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The ~1245 yr BP Asososca maar: New advances on recent volcanic stratigraphy of Managua (Nicaragua) and hazard implications

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ABSTRACT

Asososca maar is located at the western outskirts of Managua, Nicaragua, in the central part of the active, N–S trending and right-lateral Nejapa–Miraflores fault that marks an offset of the Middle America Volcanic Arc. It constitutes one of the ~21 vents aligned along the fault, between the Chiltepe Volcanic Complex to the North and Ticomo vents to the South.

Asososca consists of an East–West elongated crater filled by a lake, which is currently used for supplying part of Managua with drinking water (10% of the capital city demand). The crater excavated the previous topography, allowing the observation of a detailed Holocene stratigraphic record that should be taken into account for future hazard analyses. We present a geological map together with the detailed stratigraphy exposed inside and around Asososca crater aided by radiocarbon dating of paleosols. The pre-existing volcanic sequence excavated by Asososca is younger than 12,730+255/−250 yr BP and is capped by the phreato–plinian Masaya Tuff (<2000 yr BP). The pyroclastic deposits produced by Asososca maar (Asososca Tephra, in this work) display an asymmetric distribution around the crater and overlie the Masaya Tuff. The bulk of the Asososca Tephra is made of several bedsets consisting of massive to crudely stratified beds of blocks and lapilli at the base, and superimposed thinly stratified ash and lapilli beds with dune structures and impact sags. Coarser size-fractions (>−2ϕ) are dominated by accidental clasts, including basaltic to basaltic–andesitic, olivine-bearing scoriae lapilli, porphyritic and hypocrystalline andesite blocks and lapilli, altered pumice lapilli and ash, and ignimbrite fragments. Juvenile fragments were only identified in size-fractions smaller than −1ϕ in proportions lower than 25%, and consist of black moss-like, fused-shape, and poorly vesiculated, fresh glass fragments of basaltic composition (SiO_2~48%). The Asososca Tephra is interpreted as due to the emplacement of several pyroclastic surges originated by phreatomagmatic eruptions from Asososca crater as suggested by impact sags geometry and dune-crest migration structures. According to radiocarbon dating, these deposits were emplaced at 1245+125/−120 yr BP. The stratigraphic position of the Asososca Tephra and the well-preserved morphology of the crater indicate that Asososca is the youngest vent along the Nejapa–Miraflores fault. Explosive eruptions might therefore occur again along this fault at the western outskirts of Managua. Such kind of activity, together with the strong seismicity associated to the active fault represents a serious hazard to urban infrastructure and a population of ca. 1.3 million inhabitants.

1. Introduction

The Nejapa–Miraflores fault (NMF) is a North-South trending, 15 km long fault, with a right-lateral movement (La Femina et al., 2002), located west of Managua City, Nicaragua (Fig. 1). This fault has been active since the Late Pleistocene (<30,000 yr BP), with associated eruptions that produced basaltic, basaltic–andesitic, and rhyolitic pyroclastic deposits, together with basaltic and andesitic lava flows (Walker, 1984a,b; Bice, 1985). The high frequency of eruptions is evidenced by the alignment and clustering of more than 21 vents along the NMF, including stratovolcanoes, tuff rings, scoria cones, and maars located between the Chiltepe Volcanic Complex to the North and Ticomo vents to the South (Walker, 1984a,b; Bice, 1985; Havlicek et al., 1997). Because of vent clustering and superposition of related deposits, the distribution of volcanic products along the fault is complex. Stratigraphic and geochronologic data for most of the eruptive vents located along the NMF are scarce. We performed a stratigraphic study inside and around Asososca, which was first described as a pit crater by McBirney (1955) and then as a "maar related to crustal fissures" by Badilla et al. (2001). Asososca is located in the central part of the NMF (Fig. 1), at the western outskirts of Managua. The crater has a well-preserved morphology compared to other NMF-controlled craters that

