Chapter 9

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A Model of the Quindío and Risaralda Quaternary Deposits

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Abstract Quaternary deposits of the Quindío–Risaralda Basin are widely linked to neotectonic activity of the Romeral Fault System; its study and characterization are important due to the seismic threat and the risk it represents for populations in the Quindío and Risaralda Departments.

These Quaternary deposits are classified into four units: The ancient Quaternary Quindío–Risaralda Fan, which is divided according to geomorphology, geology, and petrography into three assemblages—the proximal, intermediate, and distal fans; recent Quaternary alluvium, represented by subhorizontally bedded deposits that occupy small basins of less than 10 km²; nearly active and active Quaternary colluvium and alluvium, related to faults; and pyroclastic deposits, nearly active and active, which are separated into two types: Ash falls and reworked or redeposited ash.

The genesis and evolution of the Quindío–Risaralda Basin are subdivided into four stages: The formation of the Quindío–Risaralda depression controlled by normal faults, which occurred after a phase of folding during the Pliocene in the Cauca–Patía Basin; the beginning of the constructive phase of the Quindío–Risaralda Fan in the early Quaternary, characterized by the deposition of proximal fans during strong volcanic activity; the uplift of the Quindío–Risaralda Fan; and the destructive phase, which generated intermediate and distal fans associated with the uplift phase.

Keywords: *Quaternary deposits, Romeral Fault System, faults, Quindío–Risaralda Basin.*

Supplementary Information:
S: https://www2.sgc.gov.co/LibroGeologiaColombia/tgc/sgcpubesp38201909s.pdf

Resumen Los depósitos cuaternarios en la Cuenca Quindío–Risaralda están ampliamente relacionados con la actividad neotectónica del Sistema de Fallas de Romeral; su estudio y caracterización recobran importancia debido al panorama de amenaza sísmica y el riesgo que el Sistema de Fallas representa para las poblaciones de los departamentos de Quindío y Risaralda.

Estos depósitos cuaternarios se agrupan en cuatro unidades: el Cuaternario antiguo que corresponde al Abanico de Quindío–Risaralda, el cual se divide de acuerdo a su geomorfología, geología y petrografía en tres grupos —abanicos proximales, abanicos intermedios y abanicos distales—; el Cuaternario reciente aluvial, representado por depósitos con estratificación subhorizontal distribuidos en pequeñas cuencas de menos de 10 km²; el Cuaternario aluvial y coluvial activo y casi activo, asociado a fallas; y los depósitos piroclásticos activos y casi activos, que se pueden dividir en depósitos de caída de ceniza y depósitos de ceniza retrabajados o redepositados.

La génesis y evolución de la Cuenca Quindío–Risaralda son subdivididas en cuatro etapas: la formación de la depresión Quindío–Risaralda controlada por fallas nor-

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males, la cual ocurrió tras una fase de plegamiento durante el Plioceno en la Cuenca Cauca–Patía; el inicio de la fase constructiva del Abanico de Quindío–Risaralda en el Cuaternario temprano, caracterizada por el depósito de abanicos proximales durante un período de fuerte actividad volcánica; el levantamiento del Abanico de Quindío–Risaralda; y la fase destructiva, en la que se depositaron abanicos intermedios y distales como resultado de la fase de levantamiento.

Palabras clave: *depósitos cuaternarios, Sistema de Fallas de Romeral, fallas, Cuenca Quindío–Risaralda.*

1. Introduction

1.1. Background

The Quindío earthquake of 25 January 1999, a shallow earthquake with its epicenter in Córdoba (Quindío, western flank of the Central Cordillera of the Colombian Andes) that cost some fifteen hundred lives and caused serious damage in twenty–six Colombian municipalities, confirmed the great importance of studying the active Quaternary faults in the region. Fortunately, such study had been started a short time earlier. Investigations of the historical seismicity of the region detected the occurrence of shallow earthquakes in Risaralda, Quindío, and Caldas along faults of the Romeral Fault System, mainly on the Silvia–Pijao Fault. This seismicity, not studied earlier, was understood as due to the historical activity of these faults, and subsequently, their study became a priority for the region. The issue was also very prominent at the national level because after approximately 70 years had passed without major events, shallow seismicity wreaked havoc in Colombia with earthquakes such as Popayán in 1983, Murindó in 1992, Páez in 1994, and Tauramena in 1995.

In the study of active faults in Colombia, researchers always faced difficulties related to the lack of sufficiently detailed knowledge of the local Quaternary geology. For this reason, the author proposed a different approach: Knowledge of the regional Quaternary deposits would be an initial step in the study of active faulting.

The Quaternary units of Quindío and Risaralda were essentially undifferentiated in the geological literature until this time. A large unit had been identified in each region on the geological map sheets 243 Armenia (McCourt et al., 1985) and 224 Pereira (Caballero & Zapata, 1984) and in the geological maps of Quindío (González & Núñez, 1991) and Risaralda (González, 1993), with different nomenclatures, which are discussed later. The study of the local Quaternary deposits and active faults in Quindío started in 1999, and the results of the first phase were submitted in November of the following year. In this first study, basic observations of the Quindío–Risaralda Quaternary deposits were conducted, a model of their formation was proposed, and the main units were defined.

Later studies contributed to knowledge of the subject in the region. The main contributing studies focused on the neotectonics of Quindío for the microzonation of Armenia (Espinosa et al., 1999), on the geology and paleoseismology of the Armenia Fault and on evaluation of La Vieja River basin as a source of construction materials, carried out by the regional autonomous corporations of Quindío (Corporación Autónoma Regional del Quíndio–CRQ) and Risaralda (Corporación Autónoma Regional de Risaralda–Carder).

An undergraduate thesis on active faults in the Pijao–Calarcá region directed by the Universidad de Caldas and the Universidad del Quindío was presented by Botero et al. (2004). A series of studies on the sedimentology and tectonics of the Quindío and Risaralda Quaternary deposits, directed by the Universidad del Quindío and the University of Genève, Switzerland, was performed between 1999 and 2009. Bachelor's and Master's theses on the subject were presented by Duque (2005), García (2008), Guarín (2002), Ospina–Ostios (2007), Pahud (2009), and Suter (2003). PhD dissertations were produced by Guarín (2008), Neuwerth (2012), and Suter (2008). These studies were based on a Quaternary model of Quindío and Risaralda and the generalized map presents by the previous studies. A first contribution, very important for understanding the genesis of the deposits, was presented by Guarín (2002), who characterized the old Quindío and Risaralda Quaternary deposits as lahars such as those formed by the Mount St. Helens eruption in 1980 and similar events. Guarín et al. (2004) published a synthesis of the geology of a unit that was designated the Quindío–Risaralda Fan, a term that has been adopted since then.

More recent consulting works, several of them through projects at the Universidad del Quindío, provided detailed information that allowed the Quaternary model to be refined. Among these works were projects concerning the Calarcá landfill, the threat posed by El Cofre stream in the village of La Virginia, Calarcá, and along the Armenia–Calarcá route and a series of studies of aqueduct network instability commissioned by the Comité de Cafeteros del Quindío.

In 2013, the author of this chapter started systematic geological mapping of the Quindío–Risaralda Quaternary deposits at a scale of 1:5000 for the Servicio Geológico Colombiano.

The great differences between previous maps of the Quaternary units of the region, including sheets 224 Pereira (Caballero & Zapata, 1984) and 243 Armenia (McCourt et al., 1985), were one of the main reasons that prompted these studies. They were the subject of annual reports.

This chapter presents a model of the deposition of the Quindío and Risaralda Quaternary deposits; this model was proposed in the first study of the Quindío faults, refined by later works by the same author and adopted in the studies by the other cited authors. In addition, the chapter proposes a model of the genesis and evolution of the Quindío–Risaralda Basin and the deposits within.

1.2. Geographic Setting

The study area spans the Quaternary deposits of Quindío and Risaralda as defined in the regional geological mapping (Caballero & Zapata, 1984; González & Núñez, 1991; McCourt et al., 1985) and the Quaternary units of the piedmont of the Central Cordillera in the region. This area corresponds hydrographically to La Vieja River basin with its tributaries (Barragán, Quindío, Espejo, Roble, Barbas, and Consota Rivers) and a small portion of the Otún River basin. The northern limit of the study area is the Otún valley, north of Pereira (Figure 1).

2. Regional Geologic Framework

2.1. Sources of Information on Regional Geology

Studies of the regional geology began in the Quindío with the classic work of Nelson (1962), which focused on the geologic units between Ibagué and Armenia (a geologic profile of the Central Cordillera). The mapping was later advanced systematically in Quindío by Servicio Geológico Colombiano between 1980 and 1985, as an extension of the cartography of the Central Cordillera, and published at a scale of 1:100 000 (McCourt, 1985; McCourt et al., 1985); a map of Risaralda by Servicio Geológico Colombiano was also published (Caballero & Zapata, 1984); the previous publications correspond to sheets 243 Armenia, 262 Génova, and 224 Pereira mentioned in previous paragraphs.

In 1991, Servicio Geológico Colombiano published a synthesis of the Quindío mapping titled Mapa geológico generalizado del departamento del Quindío, at a scale 1:100 000 (González & Núñez, 1991), which presents an overview of the abovementioned works. Shortly afterward, a similar study of the Risaralda area was published (González, 1993). These publications used the nomenclature adopted for the Central Cordillera of the Colombian Andes by the symposia of regional geology organized by Servicio Geológico Colombiano (Maya & González, 1995). This nomenclature is accepted nationwide and therefore is used in this work.

