Holocene paleo-earthquakes recorded at the transfer zone of two major faults: The Pastores and Venta de Bravo faults (Trans-Mexican Volcanic Belt)

María Ortuno1,2, F. Ramón Zúñiga1, Gerardo J. Aguirre-Díaz1, Dora Carreón-Freyre1, Mariano Cerca1, and Matteo Roverato1,3
1Centro de Geociencias, Universidad Nacional Autónoma de México, Boulevard Juriquilla, 3001, 76230, Juriquilla, C.P. 76230, Querétaro, Mexico
2Departamento de Geodinàmica i Geofísica, Universitat de Barcelona, c/Marti i Franquès s/n, 08028, Barcelona, Spain
3IGC Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562 Cidade Universitária 05508080, São Paulo, SP, Brazil

ABSTRACT

We present evidence of five late Holocene earthquake ruptures observed at two paleoseismological trenches in the Laguna Barih sag pond (Trans-Mexican Volcanic Belt, central Mexico). The trenches exposed two fault branches of the western termination of the Pastores fault, one of the major fault systems within the central Trans-Mexican Volcanic Belt. The site was studied by combining geomorphological and structural approaches, volcanic mapping, ground-penetrating radar, and paleoseismological analysis. The study revealed that coseismic surface rupture was noncharacteristic, and that the exposed fault branches had not always moved simultaneously. The fault tip has ruptured at least 5 times within the past 4 k.y., and the rupture events followed and preceded the deposition of an ignimbrite. The close temporal relationship of the seismic rupture with the volcanic activity of the area could be the result of volcanism triggered by faulting and its associated seismicity. The relatively high recurrence of seismic events (1.1–2.6 k.y.) and the noncharacteristic fault behavior observed at this tip of the Pastores fault suggest that the fault might have been active as a primary fault rupturing along segments of variable length or depth, and/or that the fault ruptured eventually as a secondary fault. The secondary ruptures would likely be related to earthquakes produced at major neighboring faults such as the Acambay fault, which moved during the 1912 Acambay earthquake, or the Venta de Bravo fault. A relatively large slip rate estimated for this fault branch (0.23–0.37 mm/yr) leads us to contemplate the possible connection at depth between the Pastores and the Venta de Bravo faults, increasing the maximum expected magnitude for central Mexico.

INTRODUCTION

In intracratonic regions, deformation rates of active faults are relatively low, so that recurrence periods of seismogenic ruptures occurring at a particular fault may exceed thousands of years (Stein and Liu, 2009). In these regions, the social perception of seismic hazard is lower than in active continental margins, which are affected by destructive earthquakes every few decades. The low rate of seismicity in intracratonic areas has led to an increasing use of the paleoseismological research as the complexity of fault dynamics. In large normal fault systems, faults are frequently corrugated due to en echelon arrays or overlapping segments that might move simultaneously during a seismic event (e.g., Ferrill et al., 1999). If extension occurs on a body wave magnitude, mb = 6.9; Suárez, 1992). This high seismic activity is a danger for cities on the fault has generated them.

The central region of Mexico is an example of an intracratonic zone in which the activity of faults has led to historical destructive earthquakes. Examples are the earthquakes of 1568 in the Chapala graben (M ~ 7; Suárez et al., 1994) and 1875 at Jalisco (M ~ 7.1; García-Acosta and Suárez, 1996), or the 1912 earthquakes at Acambay (surface wave magnitude, Mw = 6.7; Suter et al., 1996), and at Jalapa, 1920 (body wave magnitude, Mw = 6.9; Suárez, 1992). All these earthquakes were produced by faults located within the Trans-Mexican Volcanic Belt (TMVB), a middle Miocene to Quaternary arc related to the subduction of the Cocos and Rivera plates beneath the North American plate (Demant, 1978; Nixon, 1982; Aguirre-Díaz et al., 1998; Siebe et al., 2006; Ferrari et al., 2012; Fig. 1). Some of the largest cities in Mexico (e.g., Mexico City, Guadalajara, Toluca, Querétaro) are within this region; because they are located above or near active faults, with...
the added factor of abnormal amplification of seismic waves (Ovando-Shelley et al., 2012), a large proportion of Mexico’s population is at significant risk of the consequences of earthquakes. Seismic risk plans should therefore be well established, incorporating well-constrained seismic hazard parameters based on reliable geological data.

This paper focuses on the activity of the Pastores fault, the southern boundary of the Acambay graben and one of the most active faults of the TMVB (Suter et al., 1991, 1992, 2001; Figs. 2 and 3); the seismogenic behavior of the fault is revealed through the study of paleoseismological trenches at its eastern tip (Langridge et al., 2013). In addition to moving as a primary seismogenic source, the activity of this fault as a secondary structure of the Acambay fault was inferred by Suter et al. (1996, 2001) on the basis of the earthquake effects of the 1912 Acambay earthquake reported by Urbina and Camacho (1913). Moreover, the link between the Pastores fault and the Venta de Bravo fault, the larger fault in the Acambay graben, has also been considered (e.g., Suter et al., 1992, 2001; Langridge et al., 2013). These two faults are aligned and form the southern boundary of the Acambay graben. The Pastores fault western termination overlaps the Venta de Bravo fault along a 14–15-km-long zone. The study of this area is thus relevant for the evaluation of the activity as a transfer zone between two major systems that might be linked at depth, implying a significant seismic hazard.

The main objective of our study is to search for the evidence of Holocene earthquake ruptures at the westernmost Pastores fault zone, characterizing the tectonic style and establishing a paleo-earthquake chronology that could help us to better understand its link to the Acambay and the Venta de Bravo faults. For this purpose we rely on neotectonic techniques and ground-penetrating radar prospecting (see Appendix for details on the methods). Understanding the late Quaternary evolution of the area was possible by the construction of a map (Fig. 3) containing the main tectonic structures, landforms, and geological materials, allowing us to discuss the geological significance of the paleo-earthquakes detected. With the paleoseismological and volcanic data shown here, we aim at improving estimates of seismic and volcanic hazard for this area and ultimately to mitigate the natural hazards to the population.

** GEOLOGICAL AND GEOMORPHOLOGICAL SETTING**

The TMVB traverses the center of Mexico from the Pacific coast to the Gulf of Mexico (Fig. 1). According to some (e.g., Pardo and Suárez, 1995; Gómez-Tuena et al., 2005), the obliquity of the TMVB with respect to the Mesoamerican trench is directly related to differences in the angle of the subducting plate. This angle reaches 70° in the central and western part of the arc and it is locally very low (near 25°) at the easternmost part, as revealed by the analysis of the seismicity along the subduction zone (Pardo and Suárez, 1995; Soto et al., 2009) and by geophysical transects such as gravimetric or seismic tomography (Urrutia-Fucugauchi and Flores-Ruiz, 1996; Rogers et al., 2002; Pérez-Campos et al., 2008; Husker and Davis, 2009; Yang et al., 2009; Stuhalio et al., 2012). The structure and kinematic of faults in the TMVB have been addressed regionally (e.g., Pasquaré et al., 1987; De Cserna, 1989; Aguirre-Díaz et al., 1998; García-Palomo et al., 2000). The Pastores fault is located in the central part of the TMVB, which comprises a complex mosaic of horsts and grabens and extends from Guadalajara City to Mexico City valley (Fig. 1; Aguirre-Díaz, 1996; Aguirre-Díaz et al., 1998). The central part of the TMVB was referred to as the Chapala-Tula fault system by Johnson and Harrison (1990). Regional extensional and transtensional kinematics of this zone since the Miocene are well documented (Johnson and Harrison, 1989; Martínez-Reyes and Nieto-Samaniego, 1990; Garduño-Monroy et al., 2009), and a minor left-lateral component in the overall extension has been identified (Suter et al., 1992, 1995, 2001; Ramírez-Herrera et al., 1994; Ramírez-Herrera, 1998; Ego and Ansar, 2002; Norini et al., 2006). According to Suter et al. (1995, 2001) and Ego and Ansar (2002), the central TMVB has been dominated by transtensive stresses since the middle Quaternary, with σ3 oriented northwest-southeast. In addition to this east-west intra-arc fault system, there is a northwest-trending fault system named Taxco–San Miguel de Allende between Querétaro city in the northwest and Taxco in the southeast (Demant, 1978; Aguirre-Díaz et al., 2005; Alaniz-Alvarez and Nieto-Samaniego, 2005), also named the Queretaro fault system (Johnson and Harrison, 1990). This fault system coincides with a change in the regional crustal thickness and marks a gradient in the regional gravity anomaly of central Mexico, and thus represents an important crustal discontinuity (Aguirre-Díaz et al., 2005). It passes through the central part of the Acambay graben at depth, marked by an alignment on some vol-

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**Figure 1. Regional map showing the geodynamic setting of the Acambay graben within the Trans-Mexican Volcanic Belt. Box indicates location of Figure 2. EPR—East Pacific Rise, TR—Tehuantepec Ridge; FZ—fracture zone.**

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[Diagram showing the regional map of the Acambay graben within the Trans-Mexican Volcanic Belt.]
canic structures and a change in the width of the graben (Suter et al., 1991, 1995; Aguirre-Díaz, 1996).

Paleoseismicity and Seismicity in the Central TMVB

The Acambay graben is located at the central-eastern part of the central TMVB (Fig. 2). The faults identified in the central TMVB have an approximate east-west trend and mainly affect Neogene and Quaternary cinder cones, domes, and lava bodies (basaltic, andesitic, and rhyolitic), as well as pyroclastic deposits (Suter et al., 1991; Aguirre-Díaz, 1995, 1996; Aguirre-Díaz et al., 2000; Garduño-Monroy et al., 2009; Ferrari et al., 2012). The faults also affect Cretaceous metamorphic rocks in some regions (Fig. 3; Suter et al., 1991, 1992; Aguirre-Díaz, 1995, 1996), and to a lesser extent, Pliocene–Quaternary lacustrine and fluvial deposits that fill the recent tectonic depressions (e.g., Suter et al., 1995, 2001). Further slip rates have been provided for the Acambay fault, 0.17 ± 0.02 mm/yr (Langridge et al., 2000), and for the Pastores fault, which moves at 0.03–0.04 mm/yr (vertical rates near its intersection with the Lerma River; Suter et al., 1992; Langridge et al., 2013). Due to the scarcity of available ages and to the lack of paleoseismological studies, Suter et al. (2001) distinguished only four faults with proven activity during the late Quaternary–Holocene in the central TMVB. These are the Acambay, Pastores, Temascalcingo, and Morelia faults (Fig. 2). Ramírez-Herrera (1998) also considered the Venta de Bravo fault as being active during the late Quaternary on the basis of lacustrine sediments (1σ calibrated age of 41–34 ka), tilted 7° to the north, and covered by pyroclastic flow and fall deposits and more recently slope deposits. Lacustrine deposits affected by faulting have also been observed in natural outcrops at the foot of the escarpment by Ramírez-Herrera (1998) and Suter et al. (1995).

