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Tocuila Mammoths, Basin of Mexico: Late Pleistocene–Early Holocene stratigraphy and the geological context of the bone accumulation

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ABSTRACT

We report new stratigraphic, tephrochronology and dating results from the Tocuila Mammoth site in the Basin of Mexico. At the site there is evidence for a thin meteorite airburst layer dated between 10,878 and 10,707 cal BC at the onset of the Younger Dryas (YD) cool period. The Upper Toluca Pumice (UTP) tephra marker, caused by a Plinian eruption of the Nevado de Toluca volcano, dated from 10,666 to 10,612 cal BC, is above that layer. The eruption must have caused widespread environmental disruption in the region with evidence of extensive reworking and channelling by the Lake Texcoco shoreline and contributed to the widespread death and/or extinction of megafaunal populations, as suggested by earlier authors, but the new work reinforces the view that both catastrophic events must have caused large environmental disruption in a short time period of around two hundred years. There is no evidence for megafauna (mammoths, sabre toothed cats, camels, bison, glyptodonts) after the UTP volcanic event and subsequent lahars in the Basin of Mexico. At Tocuila, although there are some *in situ* tephra markers in nearshore lake sediments, such as the Great Basaltic Ash (GBA) and the UTP Ash, there is evidence of much reworking of several tephra populations in various combinations. The mammoth bone accumulation is reworked in a lahar sequence (volcanic mudflow) derived from several source sediments but associated with the major UTP Plinian eruption. Paleoindian populations were also present in the Basin of Mexico during the YD period, where several Paleoindian skeletons were found associated with the UTP ash deposits, e.g. Metro Man, Chimalhuacan Man and Tlapacoya Man.

1. Introduction

We report detailed new work and a re-interpretation of the sedimentology, dating and origin of the San Miguel Tocuila Late Pleistocene mammoth site, one of the most important Late Pleistocene and early Holocene palaeontological sites in the Basin of Mexico (Morett et al., 1998a,b). In what follows we discuss the complexities of the tephra stratigraphy, the mammoth assemblage and describe a newly recognised and dated meteorite airburst layer that extends the geographic range of the reported YD meteorite burst event (Firestone et al., 2007) to west central Mexico (Israde-Alcántara et al., 2012) and the Basin of Mexico. Tocuila is located in a western suburb of Texcoco, Mexico State (19°31.23 N, 98°54.49 W) in a former near-shore, Late Pleistocene, higher stand of Lake Texcoco, to the north-east of Mexico City (Fig. 1).

The site was discovered by chance on July 30th, 1996 and initial excavations were undertaken by Luis Morett-Alatorre and his team from Chapingo University between August and October. In this early phase of excavation the remains of at least seven mammoths (*Mammuthus columbi*, *Falconer 1857*) were identified approximately 3 m below the surface in an area of 28 m^2 (Morett et al., 1998a,b). Also evidence for worked mammoth bones in the assemblage was presented (Arroyo-Cabrales et al., 2001). Subsequently sedimentological and tephrochronological work from the deposits was carried out by Siebe et al. (1997, 1999) who suggested that the mammoth remains were incorporated into a lahar derived from the Pumice with Andesite (PWA) eruption of Popocatépetl and hence with an age of between 16,026 and 15,636 cal BC. Subsequently Gonzalez and Huddart (2007) challenged this view and suggested that the stratigraphy was much more complicated and

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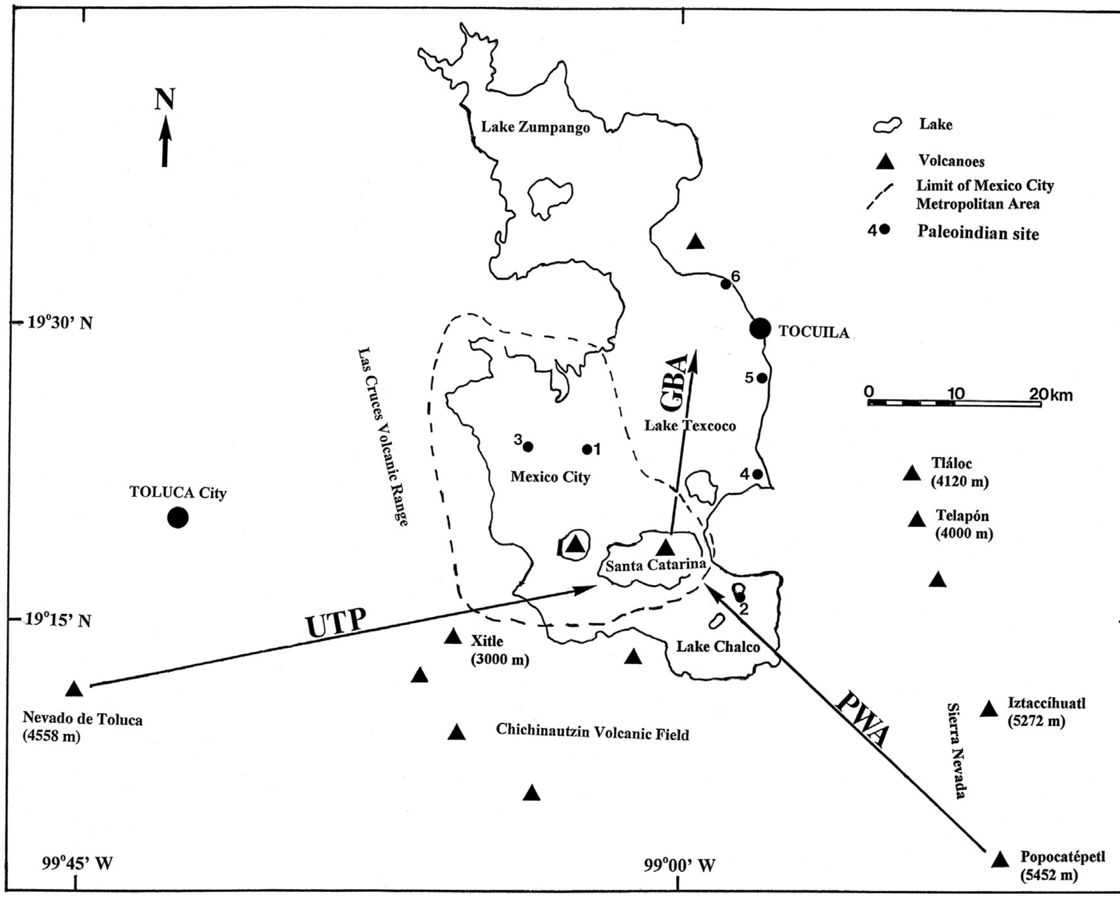


Fig. 1. Location of the Tocuila Mammoths site in the Basin of Mexico, showing with a black line the maximum extent of the Late Pleistocene lake before drainage. Also shown are the names of sub-lake basins after partial drainage after Spanish colonisation and the main volcanoes that produced the main tephra markers: Sierra de Santa Catarina for the GBA (Great Basaltic Ash), Popocatépétl Volcano for the PWA (Pumice with Andesite ash) and the Nevado de Toluca Volcano for the UTP (Upper Toluca Pumice). The black arrows indicate the main dispersion axes for the ash falls. Paleoindian sites: 1) Peñon Woman III, 2) Tlapacoya Man I, 3) Metro Man, 4) Chimalhuacan Man, 5) San Vicente Chicoloapan Man, 6) Tepexpan Man.

the mammoths were incorporated into an UTP laharic event and so much younger. The subsequent work between 2007 and 2013 reported here reinforces this conclusion but adds the recognition of a meteorite airburst layer in the Tocuila sequence.

Mammoth bones are found frequently in the Basin of Mexico and adjacent areas of the Mexican High Plateau (Freudenberg, 1922; Reyes, 1923; Hay, 1925; Díaz-Lozano, 1927; Ordoñez, 1939; Martinez del Río, 1952; Pichardo de Barrio et al., 1961; Lorenzo and Mirambel, 1986a,b; García-Bárcena, 1989; Carballal-Staedtler, 1997). At some localities, such as Santa Isabel Iztapan I and II and San Bartolo Atepehuacán, mammoth bones have been found associated with Paleoindian artifacts, confirming the presence of humans in this area during the Late Pleistocene (Aveleyra de Anda and Maldonado-Koerdell, 1952a,b; Aveleyra de Anda, 1955; Armenta-Camacho, 1959; Irwin-Williams, 1978; Lorenzo and Mirambel, 1986a,b). However, there has often been controversy as to the association of mammoth bones and artefacts and the dating of these sites (e.g. Gonzalez et al., 2001; Huddart and Gonzalez, 2006; Gonzalez and Huddart, 2008; Lamb et al., 2009). Tocuila is important as it adds to these data and the current work places the palaeontological and archaeological finds in a sedimentological, tephrochronological and radiocarbon dated framework. The location of the site is around 2240 m a.s.l. in the north-eastern, flat-floored, Basin of Mexico, in a closed hydrographic system existing since about 700 ka BP (Vázquez Sanchez and Jaimes Palomera, 1989). There were a series of former lakes (Fig. 1) in sub-basins that formed a larger lake approximately 1000 km^2 in area prior to artificial drainage (Sanders et al., 1979). Lake Texcoco was the lowest and most saline of these sub-basins, but after draining in the 1900s (Bradbury, 1971, 1989) the lake occupies now a very restricted area to the north-east of Mexico City and it is surrounded by salt marshes and former shallow gradient, deltaic and river floodplain environments. The Tocuila mammoth site is located within a rapidly growing western suburb of Texcoco on sediments deposited in a nearshore lacustrine environment of the former Late Pleistocene lake. To the east lies the western slope of the northern Sierra Nevada and Tláloc volcano which is now known to have been active also during the Late Pleistocene (Huddart and Gonzalez, 2004; Huddart and Gonzalez, 2006; Huddart and Gonzalez, 2012; Macías et al., 2012). Pyroclastic flows, ashes, block-and-ash flows, lahars and fluvial sediments make up an extensive volcaniclastic piedmont linking the volcano to the lake basin to the east and south-east of Texcoco. Other potential sources of volcaniclastic sediments are from small monogenetic volcanoes in the Basin of Mexico e.g. Cerro Santiago, Cerro Totolcingo close to Tepexpan to the north and the larger stratovolcanoes of Nevado de Toluca (producing the UTP tephra) and Popocatépetl (producing the PWA tephra), south-west and south-east respectively (Fig. 1 shows the main dispersion axes for these large tephra falls), (Bloomfield and Valastro, 1974, 1977; Robin, 1984; Boudal and Robin, 1989; Macías and Arce, 1997; Macías et al., 1997; Arce, 1999; García-Palomo et al., 2002; Arce et al. 2003; Schaaf et al., 2005; Espinoza-Pereña and Martin-Del Pozzo, 2006; Siebe and Macías, 2006; Macías, 2007; Macías et al., 2012). The basin climate today is subtropical with rainfall predominantly in the summer (c.500–1000 mm) but to the east the mountains provide a wide range of temperature and rainfall gradients and the basin seems highly sensitive to climatic change (Metcalfe et al., 2000). There is no modern vegetation remaining around Tocuila due to anthropogenic influence but the altitudinal gradient would have formerly ranged from juniper forest, xerophytic scrubland, pine-oak forests, silver fir forest, grassland and subalpine grassland (Rzedowski and Rzedowski, 1979, 1985). Immediately adjacent to Tocuila the pre-drainage environment would have been one supporting emergent and sub-emergent lakeshore vegetation. Climatic variation though in the last 50,000 ka BP has seen fluctuations in vegetation and lacustrine environments (e.g. Lozano-García and Vázquez Selem, 2005; Lamb et al., 2009). The climate of the Lake Texcoco basin during the last 20,000 ka BP has been summarised in Lamb et al., 2009, (Table 1, p.2002).