2.2. Regional Geological Units

The units in the study area and surroundings include marine and continental rocks of Paleozoic and Mesozoic age, which are intruded by late Mesozoic and Tertiary igneous bodies and overlain by Tertiary sedimentary sequences. These units, which compose the basement in the region, are offset by large regional faults and are covered by the Quaternary sediments of Quindío and Risaralda, which are the subject of this study. A generalized geological and tectonic map of the area is presented in Figure 1.

The Paleozoic and Mesozoic units of the region are the Cajamarca, Quebradagrande, and Arquía Complexes (listed from east to west), fragments of ultramafic rocks, and the Igneous Complex of Córdoba. The first three of these units are longitudinally continuous along the Central Cordillera, exposed as NNE–trending strips bounded by large regional faults, which is a notable feature of the geology of the Colombian Andes. The Tertiary sedimentary sequences consist of the Cinta de Piedra, La Paila, and La Pobreza Formations.

2.2.1. Cajamarca Complex

The Cajamarca Complex was defined by Nelson (1962) as a metasedimentary and metavolcanic sequence in which greenschists, black schists, quartzites, and marbles predominate. Authors who have studied this complex have assigned it a Paleozoic age (Nelson, 1962; McCourt et al., 1985).

2.2.2. Quebradagrande Complex

The Quebradagrande Complex is a mafic marine volcanic unit composed of basalts and associated rocks with intercalations of sedimentites such as siltstones, chert, and graywackes. The regional mapping shows that the complex contains a volcanic unit and a sedimentary unit; generally, the first unit is predominant.

2.2.3. Arquía Complex

The Arquía Complex consists of a series of rocks including metagabbros, amphibolites, hornblende schists, eclogites, and metasedimentary units of oceanic origin. On its edges and locally within the interior are fragments of ultramafic rocks that were emplaced tectonically. In the Quindío region, the geological mapping at a scale of 1:100 000 shows the Arquía Complex containing a unit of mafic igneous rocks known regionally as the Rosario Complex and a unit of greenschist rocks known as the Bugalagrande Schists (McCourt et al., 1985).

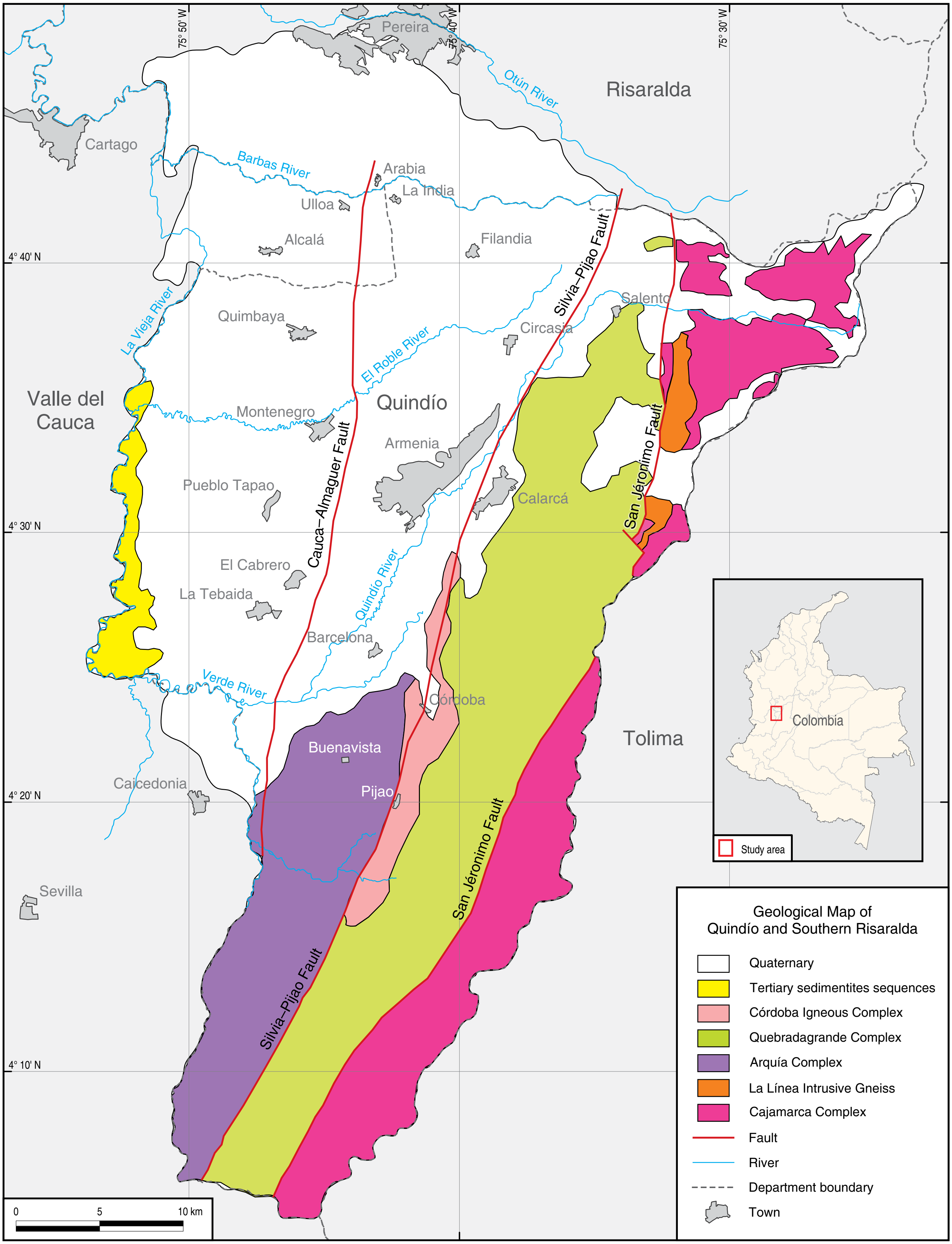
75° 50' W
75° 40' W
75° 30' W
4° 40' N
4° 30' N
4° 20' N
4° 10' N
Pereira
Otún River
Risaralda
Cartago
Barbas River
Arabia
La India
Ulloa
Alcalá
Filandia
Silvia–Pijao Fault
Salento
Quimbaya
Circasia
La Vieja River
El Roble River
Valle del Cauca
Quindío
Montenegro
Armenia
Cauca–Almaguer Fault
San Jéronimo Fault
Pueblo Tapao
Calarcá
El Cabrero
La Tebaida
Quindío River
Barcelona
Verde River
Córdoba
Tolima
Buenavista
Pijao
Caicedonia
Sevilla
Colombia
Study area
Geological Map of Quindío and Southern Risaralda
Quaternary
Tertiary sedimentites sequences
Córdoba Igneous Complex
Quebradagrande Complex
Arquía Complex
La Línea Intrusive Gneiss
Cajamarca Complex
Fault
River
Department boundary
Town
0
5
10 km

Figure 1. Geological map of the study area and the Central Cordillera in Quindío. Adapted from González & Núñez (1991).

2.2.4. Fragments of Ultramafic Rocks

Along the large regional faults, particularly the Silvia–Pijao Fault (Figure 1), a series of tectonically emplaced ultramafic rocks is exposed. The rocks are present as bodies of small lateral extent, a maximum of a few square kilometers, elongated parallel to the large faults.

2.2.5. Amaime Formation

In the Quindío area, the Amaime Formation is covered by Quaternary deposits and crops out in the Barbas River canyon. This unit consists of a sequence of basalts and associated rocks of oceanic affinity and Cretaceous age.

2.2.6. Igneous Complex of Córdoba

The Igneous Complex of Córdoba is an elongated body approximately 20 kilometers long and 1 to 2 kilometers wide that was emplaced along the Silvia–Pijao Fault, that is, between the Arquía and Quebradagrande Complexes. Its age is Late Cretaceous, and its composition is dioritic to tonalitic.

2.2.7. Tertiary Sedimentary Rocks

The sequence of Tertiary sedimentary rocks in Quindío is part of the sedimentary stack that composes the serranía de Santa Bárbara on the western boundary of the Quindío–Risaralda Fan, which, according to regional mapping (McCourt et al., 1985), consists of the Cinta de Piedra, La Paila, and La Pobreza Formations, listed from oldest to youngest. Their ages span from the late Oligocene to the Pliocene, according to McCourt (1985). These sequences are detrital and composed predominantly of sandstones and conglomerates whose source was in the Central Cordillera.

Unconformably overlying the Tertiary sediments is an unfolded unit, the Zarzal Formation, defined by van der Hammen (1958). It is a sequence of sandstones, claystones, diatomites, and minor conglomerates. Its age is Pliocene to Pleistocene.

2.2.8. Quindío–Risaralda Quaternary Deposits

The Quindío–Risaralda Quaternary deposits are well developed and extend over a large area in the region, nearly half of the Quindío Department. Although few ages are available for the regional Quaternary deposits, the relationships between the large units are clear and allow the basic stratigraphy to be established.

Traditionally, the Quaternary deposits of the region have been grouped as a single unit with various names, with the name *Glacis del Quindío* predominating (González & Núñez, 1991). Recent studies indicate that the regional Quaternary materials are more complex and can be divided into four large units:

1. Ancient Quaternary deposits;
2. Recent Quaternary alluvium;
3. Nearly active and active Quaternary colluvium and alluvium; and
4. Pyroclastic outfall deposits, nearly active and active.

