Preliminary paleoseismic results from the Pastores fault and its role in the seismic hazard of the Acambay graben, Trans-Mexican Volcanic Belt, Mexico

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ABSTRACT

Shallow, crustal normal faulting earthquakes represent a significant seismic risk to the local towns and regional cities of central Mexico. Within the Acambay graben, the Pastores fault is a ca. 33 km long active, east-west striking, north-dipping normal fault. Two paleoseismic trenches were excavated at the Manto del Río site to estimate preliminary active fault and seismic hazard parameters. Both trenches showed evidence for at least two latest Pleistocene to Holocene paleo-earthquake ruptures, constrained by radiocarbon dates from the West trench and through correlation of pyroclastic units between the trenches. The oldest faulting event (Event III) is bracketed within the interval ca. 31.5–41.0 cal kyr BP. Units higher in the trench are less displaced and provide evidence for at least one younger event. Rupture event II is bracketed within the interval ca. 23.9–34.6 cal kyr BP. The youngest faulting event (Event I; 12.2–12.6 cal kyr BP) is inferred from the presence of organic infill within the main fault zone (fissure). These results yield a preliminary recurrence interval of surface faulting of ca. 10–15 kyr for the Pastores fault. Based on a maximum single-event displacement (SED) of ca. 50 cm, an average SED of ca. 30 cm, and fault rupture lengths of up to 33 km, a magnitude of M 6.6–6.8 is estimated for surface rupturing events. Both the SED and latest Pleistocene to Holocene slip rate (ca. 0.03 mm/yr) at the trench site are likely to be less than values measured toward the western end of the fault where the rangefront is larger. The Acambay graben has distinct eastern and western halves, being divided by a N- to NNW-striking structural zone corresponding to the Taxco-San Miguel de Allende fault system. Paleoseismic data and empirical relationships suggest that the Pastores fault constitutes both a distinct seismic source from other active faults of the Acambay graben and a significant seismic hazard.

Key words: paleoseismicity, active faulting, Pastores fault, Acambay graben, Trans-Mexican Volcanic Belt, Mexico.

RESUMEN

Los terremotos corticales someros representan un riesgo significativo para las comunidades de la región del centro de México. Dentro del graben de Acambay, la falla de Pastores es una falla activa de cerca de 33 km de largo, de mecanismo normal, con rumbo E-W y buzamiento hacia el norte. Dos

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trincheras paleosísmicas fueron excavadas en la localidad de Manto del Río para estimar los parámetros preliminares de actividad y de riesgo sísmico. Ambas trincheras mostraron evidencia de al menos dos paleo-rupturas en el Pleistoceno Tardío al Holoceno, según las fechas de radiocarbono obtenidas de la trinchera oeste, y mediante la correlación de unidades piroclásticas entre las trincheras. El evento más antiguo (Evento III) se encuentra en el intervalo de ca. 31.5–41.0 cal ka BP. Las unidades superiores de la trinchera están menos desplazadas y proporcionan evidencia de al menos un evento más joven. La ruptura del Evento II se encuentra en el intervalo de ca. 23.9–34.6 cal ka BP. El fallamiento más joven (Evento I; 12.2 a 12.6 cal ka BP) se infiere por la presencia de relleno orgánico dentro de la zona principal de falla (fisura). Estos resultados arrojan un intervalo de recurrencia preliminar de ruptura superficial de aproximadamente 10–15 ka para la falla de Pastores. Se estima una magnitud de 6.6 a 6.8 M para la falla de Pastores con base en un desplazamiento cosísmico (single event displacement, SED) máximo de aproximadamente 50 cm, un SED promedio de aproximadamente 30 cm, y la longitud de ruptura de falla de hasta 33 km. Es probable que tanto el SED como la tasa de deslizamiento del Pleistoceno tardío al Holoceno (ca. 0.03 mm/año) en el sitio de la trinchera, sean menores que los valores medidos hacia el extremo occidental de la falla. El graben de Acambay muestra diferencias claras en sus partes oriental y occidental, siendo dividido por una zona estructural con rumbo N a NNW que corresponde al sistema de fallas Taxco-San Miguel Allende. Los datos paleosísmicos y las relaciones empíricas sugieren que la falla de Pastores constituye a la vez una fuente sísmica diferenciada de otras fallas activas del graben de Acambay, así como un riesgo sísmico significativo.

Palabras clave: paleosismicidad, fallamiento activo, falla de Pastores, graben de Acambay, Cinturón Volcánico Transmexicano, México.

INTRODUCTION

Though typically smaller than interplate thrust or strike-slip earthquakes, moderate to large magnitude (M_w 6–7) normal faulting earthquakes have caused significant loss of life and damage to infrastructure, particularly in vulnerable regions such as under-developed and Mediterranean nations, where either weak or older building stock may be substandard. Recent examples of destructive, moderate to large magnitude normal faulting events include the 2009 M_w 6.3 L'Aquila earthquake, Italy (Serpelloni *et al.*, 2012), the 1993 M_w 6.0 Klamath Falls, Oregon earthquake (Braunmiller *et al.*, 1995), the 1990 M_S 6.9 Campania-Lucania earthquake, Italy (Pantosti and Valensise, 1990), 1987 M_L 6.3 Edgecumbe earthquake, New Zealand (Beanland *et al.*, 1989), and several Basin and Range earthquakes during the 20th century, including the 1954 M_S 7.2 Fairview Peak and M_S 6.8 Dixie Valley earthquakes, Nevada (Wallace, 1984; Caskey *et al.*, 1996). The loss of life and damage resulting from such earthquakes shows that seismic hazard studies are important for regions of extension even where rates of tectonic activity are relatively low (Pezzopane and Weldon, 1993; Langridge, 1998).

Historically, and in addition to the seismic hazard posed by the subduction zone boundaries around it, moderate to large magnitude crustal normal faulting earthquakes have also occurred in Mexico during the last 125 years (Figueroa, 1970; Singh and Suárez, 1987; Suter *et al.*, 1992, 1996). These include the 1979 m_b = 5.3 Maravatío earthquake (Astíz-Delgado, 1980), the 1912 M_w 6.9 Acambay earthquake (Suter *et al.*, 1996; Langridge *et al.*, 2000) and the 1887 M_w 7.5 Sonora earthquake (Suter, 2006; Suter and Contreras, 2002). It is therefore relevant for future planning that shallow crustal earthquakes be considered as a significant seismic hazard to the people and infrastructure of Mexico. In particular, the central part of the country, where the vast proportion of the population live, is traversed by both the active Trans-Mexican Volcanic Belt (TMVB) and by semi-continuous zones of active intra-arc normal faulting aligned sub-parallel with the TMVB (Johnson and Harrison, 1990; Suter *et al.*, 1992, 1995a) (Figures 1, 2).

Normal faulting and extension in the central part of the TMVB is accommodated through the Chapala-Tula fault zone (CTFZ), which is over 450 km in length and up to 50 km wide (Figure 2). The CTFZ is characterised by NNE- to NNW-directed active extension at low rates (<0.3 mm/yr; Aguirre-Díaz *et al.*, 1997, 2005; Langridge *et al.*, 2000). Of particular relevance to the hazard posed by active faulting was the occurrence of the November 19, 1912 M_w 6.9 Acambay earthquake within the Acambay graben (Urbina and Camacho, 1913; Abe, 1981; Suter *et al.*, 1996) (Figures 2, 3). This event was one of the largest earthquakes to have occurred in the TMVB and caused loss of life and extensive damage as well as surface fault rupture on the Acambay-Tixmadejé fault (Urbina and Camacho, 1913; Suárez *et al.*, 1994). Seismic hazard parameters for the Acambay-Tixmadejé fault (ATF), surface fault rupture associated with the 1912 Acambay earthquake, and the paleoseismicity of the ATF were studied in detail by Langridge *et al.* (2000).

The aim of this study is to further the understanding of the seismic potential of the Acambay graben by examining its southern boundary fault: the Pastores fault (Figures 2, 3). In this paper we present preliminary results from geomorphic, stratigraphic, and paleoseismic studies of the Pastores fault, and attempt to understand its role as part of the Acambay graben. Characterisation of slip rate and earthquake potential for the Pastores fault was obtained through paleoseismic trenching, while fault mapping was undertaken

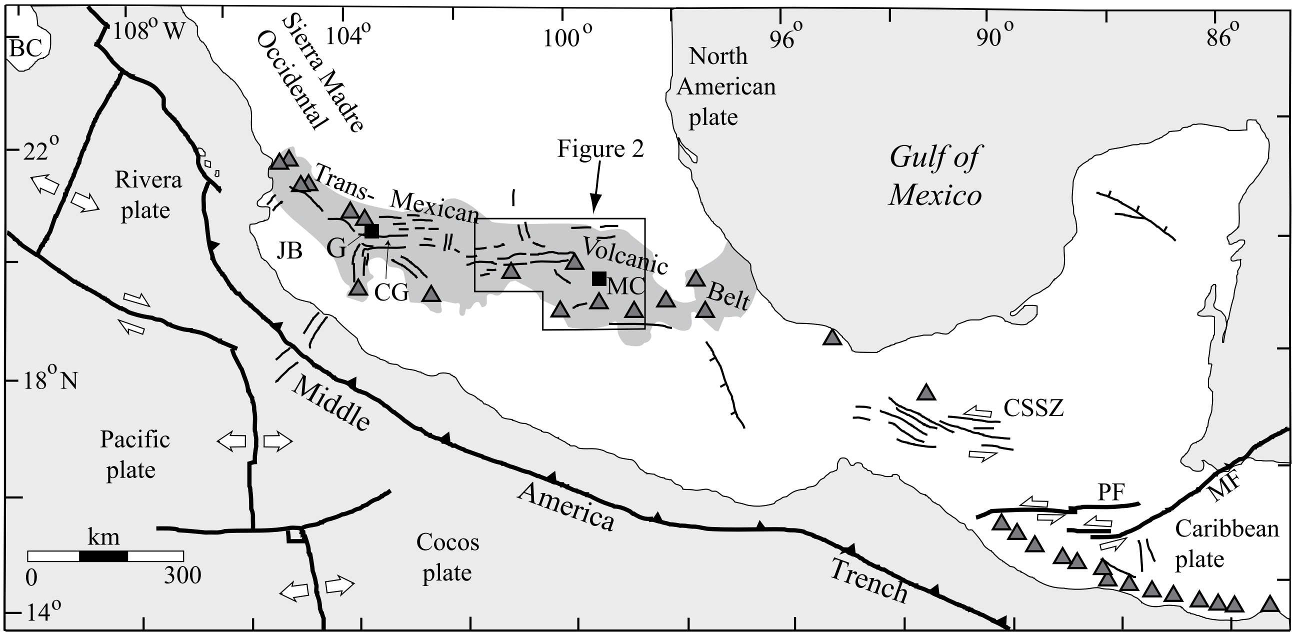

Figure 1. Simplified plate tectonic map of southern Mexico, including the major tectonic features, fault zones and arc volcanoes (triangles), after Langridge *et al.* (2000). Rocks associated with the Trans-Mexican Volcanic Belt are shaded. Abbreviations: BC, Baja California; CG, Chapala graben; CSSZ; Chiapas strike-slip zone; G, Guadalajara; JB, Jalisco block; MC, Mexico City MF, Motagua fault; and PF, Polochic fault.

with the aid of aerial photographs, digital elevation models and field control. In addition, the post-earthquake report of Urbina and Camacho (1913) also provides a basis for reconsidering the role of the Pastores fault with respect to the 1912 Acambay earthquake. Landsliding from steep rangefront slopes and from the sides of volcanic edifices also poses a significant hazard within the Acambay graben (Norini *et al.*, 2010). Finally, we hope to contribute not only to local hazard, but also to the estimation of seismic hazard to large cities within 100 km of the Acambay graben including Querétaro and Mexico City, particularly with respect to estimating the effects of an 'Acambay' earthquake occurring today amongst a more populated and developed society (Singh *et al.*, 2011).

