Large Magnitude Late Holocene Seismic Activity In The Pereira-Armenia Region, Colombia

Chapter *in* Special Paper of the Geological Society of America · July 2011

DOI: 10.1130/2011.2479(03)

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The Geological Society of America
Special Paper 479
2011

Large-magnitude late Holocene seismic activity in the Pereira-Armenia region, Colombia

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ABSTRACT

The Pereira-Armenia region, located west of the Colombian Central Cordillera, is crosscut by the Romeral fault system, which consists of an active north-south–trending, left-lateral, strike-slip fault system with a secondary thrust component in the Eje Cafetero zone (4°N–5°N). The terrain where the Liceo Taller San Miguel high school sits—9 km south of Pereira—is draped with an ~2-m-thick layer of volcanic ash younger than 30 k.y. in age. This locality has been affected by both N40°E- and E-W–trending faults that correspond to thrust faults or folds and normal right-lateral, strike-slip faults, respectively, in the tectonic model for the zone. Two kinds of strong field evidence for the E-W faults were found at a site named Canchas: (1) the 50°N tilt of the late Quaternary interbedded sequence of volcanic ash and three paleosols, and (2) a vertical fault throw of ~1.70 m affecting the sequence (layers). A normal vertical throw of ~0.65 m at Parqueadero stands as a proof of the activity of the N40°E-trending faults. This latter faulting does not correspond with the stress tensor proposed for this region, and thus this deformation could be interpreted as being a consequence of flexural slip induced by a NE-SW–striking blind thrust, where reverse faulting along bedding at depth is seen as normal faulting at the surface. Measured offsets could have generated seismic events of at least Mw 6.6 for the NE-trending fault that affected the paleosols and volcanic ash sequence at 13,150 ± 310 ^{14}C yr B.P., and a seismic event of Mw 6.9 for the E-W–trending fault that affected the paleosols and volcanic ash sequence at 19,710 ± 830 ^{14}C yr B.P. These two recently identified

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Lalinde P., C.P., Toro, G.E., Velásquez, A., and Audemard M., F.A., 2011, Large-magnitude late Holocene seismic activity in the Pereira-Armenia region, Colombia, *in* Audemard M., F.A., Michetti, A.M., and McCalpin, J.P., eds., Geological Criteria for Evaluating Seismicity Revisited: Forty Years of Paleoseismic Investigations and the Natural Record of Past Earthquakes: Geological Society of America Special Paper 479, p. 79–89, doi:10.1130/2011.2479(03).

faults are now named the Tribunas (NE-SW) and the Cestillal (E-W) faults. Up to now, the fault and its seismogenic potential determinations in this region have been based solely on morphologic evidence. The maximum seismic magnitude estimated for this region ranged from Mw 6.2 to Mw 6.6 for seismic sources 35 km away from the site. Seismic magnitudes like the one calculated in this work (Mw 6.9) were previously estimated only for source-site distances greater than 50 km. This work provides field evidence that leads to a better understanding of the seismic activity of this region in the last 30 k.y. and confirms the occurrence of local Mw >6.5 seismic events in this region. Although volcanic ash drapes and eventually hides the geomorphic evidence of active deformation, it turns out to be a perfect chronometer of a fault's activity whenever the deformation is revealed, as in this case. After the Armenia event of 1999, it is imperative to examine the seismic hazard assessments of this region in terms of local crustal seismicity.

INTRODUCTION

Northern South America lies at the junction of the Nazca, Caribbean, and South American plates (Fig. 1). The accumulated stress of the plates is released over the Andean block, which includes the Eastern, Central, and Western Cordilleras (Cline et al., 1981; Ego et al., 1996). Holocene intracontinental deformation in the Andean block can reactivate older fault systems like the Romeral, which is one of the most important fault systems extending across Colombian territory (Page, 1986).

The Pereira-Armenia region is located west of the Central Cordillera of Colombia, and it is characterized as a fluvial fan system (Thouret, 1983). The Romeral fault system, which crosses the Pereira-Armenia fan in a north-south direction, is a left-lateral, strike-slip fault system with a secondary thrust component. All faults that cross the Pereira-Armenia fan are part of the Romeral fault system. North of 5°N, at present, a maximum NW-SE–oriented horizontal stress (σ_1) is assumed (Guzmán et al., 1998). According to the deformation model (Silvestre and Smith, 1976 *in* Yeats et al., 1997; Keller, 1986), the Pereira-Armenia region should display normal faults trending NW, thrust faults trending NE, and right-lateral normal faults trending E-W. The Liceo Taller San Miguel high school is located 9 km south of the city of Pereira, over the upper part of the Pereira-Armenia fan near its apex. In this area, the volcanic ash cover is ~2 m thick and younger than 30 ka (19,710 ± 830 ^{14}C yr B.P. and 13,150 ± 310 ^{14}C yr B.P.).

Paleoseismic studies in Colombia are needed to complement instrumental records that only cover less than 100 yr and historical records that extend back to the beginning of the sixteenth century. Therefore, the only way of enlarging the seismic record back in time is through the study of paleoseismicity. Our approach is to estimate the maximum seismic event per fault, maximum rupture length, time to the next event, and recurrence interval between equivalent events.

The Pereira-Armenia region became the focus of paleoseismic interest in January 1999, when a Mw 6.1 shallow crustal earthquake occurred near the city of Armenia. At that time, the scientific community became aware of the need for a study of intraplate faults and their seismic potential in the Pereira-Armenia region, thus moving beyond the evaluation of the regional seismic hazards generated by seismicity of Nazca plate subduction.

For this study, we collected and assessed seismic information from previous studies in the Pereira-Armenia region. We also studied the volcanic ash sequence that covers the region, going back 50 k.y. Based on the geomorphologic study, fieldwork, aerial photographic interpretation, and the assessment of previous works, we selected different places to study the paleoseismicity of the region. One of these places was the Liceo Taller San Miguel, where we mapped two artificial exposures made during the building of a school.

Besides the scientific interest of the Pereira-Armenia region, important future human settlements and economic developments urgently require a rigorous knowledge of past seismic events in order to reduce uncertainties in seismic hazard assessment.