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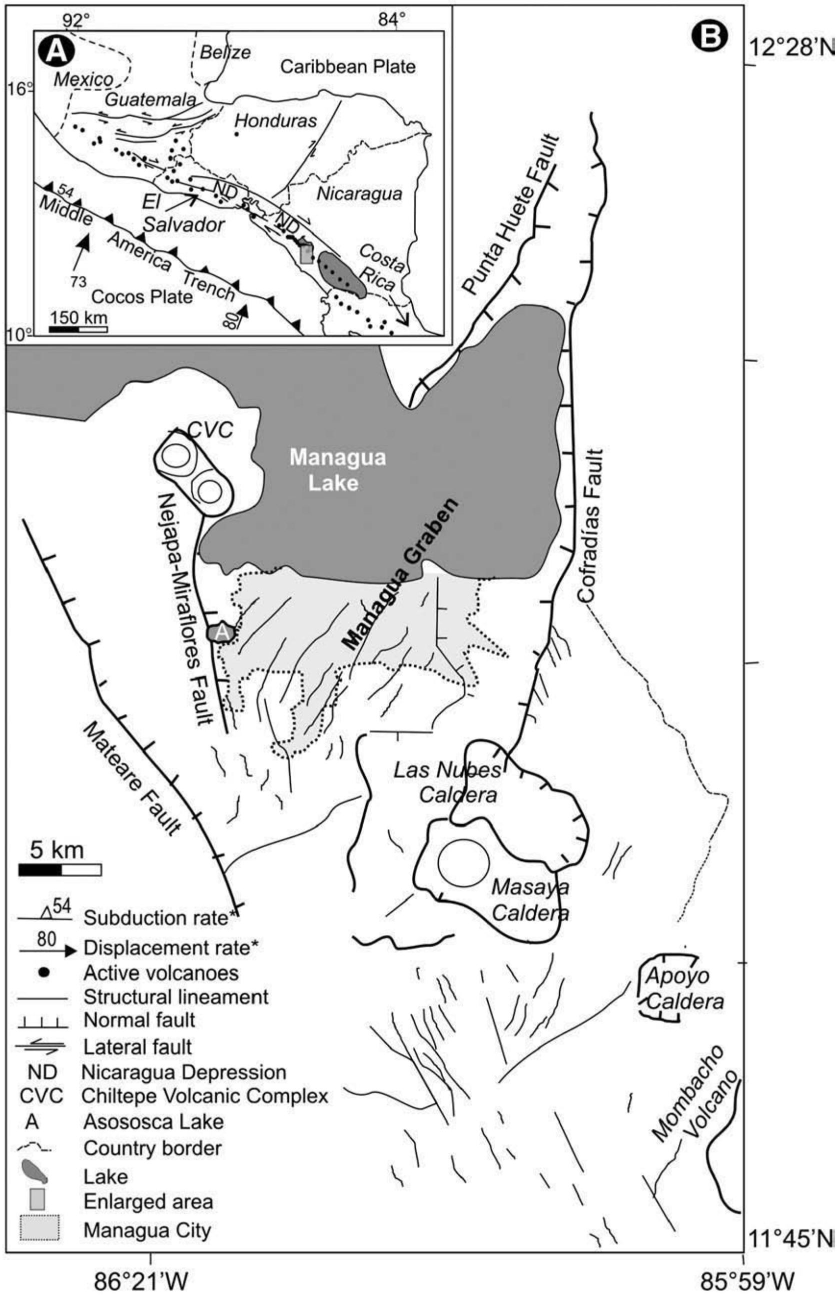

Fig. 1. Geological setting. A. Nicaragua regional tectonic setting showing active volcanoes associated to the subduction of the Cocos Plate beneath the Caribbean Plate along the Middle American Trench. The active volcanic arc and the Nicaragua Depression (ND) run parallel to the trench. *Rates in mm/yr taken from Frischbutter (2002). B. Modified from van Wyk de Vries (1993) and Girard and van Wyk de Vries (2005). The Managua Graben is localized in the central part of the Nicaragua Depression; it is delimited by the Cofradías, Punta de Huete, and Nejapa–Miraflores faults. N–S, NW–SE, and NE–SW lineaments are also shown.