The ancient Quaternary deposits correspond to the most extensive units. These units were identified in the earliest studies and were called the *flujo de lodo del Quindío* (Mosquera, 1978), Armenia Formation (McCourt et al., 1985), and Glacis del Quindío (González & Núñez, 1991) in Quindío Department, and *flujos de lodo volcánico* (Caballero & Zapata, 1984) and Glacis del Quindío (González, 1993) in Risaralda Department. These ancient Quaternary deposits of Quindío and Risaralda, which were traditionally regarded as two different assemblages, can be treated as a single unit because, their oldest portions belong to a single alluvial fan that later split when the basins of the Quindío and Otún Rivers separated. Nevertheless, the mechanism of development of the two deposits has been the same throughout their geologic history. The result is the Quindío–Risaralda Fan, which is not a simple unit but rather an amalgam of units, each of which is an alluvial fan.

The recent Quaternary alluvium consists of a series of deposits identified by previous works and by specific studies. These deposits unconformably overlie the Quindío–Risaralda Fan and occupy small tributary basins of the Quindío River and their tributaries in the foothills of the Central Cordillera.

The nearly active and active Quaternary deposits consist of a set of colluviums that is mappable at a scale of 1:25 000 and underlies the western flank of the Central Cordillera at the boundary with the Quindío–Risaralda Fan. Associated with these deposits is nearly active alluvium deposited by streams that drain the flank of the cordillera; those of El Cofre River were recently described. The nearly active terraces of the major rivers and the active alluvium also belong to this group.

The pyroclastic deposit is volcanic ash from the nearby volcanoes of the Central Cordillera, which covers and sculpts all the deposits of the region. A large portion of these materials was redeposited later in the basins of the region.

2.3. Regional Structure

Several fault systems have been identified by authors who have studied the region. A synthesis of the geology of Quindío by González & Núñez (1991) noted the presence of three fault systems: The Romeral Fault System, which trends N–S; the Salento Fault System, which trends N55°W; and the Palestina Fault System, which trends N20°E. The first of the three systems dominates the tectonics in Quindío, and the other two display some surface expression in this area. The San Jerónimo and Silvia–Pijao Faults dominate the Romeral System. The former juxtaposes the Cajamarca and Quebradagrande Complexes, and the latter juxtaposes the Quebradagrande and Arquía Complexes. These faults, according to the abovementioned authors, display strong basement expression, whereas in the Quindío Quaternary deposits, their surface expressions consist only of lineaments.

Folding is well developed in the Tertiary sequences. These sequences are intensely folded, forming tight and sometimes faulted anticlines and synclines with axes parallel to the large faults of the Romeral System, i.e., approximately N15°E.

Unconformably overlying the folded Tertiary sequences, the strata of the Zarzal Formation are in a subhorizontal position; they are in turn unconformably overlain by the various levels of the Quindío–Risaralda Fan. This contact is an angular unconformity observable in numerous locations along the serranía de Santa Bárbara (Figure 2). One such location is between La Tebaida and La Vieja River on the Armenia–Cali route. The folding occurred after deposition of the Cinta de Piedra, La Paila, and La Pobreza Formations and prior to deposition of the Zarzal Formation. It has been traditionally thought that the age of the folding is Pliocene, immediately prior to deposition of the Zarzal Formation (van der Hammen, 1958). The folding corresponds to a well–known phase of compression that was responsible for similar folding of all pre–Pliocene Tertiary sequences throughout western Colombia.

3. Ancient Quaternary Deposits in Quindío and Risaralda

As stated earlier, the Quindío–Risaralda Quaternary deposits consist of four large units, of which the ancient Quaternary material is the best developed. This material composes the Quindío–Risaralda Fan. The unit represents more than 90% of the Quaternary deposits of the region and spans the longest period of deposition, almost the entire Pleistocene.

3.1. General Characteristics

In the Quindío–Risaralda Fan, lahars (debris flows and hyper–concentrated flows) predominate in the distal and intermediate zones; these lahars originated from the erosion of primitive volcanic units. The distal part consists of fine sediments resulting from the erosion of the intermediate portion of the fan. Thawing glacial ice caps (due to volcanism or climatic phenomena) and uplift of the Central Cordillera during the Quaternary played important roles in the generation of these deposits. Generally, the apex or proximal part of the fan corresponds to the area of the high valleys of the Quindío and Otún Rivers, and the distal parts are situated near the mouths of the Quindío, Roble, and Barbas Rivers in La Vieja River basin.

Traditionally, the ancient Quindío–Risaralda Quaternary deposits appeared in regional studies as an internally undifferentiated unit. Thouret (1988) was the first author to differentiate the unit, dividing it into three subunits.

The geomorphology, basic geology, stratigraphy, and petrography of the Quindío–Risaralda Fan indicate that it consists of deposits from a series of events. Observations that support this idea were proposed in the first studies of the Quaternary deposits of the region, as described below.

3.1.1. Steps in the Fans

Topographically, the Quindío–Risaralda Fan displays a set of very clearly defined steps. There is a series of levels descending from the apex to the distal parts of the fan. The communities on the fan are located at very distinct topographic levels. These communities are Filandia, Salento, Circasia, Armenia, Calarcá, La Tebaida, Montenegro, Quimbaya, Alcalá, Ulloa, and Pereira. Figure 3 illustrates the steps in the Calarcá–Armenia region. This distinct feature of the topography of the Quindío–Risaralda Fan suggests that it consists of alluvial terraces in a broad sense and that each step or scarp corresponds to a boundary between two units, the lower of which has been embedded in the higher after erosion of the older unit.

3.1.2. Degree of Incision

The drainage systems at the various levels in the Quindío–Risaralda Fan display notable differences. Drainage systems with different orientations and with diverse degrees of incision are observed. In general, the more proximal the system is, the greater the incision, i.e., the deeper and wider the valleys. The proximal units are older than the distal units and therefore have been exposed longer to stream erosion, and they are positioned higher relative to base level (La Vieja River); both factors have led to deeper drainage incision.

3.1.3. Original Deposit Slope

Although the original surfaces of the deposits have been affected by erosion, especially the oldest ones, remnants of these surfaces can be observed in a profile. The proximal deposits display original slopes that are markedly better developed than those of the distal deposits. Although there has undoubtedly been tectonic tilting associated with the uplift of the Central Cordillera, this feature must also correspond to differences in the compositions of the deposits.

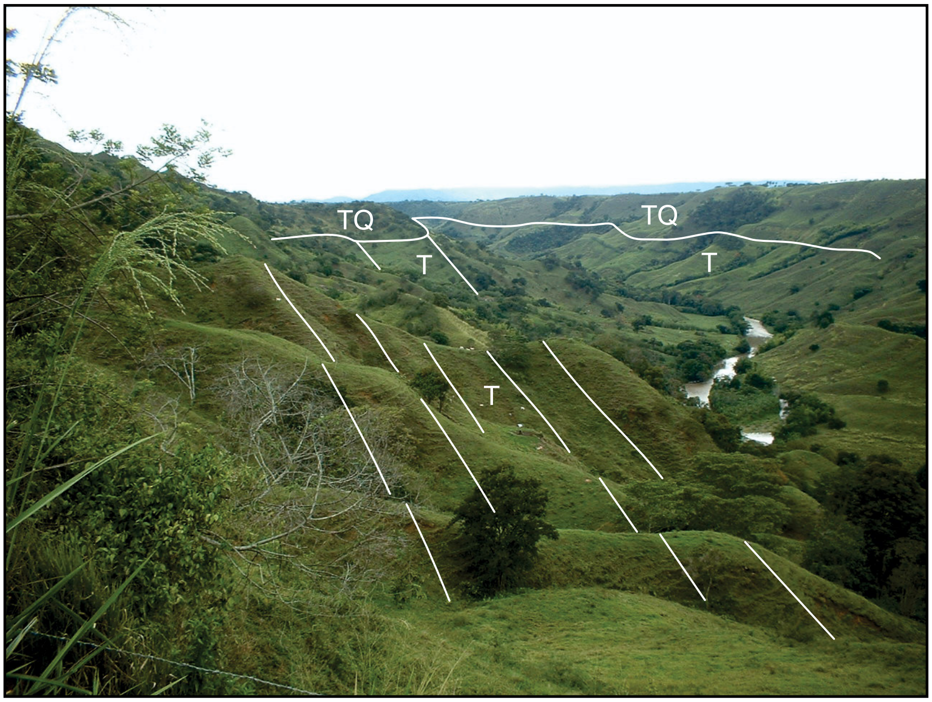

Figure 2. Upper Tertiary – Quaternary unconformity: Zarzal Formation and Quindío–Risaralda Fan (TQ) overlying the folded Tertiary (T) rocks in the valley of La Vieja River, Pereira–Cartago zone. The view is northward from the Quimbaya–Cartago road, Piedra de Moler sector.