2. Methods

2.1. Stratigraphy

The location of the Tocuila site is shown in Fig. 1. Ten stratigraphic sections were described and studied in detail to illustrate the major stratigraphic changes at the site (Fig. 2), including the section described in Siebe et al. (1999) (equivalent to our stratigraphic section 4). The sections ranged in thickness from 1.63 to 3.59 m (Fig. 3a and b) and were described in terms of their lithology, grain size, colour, tephrochronology, macro- and microfossils (pollen and diatoms) where appropriate. Representative samples from each stratigraphic layer were taken including all identified tephras and where there were changes in lithology. Five of the stratigraphic sections were located in the main Tocuila Mammoth Museum trench which is kept permanently open for public display (stratigraphic sections 1–4 and A). To the south of the museum trench five sections (B–F) were studied in trenches opened in 1998 by Luis Morett-Alatorre and his team to establish the extent of the mammoth bone accumulation at the site. These are no longer exposed but were described and sampled by two of the authors (SG, DH) at the time.

2.2. Tephrochronology

For each of the volcanic ash (tephra) units identified, representative samples were taken to obtain tephra (volcanic glass) major element geochemistry at the NERC Electron Microprobe Unit at Edinburgh University using a Cameca SX100 Electron Probe Microanalyser. Samples were impregnated in araldite on microscope slides; sample surfaces were polished with 6 μm and 1 μm diamond paste and then cleaned in an ultrasonic bath for forty minutes with deionised water. The slide samples were carbon coated and analysed using the wavelength dispersive method, with an acceleration voltage of 15 kV, a 5–8 μm beam size and a 2 nA beam current. Homogenous Lipari glass and an andradite (garnet) were analysed at regular intervals, every 30–40 analyses, as a quality check and to establish the probe stability. Oxide totals above 95% were normally achieved and the results compared with the tephra database from Central Mexico (www.tephrabase.org).

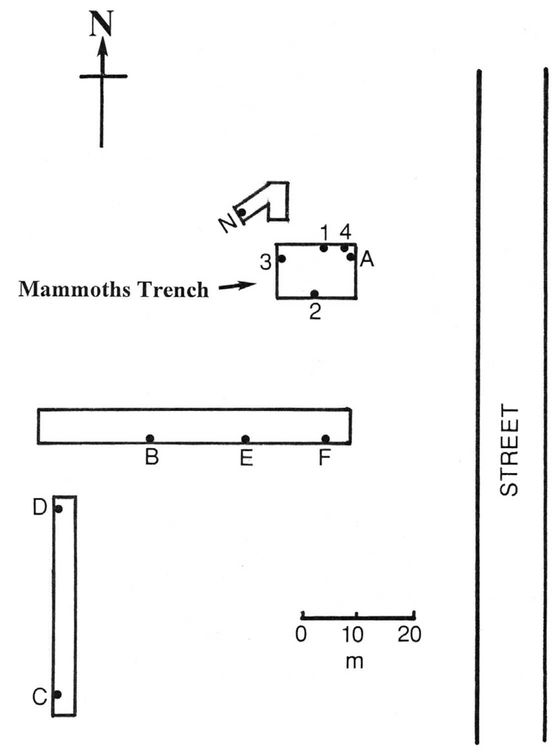


Fig. 2. Location of stratigraphic sections studied at Tocuila. Stratigraphic sections A, B, C, D, E and F, described and sampled in 1998. Stratigraphic sections in main Mammoths Museum trench: 1, 2, 3 and 4 described and sampled in 2000.

2.3. Pollen and diatoms studies

For pollen analysis a 1 cm^3 of sediment was taken and a routine pollen extraction technique was used (Faegri and Iversen, 1989). The samples were treated successively with solutions of HCl, KOH, HF, HCl and acetolysis. Minimum counts of 100 pollen grains of

Table 1
Radiocarbon dates from Tocuila and other Late Pleistocene Paleoindian sites or tephra deposits in the Basin of Mexico: a) After Gonzalez et al. (2003 and 2006); b) This paper. c) After Arce et al. 2003. d) After Mooser 1997. For the lahar deposits containing the mammoths Siebe et al. (1999) reported radiocarbon dates from charcoal fragments between 12,615 ± 95 BP (13,335–12466 cal BC) at the base and 10,430 ± 75 BP (10,611 to 10,105 cal BC) at the top of the lahar sequence but some of the reported dates were inverted due to the reworking of the deposits. *Calibration calculated using OxCal 4.2, IntCal13 curve, after Bronk-Ramsey, 2009.

Material	Lab. Number	Specimen number/layer	Species	$\delta^{13}C$	AMS years BP uncalibrated	Calibrated dates years BC*
Gastropods, Tocuila	OxA-15840	Section 1–11	–	−9.8	10,016 ± 39 (b)	9762–9365 cal BC
Tlapacoya Man I, Paleoindian	OxA10225	16/1968/DAF/INAH	*Homo sapiens*, skull	−15.4	10,200 ± 65 (a)	10,199–9664 cal BC
Upper Toluca Pumice (UTP), charcoal	–	–	–	–	10,500 ± 50 (c)	10,666–10,426 cal BC
Peñon Woman III, Paleoindian	OxA-10112	07/1959/DAF/INAH	*Homo sapiens*, humerus	−11.6	10,755 ± 75 (a)	10,816–10,612 cal BC
Charred vegetation, Tocuila	Beta-325672	Section A-6 (meteorite layer)	–	−22.1	10,800 ± 50 (b)	10,878–10,707 cal BC
Mammoth bone, Tocuila	OxA-7746	Toc-793, mammoth 5	*Mammuthus columbi*, skull	−12.6	11,100 ± 80 (a)	11,154–10,820 cal BC
Mammoth bone, Tocuila	OxA-10307	Chapingo Museum collection	*Mammuthus columbi*, rib	−15.3	11,255 ± 75 (a)	11,335–11,041 cal BC
Pumice with Andesite (PWA) charcoal	–	–	–	–	14,600 ± 65	16,026–15,636 cal BC
Great Basaltic Ash (GBA) charcoal	–	–	–	–	28,600 ± 200(d)	31,366–9664 cal BC

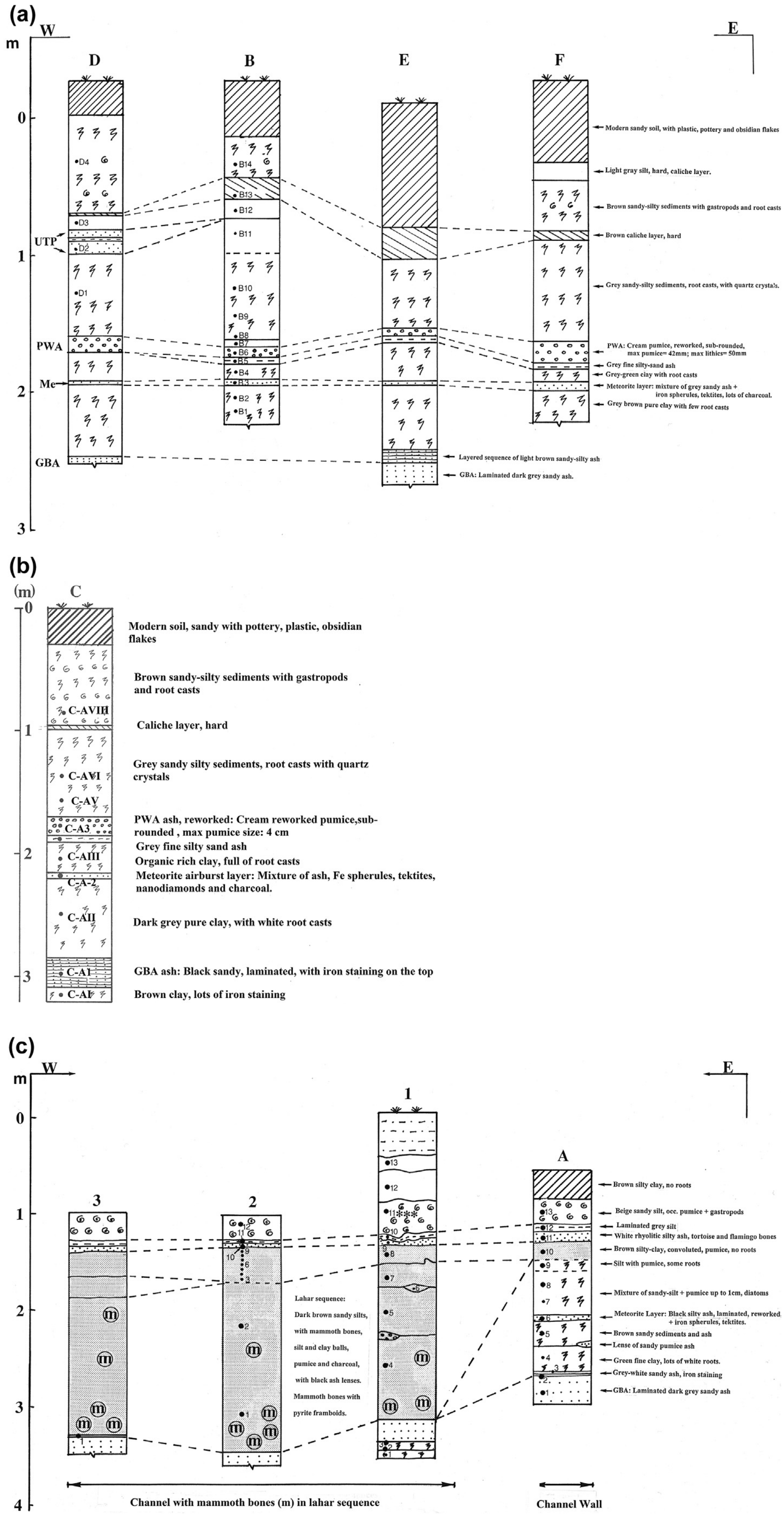


Fig. 3. a) Stratigraphic sections measured in Tocuila south of the Mammoth Trench: B, D, E and F. Me: shows the position of the meteorite outburst layer and UTP, PWA and GBA show the position of the main tephra layers in the sequence. b) Stratigraphic section C, south of main Mammoth Trench. c) Sections in main Mammoth Trench: 1, 2, 3 and A. Letter "m" in a black circle refers to presence of mammoth bones in the sequence. Numbers and letters on sections refer to where sediment samples were taken. Samples A1 to A6 from section A were sampled for pollen and diatoms (See Fig. 7).

woody taxa were made for each sample. Pollen diagrams were constructed using C2 (Juggins, 2003–2011). A Pinus/Pinus + Quercus (P/P + Q) ratio (Park et al., 2010) was calculated using pollen raw data. This ratio is related to precipitation, indicating drier conditions as the ratio becomes higher.

