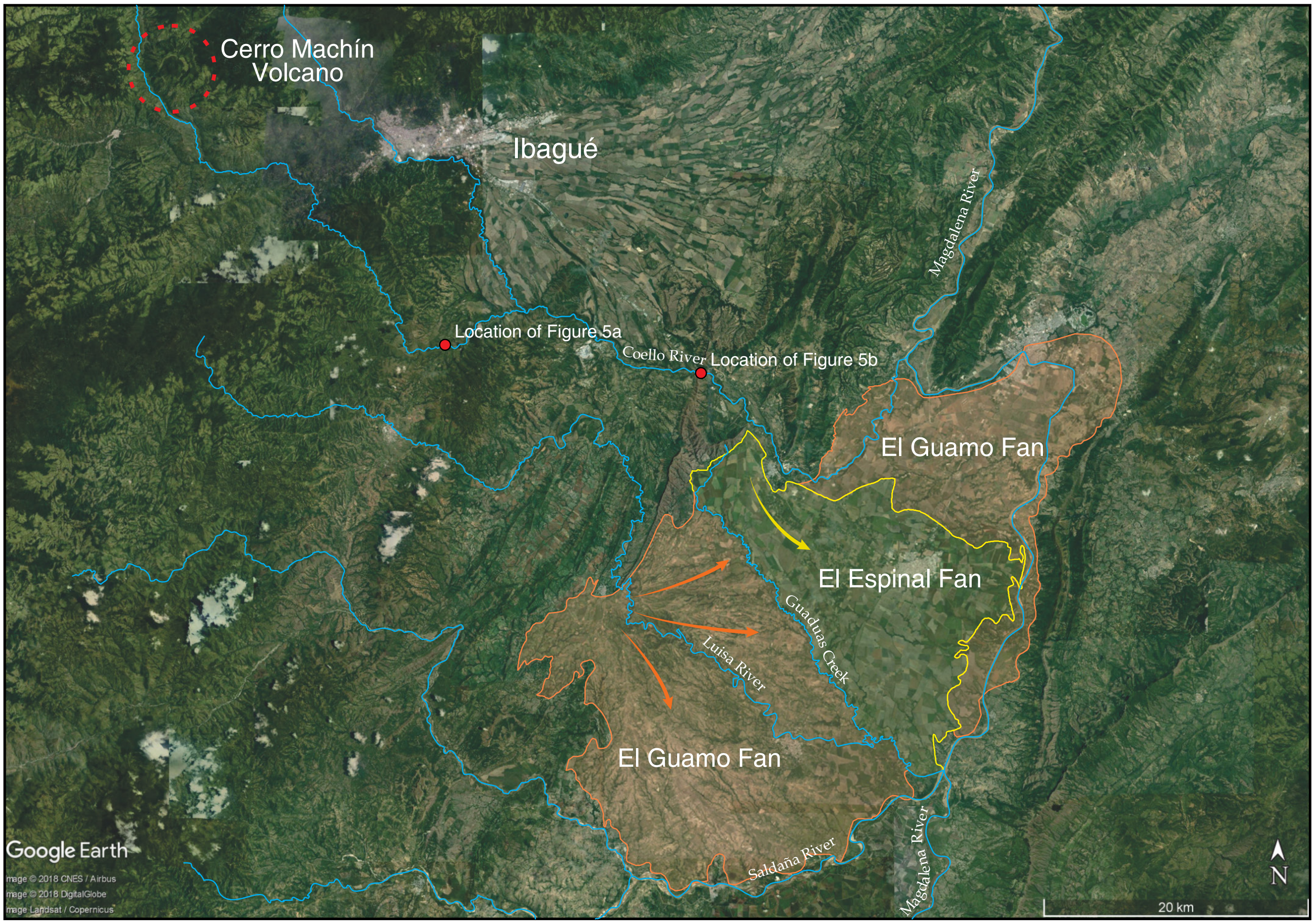

Figure 3. Google Earth image of the study area, in which El Guamo and El Espinal Fans are composed of lahar deposits from the CMV, which demonstrate the effects of explosive volcanic eruptions in the drainage basins and sedimentation in the area of influence of active volcanoes.

outcrops of the four oldest and largest units proposed by Cortés (2001a, 2001b), which verified the stratigraphic sequence proposed by the author.

3.2. Lahars

Lahar is an Indonesian word that describes discrete and rapid flows of high–concentration saturated mixtures that are driven by gravity and contain water and particles of rock, ice, wood, and other debris originating from volcanoes (Vallance, 2000).

Lahars can be primary, which are those generated during eruptions by several mechanisms associated with the eruption itself, or secondary (post–eruptive or unrelated to eruptions), which are those most commonly generated by tephra entrainment during heavy rains. Both types of lahars significantly threaten the safety, economic well–being, and community resources downstream of active volcanoes (Vallance & Iverson, 2015).

Lahars include one or more types of flows, including debris flows, transition or hyperconcentrated flows, and mudflows. Flow transitions are commonly defined in terms of their solid fractions; however, such transitions are gradual and depend on other factors, such as the distribution of sediment size, clay mineralogy, particle agitation, and flow energy (Vallance & Iverson, 2015). The different types of lahars have different consistencies; debris flows are thick and viscous and resemble wet concrete, whereas hyperconcentrated flows are more fluid, contain mostly mud and sand, and resemble motor oil in consistency. These two types of flows commonly occur in all types of mountainous terrain worldwide, but the largest and most far–reaching flows originate from volcanoes, where extremely large volumes of unstable rock debris and water can be mobilized (Mothes et al., 1998; Vallance & Scott, 1997).

According to Vallance & Iverson (2015), debris flows, as the name indicates, are mixtures of debris saturated with water that move downward by gravity, in which the solid and liquid fractions are volumetrically similar and move practically in unison. Hyperconcentrated flows correspond to transition flows between debris flows and stream flows. Unlike stream flow,

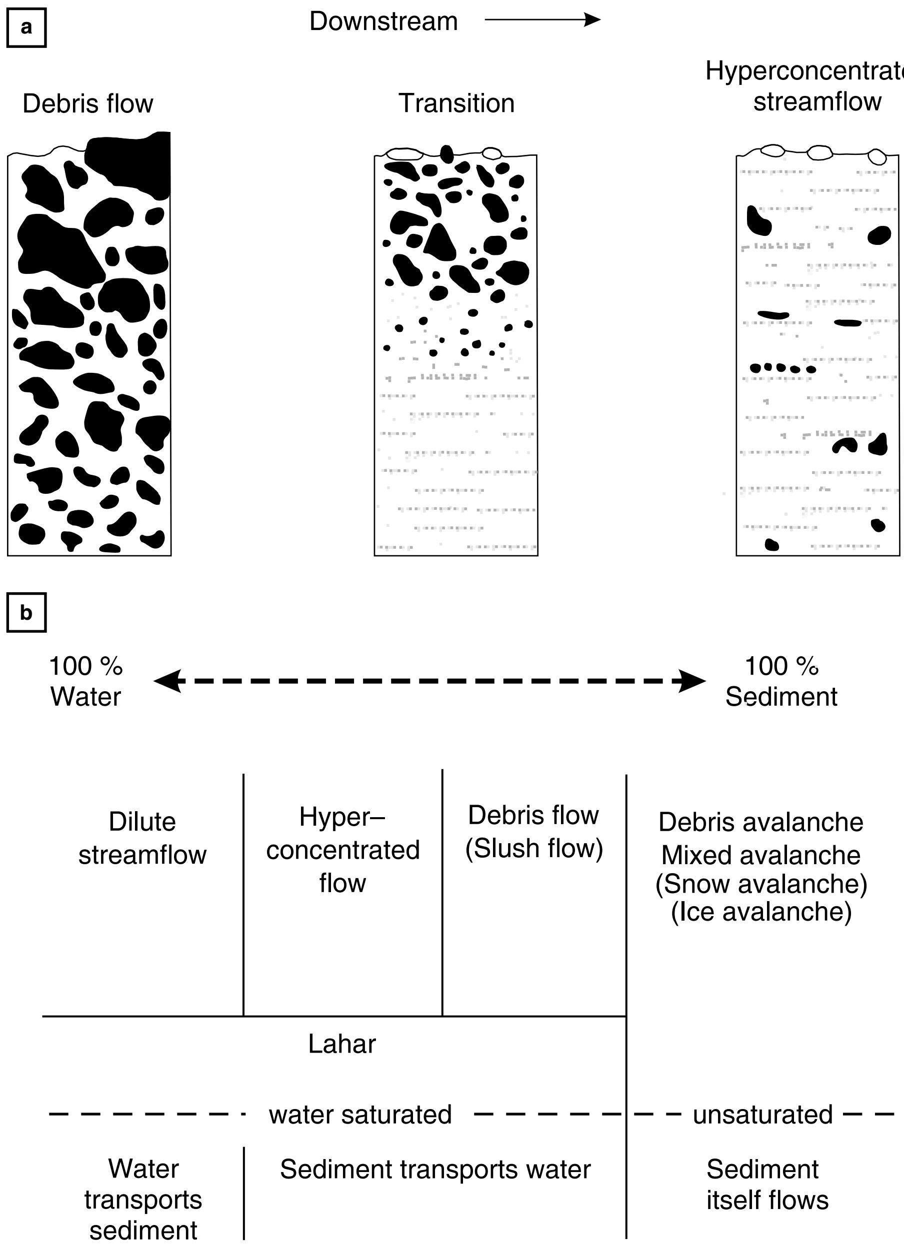

Figure 4. (a) Facies of deposits associated with lahars (Pierson & Scott, 1985). The debris flow deposits are poorly sorted and have a broad grain size distribution. The hyperconcentrated flow deposits are massive to slightly laminated and have a more restricted grain size distribution. **(b)** Diagram of flow types involving water and sediment based on the relative proportions of these two components (Pierson & Costa, 1987).

hyperconcentrated flow carries high sediment loads; furthermore, unlike debris flow, coarse–grained solids tend to separate vertically from the slurry (Figure 4a).

The behavior of the flows is highly dependent on the sediment grain–size distribution and the relative proportions of sediment and water, which can change during the flow (Figure 4b). Once the flow starts, it will find and incorporate erodible material in its course, thus increasing its volume; this process is known as bulking.

Lahar deposits are similar to those of a pyroclastic flow because they are composed of the same materials. Lahars can be generated by a variety of mechanisms. Pareschi (1996) synthesized and related the mechanisms to the source of water that mixes with volcanic sediments. Vallance & Iverson (2015) regrouped the mechanisms referred to by Pareschi (1996) into two categories: (1) lahars caused by melting snow and ice, floods, or heavy rains, and (2) lahars caused by flank collapses. The lahars in the first category are generated by a sudden release of water that may occur in four ways: by the rapid melting of snow and ice as a result of pyroclastic flows and surges (Lowe et al., 1986; Major & Newhall, 1989; Pierson & Janda, 1994; Pierson et al., 1990); by displacement

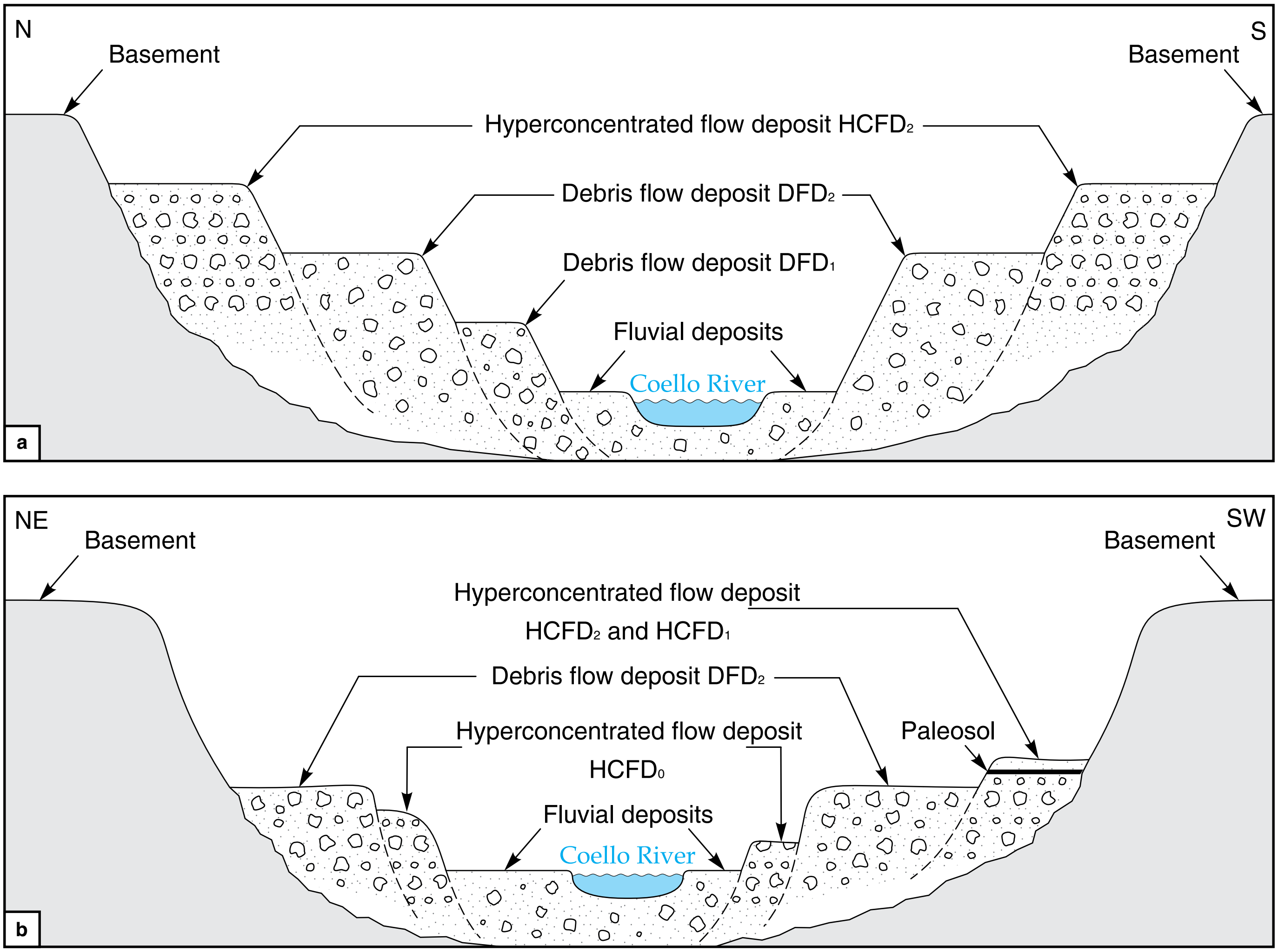

Figure 5. Stratigraphic sequences (not to scale) of lahar deposits of the CMV exposed in cross–sections of the Coello River valley. **(a)** Carmen de Bulira area (35 km). **(b)** Gualanday area (60 km). Modified from Cortés (2001a, 2001b).

