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(Plio-)Pleistocene alluvial-lacustrine basin infill evolution in a strike-slip active zone (Northern Andes, Western-Central Cordilleras, Colombia)

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ABSTRACT

The (Plio)-Pleistocene Zarzal Formation was deposited in the Cauca Depression and Quindío-Risaralda Basin between the Western and Central Cordilleras (Northern Andes). This area is structurally located on the transcurrent Romeral Fault System (RFS). Because of the interaction between the Nazca plate and the Chocó-Panamá block (an active indenter), the RFS strike-slip component changes direction around the study zone (dextral in the south, senestral in the north). Zarzal sediments are the oldest ones not to have been affected by the Pliocene Andean tectonic phase. Their study aims at better understanding the subsidence of these two interandean sedimentary basins within a regional compressional regime. The two basins are separated by the the Serrania de Santa Barbara (SSB), made of Tertiary sediments thrusted during the Pliocene tectonic phase. Zarzal sediments are fluvio-lacustrine: diatomites are encountered on both sides of the SSB and are alternating with braided stream or alluvial deposits. Sedimentation was strongly influenced by volcanic processes which led to the deposition of the Quindío-Risaralda and Cartago volcaniclastic fans sourced from the Central Cordillera. These volcaniclastic mass flows mixed with the Zarzal sediments, and even dammed and infilled a lake in the Quindío-Risaralda Basin (east of the SSB). Numerous extensional features affect Zarzal sediments with a mean extensional trend subparallel to the SSW-NNE trending cordilleras. The syndepositional tectonic activity is demonstrated by numerous seismites. In the Cauca Depression, sediments are infilling the basin more rapidly than it subsides or than the relief lifts up, thereby drowning the topography. This might be related to the tectonically-induced, downstream damming of the Cauca River valley to the north by the Chocó-Panamá block.

KEYWORDS **Romeral Fault System. Extension. Quindío-Risaralda. Seismites. Subsidence. Zarzal Formation. Diatomites. Volcaniclastics.**

INTRODUCTION

North of the equator, the Andes are under the influence of three convergent tectonic plates: the Nazca, South American and Caribbean plates (Pennington, 1981; Freymueller et al., 1993; Van der Hilst and Mann, 1994; Kellogg et al., 1995; Ego et al., 1996; Taboada et al., 2000; Trenkamp et al., 2002; Corredor, 2003, Cortes and Angelier, 2005, Montes et al., 2005). In the convergence zone between these three major plates, the deformation stress is absorbed by the displacement of three blocks or microplates (Fig. 1): the North Andes, Chocó-Panamá and Maracaibo blocks. The three SSW-NNE trending cordilleras of Colombia reflect these interactions. They are separated by two large interandean valleys within which the Cauca and Magdalena rivers flow northwards towards the Caribbean Sea.

Focussing on the Cauca River valley on a digital elevation model (DEM, Fig. 2), one notices that the northward flowing river does not show the normal profile of a balanced river with upstream erosion and downstream deposition. Between Cali and La Virginia the upstream part of the Cauca River is filling a large continental sedimentary basin, whereas its downstream part incises the cordilleras down to the northern lowlands of Colombia.

What are the mechanisms which have led to the deposition of more than 3,000 m of sediments in some parts of this Cauca Valley Basin (McCourt et al., 1984; Alfonso et al., 1994), whereas the regional tectonic regime is clearly compressional? James (1986) already observed that the infilling Tertiary sedimentary sequence is quite complete south of La Virginia and incomplete to the north of this city, because of a difference in the rate of uplift. Among

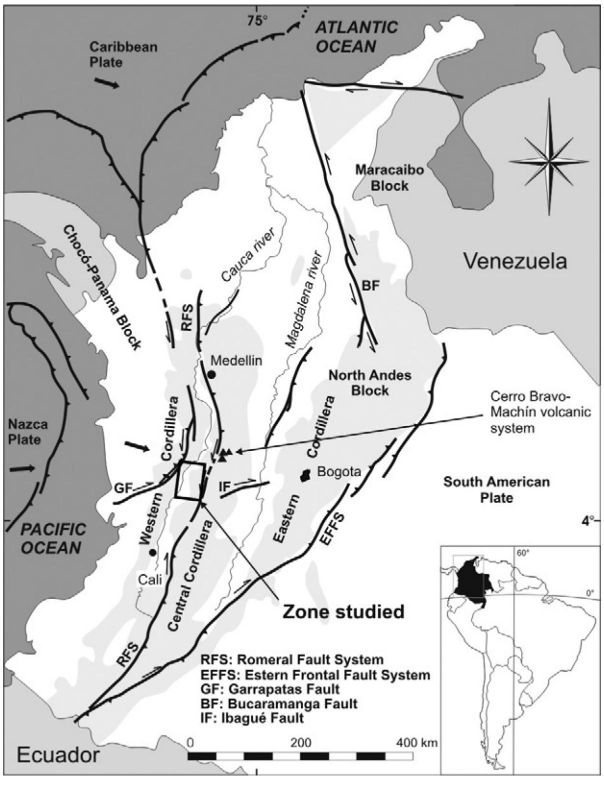

FIGURE 1 **Megatectonic framework of Colombia and location of studied area (Faults: after "Neotectonic map of the northern Andes", Taboada et al., 2000). The black arrows indicate the plate motion directions with respect to the South American Plate.**

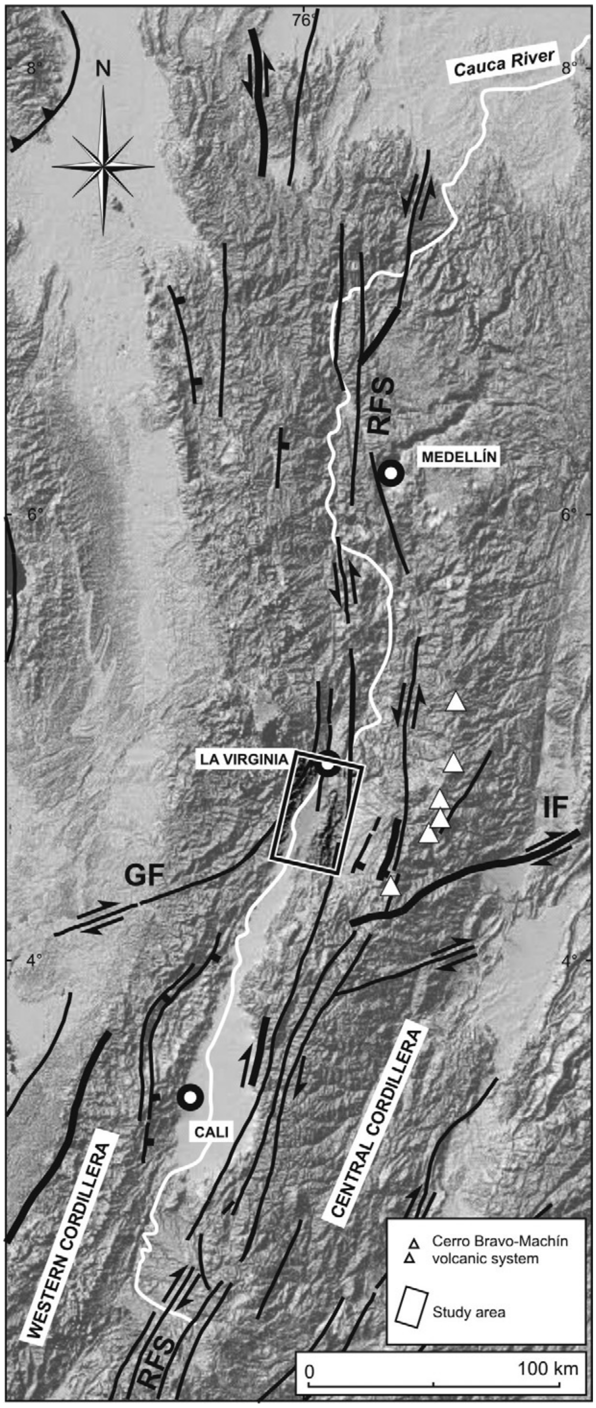

FIGURE 2 **Radar-based digital elevation model (DEM, USGS, 2005) showing the major structural elements of Central Colombia (Paris et al., 2000). Note the sedimentary basin between Cali and La Virginia. The Cauca River flows northwards.RFS: Romeral Fault System; GF: Garrapatas Fault; IF: Ibagué Fault.**

the sediments infilling this basin, the Plio-Pleistocene Zarzal Formation (Fm) represents the oldest deposits which have not been compressed by the Pliocene Andean tectonic phase.

Therefore, the detailed study of this formation may bring some answers about the infilling of this large interandean sedimentary basin. This paper proposes a sedimentary model for the Zarzal Fm and demonstrates evidences of ongoing superficial extensional tectonic activity.

GEOLOGICAL FRAMEWORK

The studied zone is located between the Central (CC) and Western Cordilleras (WC), between 4 and 5 degrees of latitude north (Figs. 1 and 2). Geomorphologically it comprises the entire Serranía de Santa Barbara (SSB) and its surroundings, the Cauca River plain (Cauca Depression, Fig. 3; MacDonald et al., 1996) north of the city of Zarzal and the eastern foothills of the WC (Fig. 3). Towards the east, the Cartago volcaniclastic fan and the distal part of the Quindío-Risaralda volcaniclastic fans (Guarín et al., 2006) are also included in the studied area.

The Cauca Depression south of La Virginia (Fig. 3) was interpreted as a graben (Acosta, 1978; McCourt et al., 1984; Droux and Delaloye, 1996; MacDonald et al., 1996) or as a left lateral transtensional pull-apart basin (Kellogg et al., 1983; Alfonso et al., 1994). Recent studies demonstrated an active, compressional, E-W trending tectonic regime in the Cauca Valley some 50 km north of Cali, which generated the thrusting of Tertiary over Quaternary sediments (López and Moreno, 2005; López et al., 2005). From a structural point of view, the studied area is located on the transcurrent Romeral Fault System (RFS) (Fig. 4), which marks the boundary between continental basement to the east and Upper Cretaceous accreted terranes to the west (Cline et al., 1981; McCourt et al., 1984; Aspden et al., 1987; Paris and Romero, 1994; Ego et al., 1995; MacDonald et al., 1996; Nivia, 1996; Paris et al., 2000; Taboada et al., 2000). The RFS has a S-N to SSW-NNE trend and crosses the entire Colombian territory from Guayaquil (Ecuador) up to the Carribbean Sea. South of the studied area, the RFS is under the influence of the W-E to WSW-ENE trending subduction of the Nazca Plate and shows a dextral strike-slip component (Fig. 2). North of 5° N the RFS shows a senestral strike-slip component because of the W-E to WNW-ESE trending indentation of the Chocó-Panamá block (Trenkamp et al., 2002) into the WC (Fig. 1). The zone where this transcurrent component changes direction is not clearly defined, but it may lie somewhere to the west of the Ibagué fault (Fig. 2; G. Paris, pers. comm.). In the studied area, the major S-N to SSW-NNE trending structures belonging to the RFS are senestral (Guzmán et al., 1998; Espinosa, 2000; Paris et al., 2000).