Diatom analysis: For diatom processing a 0.5 gr subsample of sediment was taken and 50 ml of 30% hydrochloric acid was added and heated on a hot plate at 100 °C until total digestion, in order to remove carbonates. After that 100 ml of 30% hydrogen peroxide was added and samples were heated until evaporation of organic material, then the sample was repeatedly washed with distilled water until neutralized. After treatment, diatoms were mounted in Naphrax® (R. I. = 1.74). Taxonomic identification of diatoms was based on specialized literature, e.g. Battarbee (1986).

2.4. Potential meteorite airburst layer materials

After the identification and study of the different stratigraphic units present (sediments and tephras) and two new radiocarbon dates (see Table 1), it was decided to study in more detail all the layers from the stratigraphic section A (channel wall) in the main mammoth trench to see if the layer associated with the YD meteorite airburst layer described by Firestone et al. (2007) was present at the site. This was because of the age of the sequence. It was found that only in layer A-6, 10 cm thick, was there evidence of materials potentially associated with a meteorite airburst impact. There were large amounts of charred vegetation and charcoal, which were radiocarbon dated, and microscopic Fe spherules, microscopic tektites (melted SiO_2 spherules) and nanodiamonds which were analysed (see below).

2.4.1. Magnetic Fe microspherule and nanodiamond analysis

Concentration of microscopic Fe spherules from the layer was carried out manually using a strong Neodymium magnet following the method proposed by Firestone et al. (2007). Individual Fe spherules were separated and their morphology was examined using a binocular microscope and mounted on transparent tape. Their chemical composition was obtained using an electron scanning microscope (SEM) and photographs taken. Nanodiamonds were extracted and analysed by Wendy Wolbach at De Paul University, USA (for methodology see Israde-Alcántara et al., 2012).

3. Results

3.1. Stratigraphy at Tocuila

The studied stratigraphic sections are divided into two main areas: A) Sections to the south of the main Mammoth Trench (Fig. 3a) and B) Sections in the main Mammoth Trench (Fig. 3b and c).

The lowest two stratigraphic units can be found in all the studied sections if they are deep enough but in the excavated sections to the south of the Mammoth Trench there is no Pleistocene bone material present and only one, poorly sorted, silty, sandy unit, possibly a lahar is present. This unit is in major contrast to the main Mammoth Trench which has yielded a large number of Late Pleistocene vertebrate bones (mainly *M. columbi*) (Fig. 4a) incorporated in several thick units of poorly sorted, silty, sandy units interpreted as lahars by Siebe et al. (1999). However, other mammoth bones are also located by chance periodically close-by as shown in Fig. 4b from a large ditch excavated approximately 250 m NW of the Tocuila Museum where more lahar deposits with mammoths were found and sampled (sample U3A, see supplementary information). The common stratigraphic units at the Tocuila site are described first, then the sections to the south, followed by the main Mammoth Trench sections.

3.1.1. Common units present in all stratigraphic sections

In stratigraphic order from oldest to youngest (Table 2) there is a:

a) Grey or brown, iron-stained, silty clay, or a grey, laminated clay at the base of the measured sections.
b) Black, basaltic-andesitic sandy ash.
c) Lighter coloured ash on top of previous ash.

3.1.2. Sections to the south of the Tocuila Mammoth Trench

These sections are illustrated in Fig. 3a and summarised/interpreted in Table 2. Only in section D above the silts/silty sands/clays is there found a series of three ashes, interpreted as the *in situ* UTP ash, the only location where this unit is *in situ*.

3.1.3. Tocuila Mammoth Trench sections

The location of the stratigraphic sections is shown in Fig. 2, and the measured stratigraphic sections in Figs. 3b, 6a and 6b. Above the common basal silty clays and indurated black sandy ash at the base (Sample A-1), the sediment sequence is infilling a channel and it is very different from the stratigraphic sections studied to the south. The exception is section A (on the channel wall) which has 55 cm of brown clay, with white root casts. Incorporated into this unit is a lens (4 cm × 5 cm) of sandy ash, which shows two tephra populations. One has a mean SiO_2 from four shards of 55.5% and the other a mean SiO_2 from three shards of 74.4%. This is overlain by a conspicuous 10 cm thick layer of black, finely laminated, reworked dark grey silty/sandy ash, waterlaid, with large amounts of charcoal, volcanic glass, with a few microscopic melted quartz crystals (tektites), microscopic black iron spherules, pyrite framboidal spherules and nanodiamond traces (See stratigraphic section A, sample A-6 in Fig. 3b). This layer is ~1.30 m below the surface and shows two populations of tephra shards (the mean of eight shards is 55.3% SiO_2 and the mean of three shards is 67.8% SiO_2). This is overlain by 45 cm of sandy silt, with white root casts and diatoms. There are also pumice clasts, up to 1.0 cm in diameter in this silt, which grades transitionally into a further silt unit, with pumice clasts and root casts. This is overlain by a silty-clay, with no root casts in contrast to the units below. It is followed by 9 cm of pale-grey, silty ash, which becomes whiter towards the top of the unit. This unit has a mean SiO_2 for six tephra shards of 66.3% and a mean SiO_2 for four shards of 74.6%. This grey-white ash is overlain by 8 cm of dark grey, laminated, silty clay with diatoms. The section is completed by 45 cm of sandy clay and grey-brown, silty clay, with gastropods throughout.

In the other Mammoth Trench sections, the upper layers are nearly identical and the pale-grey-white, silty ash and the overlying grey, laminated clay are distinctive marker horizons. In these sections the white fine sand ash contains diatoms and fragments of a turtle (*Kinosternon*) carapace. However, the lower parts of the stratigraphic sections 1, 2, 3, and 4 are very different from section A and the sections to the south. Section 2 was measured in the same location as a section measured by Siebe et al. (1999). It is dominated by an ungraded, poorly sorted unit, 1.75 cm thick which has a silty-sandy, ash matrix. It has included rounded silt balls up to 1 cm in diameter, pumice lapilli clasts up to 3.5 cm in diameter and andesitic lithic clasts. The clasts show a macrofabric orientation (Fig. 5a) which indicates a transport direction from SE–NW. This is the unit interpreted as a distal overbank lahar facies by Siebe et al. (1999). They distinguished two flow units which are "separated by a barely visible, flat discontinuity." This unit contains many

Fig. 4. Mammoth remains in Tocuila. 4a) Mammoth bones in the main Museum Trench. 4b) Isolated mammoth bones found in a lahar channel outside the main Museum during waterworks street excavations in the continuation of the Tocuila channel to the NW (Sample U3A in Supplementary Information).

Table 2
Sections to the South of the Mammoth Museum Trench: A review of stratigraphic units from older (base) to younger (top). Also SiO_2 content of main tephra units.

Stratigraphic Unit Description	Maximum thickness (cm)	SiO_2%	Interpretation
Sandy silt, pottery, obsidian flakes; modern debris like plastics	90	NA	Made ground, anthropogenic, reworked.
Silty sand/silty clay, root casts, gastropods	72	NA	Lake
Indurated, sandy silt, root casts	0.5–25	NA	Lake, caliche
Poorly sorted, sandy silt, $CaCO_3$ pyroxenes, quartz	17	67.3–72.7 (12 shards). One shard 76.0	UTP ash reworked as a lahar
3 ashes in section D, Light grey sandy ash	18	68.7–71.7 (13 shards); Bulk composition: 62.3	UTP ash (rhyolitic)
Grey sandy silt with root casts	70	NA	Lake
Cream pumice, lapilli to coarse sand	14	55.6–61.5	PWA ash reworked
Organic clay with root casts	25	NA	Lake
Dark grey, laminated sandy ash	7	56.37–61.87 (7 shards); 72.5–76.3 (3 shards)	Meteorite layer, mixed ash populations, with Fe spherules, tektites, nanodiamonds and charcoal
Dark grey clay with root casts	63	NA	Lake
Beige, sandy-silty ash	1.5	68.2 (4 shards)	Part of GBA ash, top
Black, sandy ash, subrounded pumice and lithic fragments.	30 cm	55.6–61.5 (18 shards) Mean value: 58.06 Bulk composition: 55.7	GBA ash (basaltic-andesitic)
Grey, laminated clay, root casts	93 cm +	NA	Lake

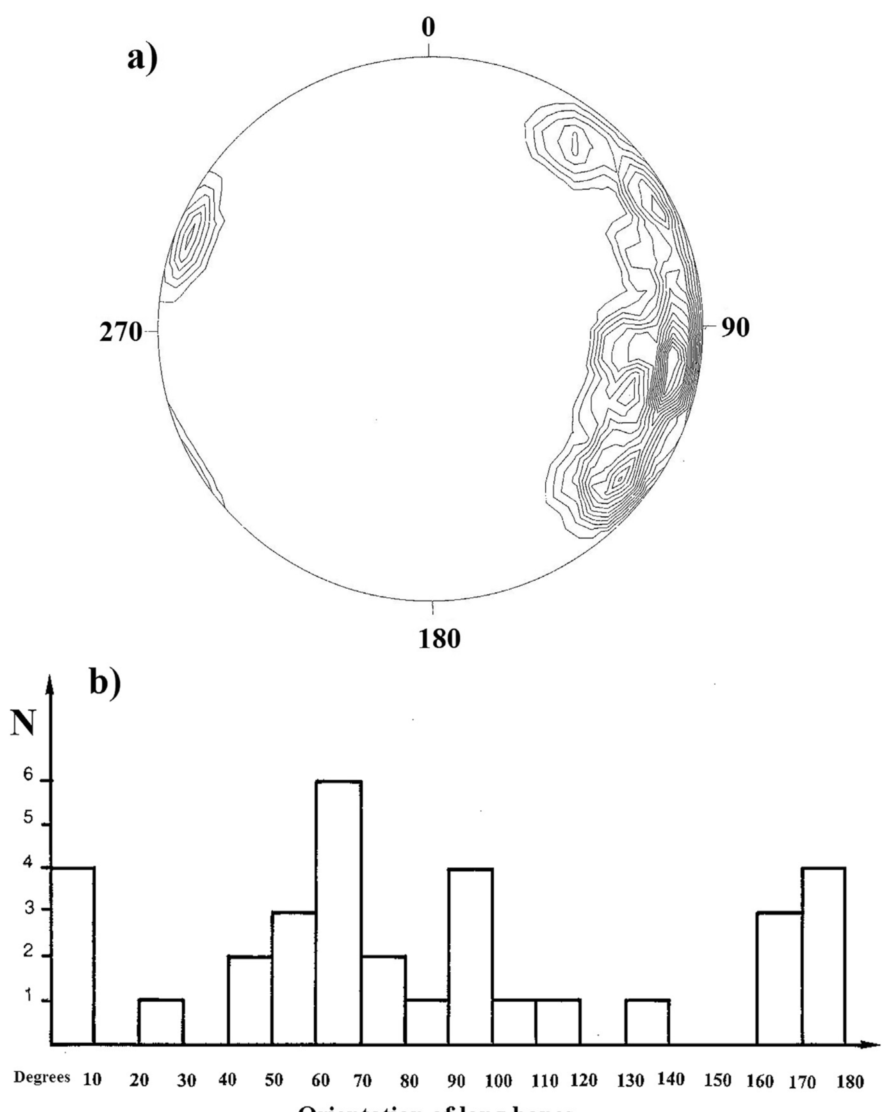


Fig. 5. a: Stereonet showing three dimensional macrofabric orientation from clasts in the Tocuila lahar (volcanic mudflow) deposits, plotted on the lower hemisphere of a Lambert/Schmidt equal area projection. b: Histogram showing the orientation of 33 elongated mammoth bones (ribs, femurs, tusks) found in the main lahar unit at Tocuila.

charcoal fragments and seeds throughout that have been dated by AMS ^{14}C to between 10,220 ± 75 BP at the top of the unit and 12,615 ± 95 BP at the base (Siebe et al., 1999). Towards the base of this unit there is a large concentration of bones (bone bed) and of approximately one thousand bone fragments excavated over 90% belong to *M. columbi* and have been attributed to at least seven individuals, including three almost complete skulls, two incomplete skulls and four mandibles (Morett et al., 1998a, b). The skeletons are disarticulated and the elongate bones tend to be subhorizontal and aligned in an ESE–WSW direction which suggested flow alignment to Siebe et al. (1999). However the bones in general look well preserved and the tusks are still attached to some skulls, suggesting that they have not been transported far. In the work reported here the orientation of thirty-three elongate bones (femurs, ribs, and tusks) are plotted in Fig. 5b. The excavation has also yielded other faunal species, including fragments of horse (*Equus sp*), bison (*Bison sp*), duck (*Anas sp*), goose, flamingo (*Phoenicopterus cf. ruber*), rabbit, camel (*Camelops hesternus*), turtle (*Kinosternon*), although no stratigraphic positions in the sequence were given (Corona and Arroyo-Cabrales, 1997; Siebe et al., 1997).