during eruptions of large volumes of water from the crater and caldera lakes or a noneruptive lake breakout from dams created by volcanic debris (Cronin et al., 1997; Nairn et al., 1979; Scrivenor, 1929; Thouret et al., 1998); by the release of water trapped in subglacial lakes triggered by subglacial eruptions (Björnsson, 1975; Kilgour et al., 2010); and as a result of heavy rains that occur after eruptions (Barclay et al., 2007; Hodgson & Manville, 1999; Lavigne & Thouret, 2003; Manville et al., 2000; Rodolfo et al., 1996). All of the first–category lahars are generally poor in clay. Magmatic or phreatic volcanism, volcanic or tectonic earthquakes, pressurization of hydrothermal groundwater, and flank inflation caused by magma intrusion (Vallance & Iverson, 2015) can trigger lahars induced by flank collapse. The hydrothermal alteration of rocks increases the probability of this type of lahar occurrence, material is commonly rich in clay and is most typical among ice–covered volcanoes. One of the recent historical examples occurred when the northern sector of Mount St. Helens collapsed to be emplaced as a debris avalanche deposit in the upper tributary of the Toutle River on 18 May 1980 (Voight et al., 1981). Some hours after the emplacement, lahars were generated descending through the Toutle, Cowlitz, and Columbia Rivers (Janda et al., 1981). Another example occurred in Colombia when the southern flank of the Nevado del Huila Volcanic Complex collapsed between 46 000 and 200 000 y BP, generating a debris avalanche that traveled 14 km to the Páez River. The lack of juvenile material and because material was not associated with pyroclastic deposits allowed to classify it as an Unzen type (nonvolcanic) debris avalanche triggered by seismic activity (Pulgarín et al., 2004), as was the 1994 Páez debris flow (Martínez et al., 1995). The 6 August 2012 eruption from the Tongariro Volcano's Te Maari vent is a good example of phreatic or hydrothermal system–triggered collapse. The eruption appears to have been triggered by the sudden unroofing of a pressurized hydrothermal system following a landslide along a clay–rich failure plane; the

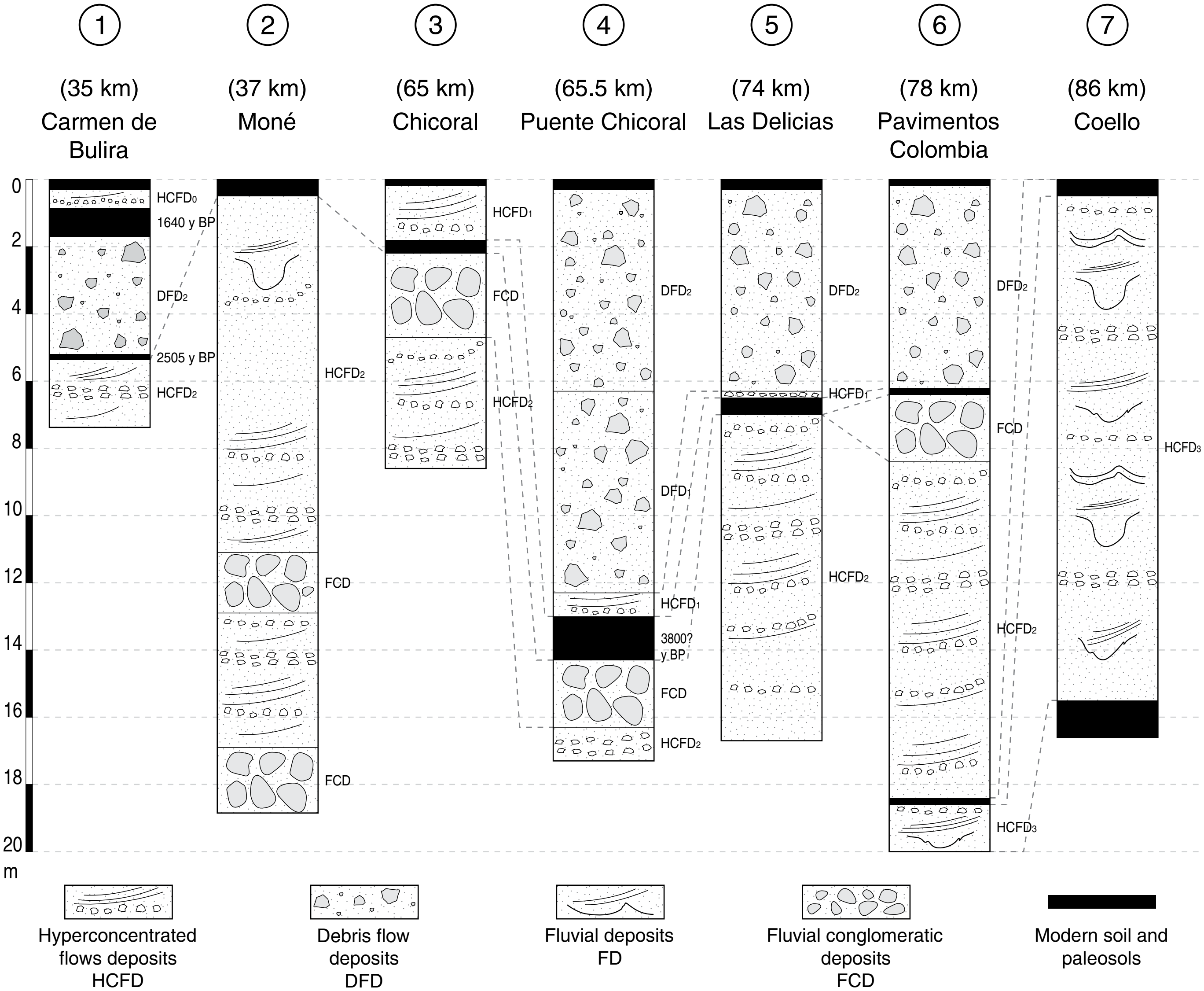

Figure 6. Stratigraphic columns along the Coello River showing the relationships between the lahar deposits of the CMV. Modified from Cortés (2001a, 2001b).

landslide transformed after 700 m into a clay–rich cohesive debris flow (Procter et al., 2014). Despite an increasing clay content and higher mobility beyond each erosion step, these authors reported that the unsaturated flow stopped 2 km from the source due to a lack of excess pore pressure.

Figure 1 shows the current drainage network of the study area, which is key to the interpretation of the historical occurrence of lahars associated with CMV eruptions and is critical to defining the hazard and risk zones of future events. The Toche River drains the SW sector of the CMV and flows towards the SSE until it joins the Bermellón River to form the Coello River, which is the main channel through which the CMV lahars have been transported. The Coello River flows for approximately 50 km in a predominantly SE direction and changes course to the NE approximately 11 km before entering the Magdalena River.

3.3. Surface Distribution and Stratigraphy of the CMV Lahar Deposits

As previously mentioned, Cortés (2001a, 2001b) characterized the CMV lahar deposits by grouping them into six units associated with events of considerable magnitude, of which four left hyperconcentrated flow deposits and two left debris flow deposits. The flow units were designated informally and in chronological order from oldest to most recent as follows: The Coello Hyperconcentrated Flow Deposit ($HCFD_3$), El Guamo Hyperconcentrated Flow Deposit ($HCFD_2$), El Espinal Hyperconcentrated Flow Deposit ($HCFD_1$), Chicoral Debris Flow Deposit (DFD_2), Chagualá Hyperconcentrated Flow Deposit ($HCFD_0$), and Carmen Debris Flow Deposit (DFD_1).

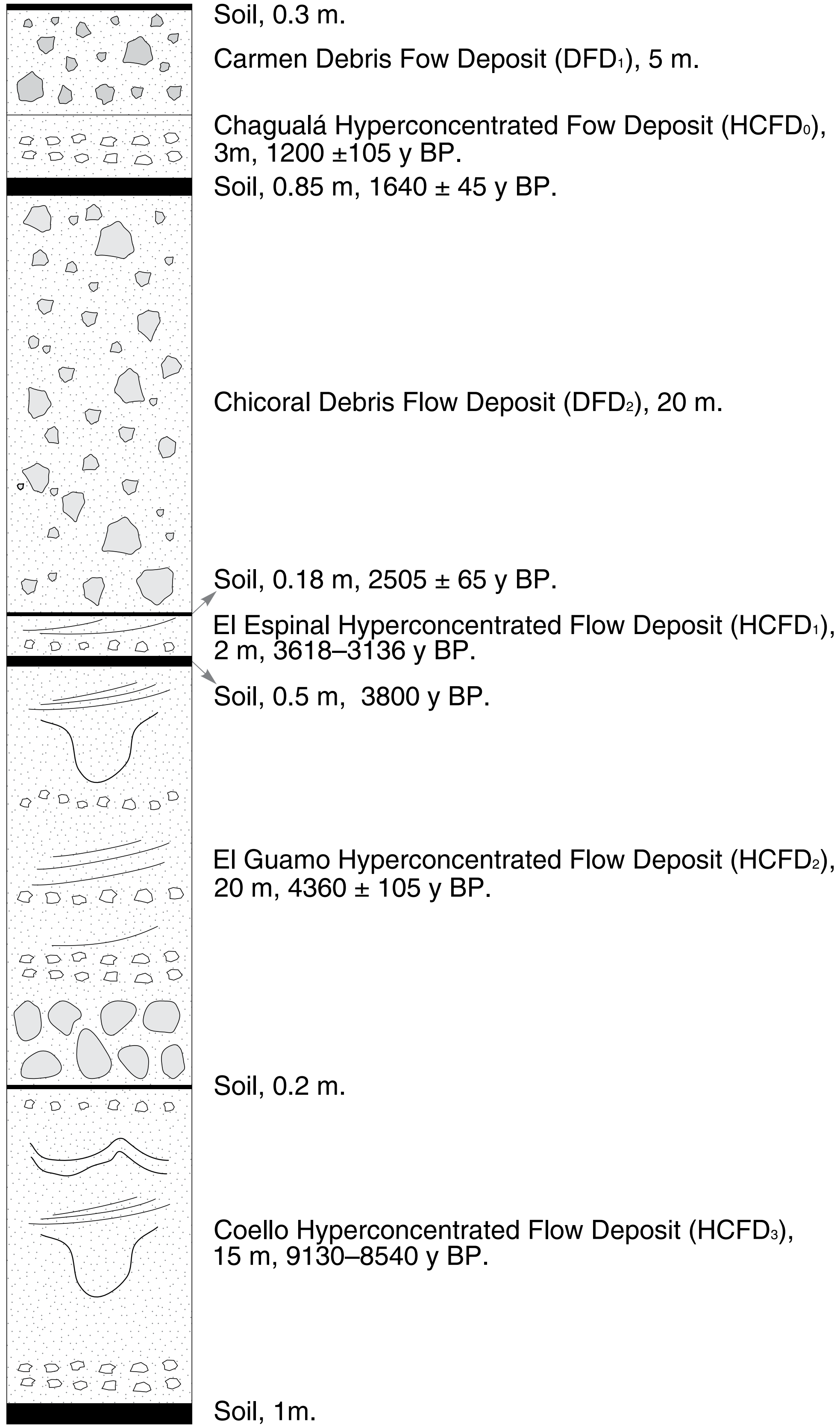

Figure 7. Stratigraphic column of the lahar deposits of the CMV. Modified from Cortés (2001a, 2001b).