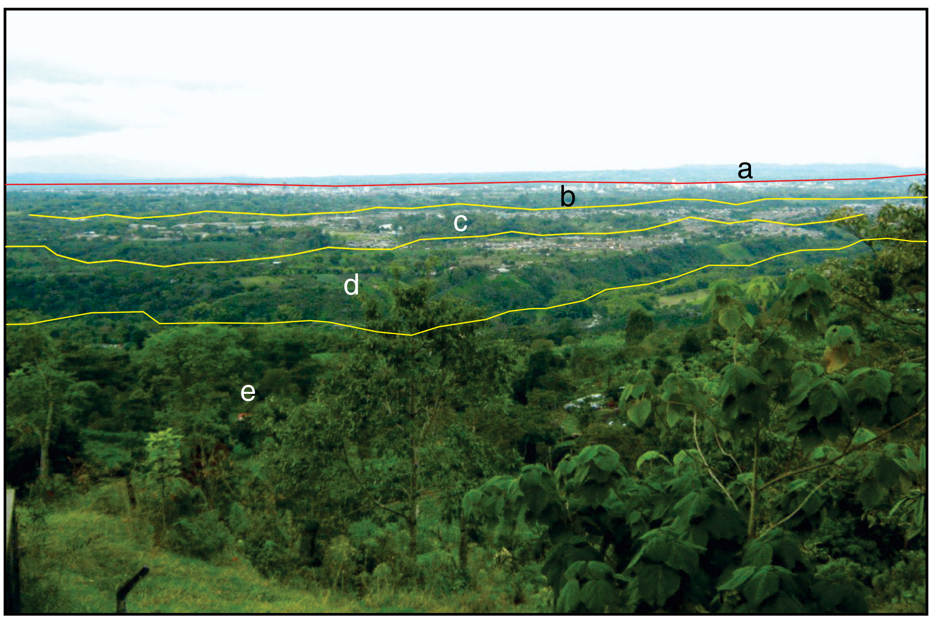

Figure 3. Steps in fans in the region of Armenia–Calarcá, viewed toward the west from the village of La Virginia, Calarcá. The city of Armenia is at the top of the photograph. (a) Filandia step; (b) Armenia step; (c) Armenia–Calarcá step; (d) Calarcá step; (e) recent terraces of the Santo Domingo River.

3.1.4. Type of Deposits

There are strong differences in the type of deposits. In general, volcanic processes were involved in deposition of the proximal units, whereas the most distal units are alluvial.

3.1.5. Degree of Compaction

The degree of compaction of the deposits varies greatly: The trend is one of gradually greater compaction toward the proximal part of the fan.

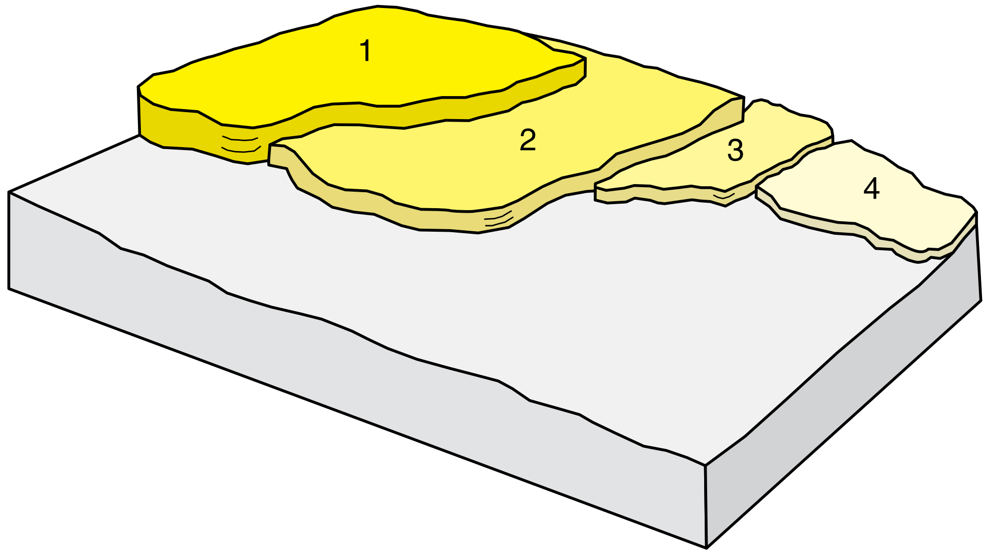

Figure 4. Mechanism of emplacement for the units of the Quindío and Pereira Fans. The numbers indicate relative ages from oldest (1) to youngest (4).

The above observations allow us to conclude that the Quindío–Risaralda Fan is the result of a series of events different from those proposed in previous studies; the events are younger toward the distal parts of the fan. Locally, the topographic features of the fan can be called alluvial terraces; however, taking into account that the units generally retain their original forms of cones or alluvial fans, we can refer to fans and assemblages of fans.

The whole group that makes up the Quindío–Risaralda Fan clearly unconformably overlies the folded Tertiary system of the serranía de Santa Bárbara. Thus, the history of the Quindío–Risaralda Fan began after the folding of the Tertiary (Pliocene) deposits. The units associated with the present–day Quindío and Otún Rivers are the youngest units of the fan, whereas the units located in the high valleys of these rivers form a common apex and are the oldest, which indicates that the two basins differentiated recently.

At the apex of the assemblage, between these two rivers are the remains of two primitive fans deposited in the basin of the ancestral Quindío–Otún River. These fans are the Cocora and Los Robles Fans, as described later. Following erosion and deposition, the Filandia Fan was deposited. In the following phase, the two basins differentiated, and in each basin, successive fans began to be deposited; each fan corresponded to a cycle of erosion and deposition within one or several previous fans. Figure 4 illustrates the mechanism of formation of the assemblage making up the Quindío–Risaralda Fan.

3.2. Large Assemblages and Units of Quindío–Risaralda Fan

The Quindío–Risaralda Fan can be divided into three large assemblages: The proximal, intermediate, and distal fans. They correspond to clearly and strongly observable features in the field. The three assemblages are units that stand out topographically and individually display a characteristic geomorphologic expression. They likely correspond to three large depositional cycles and are related to distinct phases of volcanism, tectonism, and climatic change (Figures 5, 6).

3.2.1. Assemblage of Proximal Fans

This assemblage occupies the common apex of the Quindío–Risaralda Fan (Figure 7), and its distal limit passes through Circasia and west of Filandia. It consists of three successive large fans, i.e., Cocora, Los Robles, and Filandia, and two smaller fans embedded within them (see Supplementary Information). It is the oldest assemblage and has undergone the greatest incision by the drainage system. Its deposits tend to be volcanic within the Cocora and Los Robles Fans and fluvio–volcanic within the Filandia Fan. Geomorphologically, the assemblage displays abrupt expression with strong slopes and a sparse drainage network.

The succession of events responsible for the emplacement of the units can be discerned to a large extent from the view of the geological map (see Supplementary Information).

The formation of the assemblage of proximal fans began with the emplacement of the Cocora Fan, which is composed mostly of debris avalanche deposits resulting from the collapse of one of the volcanic edifices located in the northeastern corner of the modern Quindío–Risaralda Fan, probably the Nevado del Quindío. The deposit, which is large, filled all the depression and today is at the base of many of the younger fans. It was followed by Los Robles, Filandia, Boquía–Río Otún Fans (debris flows), each of them embedded in one or two older fans.

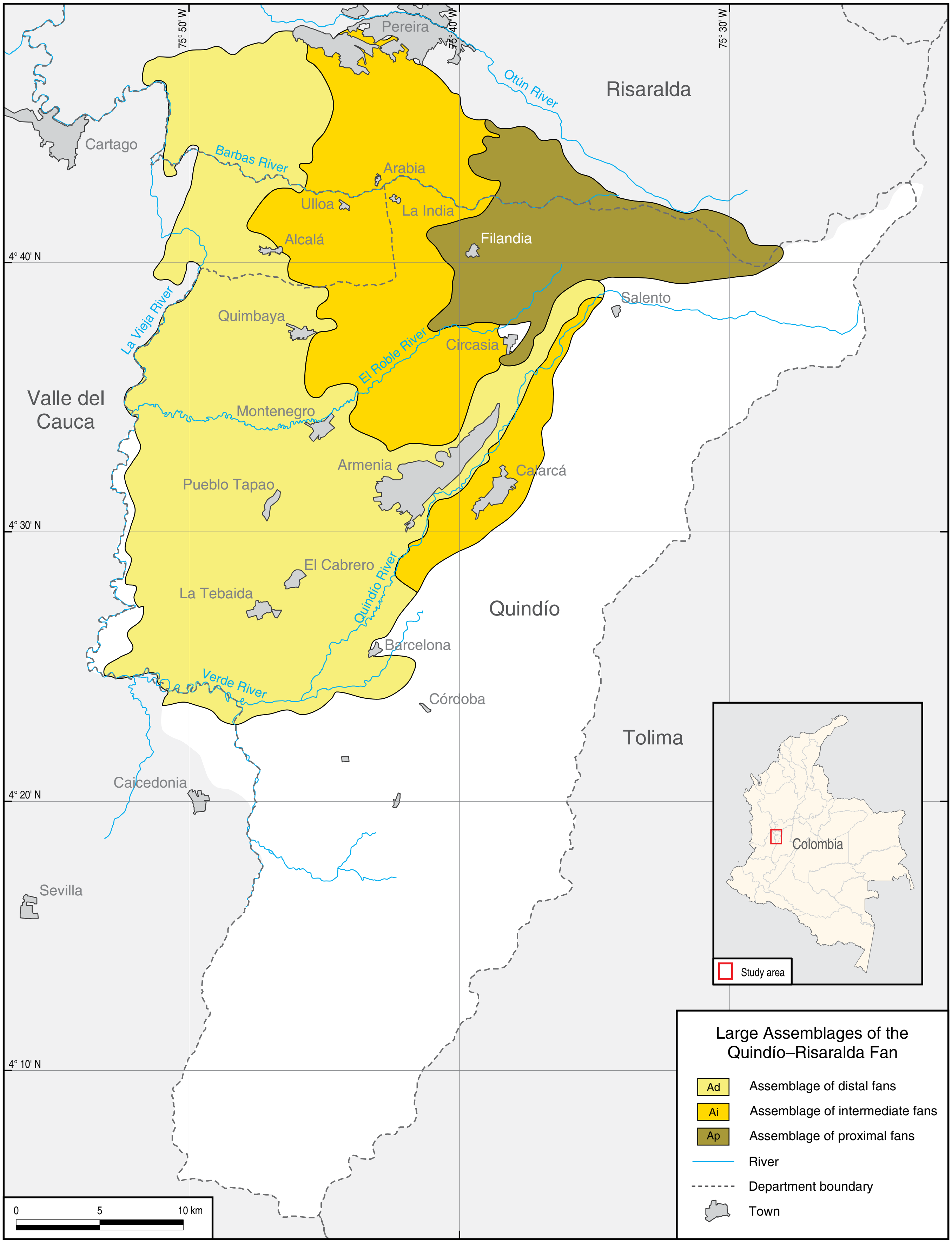

Figure 5. Large assemblages of the Quindío–Risaralda Fan.