Paleoseismological studies on faults in Mexico concentrate in the central TMVB. Three of these studies are located in the eastern part of this region, including the Tixmadejé–Acambay fault (Langridge et al., 2000), the central-eastern part of the Pastores fault (Langridge et al., 2013), and the central faults of the Acambay graben (Ortuño et al., 2011) (Fig. 3). Other studies are focused in the western part, including Rodríguez-Pascua et al. (2004) on Lake Patzcuaro (nearly 50 km to the west of Morelia), and...
Figure 3. Simplified geologic map of the Acambay graben showing the main lithostratigraphic units and geomorphological fault traces identified within the graben (mapping by Aguirre-Díaz). Also shown are reported paleoseismological trench sites from other studies. Shaded relief derived from the 30-m-resolution digital elevation model using data from Instituto Nacional de Estadística y Geografía de México (INEGI, 2011) is used as a background. Area of Figure 4 is outlined. Plio—Pliocene; Qt—Quaternary.
Garduño-Monroy et al. (2009) on La Paloma fault, which traverses the City of Morelia (Fig. 2). These studies have reported fault displacements from earthquakes that occurred in pre-Columbian time (Rodríguez-Pascua et al., 2004; Garduño-Monroy et al., 2009) as well as in the twentieth century (the 1912 Acambay earthquake; Langridge et al., 2000).

The Acambay earthquake (19 November 1912, $M_s = 6.7$, Suter et al., 1996) is the only instrumental earthquake in the TMVB with known associated surface rupture. During this event, three faults seem to have broken the surface, as described by Urbina and Camacho (1913), the Acambay-Tixmadejé fault (main fault with a maximum displacement of 50 cm), Temascalcingo fault (with a maximum displacement of 30 cm), and Pastores fault. It is not clear if this latter fault ruptured the surface coseismically during this event or it only showed open fractures along its trace; from the descriptions compiled by Urbina and Camacho (1913), Suter et al. (1995) estimated surface rupture lengths of 41 km and 20 km lengths for the Acambay-Tixmadejé and Temascalcingo faults, respectively, and Pastores fault. However, according to the paleoseismic data of Langridge et al. (2000, 2013) on two trenches excavated on the eastern tip of Pastores fault, the fault did not rupture the surface during the 1912 earthquake.

The paleoseismological study of the Acambay-Tixmadejé fault enabled Langridge et al. (2000) to identify 4 Holocene ruptures with an average dip displacement of 60 cm per event, a recurrence period of 3600 yr, and an average vertical slip rate of 0.17 ± 0.02 mm/yr. Moreover, Langridge et al. (2013) showed no Holocene deformation on the Pastores fault, although they found 3 paleoseismic events with a minimum displacements of 35–50 cm occurring at 31.5–41 cal. kyr B.P., at 23.9–34.6 cal. kyr B.P., and at 12.2–12.6 cal. kyr B.P. Paleoseismological studies by Rodríguez-Pascua et al. (2010) indicate that the area has had at least five earthquakes of moment magnitude ($M_w$) > 5 that affected Pleistocene lake sediments located at the foot of the Pastores fault. In addition to the Acambay earthquake of 1912, other known preinstrumental earthquakes in the region have been recognized. In the central part of TMVB led Suter et al. (2001) to recognize that most of the epicenters are in the western segment of the graben, which is bounded by the Epitacio Huerta and Venta de Bravo faults. The only focal mechanism determined for instrumental earthquakes in the region is that of the Maravatío earthquake (22 February 1979). This earthquake had an $m_c = 5.3$ and an epicentral location north of the Venta de Bravo fault, and corresponds to a focal mechanism with nodal planes showing normal faulting with lateral component in east-west– and northeast-southwest–oriented planes (Astiz-Delgado, 1980; Ego and Ansan, 2002; Fig. 2). Two medium-size earthquakes ($M_c$, coda magnitude = 3.8 and 3.7) took place near the town of Maravatío on 8 February and 15 March 2013. Even though the focal mechanisms are not well constrained, they are consistent with a north-south extension, which agrees with that of the 1979 event. The location of the epicenter and the intensity distribution of the main shock suggest that the Venta de Bravo fault was the seismogenic source of this earthquake. Kinematic data from geological observations along this fault are in agreement with the left-lateral slip component observed in the focal mechanism (Suter et al., 1992).
STRUCTURAL AND GEO MORPHOLOGICAL FEATURES

Pastores Fault

The Pastores fault is one of the most active faults within the Acambay graben, according to its geomorphological expression (Figs. 3–6). Its rectilinear trace extends along 32 km and can be differentiated in two segments, the eastern (11.5 km) and the western (20.4 km). The eastern segment is from the Lerma River north of Atlacomulco to the western end of the San Andrés range (Fig. 3), with a variable scarp height reaching a maximum value of 200 m. The fault mainly affects Miocene dacitic lavas and block and ash flow deposits of a north-south–trending lava dome range between Acambay and Atlacomulco, and Pliocene–Quaternary dark gray aphaniitic andesitic lavas with platy jointing and/or vesicular blocky structure. The vents of these lavas are not defined, but the ramp structures observed in some of them suggest that it is possible that their vents are located south of the Pastores fault. This part of the fault has several secondary faults developed on the hanging wall as well as near scarps of probable gravitational origin affecting the slopes of the May mountain range (Fig. 3).

The western segment of the Pastores fault (WPF) extends from the Lerma River to Canchesdá. Its trace is continuous and gradually increases toward the middle part of the scarps, reaching a height of 120 m (Figs. 4 and 5). The fault affects Pliocene dacitic lava domes (Baños lava domes) and Pliocene–Quaternary aphaniitic dark gray andesitic lavas, which are interbedded with lahar deposits rich in blocks of dark gray andesite and gray porphyritic dacite. The more linear trace of the WPF and the lower scarp height could be explained by the relatively younger age of the volcanic material affected, which is consistent with the poor development of the fluvial network at the uplifted southern block compared to the eastern Pastores fault. The area between the Pastores and Venta de Bravo faults is occupied by a sag pond, interpreted by some (e.g., Suter et al., 1991, 1992, 2001; Ramírez-Herrera, 1998) as indicative of a left-lateral slip component in the faults. We suspect, as suggested by others (e.g., Suter et al., 1992, 1995, 2001), that the Pastores and Venta de Bravo faults could be linked at depth in a more complex system, i.e., the Venta de Bravo–Pastores fault system (Fig. 3). However, Langridge et al. (2013) considered it unlikely that these faults could act as a single seismogenic fault source, owing to the hypothetical presence of a crustal major boundary in the relief zone, the Taxco–San Miguel de Allende fault zone, and to the fact that this area matches with the western end of the surface rupture during the 1912 Acambay earthquake. (This issue is addressed further in the Discussion.)

Pastores Western Termination and the Laguna Baños Pull-Apart Basin

The western termination of the WPF cannot be straightforwardly defined based on its geomorphological trace. Some (e.g., Langridge et al., 2000, 2013) have considered that the Pastores fault has a single trace, with a bend toward the south at its western tip (next to its intersection with the Mexico-Guadalajara highway). We interpret that the WPF ends toward the west into a splay of two faults, the southern WPF (the trace defined by Langridge et al., 2013) and the northern WPF, which is in continuity with the main trace near Canchesdá and also bends to the south a few kilometers to the west (Figs. 4 and 5). This type of splay has been observed at many normal faults systems (e.g., Bahat, 1981; Ferrill et al., 1999; Soliva et al., 2008) and is present at the termination of other faults within the graben, such as those described by Suter et al. (1992) and Ramírez-Herrera (1998). A pull-apart basin has been associated with each of these bends. This basin is currently occupied by the Laguna Baños lacustrine area, which is a natural pond occasionally drained for agricultural purposes (Fig. 5). The bent geometry of the fault trace is characteristic of many other east-west faults in the central TMVB, and might be the result of the linking of right-stepping faults or the interaction of east-west–oriented faults with north-northeast–south-southwest preexisting fractures (Figs. 2 and 3). Some other pull-apart basins and sag ponds have been identified in other neighboring sites, for example, some of the Venta de Bravo faults bends and secondary fault segments (Figs. 3 and 4).

We chose this study location because it is one of the few places where the Pastores fault seems to affect rocks of Holocene age. The surface expression of the faults is very conspicuous because the volcanic rocks affected are highly resistant (e.g., lava flows and domes as well as welded scoria deposits and ignimbrites), leading to excellent preservation of the fault scarps, which maintained rectilinear traces through hundreds of thousands of years and make the faults easily detectable even in far-field satellite images (e.g., Johnson and Harrison, 1989). However, the same fact acts against the paleoseismological record due to the absence of sedimentary traps on top of the scarps. This absence is because (1) the low degradation rate affecting the resistant scarps does not allow the development of local lowlands on them, such as incised valleys or degraded scarps with associated piedmonts, and (2) there is no fine alluvial sediment supply that could cover the scarps; because the uplifted block is difficult to erode, no alluvial drainage developed that would provide sorted sediment supply as alluvial fans. The most common recent rocks affected by fault activity in this setting are the slope talus or colluvium deposits made up of coarse blocks falling from the free faces of the scarps, which evolve as a retreating-type scarps. At some locations, volcanic fall or flow deposits might be preserved. If affected, and when the thickness of the deposit is not too high, these are appropriate sites to look for the paleoseismological record. In such an environment, the small pull-apart basins generated in the fault bends are exceptional localities in which we might find late Quaternary sediments affected by the activity of the faults. In addition, studying the tips of the faults is a further alternative to the problem of having scarps that are too high; the fault displacement is smaller at those parts of the fault, so there are more chances for the scarps to be buried after an earthquake (e.g., Ortuño et al., 2012a). The Pastores fault western termination at the Baños site meets these two conditions: it is a fault tip and coincides with a fault bend associated with a pull-apart basin filled with recent lacustrine sediments. The main evidence suggesting the continuity of the Pastores trace toward the west along the northern WPF (in the direction of the Laguna Baños site) is the mapped rupture of the 1912 Acambay earthquake as described by Urbina and Camacho (1913) and revisited by Rodríguez-Pascua et al. (2012). Even though there is no report about the displacement along this fault, open fractures were documented and mapped along the western Pastores fault with a rupture that extends across a lowland located next to Santiago Cochochitlán (Fig. 4).