are partially collapsed or eroded, faulted and filled with sediments. Asososca crater hosts a 1.1 × 0.8 km wide lake that serves as one of the main sources of potable water for the city, and is currently exploited by the Empresa Nicaragüense de Acueductos y Alcantarillados (ENACAL). In this study we present the geologic map and stratigraphy of Asososca that is supported by radiocarbon ages obtained on paleosols, as well as 20 whole-rock chemical analyses.

2. Geological setting

Nicaragua is located in Central America, between the Pacific Ocean and the Caribbean Sea. The intense seismic and volcanic activity in this country is related to the subduction of the Cocos Plate beneath the Caribbean Plate along the Central American Trench (Carr et al., 1982; DeMets, 2001; La Femina et al., 2002) (Fig. 1). Most of the active volcanoes are located along the axis of the Nicaragua Depression, which runs parallel to the Middle America Trench (McBirney and Williams, 1964). The Managua Graben lies inside the Nicaragua Depression (Weyl, 1980), and hosts the city of Managua. The NMF defines the western border of the graben (Frischbutter, 2002; La Femina et al., 2002) and is evidenced by a N–S to N15°W alignment of small volcanoes (Figs. 1 and 2A). The most prominent volcanic structures along the NMF are the Chiltepe Volcanic Complex to the North, Asososca and Nejapa in the middle, and Ticomo vents to the South (Fig. 2A and B).

The oldest rocks known in the Nicaragua Depression belong to Las Sierras Formation, defined as a "thick succession of dacitic to basaltic ignimbrites and lava flows" (Kuang, 1971 in: Bice, 1985). Las Sierras Formation is overlain by the Managua Formation which consists of