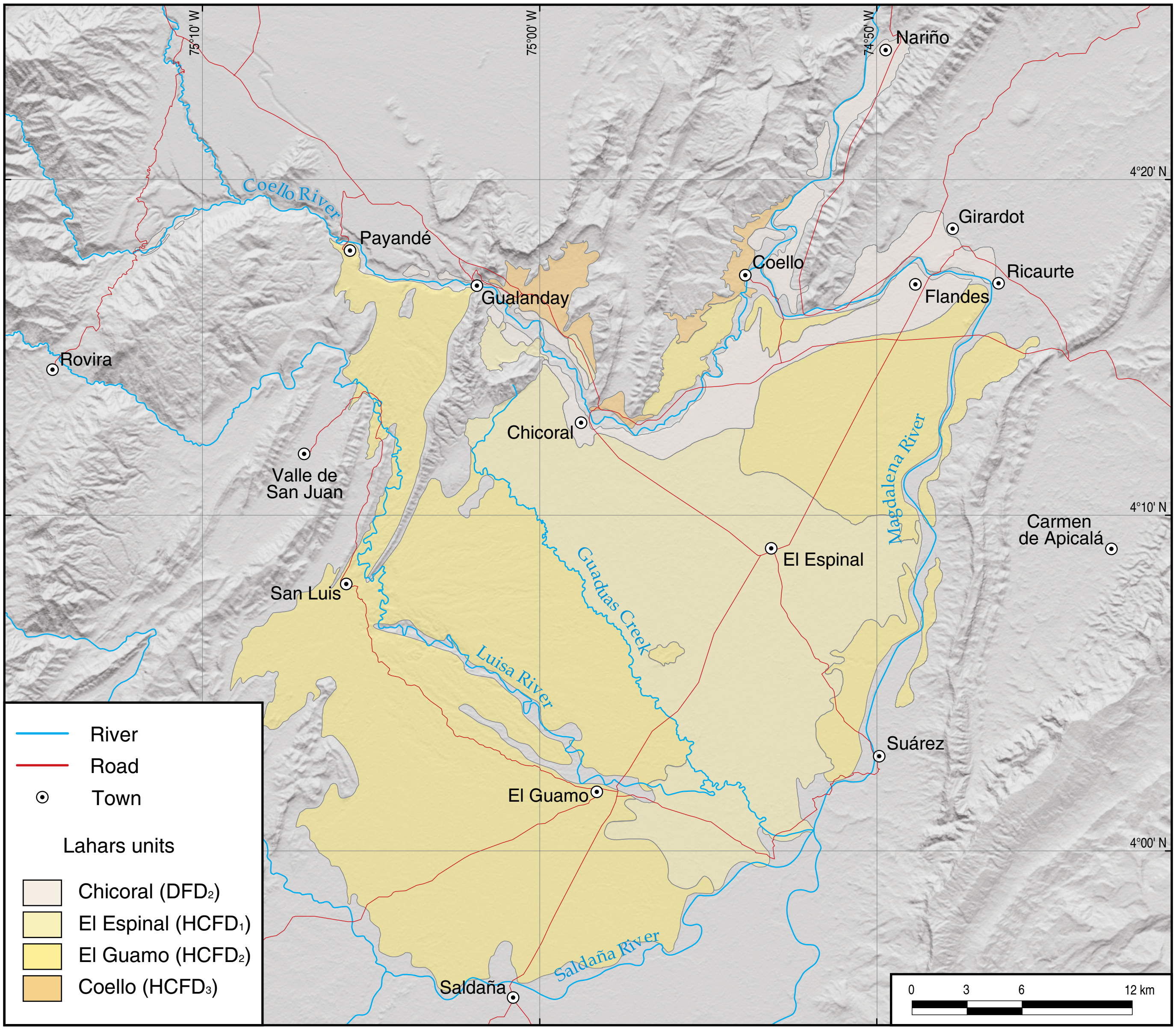

Figure 8. Geological map of the largest lahar units of the CMV. Adapted from Cortés (2001a, 2001b).

These lahar units of the CMV were recognized along the valleys of the Coello and Magdalena Rivers and some of their tributaries as well as their areas of influence. Within these valleys, several terraces were recognized with local and regional variations in their number, morphology, composition, and origin. The units associated with the larger events correspond to extensive lahar deposits that have an alluvial fan morphology (Figure 3) and terraces (Figure 5a, 5b), whereas those from smaller magnitude events have been eroded and are preserved in confined, discontinuous terraces with smaller dimensions and extents.

The correlation of type stratigraphic columns along the Coello River (Figure 6) enabled the definition of the chronological sequence of the lahar events and the aggradation of remobilized volcanic material associated with the eruptive activity of the CMV to be defined, which is represented by a generalized stratigraphic column (Figure 7).

Figure 8 shows a geological map of the four largest lahar units, which are in contact with Quaternary alluvial deposits, intrusive rocks of the Ibagué Batholith (Jurassic), rocks from the Honda and Gualanday Groups (conglomerates, sandstones, and claystones), the Seca, Guaduas, and Guaduala Formations, the Olini (Upper Cretaceous mudstones), Guadalupe, and Villeta Groups, the Caballos and Yaví Formations, the Payandé Formation (Upper Triassic siltstones and mudstones), and the Cajamarca Complex (Paleozoic schists and quartzites) (Rodríguez & Núñez, 1999). These geological units controlled the course and deposition of the three oldest lahar units.

Figure 9. Outcrop of the Coello Hyperconcentrated Flow Deposit ($HCFD_3$) on the left bank of the Coello River before it flows into the Magdalena River. The municipality of Coello is located on the terrace that forms this deposit.

The minimum area covered by the units is 1074 km^2, and the estimated minimum volume is 22 493 km^3.

3.3.1. Coello Hyperconcentrated Flow Deposit ($HCFD_3$)

$HCFD_3$ corresponds to a thick sequence formed by several hyperconcentrated flow deposit units that are interspersed with layers of fluvial and/or lacustrine deposits. In general, the hyperconcentrated flow deposits are beige, massive to faintly stratified, hetero–lithological, vesiculated, and matrix–supported by fine to coarse sand with plagioclase, biotite, amphibole, and quartz crystals, predominantly subrounded pumice clasts up to 20 cm in size and a smaller proportion of subangular dacitic lava lithics and fine gravel schists (less common pumice lenses in these units give the deposit a stratified appearance).

The individual depositional units vary in thickness from an average of several tens of cm to 15 m. The type section of this unit can be observed on the slope at the entrance to the Coello municipality (4° 17’ 17.09’’ N; 74° 53’ 53.51’’ W), where five depositional sequences that are laterally in erosive contact are observed as individual channels. The absence of soils within the sequences suggests that little time passed between each sequence and that they are possibly associated with the same eruption event of the CMV (Figure 9).

The $HCFD_3$ corresponds to the oldest lahar unit associated with the activity of the CMV. Accelerator mass spectrometry (AMS) carbon dating of a carbon sample found in this unit (Table 1) indicates a calibrated age between 9130 and 8540 y BP. The photogeological study and field observations suggest that this unit has been considerably eroded and has a morphological expression of discontinuous terraces with a smooth undulating surface. The remnants of the $HCFD_3$ are located on the innermost portion of the left bank (downstream) of the Coello River valley (Figure 8) and show that the event or the successive laharic events it originated from were relatively large. For example, on the left bank (downstream) of the Chagualá Creek, near the crossing with the Coello River, the $HCFD_3$ completely fills an old channel (Figure 10a, 10b). The $HCFD_3$ covers an area of approximately 25 km^2. The minimum calculated volume of this unit is 0.375 km^3.

3.3.2. El Guamo Hyperconcentrated Flow Deposit ($HCFD_2$)

This unit is composed of several units of hyperconcentrated flow deposits that are gray to beige, massive to faintly stratified, hetero–lithological, vesiculated, and matrix–supported by fine to medium sand with abundant white subrounded pumice clasts up to 30 cm in diameter.

Subangular dacitic lava lithics and schists from the basement ranging from fine gravel to a few tens of cm are present in a smaller proportion. The dacitic lava clasts are both gray and reddish, whereas the schists are black and green. The presence of pumice lenses is also a characteristic. The matrix is composed of crystals and pumice fragments, dacitic lava lithics, and schists. The crystal types are predominantly plagioclase, biotite, amphibole, and quartz.

The type sections in the proximal, middle, and distal parts of the $HCFD_2$ are located in the Carmen de Bulira–Hacienda Moné sectors (4° 18’ 13.59’’ N; 75° 11’ 59.08’’ W), in San Luis (4° 08’ 03.13’’ N; 75° 05’ 40.41’’ W), and along the left bank of the Magdalena River in the vicinity of El Guamo (4° 01’ 54.08’’ N; 74° 58’ 15.05’’ W) and El Espinal (4° 09’ 01.11’’ N; 74° 53’ 04.62’’ W), respectively (Figure 11a, 11b). This unit is similar to the $HCFD_3$ but has a greater areal distribution (Figure 8); it covers approximately 1009 km^2, with an average thickness of 20 m and a minimum calculated volume of 20.18 km^3. Due to the wide distribution and volume of its deposits, it is considered the largest unit.

This unit is younger than the $HCFD_3$; the ^{14}C data of a carbon sample collected in this unit (Table 1) yielded an age of 4360 ± 105 y BP. It is located along the banks of the Coello River in the Carmen de Bulira region and forms the middle and distal parts of the so–called El Guamo Fan along the right bank of the Coello River and the left banks of the Cucuana, Saldaña, and Magdalena Rivers (Figure 1). Based on the photogeological study and field observations, this unit is dissected forming hills, presenting an irregular morphology (Figure 12). The deposition of this unit was controlled by the topography of the older geological units. The locality of El Guamo is located on this unit.

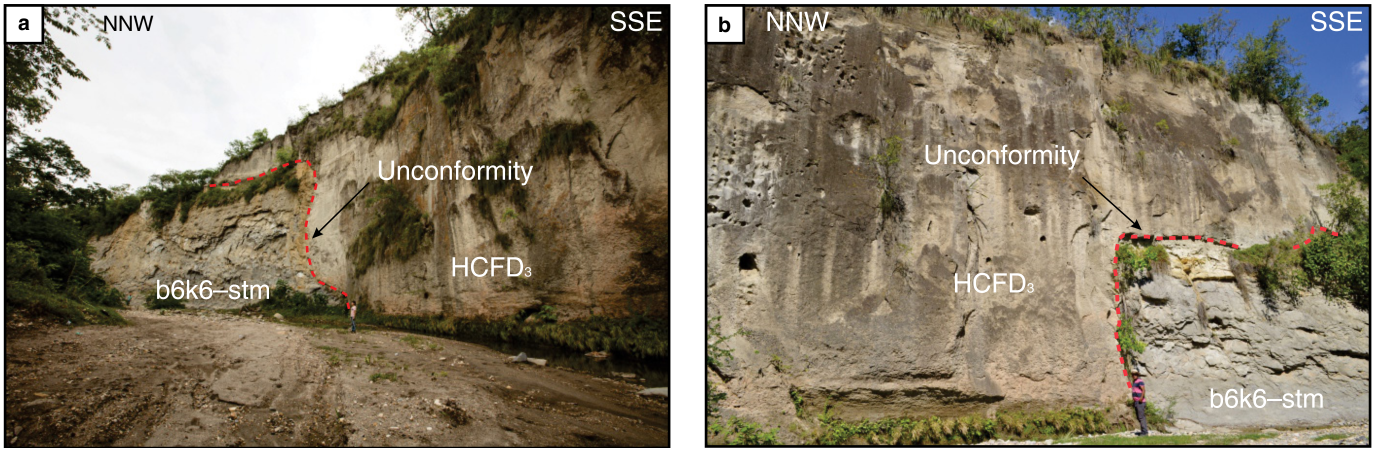

Figure 10. Outcrop on the left bank of the Chagualá Creek before its outlet to the Coello River. The Coello Hyperconcentrated Flow Deposit ($HCFD_3$) overlies the basement rocks (b6k6–stm Cretaceous sedimentary rocks), completely fills an old channel and forms the terrace on which the municipality of Coello was established. **(a)** Left bank of the paleochannel. **(b)** Right bank of the paleochannel. The Geological Map of Colombia 2015 (Gómez et al., 2015) groups under the term b6k6–stm Cretaceous units (Hondita and Loma Gorda Formations, Olini Group, shales and sands level, and La Tabla Formation).

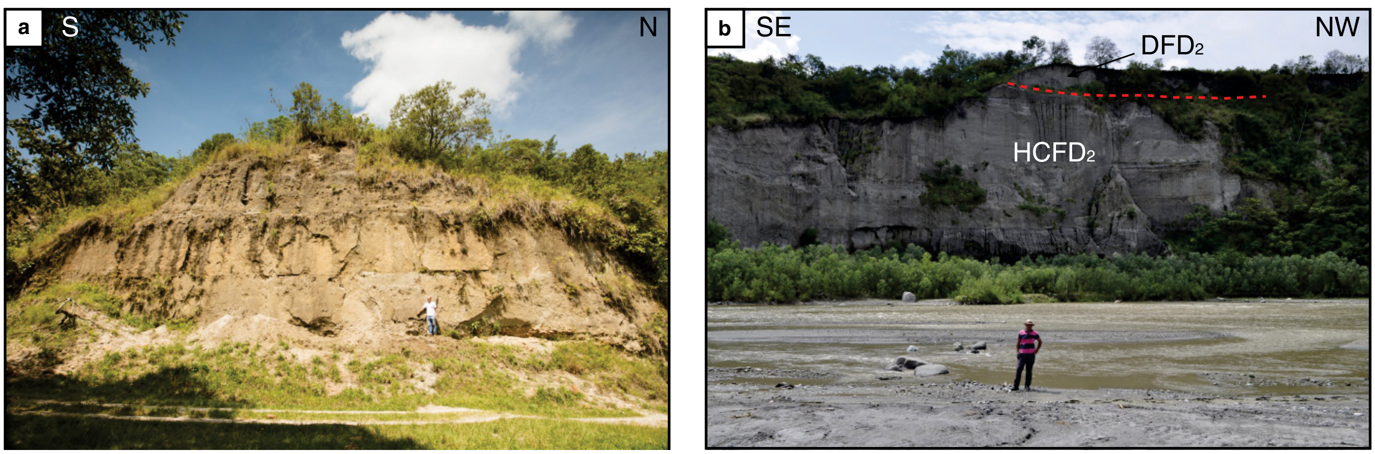

Figure 11. El Guamo Hyperconcentrated Flow Deposit ($HCFD_2$). **(a)** Hacienda Moné proximal depositional area, left bank of the Coello River near Carmen de Bulira. **(b)** Triturados del Tolima distal depositional area, right bank of the Coello River between Chicoral and El Espinal.

3.3.3. El Espinal Hyperconcentrated Flow Deposit ($HCFD_1$)

This lahar unit also corresponds to a hyperconcentrated flow deposit that is beige, massive, matrix–supported by fine sand with low density clasts of predominantly subrounded pumice and rare dark gray vitreous lithics. The matrix contains mainly biotite, amphibole, plagioclase, and quartz crystals.

The type section is in the locality of Las Mercedes (4° 13’ 32.55” N; 75° 00’ 18.80” W) along the initial part of the Jaramillo Channel. This unit morphologically forms the so–called El Espinal Fan. The $HCFD_1$ is observed on the right bank of the Coello River. It extends from La Laguna area, where its distribution is controlled by the Carrasposo–La Jagua Hill and the Cresta del Indio to the Magdalena River. On El Espinal Fan lies the locality of El Espinal. The photogeological study and field observations indicate that this unit is extensive and has a flat upper surface (Figure 13a), in contrast to El Guamo Fan. The distribution of the deposit towards the SW is limited by the Guaduas Creek, which marks one of the contacts with the $HCFD_2$.