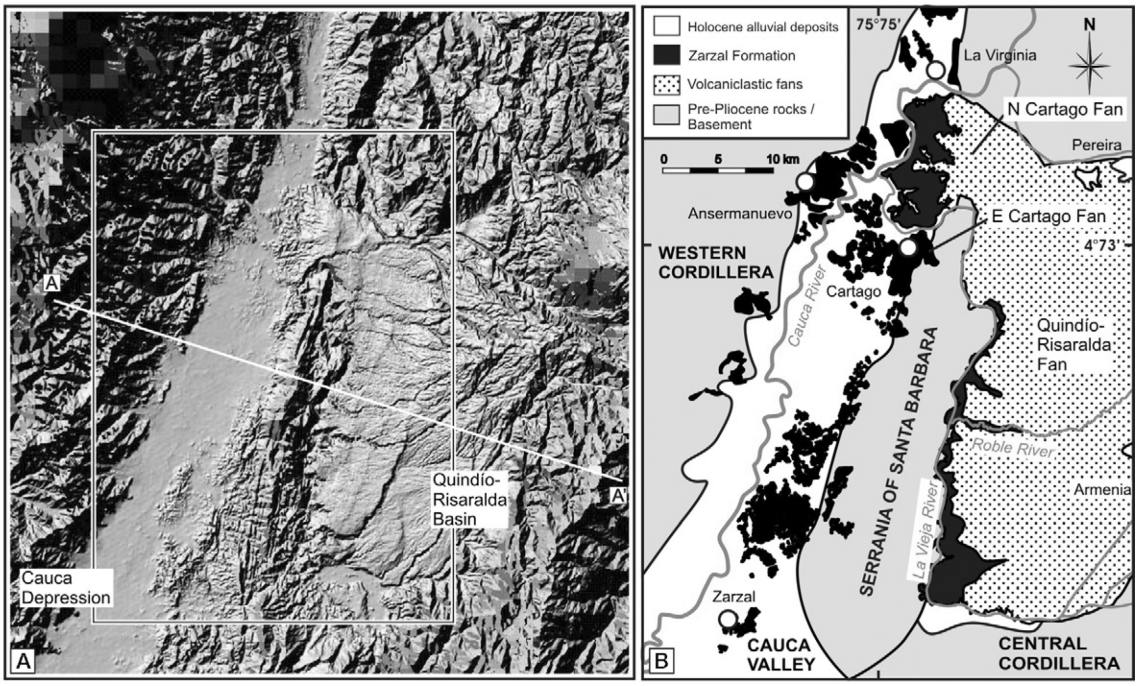

FIGURE 3 | **Geomorphology and geology of studied area: A: Digital elevation model (DEM; USGS, 2005). The framed area corresponds to Figure 3B and profile AA´ to Figure 4. B) Simplified geological map after González and Núñez (1991), Nivia et al. (1995) and Suter et al. (2005).**

Figure 4 shows a hypothetical, simplified, geological profile across the interandean Cauca-Quindío depression from the WC to the CC (see Fig. 3 for location). It is coherent with a NW-SE compressional tectonic regime, which generates in the SSW-NNE trending RFS localized zones of senestral transpression or transtension. The basement of the CC is made of Palaeozoic to Cretaceous metamorphic rocks intruded by some Cretaceous igneous intrusions (McCourt, 1984; INGEOMINAS, 1988; González and Núnez, 1991). The first oceanic terrane to accrete along the RFS during the Barremian is the Amaime Terraine followed by the Diabase Group (McCourt et al., 1984) and the "complejo estructural Dagua" (Nivia et al., 1995). During the Oligocene, the Cartago Fm was deposited on the suture between the accretionnary prism and the CC (Ríos and Aranzazu, 1989). It consists of fluvial sediments derived mainly from the CC and unconformably deposited on the basement. During the Andean tectonic phase (Cooper et al., 1995), these Lower Tertiary rocks were folded, the CC uplifted and the La Paila Fm deposited. The latter sediments comprise reworked material originating from the CC and the underlying continental clastic Oligocene sediments of the Cartago Fm. Based on palynological data, Van der Hammen (1958) gives a Miocene age to the La Paila Fm. Its lower part unconformably overlies the Cartago Fm with an angle locally as high as 90° (Alfonso et al., 1994). Some authors (e.g., Mc Court, 1984) make a distinction between the La Paila Fm and a younger La Pobreza Fm based on lithological differences in the reworked clastic material. Keith et al. (1988) and Ríos and Aranzazu (1989) consider both units as part of one big alluvial fan, the La Pobreza Fm being the distal part of the fan, and the La Paila Fm the proximal part. These rocks form the Tertiary fold and thrust belt described by Alfonso et al. (1994) and named the Serranía de Santa Barbara (SSB). The SSB thrust roots are very deep: it is a basement-involved thrust belt showing a thick skin tectonic style (Fig. 4) where Oligocene rocks are thrusted westwards over Miocene rocks. Around the SSB, Plio-Pleistocene sediments unconformably overlie this small mountain belt. They are constituted by the Zarzal Fm (Van der Hammen, 1958; De Porta, 1974; Cardona and Ortiz, 1994) and the volcaniclastic Armenia Fm (McCourt, 1984). The latter is also called (Fig. 5) Abanico del Quindío or Quindío

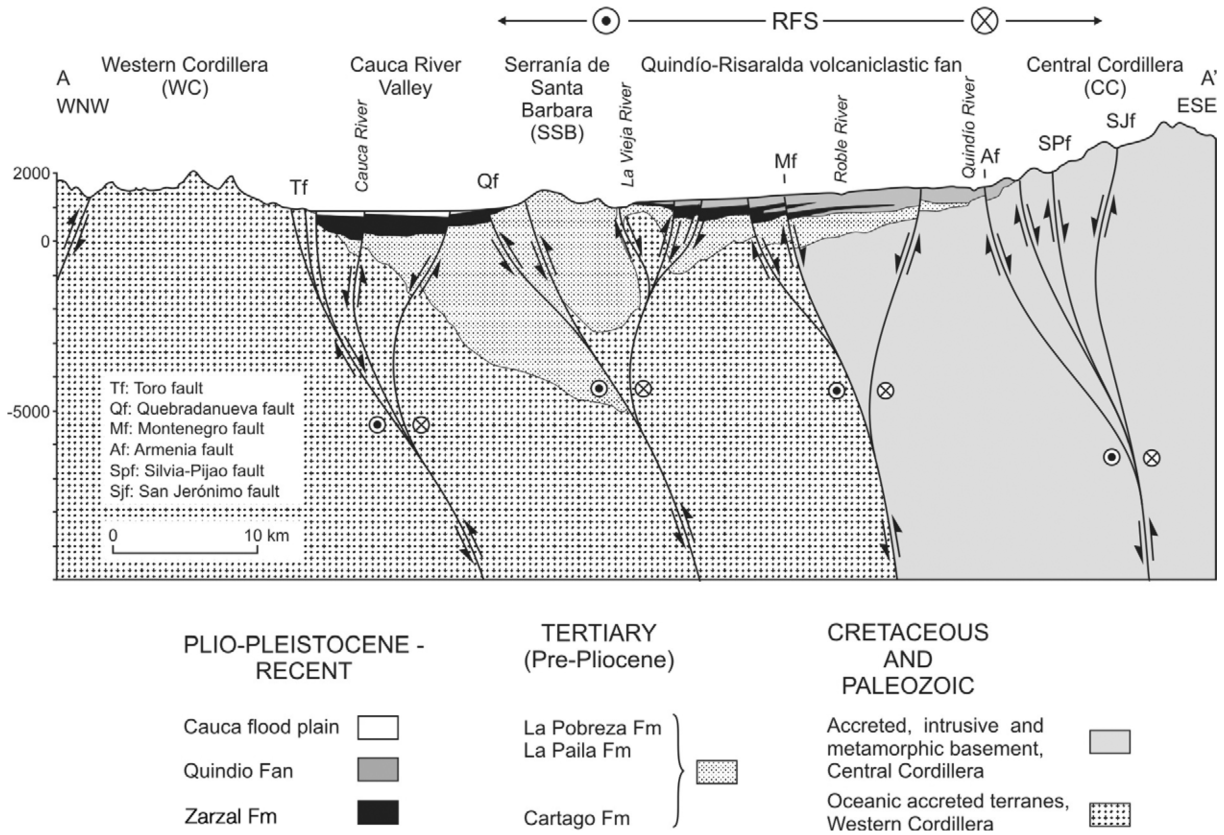

FIGURE 4 **Simplified geological cross-section from Western to Central Cordilleras (profile AA´ in Figure 3A) after Alfonso et al. (1994), Guzmán et al. (1998), INGEOMINAS (1999), Paris et al. (2000), Taboada et al. (2000), Suter (2003), Gallego et al. (2005), USGS (2005). This interpretation allows for localized zones of subsidence (Cauca and Quindío-Risaralda Basins) within a regional, compressional tectonic regime.**