In our stratigraphy there is a transitional contact with 35 cm, yellow-brown silt which has charcoal fragments throughout and vertical joints. This unit is below the marker white sandy ash. Siebe et al. (1999) suggest that their 68 cm lahar unit grades vertically into a silty loam palaeosol but we do not recognise this unit.

In our section 3 the poorly-sorted lahar unit is 1.42 m thick and is overlain by brown, clayey silt which has isolated silt balls, isolated subrounded pumice clasts and charcoal fragments. In section 1 above the basal black basaltic andesitic ash there is an 86 cm unit of poorly-sorted lahar sediment which shows small channels eroded into it. There are three lahar units above (52 cm, 25 cm and 19 cm respectively) which have the following common characteristics: subrounded pumice clasts, rounded silt clasts and convolute lamination in a sandy silt matrix. Included at the top of the lowest of these three units is a clast of ash, 15 cm × 10 cm. Laterally to the east section 1 passes into the section 4 (Fig. 6a and b). The lahar sequence cuts a channel across the lower, fine sediment/ash succession, which is seen in Fig. 6a. The erosional margin shows small lenses of reworked, PWA ash higher than their *in-situ*, stratigraphic position. The lahar deposits are composed of the same units as described in section 1, although the lower unit is much thinner and the second unit thicker than in section 1. The latter has small clasts of black ash. The third, 45 cm unit has small, basal, erosional channels which are infilled with convoluted, brown, clayey silt. Similarly the top unit, with a maximum thickness of 30 cm, is composed of convoluted, olive, sandy silt.

The stratigraphy in the trench to the north (section N) shows the same basal sequence of ashes, clays and fine sands. The lahar deposit here is much thinner in the measured section but thickens to the north-east. It is 43 cm thick and fills a small channel which in the basal part has granule gravel, with occasional pumice clasts up to 2 cm in diameter and occasional clay balls. It grades vertically to sandy silt, without clasts. It is capped by blue-grey, clayey silty ash which has been noted as an easily recognisable, marker unit in the main Mammoth Trench. Above are clayey silts and brown, organic silts, with layers of compressed vegetation.

3.2. Tephrochronology results

The geochemistry results for the tephra samples are summarised in Table 3. All results of this study are included in the supplementary information and the tephra samples studied are stored at the Liverpool John Moores University Tephra Collection, UK, along with all other Tocuila sediment samples.

3.2.1. Pollen results

Selected pollen samples were studied from samples taken from stratigraphic section A (channel wall) in the Mammoth Trench (Fig. 3b) from the base of the section (GBA ash) to the layer A-6 (with the evidence of meteorite impact minerals) and a pollen diagram was constructed (Fig. 7). A sample from the GBA ash (A-1), showed evidence of an open temperate forest with taxa like Pinus, Quercus, Alnus. These taxa were in the same proportion as Compositae and Gramineae, indicating a tendency to arid conditions. This was corroborated by the high P/P + Q ratio, which is related to arid conditions Park et al. (2010). After this period the forest cover increased (sample A-5) and the taxa from open habitats decreased, indicating that the environment became wetter, favouring the development of a forest dominated by Pinus and freshwater conditions but always a low lake level with a macrophyte belt. After this event the conditions remain wetter with low P/P + Q ratio values. Sample A-6 (meteorite layer) showed an increase in Alnus indicating cool conditions and a change that caused the formation of an open forest.

3.2.2. Diatom results

Diatom analysis was carried out on the same samples studied for pollen in the section A (Fig. 7) Sample A-1 diatoms are characterised by epiphytic diatoms (Navicula spp., Nitzchia, Pinnularia), periphytic diatoms (*Staurosira construens*) and *Cyclotela meneghiniana*, suggesting an increase in ionic conditions in the lake that reach their maximum concentration in A-3 with the Campylodiscus, Surirella and *Anomoeoeneis spharaeropora* associations. In sample A-4 the diatom record is characterised by epiphytic species, there is evidence for the development of a saline lake with high ionic concentrations, with the characteristic *Campylodiscus clypeous* and *Anomoeoeneis sphaerophora*. In sample A-5a the lake decreases in salinity promoting the development of a large diversity and abundance of diatom flora, although still with saline conditions, indicated by the presence of *C. clypeous*, *Surirella peisonii* and *Anomoeoeneis sphaeropora*, followed by *Rhopalodia gibberula*, *Amphora lybica* and other epiphytic diatoms. In sample A-5 the previous diatom association changes to a flora with *Navicula aff microcari*, *Navicula cuspidata* and *Naviculaaff lybonensis*, *Achnantes lanceolata*, *Epithemia turgida*, *Fragilaria construens* and *Rhoicosphenia*. This indicates less saline conditions but always with a low lake level with a macrophyte belt to sustain the epiphytic taxa. The flora at level A- 6 (meteorite airburst layer) is dominated by *Navicula* followed by Gomphonema, Anomoeoneis, Fragilaria and Eunotia, which indicates a marsh environment, with freshwater conditions at the time of the meteorite burst.

The pollen and diatom samples are stored at the Geology and Mineralogy Department at the Universidad Michoacana de San Nicolás de Hidalgo, Mexico.

3.3. Potential meteorite airburst layer results

In sample A-6 taken from a layer 10 cm thick from section A, at 1.60 m below the surface, we found evidence for the following minerals, associated with a meteorite impact burst event (with no evidence of a crater): magnetic Fe microspherules, microtektites, pyrite framboids, large amounts of charcoal with a radiocarbon date of 10,878 to 10,707 cal BC and traces of nanodiamonds. Using the SEM the microscopic Fe spherules showed common surficial dendritic patterns or polygonal structures associated with melting and quench-melt textures (Fig. 8). This pattern has been found at several other proposed YD meteorite impact field sites (Wittke et al., 2012). The Fe spherules showed diameters between 40 and 90 microns, averaging 65 μm. Spherule shapes commonly are spherical and slightly oval. In comparison with the Cuitzeo Lake

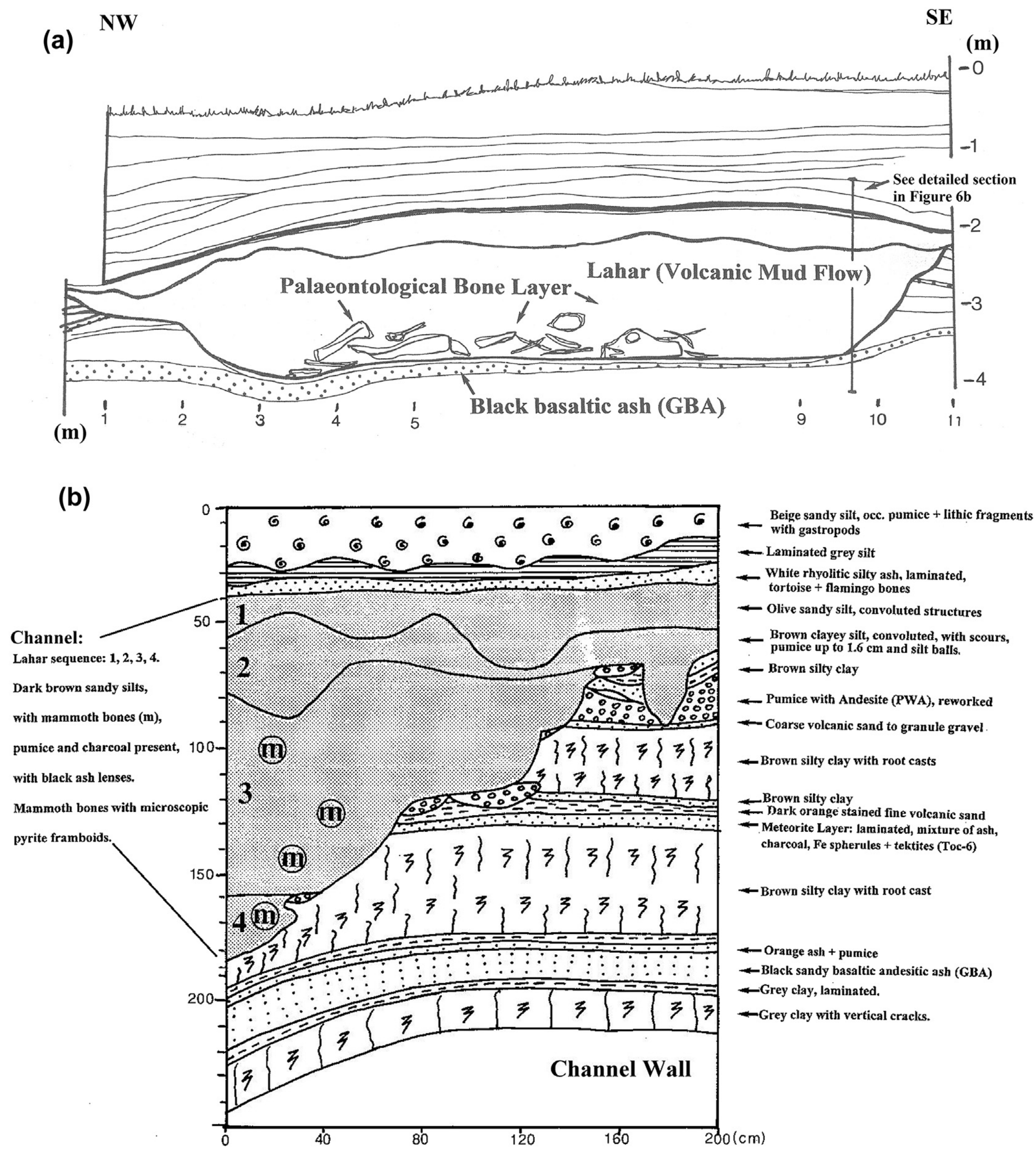


Fig. 6. a: Cross section (NW–SE) of small channel infilled with lahar material, showing the position of the palaeontological bone bed containing the mammoth remains and the position for Fig. 6b. b: Stratigraphic Section 4 in main Mammoth Trench, showing the channel edge. For location see Fig. 2.

core samples, to the west of the Basin of Mexico in the Trans-mexican Volcanic Belt (Israde-Alcántara et al., 2012) where the Fe spherules shapes were more ovoid or elongated, and often showed interspherule collisions and fusion in the process of solidifying.