Western Pastores Fault Exposures

Several outcrops along the western end of the Pastores fault allow a direct observation of the materials affected by the neotectonic activity of the fault and its most relevant structural features (Figs. 4–6). These observations are described as the following three distinct sites.

Site A

Site A (19°51'28"N, 100°01'52"W) is located at the eastern margin of a watercourse oriented perpendicular to the Pastores fault, south of the Santiago Cochochitlán locality (near Boquitown; Fig. 4). At the head of the watercourse, the Pastores fault has a 1–2-m-thick fault breccia on Pliocene lavas of dacitic composition belonging to the Baños lava domes unit. Fracturing in the footwall lava has a decimeter spacing, yielding the aspect of a foliated rock. Fluvial-lacustrine
Figure 5. (A) The Laguna Bañí study area (see Figs. 3 and 4). WPF—western Pastores fault. (B) Laguna Bañí site (location in A) showing the two trenches described in this study and the ground-penetrating radar profiles (Ruedo).
recent materials deposited on top of the fault nation of the Pastores fault (Fig. 6G) that shows middle Pleistocene lavas. Two neighboring outcrops of the WPF affecting structural data (reported by Suter et al., 1995) in terms of displacement with as much as 1 m of throw, a pitch of 50°–65°W, indicating north-northwest toward the north, and contain slickenlines with a trend N75E–N097E, dip between 50° and 70°. Fault planes measured planes and sigmoid fault branches (Fig. 6C). Discrete faults within this fault zone show S-C planes (Fig. 6D, 6F). Fault planes measured trend N75E–N097E, dip between 50° and 70° toward the north, and contain slickenlines with a pitch of 50°–65°W, indicating north-northwest to northwest extension (Fig. 6C). The data indicate extensional and left-lateral components of displacement with as much as 1 m of throw affecting the fluvial materials, in agreement with structural data (reported by Suter et al., 1995) in two neighboring outcrops of the WPF affecting middle Pleistocene lavas.

**Site B**

Site B (19°51′34″N, 100°02′44″W) is an artificial cut oriented north-south at the termination of the Pastores fault (Fig. 6G) that shows recent materials deposited on top of the fault scarp. At the base, there is a lahar deposit on top of pink volcanic ash deposits. A paleosol is preserved on top of the lahar unit. Overlying this paleosol is a pyroclastic flow deposit. Talus detritus <10 cm thick covers the sequence. No clear faults are observed in this outcrop, although some subsurface faulting is inferred from the geometry of the layers and the steps in the present-day surface (surface previous to the quarry). We did not find a clear surface scarp in the surroundings, but noticed that some limits of agricultural crops are parallel to the fault trend, possibly because the fault has caused secondary fractures that are difficult to erase by farmers. One of these fractures has been locally widened and has been used as an agricultural drainage channel.

**Site C**

Site C (19°52′36″N, 100°03′42″W) corresponds to the Laguna (lake) Bañí, which is in a topographic depression located at the left stepover of the northern WPF (Figs. 4, 5, and 6B). In this area, the hanging wall is occupied by a fluvial-lacustrine system interpreted here as a tectonic sag pond. The fluvial-lacustrine area is limited to the south by the fault, which is affecting tabular lava flows of dacitic composition corresponding to low lava domes with flat tops and vertical margins, and to the north, by other dacitic domes of the same group. These dacitic lava domes, informally called the Bañí dacitic domes (Fig. 3), form a dome complex that extends across the central portion of the Acambay graben, between the volcanoes of Temascalcingo and Altamirano, and continue to the south beyond the Pastores fault. The fault also affects block and ash flow deposits identified along the scarp on top of Pliocene dacitic lava flows. At this site, the geometry of the fault trace shows a bend, which seems to result from the linking of two faults that have a stepping geometry (Fig. 5A). A splay of faults is expected to have formed near the fault bend, causing a partition of the deformation of the surface along minor fault branches. The southern fault branches would be responsible of the main scarp, so they are called the Hill fault branch (HFB), whereas the northern fault branches would be covered by lacustrine deposits, so they are called the Lake fault branch (LFB; Fig. 5B). The HFB is mostly covered by trees and talus material, which makes it difficult to observe clear fault surfaces (Fig. 6E). Lavas and domes are Pliocene age, according to our mapping and the stratigraphy of Aguirre-Díaz

![Figure 6](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/11/1/160/3333754/160.pdf)
The fault scarp has a maximum height of 30 m and a maximum slope of 35%–40% near the sag pond. Near the lacustrine area, two fan-like forms interpreted as debris cones and a possible rear scarp on the upthrown block account for the lack of straightness of the fault trace. The base of the scarp toward the east is artificially modified by an irrigation channel that follows the fault trace (Fig. 5A). Although this area was not included in the Urbina and Camacho (1913) mapping of geological effects of the 1912 Acambay earthquake, the inhabitants of the area were told by their grandparents that a natural spring next to the lake stopped providing water right after that earthquake; we interpret this as evidence of coseismic shaking.

**PALEOSEISMOLOGICAL TRENCHES AT THE NORTHERN WPF; THE LAGUNA BAÑI SITE**

The Laguna Bañi site was selected for ground-penetrating radar (GPR) prospecting and paleoseismological trenching by the following reasons. (1) The lacustrine area is a sedimentary depocenter facilitating a more complete geological record (e.g., burial and preservation of coseismic displacements) than other sites in which the scarp is evident but erosive processes predominate. (2) The lacustrine environment favors the accumulation of organic matter, making possible the dating of the layers possibly affected by faulting. (3) The expected fault splay geometry is appropriate for the study of a complete faulting chronology due to the partitioning of the deformation in different branches. (4) Because the area corresponds to the fault termination, smaller slip-per-event displacements are expected, which are more easily buried than greater displacements. (5) We have considered that secondary faulting or crack opening during the 1912 Acambay earthquake (1996) and Aguirre-Díaz and McDowell (2000) march 11.3.
bay earthquake might have occurred in the area, based on the earthquake hydrological effects reported by the local people. Consequently, the site seems a good location to look for evidence of secondary coseismic behavior of Pastores with respect to Acambay fault.

Two trenches were excavated in Laguna Bañí: Laguna east and Laguna west. Both trenches were oriented north-south, approximately perpendicular to the main trace of the northern WPF, and showed deformation along the LFB (Fig. 5B). We describe here the geological materials and the tectonic deformation affecting the trenches, the data analyzed to obtain a paleo-earthquake chronology. The ages of the events were constrained by the radiocarbon dating results summarized in Table 1. Figures 7 and 8 show the stratigraphic record observed at the trenches and GPR profiles along with a detailed sedimentological description.

**Laguna West Trench**

This trench was located in a higher position on the topographic scarp relative to the other trench (Laguna east; Fig. 4). The trench was 15 m long, 2–3 m deep, and 2 m wide and exposed 5 coluvial deposits (C.1–C.5; Figs. 7A–7C) derived from the topographic scarp located to the south. These deposits are interlayered with a pyroclastic flow deposit named the Bañí ignimbrite, which thickens toward the north of the trench. The present-day soil (S.1) is developed on top of fine-grained colluvial material (Figs. 7A, 7B). The Bañí ignimbrite is massive, gray when fresh, and brown in weathered zones, and is mostly composed of ash, which supports gray pumices and a few small (<2 cm) lithics of andesite. Pumice clasts are angular and ≤2 cm. Pumice and matrix include plagioclase, hornblende, biotite, and quartz. Based on this mineralogy, the composition should correspond to dacite or rhyolite, but it has not been chemically analyzed to confirm this. The ash matrix has been replaced by brown clay at the base and top of the deposit due to weathering processes. The ignimbrite contains small charcoal clasts that were sampled for ¹⁴C dating. The most probable volcanic sources of this ignimbrite are the Temascalcingo volcano or the Altamirano volcano (Fig. 3); further studies are needed to confirm which of these produced the Bañí ignimbrite. The sequence is affected by three discrete faults cutting all units except for the upper soil (C.1 unit). These faults are oriented N097°E–N088°W with dips of 80°–88°N. Dip fault displacements, between 9 and 20 cm, were documented and are discussed within the description of the paleoseismic events. The fault F 1.1 is the most evident (Fig. 8). Faults F 1.1 and F 2 are normal and F 1.2 and F 3 are reverse. In other observed fractures, it is difficult to assign a magnitude of displacement, either because lower layers are apparently unaffected or because the stratigraphic contacts are highly irregular.

**Laguna East Trench**

The Laguna east trench extends from the base of the scarp toward the lacustrine plane (Fig. 4). The trench was 47 m long, 2–3 m deep, and 2 m wide. In its southern part, this trench exposed a succession of three colluvial units (C.1, C.4, C.5) derived from the topographic scarp located to the south. The colluvial units are interlayered with the Bañí ignimbrite and with lacustrine deposits toward the north. The ignimbrite is covered by brown sand deposits showing cross bedding and mostly composed of volcanic ash and small clasts of pumices and andesitic lavas. This deposit apparently resulted from reworking of loose ash, pumice, and lithics from the nonwelded top of the Bañí ignimbrite. The lacustrine sequence consists of two silt units (FL.2–FL.3) at the base of the trench and of a fine grained conglomerate, sand and minor silt layers at the top of it (FL.1; Figs. 7D and 7E). In the central and northernmost parts of the trench, the ignimbrite overlies a brown paleosol (S.2) and has a total thickness of ~1 m. Present-day soil (S.1) developed either on fine-grained colluvial deposits of the footwall or on the sand and silt fluvial deposits of the hanging wall (Figs. 7C, 7D, and 8).