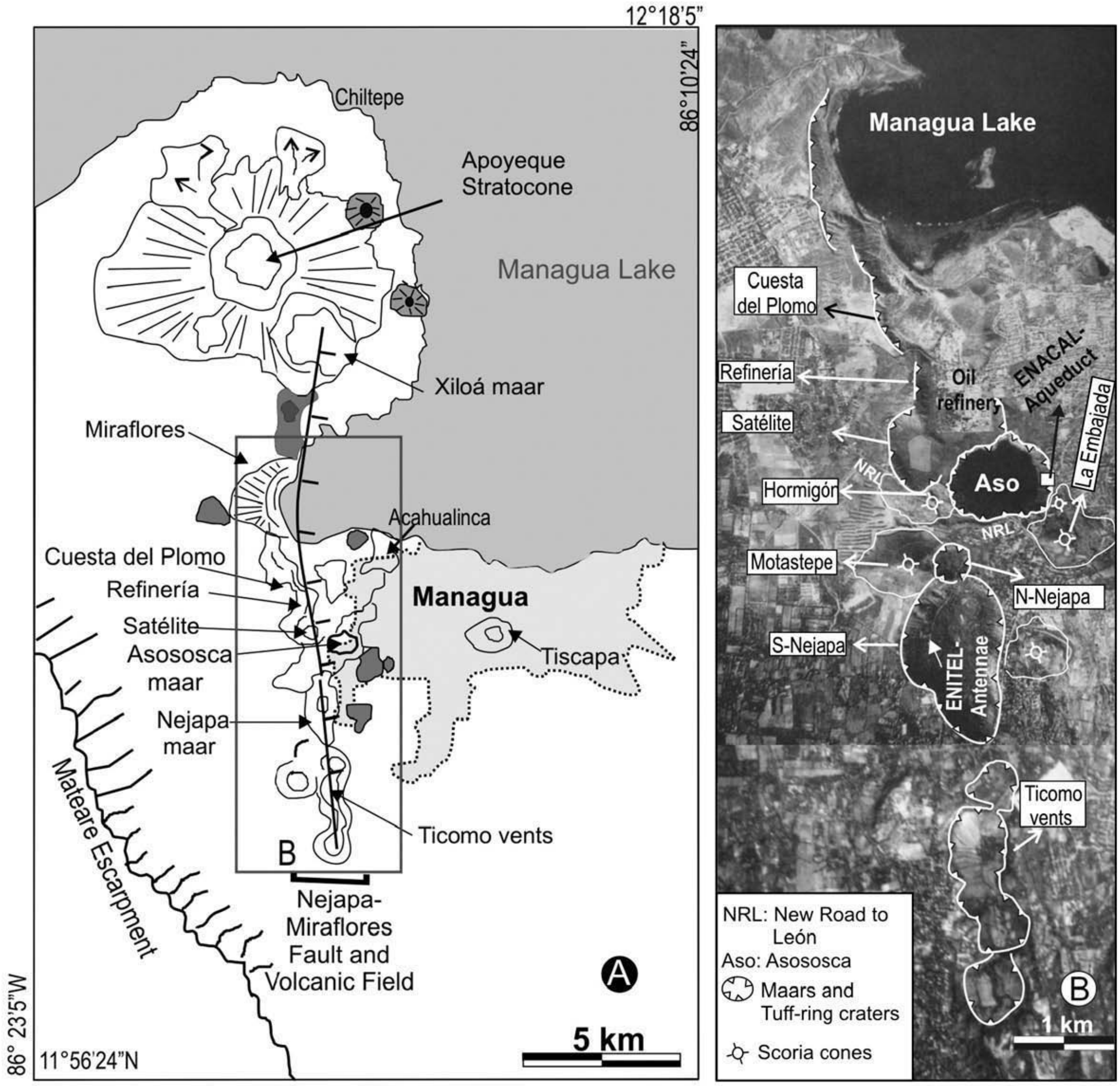

Fig. 2. A. Sketch map showing the N–S Nejapa–Miraflores Fault (NMF) and the alignment of more than 21 volcanic vents that occur between the Chiltepe Peninsula (N) and the Ticomo vents (S). The principal volcanoes from N to S are: Apoyeque stratocone, Xiloá, Miraflores, Cuesta de Plomo, Acahualinca, Refinería, Satélite, Asososca, Nejapa, and Ticomo. The Asososca maar is located in the central part of the NMF. The sketch is modified from Bice (1985). B. Aerial photograph of the NMF showing the principal vents west of Managua City. It is noteworthy that Asososca crater is well preserved in comparison to the other vents that are partially collapsed, smoothed, or cut by Asososca crater walls.

basaltic to basaltic–andesitic plinian to phreato-plinian deposits emitted from Masaya caldera (Pérez and Freundt, 2006; Kutterolf et al., 2007), dacitic plinian deposits from Apoyo Caldera (Sussman, 1985), basaltic to rhyodacitic fallout and pyroclastic surge deposits from undefined vents located along the NMF (Bice, 1985), interstratified with rhyodacitic plinian deposits from the northern Chiltepe Volcanic Complex (Kutterolf et al., 2007).

The first Late Pleistocene–Holocene stratigraphy in west-central Nicaragua was proposed by Bice (1985). Later studies by Havlicek et al. (1997) identified the Masaya caldera, the Apoyeque stratocone, and the craters along the Nejapa–Miraflores fault as the main sources of pyroclastic deposits around Managua. Freundt et al. (2006a,b) and Kutterolf et al. (2007) re-defined the stratigraphy of major Plinian eruptions, which originated either to the North of Managua, at the Chiltepe Volcanic Complex, or to the South of the city at the Apoyo and Masaya calderas (Bice, 1985; Freundt et al., 2006a). Kutterolf et al. (2007), based on major Plinian eruptions from the Chiltepe Volcanic Complex, indicated this eruptive center as the most likely locus for the next large eruption in central Nicaragua. Other studies (Pérez et al., 2006; Pérez and Freundt, 2006) focused on plinian and phreato-plinian deposits from the Masaya caldera that are widespread all over Managua, and represent excellent tephro-stratigraphic markers.