EDS analyses of the Tocuila microspherules show mainly compositions containing Fe oxide between 65 and 72%, O and C, with low concentrations of Al or Mn in weight % (Fig. 9). There is no titanium present, eliminating the hypothesis that the spherules are titanomagnetite grains. There are no Fe spherules in the overlying and underlying layers in the studied sequence.

In the marker strata (A-6) we found 260 spherules per kg, almost 1/10 of the concentration found in the Cuitzeo core (with 2000 spherules per kg) (Israde-Alcántara et al., 2012) and below the mean value for of YD spherules at 28 field sites around four continents (388 spherules per kg) (Wittke et al., 2012).

Nanodiamonds, a well known proxy associated with meteorite impacts, were also found in Tocuila in sample A-6 as traces, with no evidence found in the layers above and below.

4. Interpretation of results

4.1. Origin of the sediments in the sections south of the Mammoth Trench

The overall sequence to the south of the Mammoth Trench shows a slightly coarsening upwards lacustrine sequence which indicates a transition from deeper saline water lake to a more nearshore facies. The lowest indurated black basaltic-andesitic ash at the base is interpreted as an ash fall into the lake because it is laminated and it is interbedded with lake sediments. It is correlated with the GBA ash event. The iron-staining on the upper surface of this ash is probably related to a post-depositional, re-precipitation of iron after translocation through the sediments above. In section 3 the black ash is immediately overlain by beige, sandy silty ash which has very round pumice clasts with cracked surfaces. In section A this black ash is overlain by a brown, clayey, silty ash and a white, sandy ash. These ash sequences, up to 36 cm thick, are likely

Table 3
Geochemistry Data for Tephra Markers from the Basin of Mexico.

A) Pumice with andesite tephra (PWA):

SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Total alkali
Sample: Toc 2 lahar (Siebe et al., 1999)											
58.58	0.8	15.88	6.13	0.10	4.58	6.34	3.88	1.58	0.19	98.93	6.46
Sample : 95132 Ta-4Ap Popocatepetl,Tutti Frutti fall (Schaaf et al., 2005)											
59.12	0.81	16.84	6.09	0.1	4.42	5.93	3.61	1.41	0.19	100.72	5.02
Sample : 95132 Ta5 Popocatepetl, Grey pumice fall (Schaaf et al., 2005)											
60.22	0.77	16.37	5.75	0.09	4.53	5.69	4.01	1.67	0.21	100.80	5.68
Sample : 9463tf Tutti Frutti pumice (Schaaf et al., 2005)											
59.32	0.83	16.52	5.45	0.10	4.57	6.14	3.70	1.49	0.18	99.45	5.19
Sample: 9490 g Grey Pumice (Schaaf et al., 2005)											
58.99	0.81	16.51	5.78	0.09	4.41	5.78	4.11	1.57	0.22	99.47	5.68

PWA (from this study)	*N*	Mean SiO_2	S.D.	Variance	Range %
Tocuila Section C-A3	11	60.68	4.62	21.34	55.67–72.62
Tocuila A-5a (lens)	7	63.64	10.28	105.66	51.57–74.49

B) Great Basaltic ash (GBA) or Tlahuac tephra:

Sample	*N*	Mean SiO_2	S.D.	Variance	Range %
Samples from Ortega and Newton, Chalco Lake (1998):					
Tx4a	17	55.5	0.56	0.32	54.6–56.7
Tx4b	16	57.9	1.23	1.5	56.5–60.1
Tlahuac-c	18	57.1	2.36	5.59	52.7–59.6
Tlahuac-b	15	57.5	0.68	0.46	55.9–58.7
Tlahuac-a	11	58.2	0.70	0.48	57.1–59.2
Tocuila, GBA samples from this study:					
Section C-A1	18	57.0	1.24	1.54	54.6–59.3
Section A-1	11	58.1	1.33	1.78	55.9–60.3
Section A-3	10	59.4	2.51	6.29	55.7–61.3
Section 3-1	13	58.6	2.54	6.45	54.4–62.9

C) Upper Toluca Pumice (UTP) tephra:

Sample	*N*	Mean SiO_2	S.D.	Variance	Range %
Samples from Newton and Metcalfe, Toluca Valley (1999):					
Arroyo Ojo de Agua 9	33	70.7	0.71	0.50	69.4–72.4
Texcalyacac, site 3	4	71.1	1.07	1.15	69.6–72.1
San Nicolas Peralta	32	71.6	1.35	1.82	68.4–73.9
Canal Rio Lerma, site 7	5	72.6	1.94	3.77	70.4–75.6
Tocuila, UTP samples from this study:					
Section D-3 (UTP lahar)	8	71.0	2.13	4.52	69.5–72.7
Section D-2 (*in situ*)	15	70.2	1.27	1.61	68.3–73.3
Section 1–9 (UTP reworked?)	11	73.5	1.07	1.14	71.4–74.3

D) Meteorite airburst layer:

Sample	*N*	Mean SiO_2	S.D.	Variance	Range %
Section A-6	9	60.81	5.54	30.74	53.86–69.68
Section C-A2	12	64.28	7.54	56.83	55.78–76.35

to represent multiple ash fall phases of this major volcanic eruption, in part with evidence of weathering and alteration.

The sequence continues with lacustrine, grey clays, with white root casts, although in between there is one conspicuous finely laminated dark grey silty-sandy unit 2–10 cm thick, that has a mixed andesitic and rhyolitic ash composition, with microscopic iron spherules, microscopic melted quartz crystals (tektites), nanodiamonds as traces and large amounts of charred material (Fig. 7) that was radiocarbon dated between 10,878 and 10,707 cal BC in section A (Table 1). This unit is interpreted as the YD Meteorite Airburst Layer, which has been recognised in several important mammoth Paleoindian sites in SW America, e.g. Murray Springs, Blackwater Draw, Topper, Arlington Springs, and is associated there with the presence of black organic mats and the presence of nanodiamonds and elevated iridium concentrations in bulk sediments (Firestone et al., 2007; Kennett et al., 2009). It has been suggested that this impact is associated with the extinction of megafauna and the onset of the YD cold interval (Firestone et al., 2007). This marker layer has already been identified in the depocenter of Cuitzeo Lake, in Central Mexico (Israde-Alcántara et al., 2012) but not in association with megafaunal remains and instead it is interlayered with organic sediments dated to 10,900 cal BC. At Tocuila this is the first time that the meteorite burst event marker has been found in association with mammoth bones in the Basin of Mexico. However here the marker layer is not associated with black organic mats but is mixed with basaltic-andesitic tephras and charcoal. We have found traces of nanodiamonds at both the Tocuila and Cuitzeo Lake sites. However there are larger concentrations per volume and larger Fe spherule sizes at Cuitzeo Lake and other sites around Michoacan state which indicates that the force and effects of the meteorite impact burst were larger in that region. More research is ongoing to study and map these differences found across several field sites in Mexico.

On top of the lacustrine lake clays there is a thicker, coarse ash, composed of subrounded pumice and lithics with a mixed andesitic and rhyolitic tephra composition which is interpreted here as the reworked PWA tephra. It has been dated by Mooser and González-Rul (1961) and Mooser (1967) to 16,026 to 15,636 cal BC but in

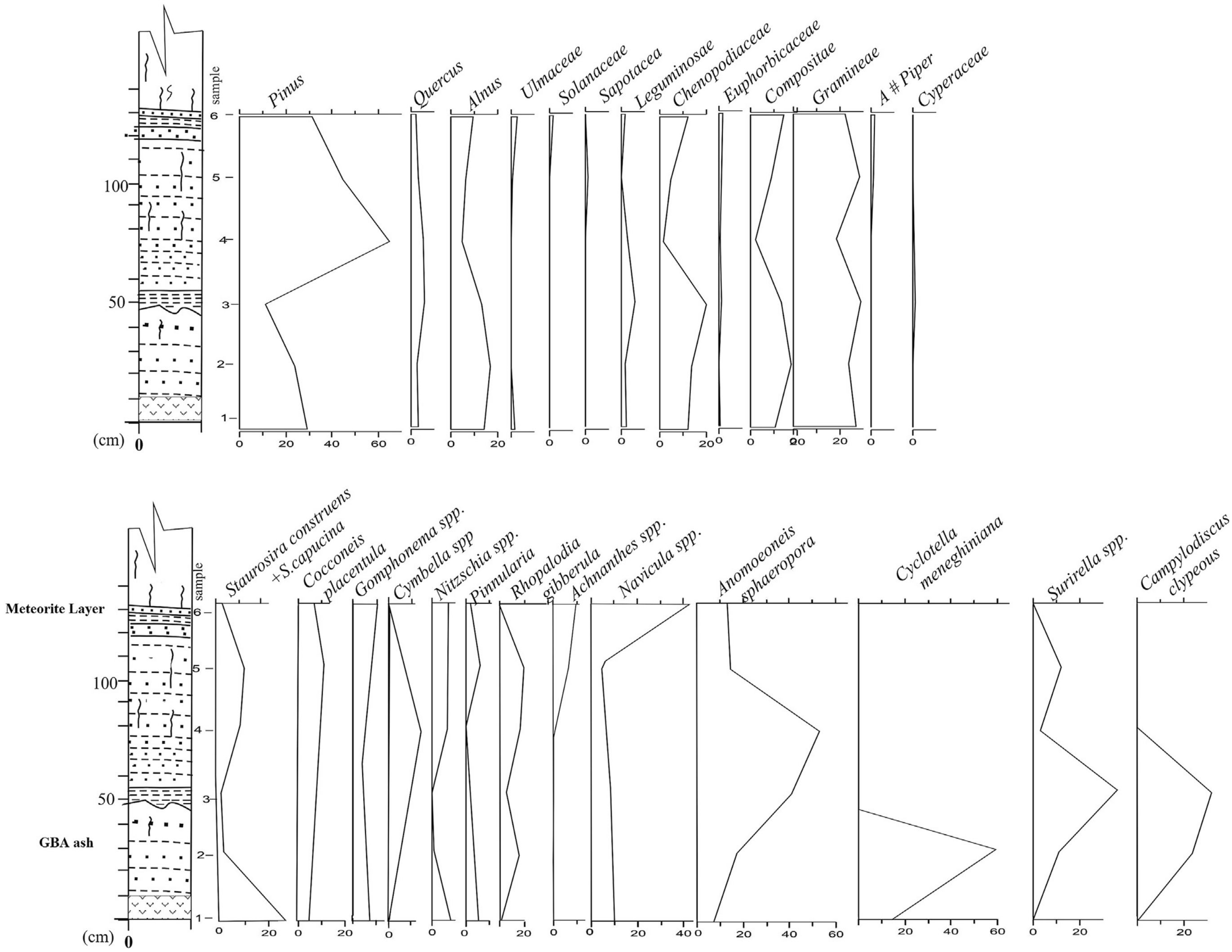


Fig. 7. Pollen (top) and diatom (bottom) diagrams from samples from the base of stratigraphic section A. The samples A1, A2 and A-3 are associated with the GBA ash at the base, while sample A-6 is associated with the meteorite airburst layer.

Tocuila it appears to be in an "incorrect" stratigraphic position, because it is found on top of the YD meteorite airburst layer. For this reason it has to be reworked. Above this reworked PWA tephra there is another lacustrine sequence of clays or silts, with root casts.