This lahar unit is characterized by its thin (average of 2 m) but wide distribution (Figure 8), which covers approximately 294 km^2. The minimum calculated deposit volume for this unit is 0.588 km^3. The $HCFD_1$ is younger than the $HCFD_2$ (Figure 13b). AMS ^{14}C radiometric dating from a carbon sample in this unit is available (Table 1) and indicates a possible age between 3618 and 3136 y BP.

Figure 12. Hill morphology of El Guamo Hyper Concentrated Flow Deposit ($HCFD_2$) on the left bank of the track between Payandé and San Luis. In this area, the unit is not overlain by other lahar deposits and is characterized by significant dissection, which is typical of El Guamo Fan.

3.3.4. Chicoral Debris Flow Deposit (DFD_2)

This lahar unit corresponds to a deposit originating from a debris flow that is gray, massive, very poorly sorted, hetero–lithological, vesiculated, consolidated, and matrix–supported by sand and composed mainly of subangular and subrounded clasts of dacitic lava lithics up to 1.9 m in diameter that are gray and reddish with a porphyritic texture. It also consists of occasional angular to rounded fragments of mainly black and green schists up to 80 cm in diameter and a variety of material incorporated from the channels and streams through which it flowed. The matrix is composed of lithics of the same composition as the clasts described above and by biotite, amphibole, plagioclase, and quartz crystals. In some areas, there are two flow units (Cortés, 2001a, 2001b), which Hurtado & Murcia (2003) and Murcia et al. (2008) referred to as lower and upper units, respectively (Figure 14a–c).

Based on the photogeological study and field observations, this unit forms undissected terraces with flat surfaces and vertical escarpments that vary in height and are consolidated and resistant to erosion (Figure 15). The flat morphology similar to that of the $HCFD_1$ made it difficult to establish the stratigraphic relationships and the lateral contact between these two units, but it is a distinctive feature of the oldest hyperconcentrated flow deposit units. The deposits of the DFD_2 and $HCFD_1$ units form El Espinal Fan (Figure 13a).

Hurtado & Murcia (2003) and Murcia et al. (2008) carried out a detailed study of this unit and confirmed that it comprises two volcaniclastic units that are rich in dacitic volcanic lithics. Granulometric analysis revealed that the matrix content and degree of sorting increased with distance, whereas the average grain size decreased. In the lower unit, the gravel content decreases with distance, from 63% at 60 km to 20% at 113.5 km from the volcano, and the matrix increases with the same distance according to the abundance of the sand and silt fractions, which increase from 36.53 to 79.5 %. The clay fraction remains almost constant, with an average of 0.92%. The upper unit has a more homogenous content of gravel, with a minimum of 27% at 66 km and a maximum of 42% at 75.6 km. The clay content in the matrix has an average of 1.16% (Murcia et al., 2008).

Based on the clay content of the matrix (approximately 1%), the authors categorized the deposit as a non–cohesive debris flow. These authors also performed macro– and microanalyses of the components of the DFD_2 as well as X–ray diffraction analyses, which confirmed a homogeneous composition with primary fragments of dacite and occasional accidental lithics (less than 10%) of black and green schists, black mudstones, reddish conglomerates, granodiorites, and monzonites from the basement that eruption picked up and from bulking processes from river beds. The X–ray diffraction analysis identified large amounts of quartz as well as feldspars, amphibole, calcite, and cristobalite. The clay minerals include smectite, chlorite, illite, and kaolinite.

The unit is discontinuously distributed over the channels of the Coello and Magdalena Rivers and extends laterally up to 4 km (Figure 8).

In the proximal part of the banks of the Coello River, the sequence is observed in the Carmen de Bulira region (Figure 16a, 16b) in the Tolima Department (42 km from the CMV summit). In the middle part of the left bank of the Coello River, it is observed in the area of Payandé de la Vega, where it forms the terrace on which the locality of Gualanday and the Potrerillo region are located. On the right bank, it forms the land on which the localities of Chicoral and Flandes are located. In the distal part of the right bank of the Magdalena River, it forms the land on which the sectors bordering Girardot and Nariño in the Cundinamarca Department are located (114 km from the CMV summit).

The type section is located in the region between Gualanday (4° 16’ 59.95’’ N; 75° 01’ 54.33’’ W) and Chicoral (4° 12’ 49.40’’ N; 74° 58’ 50.61’’ W). This unit is younger than the $HCFD_1$; it overlies a paleosol that is dated at 2505 ± 65 y BP and underlies a paleosol dated at 1640 ± 45 y BP (Table 1; Cortés, 2001a, 2001b). According to additional radiocarbon data and information reported by Méndez (2001), this lahar is associated with the eruption known as El Guaico, which was dated at 2550 ± 70 y BP and produced block and ash flow deposits that filled the Toche River valley, 5 km from the volcano.

The initial data on the areal distribution, average thickness, and volume estimated by Cortés (2001a, 2001b) were refined by Hurtado & Murcia (2003) and Murcia et al. (2008), who indicated that the DFD_2 forms terraces that vary in thickness between 3 and 20 m, reach a distance of 109 km from the source, cover a minimum area of 62 km^2, and have a minimum volume of 0.74 km^3, which falls in the range between very long and extremely long according to the classification

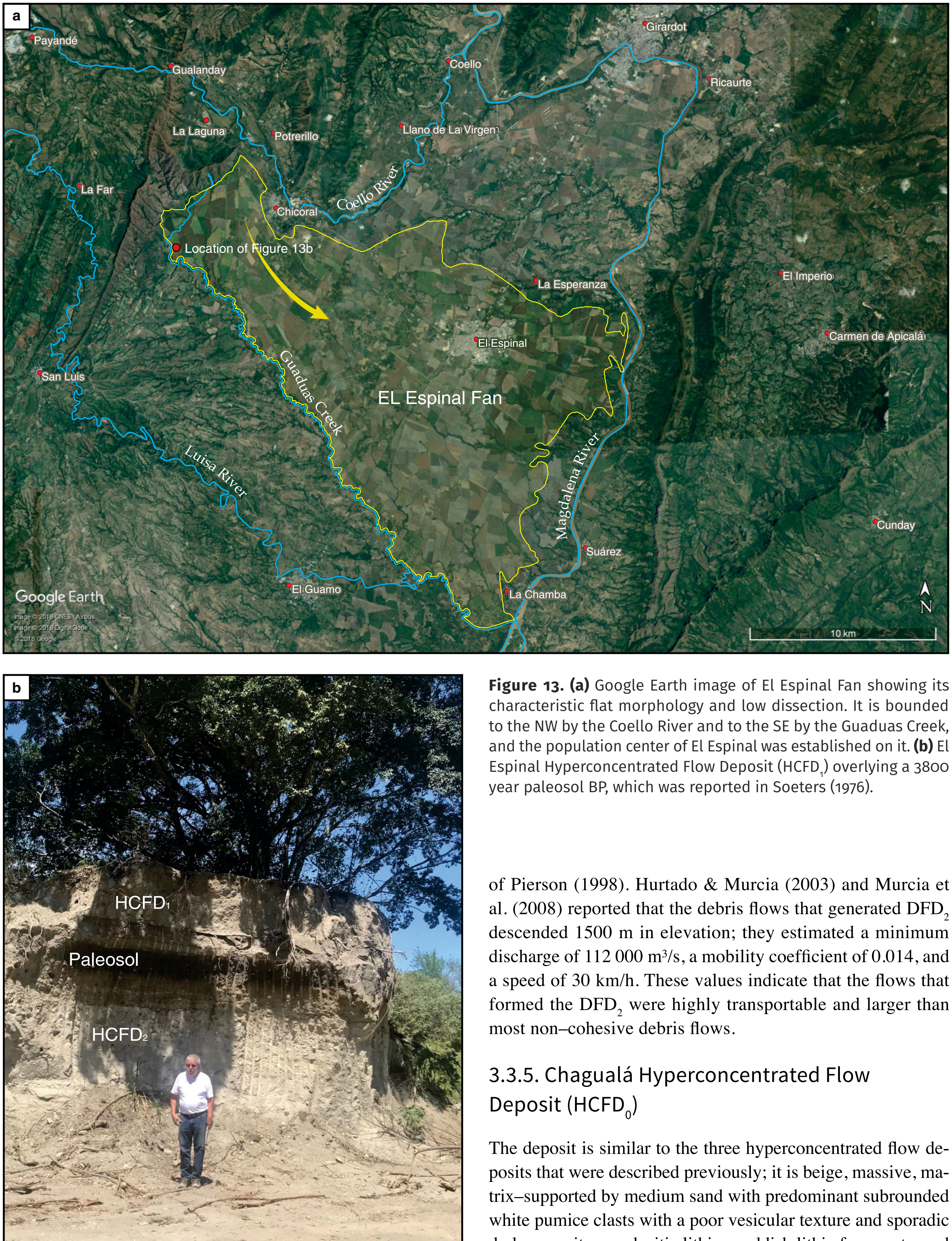

Figure 13. (a) Google Earth image of El Espinal Fan showing its characteristic flat morphology and low dissection. It is bounded to the NW by the Coello River and to the SE by the Guaduas Creek, and the population center of El Espinal was established on it. **(b)** El Espinal Hyperconcentrated Flow Deposit ($HCFD_1$) overlying a 3800 year paleosol BP, which was reported in Soeters (1976).

of Pierson (1998). Hurtado & Murcia (2003) and Murcia et al. (2008) reported that the debris flows that generated DFD_2 descended 1500 m in elevation; they estimated a minimum discharge of 112 000 m³/s, a mobility coefficient of 0.014, and a speed of 30 km/h. These values indicate that the flows that formed the DFD_2 were highly transportable and larger than most non–cohesive debris flows.

3.3.5. Chagualá Hyperconcentrated Flow Deposit ($HCFD_0$)

The deposit is similar to the three hyperconcentrated flow deposits that were described previously; it is beige, massive, matrix–supported by medium sand with predominant subrounded white pumice clasts with a poor vesicular texture and sporadic dark gray vitreous dacitic lithics, reddish lithic fragments, and

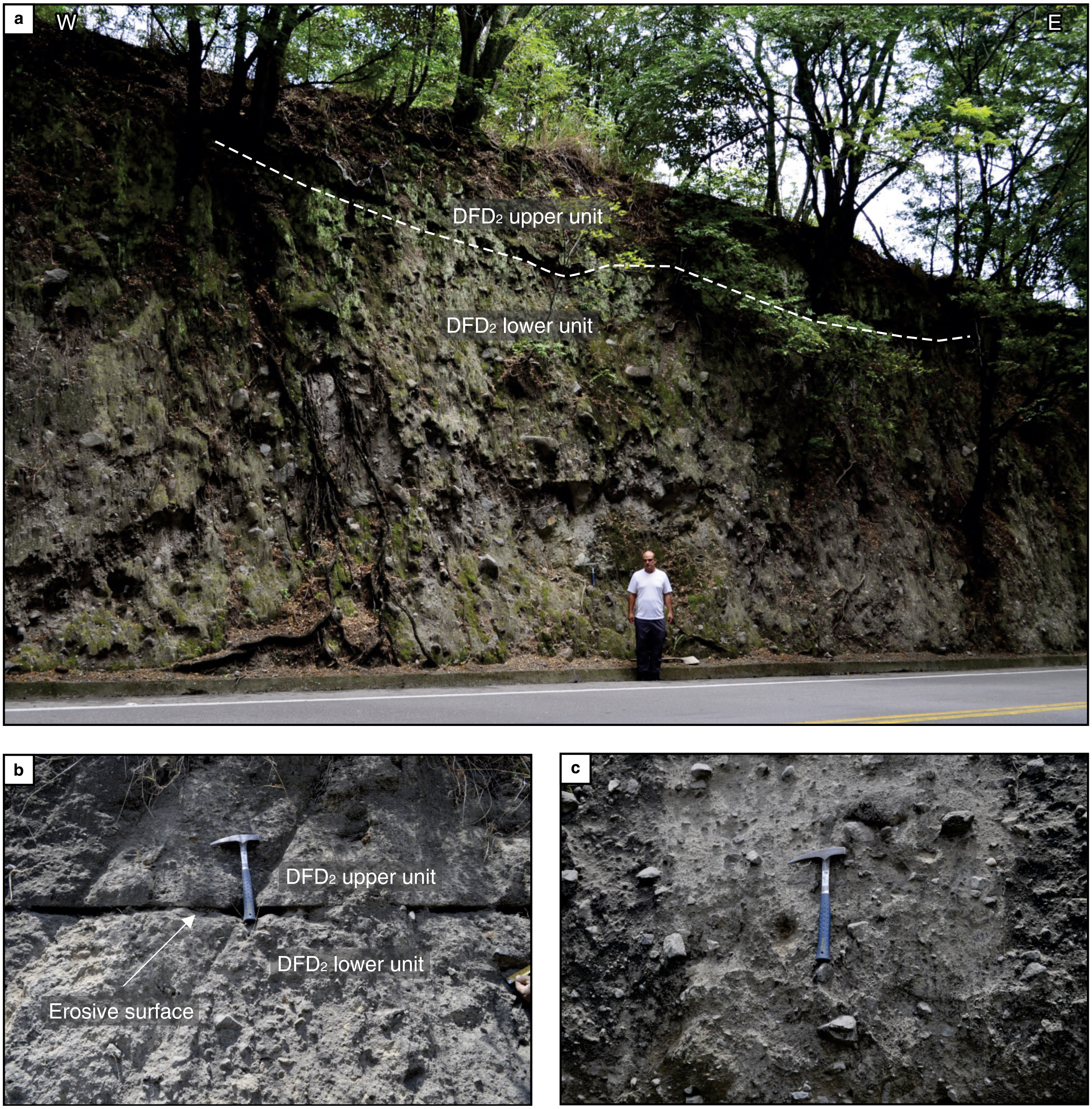

Figure 14. (a) Overview of the Chicoral Debris Flow Deposit (DFD_2). **(b)** Detail of the contact between the upper and lower units, and **(c)** detail showing the subangular to subrounded volcanic lithic components embedded in the sandy matrix.

schist fragments. The matrix mainly contains plagioclase, biotite, amphibole, and quartz crystals.