3. Asososca crater: geomorphology and geological map

Geomorphological, stratigraphical, sedimentological and compositional features, together with radiometric ages on paleosols were used to define depositional units and to construct a 1:10,000 geological map (Fig. 3) with related cross-sections (Fig. 4). Previous authors interpreted Asososca as a pit crater (McBirney, 1955), but this interpretation disagrees with the presence of surrounding pyroclastic deposits that indicate a related explosive event. The Asososca maar (*"water with the color of the sky"* in *Nahuatl*) is characterized by an East–West elongated irregular crater (Figs. 3–6), excavated into an older volcanic sequence consisting from the base toward the top of base surge deposits, ash fallout deposits with accretionary lapilli, scoria fallout deposits, and pyroclastic ash-flow deposits, separated by paleosols and covered by basaltic lava flows. The crater has inner walls dipping 33 to 57° towards the center; locally the walls are nearly vertical (up to 86°) at the lake level, and become gentler inside the lake. The rim is 160 m a.s.l. and external walls dip less than 10° (Figs. 5

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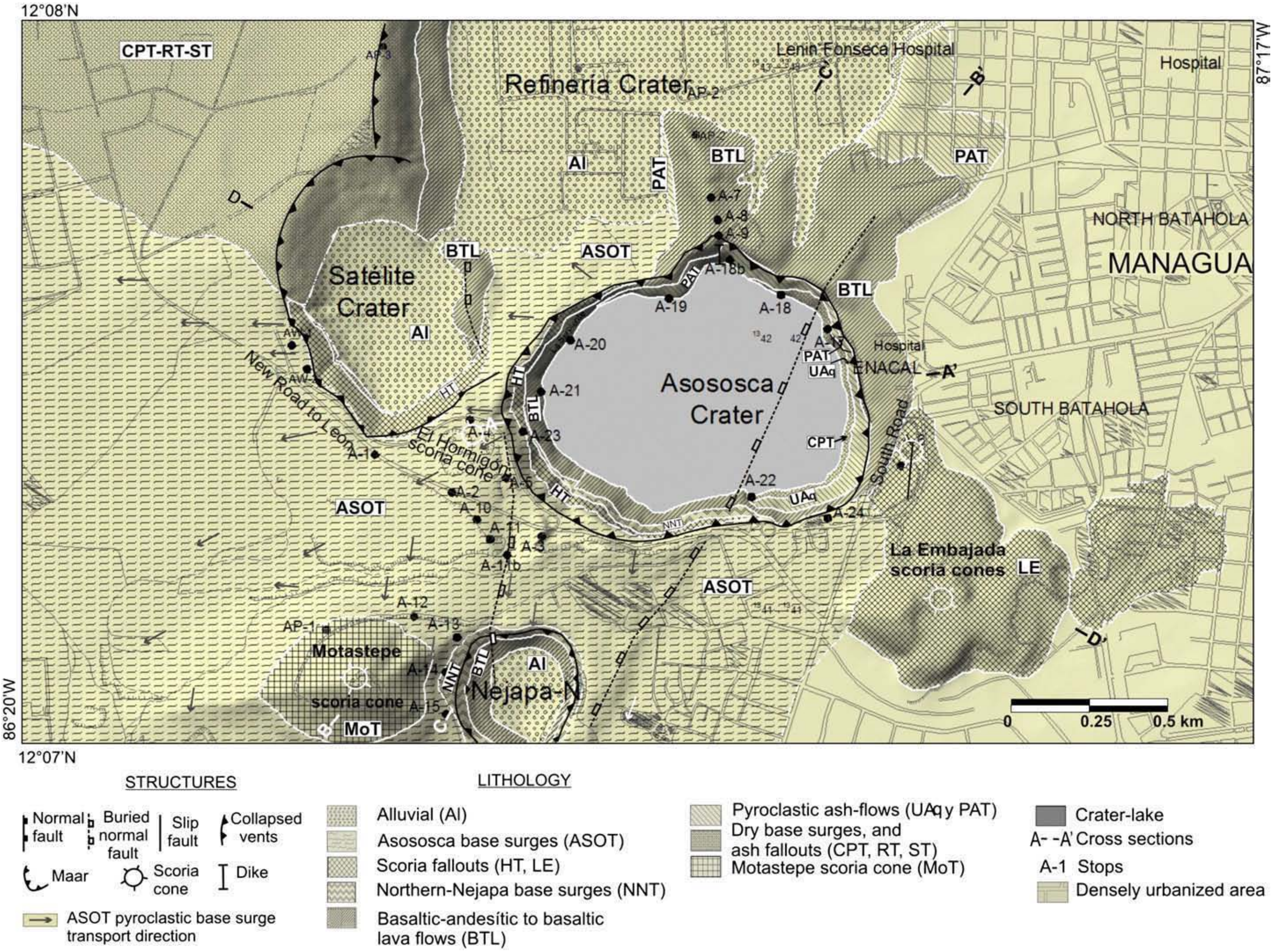