Only in log D above this lake sediments sequence is there a series of three, *in situ*, rhyolitic ashes (Sample D-2) which are correlated here with the UTP ash produced by the Nevado de Toluca Volcano (Fig. 1), dated originally by Bloomfield and Valastro (1974, 1977) to about 11,600 BP. However more recently Arce et al. (2003) dated this tephra to 10,666–10,426 cal BC. This ash represents the distal fallout from the PC1 and PC2 volcanic events (Arce et al., 2003) which had eruptive column heights between 38 and 42 km. It is difficult to understand why the UTP is only found in section D, south of the main Mammoth Trench, because this ash was deposited as an ash fall in the lake basin, with evidence only for quiet water deposition and the ash must have been deposited uniformly in the lake. There is evidence of reworking of volcanic ash at other sections from the Mammoth Trench but they are usually associated with channels and there is evidence of reworked ash clasts.

In section D the UTP tephra is immediately overlain by a 17 cm poorly sorted, sandy silt with an identical chemical composition to the UTP tephra. This is interpreted as nearshore lake sediment because of the root casts and gastropods but with large amounts of reworked UTP ash. There is no evidence of channelling and reworking was by thin sheetflows. Above there is a variable thickness of secondary hardening of the sandy silt to produce a caliche layer but this only alters the pre-existing lake sediments which in sections C and D are indicated by silty sand or silty clay, with gastropod shells and root casts. The top of the sequence is composed of a variable thickness of made ground.

4.2. The origin of the sediments in the main Mammoth Trench

The lower part of the stratigraphic sequence is the same as the sections studied to the south with basal lake sediments and the GBA tephra marker. However, above this ash in all the sections, except in section A (channel wall) there is a poorly sorted, diamicton which has been interpreted as a channel infilled with lahar sediments, with concentrated and orientated mammoth bones forming a " palaeontological bone bed" (Figs. 4a and 6a).

The term lahar has been used as a general term for a rapidly flowing, water-saturated mixture of rock debris, ash, charcoal and water from a volcano as a distinct event (Smith and Fritz, 1989).

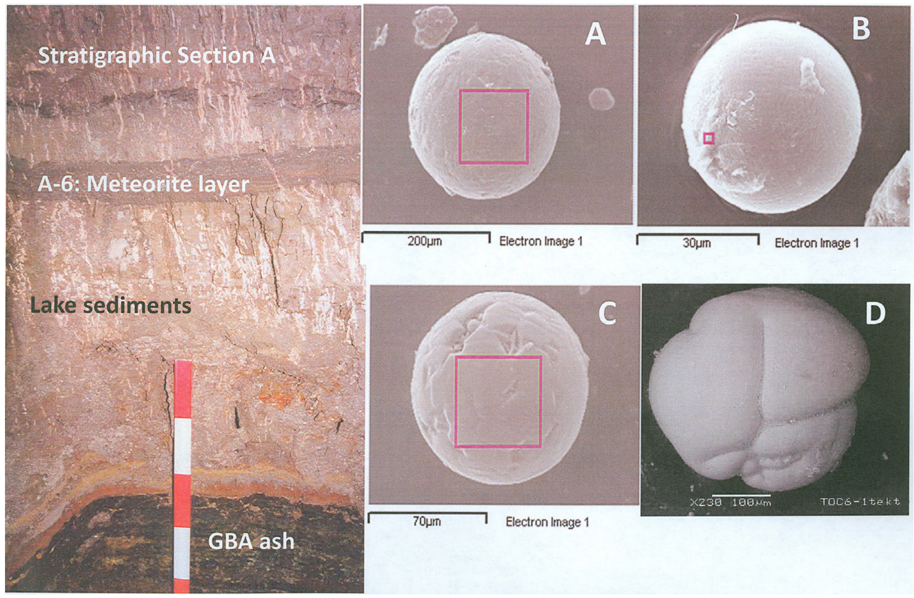
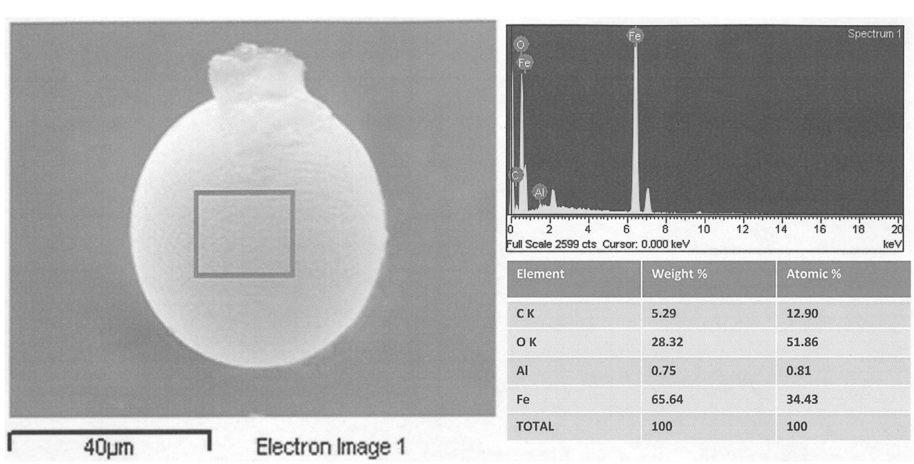


Fig. 8. Stratigraphic section A showing the meteorite layer and some of the impact minerals found associated with the Younger Dryas meteorite airburst impact. A + B + C: SEM photos of Fe microspherules and textures. D) SEM photo of melted SiO_2 droplet (tektite).

Similarly Vallance (2000) defines lahar as a process for the formation of a debris flow, transitional flow or hyperconcentrated flow from a volcano, with a modern analogue for this type of depositional environment being the Pinatubo volcano in the Philippines (Newhall and Punongbayan, 1997). The term has been used to specify the origin of the flow as at Tocuila, where the deposit originated from the remobilisation of unconsolidated, water saturated volcanic ash. There is usually too evidence for a pulsating flow (Davies, 1985, 1990; Major, 1997; Hodgson and Manville, 1999).

In section A and section 4 it is possible to identify the YD meteorite airburst marker. In section A (channel wall) the succession shows a clay and silt lacustrine sequence which often shows root casts, some units have diatoms and the upper clay unit has gastropod shells throughout. Interbedded in this lake sequence there are ash fall layers which are *in situ* and apparently fell directly into the lake. The lowest ash however, contains two markedly different, tephra shard populations with mean values of 57.3% and 67.8% SiO_2. This indicates reworking and mixing of two tephra populations from the nearby shoreline and current transport, probably as a sheetflow into the nearshore lake environment. This is also shown by a lens of sandy ash in log 5a which again shows two tephra shard populations in the lowest lake clay. However, the pale grey/white silty ash is much more rhyolitic, although two populations appear to be present, with mean values of 66.3% and 74.6% $SiO_{2.}$ The grey/white ash is overlain by 8 cm of dark grey, laminated, silty clay with diatoms. The section is completed by 45 cm of lacustrine sandy clay and grey-brown silty clay with gastropod shells throughout indicating an increase of lake level.

The other stratigraphic sections, 1, 2, 3 and 4 indicate a different sub-environment above the GBA ash and the lowest units were recognised as a distal overbank lahar facies by Siebe et al. (1999). This is the sediment unit that contains the mammoth bone assemblage, primarily towards the base of the unit. They recognised three flow units, although only the lower two were discussed in their paper and Arroyo-Cabrales et al. (2001) suggest that above the main lahar there are deposits derived from smaller lahars. The fabric in the main lahar unit and orientation of the long bones in the unit indicates a transport direction from the south-east towards the



Element	Weight %	Atomic %
C K	5.29	12.90
O K	28.32	51.86
Al	0.75	0.81
Fe	65.64	34.43
TOTAL	100	100

Fig. 9. Tocuila Fe microspherule showing chemical composition obtained by SEM analysis. There is no titanium present, therefore it is not a titanomagnetite.

north-west (Fig. 5a and b). The eastern margin of the lahar sequence is shown in Fig. 6a and b and indicates an erosional channel margin or gully, with erosion of the *in situ* ash layers along the channel flanks and incorporation into the lahar sediment. This indicates that the lahar probably eroded a channel at this locality which was approximately 2 m deep and at least 11 m wide as can be seen in Fig. 6a. The western flank of the channel was also recognised in a section to the north of the main Mammoth Trench (section N) where the lahar facies thickens to the north–east. The upper parts of the lahar sediment indicate small scale channelling in much finer sediment, with convolute lamination throughout which resulted from slight density contrasts as the later, finer pulses of lahar sediment came out of suspension. This may be similar to the lahar described in Hodgson and Manville (1999) where multiple units are present in the Mangatoetoenui Stream. The lower units at Tocuila are scoured and truncated and small channels cut into the lower units are occasionally present. It is therefore suggested that there was only one phase of lahar sedimentation, with erosion during waning flow caused by pulses. It was channelised in a gully and does not represent a distal overbank lahar facies as suggested by Siebe et al. (1999). They suggested that the topography and geomorphological position of the Tocuila site on a flat, deltaic plain near the shores of Lake Texcoco pointed to that origin, as did its relatively fine-grained nature and low thickness. However, although the lahar unit is undoubtedly distal because of the lack of coarse clasts in the poorly sorted matrix, it is channelised and there are indications of bank erosion, with local, reworking of bank sediments. Arroyo-Cabrales et al. (2003) suggested that the lahar had flowed through and filled the channel of a Late Pleistocene stream cut prior to the deposition of the unit containing the mammoth remains but this seems unlikely because there are lake sediments stratigraphically above and below and the evidence of bank erosion from the lahar sediments. The palaeosol suggested by Siebe et al. (1999) has not been recognised.

The field observations and experimental studies of debris flows show that the deposition of similar, yet separate debris flows produces a homogeneous, massive deposit, in which the separate events cannot be distinguished (Major, 1997), even when the debris flows occur days apart. However, the suggestion that the lahar units at Tocuila did not form contemporaneously but formed over a period of about a thousand years, based on the radiocarbon dating of charcoal clasts in the deposit (Siebe et al., 1999) and Table 1, seems highly unlikely. For example, the entire Mangatoetoenui lahar event occurred over a space of hours (Hodgson and Manville, 1999) and they also noted marker horizons that allowed each flow to be distinguished which occurred in flows that were transforming from debris flow to hyperconcentrated flow. These flows created thin sandy layers as denser material accumulated at the base of each depositing flow surge. On the other hand, in surges that had been completely transformed to hyperconcentrated flow, water escaping upwards through the deposit entrained silt and clay that was then deposited on the surface forming layers of mud. This process could be responsible for the convolute lamination observed in the upper Tocuila lahar units. Several depositional units can be deposited over a short period of time and the likelihood is that the Tocuila lahars were deposited quickly. As the sediment below and above the lahar unit is lacustrine it seems that the lahar event eroded a sublacustrine channel in the nearshore lake zone and probably the lahar sediment was deposited in a depositional phase of only a few hours. The uppermost units with convolute lamination in silts indicate a soupy mixture of sediment coming out of suspension in the lake after the main lahar unit had been deposited. This sediment was deposited from hyperconcentrated flows from the body or tail of a composite sediment-laden flow (Sohn et al., 1999). The radiocarbon dates obtained from the lahar sediments (Table 1) likewise indicate erosion and reworking of pre-existing sediments and cannot be used to argue a case for a long time period of deposition in one lahar unit as suggested in Siebe et al. (1999).