This unit is discontinuously observed on both banks of the Coello River, and it forms some of the youngest and most external terraces identified by Cortés (2001a, 2001b). The lahar it originated from was significantly channeled and did not flood the river banks because its course and subsequent distribution was controlled by large vertical walls formed by the oldest and largest previously described units.

The $HCFD_0$ has an average thickness of 3 m. The observed geological features indicate that it has been significantly eroded and affected by the fluvial dynamics of the Coello River, mainly due to its proximity to the channel and the smaller volume of material. This deposit has a flat to slightly undulating upper

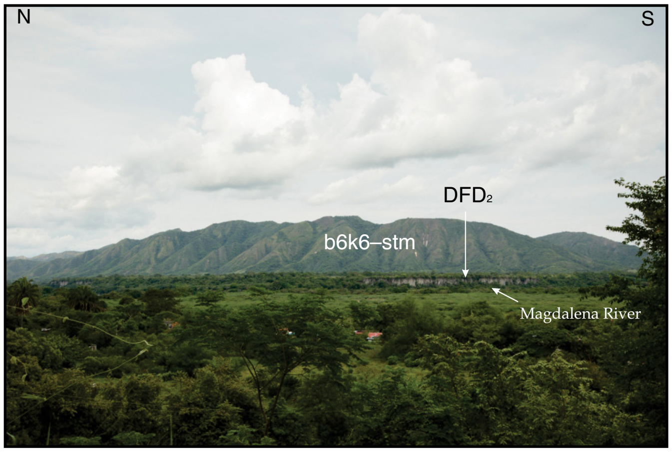

Figure 15. Typical flat morphology of the terraces formed by the Chicoral Debris Flow Deposit (DFD_2) on the right bank of the Magdalena River between Girardot and Nariño. b6k6–stm Cretaceous units of Gómez et al. (2015).

surface. Outcrops of the $HCFD_0$ are uncommon and are not mappable at a 1:100 000 scale; they were observed sporadically on both banks of the Coello River between Chicoral and the area known as La Joya (Figure 17). This unit correlates with an eruption that occurred 1200 years ago (Cepeda et al., 1996a).

3.3.6. Carmen Debris Flow Deposit (DFD_1)

This lahar unit corresponds to a debris flow deposit similar to that of the DFD_2 but is several orders of magnitude smaller, with an average thickness of 3.5 m. It is gray to beige, massive, hetero–lithological, vesiculated, hardened, poorly sorted, and matrix–supported by fine sand with predominantly angular to subangular gray and reddish clasts of fresh dacitic lava lithics with porphyritic textures up to 83 cm in diameter, characteristic green lithics, and altered lithics of various colors. It also consists of black and green schists. The matrix is composed of lithics with the same compositions as the clasts described above and by plagioclase, biotite, quartz, and amphibole crystals.

In initial studies, the best outcrops were identified immediately after those sectors where the channel was narrower, such as the crossings with the road to Rovira and Payandé. Recently, with the opening of new access routes to the channel of the Coello River as part of the new work on the CMV lahars, this unit was identified directly in the channel of the Coello River (Figure 18a–c) and on the right and left banks on terraces overlaid by conglomerates with a maximum height of 6 m. In some areas downstream of the Coello River, the deposit shows indications of being transformed to a hyperconcentrated flow deposit (70 km from the volcano). This unit is currently being eroded by water and has been in the past, which makes the geological record localized and sporadic. This unit is not mappable at a scale of 1:100 000, but it is important from stratigraphic and volcanic hazard points of view. Although no material for dating this unit has been found, the stratigraphic relationships indicate that it is one of the most recent CMV lahar units that has left a geological record.

Although the recognized CMV lahar units have been described individually, the excellent outcrops that corroborate the stratigraphic relationships between units that are inferred from the proximal region in terraces on both banks of the Coello River are described below. The vertical contacts between the $HCFD_2$, $HCFD_1$, and DFD_2 are clearly observed in outcrops in quarries for construction materials, which are located mainly on the right bank downstream of the Coello River in the areas of Las Delicias, La Joya, Agua Blanca, and Pavimentos Colombia.

In particular, the existing outcrops in the area of the Pavimentos Colombia Company, which resulted from the search for new areas for the exploitation of construction material and roads to access the Ibagué–Bogotá depression on the right bank downstream of the Coello River, expose a large part of the stratigraphy of the lahar deposits of the CMV that originated El Guamo and El Espinal Fans, including an important part of the Tolima Department, in which some of the most significant rice–growing areas in Colombia are located. These outcrops are important because they illustrate the different mechanisms of lahar formation and the associated dynamics; for this reason, they have been included in important geological field trips in the area (Cortés et al., 2005; Gómez et al., 2016; Navarro et al., 2011).

Figure 19 shows the upper part of a volcaniclastic sequence that begins at the channel level of the Coello River on its right bank. It highlights the conglomerates observed towards the base and upper part of the outcrop as well as the presence of two paleosols that separate several lahar units of the CMV. The lower paleosol is brown, 10 cm thick, eroded, and only observed in the left part of the outcrop. The upper paleosol is brown, deformed, and has an average thickness of 20 cm; it underlies the $HCFD_2$ and overlies other lahar deposits. At this location, the $HCFD_2$ is 10 m thick and is characterized by the largest charred wood fragments observed in CMV lahar deposits. The importance of this outcrop is attributed to the fact that the paleosol at the base of the $HCFD_2$ and the significant content of charred wood observed. Future ^{14}C dating of recently discovered paleosols and charred wood will improve the information available on the age of the $HCFD_2$ and older units observed at this location. Ascending in the stratigraphic sequence to younger outcrops, the $HCFD_2$ deposit is separated from the DFD_2 by a paleosol from 2500 y BP. In Figure 20, the base corresponds to the $HCFD_2$ sequence (4360 ± 105 y BP), which is eroded and overlain by a greenish–gray silty unit. The sandy levels are thin. El Espinal Hyperconcentrated Flow Deposit (3618–3136 y BP) overlies the lacustrine deposit on an erosive contact and follows the channel topography. A brown, crystalline, and hardened 40 cm thick paleosol is located above this unit. In the upper part, the DFD_2 is observed with a sole layer of 30 cm thick.

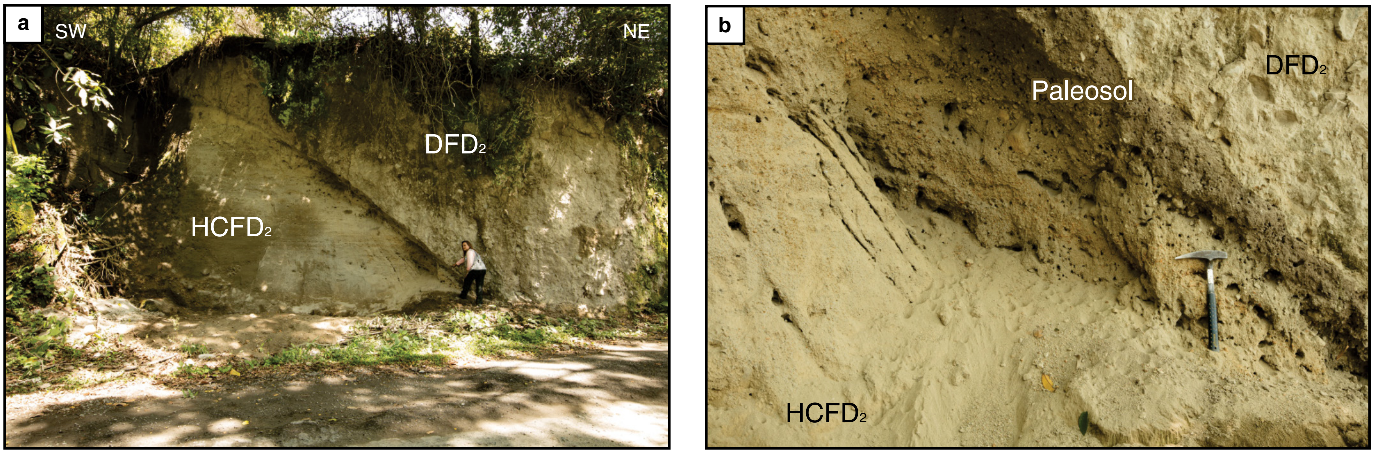

Figure 16. (a) Photograph of the Hyperconcentrated Flow Deposits of El Guamo (HCFD$_2$) and the Debris Flow Deposits of Chicoral (DFD$_2$) in erosive contact. The DFD$_2$ forms a paleochannel perpendicular to the present–day Coello River channel. **(b)** Detail of the deposit and the paleosol that separates the two units.

It is important to highlight the presence of silty lacustrine deposits in layers that are part of the volcaniclastic sequences formed by hyperconcentrated lahar deposits, as described in the previous paragraph, and in thicker and more extensive levels that have a flat morphology on the terrain. These features contrast with the typical morphology of the lahar deposits with which they are in contact and have important genetic relationships, which will be discussed later. An example of this is observed in areas such as the Valle de San Juan and Suárez (Figure 21a, 21b).

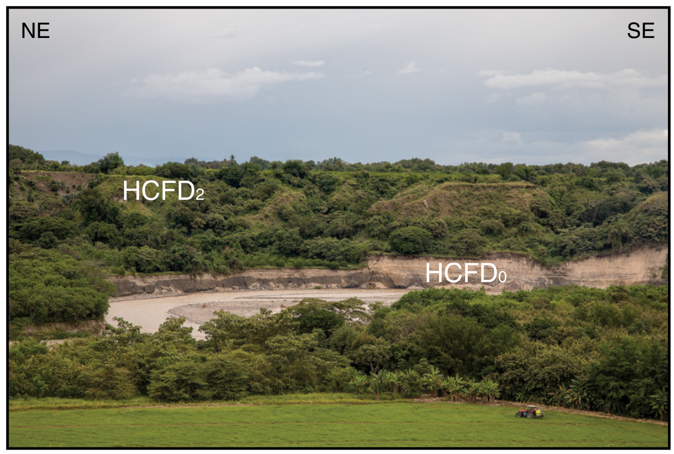

Figure 17. Chagualá Hyperconcentrated Flow Deposit (HCFD$_0$). Photograph taken from terrace on the left bank of the Coello River, La Pradera sector.

4. Discussion

4.1. Occurrence of Lahar Events Associated with the Eruptive Activity of the CMV

Approximately 9000 y BP, a Plinian–type explosive eruption occurred in the CMV, and the collapse of the eruptive column generated pyroclastic flows, whose deposits filled the river valleys originating from the volcano and became the primary sediment source for the secondary lahars that followed in the Coello River valley, which were restricted by the geological barrier of Gualanday and flowed southward along the valley that forms the Potrerillo Formation, which is the clayey level of the Gualanday Group (Gómez et al., 2016). The lahars advanced to the area where the city of San Luis (Figure 1) is currently located, where it diverged to the NE and E and deposited large amounts of sediment in low–lying and flat areas in the distal part of the volcano (Figure 22a, 22b). Apparently, the thick sequence of hyperconcentrated flow deposits affected the dynamics of several channels, creating dams and filling channels, as indicated by the slope on which the municipality of Coello is located. The hyperconcentrated flow deposits (HCFD$_3$) were eroded for many years, with some areas remaining mainly on the left bank of the Coello River.

A subsequent cycle of similar eruptive activity took place approximately 4360 y BP, which generated pyroclastic flow deposits of pumice and ash that were transported as lahars to distal zones. The Coello River channel was again occupied by large volumes of hyperconcentrated flow deposits (HCFD$_2$) that overflowed its right bank near the locality of Payandé and El Hobo and Santa Isabel villages and were controlled by the Gualanday barrier (Figures 23, 24) and other topographic barriers following the same path as the lahars that generated the HCFD$_3$. The HCFD$_2$ reached the Cucuana, Saldaña, and Magdalena Rivers and led to the formation of El Guamo Fan (Figure 22c). The topographic barriers confined the HCFD$_2$ deposits in the Valle de San Juan area, where lacustrine deposits provide evidence of damming (Figure 21a). The HCFD$_2$ deposit dammed the Magdalena River (Figure 22d, 22e), as

Figure 18. Debris Flow Deposits of Carmen (DFD_1) in El Limón area over the Coello River. **(a)** General overview of the current erosional process of the deposit, **(b)**, and **(c)** detailed photographs showing volcanic lithic components of dacitic composition in a sandy matrix.

shown by its geological record that is currently exposed on the left and right banks and by the lacustrine deposits observed in Suárez (Figure 21b). Additionally, once the powerful sequence of the $HCFD_2$ had been deposited (which is currently 20 m thick on the left bank downstream of the Coello River), the channel of the Magdalena River may have changed its course towards the eastern mountain range because it was easier to follow the interface between the lahar deposits and the basement rocks than to cut through the lahar deposits for a distance of approximately 64 km. As previously mentioned, the most significant topographic and morphological features in the area had a significant effect on the course definition and deposition of the lahars and therefore on the current morphology of the region. For example, the $HCFD_2$ reached several high topographic features without completely covering them, which today allow several morphological contrasts and outcrops of

Figure 19. El Guamo Hyperconcentrated Flow Deposit ($HCFD_2$) in the area of Pavimentos Colombia on the right bank of the Coello River channel. Several units of the $HCFD_2$ deposit overlie an eroded brown paleosol that overlies another hyperconcentrated deposit unit, possibly the $HCFD_3$. The volcaniclastic sequence ends with a conglomeratic deposit and the current soil.