Fig. 3. Geological map of Asososca drawn on a 5 m resolution Digital Elevation Model (DEM). The clustering of maars and scoria cones as well as the distribution of the principal stratigraphic units identified inside and around Asososca lake is shown. Arrows indicate transport direction of the youngest pyroclastic base surges as inferred from dunes and impact sags. Observe the location of Managua's western outskirt, principal roads, and infrastructure close to the vents on recent pyroclastic deposits.

and 6). The crater has a mean diameter/total-crater-depth ratio (D/d) equal to 3.9, where d is measured from the top of the crater rim to the bottom of the lake. This value is characteristic of a barely eroded crater with a scarce sediment infill that suggests a young age (e.g. Carn, 2000). The bathymetry of Asososca lake (UNAN-EAM, 1978) shows two bottoms located at different depths and separated by an arched wall (Fig. 5). This morphology suggests that the Asososca crater might be the result of explosions occurring at coalescent vents, as has been described in other places, such as Albano maar in the Volcanic Roman Province (Funiciello et al., 2003; Freda et al., 2006). The Asososca crater excavated the surrounding 80 m a.s.l. topography and is superimposed to two older craters named here Satélite and Refinería (Figs. 2 and 3). The Satélite crater is almost circular in shape with a 1.5 km diameter and a maximum elevation of 165 m a.s.l.; it is partially eroded and filled with recent sediments. The Refinería crater, which hosts the Managua oil refinery, has a nearly circular form with a maximum elevation of 130 m a.s.l., and a 1.9 km diameter.

A third roughly elliptical, partially eroded and sediment-filled structure is located to the South of Asososca by the intersection of two craters: the Northern Nejapa crater is almost circular with a 500 m diameter and the Southern Nejapa crater is elliptical, with a N–S long axis of 1720 m, and is partially occupied by a 2.5 m deep crater-lake that has been progressively drained by inhabitants (Fig. 2B). The mean diameter/depth (D/d) ratios of 5.6 (N-Nejapa) and 6.3 (S-Nejapa) suggests an older age with respect to Asososca, indicating a longer time of erosion and sediment infilling.

In addition, three scoria cones were identified around Asososca. The remains of the El Hormigón scoria cone are exposed to the Southwest and other two cones named here La Embajada scoria cones are located 100 m to the East and 400 m to the Southeast of Asososca (Figs. 2B, 3, and 4).