Three fault zones (F 4, F 5, and F 6) were identified along with two gentle folds affecting the lacustrine basal layers. The faults affect all the stratigraphic levels except the younger colluvium (C.1), the upper lacustrine unit (FL. 1), and the present-day soil developed on top of them. Gentle folding was observed in the lower silt layer (FL. 3) in the northern part of the trench. Displacement of the stratigraphic layers was observed in three fault zones (F 4, F 5, and F 6) and is discussed in the following. Single dip-slip values observed in this trench range from 14 to 44 cm and are discussed in detail in the following description of the paleoseismic events. Fault zone 4 corresponds to the main trace of the Pastores fault, striking N80°–94°E and dipping 65°–68°N. In this fault zone, three fault planes are distinguishable on both walls of the excavation (F 4.1, F 4.2, F 4.3). The faults displace the basal colluvial deposits and the ignimbrite. Several observations lead us to recognize an increase in the fault thrown toward the east and a spay geometry of the fault array: (1) deformation of C.4 is greater on the eastern wall (Fig. 7C) than on the western wall (Fig. 7D); (2) the C.5 (or basal) unit is not exposed in the eastern wall, probably because it is affected by a greater downthrown displacement; (3) the distance between F 4.1 and F 4.2 is larger in the west wall. The horizontal branching, in scale, seems to correspond to the horse-tail spay of the main fault. Fault 4.1 is oriented N94°E and dips 65°N and has slickenslides with a pitch of 85°N, indicating a minor right-lateral strike-slip component. In the colluvial levels affected by the fault F 4.1, a large broken block aligned with the fault has slickenslides in agreement with the fault kinematics (pitch 86°E within a pebble side oriented N80°E, dip 50°N; Fig. 8C). Evidence of deformation accommodation by this fault relies on an open fracture filled with material falling from the surface, as can be seen in the east wall (Fig. 8E). Northward, other faults and fractures filled by the ignimbrite (F 4.4 and F 4.5; Figs. 7D, 7E) suggest that the deformation was distributed in several structures with millimeter-scale displacements. Fault zone 5 (F 5; Fig. 7D) is oriented N74°E and only affects the lower silt layer (FL. 3). As F 3, this fault is composed of multiple discontinuities characterized by tension fractures affecting the upper silt layer (FL. 2) and filled by

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**TABLE 1. DATING RESULTS FOR THE SAMPLES COLLECTED AT LAGUNA EAST AND LAGUNA WEST TRENCHES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Radiocarbon age</th>
<th>Error (yr)</th>
<th>2σ calibrated age range</th>
<th>Comment</th>
<th>Location*</th>
</tr>
</thead>
<tbody>
<tr>
<td>C22</td>
<td>4410</td>
<td>40</td>
<td>3324–2914 B.C.</td>
<td>Out of sequence, probably reworked</td>
<td>Young colluvial (unit C.1)</td>
</tr>
<tr>
<td>C1</td>
<td>983</td>
<td>36</td>
<td>A.D. 990–1155</td>
<td>Fracture infill</td>
<td>Fracture infill (Tr-1-E)</td>
</tr>
<tr>
<td>C6</td>
<td>356</td>
<td>35</td>
<td>A.D. 1452–1635</td>
<td>Probably rejuvenated by edaphic bleaching</td>
<td>Ignimbrite (l.1)</td>
</tr>
<tr>
<td>C19</td>
<td>2440</td>
<td>40</td>
<td>753–406 B.C.</td>
<td>Probable age of the ignimbrite</td>
<td>Ignimbrite (l.3)</td>
</tr>
<tr>
<td>C8</td>
<td>1205</td>
<td>30</td>
<td>A.D. 694–894</td>
<td>Probably rejuvenated by edaphic bleaching</td>
<td>Ignimbrite (l.3)</td>
</tr>
<tr>
<td>C5</td>
<td>3500</td>
<td>130</td>
<td>2196–1512 B.C.</td>
<td>Probably reworked</td>
<td>Ignimbrite (l.3)</td>
</tr>
<tr>
<td>C11</td>
<td>3630</td>
<td>40</td>
<td>2134–1891 B.C.</td>
<td>Age of the buried paleosol</td>
<td>Paleosol (S.2)</td>
</tr>
</tbody>
</table>

Note: Radiocarbon ages are ¹⁴C yr B.P. (before present—A.D. 1950).

*See Figure 7 for locations of samples.
the Bañí ignimbrite. At the southern part of this fault zone, gentle folding forming a monocline is affecting the upper silt layer (FL. 2) and at the ignimbrite base (I.3), possibly associated with a north-dipping blind inverse fault. The intermediate level of the ignimbrite (I.2) and upper layers appear to be undeformed by this fault zone.

Fault zone 6 is oriented N62°–68°E and displaces the lower (FL. 3) and upper (FL. 2) silt layers, and to lesser extent, the ignimbrite (F 6; Fig. 7D). In contrast to previously described faults, no tension fractures are present. This fault zone is apparently associated with folding in the silt layers, which produced two anticlines and a syncline between. The ignimbrite unit fills the paleotopography deformed by the folds.

Paleo-Earthquake Analysis of Trenches at Laguna Bañí Site

The analysis of the temporal relationship between the fault displacement and the deposition of the stratigraphic units was made following the criteria proposed by Villamor et al. (2011) for the study of paleoseismolog-

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**Figure 7 (on this and following page).** Logs of the two trenches studied, comparison with ground-penetrating radar (GPR) results, and legend of the exposed units. Valid radiocarbon ages are in black, invalid are in red. (A) Laguna west E-wall. (B) Laguna east W-wall. (C) Laguna east E-wall.
Figure 7 (continued). (D) Laguna east W-wall. (E) GPR Ruedo 2 profile, which corresponds to the Laguna east trench section. Not all the discontinuities observed in the reflectors match with the ones observed in the trench. Note that several of the main fault zones (F 4.1, F 4.2, F 6) can be identified in the GPR profile, as well as the folds affecting the lower lacustrine units. Letters at the left part and numbers at the bottom or top of the logs refer to the 1 m horizontal x 0.5 m vertical net used to compose the log. Stratigraphic units are labeled C.1, S.1, I.1, etc., according to the legend in D and E. Radiocarbon samples are labeled C3 to C22 and geomechanical samples are labeled C9 2 to C9 7 and C43 1 to C43 6.
Figure 8. Photographs of the paleoseismological site and trench exposures. (A) View of the Laguna east and west trenches at the toe of the main western Pastores fault scarp. (B) Open fractures on the basal lacustrine unit FL. 3, columns 36–37 in Fig. 7D. (C) Striated block in fault zone 4.1 in Fig. 7D. (D) Fault zone 4.2, columns 3–5 in Fig. 7D. (E) Open fracture and filling in fault zone 5.3 in Fig. 7B. (F) Fault zone 1.1, column 0 in Fig. 7A. The picture was flipped for easier correlation with the log of Fig. 7A.
Holocene paleo-earthquakes in the Trans-Mexican Volcanic Belt

1 Within unit C.1 ca. A.D. 990–1155

2 Event

This is the youngest event and was identified by the stratigraphic discontinuity between the present-day soil level developed on top of colluvial unit C.1 and the ignimbrite. Unit C.1 fills a tension fracture of 26 cm of maximum aperture, observed only on the Laguna east trench E-wall (Figs. 7C and 8E). This fracture is parallel to fault F 4.3. Neither the top nor the bottom of the ignimbrite seems to be vertically displaced along this fracture. Nearby joints affect the ignimbrite level (F 4.1 and F 4.2). Because the fracture is present only in one trench wall, and given the cutting relationships, the deformation cannot be straightforwardly assigned to a seismic event in this fault. It is probable that the fracturing was produced as a secondary geological effect associated with the rupture of a different fault or fault segment, as it could be the central part of the Pastores fault or any other seismogenic fault in the area. A maximum age for this event of A.D. 990–1155 was yielded by a sample of the soil filling the F 4.3 fracture (Fig. 8E). This age should be considered only indicative of the maximum age, because the colluvial material filling the fracture could have formed in a previous, undetermined time before the opening of the coseismic fracture.

The Bañí site is at only ~24 km from the 1912 earthquake epicenter and 4 km west of the tip of the fault segment of the Pastores fault coseismic rupture, mapped by Urbina and Camacho (1913), and revisited several times (e.g., Suter et al., 1995; Langridge et al., 2000; Rodríguez-Pascua et al., 2012). We suspect that coseismic opening of fracture F 4.3 is contemporaneous with the 1912 Acambay earthquake; according to the testimony of the local inhabitants, a natural spring located next to the Laguna Bañí dried up during the 1912 Acambay earthquake and was never active again. We have interpreted this observation as possible evidence of hydraulic alteration due to coseismic shaking, which would correspond to an intensity VIII–X in the Environmental Seismic Intensity scale proposed by Michetti et al. (2007). For such intensity, the areas showing secondary earthquake effects range between 100 and 5000 km², so the Bañí site is located within the expected affected area.

Event 2

The second most recent event was inferred from the clear displacement of the base of the Bañí ignimbrite by several faults (F 3, F 4) and fold-related faults (F 5). This deformation, observed at both trenches, does not affect the upper part of the unit. In the Laguna west trench, it can be observed that fault F 3 displaced the base of the ignimbrite and the underlying colluvial units (C.2 and C.4). The offset is ~15 cm with an apparent vertical displacement to the south. Fault F 1.1 offsets the base of colluvial unit C.3 by 9 cm along dip and does not affect unit C.1. We know that event 2 is contemporaneous with the ignimbrite, so the time bracket for this displacement (between units C.3 and C.1) is compatible with this earthquake as well as with the previous one. In the Laguna east W-wall (Fig. 7B), fault F 4.5, material from unit C.4 seems to be injected up into the ignimbrite. In the Laguna east trench E-wall, faults F 4.1 and F 4.3 displaced the base of the ignimbrite by 18 and 11 cm, respectively, with an apparent dip displacement to the north, resulting in 29 cm summed slip (maximum slip observed; Fig. 7C). The different displacements observed from one trench wall to the other suggest a lateral decrease toward the west in the fault displacement, which is also observed in the deformation caused in event 1. Event 2 should have occurred during the ignimbrite deposition (ca. 753–406 B.C.), since only its base is affected. This fact can be explained if the paleo-earthquake occurred just after the deposition of the first phase in the eruptive activity that formed the ignimbrite.

Event 3

This event deformed all layers deposited before the Bañí ignimbrite and is associated with several unconformities and structural features including (1) open fractures developed in the layers beneath the ignimbrite; these fractures are observed at the Laguna east W-wall and are coincident with faults F 4.2, F 4.3, F 4.4, and are filled with ignimbrite material from ignimbrite L1 in the southern area (Figs. 7D and 8B); (2) a fold observed at fault zone F 5 (Fig. 7D); the lacustrine deposits FL. 1 and FL. 2 are folded, implying a vertical apparent throw.