STUDY AREA

The Pereira-Armenia fan is a torrential volcanic fan, the origin of which is related to the activity of the Ruiz Tolima massif during the past 4.5 m.y., the uprising of the Central Cordillera of Colombia, and movements of the faults that cross the region (Thouret, 1983) (Fig. 1). On the Pereira-Armenia fan surface numerous faults were identified (Fig. 2); anomalous geomorphologic and topographic features are common, such as folds in its distal part, drainage anomalies, benches, and other anomalies that are difficult to explain in relation to the normal evolution of a torrential volcanic fan (e.g., Thouret, 1983; Page, 1986; Guzmán et al., 1998).

A more detailed description of the Pereira-Armenia region shows a very complex fan where 14 geomorphologic units are recognized (Lalinde, 2004). Despite these efforts, the sequence of events that formed the Pereira-Armenia fan and their precise chronology are not well known. More detailed investigation is needed to identify the different volcano-sedimentary events, gain more precise knowledge of their chronology, and interpret their

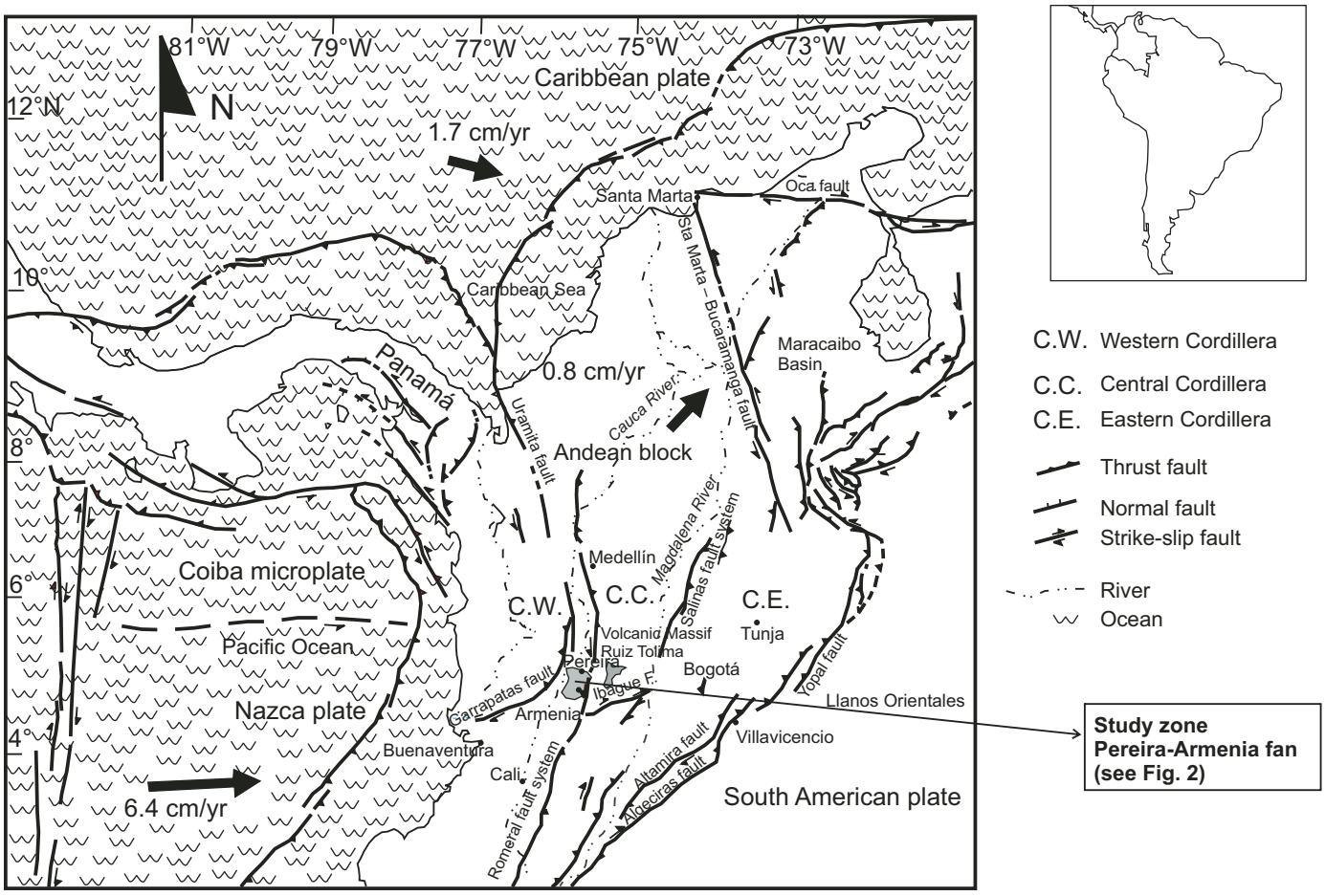


Figure 1. The study zone, Pereira-Armenia fan, located in the western flank of the Central Cordillera (C.C.), and a part of the Andean block. Figure is modified from Taboada et al. (2000). The movement vectors are from Freymueller et al. (1993) and Kellogg and Vega (1995).

paleoseismic information. We interpret the main scarps in the fan as fault movements. Though there is also an erosional component, based on the available information, it is not possible to resolve this component. By knowing the fan terrace surfaces and their ages, these two components can eventually be separated in the future.

Lalinde (2004) described the Pereira-Armenia fan based on topographic profiles (scale 1:25,000) as follows:

(1) The Pereira-Armenia fan is highest in the northern and middle parts, and its height gradually decreases to the south from the Roble River. This is evident in the N-S profiles B–B′, C–C′, and F–F′ (Figs. 3 and 4). In the distal part, the fan shows a flat surface (Figs. 3 and 4, profiles N–N′, H–H′), with some uplifted blocks that could be the result of erosional and tectonic processes. These rivers are more incised on the eastern part of the fan than to the west. Depth changes in the river profiles suggest active tectonism and vertical movement associated with E-W faults. West of the fan, there is a series of steps that corresponds to N30°–60°E faults.

(2) The NW profiles show the same evidence in the northern and southern parts of the fan and suggest a division at Cestillal drainage or Barbas River. This change corresponds to the trace of Cestillal fault (Figs. 3 and 4).