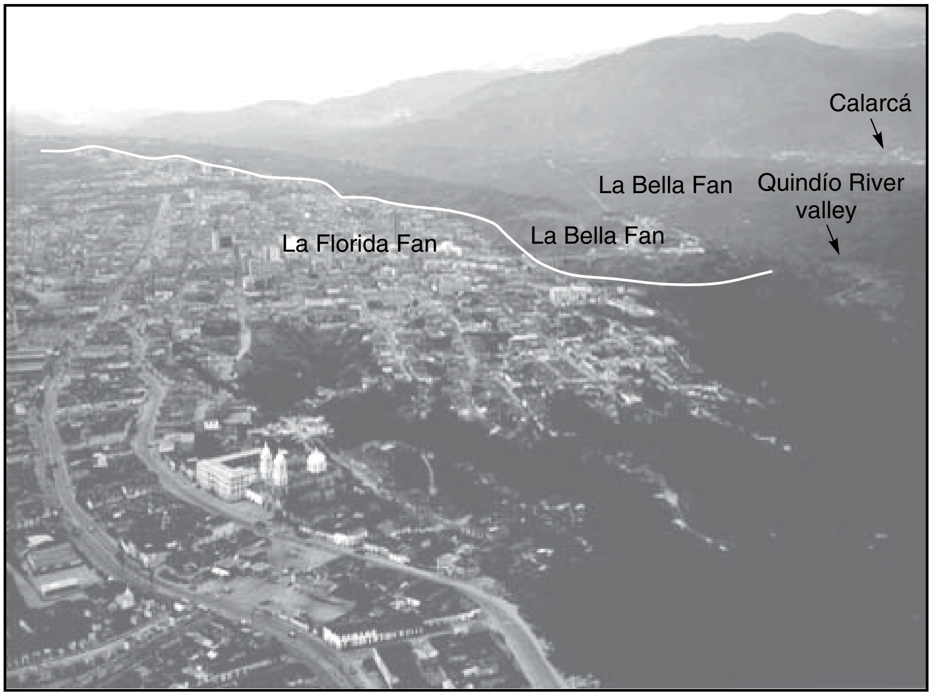

Figure 6. Oblique aerial view of Armenia in the 1970s, view toward the northeast. The clear boundaries of La Bella and La Florida Fans are also those of the intermediate and distal fans.

3.2.2. Assemblage of Intermediate Fans

The assemblage of intermediate fans is a fairly wide strip located west, southwest, and south of the previous unit, whose distal boundary passes north of Armenia, east of Montenegro and Quimbaya, and west of Ulloa. The average slope gradient is gentler than that of the assemblage of proximal fans, and the degree of incision is less. This forms a very dense network. The assemblage consists of numerous fans on both the Quindío and Risaralda sides, associated with a much more complex drainage network at the time of deposition (Figure 8). The intermediate fans have their apices toward the front of the proximal fans, which indicates that they are the result of the erosion of the former. A similar situation can be observed in the distal fans in relation to the intermediate fans.

The assemblage of intermediate fans forms the sector of a crown of approximately 90° toward the SW, whose center (common apex of the fans) is near the Nevado del Quindío. It is possible to distinguish a northern and a southern sector separated by a radius that passes through Circasia and Montenegro. The northern sector includes a series of fans that are the result of erosion of Los Robles and Filandia Fans: Consota I, La Arabia, Altagracia, La India, Ulloa, El Paraíso, and the northern part of Circasia (see Supplementary Information). Figure 9 shows the units in the region of southern Pereira. The southern sector is made up of fans that resulted from the erosion of the Circasia Fan, a unit that initially occupied a large area, and is currently eroded and dismembered. These fans are La Floresta, La Soledad, Las Lomas, Las Marias, Portachuelo, and La Bella Fans, which represent erosion of the distal part of the Cocora Fan (see Supplementary Information). The intermediate fans can be regarded as coalescent and more or less contemporaneous during a long period of the Quaternary, perhaps approximately 200 000 years. Debris flow deposits dominate these fans; in some of the deposits, blocks of eroded fans are preserved in the form of intraclasts.

3.2.3. Assemblage of Distal Fans

West and south of the intermediate fans, the last, and most extensive Quindío–Risaralda Fan units were deposited, i.e., the assemblage of distal fans (Figure 10). This unit is bounded on the west by the folded Tertiary sediments of the serranía de Santa Bárbara, on which it was unconformably deposited. The geomorphologic expression of the assemblage is strong, as it is for the other two assemblages. Its slope gradient is very low, as is the degree of incision. The number of fans that make up this unit is also very large, greater than that of the intermediate fans, which reflects a large number of sources.

Two successive cycles of deposition from east to west can be recognized in the assemblage of distal fans.

The fans of the first cycle are, from north to south, the Consota II, Morelia, La Estrella, El Retiro, Betulia, Venecia, Alcalá, Quimbaya, El Chaquiro, El Laurel, Montenegro, Hojas Anchas, Pueblo Tapao, La Y, and Barcelona Fans (see Supplementary Information). They can also be considered coalescent and contemporaneous across a relatively long time period. Debris flows and

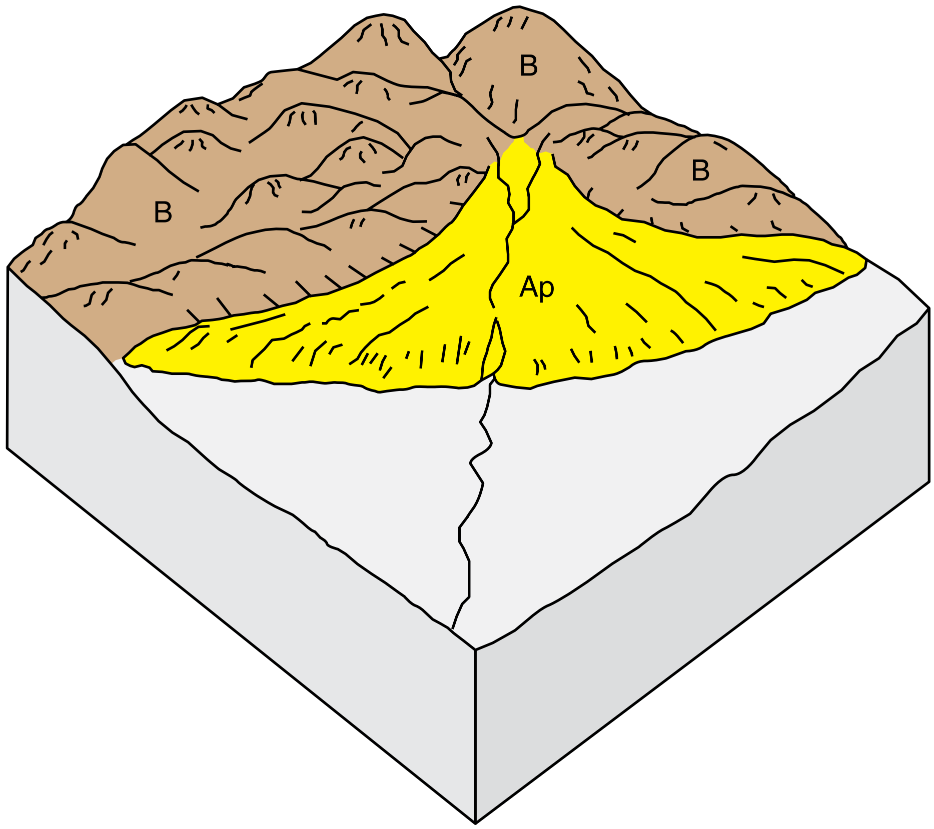

Figure 7. Schematic depositional model of the assemblage of proximal fans. (B) Pre–Quaternary basement; (Ap) assemblage of proximal fans.

hyper–concentrated flows are the predominant deposits. The fans of the second cycle are El Tigre, Cestillal, Río Barbas, Piedra de Moler, San Felipe, Puerto Alejandría, Buenavista, Quebrada La Estrella, El Ocaso, Río Roble, Vereda El Cuzco, Las Palmas, Vereda Buenos Aires, La Florida, and La Tebaida Fans (see Supplementary Information). The distal parts of these fans unconformably overlie the folded Tertiary units of the serranía de Santa Barbara. In the deposits, some hyper–concentrated flow deposits are found, but in the distal parts, typical sedimentary sequences predominate: Sandstones, siltstones, and claystones.

4. Recent, Nearly Active, and Active Quaternary Deposits

Several units deposited on the ancient Quaternary fan have been divided into the recent Quaternary alluvium (Qar), the nearly active and active Quaternary colluvium and alluvium (Qs, Qal), and the pyroclastic fallout deposits.

4.1. Recent Quaternary Alluvium

Disconformably overlying the basement and the ancient Quaternary fans, there are alluvial sequences that occupy small basins of less than 10 km^2 located in the zone between the ancient Quaternary deposits and the basement of the Central Cordillera.

The geomorphologic features of these basins are clear. Subhorizontally bedded deposits that converge toward the Santo Domingo River are present both on the eastern and western sides (La Sonadora and Quebradanegra Rivers) and near the Verde River in the Córdoba region.