Table 2: Paleoseismic Events Defined in the Analysis of Laguna East and Laguna West Trenches, Considering Model A.2 as the Most Probable Chronology

<table>
<thead>
<tr>
<th>Event</th>
<th>Bracketing unit: lower/upper</th>
<th>Age (calendar years)</th>
<th>Apparent displacements* (cm)</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Within unit C.1</td>
<td>ca. A.D. 990–1155</td>
<td></td>
<td>Open fracture, fractures developed up to top layers of the ignimbrite (Laguna west E-wall), with no clear displacement. The age of the event must be similar or younger than the fracture infill.</td>
</tr>
<tr>
<td>2</td>
<td>Base of the ignimbrite/Laguna east FL. 1 (Laguna east W-wall; Laguna east E-wall)</td>
<td>753–406 B.C.</td>
<td>Laguna west E-wall: possibly 9 (F 1); −15 (F 3); Total max.: 29, Laguna east E-wall: 18 (F 4.1–4.2); 11 (F 4.3); W-wall: −28 (gentle fold F 5)</td>
<td>This event closely postdates the ignimbrite deposition.</td>
</tr>
<tr>
<td>3</td>
<td>Immediately before Ignimbrite I-3/FL. 2; I.2/C.3(C.2)</td>
<td>ca. 753–406 B.C. younger than 2134–1891 B.C.</td>
<td>Laguna west E-wall: 9 (F 1, if not occurred in event 2); Total max.: −16, Laguna east W-wall: −3 (F 5.1); −7 (F 6.1)</td>
<td>This event very closely precedes the ignimbrite deposition.</td>
</tr>
<tr>
<td>4</td>
<td>Sometime before ignimbrite: intra C4’ and intra FL. 2/S.2 (preferred age)</td>
<td>ca. 2134–1891 B.C.</td>
<td>Laguna west E-wall: 7 (16–9, F 1.1), −20 (F 1.2), 20 (F 2), Total max.: 37, Laguna east W-wall: 29 (F 4.1), −4 cm (F 5.2), −13 (−20 + 7 in F 6.1); 25 (19 + 6 in F 6.2)</td>
<td>This is possibly a multiple event; it creates a scarp controlling the geometry of unit C.5.</td>
</tr>
<tr>
<td>5</td>
<td>C.4/C.5</td>
<td>older than 2134–1891 B.C.</td>
<td>Total max.: 65, Laguna west E-wall: 85–20 (F 2); Total max.: 37, Laguna east W-wall: 21 (F 4.3)</td>
<td></td>
</tr>
</tbody>
</table>

Note: See text and text illustrations for explanations of events and abbreviations used. The displacements, as analyzed by each fault branch during each event, have been included; bold type indicates the maximum (max.) observed displacement.

*Positive values are dip slip; negative values are reverse slip.
to the south of 28 cm, and it is sealed by the ignimbrite deposit; (3) displacement along two fault zones (F 1 and F 6.1); 9 cm of apparent dip displacement was measured along F 1.1 (down to the north) and 7 cm was measured along F 6.1 (down to the south; Figs. 9 and 10). The maximum amount of displacement is 10 cm down to the south in the Laguna east W-wall. This event took place after the deposition of colluvial units C.3 and C.2, after the formation of paleosol S.2 (2134–1891 B.C.), and shortly before the ignimbrite emplacement, i.e., before 753–406 B.C. The tension fractures were preserved with rectilinear geometries, indicating a small elapsed time between their formation and the deposition of the ignimbrite, which acted as a sealing deposit.

**Event 4**

The analysis of the deformation affecting the basal colluvial deposits (base of C.4 and C.5) near the major fault scarp (faults F 1, F 2, and F 4) allowed the identification of this event in the two trenches. The event also activated faults F 5 and F 6, affecting the lacustrine basal units FL. 2 and FL. 3. In the Laguna west trench, this event caused deformation distributed in at least 3 fault branches, offsetting the top of unit C.4 with 7 cm of dip displacement along F 1.1 (16 cm minus 9 produced in event 3 or 2), 20 cm of reverse displacement along F 1.2, and a total of 20 cm of dip displacement along F 2. On fault F 2, the deformation is accomplished by several faults resulting in the apparent downthrown injection of fragments of level C.4′ into C.4″. This latter feature, also observed in F 4.5 during event 2, and the combination of apparent normal and reverse faulting are interpreted as resulting from local transpression, which might be occurring in particular fault bends (Fig. 7A).

In the Laguna east trench W-wall, fault F 4.1 cuts through the top of C.5 with 29 cm of apparent dip displacement, and displaces the basal part of C.4, but not the upper part. At a close view fault F 4.1 shows 29 cm of apparent dip displacement, but the surface envelope of C.5 does not show vertical offset. A plausible explanation for this inconsistency is the obliteration of the vertical component of slip by erosion along the slope; thus, the contact between C.5 and C.4 might be an erosive boundary, implying a leveling of the paleosurface of the upthrown and downthrown blocks on both sides of F 4.1. Fault zone 5 presents open fractures affecting the lacustrine deposits FL. 2 and FL. 3. These fractures are filled with material from the paleosol S.2. Fault zone 5 also causes discrete displacements of these units (Fig. 7D; Table 2). At fault zone 6, a fold with associated faulting affects FL. 2 and FL. 3 and is sealed by paleosol S.2. Nearly 12 cm of apparent dip displacement (down to the south) is inferred in relation to the fold accommodation. This value is derived from 13 cm of reverse faulting at F 6.1, resulting from the 20 cm of down-to-the-south minimum displacement of FL. 2 minus 7 cm added by event 3, and 25 cm of normal faulting at F 6.2, which is the sum of 19 and 6 cm dip slip affecting the FL. 2-F. 1 contact. The total amount of displacement recorded in this event is 37 cm down to the north. This event occurred during the deposition of unit C.4′ (between C.3 and the base of C.4″), as shown in the Laguna west trench. At Laguna east, the event is constrained by FL. 2 and S.2; it should have occurred right before or during the formation of paleosol S.2. Because S.2 is filling some fresh fractures but it is not affected by the folds and faults, we infer that it could be already present at the surface as an unconfined cover when the earthquake occurred. So, a preferred age for this event is that of paleosol S.2 at 2134–1891 B.C.

**Event 5**

An older event is inferred to be recorded in both trenches. The main evidence for this is derived from the geometry of the basal part of unit C.4. In the Laguna west trench, the C.4″ unit is only observed in the downthrown block of fault F 2, which suggests that a topographic scarp had been formed prior the deposition of this unit. In the Laguna east W-wall, the thickness of C.4 unit increases abruptly on top of F 4.3, which likely results from the filling of a topographic relief controlled by the fault activity. Evidence of displacement in this fault zone also comes from the fault striations preserved in a clast located along F 4.1. The striations have a pitch of 86°E on a clast side oriented N92°E, parallel to the fault zone (Figs. 7A, 7D, and 8C). In F 2, the faults are not coincident with the paleoscarp, but are separated more than 2 m (F 2). This feature could be related to the scarp retreating linked to the erosive processes controlling the slope dynamics. There is evidence suggesting that this is a multiple event. On the one hand, the exceptionally large displacements observed (compared to the displacement estimated for the posterior events) are more easily explained by the sum of at least two consecutive events; the step on the paleosurface sealed by C.4 near F 2 implies a downthrown offset of 85 cm, 20 cm of which are attributable to younger events. This yields 65 cm of dip displacement for the event 5 in F 2 (Laguna west E-wall; Fig. 7A).

Fault F 4.3 apparently displaced the top of C.6 by 21 cm (Laguna east W-wall; Fig. 7B). On the other hand, the large scarp retreat observed in fault F 2 (more than 2 m and only observed in this event) implies a large time lapse before deposition of C.4, allowing erosion to act. The age of this event is constrained by the deposition of colluvium units C.4 and C.5. As with event 4, paleosol S.2 is the only age bracket (upper boundary) for this possibly multiple-phase event, i.e., 2134–1891 B.C.

**Striation Data and Net Slip Rate**

Slickenlines observed in the striated pebbles located along different fault planes and in fault zone F 4.1 indicate that the slip in this fault zone is essentially dip slip. These striations have pitches between 50° and 86°E in planes oriented N90°–110°E, which indicates a main north-northeast–south-southwest extension with a small dextral component. These data suggest that a local variation of the stress is being reflected in the most recent Bath events, or that small rotation of the axis of extension with respect to the Pleistocene northwest extension could have taken place in the late Holocene.

Another relevant structural observation refers to the varying total slip in the faults exposed in the trenches. Several faults show a throw opposite to the main fault, i.e., down to the south instead of down to the north. As a result, the summed slip in one of the events (event 3) results in 10 cm of throw toward the south (Table 2). It is likely that the faults with down-to-the-south throw are antithetic. For this event we suspect that some other fault not exposed in the trenches, such as the southermost branch of the splay, must be accommodating a larger throw to north. Alternatively, the anomalous displacement could be due to the system acting as a secondary structure related to an earthquake in a major neighboring fault. Transient and local variations of the stress regime produced by stress transfer after major earthquakes (e.g., Quigley et al., 2012) could also be evoked as an explanation of the reverse total throw.

In order to calculate the total amount of net displacement through the studied fault we considered an average 85°E pitch for the main faults. This is the average pitch observed in fault zone 4, and in a striated pebble contained in it. The accumulated total vertical displacement calculated is 118 cm. This displacement initiated since the older colluvial unit (C.5) was formed. As we do not have an age for this colluvial unit, we estimated the maximum slip rate by considering the time span since the time of deposition of the paleosol S.2 (2134–1891 B.C.) until present (A.D. 1950), which gives a maximum vertical slip rate of 0.29–0.30 mm/yr. This value should be considered a maximum, since the age of the marker considered is older than paleosol S.2. A rough estimate of the minimum vertical slip rate could be obtained by consid-
Figure 9. South-north ground-penetrating radar (GPR) Ruedo profiles using the 900 MHz antenna and a time window of 100 ns. Vertical scale corresponds to depth with an estimated velocity of propagation of 11.34 cm/ns. Locations of profiles are indicated in Figure 5B. HFB—Hill Fault Branch; LFB—Lake Fault Branch. Lengths are variable. (A) Ruedo 1, 35 m. (B) Ruedo 2, 37.5 m. (C) Ruedo 3, 32 m. (D) Ruedo 4, 25 m. Ruedo 2 shows the logs of the analyzed sequences in column 9 and column 43 (out of the profile). (Columns are described in Figs. 7D and 7E.) The records of fault branches are indicated. Note vertical displacements in Ruedo 3 profile. An overall displacement of the ignimbrite unit can be estimated as more than 60 cm.
Figure 10. Detailed stratigraphic and structural analysis of the Ruedo 2 ground-penetrating radar (GPR) profile. Stratigraphic logs include the variation of grain size distribution with depth. Column 43 log is located out of the profile. Column 9 log shows a sequence of massive ashes with some weathered joints, with increasing clay content toward the top, which has been well recorded in the GPR profile. Column 43 log shows a mainly silty sequence of fluvial deposits overlying the gray ignimbrite; local variations of sand and clay contents permitted to record the stratigraphic contacts and to estimate the propagation velocity of electromagnetic waves. The fault branch radar signature is enhanced by the lack of continuity of the identified layers.
ering that the age of this older colluvial unit should not be more than 2000 yr, the age of the paleosol S.2. Such a long time span is sufficient for a soil to form in a setting such as middle-late Holocene central Mexico, and also enough to ensure that there has not been a critical change in the environmental or depositional conditions of the site. Accordingly, the time span since 4134–3891 B.C. leads to a minimum vertical slip rate of 0.19–0.20 mm/yr. We can estimate the net slip rate of this fault branch by calculating the net slip corresponding to a 60° dipping fault with an 85° pitch, which results in 141 cm. Such a net slip accumulated along the same time spans gives a maximum net slip rate of 0.34–0.37 mm/yr and a minimum net slip rate of 0.23–0.24 mm/yr. These values of slip rate must be taken as approximate values because they are based on the deformation observed in only two fault branches and accumulated during the most recent 4–5 seismic events.