GEOLOGIC AND SEISMOLOGIC SETTING

The east-west striking Acambay graben, of which the Pastores fault is a major element, occurs within the TMVB in central Mexico (Figures 1, 2). The TMVB is an active, mostly calc-alkaline volcanic arc that traverses from the Pacific Ocean to the Gulf of Mexico (De Cserna, 1989; Aguirre-Díaz *et al.*, 1998; Ferrari *et al.*, 2012), and is associated with subduction of the Cocos and Rivera plates beneath the North America plate (Nixon, 1982; Suárez and Singh, 1986) (Figure 1). The active volcanic arc and associated tectonism is oblique to the Middle America Trench, which may be caused by variable slab dip beneath Mexico (Urrutia-Fucugauchi and Del Castillo, 1977; Singh and Pardo, 1993; Pardo and Suárez, 1995). The TMVB is characterised by a wide variety of styles and compositions of volcanism, from monogenetic basaltic fields (e.g., Michoacán-Guanajuato volcanic field) to large andesitic stratovolcanoes (e.g., Popocatépetl, Jocotitlán) to rhyolitic volcanism characterised by large silicic calderas and ignimbrite flows (e.g., Amealco Caldera, Siebe *et al.,* 1992; 2006; Aguirre-Díaz *et al.*, 1998) (Figure 2).

The central TMVB is characterised by normal faulting, typified by the intra-arc rift basins of the CTFZ (Johnson and Harrison, 1990; Langridge, 1998). The major components of the CTFZ are from west to east: the Chapala graben, the Cuitzeo graben, and the Acambay graben (Suter *et al.*, 1995a; 2001) (Figures 1, 2). The TMVB has been superimposed on the NNW-trending Sierra Madre Occidental volcanic province of Mexico as a result of plate boundary readjustments since the Miocene (Ferrari *et al.*, 1999, 2012; Cerca-Martínez *et al.*, 2000). Evidence for Sierra Madre- or 'southern Basin and Range'-style deformation is widespread, e.g., the NNW-trending Taxco-San Miguel de Allende fault zone (Aguirre-Díaz, 1996; Aguirre-Díaz *et al.*, 2005; Dávalos-Álvarez *et al.*, 2005; Alaniz-Álvarez and Nieto-Samaniego, 2005). Faults of the CTFZ cut Neogene to Quaternary volcanic rocks of the TMVB (Sánchez-Rubio, 1984; Nixon *et al.*, 1987; Suter *et al.*, 1991). The Lerma River system flows through many of the grabens within the CTFZ, exposing Neogene and Quaternary rocks of lacustrine, volcanic, and alluvial origin (Figures 2, 3; Langridge, 1998).

The central TMVB has experienced a moderate level of instrumental seismicity, highlighted by the 1912 M_w 6.9 Acambay earthquake, which caused 161 fatalities and extensive damage to the buildings in the area, and produced strong ground motions experienced as far away as Mexico City (Urbina and Camacho, 1913; Singh *et al.*, 1984, 2011). The next largest local and instrumentally-recorded earthquake in the central TMVB is the February 22, 1979 $m_b = 5.3$ Maravatío earthquake (Astíz-Delgado, 1980; Suter *et al.*, 1996). Suter *et al.* (1992) mention other earthquakes of similar magnitude that occurred in 1734–1735 and 1853–1854 near the trace of the Venta de Bravo fault (Orozco and Berra 1887; García-Acosta and Suárez-Reynoso, 1996). In addition, there are reports of large pre-instrumental earthquakes in the western TMVB (Ordoñez, 1912; Suárez and Ponce, 1986; Suárez *et al.*, 1994) and of several small earthquakes in the area of the Mezquital and Aljibes half-grabens (Suter *et al.*, 1995b, 1996; Quintanar *et al.*, 2004) (Figure 2). More recently, in January 1998, seismic activity (m_b<3.5) was reported along a NNW-striking normal fault 15 km to the SE of Querétaro and about 40 km north of Acambay (Zúñiga *et al.*, 2003). On this basis, and on the structural and geological study of the NNW-striking faults between Querétaro and the Acambay graben, Aguirre-Díaz *et al.* (2005) proposed that ENE-directed extension is also active in the northern portion of the Taxco-San Miguel de Allende fault system. These events highlight the seismic potential of normal faults within and close to the TMVB.

The Acambay graben

The Acambay graben is one of the most prominent structural features within the TMVB and has been the subject of numerous neotectonic studies (Suter, 1991; Suter *et al.* 1992, 1995a, 1996, 2001; Ramírez-Herrera *et al.*, 1994; Ramírez-Herrera, 1998; Langridge *et al.,* 2000; Aguirre-Díaz *et al.*, 2005) (Figure 3). The Acambay graben is defined by four major E-W striking normal faults: the Acambay-Tixmadejé and Epitacio Huerta faults in the north; and, the Venta de Bravo and Pastores faults in the south (Suter *et al.*, 1992; 1995a) (Figure 3). The graben is up to 80 km long and 15–38 km wide.

Volcanic rocks of the TMVB that surround the Acambay graben are Miocene to Quaternary in age and aid in constraining the age and amount of extension associated with the graben. These rocks form the footwall blocks of the graben and the basement of the hangingwall (Sánchez-Rubio, 1984; Aguirre-Díaz, 1993, 1996; Aguirre-Díaz *et al.* 2000). The history of faulting for some faults, e.g., the Epitacio Huerta fault (activity since at least 2.2–2.5 Ma), is known from its association with the Amealco caldera (Aguirre-Díaz, 1995, 1996; Aguirre-Díaz and McDowell, 2000). In addition, there is evidence for intra-graben volcanism continuing during the Quaternary, e.g., Temascalcingo

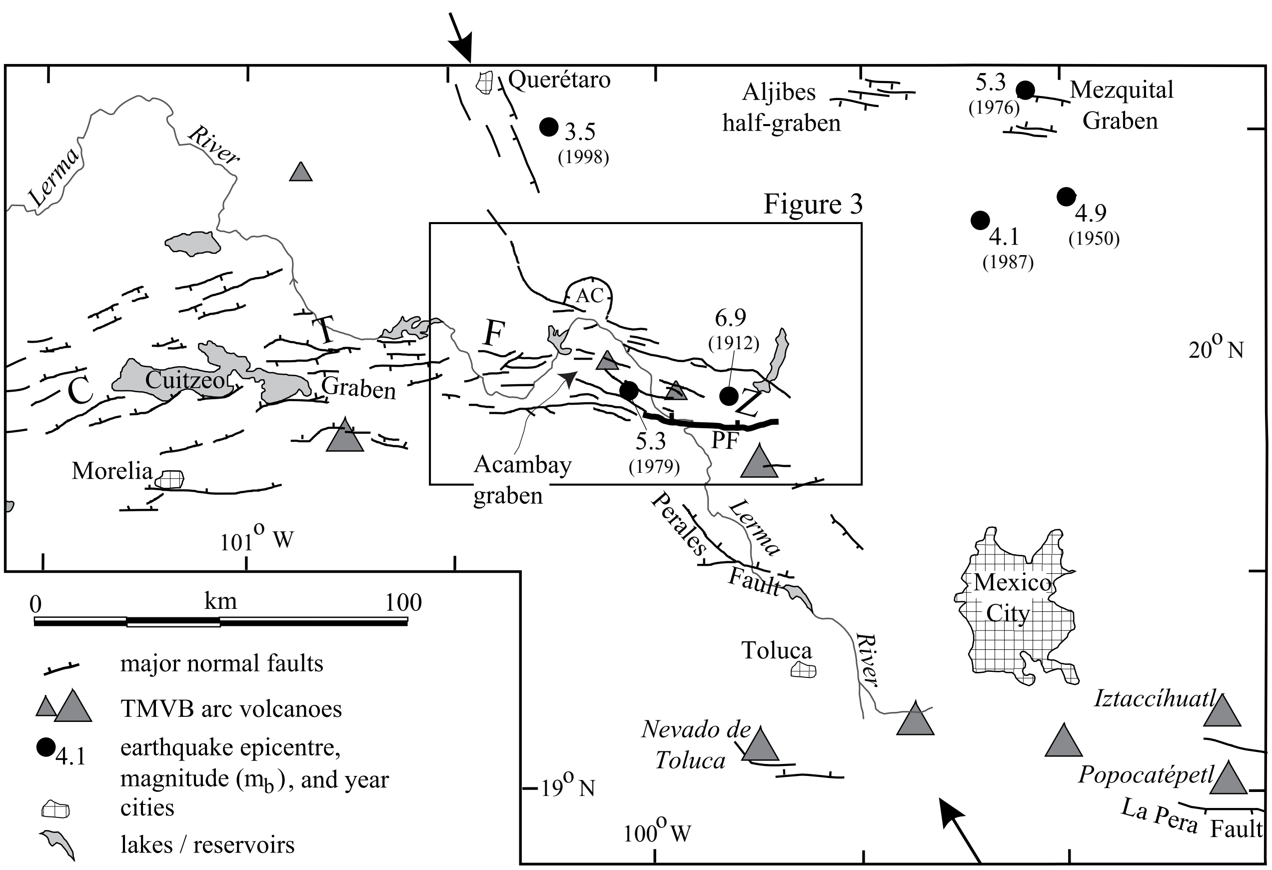

Figure 2. Map of the eastern half of the Chapala-Tula fault zone (CTFZ), including the study area within the Acambay graben. Normal faults of the CTFZ are shown with ticks on the downthrown block, including the Pastores fault (PF, bold). Historic macro-seismic earthquake (m_b) data from Suter *et al.* (1996) for the Trans-Mexican Volcanic Belt. Bold arrows mark the trend of the Taxco-San Miguel de Allende fault system. AC, Amealco caldera.

volcano, that has been displaced by several intra-graben faults (Figure 3; Roldán-Quintana and Aguirre-Díaz, 2006; Roldán-Quintana *et al.*, 2011; Aguirre-Díaz *et al.*, 2000).