Author(s)	Name	Area	Description
Mosquera, 1978	**Quindío Mud-flow**	(In Espinosa, 2000; Guarín et al., 2006)	
Thouret, 1988	**Quindío-Pereira Fan**	Corresponds to the Quindío, Risaralda and N Cartago Fans of this study.	> 100 m thick volcaniclastic deposits overlain by weathered fluvial deposits and a ca. 10 m thick layer of weathered volcanic ashes.
McCourt, 1984	**Armenia Formation**	Western flank of Central Cordillera to the north of Sevilla town (e.g., Quindío-Riseralda Fan in Fig. 3b).	Sediments dominated by poorly- or semi-consolidated ash-fall deposits and volcanic mudflows; lava flows, tuffs and agglomerates are absent.
González and Núñez, 1991	**Quindío Glacis**	Name given to the part of these deposits lying within the Quindío Department.	Unconsolidated deposits, volcanic ashes, mudflows and foothill deposits.
Cardona and Ortiz, 1994	**Pereira Formation**	Limited to the SE by the Quindío River, to the S and SW by the La Vieja River, to the NW by the Cauca River and to the N by the Otún River.	Volcanic, volcaniclastic and sedimentary rocks cropping out in the Risaralda, Quindío and Valle del Cauca Departments. Environments observed: braided stream with intercalated debris-flow deposits, floodplain, small lakes, and subaerial environments (palaeosoils and ashfalls).
Espinosa, 2000	**Quindío Fan (Abanico del Quindío)**	Name given to the part of these deposits lying within the Quindío Department.	Mostly catastrophic mudflows , originating from the melting of ice in the Central Cordillera glaciers or from erosive processes.
Guarin et al., 2006	**Quindío-Risaralda Fan**	Corresponds to the Quindío-Riseralda Fan of this study.	These authors distinguish a sequence of many stacked volcaniclastic units between the SSB and the Central Cordillera foothills. These units are characterized geomorphologically through terraces and fans.
This study	**Quindío Fan, Risaralda Fan, N Cartago Fan, E Cartago Fan**	These are geographical names meant to locate precisely each part of this vast volcaniclastic complex, which extends from the Central Cordillera to the western Cordillera foothils, between the towns of Zarzal to the S and La Virginia to the N. These deposits are interfingering with other units such as the Zarzal Formation or the fluvio-lacustrine sediments described in this study in the eastern foothills of the SSB and attributed to the Zarzal Formation. A new stratigraphic nomenclature is required, taking into account the new data related to these three interfingering volcaniclastic units .	

FIGURE 5 **Different published nomenclatures for the Quindío, Risaralda, N Cartago and E Cartago fans. A short description given by each author as well as the area covered by these deposits is also indicated.**

Fan (Espinosa, 2000), or Quindío-Risaralda Fan (Guarín et al., 2006) and can be subdivided into four parts, the Quindío, Risaralda and Eastern and Northern Cartago fans (Fig. 3). The Zarzal deposits interfinger with the Cartago fans and the distal part of the Quindío-Risaralda fans (Cardona and Ortiz, 1994; Suter et al., 2005). Holocene to recent alluvial deposits (Fig. 3) are present in the Cauca River valley and in some parts of the La Vieja River valley (e.g., the alluvial plain southwest of the Quindío Fan).

From a sedimentological point of view, the clastic composition of Plio-Pleistocene to recent sediments reveals a high content of volcanic constituents. This indicates that, in this active compressional tectonic regime, sedimentation was strongly linked to the volcanic activity in the CC, i.e. where the present-day Cerro Bravo-Machin volcanic system (Alfaro and Aguirre, 2003; also referred to as Ruiz-Tolima volcanic system, Guarín et al., 2006) is located (Fig. 2).

STATE OF KNOWLEDGE PRIOR TO THIS STUDY

The Zarzal Fm has been so far poorly studied. Boussingault (1903) was the first one to describe siliceous deposits intercalated with sand and sandy clay beds in the Cartago area, which form low-relief hills. He considered these sediments as the infill of a lake. The name Zarzal Fm was given in 1955 to these deposits made of diatomites, clays and volcanic sands (Van der Hammen, 1958; De Porta, 1974).

Cardona and Ortiz (1994) were the first ones to analyze in detail the depositional environment of these sediments. They interpeted three types of facies: braided-stream, floodplain and lake deposits. They also observed the geomorphological expression of this unit: low-relief hills dissected by a well-marked drainage pattern and numerous surface fractures. They recognized traces of block tectonics younger than the Pliocene Andean orogeny and described the interdigitation of the Zarzal Fm with the volcaniclastic Cartago, Risaralda and Quindío fans to the east. In the initial stages of the present study, Neuwerth et al. (2006) described the frequent occurrence of seismites within the Zarzal sediments, which testifies to an intense syndepositional tectonic activity.

So far, no precise age dating has been attributed to the Zarzal Fm. A probable Pliocene age is assumed without any palynological evidence (Van der Hammen, 1958). The Zarzal Fm unconformably overlies the Miocene La Paila Fm on the western flank of the SSB (McCourt, 1984; Nivia et al., 1995). In the Cauca Valley, the Zarzal Fm is unconformably overlain by gravels of alluvial fans fed by the surrounding reliefs, by grey palaeosols rich in volcanic material and by recent alluvial sediments (Nivia et al., 1995). In fact, prior to the present research, the only certainty that exists is that the Zarzal Fm postdates the synkinematic deposition of La Paila Fm during the Pliocene Andean compression (Cooper et al., 1995), i.e., it has a Late Pliocene to Pleistocene age. Within the framework of the present study, palynological investigations (Neuwerth et al., 2006) have shown the presence of *Alnus* pollen in clays of the Zarzal Fm. Because the first record of this tree in Colombia dates back to less than 1 Ma (Hooghiemstra and Cleef, 1995), a large part of the Zarzal Fm is probably of Pleistocene age.

DEPOSITIONAL RECORD

Sedimentology

Detailed field studies confirm the observations of Cardona and Ortiz (1994). The Zarzal Fm consists of black to grey sands which comprise a large amount of volcanic material. These sands represent a key lithology which crops out on both sides of the SSB and interfingers with other lithologies like diatomites, silts, clays, conglome-

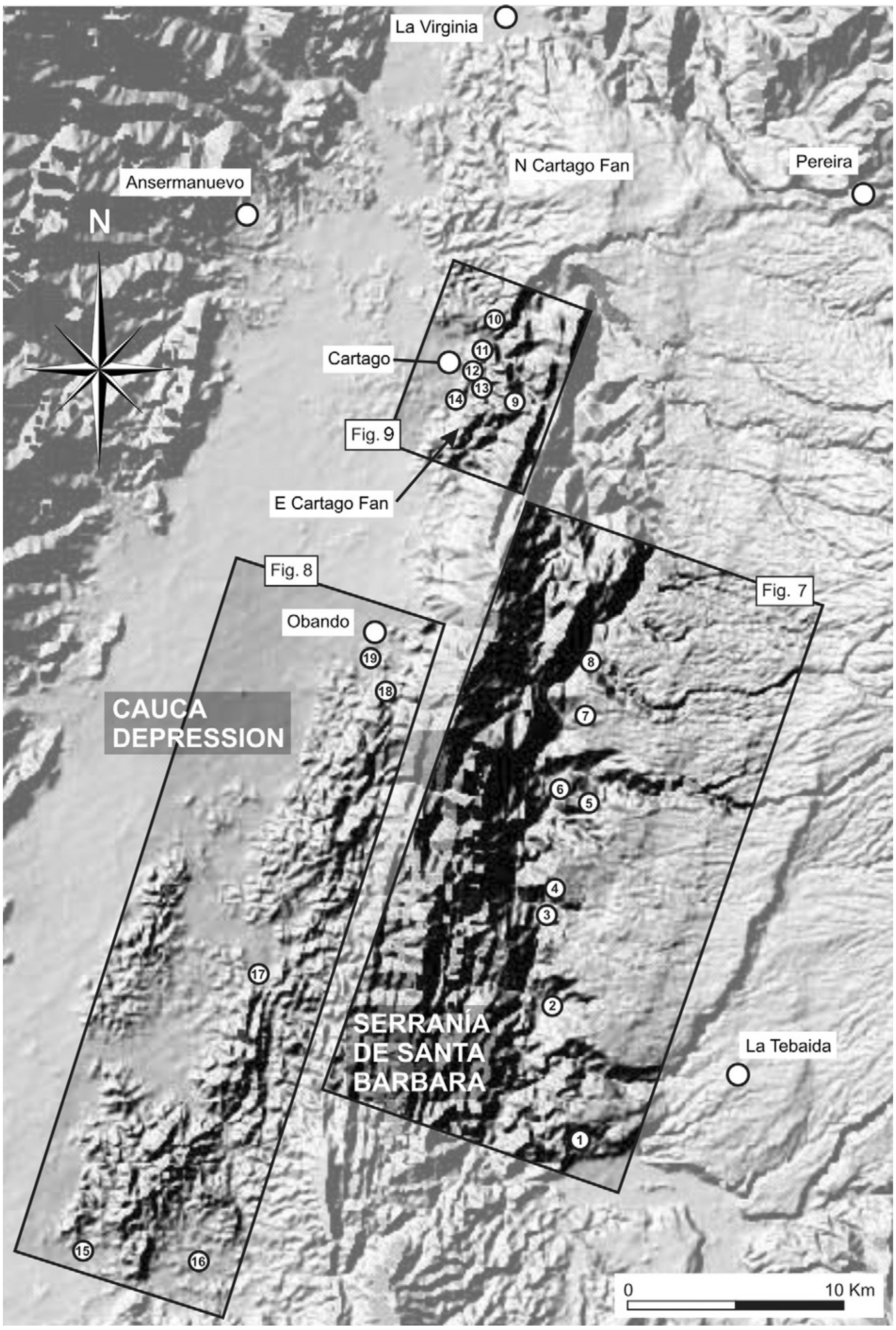

FIGURE 6 **Location of field sections on the DEM of Figure 3A. Three zones are highlighted: 1: the eastern foothills of the Serranía de Santa Barbara (SSB; sections 1 to 8, Figure 7); 2: the E- and N-Cartago Fans (sections 9 to 14, Figure 9); 3: the western foothills of the SSB (sections 15 to 19, Figure 8).**

rates and volcaniclastic mass flows of different grain size. These sands are mainly composed of material derived from the CC. The volcanic material included in these sands may originate directly from the CC volcanoes and/or from the reworking of a volcaniclastic palaeofan situated at the foothills of the CC.

Field sections were studied in three areas (Fig. 6). Although the type of deposits is different in each zone, the characteristic Zarzal black sands are present over the whole studied area. Each zone will be looked at separately in order to accurately analyze the processes that led to the infill of the basin.

1. East of the SSB, sequences of fluvial, flood plain and lake deposits are overlain by mass flows of the Quindío Fan (Fig. 7). Only volcaniclastic mass flows were encountered north of field section 8. There is a general coarsening-up trend in all sections (Fig. 7). The lower part is composed essentially of clays, laminated fine silts, and some fine sands layers increasing stratigraphically in number and grain size. The upper part shows a series of stacked, generally coarsening-up, volcaniclastic mass flows locally interbedded with black to grey, through cross-bedded sand layers and fluvial conglomerates. The transition between lower and upper parts may be progressive through the increase in number and granulometry of the fine grey sand levels, or quite sharp like in sections 4 and 7. Columns 1, 2, 3 and 5 show that the first volcaniclastic mass flows have a fine grain size with respect to the uppermost ones. In each section, volcaniclastic mass flows are different in grain size and in mineralogical and matrix compositions. In section 3, a single sand layer separates the lowermost mass flow from the underlying Lower Tertiary folded deposits. No mass flows are present in sections 6 and 8.