(3) The NE profiles confirm the differences between the north and south parts of the fan (Figs. 3 and 4). As mentioned already, the Pereira-Armenia fan is crossed by numerous faults that belong to the Romeral fault system (Fig. 2) (Thouret, 1983; Page, 1986; Guzmán et al., 1998). Among them, here we report two important faults with evidence of activity at Liceo Taller San Miguel that were not previously defined (Figs. 2, 5, and 6). These faults are the Cestillal fault and Tribunas fault.

Cestillal Fault

The Cestillal fault is an EW/50°S normal fault that crosses the Pereira-Armenia fan. In the topographic profiles (Figs. 3 and 4), the northern block appears to be 50 m high; part of this displacement could be due to the erosional process. This fault is not

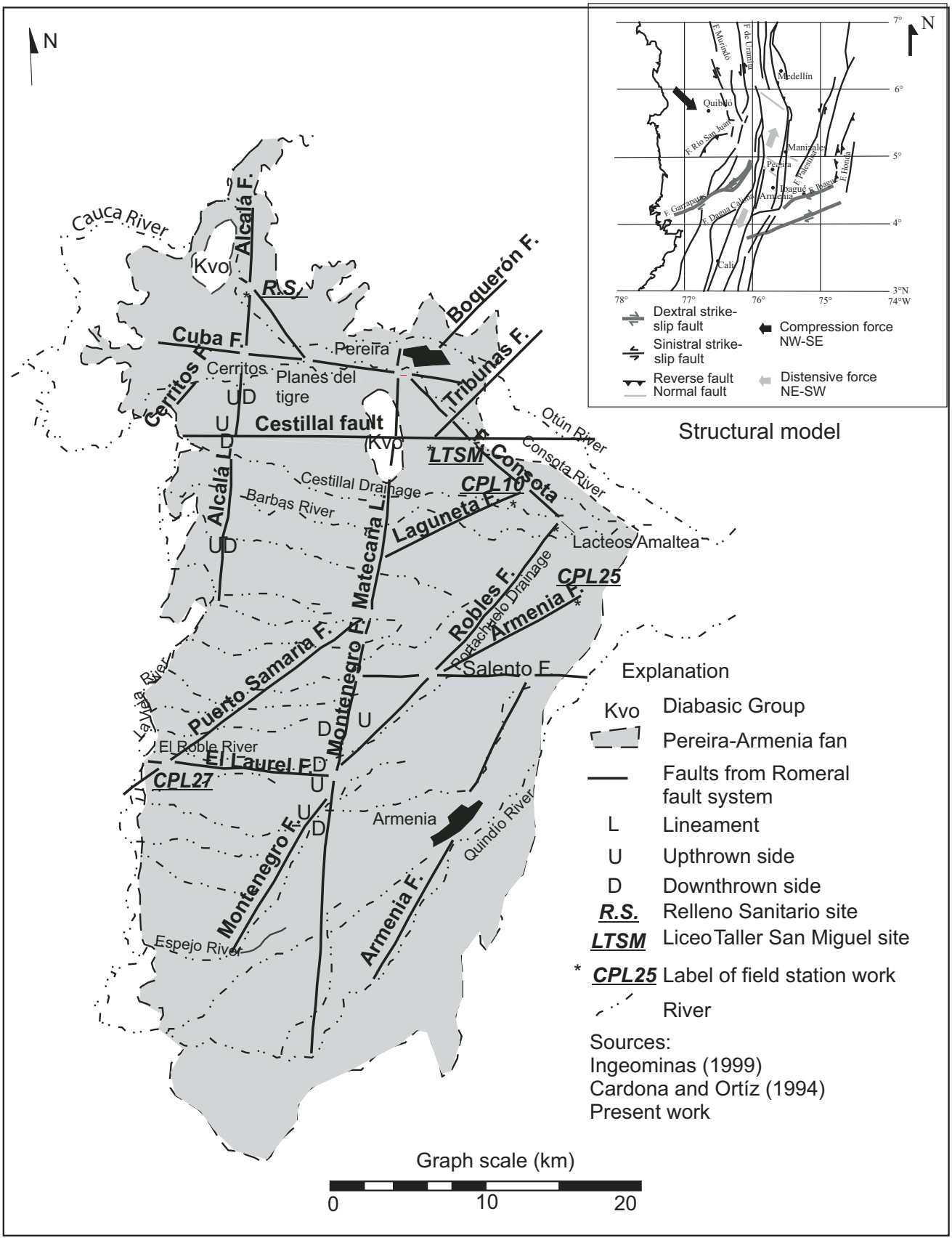


Figure 2. Schematic map of rivers and faults on the Pereira-Armenia fan. The Liceo Taller San Miguel high school (LTSM) is located 9 km south of the city of Pereira. Figure shows the best exposed fault segments in the region. The Pereira-Armenia fan is located between 4°–5°N and 75°–76°W. F—fault.