Within the graben there is also abundant evidence for lacustrine sedimentation, distributed in small basins that are separated by N-S striking intra-graben volcanic ranges, such as the Sierra de las Cruces. Quaternary lacustrine deposition within the graben is concomitant with Quaternary extension, albeit also at low rates. For example, latest Pleistocene lake sediments exposed in the Huapango Plain can be correlated to sediments in the Acambay basin (Figure 3; Langridge *et al.*, 2000). Within the Acambay basin, uplifted and deformed Pliocene to late Pleistocene lake sediments are exposed at Tierras Blancas. These beds include index vertebrate fossils interbedded with ash-fall deposits dated at about 1.2 Ma (Langridge *et al.* 1997; Mercer *et al.*, 2003; Rodríguez-Pascua *et al.* 2004).

Western part of Acambay graben

The western part of the Acambay graben is bounded by the Venta de Bravo fault to the south and the Epitacio Huerta fault to the north (Figure 3). The Epitacio Huerta fault is separated from the Acambay-Tixmadejé fault by a ca. 8 km wide zone of right-stepping normal faults between San José de Solís and Amealco. These faults are short (ca. 2–10 km long), north-dipping normal faults, and form a stepover zone between the Epitacio Huerta fault and the ATF. Surface faulting related to the 1912 Acambay earthquake occurred on the ATF to as far west as San José de Solís and did not continue on the Epitacio Huerta fault (Urbina and Camacho, 1913; Langridge *et al.*, 2000).

The Venta de Bravo fault forms the southwestern margin of the Acambay graben (Suter *et al.*, 1992, 1995a). It is a ca. 45 km long, E-W striking and north-dipping normal fault with up to 300 m of topographic relief near the faulted San Miguel el Alto volcano (Figure 3). Geomorphic features indicative of active faulting abound along the rangefront of the Venta de Bravo fault (Ramírez-Herrera *et al.*, 1994; Ramírez-Herrera, 1998) and suggest the maximum rate of activity is within the central portion of the fault near San Miguel El Alto volcano. Cover beds on the footwall block of the fault are rotated and dip up to 3–4° to the south.

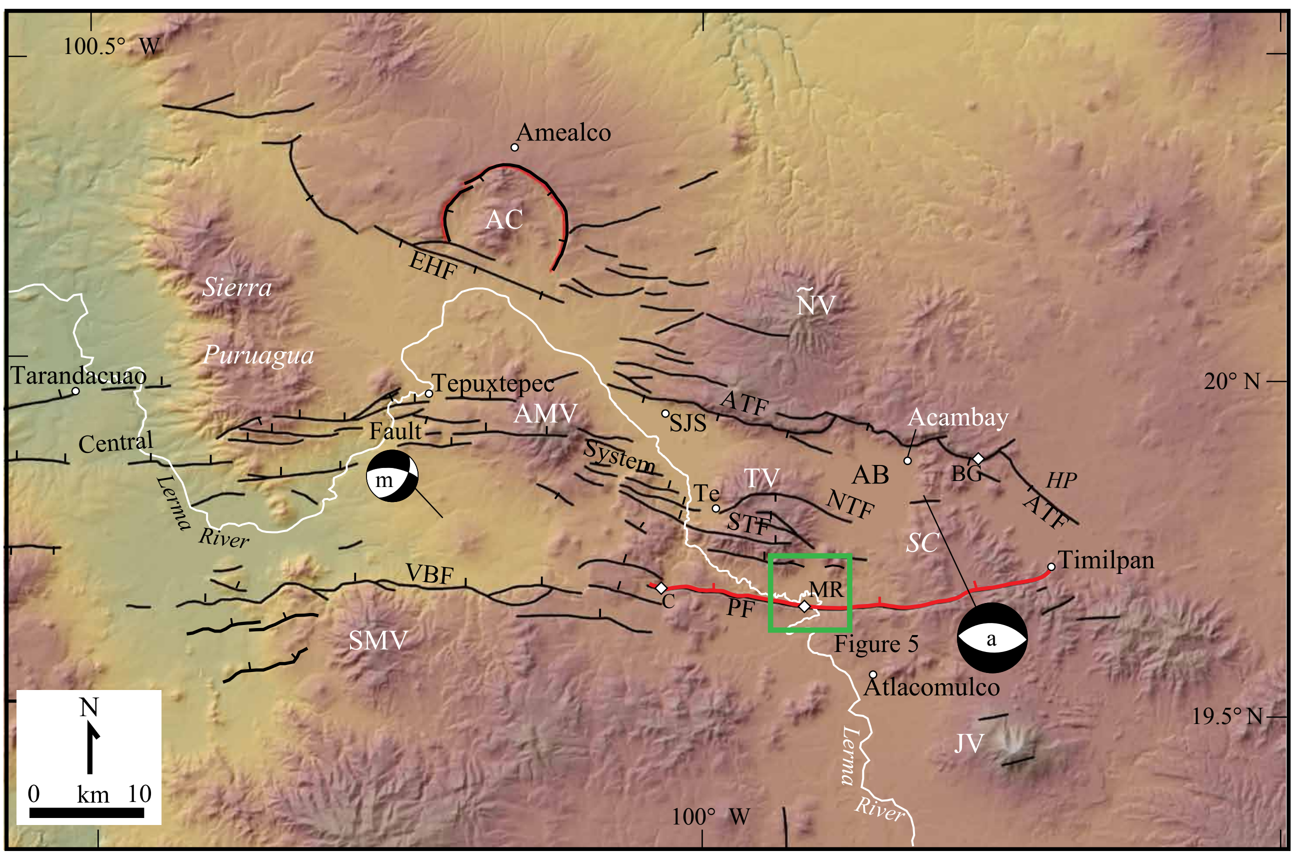

Figure 3. Active fault map of the Acambay graben after Suter *et al.* (1992). Active faults include the Pastores (PF), Acambay-Tixmadejé (ATF), Epitacio Huerta (EHF), North and South Temascalcingo (NTF, STF) and Venta de Bravo (VBF) faults. Major volcanic complexes are marked, including Altamirano (AMV), Amealco caldera (AC), Ñado (ÑV), San Miguel el Alto (SMV), Temascalcingo (TV), Sierra de las Cruces (SC) and Jocotitlán (JV). Other abbreviations: SJS, San José de Solís; Te, Temascalcingo; AB, Acambay basin; HP, Huapango Plain. Approximate locations of the 1979, m_b 5.3 Maravatío (m) and 1912, M_w 7.0 Acambay (a) earthquakes are shown by focal mechanisms, which are derived from Suter *et al.* (1992) and Langridge *et al.* (2000), respectively. The Manto del Río (MR), Canchesda (C), and Boshi Grande (BG) trench sites are indicated by white diamonds. Green box shows the location of Figure 5.

A preliminary vertical slip rate of ca. 2 mm/yr has been estimated for the Venta de Bravo fault based on an age of <23 ka on lake deposits of the Ixtapantongo Formation displaced by ca. 50 m (Sánchez-Rubio, 1984; Suter *et al.* 1992). Structural attitude and slickenside data indicate NNW-directed extension with a minor sinistral component across this fault (Suter, 1991; Suter *et al.*, 1995a). These data are consistent with the focal mechanism of the 1979 Maravatío earthquake (Astíz-Delgado, 1980; Suter *et al.*, 1992). The depth (ca. 8 ± 3 km) and the dip of the nodal plane are consistent with this event having occurred on the Venta de Bravo fault (Figure 3).

A series of active intra-graben faults are mapped between Altamirano volcano and Tarandacuao. These faults cut a number of Neogene to Quaternary intra-graben volcanic complexes including Altamirano and the Sierra Puruagua, and also cut alluvial surfaces of the Lerma River valley where it crosses this fault system south of Tepuxtepec and near Tarandacuao (Figure 3). At least in number and in length (i.e., their surface expression), these faults appear to have an important role in the Quaternary tectonic activity of the Acambay graben (Ortuño, 2012; Ortuño *et al.*, 2011).

Eastern part of Acambay graben

Three major E-W oriented fault systems define the eastern half of the Acambay graben (Figure 3): (1) the Acambay-Tixmadejé fault bounding the northern margin of the graben, (2) intra-graben faults of the Central fault system in the Temascalcingo area, and (3) the Pastores fault forming the southern margin of the graben (Suter *et al.,* 1991, 1995a).

The Acambay-Tixmadejé fault (ATF) is a ca. 42 km long, steep south-dipping normal fault that forms a 400–500 m high escarpment in Neogene volcanic rocks (Figure 3) (Sánchez-Rubio, 1984; Suter *et al.*, 1992, 1995a; Aguirre-Díaz, 1993, 1996; Soler-Arechalde and Urrutia-Fucugauchi 1994). The ATF forms the northern master fault of the eastern Acambay graben and was the principal seismogenic source of the 1912 Acambay earthquake, as demonstrated by the near-continuous surface rupture, concentration of damage, and by the downdip location of the epicentre (Urbina and Camacho, 1913; Langridge *et al.*, 2000). The ATF is primarily a normal fault that drives NNE-directed extension, but may also have a small component of left-lateral movement indicated from both the 1912 surface rupture and trench exposures on the Huapango Plain (Figure 3; Langridge *et al.*, 2000). Post-seismic investigations by Urbina and Camacho (1913) revealed surface ruptures with vertical displacements of up to 50 cm along the main rangefront. Geomorphological features including offset drainage, shutter ridges, triangular facets, sag ponds, linear ridges, compression ridges and pull-apart structures have been used as evidence for a strike-slip component of deformation (Ramírez-Herrera *et al.*, 1994).

Paleoseismic studies by Langridge *et al.* (2000) on the ATF led to estimates for a number of the key fault parameters along the rangefront of the fault, including the dip-slip rate (ca. 0.17 mm/yr) and average single-event displacement (ca. 60 cm). Several latest Pleistocene and Holocene paleo-earthquake ruptures were also dated, allowing for an estimation of the average recurrence interval of surface faulting (ca. 3600 yr). Recent studies show that large, presumably co-seismically generated, landslide masses have emanated from the rangefront of the ATF near San José de Solís (Norini *et al.*, 2010).

Faults of the Central fault system cut Temascalcingo volcano, forming a graben in the crown of the edifice and affecting the summit caldera of the volcano (Figure 3; Ortuño *et al.*, 2011). Co-seismic normal displacements of up to 30 cm were measured on the North and South Temascalcingo faults following the Acambay earthquake (Urbina and Camacho, 1913). Minimum co-seismic rupture lengths of 0.66 and 1.05 km, and of up to 10 km are suggested by Langridge *et al.* (2000) indicating that triggered slip occurred on these intra-graben faults in 1912.