Sedimentary processes are very different in the lower and upper parts. The lower part is interpreted as reflecting lacustrine sedimentation with an increasing-upward terrigenous input. The clastic source becomes more active as indicated by the upward increase in number and grain size of fine sands. In the upper part the depositional environment is fluvial and dominated by catastrophic events marked by volcaniclastic mass flows. The latter originate on the CC slopes and form the vast volcaniclastic fan (Figs. 3 and 4) called Armenia Fm (McCourt, 1984) or Quindío-Risaralda Fan (Guarín et al., 2006). The various

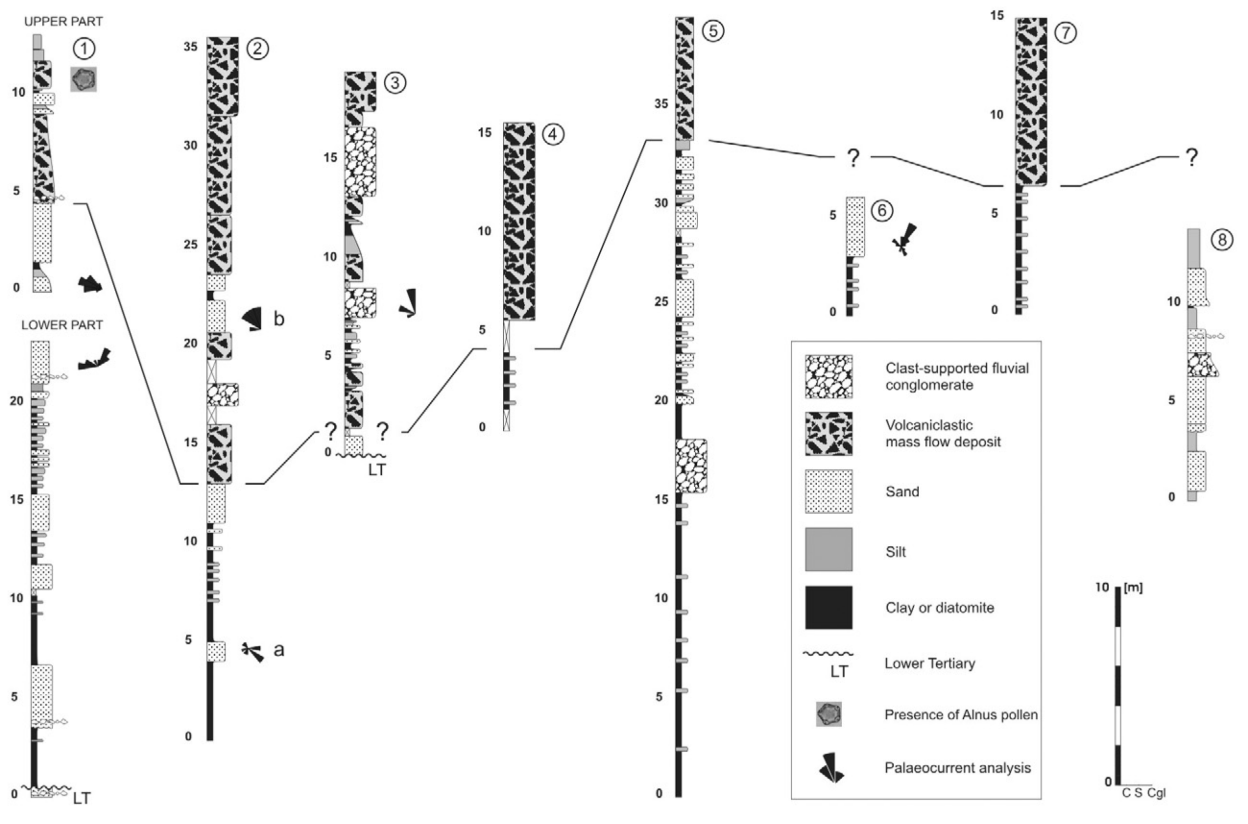

FIGURE 7 **Field sections in the eastern foothills of SSB, along the La Vieja River (see Figure 6 for location of sections). The first occurrence of volcanic mass flows at each location is correlated with a black line in order to highlight the change in sedimentary regime. This line does not correspond to a time line, because mass flows were first deposited in the northeastern part of the Quindío-Risaralda Basin before moving westwards and southwards (Espinosa, 2000; Guarín et al., 2006).**

nomenclatures used in the literature to describe the deposits studied here are shown in Fig. 5. The deposition of this fan started on the CC foothills between Armenia and Pereira, before advancing westwards onto the alluvial plain. When it reached the SSB eastern slopes, it dammed the northward outlet of the alluvial plain and formed a lake. The stratigraphic record of mass flows appears to have registered the advance of the fan into the lake (Fig. 7). Clays at the base of sections 2 and 5 may be related to an alluvial plain preceding the lake formation.

2. The SSB formed a physical barrier between the Cauca Depression and the Quindío Basin to the east (Figs. 3 and 4). Field sections in the SSB western foothills (Fig. 8) contain a large amount of pure diatomites. Diatomites are autochthonous lacustrine sediments related to the proliferation of diatoms in a nutrient-rich environment. In this area, the overall grain size of the Zarzal sediments is fine. Besides diatomites, they contain clays, silts and sands. Fine silt and sand levels represent the terrigenous input into the basin. Silts can be finely laminated with a variable proportion of diatomite matrix, or form thicker, fining-upward layers with a diatomite matrix. Sandy layers are always fining upwards and contain a diatomite matrix when they overlie diatomites. Locally, sands appear to have flown down into the underlying diatomite. Thin intercalations of volcanic ashes are also encountered within diatomite layers. Section 19 presents at its base a black sand, fluvial interval, which is thicker than 5 m (Fig. 8).

This area represents part of a lake located away from a terrigenous source. The diatomite matrix within terrigenous layers indicates that the depositional process of the siliciclastics was sufficiently energetic to affect the lake bottom and mix with the diatomite mud. Therefore, silt and sand layers may be the record of some big floods or of the distal part of mass flow events deposited northwards in the Cartago fans (see below). The downward sinking of clastic material into underlying diatomites may be related to postdepositional uneven loading or syndepositional seismicity. The important diatomite production could be related to a period of intense volcanic activity which liberated enough silica and nutrients (Moyle and Dolley, 2004). Alternatively, a period of strong erosion of the CC may have led to the reworking and subsequent deposition into the lake of vast amounts of siliceous sediments. The fluvial sand layer at the base of section 19 and clay intervals in the other locations (Fig. 8) indicate that fluvial sedimentation took place before the onset of the lake.

3. Various sections were studied east of Cartago (Figs. 6 and 9), all but one (section 10 situated in the southern part of the N-Cartago Fan; Fig. 9) belonging to the E-Cartago Fan. In the latter fan, section 9 is situated in the proximal part and lies some 100 m higher than the more distal section 13. Except for sections 9 and 13, all stratigraphic sections begin with a basal fluvial conglomerate, the lithological composition of which being similar to that of the black sands. Well-rounded pebbles reach some tens of centimeters in diameter. White-to-pink, grey, and beige soft pebbles are also present. This basal conglomerate can be used as a marker for field correlation, except in section 10 located slightly higher in the N-Cartago Fan. This conglomerate is overlain by a stacked succession of black sands and clays to clayey silts with intercalated volcaniclastic mass flows, and locally pure diatomite. Volcaniclastic mass flows vary from debris flows to hyperconcentrated flows in the N-Cartago Fan, whereas only hyperconcentrated flows are encountered in the E-Cartago Fan. Some of them contain reworked plant debris. The conglomerate at the top of section 12 is lithologically dif-

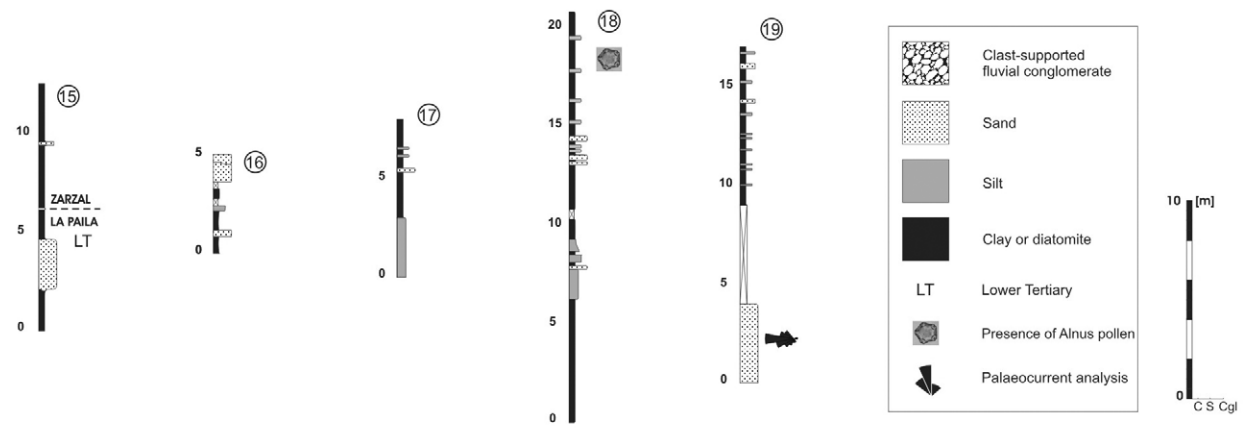

FIGURE 8 | **Field sections in the western foothills of SSB (see Figure 6 for location). The overall grain size is fine and sections contain a large amount of pure diatomites.**