Neogene and Cretaceous rocks to be observed, such as the window of the Honda Group in Paujil village and that of the Olini, Guadalupe, and Villeta Groups in Santa Isabel village. The deposits of the $HCFD_2$ forced the Coello River to change course and break the Gualanday barrier, which eroded it and formed a valley that is currently up to 3 km wide and 130 m deep (Gómez et al., 2016), as shown in Figures 23 and 24.

A similar event occurred approximately 3600 y BP. Its course was restricted to the new valley of the Coello River until it reached La Cresta del Indio area, where it overflowed the right bank, uniformly depositing a thin sequence of the $HCFD_1$ and forming El Espinal Fan (Figure 22f), whose southeastern margin was partially bounded by the Guaduas River. The $HCFD_1$ covered part of the northern section of El Guamo Fan. This laharic event had a significant magnitude but was smaller than that associated with the $HCFD_2$, as evidenced by its smaller areal distribution and lower thickness.

Later, at approximately 2500 y BP, an explosive eruption called El Guaico (Méndez, 2001) took place in the CMV, which, unlike the previous eruptions, generated block and ash flow deposits associated with the destruction of dacitic domes. The deposits blocked the channel of the Toche River and formed a temporary dam. The rupturing of the dam provided water that, when mixed with volcanic sediments, was transformed into a debris flow. The initial pulse was followed by another pulse with the same characteristics, which was transported downstream along the Coello and Magdalena Rivers channels, leaving a geological record of a debris flow (DFD_2) that reached a distance of approximately 100 km from the volcano. Initially, the flows moved along the narrow valley of the Coello River (between the current areas of the Coello–Cocora locality and Los Andes village). When the valley expanded, lateral expansion of the flow and initial sediment deposition occurred, forming the first terraces of debris flow deposits in the area of Carmen de Bulira. Later, the Coello River channel narrows again between the junction with the Combeima River and the Honda Creek; after this point (Alto del Mirador and El Capitolio Hill), the flow continued to move downstream along the Coello River valley without any significant change in slope and overflowed the right bank to the area of the Gualanday barrier. From there, deposition was continuous along both banks and contributed to the formation of the northern

Figure 20. Stratigraphic sequence containing three lahar deposit units of the CMV: El Guamo Hyperconcentrated Flow Deposit ($HCFD_2$), El Espinal Hyperconcentrated Flow Deposit ($HCFD_1$), and the Chicoral Debris Flow Deposit (DFD_2). The outcrop is on the right bank of the Coello River and crosses the section of the access road to the Pavimentos Colombia Company from the Ibagué–Girardot depression.

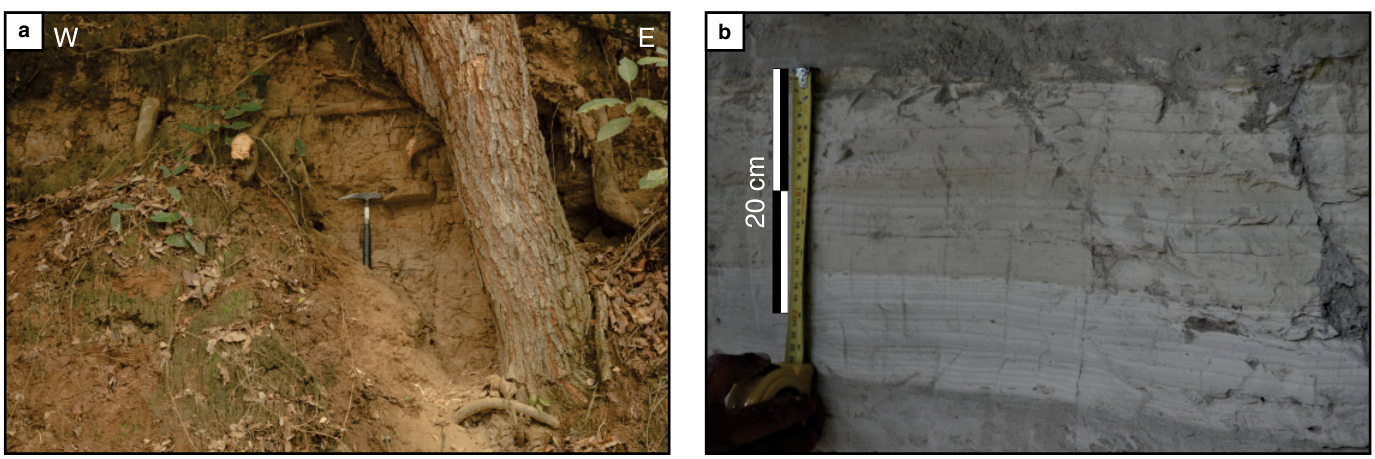

Figure 21. Lacustrine silty deposits associated with the volcaniclastic sequence of the Hyperconcentrated Deposit Unit of El Guamo. **(a)** Detail of the outcrop on the slope of the access road to Valle de San Juan locality. **(b)** Slope on the right bank of the Magdalena River near the Suárez locality.

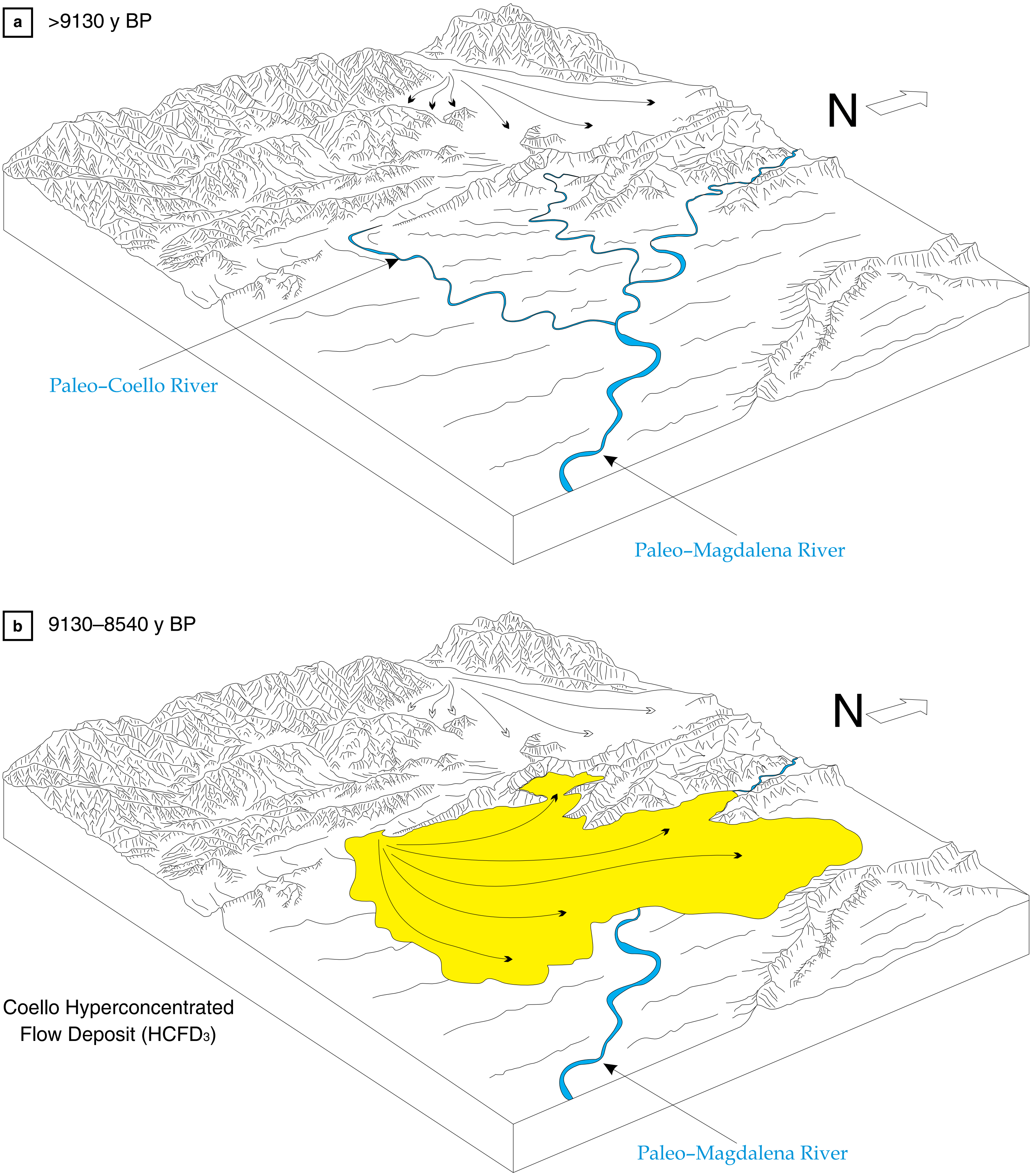

Figure 22. Block diagrams illustrating landscape changes in the study area associated with the depositional processes of powerful sequences of lahar deposits of the CMV. **(a)** >9130 y BP and **(b)** 9130–8540 y BP.

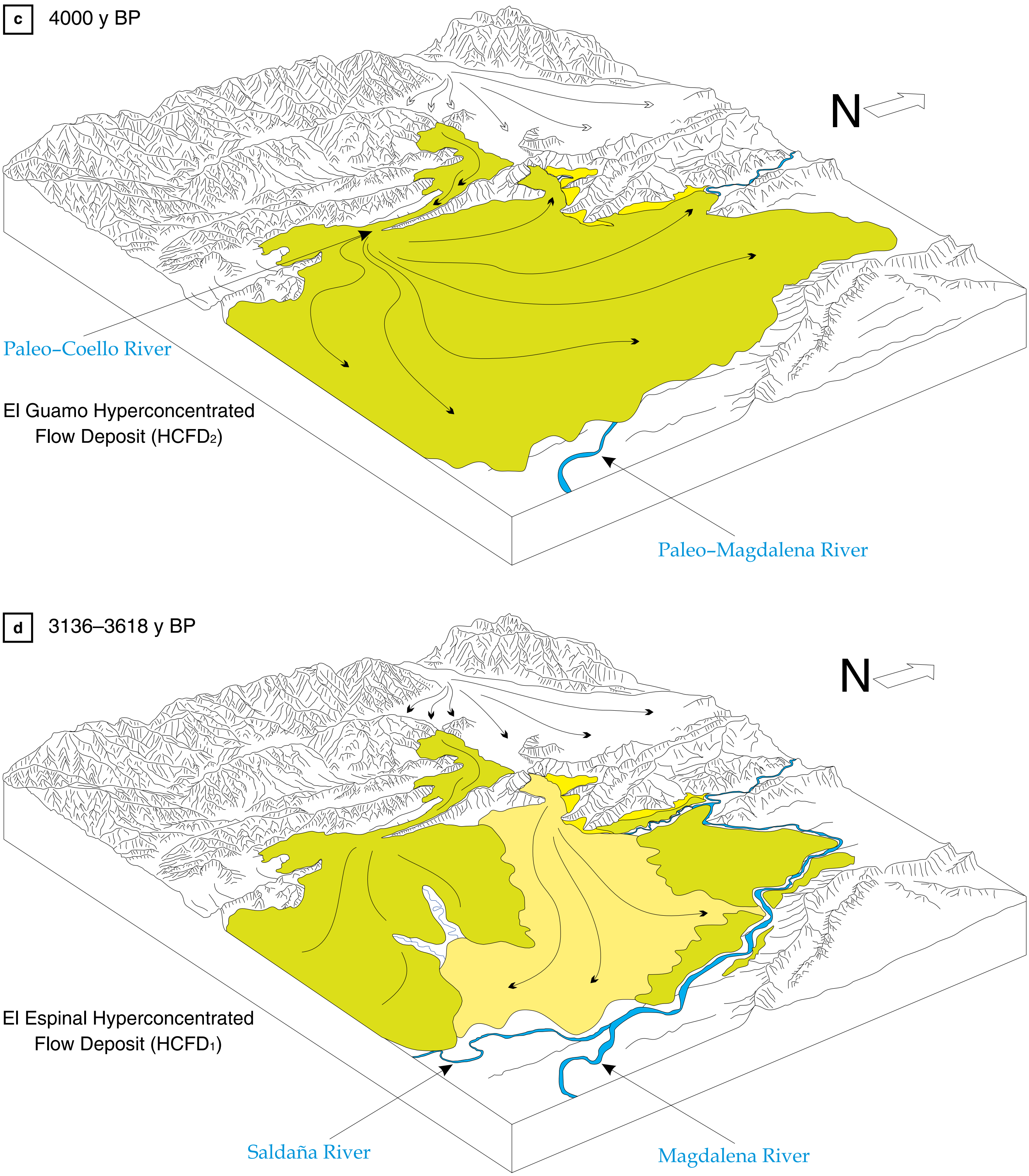

Figure 22. Block diagrams illustrating landscape changes in the study area associated with the depositional processes of powerful sequences of lahar deposits of the CMV. BP, **(c)** 4000 y BP and **(d)** 3136–3618 y BP (*continued*).