The Pastores fault

The Pastores fault is the southern master fault in the eastern part of the Acambay graben and is the main focus of this paper. The Pastores fault extends over a distance of ca. 14 km from Canchesda in the west to the Lerma River with an east-west strike, and then continues a further ca. 19 km toward Timilpan in the east, with an ENE strike and a more subdued geomorphic character (Figure 3). It is a north-dipping normal fault (45–70°) that exhibits a minor component of left lateral movement (Suter *et al.*, 2001).

Geomorphically, the western part of the Pastores fault is characterised by a steep rangefront of up to 230 m height formed in mostly hard, layered andesitic lava flows (Ramírez-Herrera *et al.*, 1994), with a broad apron of alluvial fan deposits at its foot (Figure 4). Soils formed on these aprons are medium brown to red in colour, suggesting a significant amount of time and weathering related to their development.

Lake deposits on the footwall block of the fault dip up to 7° to the south, implying a significant rotation of blocks within the central part of the fault (Suter *et al.*, 1992). According to Ramírez-Herrera (1998), the fault has a high proportion of continuous undissected escarpment and convex river profiles that indicate it is more active at its western end. Immediately east of where the Lerma River crosses the fault, mafic lavas of the Atlacomulco volcanic field (Figure 5) have flowed north and across the trace of the Pastores fault. In this area, a 15 m vertical displacement across a 400 ka old andesite lava resulted in a slip rate estimate of ca. 0.04 mm/yr (Suter *et al.*, 1995a).

In the west, the Pastores fault is separated from the Venta de Bravo fault by a similar zone of fault complexity as is observed between the Acambay-Tixmadejé and Epitacio Huerta faults (Figure 3). This zone comprises several discontinuous, stepping fault traces, highlighted by a major (ca. 1 km) step to the north near Canchesda.

Figure 4. Photographs of the Pastores fault and Manto del Río trench site. a) View to the east along the main escarpment, which is formed in volcanic rocks. The active trace of the fault occurs near the base of the escarpment. b) View to the south showing the rangefront of the fault near Canchesda where lavas are displaced vertically by ca. 50 m. The location of the active trace of the Pastores fault is marked by a white arrow. c) View to the south, showing the Manto del Río East trench excavated across an apron of sediments adjacent to the eroded rangefront edge near the Lerma River. Possible surface trace is marked with a black arrow (also in D). A white arrow marks the bedrock-alluvium contact. People are marked in white for scale. D. Excavation of the West trench, view to the east. In the middle distance the floodplain of the Lerma River occupies the valley floor in this part of the Acambay graben.

PALEOSEISMIC STUDY OF THE PASTORES FAULT

Manto del Río trench site

The Manto del Río trench site is located along the central portion of the Pastores fault, near the village of Manto del Río, ca. 7.5 km northwest of Atlacomulco (Figures 4, 5). The site is ca. 700 m west of where the Lerma River crosses the fault. Figure 5 shows an annotated aerial photograph of the area near Manto del Río, and includes locally important volcanic, fluvial, lacustrine and structural features. This area was chosen for paleoseismic studies because: (1) two lineaments are clear in the landscape, extending from the rangefront toward the river across open, uncultivated land; (2) the lineaments cross an apron of low topographic gradient where young sediments underlying the surface were possibly preserved; and (3) a young alluvial surface adjacent to the river is not deformed by the fault, providing constraints on the age of the most recent faulting. This area was therefore selected for paleoseismic trenching.

Two trenches were excavated ca. 300 m apart and named the Manto del Río East and West trenches. The excavations were quite long and deep (up to 28 m × 4 m), in order to provide certainty that the trace of the Pastores fault was intercepted, and to expose a thick section of rangefront apron sediments, whose surface has a slope of ca. 12° there (Figure 4). The trenches are ca. 20 m above the Lerma River and therefore not regularly exposed to fluvial or flood deposition. Samples were collected for radiocarbon dating and are presented in Table 1. All four results were in stratigraphic order, lending confidence to their ages being depositional ages. Radiocarbon ages have been calibrated using the OxCal 4.1 program (Bronk Ramsey, 2009) and due to their antiquity and large analytical uncertainties they are calibrated and presented at the 1 sigma level here.

Manto del Río trench stratigraphy

The stratigraphy exposed in the trenches is characterized by lacustrine and pyroclastic deposits, alluvial fan

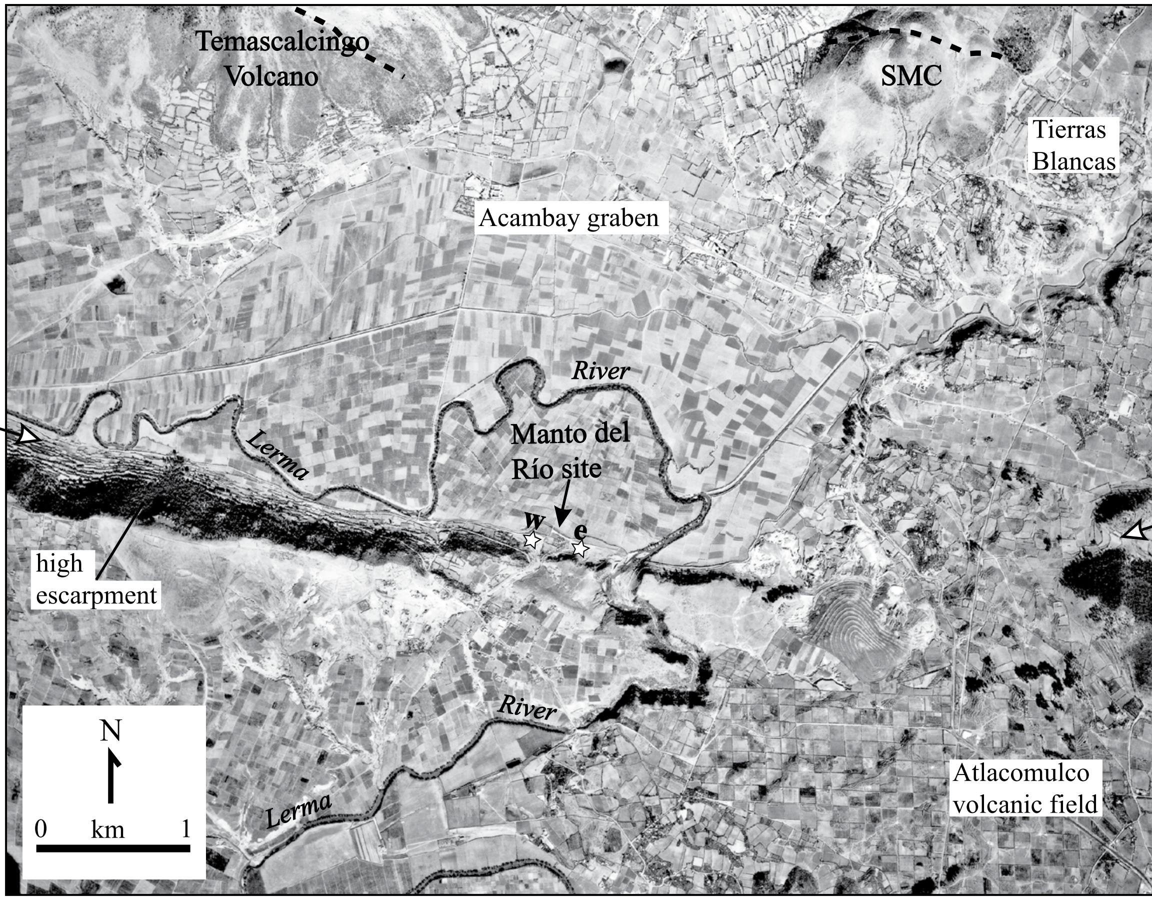

Figure 5. Aerial photograph of the southeastern part of the Acambay graben, centred on the Pastores fault (white arrows) and Manto del Río paleoseismic site (black arrows). The West (w) and East (e) trenches are marked by stars. The rangefront of the fault decreases in height from the west to the Lerma River. Basaltic lava flows of the Atlacomulco volcanic field flow across the fault trace at bottom right. The volcanic complexes of Temascalcingo and Santa María Canchesda (SMC) are shown at top; with fault traces cutting them (dashed lines).

deposits and soils, several of which have been correlated between the two trenches (Figure 6). In particular, soil development is a useful marker, indicating where a unit formed a stable geomorphic surface into which a soil developed on the alluvial fan apron at the rangefront. Expanded unit descriptions appear in Appendix A.

The oldest exposed deposits seen in the West trench are tilted, typically silty lake sediments (unit 9) that are correlated to the Ixtapantongo Formation (Sánchez-Rubio, 1984; Aguirre-Díaz *et al.*, 2000) (Figures 6, 7). The lake deposits contain occasional sand beds and bedding within the silts defines a tilt of 7° to the north. A sample of brown, organic mud from within these sediments yielded an age of 31,810 +4250/-2770 yr BP (calibrated to ca. 33.7–41.0 cal kyr BP). In the West trench, unit 9 lake sediments are unconformably overlain by a sequence of five distinct pyroclastic deposits (Figure 7b). Unit 8, a coarse pumice bed that probably originated as a plinian fallout deposit (tephra), is an important unit because it is the oldest unit that can be correlated between the two trenches.

Unit 7 is composed of two pyroclastic flow units (ignimbrites), 7a and 7b (expressed in the west trench), and a tephra, unit 7 (expressed in the east trench only). Ignimbrites 7a and 7b probably represent two separate eruptive pulses related to plinian column collapse events. Because there is little evidence of erosion or soil development on unit 8, we assert that the unit 7 ignimbrites and tephra were erupted shortly after tephra unit 8 (see Figures 6, 7 and Appendix A for more detail). The top of unit 7a is irregular due to erosion by the overlying surge deposit (unit 7b). Unit 7b and unit 7, a yellow to light brown tephra, both appear to have soil (paleosol) development within them.

Unit 7 and its soil are overlain by a pair of pyroclastic surge deposits (units 6a and 6b). A sample of charcoal from the paleosol formed within and near the top of surge 6b yielded an age of 28,555 +2400/-1845 yr BP (ca. 31.5–34.6 cal kyr BP). The lower surge unit (6a) includes a series of cross-bedded facies that indicate a paleoflow direction from the north of Manto del Río. This is suggestive of a Temascalcingo volcano source for the surges and therefore possibly for the whole pyroclastic sequence, which is continuous and without discordances. In the East trench, unit 7 tephra is unconformably overlain by unit 6b, a matrix-supported deposit comprising andesite blocks in a sandy to muddy ash matrix (Figure 7b). This unit is correlated with the lithic-rich surge unit 6b in the west trench. A black buried soil is evident within the top of the unit 6b surge deposit, (i.e., unit 5 in the East trench).