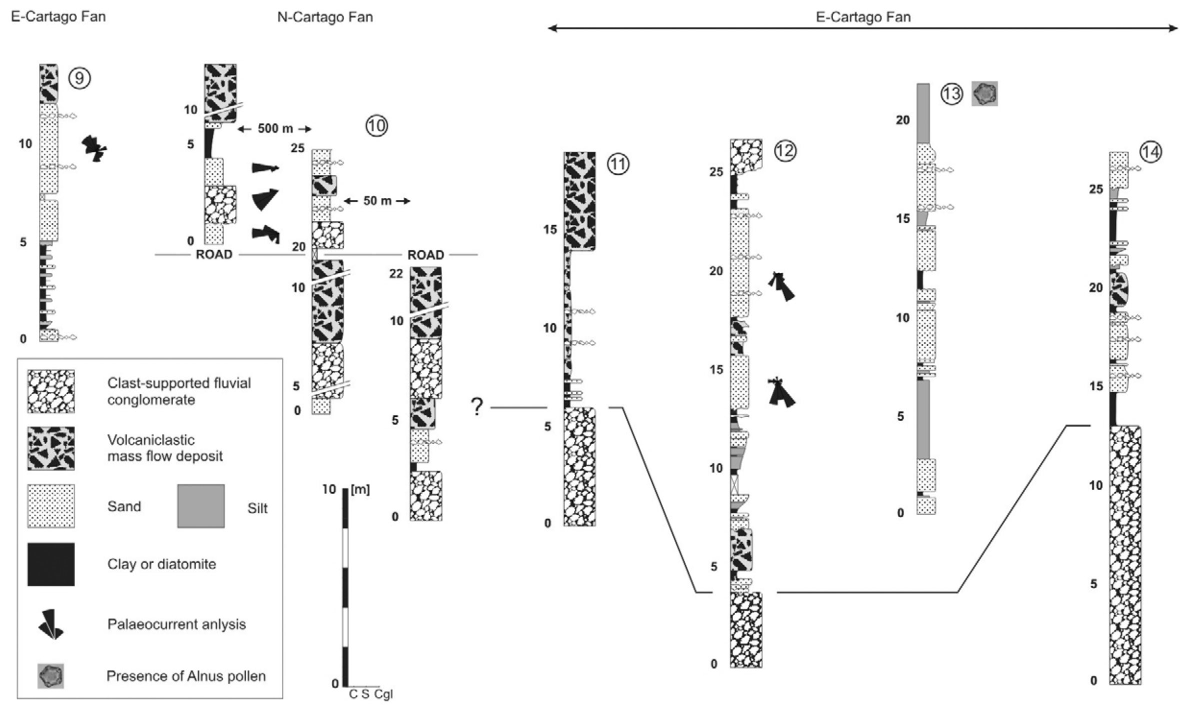

FIGURE 9 | **Field sections in Cartago fans (see Figure 6 for location). Section 9 lies topographically 100 m higher than the other sections. The black line marks the top of the basal conglomerate.**

ferent and displays an erosive base. It is probably much younger than the underlying sediments.

The basal conglomerate in the E-Cartago Fan contains sandy lenses probably infilling the channels of a braided river during the drier season. The epsilon cross-stratification is associated with trough cross-bedding (Potter and Pettijohn, 1977), which indicates the meandering channel migration and palaeocurrent directions. The sediments overlying the basal conglomerate are interpreted as alluvial plain deposits at the distal part of a large alluvial fan where different fluvial and flood plain sequences are stacked vertically through lateral channel migration. In this alluvial plain, volcaniclastic mass flows of different grain size and composition were periodically deposited. They are interfingering with flood plain sediments as well as fine lacustrine diatomite levels. Soft pebbles in the basal conglomerate indicate that an alluvial plain may have existed prior to the onset of the braided stream system.

In the three zones studied, clays in the upper part of the sections (Figs. 7, 8 and 9) have yielded numerous *Alnus* pollen grains (Fig. 10). Because the first record of this tree in Colombia dates back to less than 1 my (Hooghiemstra and Cleef, 1995), a large part of the Zarzal Fm can be interpreted as being of Pleistocene age. This interpretation is awaiting confirmation from geochronological and fission track datings, respectively in volcanic ashes and black sands.

Palaeocurrents

Palaeocurrents were measured in the trough cross-bedded, fluvial, black sands and in conglomerates with imbricated pebbles. Measurements were carried out in the

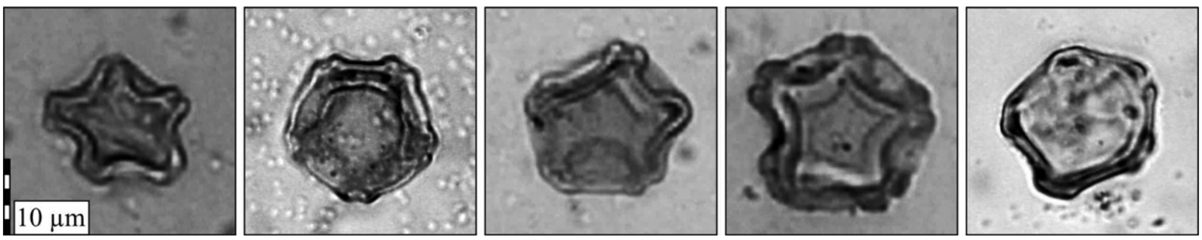

FIGURE 10 | ***Alnus* pollen grains encountered in Zarzal Formation clays (see Figures 7, 8 and 9). The first record of this tree in Colombia dates back to less than 1 Ma ago (Hooghiemstra and Cleef, 1995).**

three studied zones (Fig. 6). For each location, the major trends in current directions can be derived from rose diagrams (Fig. 11).

East of the SSB (Figs. 7 and 11), river transport was clearly towards the NNW to NNE, indicating a northward drainage of the Quindío basin. The only exception is at the base of section 2 (a in Figs. 7 and 11), where palaeocurrents are going south. This might indicate an older, southward drainage pattern or a strongly meandering river.

In the Cartago area, palaeocurrents in the southern part of the N-Cartago Fan (section 10 in Figs. 6, 9, and 11) clearly show a dominantly westward flow direction, which is coherent with the orientation of the fan. In the E-Cartago Fan (sections 9 and 12 in Figs. 6, 9, and 11) two palaeoflow patterns can be identified: a northwestward palaeoflow in the apical part of the fan (section 9) and a southward palaeoflow in the distal part of the fan (section 12). This might confirm the hypothesis that the proximal (apical) part of the E-Cartago Fan is different from the N-Cartago Fan and was fed directly from the SSB to the east. By contrast, southward palaeocurrents in the western, distal part of the fan (section 12) appear to link this part with the N-Cartago Fan.

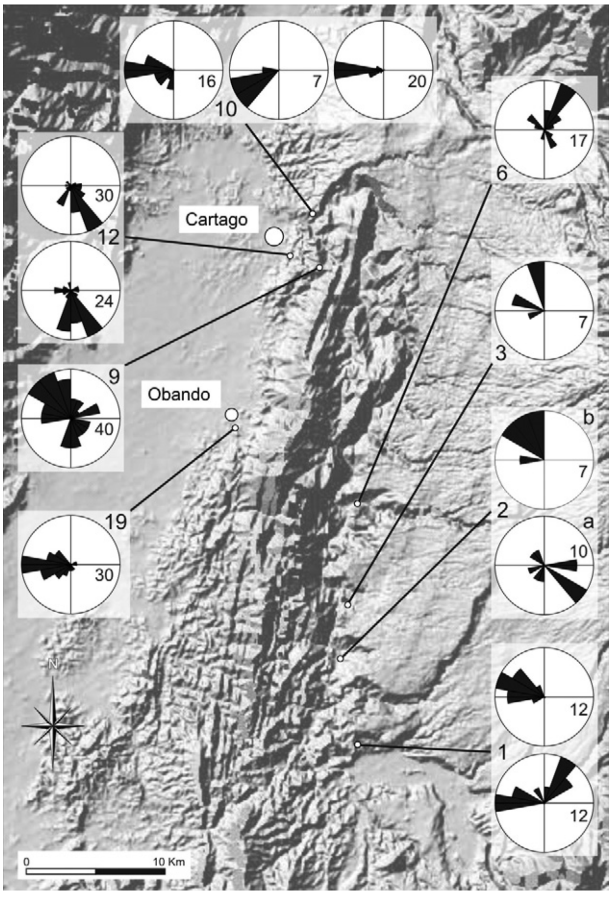

FIGURE 11 **Palaeocurrent directions measured in trough cross-bedded black sands and imbricated pebbles of Zarzal Formation. Numbers ouside the circles refer to field sections of Figures 7, 8 and 9, in which measured intervals are precisely located. Numbers within the circles correspond to the number of palaeocurrent measurements per site. The base map is the same DEM as that of Figure 6 where sections are located.**

Finally, on the western flank of the SSB, palaeocurrents measured near Obando show that a river was transporting sediments westwards prior to the deposition of the diatomites (section 19 in Figs. 8 and 11).

Soft-sediment deformation (SSD)

Numerous soft-sediment deformation structures (Figs. 12 and 13) occur in the fluvio-lacustrine sediments of the Zarzal Fm (Neuwerth et al., 2006). Deformed sediments consist of fine- to medium-grained sands, silts, clays and diatomites. These structures include load structures (simple and pendulous load casts, flame structures, attached and detached pseudonodules), water escape structures (water escape cusps, dish-and-pillar and pocket-and-pillar), soft-sediment intrusions (clastic dykes and sills) and other structures (disturbed laminites, convolute laminations, slumpings and synsedimentary faults).

Based on numerous field evidences, Neuwerth et al. (2006) have eliminated storm currents and gravity loading as triggering mechanisms for these deformations. They interpret these deposits as seismites, earthquakes being a much more plausible regional explanation for the vast lateral extension of these deformations.

Since the 1983 Popayán and 1999 Armenia earthquakes, a series of seismic hazard studies has been initiated in several parts of Colombia (Espinosa, 2003). The Red Sismológica Nacional de Colombia (RSNC) has an instrumental database of more than 29,000 events over the 1995-2004 period (Table 1). In the studied area, most of the shallow seismic activity is linked to crustal deformation processes within the Andean zone contiguous to the Romeral fault system (Franco et al., 2002). On the other hand, the epicentre of a deep seismicity focus called the Cauca nest (Cortes and Angelier, 2005) is situated in the Viejo Caldas and north of the Valle del Cauca zones (Franco et al., 2002). Moreover, there are evidences that the Romeral fault system has been active since the Early Cretaceous (McCourt et al., 1984; Aspden et al., 1987; Restrepo and Toussaint, 1988). Consequently, this record of intense seismic activity supports the interpretation that earthquakes are the most probable triggering mechanism of soft-sediment deformation in this area.