GPR SURVEY AT LAGUNA BAÑÍ SITE

Before trenching, the subsurface GPR prospecting along four profiles provided a more precise location of the faults (Figs. 5B and 9). After trenching, the GPR results were improved with a detailed stratigraphic analysis in order to identify the deformation of a transect parallel to the trench, the Ruedo 2 profile, located <10 m to the east (Fig. 10) (For the GPR survey data and methods, see Appendix.) Figure 4 shows the location of the collected GPR profiles. During prospecting, a major vertical discontinuity interpreted as the main fault plane (LFBS) was clearly recorded in the Ruedo 3 profile (Fig. 5B). Similar discontinuities observed several meters north of the main fault plane were recognized in the Ruedo 2 profile and were interpreted as secondary faults or fractures (Fig. 10). The main fault plane is clearly identified below the slope inflection in the topographic profile.

After trenching, stratigraphic units were sampled in order to measure physical and mechanical properties. Samples (2–3 kg) were taken every 30 cm along 2 vertical profiles in the Laguna east trench (Figs. 4 and 7E). These properties (Table 3) allowed us to assign a value of permittivity to the GPR profiles. The contrast in physical properties helped in the identification of possible reflectors. Original profiles were filtered after comparison with the features observed in the Laguna east (near the Ruedo 2 profile) and Laguna west trenches (directly below the Ruedo 1 profile). The Ruedo 3 profile was interpreted by interpolation of the data from the trenches and the field observations. An improved interpretation of the profiles (Fig. 10; discussed in the following) resulted from the comparison between GPR reflections and the materials described in trenches.

**Interpretation of the Deformation Based on the Comparison of GPR Profiles and Trench Logs**

There is good agreement among radar signatures, coherent reflectors, and layers (sedimentary and volcanic) affected by faulting at the western termination of the Pastores fault. The layers show variations of grain size and compaction. Electrical contrast between the interlayered silty sand and ignimbrite allowed recording of coherent reflectors in GPR profiles. The fault branches were observed in the GPR profiles and the results can be compared directly with the Laguna east trench. The physical property analyses show a good correlation with the observed stratigraphy and the recorded radar signatures. Once calibrated with the stratigraphy, textures and structures were recognized in radargrams, allowing a better differentiation of units along the profile. Figure 9 shows four GPR profiles and Figure 10 is the interpretation of the GPR reflections of the Ruedo 2 profile. GPR profiles show a distribution of reflections similar to the stratigraphy observed at the trenches; that is, layers slightly dipping to the north in the footwall, interrupted reflectors in the zone of faulting, and subhorizontal reflectors in the hanging wall. Heterogeneity of the radar signature is observed in correspondence with the presence of fractures and possibly the presence of infiltrated water and/or higher clay content. The southern part of the profile is characterized by prominent reflectors related to pyroclastic deposits or high compaction of sediments. GPR profiles also show evidence of what is interpreted as fault slip and fracturing in the hanging wall, suggesting that the deformation affects a wider zone than just fault zones 1–4 (corresponding to topographic scarp), in agreement with the interpretation of a fault splay in this area.

Results show that the GPR technique can yield good results with which to characterize deformation in wide fault zones; the technique allows us to extrapolate the observations obtained in trenches in order to identify displacements in neighboring fault transects. The interpretation of the Ruedo 3 profile (Figs. 5B and 7E) was of particular importance to identify changes in the fault geometry with respect to the Ruedo 2 profile. In this profile, the LFB-4 (fault zone 4) and the LFB-5 (fault zone 5) were recorded. Although this profile is not coincident with any trench (it is a horizontal distance of ~30 m from the east trench), it can be assumed that the main horizontal reflector corresponds to the well-consolidated Bañí ignimbrite (I.1–I.3), showing a high physical contrast with the overlying colluvial deposits. Some of the vertical displacements recorded on this unit do not correspond with topographic variations that are mainly associated with the deformation of colluvial deposits. An overall vertical displacement of the Bañí ignimbrite can be estimated to be >60 cm; 30 cm of this account for displacement by fault zone 4 in two steps at 2.5 and 4 m from the beginning of the profile, and the other 30 cm account for displacement of the fault zone 5 at a distance of 17 m from the beginning of the profile. At a distance of 30 m, another displacement of >20 cm corresponds to a fault branch that was not mapped in surface or in the trenches, but was recorded in the GPR profile.

**DISCUSSION**

WPF Seismogenic Activity

The lack of simultaneous activity among the fault branches studied and the absence of a characteristic slip have major implications on the
fault behavior of the WPF. The analysis of the overall data suggests that not all fault branches exposed in the trenches are active in each of the seismic events. For example, in the Laguna east W-wall, F 4.3 was not active after event 3 and F 4.1 does not show deformation after event 4; in the Laguna west, F 1 and F 2 were not active during events 1 and 2; this highlights the need to perform multi-trench analysis and to compare different fault chronologies when studying complex fault systems such as the Pastores fault. In this study, only the two of the three branches of the northern WPF were surveyed (Figs. 5A, 5B). Although the paleo-earthquake chronology might be well represented in only those two branches, this issue should be considered when analyzing the paleoseismic history of the complete WPF.

Another relevant observation concerning the seismic behavior of the faults studied is that it does not follow a characteristic slip pattern and that the deformation observed in a single fault branch varies highly from one event to another (Table 2). The noncharacteristic slip has been observed in many fault systems worldwide. The highly variable slip along the Gowk fault zone in two consecutive earthquakes in 1981 and 1998 is an example of observed noncharacteristic slip in observed fault ruptures (Berberian et al., 2001). Other examples of this behavior have been reported in paleoseismological studies in several zones such as the San Andreas fault (e.g., Rockwell and Meltzner, 2008), faults in New Zealand (e.g., Berryman and Beanland, 1991), or faults in Japan (e.g., Maruyama et al., 2001). In the case of the Bañí site, two plausible explanations can account for this variability. On the one hand, some of the movements observed might be secondary faulting related to earthquakes produced in neighboring faults. In the most recent morphogenic seismic event, the 1912 Acambay earthquake, it is possible that the fault zone moved by seismic triggering. This could also be happening in each or at least some of the earthquakes produced by the Venta de Bravo fault, located only 2.5 km to the south. On the other hand, even if the ruptures are primary, the fault zone might undergo variable patterns of displacement as a consequence of the rupture of different fault fragments along the trace or in depth.

It is interesting to note that transfer fault zones are commonly considered as the end of seismicogenic segments when defining individual seismic sources. However, even if the faults are not linked at the surface, they might be connected at depth and preserve an unlinked geometry on the surface over long time spans (Soliva et al., 2008). The connection at depth of the Pastores and the Venta de Bravo fault needs to be explored in order to properly evaluate the seismogenic activity recorded at the Bañí site. This hypothetical connection at depth would imply that both faults are part of a single fault system that could reach 80 km in length. The maximum expected seismic magnitude in this area would increase significantly if such a long fault is not segmented. Further research, such as obtaining subsurface data by means of seismic lines or magnetotelluric prospecting, would be helpful.

**Paleo-Earthquake Chronology and Paleoseismic Parameters**

In order to evaluate the paleo-earthquake chronology recorded at the Bañí site, we contemplate four possible models or combinations of the dating results (Fig. 11). Model A considers that the ignimbrite was deposited more recently, between 753 and 406 B.C., by giving as correct the age of sample C19 and taking as reworked sample C05. Model B implies that the ignimbrite was deposited long before, between 2134 and 1512 B.C. In this case, sample C19 is considered as rejuvenated, possibly by humic acid interaction during the edaphic processes. Two variants of models A and B are proposed by considering that (1) the opening of fracture F 4.3 is contemporaneous with the sample dated in the fracture infill (C3, 990–1155 B.C.) and (2) that the fracture opened during the Acambay earthquake (12 November 1912). The paleo-earthquake chronologies proposed are poorly constrained mainly due to the limited number of 14C samples and the fact that these are concentrated in the ignimbrite and some of them have not been considered representative of the unit in which they are found (Table 1).

Although all these chronologies are feasible, we prefer model A.2 (recent ignimbrite and coseismic features during the 1912 Acambay earthquake) as the most probable: it is more likely that the deposition of the ignimbrite had eroded one part of the geological record (that formed after paleosol S.2 representing ~1 k.y.) than the opposite option, in which the processes postdating the ignimbrite (edaphification and deposition of fluvial-lacustrine materials) would have taken place for ~2.5 k.y. However, we consider that the opening of fracture F 4.3 affects the uppermost layers, so it probably occurred during the past few centuries. The local testimony of drainage alterations in the area during the Acambay earthquake reinforces this option. Considering model A.2 and taking as a single seismic event (or crisis) the two earthquakes before and after the ignimbrite, we obtain a time span between consecutive earthquakes that ranges between 1.1 and 2.6 k.y., giving an averaged recurrence time of 1.85 k.y. This time span is much smaller than the one obtained for the Acambay fault (~3.6 k.y., Langridge et al., 2000) and the WPF eastern tip (10–15 k.y.; Langridge et al., 2013).

With respect to the Acambay fault, the WPF average recurrence obtained here could be smaller because the slip rate of the WPF fault is greater, but it could also be explained due to the alternating activity of the WPF as a primary and secondary fault. In regard to the eastern tip of the WPF, we consider that the fault chronology provided by Langridge et al. (2013) is not necessarily the complete chronology of the WPF. According to Langridge et al. (2013), the lack of evidence of fractures that could be related to the 1912 event suggests that the Pastores fault did not move during this earthquake, and that the map of Urbina and Camacho (1913) included the trace of this fault due to a misinterpretation of the earthquake effects. Because the Langridge et al. (2013) paleoseismological study was of a branch of the fault located in the middle of the slope (Fig. 3), we think it is likely that such a branch was not active during some of the events on this fault; this also explains the relative large recurrence period obtained at that site. Urbina and Camacho (1913) did not provide numerical estimations of the coseismic displacement of the Pastores fault, but the offsets are comparable to other ruptures produced by the earthquake, in this case the uplifted block to the south. The possible activation of the WPF as a secondary fault or its activation by eventual volcanic eruptions is another obstacle to establish a recurrence time for the WPF, but it could also be taken as the opportunity to have a complete record of the morphogenetic (M ≥ 5) earthquakes affecting the area. That is, the time span between successive earthquakes will not tell as much about the recurrence period of the Pastores fault as about the recurrence period of a damaging earthquake at a given point. This consideration is important when taking into account recurrence uncertainties in a risk analysis that considers all possible seismogenic sources affecting a site (Zúñiga et al., 2011).