In the East trench only, this sequence is overlain by further pumice fall deposits (unit 4), which are subdivided into units 4a and 4b (Figure 7a). Unit 4a is a thin white pumice tephra that is conformably overlain by unit 4b, a normally graded, clast-supported pumice lapilli deposit. The top of unit 4b is weathered but is distinct from unit 3.

Unlike units 6 to 8 that have typically wedge-shaped geometries, units 3 and 4 appear to fill a broad paleo-low and exhibit a channel-fill morphology (Figure 7a) that runs normal to the slope and parallel to the zone of faulting in this exposure. Unit 3 is a grey clay that contains pumice clasts and is characterised by common large, matrix supported, angular clasts of andesite. In the middle of the east trench, units 3 and 4 share a steep angular contact (Figure 7a). The shape of this relationship suggests that unit 3 is an alluvial debris flood deposit that has filled in a former gully, exposed in cross-section, similar to those seen on the fan apron today (Figure 4c).

In both trenches, the stratigraphy is capped by a brown clayey deposit that lacks pumice (unit 2) and a recent soil (unit 1). A paleosol formed in unit 2 is truncated and overlain by a younger soil (unit 1), which contains ceramic fragments (*tepalcates*) and broken obsidian arrowheads, both probably from pre-Hispanic cultures of the Acambay area. A sample of charcoal from unit 2 yielded an age of 21,815 +2400/-1845 yr BP (ca. 23.9–29.1 cal kyr BP). The unit 2 paleosol is typical of relatively weathered late Pleistocene to Holocene soils on volcanic deposits in this region (Langridge *et al.*, 2000). Both trenches lack stratigraphic units that is distinctly younger than ca. 20 ka. The youngest soil (unit 1) is mapped as topsoil that drapes the surface of the fan apron. Unit 1 is medium red-brown to brown-black in colour and because it contains fragments of ceramics it is interpreted as a Holocene soil.

Faulting

Manto del Río East trench faults

The East trench (ca. 28 m long and 3 m deep) was dug across two subtle steps in the fan surface that have heights of ca. 20 and 40 cm each (Figure 4c). No obvious zone of faulting was associated with the smaller step at the upper end of the trench. However, the lower of the two steps in the apron surface is associated with a zone of faulting, exposed ca. 6–7 m from the north end of the trench (Figure 7a). This fault zone has a dip of ca. 57° to the north near the base of the trench and steepens up to 85° N near the ground surface. The fault bifurcates within unit 5 surges and cuts all of the pyroclastic units (Figure 7a).

Near the lower part of the exposed fault zone, the top of unit 7 tephra is displaced vertically in a down-to-the-north sense by ca. 0.9 m (Figure 7a). Farther up the section, the upper and lower contacts of the unit 4b tephra are displaced by ca. 48 and 50 cm, respectively. No other contacts are clearly displaced in this trench and it is difficult to map faults upward into the surficial deposits. However, faults have been inferred (with dashed lines) toward the ground surface near the surface step. The height of the surface step in the trench wall is ca. 42 cm. Although unit 2 can be mapped on either side of the fault zone it is unclear whether it has been faulted by recent displacement events. The topsoil unit drapes the fault zone and appears to be unfaulted above the tip of fault fE, despite the occurrence of the surface step. No organic material was located for radiocarbon dating in the East trench; therefore the age of faulting events in this trench is discussed below based on a correlation of the units between the two trenches.

Manto del Río West trench faults

The West trench (ca. 24 m long and 4 m deep) was dug across a ca. 25 cm step in the fan surface near the middle of the trench (Figure 4d). Though no obvious zone of faulting was associated with it, a steep, 1–2 m wide zone of faulting

Table 1. Summary of radiocarbon dates from Manto del Río West trench.

Sample ID	Lab No.*	$\Delta^{13}C$ (‰)	Radiocarbon age (yr BP)	Calibrated age cal BP		Material and significance
				1σ cal yr BP	2σ cal yr BP	
MP-1	A-14326	-18.3	10,495 ± 80	12,222 – 12,571	12,122-12,599	Fault infill. Brown, organic clay, sheared within fault zone.
MP-3	A-14327	-18.2	21,815 +1680/-1390†	23,876 – 29,111	21,558-33,034	Charcoal fragments within brown-grey clay unit without pumice (unit 2).
MP-2	A-14324	-19.2	28,555 +2400/-1845†	31,486 – 34,631	30,525-37,345	Irregular fragments of charcoal within unit 6a surge deposit.
GAC-13-1	A-14323	-23.0	31,810 +4250/-2770†	33,704 – 41,007	31,391-46,321	Organic silt (brown mud) sampled from within unit 9 lake sediments

*Samples were analysed at the University of Arizona Radiocarbon Dating Facility. Radiocarbon age: Conventional radiocarbon age before present (AD 1950) calculated using Libby half-life of 5568 years, and corrected to $\delta^{13}C$ of -25 ‰. Quoted error is ± 1σ. Data presented following Stuiver and Pollach (1977). Calibrated age: Calendar years before present (AD 1950) using C-14 calibration programme OxCal 4.1 (Bronk Ramsey, 2009; <http://c14.arch.ox.ac.uk/>. †Calibrations for ages that have non-uniform uncertainties have been calculated using a mean uncertainty value.

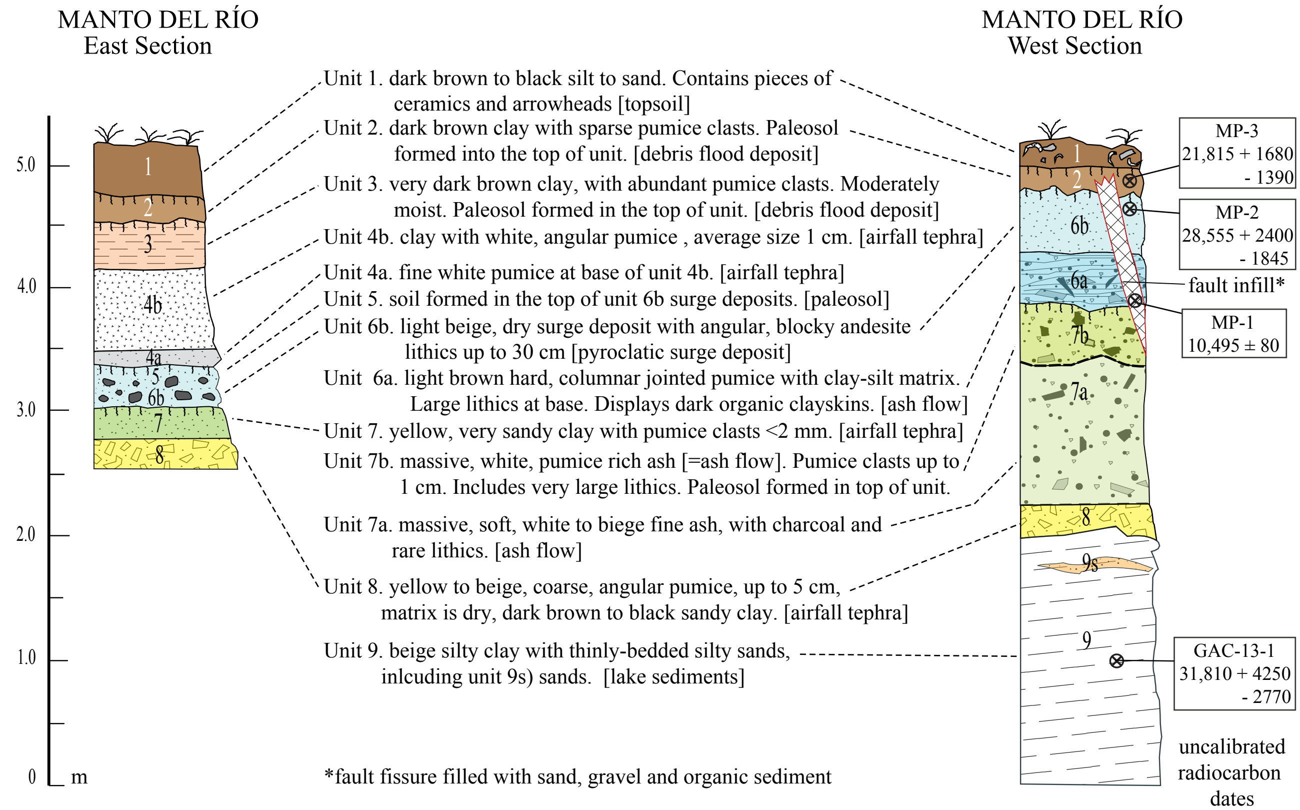

Figure 6. Stratigraphic column of units with simplified descriptions, radiocarbon ages, and key to features for the two Manto del Río paleoseismic trenches. Patterns, shades, and symbols are used in Figure 7. Name given in square brackets is an interpretation of the volcanic or sedimentary process. Sample MP-1 is placed in the column according to its position within the cross-cutting fissure fill.

characterised by an infilled fissure and a dipping fault were located near the upper end of the trench (Figure 7b).

From the base of the trench exposure, a zone of faulting comprising at least two faults widens upward into a ca. 20 cm wide, near-vertical fissure (ffw) which dips ca. 87° north. The fissure related to ffw splits upward into two branches and one branch can be traced to within unit 2, though it is inferred farther upward to the base of the topsoil unit (Figure 7b). These relations indicate that unit 2 is definitely faulted and so it is reasonable to continue the faulting to the top of that unit. In contrast, the other, more sinuous branch of the fissure and a fault (f1w) appear to terminate upwards at the base of unit 2. This branch of the fissure is truncated by the near vertical branch (ffw), implying distinct paleo-earthquake events.

The vertical displacements across the fissure are small, but measureable. The contact between sub-units 7a and 7b is displaced ca. 24 cm in a down-to-the-north sense. The upper and lower contacts of the unit 6a surge above this are displaced by ca. 10 and 14 cm, respectively, providing further evidence of more than one displacement event. A sample of organic clay (MP-1) from within the fissure and near its base has a radiocarbon age of 10,495 ± 80 yr BP (ca. 12.2–12.6 cal kyr BP). The relevance of this material and its age will be discussed below.

A second fault trace (f2w) was located ca. 1 m upslope from the main fault zone (Figure 7b). This fault dips to the north at ca. 54–77° and displaces the lower units in the trench up to, and including the unit 6a surge deposit. This fault cannot be confidently traced higher in the section. At the base of the exposure, the 7a-7b contact is displaced by ca. 20 cm, while the base of unit 6a is displaced by ca. 10 cm. Thus, the total displacement on the contact between sub-units 7a and 7b is ca. 44 cm, while the displacement on unit 6a is ca. 22 cm, down-to-the north.