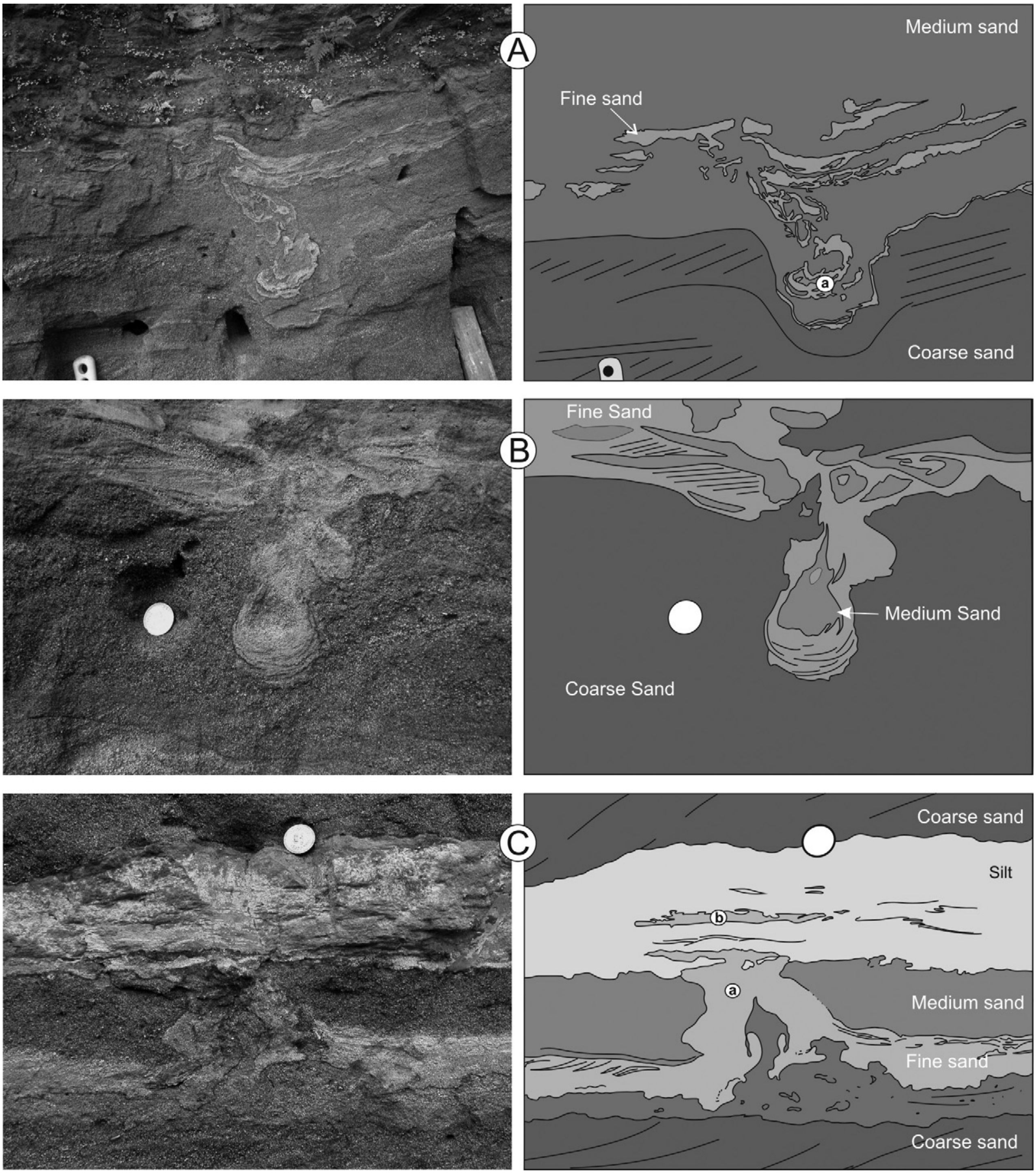

FIGURE 12 | **Soft-sediment deformations in Zarzal Formation (modified after Neuwerth et al., 2006). A) Pendulous load cast showing internal deformation (a) associated with gravity loading. B) Attached pseudonodule made of fine-medium-grained sands which sank into coarse-grained sands. C) Water escape cusp (a) formed by fine-medium-grained sands intruding medium-grained sands. This structure is capped by hardly-deformed silts which were intruded by a sandy sill (b).**

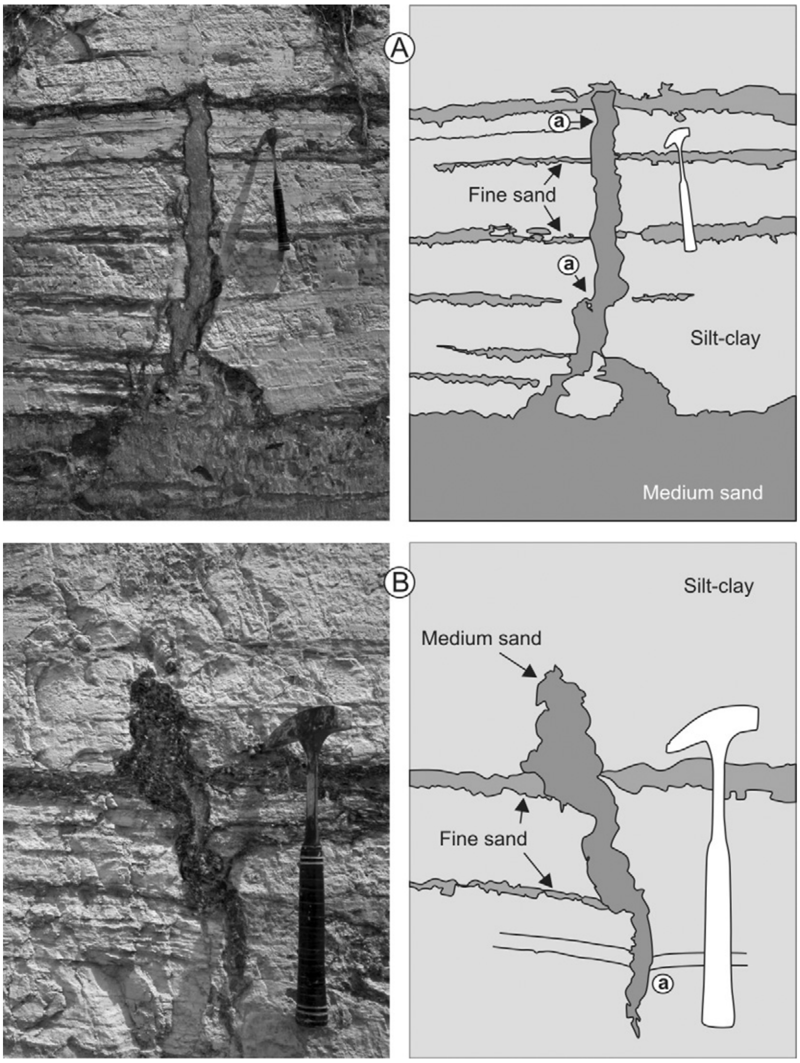

FIGURE 13 **Soft-sediment deformations in Zarzal Formation (modified after Neuwerth et al., 2006): A) rooted, vertical, medium-grained sand dyke intruding silty clays; this intrusion is partially controlled by fractures (a). B) disconnected, subvertical, medium-grained sand dyke showing downward bending of intruded, fine-grained sediments (a) in the lower part.**

DISCUSSION

Sedimentary model

Sedimentological and palaeocurrent results have been integrated with published data on the volcaniclastic Quindío-Risaralda Fan (Espinosa, 2000; Guarín et al., 2006) in order to produce a sedimentary model for the deposition of the Zarzal Fm (Fig. 14). Because precise age dating is lacking in order to correlate field sections, the two lacustrine intervals interpreted on both sides of the SSB (Figs. 7, 8 and 14) have been considered as two separate events. The Quindío, Risaralda, E Cartago and N Cartago fans has been subdivided into a succession of six units labelled I to VI based on geomorphology and digital elevation model (DEM, Figs. 3 and 6) data. The degree of incision of the drainage network increases with the age of the fan (Guarín et al., 2006).

The sedimentological model for the infill of the Cauca Depression (MacDonald et al., 1996) and the Quindío Basin (Fig. 14) is presented in five stages described below:

Stage A: The Quindío-Risaralda Fan is at an incipient stage. At its front lies a vast alluvial plain where waters flow northwards. The southward palaeocurrent direction observed at the base of field section 2 (a in Fig. 7; 2a in Fig. 11) is thought to be that of a meander in a tributary.

Stage B: The growth of the Quindío-Risaralda Fan towards the SSB dams the northern outflow of the alluvial plain and forms a lake. The relatively small size of the lake and the proximity of the volcaniclastic fan deposits explain that on this side of the SSB the autochthonous diatomite sedimentation is not pure and contains numerous terrigenous intercalations.

TABLE 1 **Magnitude of earthquakes measured between 1995 and 2004 by the Red Sismológica Nacional de Colombia.**

Magnitude ⟶	1-2	2-3	3-4	4-5	5-6	6-7
Deep (>30km) earthquakes Colombia	1296	16114	5772	738	77	7
Shallow (<30km) earthquakes Colombia	1158	3169	767	115	21	2
Deep earthquakes study area (Fig.3)	10	138	31	9		
Shallow earthquakes study area (Fig.3)	60	302	58	5	1	1

Stage C: Because of the topographical barrier formed by the SSB, the growth of the Quindío-Risaralda fan moved towards the north and south of the basin. In the south, the alluvial fan III progressively infilled the lake that developed during stage B. Palaeocurrent measurements taken above the lacustrine interval east of the SSB (Figs. 7 and 11) show a northward-flowing river system. Sediments correspond to the distal part of an alluvial fan with a strong input of hyperconcentrated mass flows. In the northwestern part of the Quindío-Risaralda Basin, the alluvial fan IV (i.e., the present-day N-Cartago Fan) started to develop and overflowed the northern prolongation of the SSB towards the Cauca valley. Part of the waters draining the southern part of this fan probably flowed southwards (field section 12 in Figs. 9 and 11), at least down to the actual location of Obando. Nevertheless, the existence in the western foothills of the SSB of a thick basal conglomerate reworking an older alluvial plain (field sections 11, 12 and 14, Fig. 9) can not be explained within this palaeogeographical reconstruction. In order to