**Simultaneous Activity of the Pastores and Acambay Faults**

Faulting along a complex fault zone involving neighboring faults and fault segments has been shown to be common in different tectonic settings, especially those occurring at extensional or transtensional regimes (e.g., Beanland et al., 1989; Berryman et al., 2008; Hauksson et al., 2011; Fletcher et al., 2014). In the Acambay graben, and according to the descriptions of Urbina...
and Camacho (1913), multiple faults ruptured during the Acambay earthquake. Comparing the paleo-earthquake chronologies of neighboring faults might help us to evaluate the probability of simultaneous ruptures (e.g., Berryman et al., 2008; Ortuño et al., 2012a). The precision of the dating results is a condition for comparing and identifying common earthquakes in different sites, based on the age of the events. In this study, the paleo-earthquake chronology only allows us to consider that the simultaneous fault rupture of the Acambay and the WPF is feasible based on the dating results, but does not allow us to infer it unequivocally.

We compared the data obtained here with the available neighboring fault chronologies, the Acambay and Pastores faults (Fig. 12). Langridge et al. (2000) identified a minimum of four Holocene paleo-earthquakes recorded along the Acambay fault. In the eastern tip of the WPF at Manto del Rio site, Langridge et al. (2013) recognized at least 3 paleo-earthquakes that occurred in the past 31.5–41.0 cal. ka B.P., the most recent between 12.2 and 12.6 cal. ka B.P. The paleoseismic events identified at the Laguna Bañí site (western tip of WPF) only reflect the most recent history of faulting in the area, i.e., the past 5–6 ka B.P., and thus can only be compared with the paleoseismic data at the Acambay fault. The five events identified at Bañí site occurred after 2134–1891 B.C. The chronology proposed in model B.1 leads us to consider that all the identified paleo-earthquakes could correspond to events on the Acambay fault; event 1 could be the secondary effect during the 1912 earthquake; events 2, 3, and 4 could be correlative of event 2 on the Acambay fault; multiple-event 5 could be event 3 on the Acambay fault. In contrast, model A.1 implies that event 2 is not contemporaneous with any event recorded in the Acambay fault. The close interaction between the ignimbrite deposition and the activity at the western tip of the WPF, as evidenced by stratigraphic relationships, can also be extrapolated to the Acambay fault, which could have influenced the formation of the Bañí ignimbrite if model B.1 is correct; i.e., Bañí ignimbrite emplacement could have been
The dating results and displacements observed at the trenches indicate minimum estimates for the WPF slip rates in the range of 0.23–0.37 mm/yr for the past ~6–4 k.y. These values for slip rates are much larger than the values obtained by Langridge et al. (2000) for the Acambay fault, estimated as 0.17 mm/yr, and are greater than the 0.17–0.18 mm/yr maximum vertical slip rates for the Quaternary faults in the central TMVB estimated by Suter et al. (2001). Other slip rates obtained for the Pastores fault are 0.03 mm/yr since ~10 k.y., ago, given by Langridge et al. (2013) for the eastern tip of the WPF, and 0.04 mm/yr since ~400 k.y. ago, given by Suter et al. (1995) for the western tip of the eastern Pastores fault. In our opinion, both estimated slip rates should be considered as minimum values; the former, 0.03 mm/yr, considers only a branch of this fault located at the middle of the WPF scarp; the latter, 0.04 mm/yr, is a rough estimate because, according to Suter et al. (1995), the slip considered is not clear. One should be cautious when comparing slip rates at paleoseismological sites with geological slip rates. Most of the published slip rates of the central TMVB are calculated considering early to middle Pleistocene volcanic markers and minimum throws, because they are based on the height of the topographic scarp but do not consider that the marker might be at a much lower position in the downthrown block, covered by most recent deposits. For example, in the Bañí transect a geological slip rate of 0.02 mm/yr was obtained using 85 m of scarp height accumulated in 3.5 m.y., which is the probable age of the lavas located to the south-southwest, based on comparison with the similar intra-caldera domes in the Amealco caldera and the Puruagua range (Fig. 3; Aguirre-Díaz, 1996).

Other Paleoseismic Parameters

In addition to the paleo-earthquake chronology, other paleoseismic data such as slip per event, event rate, and maximum expected magnitudes are commonly incorporated in the calculations of seismic hazard. The maximum vertical slip per event experience at the Laguna Bañí ranges between 29 cm (event 2) and 37 cm (event 4, Table 2). Summed slip in event 3 has been considered anomalous for being reverse slip. The net slip per event is expected to be slightly greater. For a 60° average dip and 85° pitch, this would range between 35 cm and 44 cm. These values should be taken as minimum for the Pastores fault because (1) they refer to the tip of the fault, and (2) they do not reflect the slip accommodated in other fault branches along the same transect. These values of slip are in agreement with the displacements observed in the other paleoseismological sites within the region, such as the Manto del Rio site at the WPF eastern end (~50–30 cm; Langridge et al., 2013), and the Huapango basin sites at the Acambay fault eastern end (~35 cm; Langridge et al., 2000). All these sites are located at the tip of fault systems. If considered as representative of a minimum estimate of the average displacement, the 35–44 cm slip per event in Bañí site can be related to minimum Mw, 5.8 and 5.9, according to the Wells and Coppersmith (1994) relationships for normal faults. We recommend taking these values as rough estimations, being aware that the empirical relationships used have been questioned recently (Stirling et al., 2002, 2013).

Another approach to the maximum expected magnitude takes into account the WPF total length, 20.4 km. Using the Wesnousky (2008) scaling relationships recommended by Stirling et al. (2013) for normal faults within settings of crust thicker than 10 km, the Mw is 6.7. The crustal thickness in the region is likely to range between 12 and 20 km, based on the highest densities, and the highest seismicity of hypocentral depths, for seismic events at those depths recorded by the Mexican Seismological Survey.

Figure 12. Compared paleo-earthquake chronologies of the Pastores fault and the Acambay-Tixmadejé fault (E—event). For the Pastores fault, the chronology of paleoseismic events recorded at Manto del Rio site, at the eastern tip of the western segment of the Pastores fault (WPF), is from Langridge et al. (2013). For the Acambay-Tixmadejé fault, the synthetic paleo-earthquake history is from the combination of four paleoseismological sites studied by Langridge et al. (2000).

<table>
<thead>
<tr>
<th>Event</th>
<th>Age (cal. ka B.C.)</th>
<th>Model A.1</th>
<th>Model B.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ev1</td>
<td>12,600–12,200 yrs BP</td>
<td>A.D. 1912</td>
<td>A.D. 1912</td>
</tr>
<tr>
<td>Ev3</td>
<td>10,230–2,603 yrs BP</td>
<td>A.D. 1919</td>
<td>A.D. 1919</td>
</tr>
<tr>
<td>Ev4</td>
<td>4084–3841 yrs BP</td>
<td>A.D. 1919</td>
<td>A.D. 1919</td>
</tr>
<tr>
<td>Ev5</td>
<td>multiple events prior to Ev4</td>
<td>A.D. 1919</td>
<td>A.D. 1919</td>
</tr>
</tbody>
</table>

syntectonic with faulting along the Acambay fault. The correlation between ignimbrites and extensional faults has been observed in older ignimbrites of Mexico related to Basin and Range faulting (Aguirre-Díaz and Labarthe-Hernández, 2003; Aguirre-Díaz et al., 2008). In model A.1, the Bañí ignimbrite would not be related to any paleoseismic event recorded in the Acambay fault; alternatively, it could have been influenced by the major neighboring Venta de Bravo fault, or simply associated with the Pastores fault rupturing.

In addition to the paleo-earthquake chronology, other paleoseismic data such as slip per event, event rate, and maximum expected magnitudes are commonly incorporated in the calculations of seismic hazard. The maximum vertical slip per event experience at the Laguna Bañí ranges between 29 cm (event 2) and 37 cm (event 4, Table 2). Summed slip in event 3 has been considered anomalous for being reverse slip. The net slip per event is expected to be slightly greater. For a 60° average dip and 85° pitch, this would range between 35 cm and 44 cm. These values should be taken as minimum for the Pastores fault because (1) they refer to the tip of the fault, and (2) they do not reflect the slip accommodated in other fault branches along the same transect. These values of slip are in agreement with the displacements observed in the other paleoseismological sites within the region, such as the Manto del Rio site at the WPF eastern end (50–30 cm; Langridge et al., 2013), and the Huapango basin sites at the Acambay fault eastern end (~35 cm; Langridge et al., 2000). All these sites are located at the tip of fault systems. If considered as representative of a minimum estimate of the average displacement, the 35–44 cm slip per event in Bañí site can be related to minimum Mw, 5.8 and 5.9, according to the Wells and Coppersmith (1994) relationships for normal faults. We recommend taking these values as rough estimations, being aware that the empirical relationships used have been questioned recently (Stirling et al., 2002, 2013).

Another approach to the maximum expected magnitude takes into account the WPF total length, 20.4 km. Using the Wesnousky (2008) scaling relationships recommended by Stirling et al. (2013) for normal faults within settings of crust thicker than 10 km, the Mw is 6.7. The crustal thickness in the region is likely to range between 12 and 20 km, based on the highest densities, and the highest seismicity of hypocentral depths, for seismic events at those depths recorded by the Mexican Seismological Survey.
be more relevant than the geologic rates for seismic hazard calculations. Could the WPF Holocene slip rate be larger than the geologic slip rate, thus indicating a late Quaternary acceleration of the fault rate? Is the WPF westernmost tip moving faster as a consequence of the linking at depth of the Pastores and Venta de Bravo faults, which would make this site a middle, rather than a marginal, fault segment? These questions are unresolved and could lead to future research.