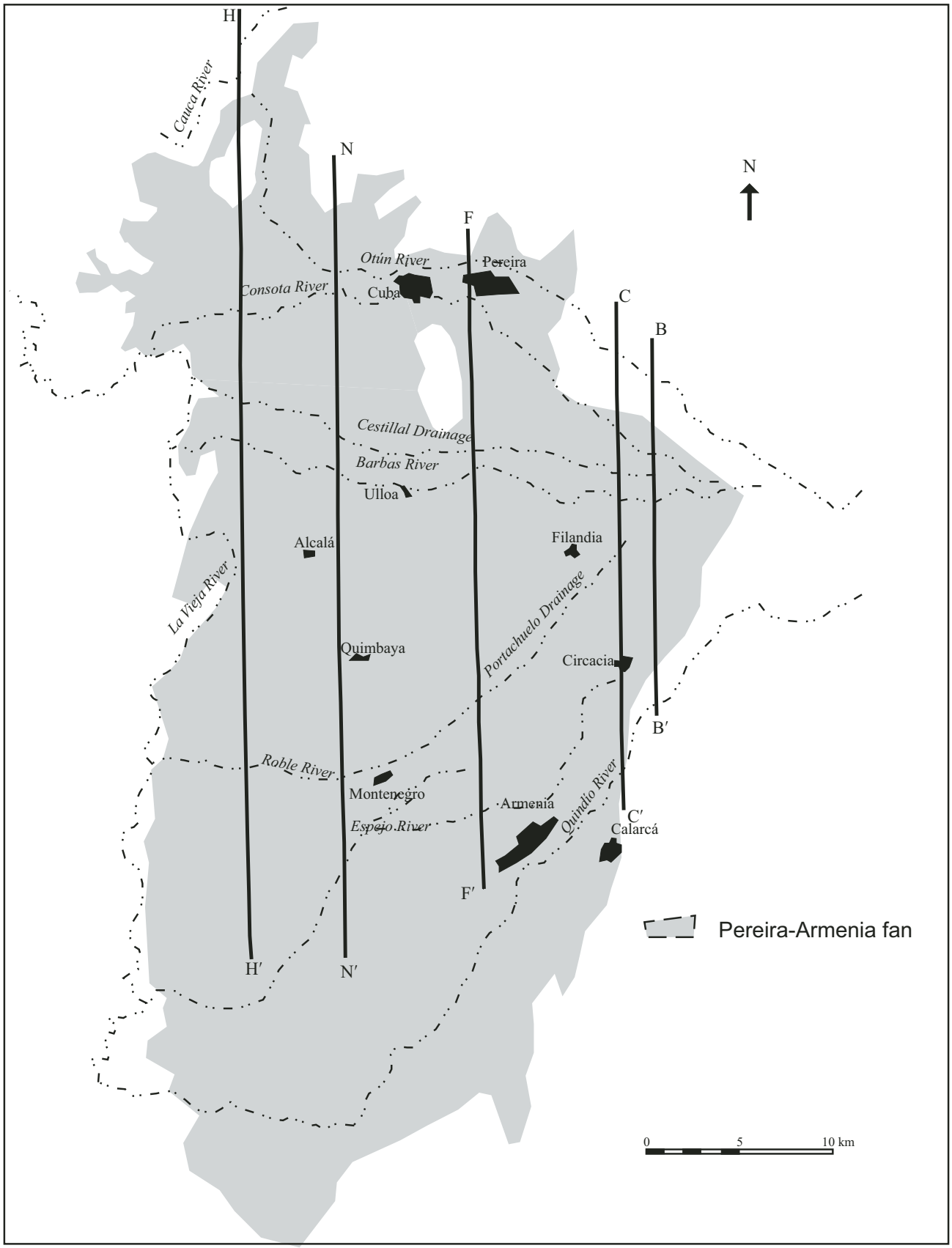
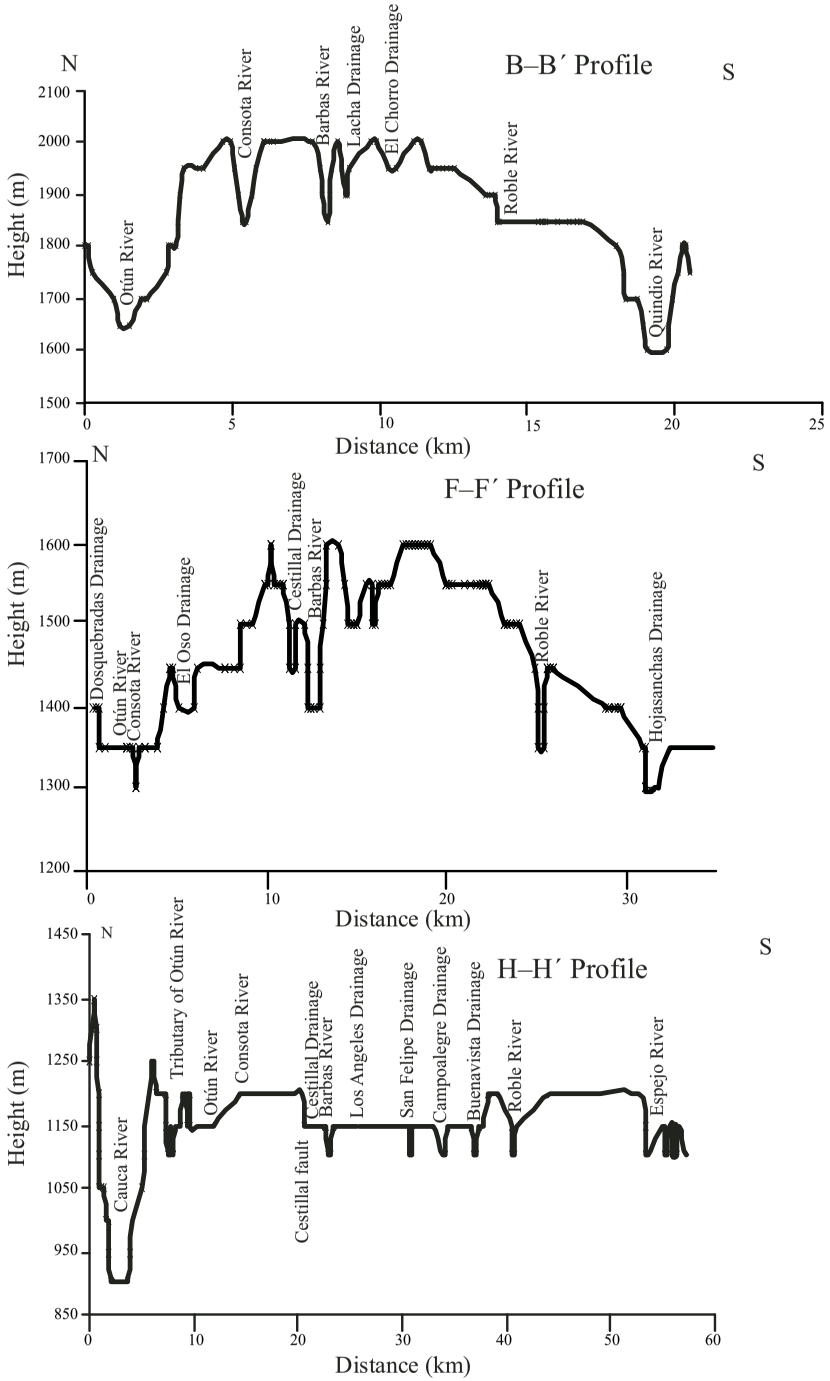


Figure 3. Location of the N-S topographic profiles. The Pereira-Armenia fan is located between 4°–5°N and 75°–76°W.