In the banks of La Sonadora River, a tributary of the Santo Domingo River, we can observe the best developed and most representative unit of this type of deposit in the Quindío–Risaralda Fan. It occupies a basin with an area of approximately 6 km^2 in the foothills of the Central Cordillera southwest of La Virginia (Calarcá). In some areas, it is associated with colluvium. At the base of the deposit, there is a conglomerate containing clasts of basaltic composition up to 30 centimeters in diameter. On the conglomerate rests a sequence of redeposited volcanic ash, in which several events and distinct laminations are evident.

4.2. Nearly Active and Active Quaternary Colluvium and Alluvium

This group includes deposits of three types: Colluvium and alluvium from the piedmont (Qsca), La Vieja, Barragán, and Quindío (Qst) terraces, and active alluvium (Qal).

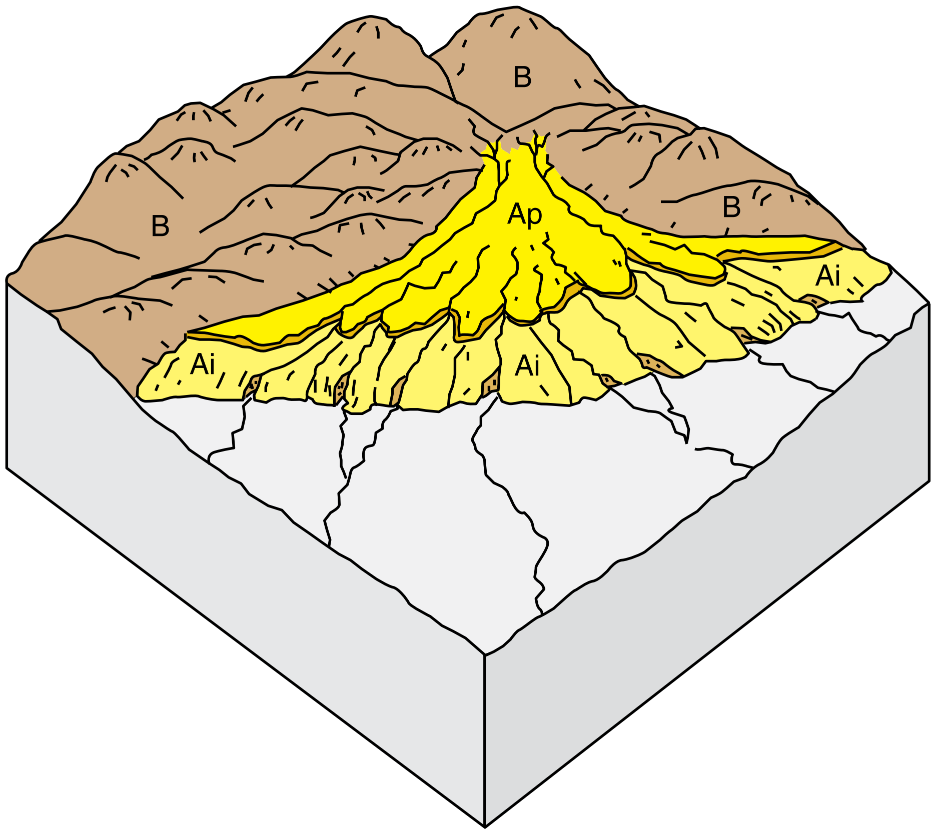

Figure 8. Diagram of the formation phase of the intermediate fans. (B) Pre–Quaternary basement; (Ap) assemblage of proximal fans; (Ai) assemblage of intermediate fans.

The nearly active and active colluvium and alluvium of the piedmont are well developed, particularly on the flank of the Central Cordillera along the Cretaceous – Quaternary boundary, east of the Salento–Calarcá–Barcelona–Caicedonia line. They are closely associated with faults, especially those with recent activity, which is why they are of great importance for understanding local neotectonics and paleoseismology.

The nearly active colluvium was derived from the basement, mainly the Quebradagrande Complex, triggered by uplift of basement blocks along local faults. The zone south of La Virginia (Calarcá), between this village and Quebradanegra, provides a good example of the development of the colluvium. It is characterized geomorphologically by an intermediate slope between that of the basement and that of the alluvium.

There is no doubt that the colluvium represents several periods of deposition. The oldest deposits have been uplifted significantly by faulting and now show inverted relief, i.e., negative relief at the time of deposition and positive relief today. Particularly well developed and perhaps the oldest are the colluvial deposits of the area of La Paloma between La Sonadora and Quebradanegra Rivers.

In small basins located within the colluvium, there are detrital deposits with thicknesses of less than 20 meters, generally located several tens of meters above the base level of the current streams and therefore good indicators of the uplift of the blocks along the regional faults.

The terraces of La Vieja–Barragán and Quindío Rivers and those of the major tributaries of these rivers (Santo Domingo, Espejo) show extensive development in the region. There are clearly several levels of terraces at elevations between 40 and 2 meters above the current level of the rivers. The last event in the development of the terrace system is represented by the active alluvium, which is also well developed in the channels of major rivers, including La Vieja, Quindío, Barragán, and Verde Rivers.

4.3. Nearly Active and Active Pyroclastic Fallout Deposits

The term volcanic ash, commonly used in the Antiguo Caldas region for decades when describing the equivalent of falling ash, is confusing. Observations by the author in the previous twenty years indicate that there are two types of deposits of these materials: Fallout ash and ash that has been reworked or redeposited. Both deposits involve the same materials, expelled by volcanoes in the region at various times during the Quaternary. However, notable differences between these two types of deposits are observed:

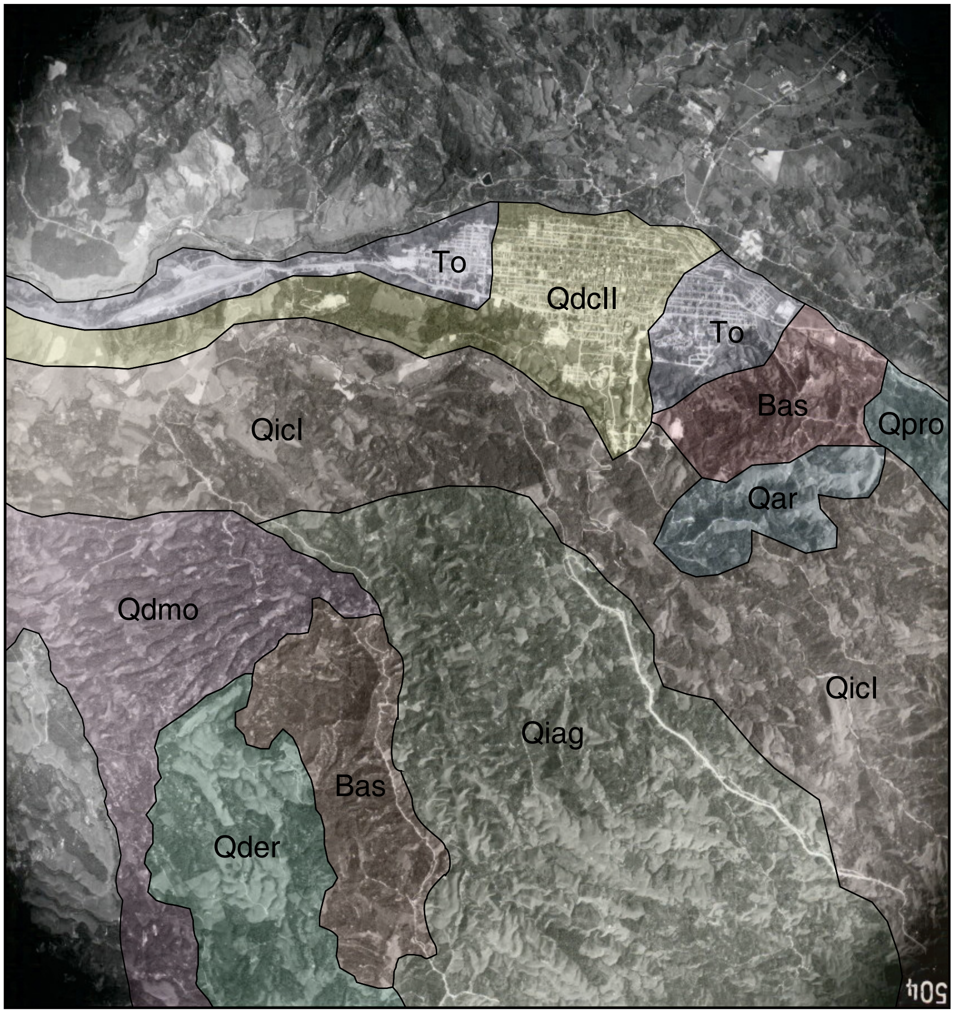

Figure 9. Fans in the southern region of Pereira. (Bas) Pre–Quaternary basement; (Qpro) Otún River Fan; (Qiag) Altagracia Fan; (QicI) Consota I Fan; (Qdmo) Morelia Fan; (Qder) El Retiro Fan; (QdcII) Consota II Fan; (Qar) recent Quaternary alluvium; (To) terraces of the Otún River. The approximate width of the picture is 20 kilometers.

- The redeposited ash displays subhorizontal bedding and unconformable contacts with older deposits (Figures 11, 12); the fallout ash displays sculpting of the topography.
- Sorting and moisture are greater in the redeposited ash. In addition, there are lateral variations and internal structures and concretion types in the process of formation of the redeposited ash.