Despite the small vertical separations across units 6 and 7, an important observation is that the main fault zone (ffw and f1W) is well developed, with cross-cutting relationships that imply two or more faulting events affecting all but the surficial units in the trench. The vertical fissure has a similar appearance to another fissure shown by Langridge *et al.* (2000) from the Las Lomas site on the Acambay-Tixmadejé fault across the Huapango Plain. At this location, historic surface ruptures with left-normal displacements documented by Urbina and Camacho (1913), were confirmed by the observation of Holocene left-normal displacement within trenches at Las Lomas. This offers the possibility that the filled fissure in the Manto del Río West trench reflects a component of lateral movement, or alternatively, that the zone of faulting observed in the trench is

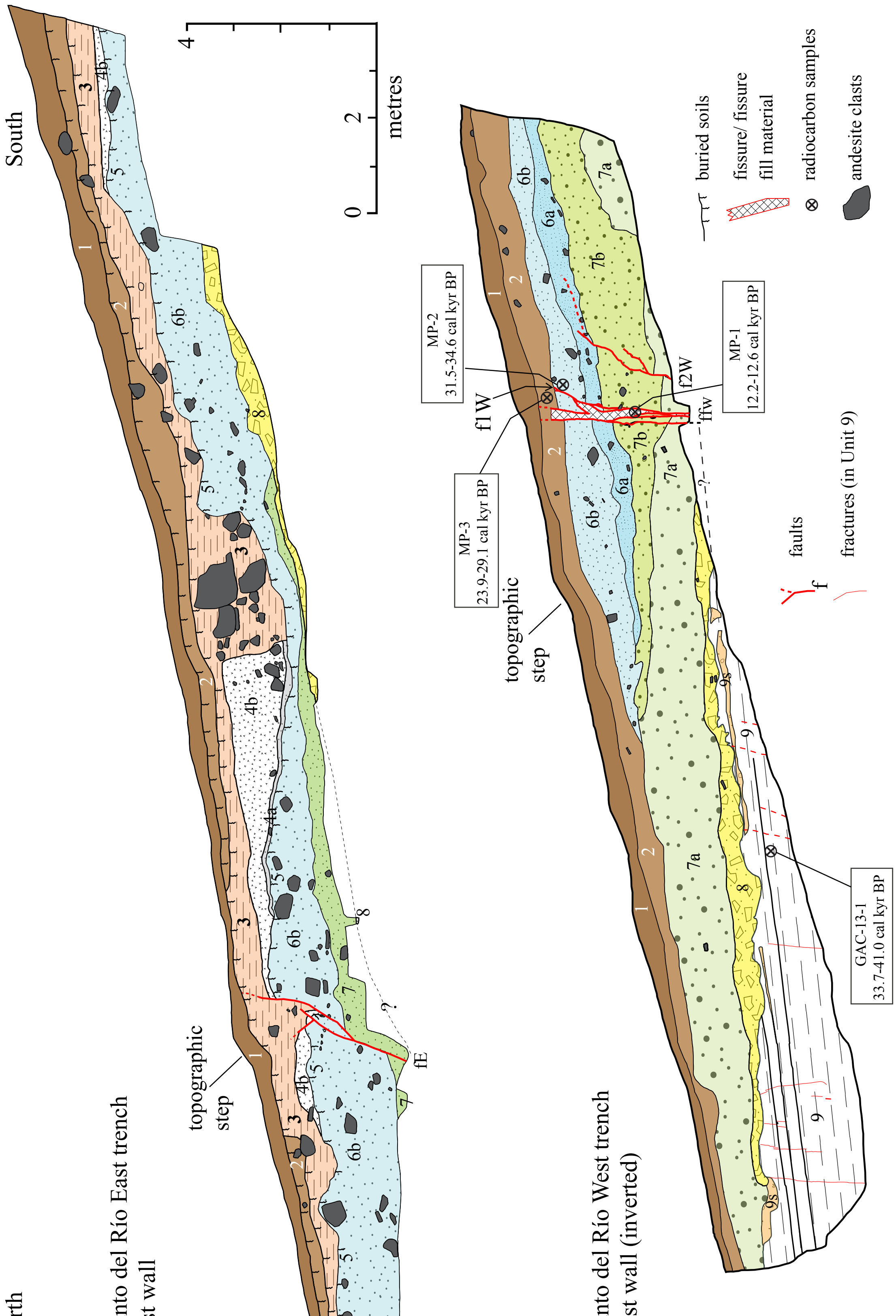

Figure 7. Logs of trenches at the Manto del Río site. Stratigraphy and symbols are those from Figure 6, and unit descriptions are contained in Appendix A. a) East wall of the East trench. Fault zone is toward the north end of the trench. b) West wall of the West trench. The view is inverted for ease of comparison. The fault zone is characterised by a wide, multi-event fissure, which is infilled with sheared clay. Radiocarbon dates are shown with their calibrated radiocarbon ages and 1-sigma uncertainties.

a secondary zone of normal to oblique-slip faulting.

One effect of the deformation related to the Pastores fault can be seen from the unit 9 lake sediments at the base of the trench. These beds are tilted ca. 7° to the north, which is unusual for beds on the immediate downthrown side of a normal fault. The vertical separation on these silts is not known, as they were not located to the south of the main fault zone. However, it is likely that these beds have been displaced more than the overlying pyroclastic deposits.

DISCUSSION

Paleoseismicity of the Pastores fault

The objective of this section is to present a preliminary record of the timing of paleoseismic events observed in the Manto del Río trenches and to estimate the recurrence interval of surface faulting. All of the parameters and calculations that follow depend on the underlying assumption that we have intercepted the main zone of deformation associated with the Pastores fault in the trenches. However, as noted from the Acambay-Tixmadejé fault, fault traces or scarps along the rangefront are difficult to identify in this semi-arid setting, even though that fault had ruptured less than a century earlier (Langridge *et al.*, 2000). Thus, low rates of alluviation/deposition and relatively minor faulting offer the possibility that the main zone of faulting occurs higher upslope at the bedrock contact, as noted by Langridge *et al.* (2000) at the Boshi Grande alluvial fan site on the ATF (Figures 3, 4c).

Evidence for paleoearthquakes was derived from the cumulative back-stripping of displacement of faulted deposits, cross-cutting relationships, and the presence of upward-terminating faults at past ground surfaces (Figure 7), in part because the trenches lacked colluvial wedge deposits typically associated with normal faults (Schwartz and Coppersmith, 1984; McCalpin, 1996). Both trenches show evidence for at least two and possibly three paleoearthquake events. However, only the West trench has age control derived from radiometric dates (Table 1). The following event record is based on these radiocarbon dates and by correlation of units between the two trenches (Figures 6, 7).

In the East trench there is clearly more displacement on the unit 7 tephra (roughly double) than on unit 6 surge deposits. This implies that unit 7 was faulted by more events and that the contact between units 7 and 6 is an event horizon, i.e., that there was a ground surface at or about the level of this contact when a paleo-earthquake occurred. In support of this, unit 7b (which is correlated to the same eruptive package as unit 7) in the West trench has a distinct paleosol developed on it, implying that it formed a stable ground surface for some time.

Based on the radiocarbon ages from the West trench, this faulting event (Event III) occurred between the dated unit 9 lake sediments, and unit 6b surge deposits. The entire interval bracketing this event based on the 1-sigma level of calibration uncertainty is from ca. 31.5 to 41.0 cal kyr BP (Figure 8). Based on the interpretation that the event occurred when unit 7 was at the ground surface and close in time to the emplacement of the unit 6 surges, it is possible that the timing of Event III is at the younger end of this range. Using the overlap of the dates for samples MP-2 and GAC-13-1, a possible refined age range of 33.7 to 34.6 cal kyr BP is suggested for Event III. This event is not well expressed in the West trench.

A second faulting event (Event II) is suggested by the sinuous upward terminating fissure and fault (f1w) in the West trench, which cannot be traced above unit 6 surge deposits into unit 2 (Figure 7b). Event II is bracketed by the date on unit 6 surge deposits (sample MP-2) and the date on unit 2 mudflow deposit (sample MP-3); i.e., between ca. 23.9 and 34.6 cal kyr BP. In the East trench this event may be expressed by faulting to a higher level in the stratigraphy, i.e., to within or even above unit 3 deposits. If this is the case, then a possible minimum age for the timing of Event

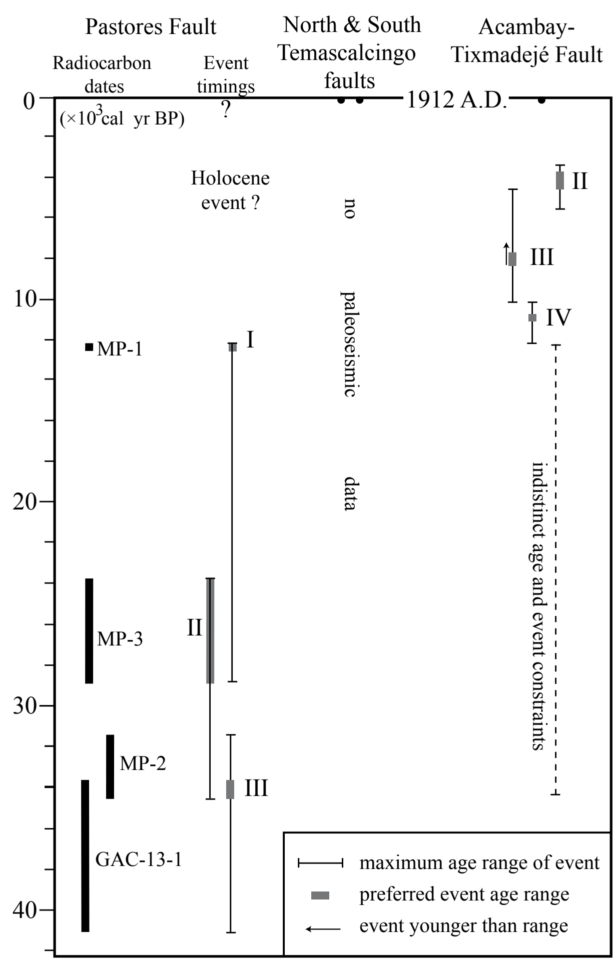

Figure 8. The timing of paleoseismic events on the Pastores fault from the Manto del Río site based on radiocarbon age data. For comparison, the timing of paleoseismic events on the Acambay-Tixmadejé fault from Langridge *et al.* (2000) and the 1912 co-seismic rupture of the Temascalcingo faults are included.

II is ≥23.9–29.1 cal kyr BP, i.e. older than, or equivalent to, the date on unit 2 (Figure 8).