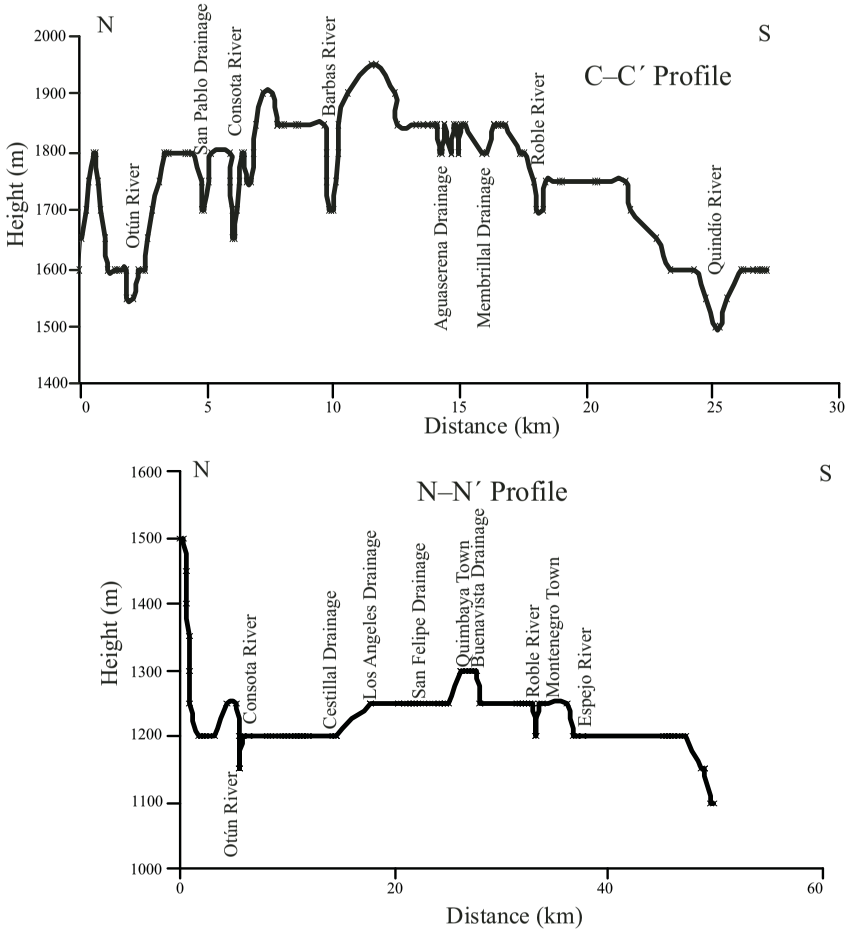


Figure 4. N-S topographic profiles. There are a lot of topographic anomalies in the Pereira-Armenia fan. In the H–H′ profile, note the topographic anomaly that corresponds to the Cestillal fault. In the other profiles, this fault is not clear; this could be because of the major cover of volcanic ash fall and paleosols or some Quaternary deposits that are not yet identified in the region.

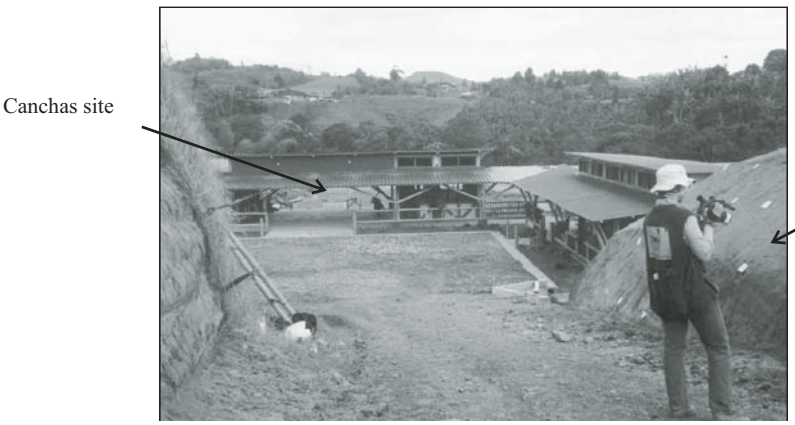
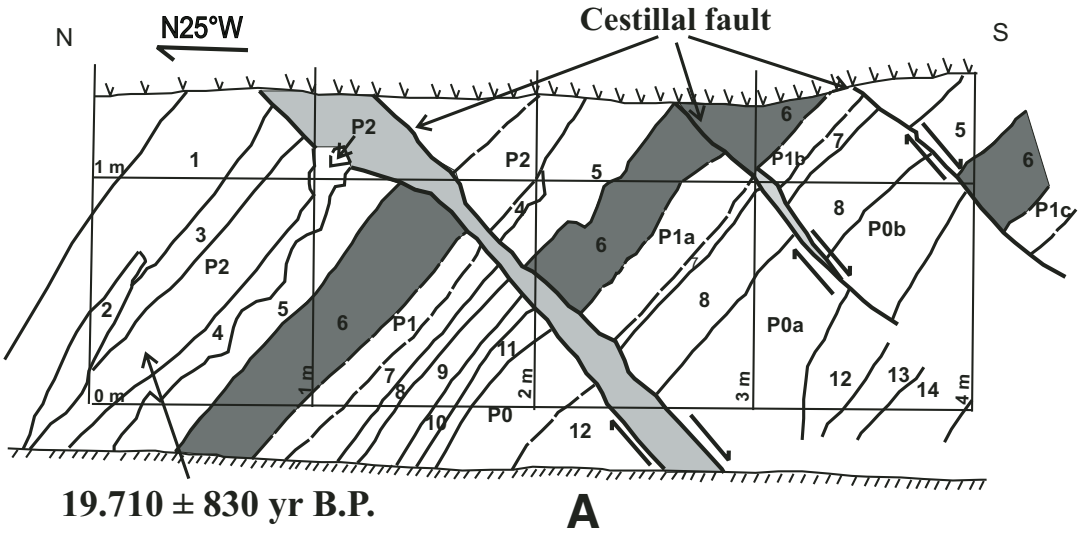
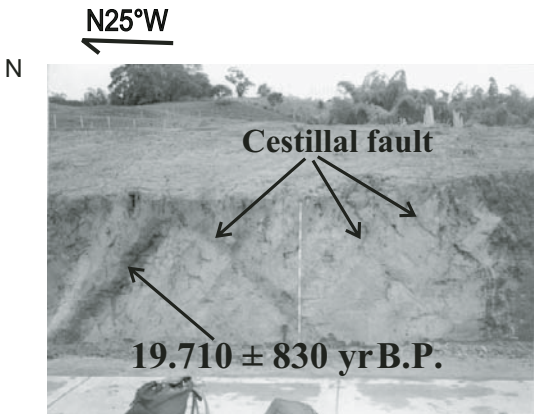