4. Stratigraphy and radiocarbon ages

The spatial distribution of deposits and the temporal succession of eruptive events in the Asososca area were determined by describing stratigraphic sections, constructing geological profiles, and identifying major structural features in the field. These data are supported by 12 radiocarbon ages of samples collected from the upper 15 cm of paleosols rich in organic matter. The exact location of the dated samples is given in Table 1, and their stratigraphic position is shown in Fig. 7. Most samples were collected inside the Asososca crater and along the new road to León, where they were thick enough to obtain at least 1 kg of material. Radiocarbon dating was performed at GeoSIMSLab of the University of Arizona at Tucson (USA). These results are chronologically listed in Table 1, and marked in the stratigraphic columns. The definition of depositional units is based on bed geometry, depositional structures, textures, and compositions. Bed

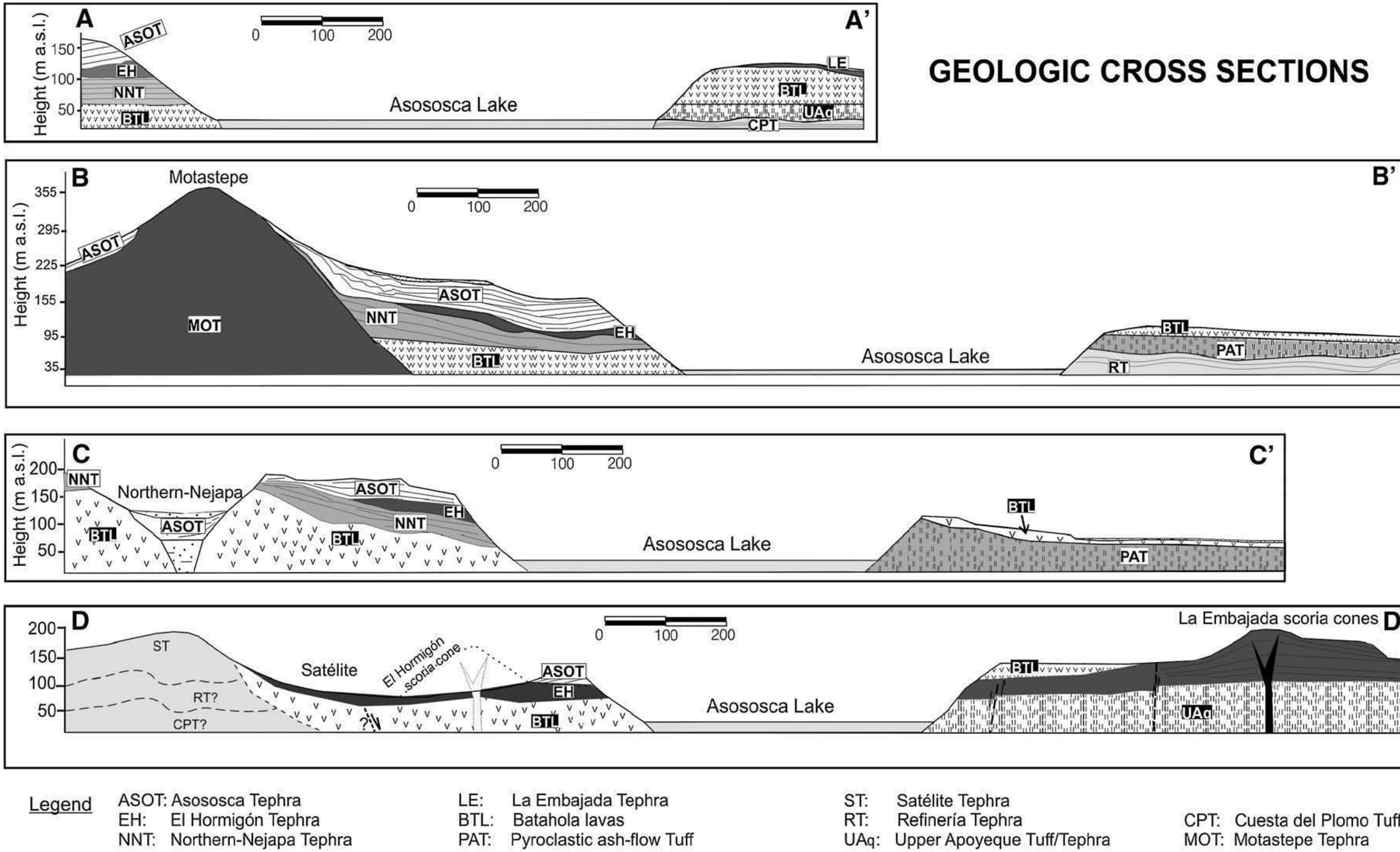

Fig. 4. Geologic cross-sections labeled in Fig. 3, showing the vertical stratigraphy units inside the Asososca crater. Note that inside the crater the same units are exposed at different heights: on the eastern part of the crater there crop out older and faulted units, capped by the un-faulted Batahola lavas (BTL), whereas younger units are exposed on the western side of the crater above BTL.