A third faulting event (Event I) is implied by the upward termination of mapped faults within or through the unit 2 brown clay deposit near the surface and by the faulting of the main fault zone by the upper, vertical portion of the ffw fissure. This event must post-date the deposition of unit 2 and possibly also the development of the soil into unit 2. Therefore, this event must post-date the age of sample MP-3, i.e., ≤23.9–29.1 cal kyr BP. A further clue to the timing of this event is the dated sample from within the ffw fissure in the West trench. What must be explained is how material with an age of 12.2–12.6 cal kyr BP filled the fissure. The age of this fault-infill must be considered as a bulk or average age of its constituent parts. One possibility, and the preferred option, is that this material fell into, or was sheared into, the fault zone coincident with that faulting event. Based on these relationships, we infer a faulting event occurred at about the time of that date (12.2–12.6 cal kyr BP); an event that sheared the entire section, with the exception of the Holocene topsoil (unit 1). A more speculative interpretation is that the fault-infill material (sample MP-1) was deposited within the fissure at the time of one rupture event (12.2–12.6 cal kyr BP) and was subsequently re-sheared by a younger, Holocene event (Figure 8).

This type of speculation highlights a significant shortcoming of the Manto del Río site, which is the lack of preserved deposition at the site between ca. 20 ka and the present. A simple rule of thumb for selecting a trench site is that the rate of sedimentation at a site should be of comparable magnitude to the slip rate of the fault. Thus, if sedimentation is too low, or if deposits are eroded or absent, (i.e., sedimentation rate ca. 0), such as at a bedrock scarp, there will not be enough deposition to capture or date individual event evidence. In contrast, if the sedimentation rate is too high compared to the slip rate, e.g., a buried scarp, then the faulting may not be able to be exposed by typical trenching methods. Thus, at Manto del Río, there is an inadequate record of faulting during the last 20,000 years at this site due to a lack of preserved deposition along this portion of the fault between the Lerma River and the high rangefront (Figure 4a). Therefore, the events and their timings as described, though not without merit, should be considered a preliminary and minimum record. To attain a more complete record of the paleoseismicity of the fault, future studies could focus on more typical alluvial fan sites along the western part of the fault, adjacent to the highest part of the rangefront (Ortuño *et al.*, 2011; Ortuño, 2012).

We did not find evidence for a very recent surface faulting event, i.e., faulting and separation of surficial units, which could be attributed to the historic 1912 Acambay earthquake (Urbina and Camacho, 1913). These authors show a straight line defining the Pastores fault in their earthquake monograph, but without any measures of displacement along it. We concur with Langridge *et al.* (2000) that the Pastores fault did not rupture to the ground surface during the 1912 Acambay earthquake, based on a lack of documented surface slip and a lack of evidence for recent surface faulting (Figure 8). It is likely that either: Urbina and Camacho (1913) simply recognized and mapped the Pastores fault because of its impressive geomorphic escarpment; or, that they observed cracking or settlement along the fault due to the strong shaking from the earthquake itself. However, we concur with Urbina and Camacho's observations that the North and South Temascalcingo faults ruptured co-seismically during the 1912 Acambay earthquake (Figures 3, 8).

From these paleo-earthquake ages it is possible to derive a preliminary recurrence interval of surface faulting for the Pastores fault. Three paleoearthquake age intervals have been described for the latest Pleistocene and Holocene. A two-event recurrence interval based on the time between the oldest and youngest events in the trenches is ca. 10.6–14.4 kyr. The paleoseismic record from the trenches indicates that there has been either no, or possibly one, faulting event during the last 12.2 kyr. That is, the paleoseismic results from the Manto del Río site suggest a long elapsed time since the last rupture event, which is consistent with the estimated recurrence interval (rounded to 10,000–15,000 yr). This result is also consistent with the lack of a well-defined surface trace across much of the landscape, particularly across the young terraces adjacent to the Lerma River, and with the lack of faulting of the Holocene soil (unit 1) that has formed concurrently with human occupation of the Acambay region.

Slip rate of the Pastores fault

In this section we discuss the amount of displacement observed in the trenches and estimate a preliminary slip rate from the displacement and age data. In paleoseismic studies, slip rates derived from a larger number of events are more reliable than those developed from a single or two events. This is because of the possibility that the most recent elapsed time (since the previous faulting event) is not close to the average recurrence interval, and also because a longer, time-averaged slip rate may take into account variability in recurrence interval through time.

In the East trench there is ca. 0.9 m vertical displacement on the top of unit 7 near the floor of the trench. We use the date from the unit 9 lake sediments (33.7–41.0 cal kyr BP) to estimate a minimum dip-slip rate of 0.02 mm/yr, while a maximum dip-slip rate of 0.03 mm/yr is calculated using the unit 6 surge deposits as a minimum bracketing unit. In the West trench, ca. 0–24 cm of vertical displacement is measured on units near the base of the trench, while more cumulative displacement on unit 9 deposits is possible. Thus, a maximum dip-slip rate for the West trench is also ca. 0.03 mm/yr. Neither of these values takes into account the possible contribution of strike-slip movement. We consider that, if present, a strike-slip component of movement must be a minor contribution overall. This is because the tectonic geomorphology of the Pastores fault is indicative of normal faulting, as implied by fault plane striation inversion measurements from volcanic rocks immediately south of the Manto del Río site (Suter *et al.*, 1995a; unpublished data), that indicate NNE-directed extension perpendicular to the strike of the Pastores fault there.

These new slip rate values are comparable to that presented by Suter *et al.* (1995a) for the Pastores fault from immediately east of the Lerma River (Figure 5; ca. 0.04 mm/yr). This is reassuring considering that the Suter *et al.* (1995a) slip rate was averaged over a period of ca. 0.4 Ma, and also gives us confidence that the trenches probably crossed the main zone of faulting related to the Pastores fault. These slip rate estimates (0.02–0.04 mm/yr) from near the Lerma River may be somewhat lower than along the western part of the fault where the rangefront has its greatest height (see Figures 3, 4a).

Our results confirm that along with low rates of sedimentation and landscape evolution, that summed rates of extension across the entire Acambay graben, including the Acambay-Tixmadejé fault and Central fault system, are relatively low (ca. 0.25 mm/yr) (Langridge *et al.*, 2000). These rates are consistent with rates of extension in the Toluca region (Norini *et al.*, 2006) and not inconsistent with estimates of geodetic strain across central and southern Mexico (Márquez-Azúa and DeMets, 2003, 2009). Paleoseismic and geomorphic studies coupled with structural observations show that the Acambay graben is dominated by normal faulting and NNE-directed extension (Suter *et al.*, 1992; Langridge *et al.*, 2000)), rather than transtension (Ego and Ansan, 2002) of which we found little direct evidence for at the Manto del Río site.

Single-event displacement and magnitude relations

Using the faulting data from the trenches it is possible to estimate the single-event displacement for the Pastores fault at the Manto del Río site. The expression of faulting and the amount of displacement varies between the East and West trenches, despite their relative proximity. In the East trench there is ca. 0.9 m dip-slip displacement on the top of unit 7 and ca. 0.5 m displacement on units higher up in the trench. If this displacement is accounted for in two events only, then the single event displacement is ca. 0.4–0.5 m. However, if we consider all three latest Pleistocene to Holocene displacement events (Events I-III), then the average single-event displacement could range from ca. 30 to 50 cm. This latter range is more consistent with the displacements and the number of faulting events indicated from the West trench, where the single-event displacement was ≤24 cm.

Based on the geologic data from the East trench it is possible to estimate the magnitude for a Pastores fault earthquake using the maximum (50 cm) and average (90 cm in three events) single-event displacement. Table 2 presents results of estimating earthquake magnitude using regressions of historical earthquake data for displacement and rupture length from Wells and Coppersmith (1994). These relationships both yield magnitudes of M 6.4 for maximum and average displacements on normal faults.

It is not clear whether such maximum or average values for the Manto del Río site are representative of the maximum and average values for the whole fault. To consider this, we constructed a profile using Shuttle radar (SRTM) topographic data that runs along the crest of the escarpment (footwall block) of the Pastores fault, running ca. 300 m south of the mapped active trace of the fault (Figure 9). The profile shows that the escarpment height is low at Canchesda, quite high and regular along the main escarpment of the fault, reaching a low where the Lerma River and Atlacomulco volcanic field cross the fault. The Lerma River area is a natural low in the profile of the fault and may also represent a low in displacement through time (slip rate) and single-event displacement, i.e., the river has found the easiest path across the fault. Conversely, in the eastern half of the fault across the Sierra de la Cruces, the fault traverses mountainous terrain but is less well expressed (as a graben) than in the west. Figure 9 displays a hypothetical slip distribution based on geomorphic observations along the rangefront of the fault (Ramírez-Herrera 1998; this study), that we consider could represent the along-strike single-event displacement or indeed slip rate. We infer that the slip rate measures presented in this study and by Suter *et al.* (1995a) and similarly the single-event displacements presented from the Manto del Río site may be biased toward lower values compared to the western part of the Pastores fault.

The inferred surface rupture length of the Pastores fault based on it geomorphic expression (i.e., from Canchesda to east of Atlacomulco) is ca. 26 ± 7 km, which equates to a magnitude of M 6.73 (range M 6.55–6.86) using the regression of Wells and Coppersmith (1994). Further, if we consider subsurface rupture lengths that extend from Canchesda to Timilpan (33 km), or also include rupture of the one of the fault traces between Canchesda and the Venta de Bravo fault (39 km total) then estimates of M 6.7 and M 6.8 are generated.

These results suggest that in terms of single-event displacement, the measurements from the Manto del Río

Table 2. Estimated earthquake magnitudes for rupture of the Pastores fault*.

	Parametric value	Magnitude M
Maximum Displacement (MD) ǂ	0.5 m	6.40
Average Displacement (AD) ǂ	0.3 m	6.35
Surface Rupture Length (SRL)	26 km	6.73
Subsurface Rupture Length (RLD)	33 km	6.68
	39 km	6.79

*Results are derived using empirical relationships in Wells and Coppersmith (1994). ǂ Data from the Manto del Río trenches.