Figure 5. Liceo Taller San Miguel high school. View to south. Photograph shows the location of the Canchas and Parqueadero sites, the two sites studied in detail. The Canchas site (left center) is located behind the building where the playground of the high school is located. The Parqueadero site (far right) is in front of the building where the parking place is located. The Canchas site is located 200 m south of the Parqueadero site, and the top of the Canchas site exposure is 2 m below the floor of the Parqueadero site exposure.





-Paleosol 1 (P1): light brown to reddish. Hard.
-Horizon 6 (6): gray clay (5Y/5/2), thixotropic.
-Horizon 5 (5): yellow sand (lapilli) (10YR/5/8), thixotropic.
-Horizon 4 (4): gray clay (2.5Y/5/2), thixotropic.
-Paleosol 2 (P2): dark, less hard than paleosol 1.
Its age is 19.710 ± 830 yr B.P.
-Horizon 3 (3): gray clay (5Y/5/2), thixotropic.
-Horizon 2 (2): white gray clay (2.5Y/7/1), thixotropic.
-Horizon 1 (1): gray clay (5Y/5/1), thixotropic.

Figure 6. Liceo Taller San Miguel, Canchas site. (A) Sketch of the east wall exposure. Grid lines are 1 m apart. (B) Photograph of the east wall. The Cestillal fault displaces the volcanic ash-fall and paleosol sequence. The sequence is tilted 50°N, and the total displacement along the three fault segments is 1.70 m. Unit 6 is shaded for ease of visualization. The north structure displaces the sequence of volcanic ash falls and paleosols 0.60 m; the middle structure displaces it 0.10 m; and the south structure displaces the sequence 1.00 m. See Figure 7 for description of layers 7–11.

clear in aerial photographs, which could be related to volcanic ash draping. The Cestillal fault has not been previously mapped or reported, so there is no information to confirm that this fault is 35 km long. Evidence of this segment is a change in course of the La Vieja River (Fig. 2), where it changes its direction from N-S to E-W near the mouths of the Barbas and Consota Rivers, and the change in the course of the Cauca River near Cartago city (Fig. 2).

Tribunas Fault

This is a N40°E normal fault that could be a secondary fault related to a blind thrust fault. The Tribunas fault is not very clear in the aerial photographs, but some drainage anomalies exist in the trace of the fault, such as a displacement of the Consota River. This fault occurs in the upper part of the Pereira-Armenia fan.

DESCRIPTION OF LICEO TALLER SAN MIGUEL

The landscape at Liceo Taller San Miguel is rather smooth, exhibiting small hills and undulations. Stream incision is superficial, and in some sites, it is common to find topographic depressions near the streams, which in general are oriented N40°–50°E. This land is used for recreational purposes, cattle grazing, and cultivation. Liceo Taller San Miguel is a high school situated on the Pereira-Armenia fan, and it lies 9 km south of the city of Pereira, near the road that links the cities of Pereira and Armenia (Fig. 2). The geographic location of Liceo Taller San Miguel high school is 4°44′56.17″N, 75°40′28.56″W (WGS84 international spheroid). During the building of the high school, some artificial outcrops were created, which happened to reveal very useful neotectonic information. We selected two specific places that showed evidence of recent tectonic activity. These places are the so-called Canchas site and the Parqueadero site. The Canchas site is located ~200 m south of the Parqueadero site, and the roof of the Canchas site is ~2 m below the floor of the Parqueadero site. Volcanic ashes cap these sites with a thickness of over 4 m.

Canchas Site

Geomorphology

Near the Canchas site, the landscape is rather smooth, exhibiting small hills and a few undulations. Stream incision is superficial, and in some sites, it is common to find topographic depressions near the streams. This site has human affectation and does not have the complete stratigraphic sequence. The most recent affectation was the artificial cut surface created for a basketball court.

Stratigraphy and Soils

At the Canchas site, the Pereira-Armenia fan is covered by a sequence of volcanic ashes and paleosols (Fig. 6). We identified two paleosols that represent periods of extended nondeposition of volcanic ash, or if there were some deposition of volcanic ashes, it was not enough to interrupt soil formation. Between these two pedogenic periods, there are three altered volcanic ash horizons. We consider that the stratigraphic sequence is incomplete due to pre-Columbian human activity, at least before 2500 yr B.P. (Cano, 2004). Because of the artificial cut, we do not know what the natural surface looked like.

Structure

The sequence of paleosols and volcanic ashes at Canchas site is tilted 50°N and displaced or cut by three faults (Fig. 6). The throws of these three faults, from north to south, are 0.60 m, 0.10 m, and 1.00 m, respectively. The minimum cumulative offset of the volcanic ash layer and paleosol in this fault zone sequence is thus 1.70 m. So, the tilt of the sequence could be the result of a seismic event previous to the one that cut it off. However, this normal faulting does not trend as expected from the regional deformation model, which would be produced by a NW-SE–striking maximum horizontal stress, as proposed by Guzmán et al. (1998).

We assume that the displacement of the sequence took place in one seismic event, because if it were the result of two or three different events, we would have found some evidence of that in the layers that were displaced in the first event. The problem is that the sequence is incomplete, so we currently interpret this evidence as the result of only one event that displaced the sequence of volcanic ashes and paleosols at the same time. We are assuming this because it would be the worst-case scenario in a region where we do not know the seismic potential of faults that cross it. The Armenia earthquake (1999) suggests that the seismic potential of the region is higher than we anticipated. Using the displacement identified at the Canchas site, we have applied the equations for all fault types that relate magnitude and maximum surface displacement, i.e., the equation based on moment magnitude (M; Wells and Coppersmith, 1994; McCalpin et al., 1996):

$$M = 6.9 + 0.74(\log MD) \text{ and } \log (SRL) = -3.22 + 0.69M, \quad (1)$$

where M is the moment magnitude, MD is maximum displacement in m, and SRL is the surface rupture length in km. We found that the magnitude of the earthquake that affected the sequence was M 6.9, and the length of the fault segment was 35 km.