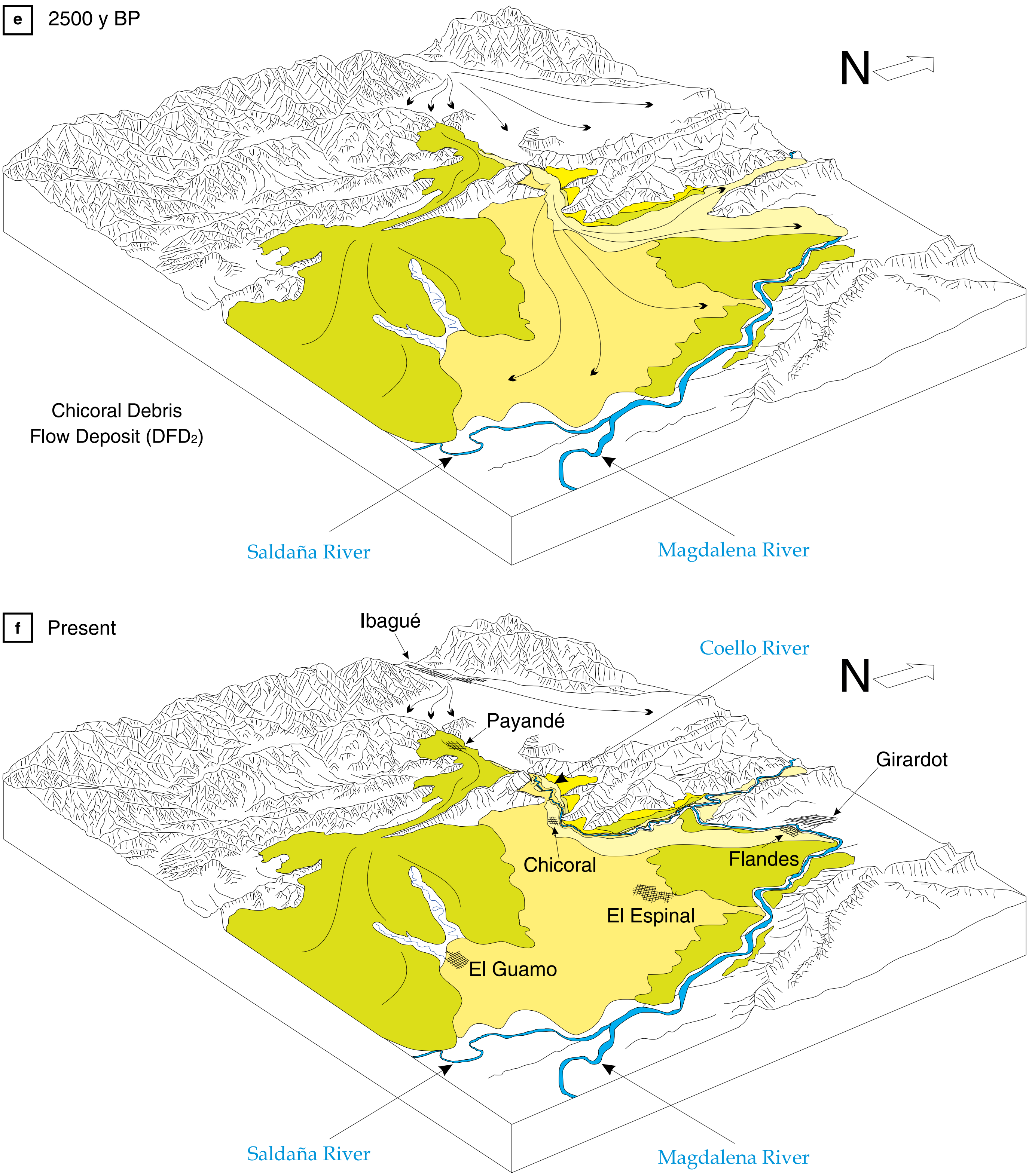

Figure 22. Block diagrams illustrating landscape changes in the study area associated with the depositional processes of powerful sequences of lahar deposits of the CMV. **(e)** 2500 y BP and **(f)** Present (*continued*).

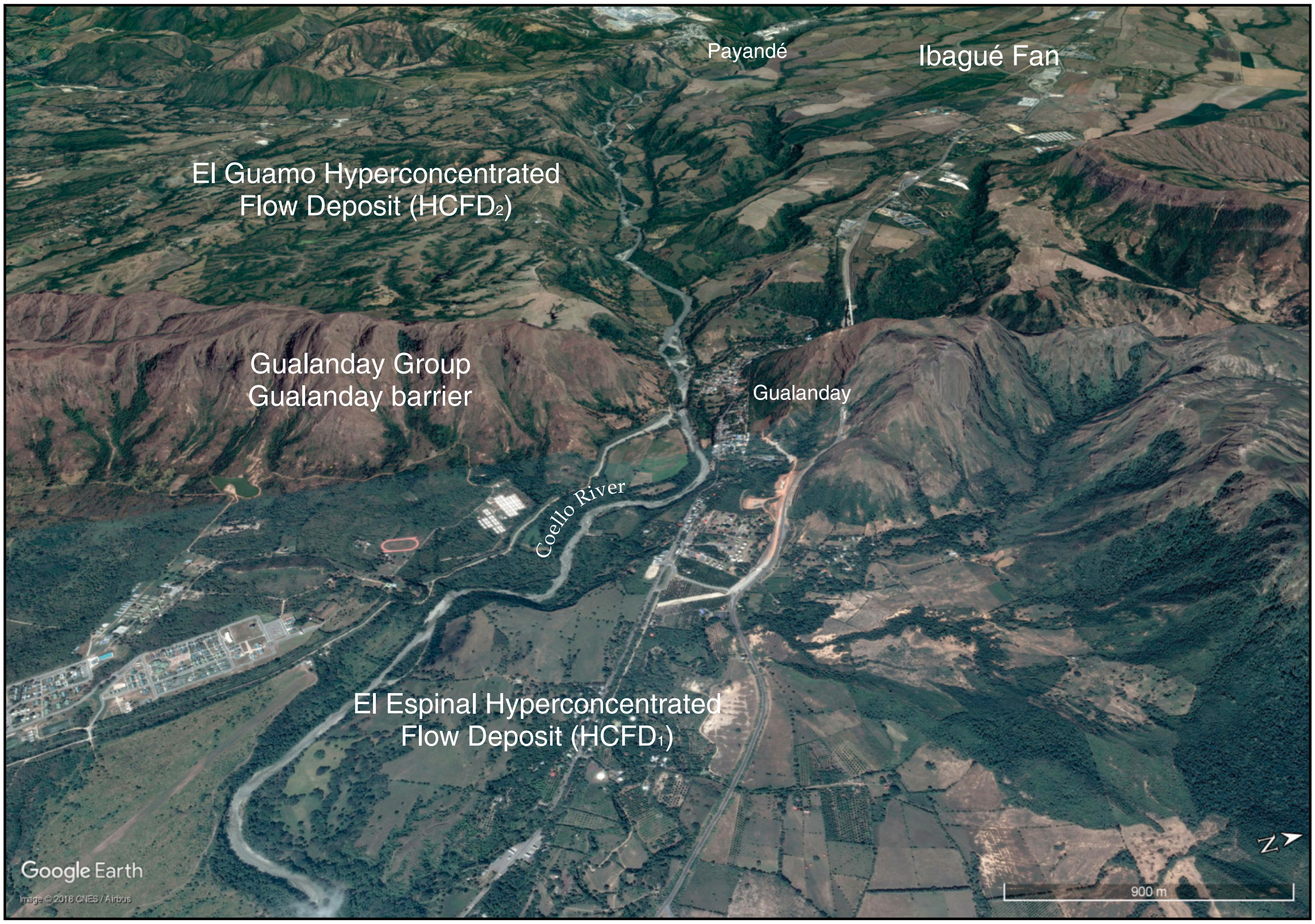

Figure 23. Google Earth image of the Gualanday barrier, the Coello River valley, and part of the study area corresponding to El Guamo and El Espinal Fans, which were formed by lahar deposits associated with large Holocene CMV eruptions.

part of El Espinal Fan (Figure 22e), where the DFD_2 currently overlies the $HCFD_2$ and is in lateral contact with the $HCFD_1$. The concentration of the debris flow remained high, and thick deposits filled the valley. The lahars reached the Magdalena River and moved upstream and downstream before being diluted and transformed into a normal flow. A new embankment formed along the channel of the Magdalena River, as is evidenced by the deposits along its banks.

The debris flow reached the area currently occupied by the town of Flandes on the left bank of the Magdalena River. Cortés (2001a, 2001b) suggested that the thickness and degree of consolidation of the deposited material modified the course of the Magdalena River, in contrast to Franco & Gómez (1978), who attributed the deflection of the Magdalena River at the height of Flandes–Girardot to the activity of the Cucuana Fault and the deposition of material from the Central Cordillera.

Two additional lahars, which are younger than 1640 y BP and were smaller than the devastating events described previously, were channeled through the course of the Coello River. One of them, possibly at 1200 y BP, generated a hyperconcentrated flow deposit ($HCFD_0$), whereas the other possibly more recent lahar formed a debris flow deposit (DFD_1). Both deposits have been significantly eroded; currently, only occasional remnants are observed in the channel and in discontinuous terraces. The possibility of minor events whose geological evidence has been eroded or has not been clearly identified should be considered.

The presence of silty deposits in the sequences of the CMV lahars in the vicinity indicates low–energy local or regional environments within or adjacent to the Coello and El Guamo units, which suggests that their origin was damming associated with thick sequences of hyperconcentrated deposits and the formation of natural lakes. Temporal changes in the sedimentation environment of the Coello River and the reworking of the CMV lahar deposits, especially the hyperconcentrated type, are evidenced by the sandy and conglomeratic levels in the volcaniclastic sequences. The paleosols observed in the study area represent important periods of volcanic inactivity in the region and are excellent markers that can be used to differentiate them, especially because monotonous lithologies are one of the most

Figure 24. Photograph from the Alto de Gualanday of a portion of Figure 23. The Gualanday barrier, the Coello River valley, and the terrace on its right bank, which is composed of lahar deposits of the CMV ($HCFD_2$ and DFD_2), are shown.

significant characteristics of CMV products. It is important to obtain additional ages of the paleosols and charcoal to improve our understanding of history in this part of the country.

4.2. Potential Hazard

It is clear that the CMV activity, specifically the lahars, has been a factor in landscape formation that has been responsible for the agricultural potential of the soils. However, lahars also represent one of the greatest hazards of future CMV eruptions. The areas impacted on several occasions by these lahars are those that may be affected by similar events in the future (Cortés et al., 2005, 2006).

In the national context, Cortés (2005) and Cortés et al. (2005, 2006) mentioned that the historical lahar of the NRV of 13 November 1985 and the Holocene lahars of the CMV are very different in terms of their mechanisms of formation, composition, and magnitude. They must be compared with a preventive approach, considering that the NRV demonstrated the destructive power of these events. These authors highlight that the Armero disaster demonstrated the destructive power of lahars caused by small eruptions; thus, future lahars of the CMV of similar or smaller magnitudes than those occurring in the past, or with a magnitude such as that of Armero, will have significant effects on life and property if the technical information about the volcanic hazard assessment is not considered in risk management and not incorporated in development plans, land planning, education, and contingency and emergency plans. Figure 25 compares the areal distribution of the CMV lahars and the NRV lahars that destroyed Armero town in 1985.

In their evaluation of the CMV hazard and especially in their proposal of future eruptive scenarios, Méndez et al. (2002) considered the 1991 eruption of Mount Pinatubo in the Philippines as the best example of future lahars that could occur from the CMV. The Pinatubo lahars filled lowland corridors at rates that were unprecedented in the history of volcanic hazard mitigation or sediment control. More than 50 000 people lost their homes, and approximately 100 died, although many more would have died if they had not been alerted in a timely manner (Janda et al., 1996). During and after the eruptions, lahars descending along volcano drainages dammed the confluences of tributary streams that drain areas outside the Pinatubo watershed, impounding ponds and lakes of variable permanence. When the impounded water overtopped the debris dams, the

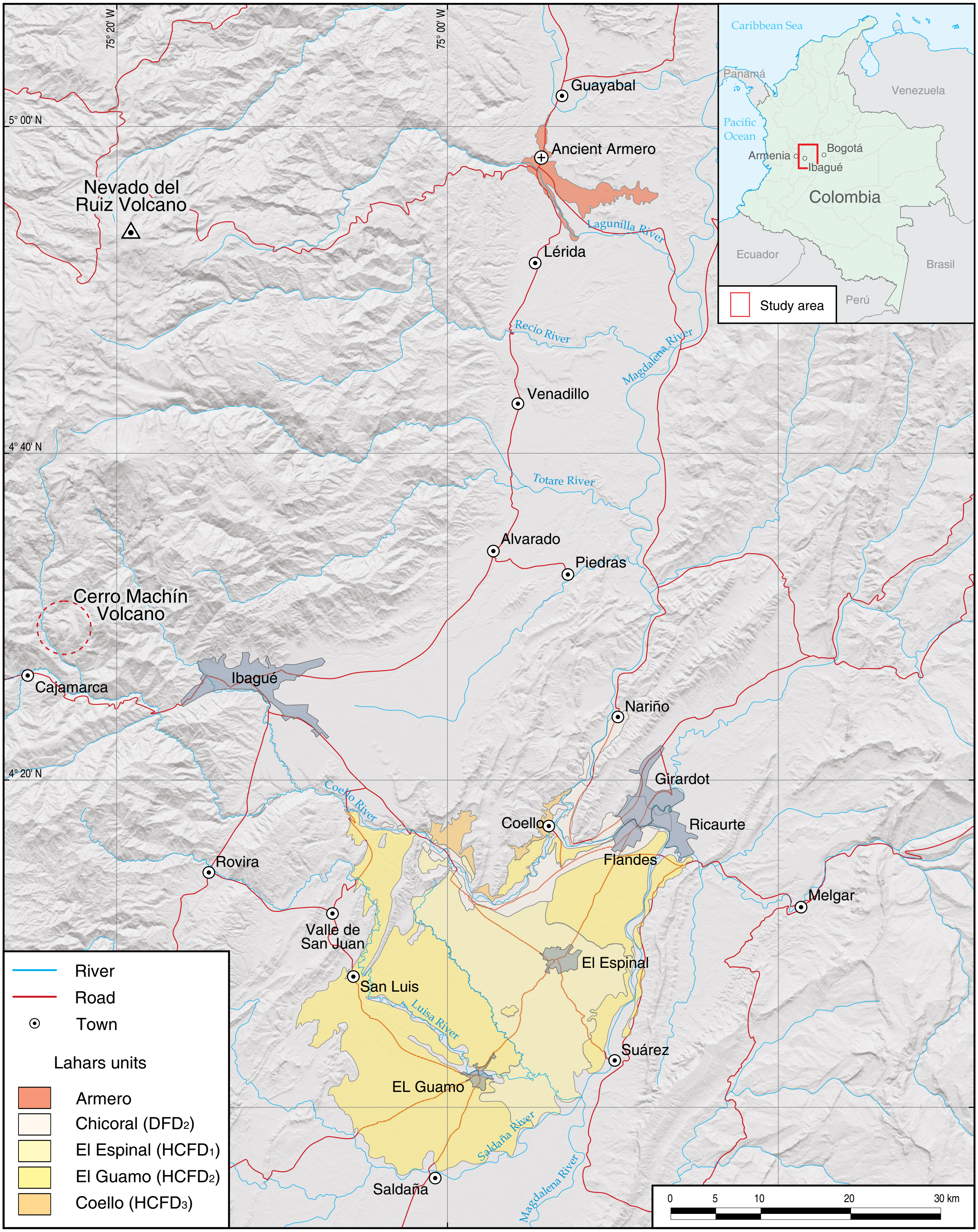

Figure 25. Comparison of the areal distributions of the four largest lahar deposits of the CMV and that of the NRV of 13 November 1985, that destroyed the population of Armero.