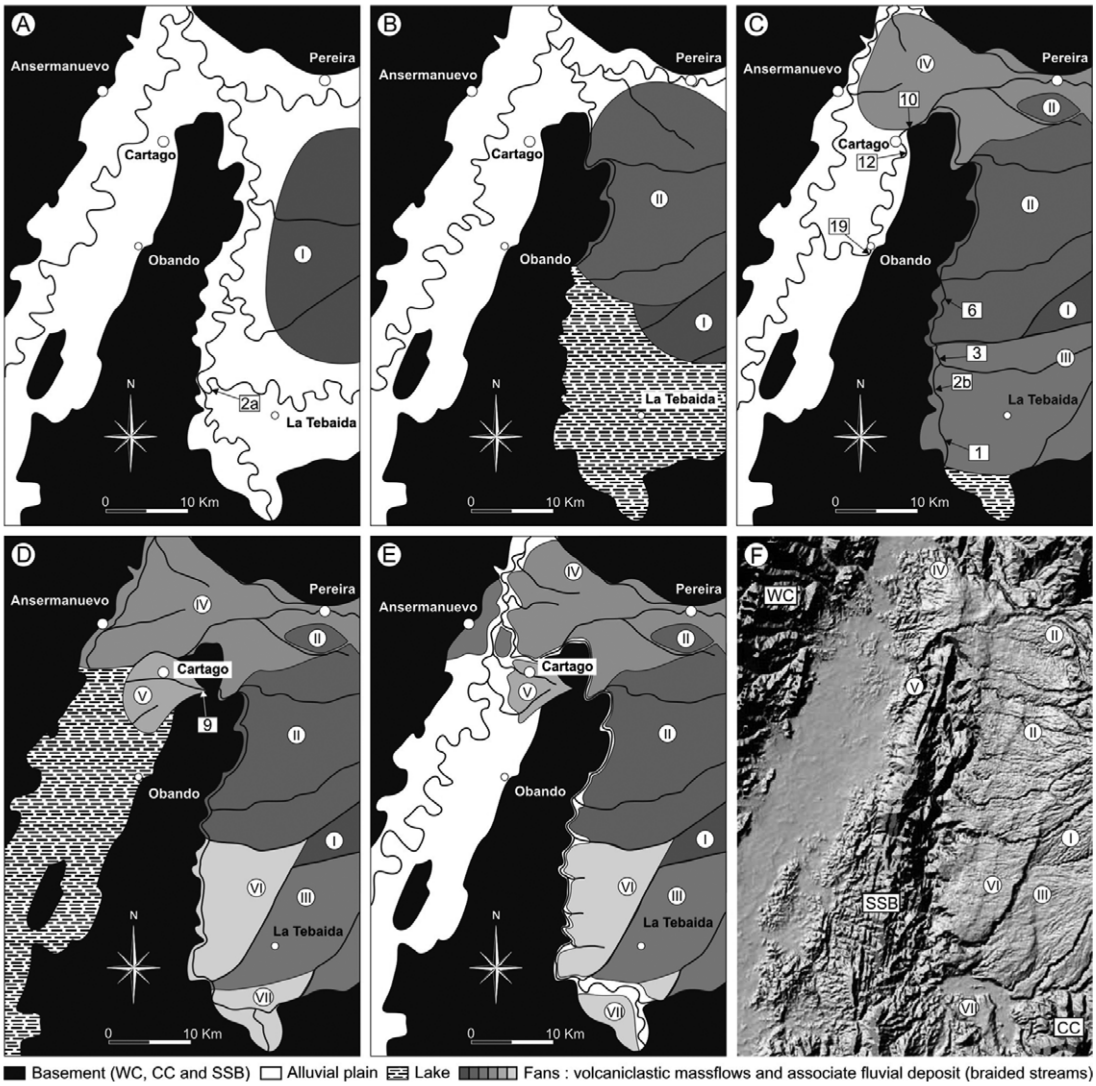

FIGURE 14 **Sedimentary model for the deposition of the Zarzal Formation showing five stages of infill of the Cauca Depression and Quindío-Risaralda Basin (stages A to E). Present-day stage F presents the subdivision of the Quindío-Risaralda and Cartago fans based on the DEM. See text for detailed discussion.**

do so, one has to take into consideration tectonic activity (see below).

Stage D: The extension of the Quindío-Risaralda Fan reached a maximum. In the south of the basin, the fan units VI and VII developed on top of unit III. In the north, the N-Cartago Fan reached the WC eastern foothills. The E-Cartago Fan (unit V) overflowed the SSB and spread over the present-day location of Cartago. The westward extension of the N-Cartago Fan may have dammed the Cauca Valley, thereby leading to the formation of the lake were diatomites formed. Nevertheless, this lake may also have existed before because of another dam downstream. The ongoing study of the basin north of La Virginia (Fig. 3) will help to solve this problem. Anyway, the Cartago fans probably supplied most of the terrigenous material intercalated with the diatomites in the Cauca Valley. Towards the south, with the increasing distance from this clastic source, the lithology becomes dominated by autochthonous diatomite sedimentation (field sections 15 to 19, Figs. 6 and 8). So far, no time relationship can be established between the E and N Cartago Fans, where tectonic activity seems to have been strong (see below).

Stage E: Tectonic subsidence of the basins (see below) associated with erosion resulted in emptying the lake and infilling the basins with fluvial sediments.

Stage F: This 90-meter resolution radar-based DEM (USGS, 2005) represents the present-day topography of the studied area, where the different fans can be identified through their degree of incision.

Tectonic activity and subsidence of the Cauca Depression and Quindío-Risaralda Basin

Although the zone where the strike-slip Romeral Fault System (RFS) changes from right to left-lateral (Fig. 2) has been extensively discussed, the precise location where the faults change their cinematic has never been defined. Ego et al. (1995) think it is between 4 and 5° north, whereas Taboada et al. (2000) locate it at 5° north. G. Paris (pers. comm.) thinks that it may be situated west of the Ibagué fault termination. Consequently, the study area may be under the influence of both senestral and dextral components of the RFS. Moreover, things are complicated by the fact that the studied zone lies exactly at the front of the Chocó-Panamá block (Figs. 1 and 2), which is considered as a rigid indenter (Trenkamp et al., 2002; Cortés and Angelier, 2005).

The tectonic complexity of this key area has been extensively discussed (Acosta, 1978; McCourt, 1984; McCourt et al., 1984; James, 1986; Aspden et al., 1987; Keith et al., 1988; Ríos and Aránzazu, 1989; Alfonso et al., 1994; Cardona and Ortiz, 1994; Pardo et al., 1994; Van der Hilst and Mann, 1994; Ego et al., 1995; Nivia et al., 1995; Ego et al., 1996; MacDonald et al., 1996; Guzmán et al., 1998; Gutscher et al., 1999; INGEOMINAS, 1999; Espinosa, 2000; Paris et al., 2000; Taboada et al., 2000; Trenkamp et al., 2002; Suter, 2003; Botero et al., 2004; Botero et al., 2005; Cortes and Angelier, 2005; Gallego et al., 2005; Montes et al., 2005; Romero et al., 2005; Guarín et al., 2006; Neuwerth et al., 2006). Although the neotectonic movement of some faults remains controversial, most of the authors have agreed to the existence of a regional compressional regime with a NW-SE compressional axis for the study area. On the other hand, some of them have also observed the presence of superficial normal faults and that sedimentation occurs on both sides of the SSB (Cauca Valley and Quindío). James (1986) noted the difference in thickness of Tertiary rocks north and south of La Virginia; he explained this with a higher rate of uplift in the north, which prevented the deposition of the Zarzal Fm north of this town. Based on the Armenia earthquake aftershocks (INGEOMINAS, 1999) and the morphotectonic study of the CC western foothills, Gallego et al. (2005) calculate a transpressive state of stress at a depth greater than 10 km (σ_1, σ_2 and σ_3 with respective orientations 308/35, 108/52 and 211/10) and extensive above (σ_1, σ_2 and σ_3 with respective orientations 287/72, 145/14, 052/07). Paris et al. (2000) observed various N to NNE trending normal faults across the Quindío and Risaralda fans. Suter (2003) noted that on the eastern side of the SSB (Figs. 3 and 6), zones of deposition often coincide with the confluence of tributaries with the La Vieja River, indicating areas of active subsidence (local pull-apart basins?). Moreover, Guzmán et al. (1998) report that many faults parallel to the NW-SE compressional axis in this area are normal. In the Cauca Depression (Fig. 3), Pardo et al. (1994) link the vertical displacement of superficial NE-SW trending normal faults between Cartago and Ansermanuevo to the activity of the dextrolateral Toro and Quebradanueva faults (Fig. 4).

Therefore, from a structural point of view, the study area is located in a so far not well-understood, complicated zone. In this area the regional tectonic regime is clearly defined as compressional with a NW-SE trend. Nevertheless the Zarzal Fm does not show any fold, but rather block tectonics (Cardona and Ortiz, 1994). Observations made in this study confirm the presence of extensional deformations within superficial rocks (Fig. 15). In most cases, the fault plane dip and azimuth could be measured. The fault plane poles were projected onto stereoplots and the mean vector of these poles calculated for each outcrop. The information was summarized on the DEM (Fig. 16), taking into account the data of Pardo et al. (1994). These data highlight a roughly NNW-SSE