Geochronology

The upper (youngest preserved) paleosol was radiocarbon dated at 19,710 ± 830 yr B.P. (Fig. 6).

Paleoseismic Interpretation

We propose coeval faulting and folding, where normal faulting was produced by moment bending during sequence folding. As mentioned previously, the Pereira-Armenia fan is 25 km wide and is covered by paleosols and volcanic ashes. This means that the Cestillal fault is covered by the same kind of soils along 25 km. An evidence of this fault can be observed in the H–H′

profile (Figs. 3 and 4), where the northern block is upthrown by at least 50 m. At the Canchas site, the north block is also displaced upward (the source of the profiles is 1:25,000 scale maps). In the B–B′, C–C′, F–F′, and N–N′ profiles (Figs. 3, 4, and 6), it is not clear whether this fault is affected by the major cover of volcanic ash and paleosols or by some other Quaternary deposits that have not yet been identified in the region; this hypothesis has to be evaluated in future studies.

A seismic hazard assessment for the region estimated that the maximum seismic magnitude would be between 6.2 and 6.6 for a seismic source located 35 km away from the city of Pereira (Guzmán et al., 1998). Magnitudes as large as M 6.9 were estimated for a seismic source located at distances greater than 50 km away.

Parqueadero Site

Geomorphology

Near the Parqueadero site, the geomorphology is rather smooth, exhibiting small hills and a few undulations. This site was artificially cut to build a parking lot, so the original geomorphology of the site is not known. An incomplete sequence of volcanic ashes and paleosols is exposed in a cut slope that contractors made in order to excavate the road that serves as access to the school building.

Stratigraphy and Soils

The description of this slope was restricted to the most important layers for paleoseismic investigation due to logistical problems. So, if the nomenclature of a layer or horizon does not appear, that means we did not collect information for this site, and missing segments could represent one or more layers of volcanic ash (Fig. 7).

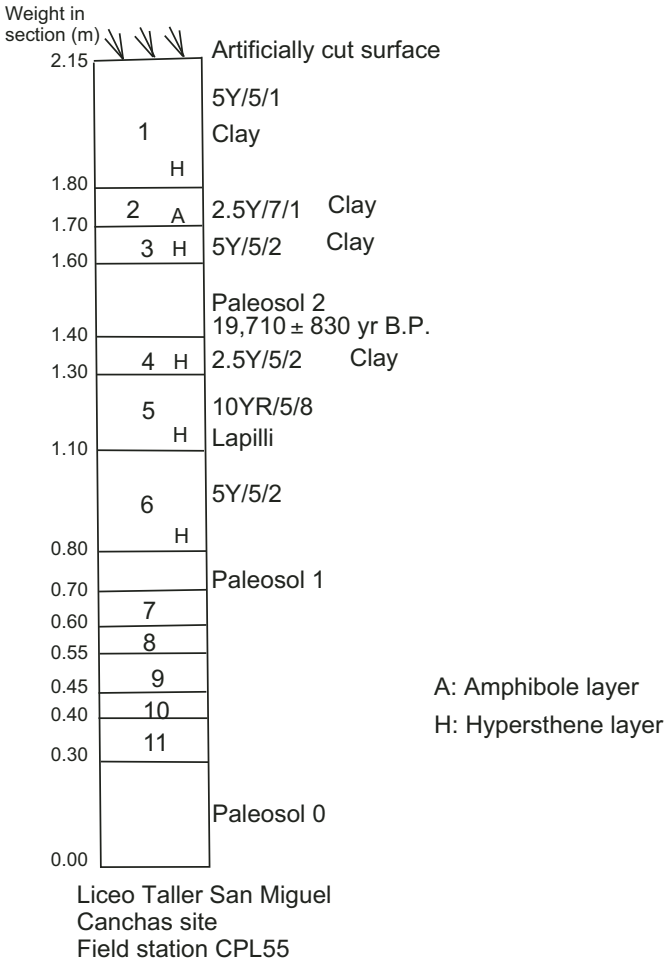


Figure 7. Stratigraphic sequence at field station CPL55, Liceo Taller San Miguel, Canchas site. This site is located 9 km south of Pereira. The sequence is tilted 50° to the north.

Structure

The stratigraphic succession of the Parqueadero site is affected by a N40°E fault showing the north block displaced upward. In the southern part of the slope, at the base, there is a paleosol that was cut and displaced by tectonic structures. At the bottom of horizon 1 (Fig. 8), there are some sand layers that were liquefied.

Geochronology

In the southern upper part of the slope, a paleosol (paleosol Z in Fig. 7; not shown in Fig. 6) is dated at 13,150 ± 310 ^{14}C yr B.P.

Paleoseismic Interpretation

The Tribunas fault is a N40°E normal fault. According to the deformation model for the region, NE faults have to be thrust faults. We explain this by saying that the Tribunas fault is a secondary fault associated with a blind thrust fault. In this work, we characterize the secondary fault only. At this stage, we can only affirm that the thrust fault has to generate at least the same earthquake that can be produced by the secondary fault.

Based on the fault displacement identified at the Parqueadero site and application of Equation 1, the magnitude of the earthquake that affected the sequence was M 6.6, and the length of the fault segment was 22 km. The Cestillal fault is located south of this structure, implying that it corresponds to the southern boundary of the Tribunas fault. The evidence at the Parqueadero site is in the southern part of the fault segment, in the Pereira-Armenia fan; the northern part of the Tribunas fault is outside the Pereira-Armenia fan. The continuity of the Tribunas fault segment is supported by drainage and topographic anomalies. The liquefaction evidence at the base of layer 1 suggests a seismic event of at least Mw 5.5. This evidence could be associated with the M 6.6 seismic event or a previous event.