However, some lahars can be remobilised over decades after ash deposition in the perivolcanic zone and Lirer et al. (2001) for example, indicated that the Somma-Vesuvio lahars were active for over 400 years between AD79–AD472. Time periods of this length seem to be rare and it seems that the sedimentary evidence points to rapid deposition for the Tocuila lahar sequence with mammoth bones.

5. Discussion

5.1. Age of the Tocuila deposits: tephrochronology

Huddart and Gonzalez (2006) suggested that reworking of volcanic ashes has not been considered in detail in tephrochronological studies in the Basin of Mexico to date but they did note significant reworking processes at several other Late Pleistocene Paleoindian sites, such as Tlapacoya and Santa Isabel Iztapan Mammoths II which had affected the PWA and UTP ashes. At the Tocuila site, Gonzalez and Huddart (2007) recognised that although the tephrochronology from the sediments was complicated because of this reworking, there is evidence for *in situ* key tephra markers found elsewhere in the Basin of Mexico, such as the GBA and the UTP. There is evidence of reworking for some of the tephra layers from channel margins and although the Tocuila lahar incorporated PWA tephra grains into its matrix, it was predominantly derived from remobilised UTP ash from the eastern lake margins and the slopes of Tláloc and Telápon volcanoes. Similarly at Tepexpan, Lamb et al. (2009) illustrated that reworking was a common process and that it must be recognised in the stratigraphic sections to avoid confusion and to be able to construct an accurate tephrochronology and stratigraphy. An example of this is that previously at Tepexpan, Bradbury (1971) proposed that the age of Tepexpan Man was as old as the PWA ash because he found pumice clasts from this ash in the sediments immediately below the caliche layer where the Paleoindian skeleton was found. However, there was no evidence of *in situ* PWA or UTP ashes at this site (Lamb et al., 2009) and in such marginal lake environments there was much reworking by fluvial, deltaic and volcanic lahar events. This resulted in mixed tephra populations and sedimentological characteristics like silty mudballs which have incorporated volcanic ash into their matrix during reworking. Hence in marginal lake environments it is often difficult to interpret the tephrochronology and tephra-stratigraphy accurately simply on the basis of the apparent visual presence of the volcanic ash markers. The tephra shard geochemistry needs to be carefully analysed along with the associated palaeoenvironmental evidence and radiocarbon dating of the overall stratigraphic sequence. At sites like Tocuila the extensive lateral and vertical exposure, achieved by the excavation of exploratory trenches at the site has helped in constructing this detailed interpretation but also shows how difficult the correct interpretation can be if using only one logged section, or cores. Recent further analysis of the tephrochronology and sediments has yielded results that although confirming some of the previous conclusions of Gonzalez and Huddart (2007) has added significant re-interpretation for this important Late Pleistocene palaeontological site.

5.2. Tephra markers, recognition of reworking and regional correlations

5.2.1. GBA or Tlahuac ash

Towards the base of the exposed sediment succession in Tocuila there is evidence of an *in situ*, black, fine sandy ash which has a uniform basaltic-andesitic composition. The tephra shard geochemistry is included in the supplementary information and summarised in Table 3. Mean SiO_2 varies between 57 and 59.4%, with low standard deviations and ranges from 54.4 to 62.9%. Samples have relatively high FeO, MgO and CaO. Below this ash is 20 cm+ of brown, silty clay with thin laminated layers, iron staining and vertical fractures. In section 3 the black ash is succeeded by 2.0 cm of sandy beige ash, with rounded fine sand mud balls which show a surface cracking. They are interpreted as pumice clasts with ash falling into the lake as there are both ostracods and diatoms in this unit.

This ash is correlated with the GBA of Mooser (1967, 1997), although Ortega-Guerrero and Newton (1998) called this tephra the Tlahuac tephra as its composition ranges from basaltic-andesite to andesite. This unit is 55 cm thick at Tlapacoya (Lambert, 1986), 47 cm at 18.58 m depth in core B at Chalco Lake (previously described as tephra X11 by Urrutia-Fucugauchi et al., 1995) and 34 cm at Texcoco Lake as Tx_4 (Ortega-Guerrero and Newton, 1998). Huddart and Gonzalez (2006) noted 17 cm of the GBA at the Santa Isabel Iztapan Mammoth II site. The source for this tephra is unknown, although Mooser (1967) suggested that Popocatépetl could be the source because of its conspicuous thickness and its thinning to the north-west documented above. However, more recently Mooser (1997) suggested the Santa Catarina Range as a possible source. At Tocuila there were multiple phases of this ash into Lake Texcoco. The age is not precisely known either but at Tlapacoya wood below this tephra was dated at 33,500 ± 3200/2300 BP (Lambert, 1986). In Chalco core B the estimated age was over 34,000 BP as a horizon 4 cm above this tephra was dated to over 34,000 BP (Lozano-García et al., 1993). In core T the Tx_4 layer is 76 cm below an horizon dated at 26,135 ± 335 BP (Lozano-García and Ortega-Guerrerro, 1998) but Mooser (1997) on the other hand dated this tephra horizon to 28,600 ± 200 BP.

5.2.2. Reworked PWA

At Tocuila there appears to be no *in situ* PWA ash but there is evidence of much pumice as small clasts, particularly in the lahar sediments and the geochemical data suggests reworking of PWA in various combinations with other ashes. Samples from section 2-2 and section 1–11 are correlated with the PWA but the ash is reworked in a lahar. Sample C-A2 illustrates a three way mixing of the tephra from an older rhyolitic ash, the Tlahuac and PWA ashes. The PWA is indicated by high values of CaO and FeO. The reworked rhyolitic tephra is indicated by high silica values up to 75.5%. This tephra must originate from the drainage basin to the east of Tocuila on the piedmont slopes of Tláloc as can be seen from the geochemistry of the rhyolitic ashes found at Tequexquinahuac, San Dieguito Xochimanca, La Joya Quarry, Coatepec and San Vicente Chicoloapan, with mean SiO_2 values between 72.6 and 74.6% and highs of silica between 73.5 and 78.9% in individual tephra shards at different locations. Similar reworking of the PWA in a marginal lake location was indicated at the Tepexpan site by Lamb et al. (2009) where there were also high percentages of $Si0_2$ in many samples. In Tocuila the Section A-5c indicates a sandy ash lens in lake clay which from the geochemistry shows mixture and reworking of both Tlahuac and rhyolitic ash from the drainage basin to the east.

However, the PWA tephra has been described as a common tephra marker throughout the Basin of Mexico despite the difficulties of *in situ* recognition at the Tepexpan and Tocuila sites. It has been dated at about 14,600 BP, although at Tlapacoya two sets of tephra have been described (Mooser, 1967; Lambert, 1986). The older of the two is dated to 14,470 ± 280, 14,430 ± 190 and 15,020 ± 480 BP (Niederberger, 1976; Garcia-Bárcena, 1986) and is succeeded by a lacustrine silt dated to 13,180 ± 290, 14,450 ± 100 and 14,540 ± 900 BP (Garcia-Bárcena, 1986), The younger tephra overlying this silt is thought to be the PWA and is about 25 cm thick at Tlapacoya. The geochemistry of some PWA units can be seen in Table 2.

5.2.3. In situ UTP

This fine to medium sand tephra in the Basin of Mexico is up to 50 cm thick and is derived from a Plinian eruption of Nevado de Toluca (Arce et al., 2003). At Tocuila it can be seen in the Mammoth Trench in section A-11 as a silty, clayey ash whilst outside the trench to the south in Trench D it is noted in its characteristic tripartite sequence. Geochemically it is relatively high in SiO_2 and low in FeO, MgO and CaO as can be seen from Table 3 and the Supplementary Information.

Dating of the UTP both in the Toluca Basin and the Basin of Mexico has not produced consistent or reliable results (Bloomfield and Valastro, 1977). In Core D at Chalco Lake, Tephra 11 was dated to 12,520 ± 135 BP (Lozano-García et al., 1993). However, later radiocarbon dating by Arce et al. (2003) considered in detail the development of the UTP eruption and its correct age which they proposed was around 10,500 BP (Table 1).

5.2.4. Reworking of the UTP

Reworking of this tephra has been found in lahars once considered to be PWA in age by Siebe et al. (1999). Convincing evidence for this remobilisation of the UTP has been presented by Gonzalez et al. (2001) and Gonzalez and Huddart (2007) and the lahar event cannot be older than 10,761–10,455 cal BC. New radiocarbon dating in section A-6 indicates an age of 10,818 to 10,701 cal BC and this layer is older than the lahar channel (section 4). This is the layer with iron and silica spherules thought to be derived from a meteorite airburst. Gastropods within a lacustrine silt above a white silty ash with turtle and flamingo bones have been dated to 10,016 ± 39 BP in the same section. This constrains the ages of the upper part of the section 4 sequence (Fig. 6b) and the white silty ash cannot be the Pómez de Grano Fino as proposed previously by Gonzalez and Huddart (2007), but must be reworked UTP.

5.3. Age of the Tocuila deposits: radiocarbon dating

The lahar deposits in the Mammoth Trench have been previously dated by Siebe et al. (1997); Morett et al. (1998b) and Arroyo-Cabrales et al. (2003) (Table 1). The value of these dates has been discussed by Gonzalez and Huddart (2007) as they are not in stratigraphic sequence. It is not surprising to find such variability in a lahar deposit that is by its nature a reworked deposit. An average date of about 11,188 BP has nevertheless been proposed for this deposit by Morett et al., (1998b) and Arroyo-Cabrales et al. (2003), but we do not consider this to be correct.

From our stratigraphic observations and radiocarbon results available (Table 1) we interpret the lahar sequence in Tocuila with the associated mammoth and other Late Quaternary fauna to be associated with the deposition and rapid reworking of the UTP by lahars.

The UTP has been used by many workers as one of the main stratigraphic markers in the Basin of Mexico and has been estimated by Bloomfield and Valastro (1974, 1977) to be about 11,600 BP on the basis of an average of four radiocarbon dates on material collected beneath and above the UTP deposit. Four charcoal samples from an organic rich soil below the UTP gave a mean of 11,580 ± 100 BP (Bloomfield and Valastro, 1974) and a sample of humic clay below the UTP in the Sierra de las Cruces gave a date of 11,600 ± 100 BP (Bloomfield and Valastro, 1977). Bloomfield (1973) reported three dates for palaeosols buried by the Tenango basalt which is above the UTP at 8390 ± 130, 8440 ± 440 and

8700 ± 180 BP. A charcoal sample from above the UTP from a location south of Sierra de las Cruces (Bloomfield and Valastro, 1974) gave a date of 8390 ± 100 BP. All these dates represent minimum ages of the UTP event. In Arce et al. (2003) two dates from the uppermost part of the palaeosol beneath the UTP flows and surges gave dates of 11,595 ± 180 and 11,830 ± 342 BP. So if the maximum and minimum dates of Bloomfield and Valastro (1974, 1977) and Bloomfield (1973) are used the UTP was deposited between 11,950 ± 100 and 8700 ± 180 BP. Charcoal from the UTP is an obvious way to date the deposit but the UTP sequence seems poor in charcoal fragments compared with the Middle Toluca Pumice (Arce et al., 2005). Nevertheless at site 161 (Arce et al., 2003) the UTP flow deposits have charcoal dated to 12,120 ± 85 and 12,195 ± 103 BP but this correlates to the known age of the white pumice flow from the MTP (Arce et al., 2005). However, at site 70 charcoal from the UTP sequence was dated to 10,445 ± 95 and 12,090 ± 40 BP (Arce et al., 2003). The older date seems to be the MTP and the younger date corresponds to the UTP event. Similarly a C14 date from organic material below the UTP at La Isla 11 drilled in the Upper Lerma Basin gave a maximum age of 10,820 ± 365 BP (Caballero-Miranda et al., 2001). Arce et al. (2003) therefore suggested that this tephra shows multiple phases dated to around 10,500 BP (Table 1). This is the currently accepted date for this tephra marker horizon in the Basin of Mexico, correlated with the first half of the YD cool interval, a period of climatic deterioration around the North Atlantic and possibly a global event.