5. Structural Geology

The study area is, from a tectonic viewpoint, located within the corridor of the Romeral Fault System. The three major faults in this system, the Cauca–Almaguer, Silvia–Pijao, and San Jerónimo Faults from west to east, cross the region with a trend of approximately N15°E. The role of these faults has been crucial for the geologic history of the area, but their activity during the Quaternary has been variable. In addition, the zone is crossed by faults of the Salento and Palestina Systems. The study of faults is in progress, but the most relevant features of the main faults have been identified.

5.1. Romeral Fault System

5.1.1. San Jerónimo Fault

According to McCourt et al. (1985), the San Jerónimo Fault marks a Paleozoic suture between the Paleozoic metasedimentary sequences of the Cajamarca Complex and the basaltic rocks of the Quebradagrande Complex. In the Quindío–Risaralda Fan, this fault cuts the proximal fans east of Salento, forming a tall scarp in the Cocora Fan.

5.1.2. Silvia–Pijao Fault

With a length similar to that of the San Jerónimo Fault, the Silvia–Pijao Fault juxtaposes the Quebradagrande and Arquía

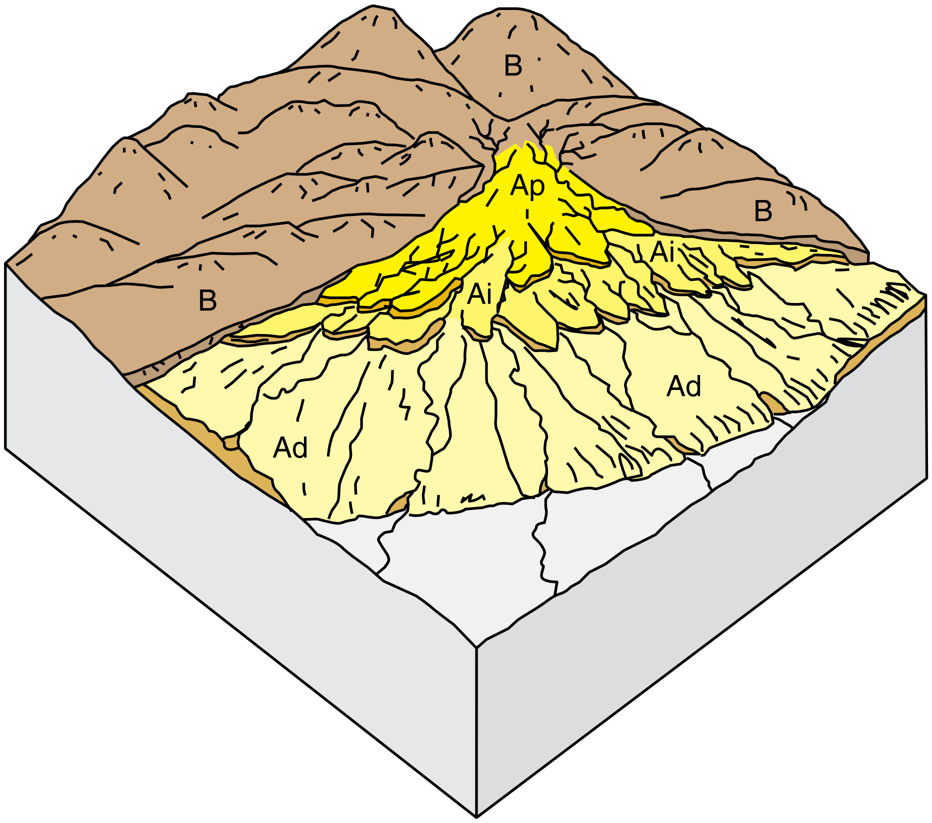

Figure 10. Diagram of the development of distal fans. (B) Pre–Quaternary basement; (Ap) assemblage of proximal fans; (Ai) assemblage of intermediate fans; (Ad) assemblage of distal fans.

Figure 11. Outcrop of volcanic ash in Armenia, avenida 19, calle 18N. Note the angular unconformity between the fallout ash and the underlying redeposited ash.

Figure 12. Sequence of redeposited volcanic ash showing subhorizontal bedding and unconformable relationship with the pre–Quaternary basement (Quebradagrande Complex). Excavation for the Intercambiador de Versalles, Calarcá, October 2016.

Complexes (Figure 1). Its geomorphologic expression in the basement and in the Quaternary units is very clear, and it is the structure of greatest interest in the region due to its proximity to urban centers (mainly Armenia, Calarcá, Córdoba, and Pijao). Recent observations have shown that this fault offsets Quaternary units in several places in the region, including two offsets of Holocene deposits.

5.1.3. Cauca–Almaguer Fault

According to McCourt et al. (1984), the Cauca–Almaguer Fault is an Early Cretaceous feature that juxtaposes the Arquía Complex and the Amaime Formation. Its expression in the Quindío–Risaralda Quaternary deposits is quite clear.

Some secondary faults of the Romeral System, such as the Armenia, Montenegro, and La Tebaida Faults, show Quaternary activity, with proven ruptures in the region.

5.2. Salento and Palestina Fault Systems

Faults of the Salento and Palestina Systems pass through Salento, Circasia, and the Verde River. They offset Quaternary deposits and have produced tall scarps in Salento, but have not been studied in detail. The Palestina System has also not been studied. A young structure with an NE orientation close to that of this system is the Altagracia Fault, which clearly offsets the Quaternary deposits south and east of Pereira.

6. Genesis and Evolution of the Quindío–Risaralda Fan

A model of the formation and evolution of the Quindío–Risaralda Fan is summarized bellow.

The Quindío–Risaralda Fan and the faults offsetting indicate that the evolution of this great unit occurred in two large phases: A constructive phase, essentially the deposition of the proximal fans in association with strong volcanic activity, and a destructive phase, i.e., the erosion of the proximal fans, which spanned the entire period of emplacement of the intermediate and distal fans and was largely controlled by the uplift of the entire sequence along the faults described earlier.

The geological studies of the Paramillo de Santa Rosa Volcano revealed deposits generated by this edifice, which infilled the primitive Otún–Quindío Basin and formed a basement. These deposits correspond to a portion of the proximal fans. In the opinion of the author, they were generated not only by the Paramillo de Santa Rosa volcanic edifice but also by the Nevado del Quindío Volcano in its northeastern part (Cocora, Salento, northern Armenia).

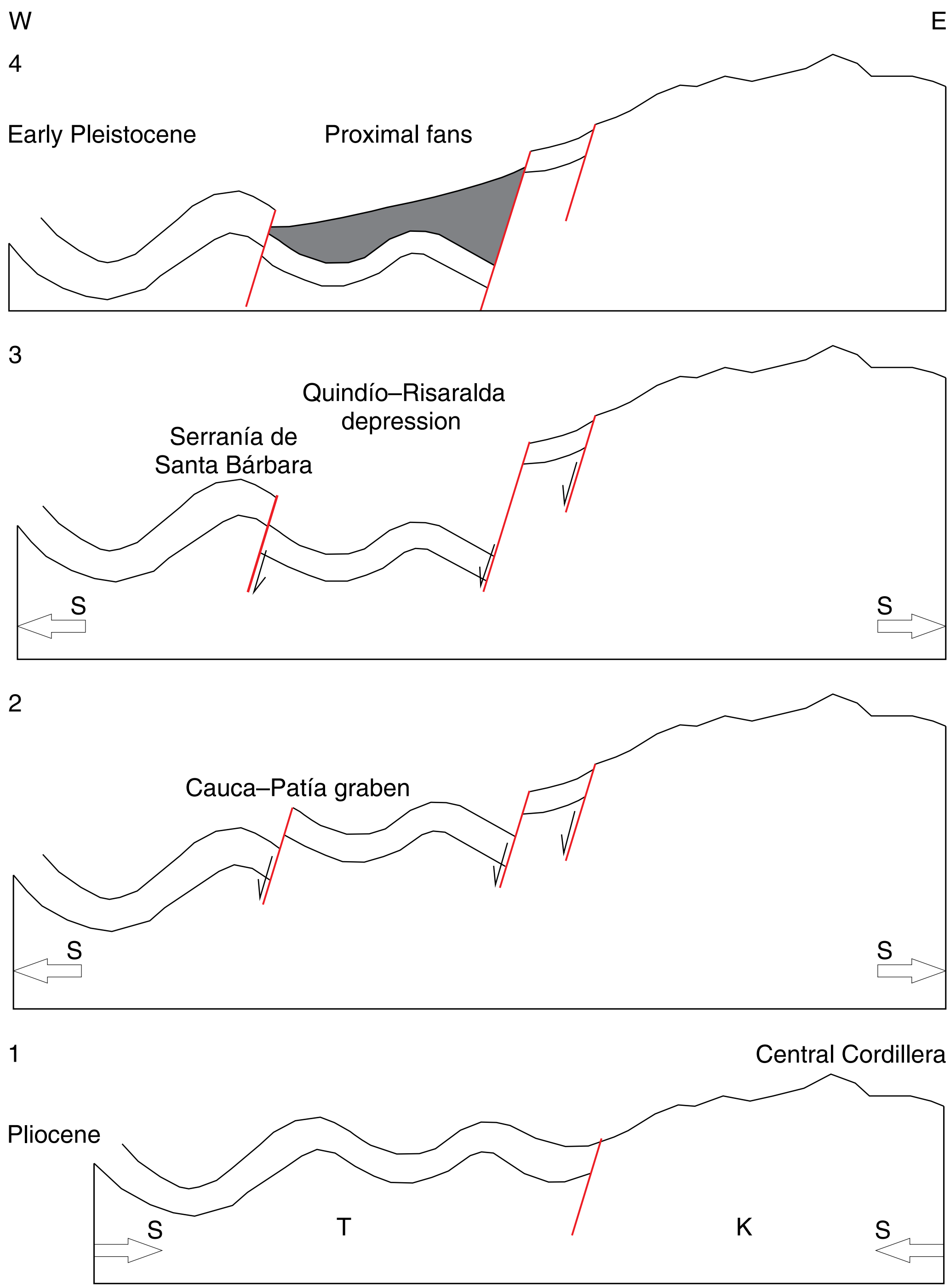

Figure 13. Diagram of the formation of the Quindío–Risaralda depression and the constructive phase of the fan (emplacement of proximal fans). (K) Cretaceous; (T) Tertiary; (S) stress.