CONCLUSIONS

Prior to this study, regional faults and their seismogenic potential had been assessed purely on morphologic evidence. The

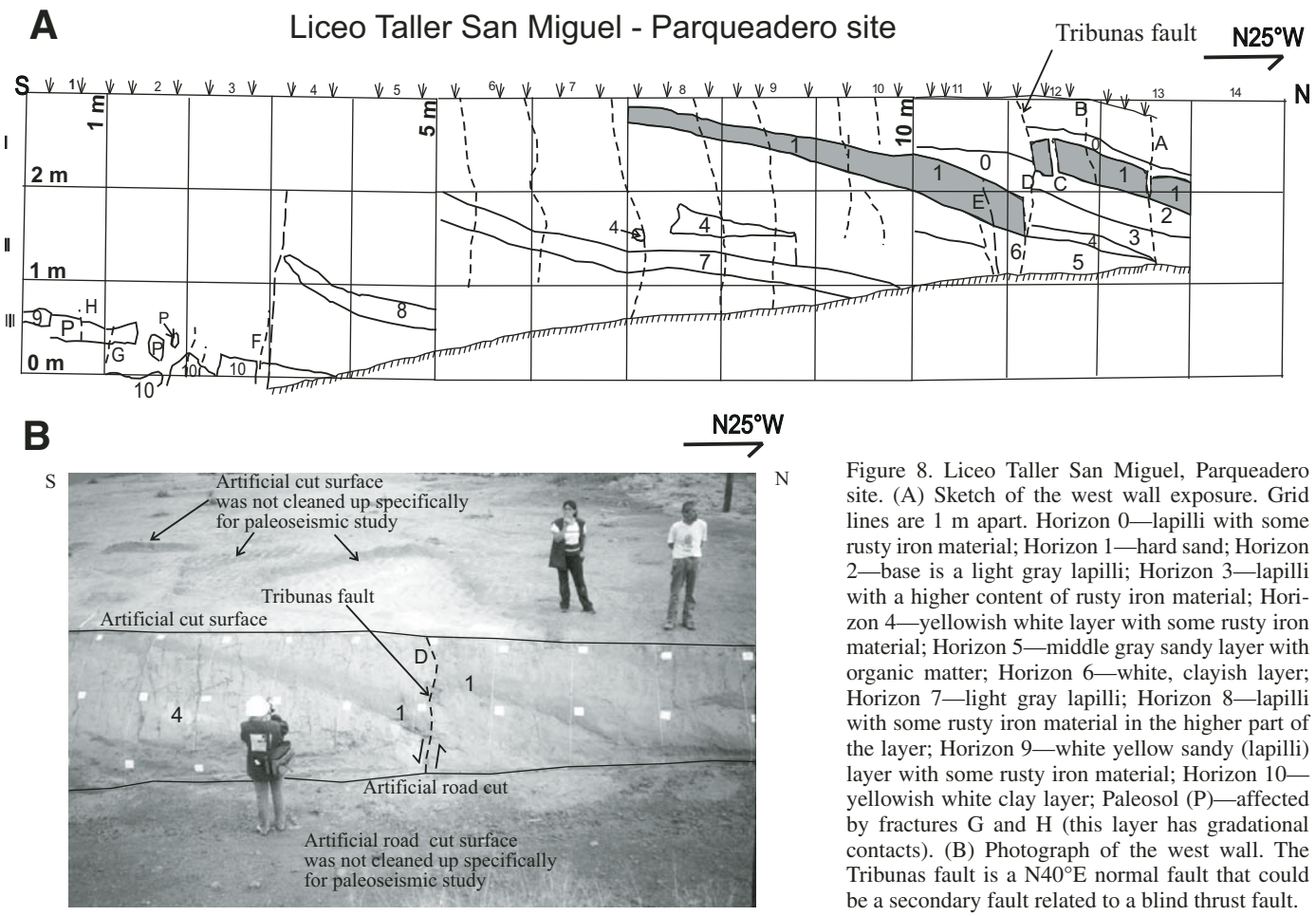


Figure 8. Liceo Taller San Miguel, Parqueadero site. (A) Sketch of the west wall exposure. Grid lines are 1 m apart. Horizon 0—lapilli with some rusty iron material; Horizon 1—hard sand; Horizon 2—base is a light gray lapilli; Horizon 3—lapilli with a higher content of rusty iron material; Horizon 4—yellowish white layer with some rusty iron material; Horizon 5—middle gray sandy layer with organic matter; Horizon 6—white, clayish layer; Horizon 7—light gray lapilli; Horizon 8—lapilli with some rusty iron material in the higher part of the layer; Horizon 9—white yellow sandy (lapilli) layer with some rusty iron material; Horizon 10—yellowish white clay layer; Paleosol (P)—affected by fractures G and H (this layer has gradational contacts). (B) Photograph of the west wall. The Tribunas fault is a N40°E normal fault that could be a secondary fault related to a blind thrust fault.

Parqueadero and Canchas sites show evidence for seismic events of at least M 6.9 for the Cestillal fault and M 6.6 for the Tribunas fault. The maximum seismic magnitude estimated for this region ranges between 6.2 and 6.6 for a seismic source being 35 km away from the site. Our field evidence confirms that local M 6.6 and 6.9 seismic events have taken place, with a possible seismic source located 9 km south of the city of Pereira. This leads us to a better understanding of the regional seismic activity for the last 20,000 yr. After the Armenia earthquake, it is important to review the seismic hazard assessment for this region and to incorporate new field data into its seismic interpretation. It is necessary to continue paleoseismic studies looking for information that may reduce the uncertainty of fault characterizations and seismic hazard evaluations.

Paleoseismic studies are necessary in countries like Colombia because our historical seismic record covers less than 500 yr and instrumental records cover less than 100 yr. The location of the Colombian region in the junction of the Nazca, Caribbean, and South American plates requires detailed paleoseismic studies in order to reconstruct its seismic history and reduce the uncertainties in seismic hazard assessments.

ACKNOWLEDGMENTS

We gratefully acknowledge the following persons and institutions for their support: geologist Michael Tistl, who informed us about this site in order to make paleoseismic studies; Teresa Tisnés, director of the Liceo Taller San Miguel high school, who allowed us to investigate this site; Andrés Velásquez, Myriam López, Fabián González, and Carolina Franco, for their help with the fieldwork; and Colciencias, Universidad EAFIT, and "Fundación para el Avance de la Ciencia y la Tecnología del Banco de la Republica–Colombia" for financial support of this investigation.

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Manuscript Accepted by the Society 7 December 2010