5.4. *The Tocuila bone assemblage and its implications*

The excavated area in the lahar has produced approximately one thousand bones, mostly of the Columbian mammoth (*M. columbi*). These represent at least seven individuals which range in age from young to adult stages. The skeletons were not complete, but some show articulation. In addition to mammoths there were bones of horse, bison, camel and rabbit, whilst in the top lacustrine units there are fish, turtle and flamingo (Corona and Arroyo-Cabrales, 1997).

It has been argued by Arroyo-Cabrales et al. (2001), Johnson (2001) and Johnson et al. (2001) that human activity was indicated by the presence of dynamic impact fracturing features on a few mammoth long bone segments and fracture debris. The suggested bone tool assemblage includes a bone core with a prepared platform and scars from the removal of a number of large cortical flakes and a cortical bone flake with remnant platform preparation (Morett-Alatorre and Arroyo-Cabrales, 2001, Fig. 10). The cortical flake conjoins with the central flake scar on the bone core. This bone tool assemblage shares the same features as those from other North American grassland mammoth sites reported in Hannus (1989, 1997), Steele and Carlson (1989), Miller (1989), Johnson et al. (1994) and Johnson (2001) and experimentally generated ones from Ginsberg (Stanford et al., 1981). The small assemblage found at Tocuila is interpreted as mammoth bone quarrying to produce cores for transport elsewhere (Johnson et al., 2001). Bone quarrying is not a subsistence activity but a technological one aimed at securing raw material shaped into a transportable, useable form. It could be an activity occurring together with the butchering of a mammoth, or as an independent activity (Johnson, 2001) but is a specialised activity that requires fresh mammoth bone. This latter point is important. How the mammoth bones became incorporated into the lahar sediments has been debated (Arroyo-Cabrales et al., 2001;; Gonzalez and Huddart, 2007). Were they previously deposited in the channel either as the result of attritional accumulation or a catastrophic event, and subsequently were covered by the mudflow, or were the mammoth remains transported into the channel with the mudflow?

With the work presented in this paper it seems unlikely that the UTP lahars killed the Tocuila Mammoths, because two AMS radiocarbon dates obtained directly on these mammoth bones gave dates of 11,154 to 10,820 cal BC and 11,335 to 11,041 cal BC that indicate that the mammoths were already dead when they were incorporated into the UTP distal lahars and concentrated in the lahar channels in the lake nearshore. The suggested time gap between the mammoths' death and their incorporation into the lahar means that the mammoths' skeletons were lying around the lake shore for two hundred years. The fact that bone quarrying requires fresh bone means that humans may have killed or scavenged the bones for tool production well before the skeletons and bone tools were incorporated into the UTP lahars found in Tocuila.

5.5. *Source of the lahar sediments in the Mammoth Trench*

Siebe et al. (1999) suggested that the closest and most prominent topographic high in the area was likely to be the source of the

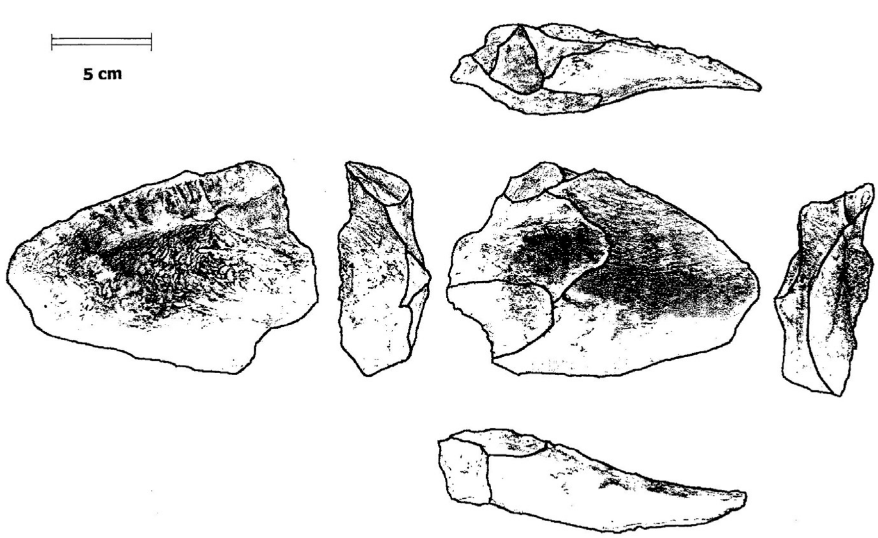


Fig. 10. Tocuila artifact made with mammoth bone, (after Morett-Alatorre and Arroyo-Cabrales, 2001, Fig. 4).

lahars. This is Tláloc volcano (4200 m) (Fig. 1). On its north-west flanks several streams originate and have formed narrow, but deep, barrancas or gullies as they flowed towards Lake Texcoco. Tocuila is situated between the Coxcacoac stream to the north and the San Lorenzo stream to the south. The lahars are likely to have originated from reworked ashfall on the upper piedmont slopes as they flowed down the barrancas into the lake. Thick lahar sequences have been described from other sites like La Joya Quarry by Huddart and Gonzalez (2004) and Huddart and Gonzalez (2006) but these are thought to be associated with reworking of pyroclastic flows and ashes that are much older than the Tocuila sequence. As Siebe et al. (1999) suggest ash and pumice fall produced by the Plinian eruptions of Popocatépetl and Nevado de Toluca volcanoes that produced the PWA and UTP ashes, undoubtedly affected the Tocuila area and the western Tláloc slopes. However, Siebe et al. (1999) suggested the source for the lahar material as the reworked PWA ash, whereas we found evidence from ash derived primarily from the UTP eruption but with evidence of much reworking of both marker ashes in the lake sediments and in the lahar deposits.

5.6. YD Meteorite burst event in the Basin of Mexico

The YD climatic interval (YD) lasted 1300 years and is characterized by a short and abrupt period of cooling between 10,900 and 9500 cal BC. At Tocuila it was possible to identify a conspicuous finely laminated black sandy-silty layer between 2 and 10 cm thick that was radiocarbon dated to the start of the YD (Table 1, sample A-6), originally interpreted as an andesitic volcanic ash (Supplementary Information). However after further detailed chemical analysis and SEM observations, we have also found additional minerals that indicate a meteorite airburst event at the start of the YD interval. The minerals include microscopic Fe spherules with highly ornamented surfaces associated with melting and quenching, tektites (melted SiO_2 glass) and nanodiamonds that indicate very high temperatures $> 2200\,^{\circ}C$ and high pressures; the mineral suite is associated with the melting and quenching of terrestrial materials.

This is in agreement with Firestone et al. (2007), Kennett, et al. (2009); Israde-Alcántara et al. (2012) and Bunch et al. (2012), that propose that fragments of an asteroid or comet exploded in the atmosphere creating a fireball at the front of the impact, creating a large shock and heat wave that affected the Earth's surface at the onset of the YD. This event left no impact crater, but produced a suite of "exotic" minerals associated with extraterrestrial impacts, including Fe rich highly ornamented magnetic microspherules and silica-rich microspherules with aerodynamic shapes (tektites) and other impact proxies like nanodiamonds, high anomalies of platinum and iridium and fullerenes (molecules of carbon that have been associated with cosmic dust) and charcoal associated with large wild fires. There are at least 18 different field sites already identified in different continents including North America, Europe and Asia, where the same impact minerals from this time period are found (Bunch et al., 2012). This suggests that the effect of the meteorite airburst event was felt at least in the Northern Hemisphere, and that it is linked with the origin of the YD cold period, the extinction of megafauna and strong cultural changes and population decline in Paleoindian populations (Firestone et al., 2007; Anderson et al., 2011).

However the hypothesis is contested. For example Haynes (2008) suggests that the magnetic spherules and charcoal particles are perhaps organic spores associated with the presence of organic rich black mats. The presence of nanodiamonds has been associated with volcanic processes and not with a meteorite impact (Scott et al., 2010) and the charcoal is associated with wild fires due to human activity (Pinter et al., 2011). What is clear from all these studies, including the Tocuila site, is that there is a marker layer during the YD.

In the Basin of Mexico however there is still megafauna until the UTP eruption, about 200 years after the meteorite airburst event, and only after this eruption and subsequent lahars are megafauna absent from the Basin. However more refined radiocarbon dating and careful stratigraphic work is required to understand these two catastrophic events. Their combined effects produced major changes in the environment, affecting the geomorphology, the composition of the lakes and the vegetation. We know that humans were already present in the Basin at the time (Table 1).

6. Conclusions

In the shallow marginal Lake Texcoco at Tocuila there is evidence for a thin layer $\sim$10 cm thick associated with the YD meteorite airburst marker, dated here between 10,878 and 10,707 cal BC. Shortly after, the Plinian UTP volcanic eruption also disrupted the environment in the Basin of Mexico approximately two hundred years later. The large volume of tephra deposited at the time caused partial damming of lakes, a drastic change in environmental conditions and the input of flood and lahar deposits. The timing of these two events, first the meteorite airburst impact and then the UTP Plinian eruption, occurred within the YD cooling event. Into the subsequent lahars was incorporated a mammalian bone assemblage that included many mammoth skeletons and a few mammoth bone tools. This UTP ash has already been found associated with some Paleoindian skeletons in the Basin of Mexico, e.g. Metro Man, Chimalhuacan Man and Tlapacoya Man, and it seems likely that both the meteorite airburst event and the UTP Plinian eruption caused widespread environmental disruption of the ecosystems, the death of human populations and are associated potentially with extinction of large megafaunal populations. The latter were already affected by human predation and climate change during the YD. There is no evidence for megafauna after this Plinian eruption in the Basin of Mexico and there is a large time gap in the archaeological record in the Basin from the YD age, with Paleoindian skeletons found again until approximately 4500 years BP (e.g. with the date of San Vicente Chicoloapan Man). This is despite the large amount of construction work and large scale excavation associated with Mexico City and its 28 million inhabitants.

At Tocuila there is evidence for *in situ* GBA (Tlahuac) and UTP marker ashes but there is also much reworking of ashes in various combinations (particularly the PWA ash) and the correct stratigraphy can be difficult to unravel without detailed stratigraphy, geochemistry, dating and good exposure of the sediment sequences in complex marginal, lake environments, like in Lake Texcoco.

Our data are consistent with the age and mineralogy for the meteorite airburst YD event reported by Firestone et al. (2007), Kennett et al. (2009) and Israde-Alcántara et al. (2012) in America and several sites around the world. We suggest that this meteorite airburst layer in the Basin of Mexico could be considered as another stratigraphic marker at the start of the YD period.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2014.02.003

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