**Paleo-Earthquake Chronology and Volcanic Activity**

Two age results were obtained for Bañí ignimbrite, 753–406 B.C. (the preferred age) and 2196–1512 B.C. Even if considering both dates, the recent age of the Bañí ignimbrite obtained in this study contrasts with all the former ages for late Quaternary volcanic deposits from the Acambay graben, with the exception of two other ignimbrites (Ortuño et al., 2011; Aguirre-Díaz et al., 2012; Lacan et al., 2013) and a tephra deposit (Langridge et al., 2013), all exposed in nearby paleoseismological trenches (Fig. 3). The trench exposures indicate that one of the seismic events occurred just prior to the ignimbrite emplacement (event 3) and one right after it (event 2). This suggests that seismic event 2 was likely triggered by volcanic activity and/or that seismic event 3 triggered the pyroclastic flow. Similar relationships between pyroclastic flow eruptions and extensional tectonics have been reported in ignimbrites of the mid-Tertiary Sierra Madre Occidental of Mexico (Aguirre-Díaz and Labarthe-Hernández, 2003; Aguirre-Díaz et al., 2008). The interaction between volcanic and tectonic activity has been detected and analyzed in different geodynamic scenarios worldwide (e.g., Gottsmann et al., 2009; Petrovich et al., 2010; Villamor et al., 2011). In the Laguna Bañí, the interaction between the ignimbrite emplacement and the fault activity might be the reflection of seismogenic activity caused by a change in local stress field as a result of volcanic activity, therefore implying subsurface magmatic processes, probably related to activity of the nearby Altamirano stratovolcano (Fig. 3). This could explain the short time span between events 2 and 3. In addition, the occurrence of event 3 could have caused a change in the magma chamber stress conditions leading to the ignimbrite-forming eruption. An alternative scenario can be envisaged, considering that no subsurface volcanic changes are needed to occur immediately before the formation of the ignimbrite, but only the previous generation of a surface dome, the explosive eruption of which is triggered by seismic amplification.

To discern the different possible scenarios, more regional data on the temporal and spatial relationship between volcanism and seismic activity are needed, as well as a better knowledge of the source and emplacement mechanisms of the Bañí ignimbrite. The volcanic-tectonic interaction within the Acambay graben is a promising and unexplored research field that has had a great impact in the evaluation of the seismic recurrence interval determined from paleoseismological studies in the region. In addition, the volcanic hazard in this part of the TMVB, which is currently considered to be very low, should be reevaluated and revised (Aguirre-Díaz et al., 2012, 2013).

**CONCLUSIONS**

The following conclusions can be drawn from the study presented here.

1. The geomorphological and structural study combined with geologic mapping allowed us to redefine the surface trace of the WPF, which has a total 20.4 km length and a west-ernmost tip composed of two fault branches. Two paleoseismic trenches were excavated in the northernmost branch of this tip, where the fault movement has generated a sag pond, where Laguna Bañí was formed. GPR prospecting of the area combined with the detailed study of the sequences led us to the location of the subsurface faults before trenching and the estimation of the average vertical displacements in the two recorded fault branches (LFFZ-4 and LFFZ-5, Fig. 9). After the excavation, characterization of samples improved radar processing as the variations of physical properties of several reflectors permitted the identification of offsets that increase to the east in stratigraphic markers along non-trenched sections. High physical contrasts between the prospected sequences, such as variations in grain-size distribution or between colluvial and well-consolidated pyroclastic deposits, are very helpful for improved assessment of local slip rates.

2. The stratigraphic and structural analysis of the sequence at the Laguna Bañí site led us to identify a colluvial-volcanic and fluviolacustrine sequence affected by complex faulting that implies discrete displacements in synthetic and antithetic faults oriented approximately east-west. We confirm late Holocene volcanic activity within the Acambay graben, indicating the need for a reevaluation of the local volcanic hazard.

3. The Bañí sequence records at least five paleo-earthquakes. Event 1 occurred after A.D. 990–1155, probably during the 1912 Acambay earthquake. Event 2 occurred during the time span (preferred by our data) 753–406 B.C. Events 3 and 4 occurred shortly after and before, respectively, the emplacement of an ignimbrite, the age of which is bracketed by the dates 2134 B.C. and 1512 B.C. Event 5 (a multiple event) occurred at some undetermined time before the ignimbrite emplacement.

4. Different fault zones within the WPF were activated at each of the paleo-earthquakes identified. This and the highly variable slip per event observed suggest that the northern WPF could move occasionally as a secondary fault of major neighboring structures such as the Acambay and Venta de Bravo faults. This idea is supported by the anomalously small time span between the successive events (1.1–2.6 k.y.).

5. The study site shows that neighboring volcanic activity is likely to have been a triggering factor and/or a consequence of the seismogenic activity. The time association of volcanic and tectonic events indicates that such interaction must be taken into account when obtaining recurrence periods from the paleoseismological record, and indicates the need for an integrated database of volcanic and paleoseismic data for this region.

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**APPENDIX. DATA, METHODS, AND DATING RESULTS**

**Geological and Geomorphological Mapping**

Detailed geological and geomorphological mapping were used to define the active trace of the Pastores fault and to choose the sites suitable for the paleoseismological study. To characterize the Quaternary activity, three sites along the fault trace were selected; sites A and B were chosen because of the recent exposure of the fault due to erosion and human activity, respectively. Site C was considered suitable for paleoseismological trenching mainly because the fault is sealed by Holocene sediments. This work was done by (1) photo interpretation of aerial photos (1:25,000 and 1:37,000 scales; provided by Instituto Nacional de Estadística y Geografía de México, INEGI); (2) analysis of topography using 1:50,000 scale vectorial topographic maps of INEGI and digital elevation models obtained from them; and (3) field reconnaissance and geological characterization of localities selected by the previous steps.
A simplified geologic map of the Acambaro graben (Fig. 3) includes the main lithostratigraphic units of the area as well as the principal volcanoes and faults. This map was a working map (Aguirre-Díaz, 1996; Aguirre-Díaz and McDowell, 2000; Aguirre-Díaz et al., 2000).

Subsurface Exploration by Ground-Penetrating Radar

Ground-penetrating radar (GPR) provides geophysical profiles of electromagnetic waves transmitted in the medium to estimate the physical properties of the surface and the geometry of stratigraphic discontinuities (Davis and Annan, 1989). By analyzing coherent reflectors and distinctive patterns between the reflectors (i.e., radar signature or radar facets) that are recorded in a profile, we can interpret soil stratigraphy and sedimentary and volcanic sequences, and identify faults and other deformational structures (Guha et al., 2005; Van Dam and Schlager, 2000; Carreón-Freyre et al., 2003; Cunningham, 2004; Comas et al., 2005; Carreón-Freyre and Cerca, 2006). The penetration depth of GPR pulses through the geological environment is more effective in media with low dielectric losses (using characteristic frequencies between 10 and 2000 MHz), in which the water content related to high electrical contrast has a greater influence (Ohtsubo et al., 1983; Saaenket, 1998).

Prospecting with GPR is especially useful for the location of faults that displace shallow markers when direct field observations are not possible. That is why in recent decades, the GPR has been applied successfully prior to trenching surveys to detect buried faults in paleoseismic studies (e.g., Mghraoui et al., 2000; Anderson et al., 2003; Ferry et al., 2004; McClymont et al., 2010; Carbonel et al., 2013).

In the site C, 4 GPR profiles (Ruedo 1–4; Fig. 5) were obtained using a Geophysical Survey Systems, Inc. (GSSI) model SIR-20 radar unit. Profiles were obtained using an antenna with a 900 MHz frequency equipped with a tachometer calibrated to collect 40 traces per meter. The time windows of 100 ns allow detailed analysis of the uppermost 3 m from the surface. The in situ profiles allowed us to locate the main trace of the Pastores fault and other secondary faults or fractures (see location of the recorded branches in Fig. 5B). The profile processing was performed using the software RADAN 6.6 (GSSI). The first step was a correction to remove high-amplitude reflections related to the direct and surface waves, followed by the removal of background noise and the application of a spatial filter (finite impulse response, FIR, filter) to eliminate the noise associated with the high and low frequency noise. The next step was a topographic correction carried out on each of the profiles. Topography was obtained by means of an optical theodolite with errors of ±1 cm. The incorporation of the mechanical properties of materials, as measured in the laboratory, enabled a significant improvement in the recognition of discontinuities related to faults and fractures.

Trench and Laboratory Analysis

The trenching approach is the technique most widely used for paleoseismological data collection (e.g., McCalpin, 2009), allowing observation of the most recent geological record affected by a fault at sites with very low or no erosion, i.e., in areas of sediment accumulation. For this study, 2 trenches 2.5 m wide and 3 m deep were excavated parallel to each other; the lengths were 47 m (Laguna east) and 14 m (Laguna west; Fig. 5B). We used a grid of 1 m × 0.5 m along the trench walls for logging purposes. The structural and stratigraphic details were drawn on graph paper and compared to rectified photomosaics. In order to determine the age of the seismic events identified, 25 samples of charcoal were collected for 14C dating (both conventional and accelerator mass spectrometry) in the laboratories of the University of Arizona and at Beta Analytic Inc. Of these, only 1 sample had a sufficient content of carbon after treatment (see results in Table 1). Samples were also taken for diatom content analysis, but their contents were insufficient.

The physical properties analyses of the rock and sediment material sampled (12 samples at 12 different levels) were carried out in the Laboratory of Mechanics of Geosystems at the Centro de Geociencias, Universidad Nacional Autónoma de México, and included grain size, density, and bulk density of solids (Table 2). The grain size was determined from sieving analysis and by the hydrometer technique for the fines fraction (American Society for Testing and Materials, 2007, 2009; ASTM D422-63, ASTM D6913-09). The specific gravity of the solid particles was determined by the pycnometer method (ASTM, 2010a; D854-10), and the Atterberg Limits (liquid limit, plastic limit, and index of plasticity) were determined according to ASTM (2010b) D4318-10, which allowed the characterization of the type of soil material according to the United Soils Classification System (ASTM, 2011; D2487-11). The analyzed materials were classified as low-plasticity silt with vertical variations of clay and sand content that can be related to the variations of fluvial deposits or weathering within the volcanic deposits.

Dating Results

Seven samples suitable for 14C dating were gathered in the Laguna west trench and only one in the Laguna east. The results of the dating are in Table 1. The basal colluvial units are not well constrained. The oldest unit that has been dated is the paleosol (S2) under the Btuñ ignimbrite, which yields an age of 2134–1891 B.C. (sample C11). Thus, colluvial units C5 and C4 should be older than this age. The best age constraint available for the Btuñ ignimbrite is the age of charcoal samples found within it. Four samples were found at different depths in the ignimbrite; we believe that two of the samples (C6 and C8) have been affected by rejuvination due to leaching related to humic acids involved in the edaphic processes that affected the unit. The high degree of weathering in the uppermost 30 cm of the ignimbrite and at several areas along the unit leads us to suspect that bleaching is plausible. The two coal samples considered as valid dates are sample C19, with an age of 753–406 B.C. and sample C5, with an age of 2196–1512 B.C. We prefer sample C19 as the most probable representative age of the ignimbrite, because sample C5 is very close to the basal contact of the ignimbrite with the paleosol, and therefore could be reworked material either dragged by the volcanic flux or introduced through bioturbation.

REFERENCES CITED


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