6.1. An Integrated Model of the Origin of the Quindío–Risaralda Fan

Based on the previously stated observations, the following integrated model of the Quindío–Risaralda Fan incorporating the local lithology, geomorphology, and tectonics is proposed.

6.1.1. Formation of the Quindío–Risaralda Depression

The Tertiary strata, their folding during the Pliocene, and the active fault features inherited from this epoch and later suggest that the pliocene folding throughout the Cauca–Patía Basin was followed by a phase of extension during which the

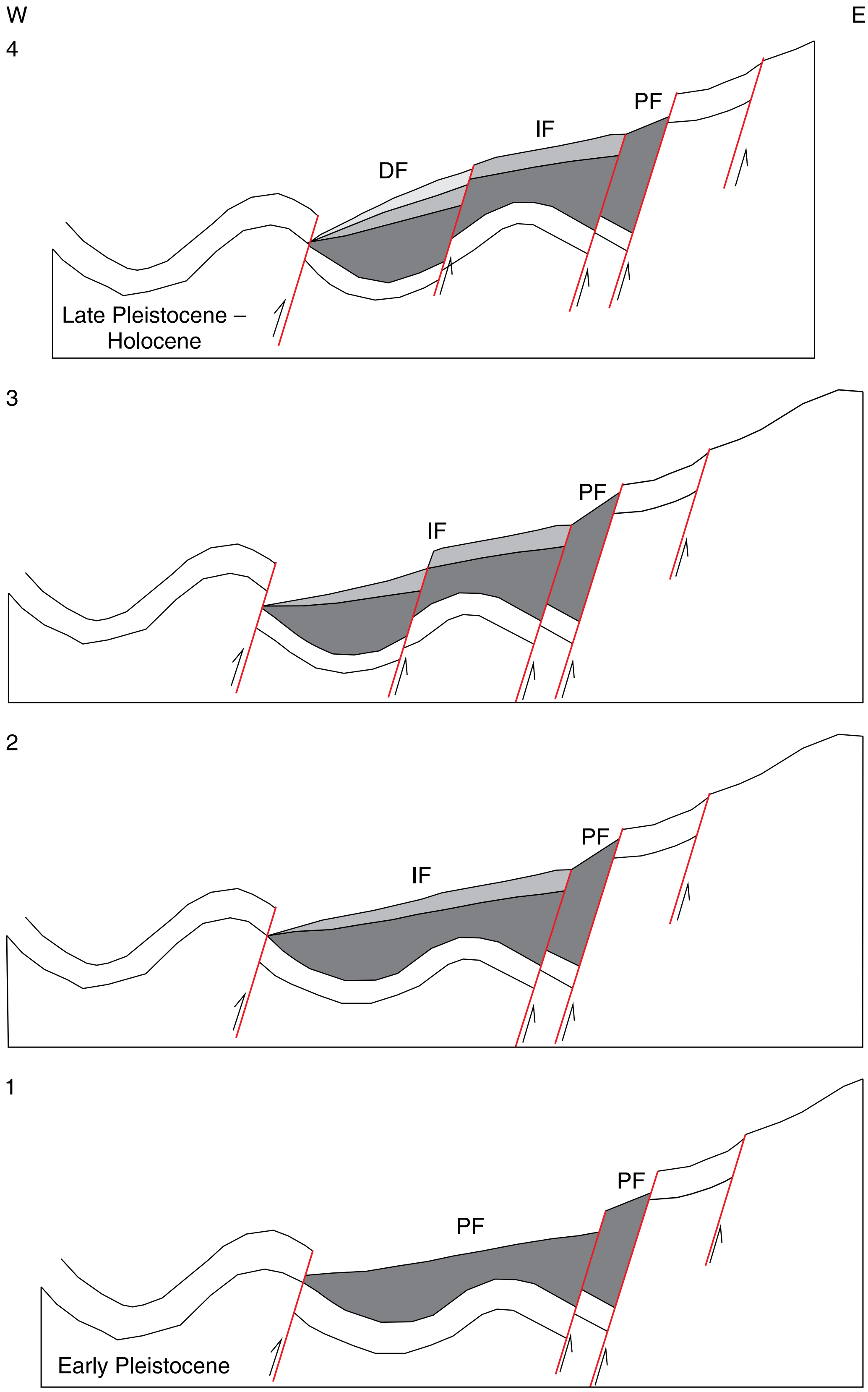

Figure 14. Diagram of the genesis of the Quindío–Risaralda Fan during the destructive phase: Uplift of the proximal fans and deposition of the intermediate fans; repetition of the cycle with the distal fans. (PF) Proximal fans; (IF) intermediate fans; (DF) distal fans.

Cauca–Patía Basin developed; it took the form of a graben controlled by normal faults on the two flanks of the mountain ranges. During this phase of extension, the collapse of a wedge between the Cauca–Almaguer and Silvia–Pijao Faults resulted in a depression in which the primitive basin of the Barragán–La Vieja River developed (Figure 13). Erosion by this river widened the depression and gave it the shape that it exhibits today.

6.1.2. Constructive Phase of the Quindío–Risaralda Fan

The phase of development of the Quindío–Risaralda Fan occurred in the early Quaternary following the formation of the Quindío–Risaralda depression on the western flank of the Central Cordillera. Large volcanic deposits, generated by the collapse of the edifices of Paramillo de Santa Rosa and Nevado del Quindío Volcanoes, infilled the Quindío–Risaralda depression. These deposits consist essentially of debris avalanches and pyroclastic flows. Their thickness exceeds 100 meters in the proximal part.

The Cocora and Los Robles Fans are remnants of the deposits from the constructive phase. In the other fans, these deposits form the base of the sequences, with some exceptions including the Altagracia Fan, where the deposits of the constructive phase are missing and the later deposits directly overlie the Cretaceous basement.

6.1.3. Uplift of the Fan

During and after the constructive phase, the primitive fan (proximal deposits) began to be cut and uplifted by the faults of the Romeral System, mainly those of the San Jerónimo subsystem. The uplift was very rapid, judging from the height of the active scarp along the main fault, north of Salento, which is approximately 200 meters high.

As the Quindío–Risaralda Fan developed, uplift of the various units started as soon as they were deposited. In order of importance and in order of age, the faults of the Romeral subsystems involved in the uplift were the San Jerónimo, Silvia–Pijao, and Cauca–Almaguer.

6.1.4. Destructive Phase of the Quindío–Risaralda Fan

The last proximal units, the intermediate units, and the distal units were the results of the uplift of the primitive fan (Figure 14) and essentially formed by erosion due to the strong rejuvenation of the drainage network incised into the unit. In general, two large successive uplift cycles were responsible for forming the intermediate fans (Silvia–Pijao subsystem) and distal fans (Cauca–Almaguer subsystem).

7. Conclusions

The Quindío–Risaralda Fan, previously identified as an undifferentiated Quaternary unit, appears to be a complex assemblage of fans strongly affected by the faults of the Romeral Fault System during most of Quaternary time. Systematic mapping and tectonic analysis allow us to propose an integrated model of its genesis and evolution. It is helpful to analyze whether this model is consistent with the features of the unit as observed on the surface.

7.1. Geomorphologic Units

There are clear geomorphologic expressions in the different units that together make up the Quindío–Risaralda Fan (which is an amalgam of fans, as described earlier). Strong features include height differences between units, sometimes up to hundreds of meters, differences between the orientations of drainages, and different degrees of dissection, which are fundamental to explaining the fan origins; the model is consistent with these geomorphologic features.

7.2. Lithology

In the Quindío–Risaralda Fan, lithologic differences essentially do not exist; the fan is practically a monomictic unit with an andesitic composition. The differences between the units are the types of deposits. The model considers that older units are more directly associated with the activity of nearby volcanoes (debris avalanches, pyroclastic deposits) and that the youngest units are lahars resulting from the erosion of older units. The monomictic character of the fan is consistent with these origins. The differences in the types of deposits had already been observed in the first studies of the Quindío Fan.

7.3. Tectonics

The strong and constant uplift of the fan is a fundamental feature of its genesis and evolution. It could even be said that this uplift is the key to understanding the unit.

The Quindío–Risaralda depression is a unique feature on the flank of the Central Cordillera and can be explained only by the tectonics of the region. The extensive surface exposures of the units are also the result of the local tectonics. This fact characterizes the unit, differentiating it from the vast majority of similar units including the Ibagué Fan and the Popayán Formation (Popayán Plateau).

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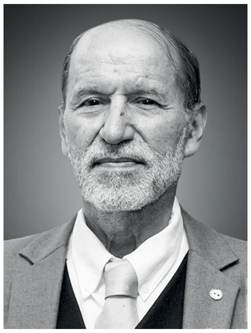
Explanation of Acronyms, Abbreviations, and Symbols:

Carder	Corporación Autónoma Regional de Risaralda
CRQ	Corporación Autónoma Regional del Quindío

Author's Biographical Notes



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