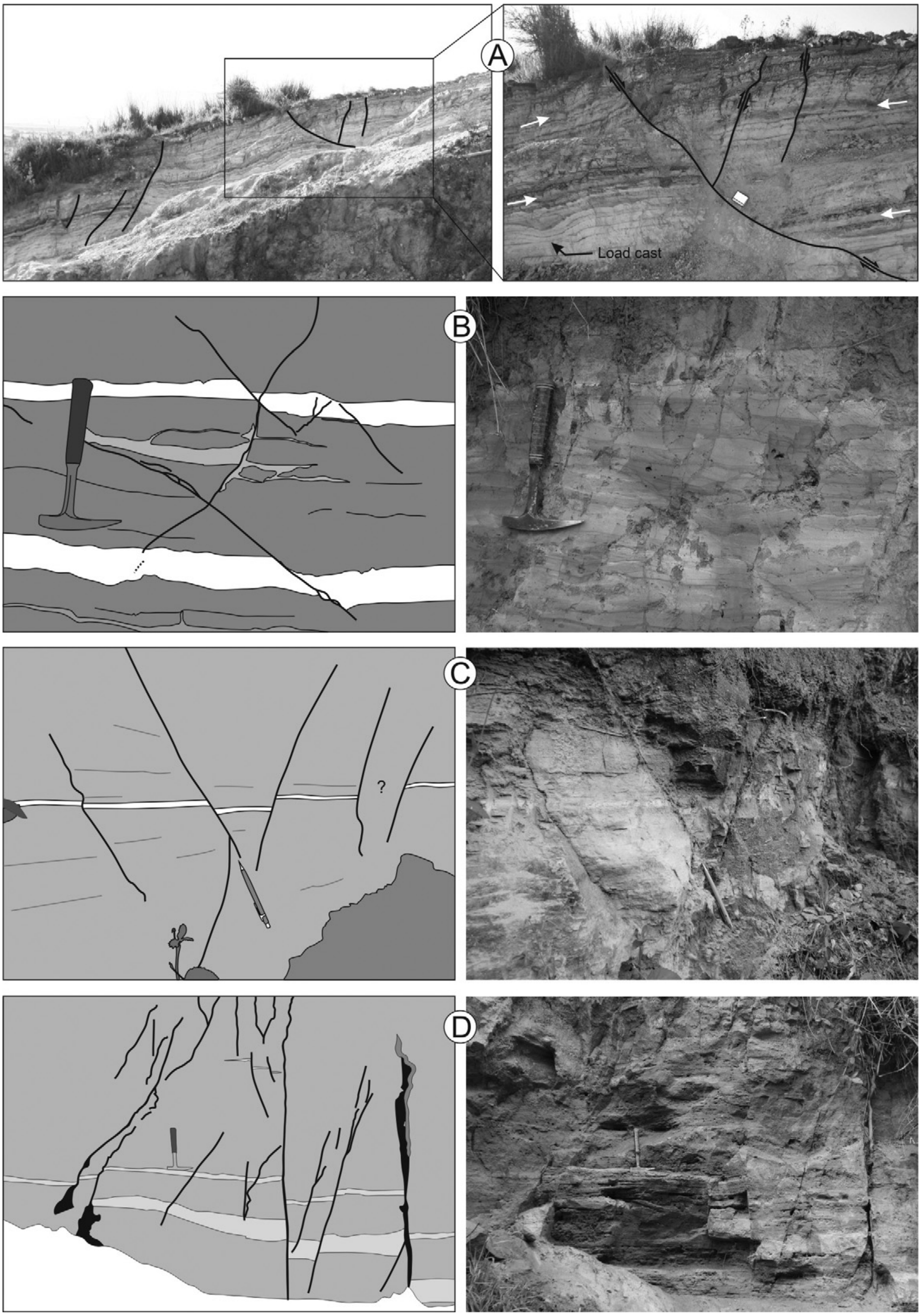

FIGURE 15 **Extensional faulting in Zarzal Formation (see Figure 16 for location of outcrops). Stereoplots of field measurements are presented in Figure 16. Field section A: white arrows at the right side show correlation of strata across the fault; see field notebook for scale.**

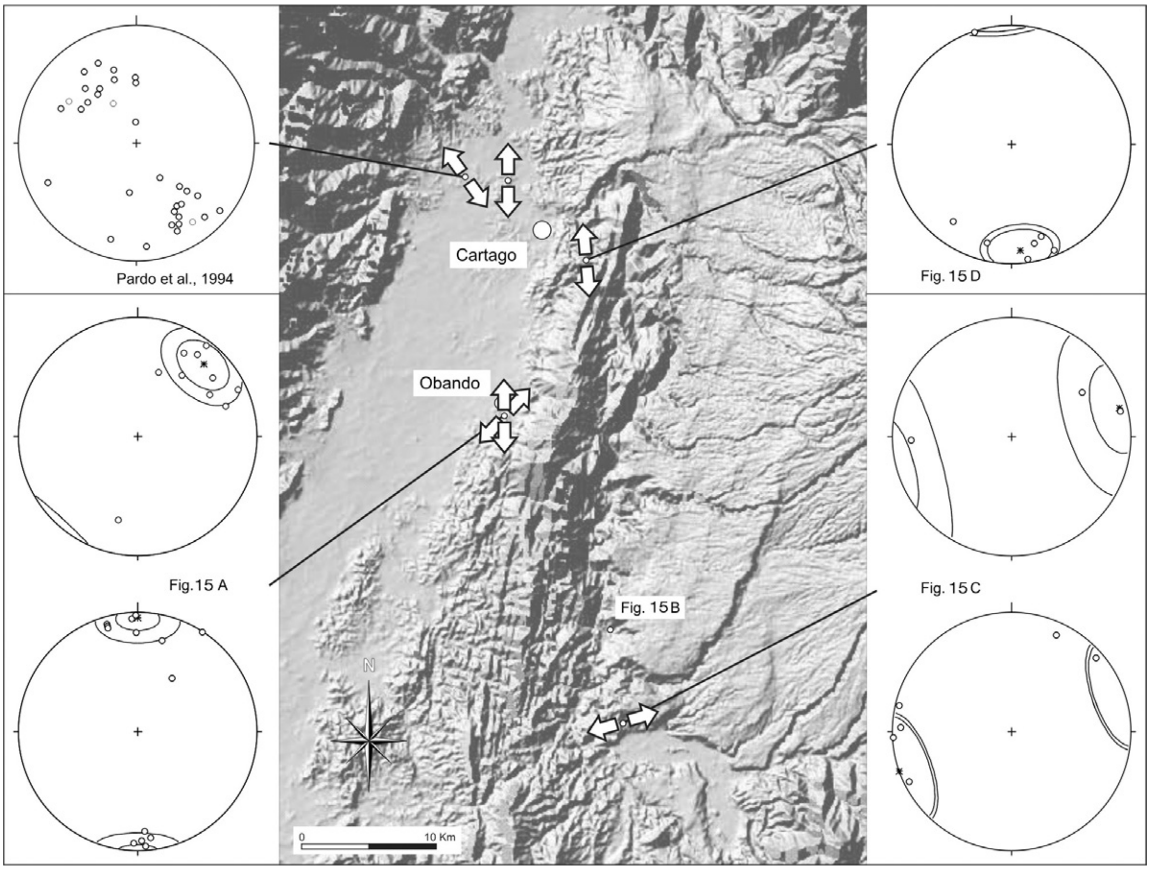

FIGURE 16 **Stereoplots of fault plane poles measured in the outcrops illustrated in figures 15A, B, C and D or derived from Pardo et al. (1994). At each location the mean vector of extension was calculated and is shown with white arrows on the DEM.**

to NE-SW extensional stress axis, more or less aligned with the general trend of the Cordilleras. Because of their limited size and because the rocks they affect are superficial (Fig. 15), these faults do not form significant features, nor do they appear to be linked to large-scale structures. A large part of these normal faults may be synsedimentary and associated with soft-sediment deformations.

On the other hand, in the WC eastern foothills (Figs. 3 and 6) the sinuosity of the mountain front suggests a weak tectonic activity and low uplift rate of the mountain front (Keller and Pinter, 2002). Moreover, in the La Vieja River valley and within the Tertiary fold and thrust belt of the Cauca River valley (Alfonso et al., 1994), Quaternary sediments are infilling the depressions more quickly than they subside or than the relief lifts up. This may explain why so far no fault cutting the recent alluvial plain in the Cauca Depression has been observed. In this case, the reason for the existence of this basin must be searched downstream to the north, where the indentation of the Chocó-Panamá block into the WC may have dammed the Cauca River valley.

CONCLUSIONS

The study of the (Plio-)Pleistocene Zarzal Fm in the Cauca Depression and Quindío-Risaralda Basin leads to the following conclusions:

1. **Sedimentology**: Whereas the existence of a (Plio)-Pleistocene, diatomite-rich, Zarzal lake has already been recognized in the Cauca Depression, the identification on the eastern side of the SSB of a lake contemporary to the deposition of the Quindío and Risaralda volcaniclastic fans is the most important contribution of this study. Sediments registering this event are encountered in the La Vieja River valley and in the lower part of its tributary valleys. This lake shows laminated fine silts with an increasing-upward proportion of sandy material, which reflects the fan advance into the lake. This lake was formed by the damming of the La Vieja River through the progradation of the Quindío-Risaralda Fan.

2. **(Plio)-Pleistocene volcanic activity**: Sedimentation in the Zarzal Fm is strongly influenced by volcanic processes. The E- and N-Cartago and Quindío and Risa-

ralda fans are characterized by a huge volcaniclastic influx. Besides the fine-grained lake deposits, the main sediment type corresponds to volcaniclastic mass flows of different grain size with some intercalations of braided stream or alluvial plain deposits. Mass flows sourced from the CC grade from hyperconcentrated flows in the more distal part to debris flows in the proximal part. Lakes on both sides of the SSB are directly related to the volcanic activity. The eastern one contains a lot of volcaniclastic material grading from clayey silts to fine sands. The western one has produced a large amount of diatomites, which are associated with the volcanic activity. Diatoms need a high proportion of silica, as well as nitrates and phosphates, which are brought in by the volcanic and volcaniclastic material derived from eruptions. As described above, these diatomite levels are alternating with volcaniclastic catastrophic events and ash layers.

3. **Tectonics**: The study area stands in a tectonically complex zone, because it is situated within the zone where the strike-slip component of the Romeral Fault System changes its direction of movement and close to the front of the Chocó-Panamá Block, which is considered as an active indenter. Nevertheless, although the regional tectonic regime is compressional with a NW-SE trending stress direction, it was possible to observe a superficial extensional pattern with faults directions ranging from SW-NE to NNE-SSW. Thus, the mean extensional axis in the study area is approximately parallel to the Cordilleras. Moreover, the vertical succession of flood plain, braided stream, flood plain and lake facies registered in the Cauca Depression near Cartago reflects a strong tectonic activity in this area marked by changes in the rates of basin subsidence or relief uplift. The ubiquitous presence of seismites within Zarzal sediments testifies to the tectonic activity.

4. **Tectonics and sedimentation**: The relation between tectonics and sedimentation is not clearly defined yet. Nevertheless, within the study area, the sedimentation rate seems to be higher than the rate of subsidence. This means that sediments are infilling the basin more rapidly than it subsides or than the relief lifts up, thereby drowning the topography. This might be related to the tectonically-induced downstream damming of the Cauca River valley to the north by the Chocó-Panamá block. In this case, the northward valley outlet would undergo an active uplift which would generate the continuous infill of the basin.

5. **Stratigraphic nomenclature**: The stratigraphic definition of the Zarzal Fm must be reconsidered. As proposed by Cardona and Ortiz (1994), it must be redefined to include all sediments described in this paper in one single formation, or a new formation must be defined for the lacustrine sequence encountered east of the SSB. The synchroneity of lacustrine deposits on both sides of the SSB has still to be established.

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