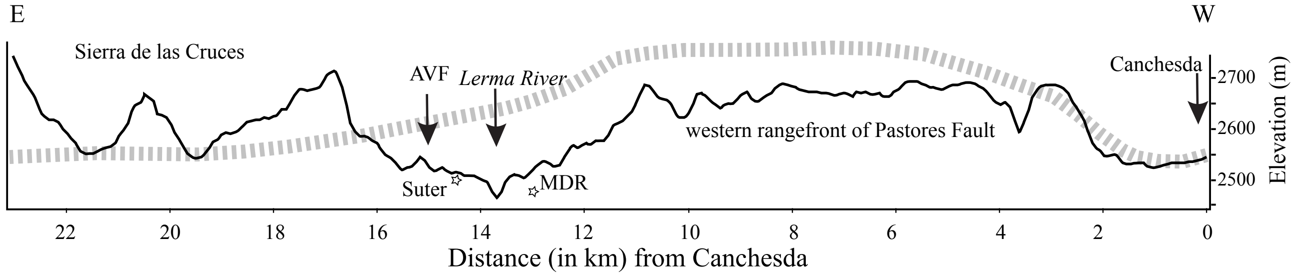

Figure 9. Profile of the rangefront elevation of the Pastores fault, viewed toward the south from Canchesda (km 0) to the Sierra de las Cruces range (black line). The Lerma River and the Manto del Río (MDR) trench site are at a topographic low in the fault profile east of the centre of the fault. The grey dashed bar represents a hypothetical displacement or slip rate profile for the fault, considering the geomorphic sharpness of the western part of the rangefront compared to river and the eastern half of the fault. The Atlacomulco Volcanic Field (AVF) and slip rate site of Suter *et al.* (1995a) are also shown.

site probably underestimate both the maximum and average displacement for the Pastores fault. In this case, we infer that the earthquake magnitudes derived from the surface and subsurface rupture lengths give more credible estimates for surface-rupturing Pastores fault earthquakes (M 6.6–6.8).

Seismic hazard posed by the Pastores fault

Overall, the preliminary results from this study highlight that the Pastores fault is active and is capable of generating a moderately large shallow and damaging earthquake. This paper documents that there have been paleo-earthquake displacements on the Pastores fault at Manto del Río, with maximum and average dip-slip displacements of 50 and 30 cm, respectively. These events are widely spaced in time (10–15 kyr) and imply a slip rate of 0.02–0.04 mm/yr, whose strain would be released by infrequent moderate earthquakes of magnitude M 6.6–6.8. These fault parameters are mutually consistent and point to the Pastores fault being capable of generating surface-rupturing earthquakes independent of other nearby fault sources. In addition, Figure 8 shows that our preliminary recurrence interval for the Pastores fault is 3-4 times longer than the ATF, and that the direct correlation of co-seismic ruptures between the ATF and Pastores fault is not practical at this time. Therefore, while rupture of all of the faults of the eastern Acambay graben (ATF, intra-graben, Pastores) is possible in a single large event (M >7), the preferred option based on the available data is for discrete rupture events on the Pastores fault. Considering that the 1912 Acambay earthquake generated ground shaking of Modified Mercalli Intensity (MMI) 7-8 in Mexico City and MMI 7 shaking in Querétaro (Suter *et al.*, 1996; Singh *et al.*, 2011), the impacts of a Pastores fault earthquake could be equally damaging to the modern infrastructure of central Mexico.

In terms of seismic hazard, another consideration is whether the Pastores and Venta de Bravo faults could rupture co-temporally. These two faults are strike equivalents and are separated merely by a small (ca. 1–3 km wide) stepover zone near Canchesda. No paleoseismic studies have yet been published for the Venta de Bravo fault, so to address this question it is necessary to further consider earthquake scaling relations, e.g., the combined fault lengths and the potential earthquake magnitude. The total length of these two southern graben-bounding faults is ca. 75 km. Rupture of the two faults co-temporally would produce an earthquake of magnitude M 7.2 with accompanying maximum and average vertical displacements of ca. 5 and 2 m (Wells and Coppersmith, 1994). This size of displacement is not observed in the trenches at Manto del Río, and large young fault scarps of this magnitude do not exist along the Pastores fault. Therefore, it is reasonable to assume that the Pastores (ca. 33 km long) and Venta de Bravo (ca. 42 km) faults would generally rupture independently in moderate to large earthquakes and that these ruptures terminate in the area of Canchesda.

Finally, it is useful to consider the structural role of the Pastores fault within the Acambay graben and what causes the differentiation of the Pastores from the Venta de Bravo faults, and similarly the eastern from western Acambay graben. Several workers have identified the break between the eastern and western halves of the Acambay graben (e.g., Suter, 1991; Suter *et al.*, 1992; Ramírez-Herrera *et al.*, 1998). These and other workers have also recognized that significant N- to NNW-striking fault systems of the Mexican Basin and Range intersect the TMVB (Suter *et al.*, 1995a; Alaniz-Álvarez *et al.*, 1998, 2002; Aguirre-Díaz *et al.*, 2000, 2005; Dávalos-Álvarez *et al.*, 2005). Aguirre-Díaz *et al.* (2005) discuss the regional effect of the Taxco-San Miguel de Allende (TSMA) fault system in central Mexico, including the Acambay graben, and mention that it is a major fault zone that apparently represents an important crustal boundary, as has been noted by other authors (Suter *et al.*, 1991; Molina-Garza and Urrutia-Fucugauchi, 1993; Soler-Arechalde and Urrutia-Fucugauchi, 1994; Alaniz-Álvarez *et al.* 1998, 2002). Within the Acambay graben, the break between the western and eastern halves corresponds to their intersection with the Taxco-San Miguel de Allende fault system across the graben. Though it shows little geomorphic expression or signs of activity cross-cutting the Acambay graben, the TSMA fault system is clearly expressed to the north of the Acambay graben as the Querétaro graben, and to the south related to the Perales fault (Figure 2; Aguirre-Díaz *et al.*, 2005). Thus, the TSMA fault system constitutes a major tectonic (terrane) boundary, and one which probably imparts an influence on the fault segmentation of the Acambay graben. This assertion is backed up by the apparent termination of the 1912 Acambay earthquake at the western end of the Acambay-Tixmadejé fault (Urbina and Camacho, 1913; Langridge *et al.*, 2000), without continuation on the Epitacio Huerta fault, and to the results presented here concerning the potential of the Pastores fault in relation to the Venta de Bravo fault.

CONCLUSIONS

The Pastores fault is a ca. 30 km long, active normal fault within the Acambay graben of central Mexico. Paleoseismic trenches excavated at Manto del Río, near the Lerma River were used to develop seismic parameters (slip rate, single-event displacement, recurrence interval, magnitude) for the fault. Both trenches showed evidence for at least two latest Pleistocene and Holocene paleo-earthquake ruptures. These were constrained by four radiocarbon dates from the West trench and through correlation of pyroclastic units between the West and East trenches.

The three paleoseismic events are bracketed at 12.2–23.9 cal kyr BP (Event I), 23.9–34.6 cal kyr BP (Event II), and 31.5–41.0 (Event III) cal kyr BP. Event I has a preferred timing of 12.2–12.6 kyr cal BP based on the occurrence of organic material included within the fault zone. The average recurrence interval of faulting is conservatively ca. 10–15 kyr. On the basis of a maximum single-event displacement (SED) of ca. 50 cm, an average SED of ca. 30 cm, and a subsurface rupture length of 34 km, a maximum magnitude of M 6.7-6.8 is suggested for surface rupturing events on the Pastores fault. The latest Pleistocene to Holocene slip rate at the trench site is ca. 0.03 mm/yr. Though moderate to large magnitude earthquakes on the Pastores fault are infrequent events, they need to be considered as part of an integrated seismic hazard plan for central Mexico, because such events can cause strong shaking (MM Intensity 7–8) out to distances of 100 km from the earthquake source, particularly in the shallow basins where the large cities are sited.

This study shows that the east-west striking Acambay graben has distinct eastern and western halves; being divided at the western ends of the Acambay-Tixmadejé fault and Pastores fault by a N- to NNW-striking structural zone, belonging to the older structure of the Taxco-San Miguel de Allende fault system.

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APPENDIX A. MANTO DEL RÍO STRATIGRAPHY

Manto del Río East trench
(19°50’39” N, 99°55’18” W)

Unit 1. Thick layer of black, massive soil [topsoil]. Blocky to columnar structure.

Unit 2. Paleosol, dark brown clay with sparse pumice clasts up to 2 mm size.

Unit 3. Paleosol developed on underlying pumice fall deposit; brown clay with abundant pumice clasts up to 1 cm in size.

Unit 4b. White, coarse pumice, normally graded, clast size 0.3 to 4 cm (maximum), average size 1 cm. Angular, clast supported deposit with matrix of clay. Contains organic clasts up to 1 cm. [Pumice fall deposit]

Unit 4a. Pumice fall deposit; fine white pumice lapilli, clasts <0.3 cm, clast supported; upper contact grades into overlying unit.

Unit 5. Paleosol with pumice clasts; yellow to brown sandy clay; formed by weathering of underlying deposit (unit 6b).

Unit 6b. Pyroclastic surge deposit; grey, matrix-supported (ash), rich in andesite blocks up to 30 cm size, but generally lithic-poor. Columnar jointed.

Unit 7. Yellow to light brown ash, moderately moist, unconsolidated deposit composed of glass shards, reworked top. [airfall tephra]

Unit 8. Pumice fall deposit; composed of coarse, white angular pumice, <5 cm, grading not clear; base not exposed.

Manto del RÍo West trench
(19°50’39” N, 99°55’21” W)

Unit 1. Recent soil; reworked material composed of sand, clay and lithics; includes pieces of pre-Hispanic? ceramics (*tepalcates*) and arrowheads. [topsoil].

Crack infill. Crack filled with sand, gravel and weathered silt. Contains organic material.

Unit 2. Massive dark brown clay. Paleosol formed in debris flood deposit. Sparse pumice clasts.

Unit 6b. Pyroclastic surge deposit 2; rich in lithics of andesite; cross-bedded; more weathered than surge 1; coarse-ash matrix with sandy appearance.

Unit 6a. Pyroclastic surge deposit 1; rich in lithics of andesite with imbrication towards the north; cross-bedded; richer in crystal content than lower ignimbrite; contains charcoal. Erosive base and top. Deposit is imbricated to the south

Unit 7b. Ignimbrite; unwelded pyroclastic flow deposit, similar to underlying ignimbrite; contains charcoal and lithic clasts; conformable with the underlying unit 7a ignimbrite and represents a second pulse of eruption; top is eroded by overlying unit. Contains some very large lithics up to 20 cm.

Unit 7a. Ignimbrite; unwelded pyroclastic flow deposit, pale brown, ash-supported, massive, contains crystals, small white pumice fragments (<1 cm), and sparse lithics of andesite; contains charcoal clasts as large as 5 cm. Contact with overlying unit is continuous and concordant; the deposit is interpreted as a dense pyroclastic flow formed during column collapse associated with underlying fall deposit.

Unit 8. Pumice fall deposit; composed of coarse, white pumice lapilli, <15 cm in diameter, and lithics of andesite, < 10 cm in diameter; grading is not evident, but deposit is clast-supported; contact with overlying unit is continuous and concordant.

Unit 9. Lake deposits; thinly bedded layers of brown, fine grained, muddy material (clay rich), in beds 4–5 cm thick, interlayered with thin (<1 cm thick) layers of red or black oxidized sand, which are rich in crystals and rounded lithic clasts; top is eroded; base not exposed.

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