released floods generated "lake–breakout" lahars, including those in the extremely devastating events in 1991, 1992, and 1994 (Major et al., 1996; Newhall et al., 1996). By the end of the 1991 lahar (rainy) season, an estimated 50 × 10^6 m^3 of volcanic materials had been deposited on the alluvial fan of the Pasig–Potrero River (Arboleda & Martínez, 1996). Following the eruptive process of Mount Pinatubo, lahars generated by rainfall runoff persisted for many years, destroyed several villages, and harmed many local economies (Major et al., 2018). The lahars associated with the 1991 eruption of Mount Pinatubo are exceptional examples of the processes and river responses to the continuous contribution of sediments and subsequently the large impacts on populations and communities after highly explosive eruptions. The comparison of the formation, erosion, and deposition processes of the lahars that occurred as a result of the 1991 eruption of Mount Pinatubo with the volcaniclastic sequences that form the lahar deposits associated with the CMV indicates the occurrence of multiple phases over extended periods (years) after the Plinian CMV eruptions. The distant areas along the banks of the Coello and Magdalena Rivers may be affected by future events, and the influence of volcaniclastic re–sedimentation, which can exceed the direct effects of other primary volcanic phenomena in terms of areal extent and persistence, must not be underestimated.

Another historical event with which the CMV lahars can be compared corresponds to the most recent eruption at El Chichón that occurred from 28 March to 4 April 1982, resulting in the worst volcanic disaster during historical times in México, killing more than 2000 people and destroying nine towns and small communities (de la Cruz–Reyna & Tilling, 2015). When eruptive activity essentially ceased and the rainy season began, several secondary lahars were triggered in valleys draining the volcano. The largest of such rain–induced lahars occurred on 26 May on the Magdalena River and was generated by the catastrophic failure of a natural dam (75 m thick) of still–hot pyroclastic debris with a minimum volume of breakout–flow deposits of 17 × 10^6 m^3 that traveled more than 35 km. The breakout–flow sequences formed approximately two months after the cataclysmic eruption of El Chichón and affected areas beyond those damaged by the primary pyroclastic flows (Macías et al., 2004, 2008). That lahar and flood killed one person, burned 3 others, and destroyed a bridge (de la Cruz–Reyna & Tilling, 2015). Macías et al. (2004) highlight the importance of evaluating the morphology and drainage system of a volcano and the surrounding terrain because of the potentially profound influences. Regarding the lahars of the CMV, it is important to clarify that the volumes of the four oldest units have larger volumes by several orders of magnitude than those associated with the eruption of El Chichón in 1982. This historic case is also very useful for illustrating the generation of CMV lahars to the community and to the authorities in order to remember the lessons related to the little importance given at that time to volcanoes without historical records, even by volcanologists (de la Cruz–Reyna & Tilling, 2015).

It is important to continue comparing the CMV lahars with other important historical and prehistorical cases worldwide to highlight these prehistoric cases in Colombia and promote more detailed studies to improve the understanding of the processes of contribution of volcaniclastic material to sedimentary basins under the influence of very explosive active volcanoes. At a global level, there are numerous data and important information on lahars generated by multiple mechanisms of different magnitudes and areal distributions. The comparison between them can be done in a detailed way by evaluating one parameter at a time; however, in this discussion, I simply want to contextualize the cases of lahars from the CMV of similar magnitude or greater to cases that are considered iconic. In all the cases reviewed, the common denominator, regardless of the magnitude of the eruptions from which they are generated, has a profound impact on the landscape. Areas affected by lahars in prehistoric cases are currently densely populated; in some historical cases, there is a desire to re–inhabited the areas (e.g., Río Claro and Armero in Colombia).

Here, it is imperative to refer to lahars associated with eruptions of volcanoes such as Mount St. Helens, USA; Rainier, USA; and Cotopaxi, Ecuador. The 1980 eruption of Mount St. Helens showed that large lahars had devasting impacts on channels and flood plains (Janda et al., 1981). These authors also reported that the impacts were less than those of some lahars associated with earlier eruptions, referring to the importance of this comparison for future hazard assessments at Mount St. Helens and elsewhere. Approximately 5600 years ago, the 3.8 km^3 Osceola mudflow from Mount Rainier, USA flowed more than 120 km down valleys (Crandell, 1971), the influx of sediment, the removal or burial of all vegetation on 210 km^2 of Puget Lowland, and the alteration of the course of the White River resulted in a catastrophic landscape disturbance (Vallance & Pringle, 2008). The 540 km^2 area it inundated is now populated by hundreds of thousands of people (Vallance & Iverson, 2015). The glacier–clad Cotopaxi Volcano has been another producer of lahars that flowed great distances downstream, spanning as far as 325 km to the Pacific Ocean. The 1877 lahars reached the main population centers of Latacunga and the Chillos Valley in slightly less than an hour (Mothes & Vallance, 2015). The Chillos Valley Lahar (CVL) formed 4500–5000 ^{14}C y BP and had a flow depth of 100 m in the Chillos Valley, with a maximum flow width of 11 km and a total bulk volume of just less than 3 km^3 (Mothes et al., 1998).

Notable examples of rainfall–runoff lahars have occurred at Irazú Volcano, Costa Rica; Soufriere Hills , Montserrat–West Indies; and Chaitén, Chile . In the 1960s, repeated ash eruptions of Irazú Volcano perpetuated the scores of rainfall–runoff lahars over several years (Alvarado & Schmincke, 1994). According to these authors, the ash of phreatomagmatic activity produced drastic changes in the vegetation, an impermeable ash surface, and destroyed the equilibrium of the river basins. Rainfall on loose volcanic debris over the Soufriere Hills Volcano, Montserrat, generates hazardous floods in the Belham Valley (Barclay et al., 2007). These authors demonstrated that even where there is only a moderate input of loose volcanic debris into a catchment, there can be a significant increase in sediment flux and consequent rapid changes to the dynamics of the river systems that can endure for many years. Rain–triggered lahars and sediment–laden floods after the 2008–2009 eruption of the Chaitén Volcano, Chile represent another excellent example of the sensitivity of landscapes to volcanic disturbance, and these events demonstrate that these hazards can quickly endanger vulnerable downstream communities (Pierson et al., 2013). A small amount of rainfall rapidly remobilized a large volume of volcanic ash, causing significant and rapid geomorphological changes in the channel of the Chaitén River. The river was filled with up to 7 m of sediment in a few hours and was forced to leave its original channel and cut a new channel through the middle of the town of Chaitén located 10 km downstream of the volcano (Major et al., 2018; Pierson et al., 2013). Although there is no geological record of lahars in basins affected by pyroclastic fall deposits to the west of the CMV, the hazard has been recognized on the western flank of the Central Cordillera towards the Cauca River basin and should be considered in the risk reduction process in the Quindío Department according to these recent examples of rainfall–runoff lahars.

Due to its location and general characteristics, the area of influence of the CMV includes a strategic region for the economy of Colombia, in which the volcanic hazard, exposure, and vulnerability result in a significantly high volcanic risk and make its management a challenge at local, regional, and national levels. In light of existing regulations (Ley 1523 de 2012), volcanic risk management of the CMV requires a complete balance of knowledge processes and risk reduction as well as disaster management to contribute to the safety, well–being, and quality of life of the people at risk and to sustainable development. Risk management cannot be separated from the development of safety plans, sustainable environmental management at all government levels, and active participation by the population. Without the help of the population, the main goal of successful risk management cannot be attained. A comprehensive plan to mitigate the potential damage or losses caused by lahars should include the four strategies proposed by Pierson et al. (2014): (1) avoiding the hazard posed by lahars through land–use planning, (2) modifying the hazard posed by lahars through engineered protection structures, (3) having lahar alert systems for evacuation, and (4) effective response and recovery to lahar events. In particular, these authors discussed the roles of education and scientists in the reduction of lahar risks.

5. Conclusions

Post–eruptive secondary lahars of debris flow facies and hyperconcentrated or diluted flow facies have repeatedly flooded distant areas of the CMV over the past 10 000 years. The large distribution and thickness of the identified lahar deposits demonstrate the large magnitude of this type of phenomenon in the past and, in turn, indicate that they were caused by voluminous and devastating explosive eruptions that generated large amounts of volcanic material in the vicinity of the volcano and extremely large volumes of volcaniclastic sediments that were transported to distant areas to form large alluvial fans (El Guamo and El Espinal). The lahar events modified the morphology of the rivers in the study area and their depositional environments and changed the pre–existing landscape. Thick sequences of lahar deposits have repeatedly dammed the Magdalena River (the largest river in the Andean region of Colombia) and changed the direction of its channel. The lahars traveled distances greater than 100 km from the CMV, mainly along the previous and current channels of the Coello River.

Volcanic activity constitutes an important hazard to the environment and human life, not only during the eruption but also during the processes of lahar generation after eruptive activity. Within each lahar event, several different phases were identified, showing their variability in space and time at the moment of the events. The character of most of the lahar deposits of the CMV shows little variation, from the proximal to the distal areas in the Magdalena valley (Nariño town), despite the great distances traveled (115 km), because the systems of the Coello and Magdalena Rivers contained insufficient water to achieve greater dilution and transformation of debris flows and hyperconcentrated flows. These lahars inundated lowland areas from the volcano. Numerous towns, such as Payandé, Valle de San Juan, Gualanday, San Luis, El Guamo, El Espinal, Chicoral, Flandes, and Coello in the Tolima Department and Girardot and Nariño in the Cundinamarca Department, have been built on these lahar deposits. The majority of the inhabitants of these towns do not know the antecedents of the formation of their territory. Natural dams formed by pyroclastic flows (the main proposed mechanism for the lahars of the CMV) and their subsequent flow of rupture are a potential devastating volcanic hazard in the area of influence of the drainage systems that are impacted. For this reason, it is particularly important to understand the processes of remobilization to prevent new disasters associated with lahars in Colombia.

It is vital to improve the understanding of the processes and hazards of lahars of the CMV through the detailed study of well–characterized events. Specifically, it is very important to parameterize one or several events to make reliable computational simulations to include in a future update of the existing hazard map. In addition, it is important to have vulnerability and risk assessment studies associated with the CMV. The scientific knowledge and the lessons left by the historical events that have generated lahars of great magnitudes must be systematized and considered both in relation to the risk reduction plans for lahars of the CMV and in relation to the management of possible emergencies or disasters associated with them. The available technical information should be used by stakeholders to implement information and teaching programs for local communities at risk for lahars.

Finally, it is worth mentioning that the CMV is a volcano with no historical record of eruptive activity; thus, all actors or stakeholders involved in lahar risk management strategies must be aware of and consider the lessons and examples that have occurred inside and outside the country. The geological record of lahars of the CMV, with no point of comparison known until now in Colombian volcanoes, and the effects of well–documented cases throughout the world allow us to dimension the magnitude of the future effects on the landscape, communities, and infrastructure in hazardous areas by lahars. The CMV is a very important case globally due to its great contribution of volcanic material to the river basins in its area of influence, the formation of natural dams, and the potential volcanic risk associated with the rupture of these dams. The reduction of lahar risk is one of the main priorities in the risk management of the CMV, in which the social appropriation of geoscientific knowledge is important; it seeks to bring science closer to communities, to contribute to redefining the roles played by all actors involved in the generation and use of knowledge and, therefore, to eliminate the existing gap between "producers" and "receptors" of knowledge (Colciencias, 2010).

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Explanation of Acronyms, Abbreviations, and Symbols:

AMS	Accelerator mass spectrometry
CMV	Cerro Machín Volcano
CVL	Chillos Valley Lahar
DFD$_1$	Carmen Debris Flow Deposit
DFD$_2$	Chicoral Debris Flow Deposit
HCFD$_0$	Chagualá Hyperconcentrated Flow Deposit
HCFD$_1$	El Espinal Hyperconcentrated Flow Deposit
HCFD$_2$	El Guamo Hyperconcentrated Flow Deposit
HCFD$_3$	Coello Hyperconcentrated Flow Deposit
NRV	Nevado del Ruiz Volcano
SGC	Servicio Geológico Colombiano
VEI	Volcanic Explosivity Index

Author's Biographical Notes

Gloria Patricia CORTÉS–JIMÉNEZ is a vulcanologist from the Servicio Geológico Colombiano (1991–present). She is a geologist (Universidad de Caldas, 1990), earned a specialization degree in geography, land use planning, and natural risk management (Universidad de Caldas, 2005), as well as MS degree in Earth sciences (Universidad de Caldas, 2019). She works for the research and monitoring of volcanic activity group at the Observatorio Vulcanológico y Sismológico de Manizales at the Dirección de Geoamenazas. She has worked on active volcanoes in Colombia, mapping volcanic deposits, preparing volcanic hazard maps, studying recent eruptions, and during last 10 years focus on volcanic risk management and social appropriation of geoscientific knowledge in the areas of influence of the active volcanoes of the northern part of Colombia. She was coordinator of the Observatorio Vulcanológico y Sismológico de Manizales between 2010 and 2018. She is a founder member of Latin American Association of Volcanology (ALVO).