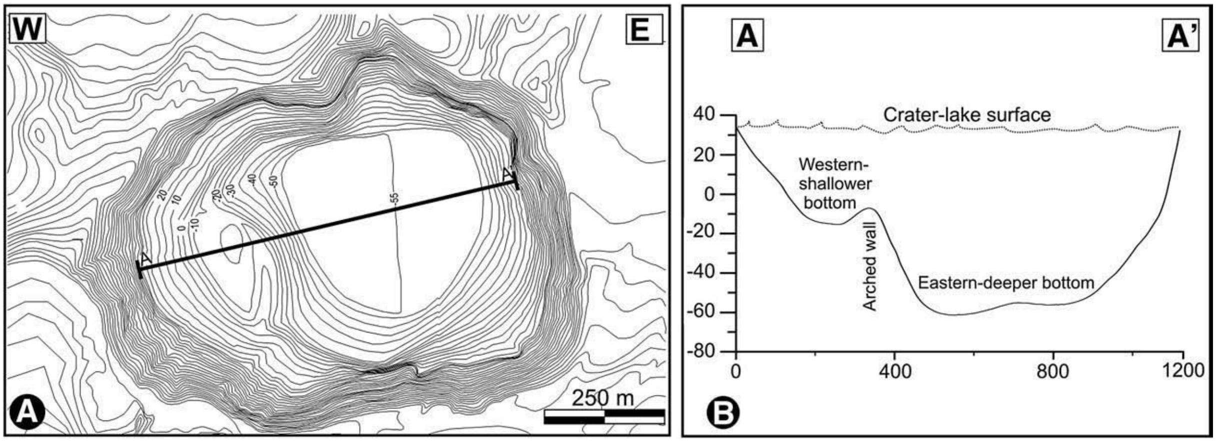

Fig. 5. Asososca Lake bathymetry. A. Bathymetric map of Asososca Lake with 5 m contour lines from UNAN-EAM (1978). B. Bathymetric profiles with a vertical exaggeration of 4, showing the configuration of the lake floor, where two bottoms appear at different depths separated by an arched wall that is convex towards the center. The eastern bottom is 55 m below sea level while the western bottom is only 18.35 m below sea level.

thicknesses were described according to Ingram (1954) and grain-sizes according to Sohn and Cough (1989). The term *bedset* is used according to Walker (1984a). Clast compositions were characterized both in the field by hand-sample observation, and in the laboratory under binocular and optical microscope. Rock samples were cut and polished for thin section analyses, and chemical analyses (major and trace elements) were performed at Actlabs (Ontario, Canada).

Clasts were separated into juvenile and accidental lithics. Juvenile clasts consist of fresh scoria or pumice fragments, and free crystals without chemical alteration. Accidental main crystalline phases were distinguished by dissolution wedges, oxidation minerals (e.g. iddingsitized olivine), and corrosion (clinopyroxene and plagioclase). Accidental lithics were discriminated by their high degree of alteration, glass matrix devitrification, and by their similarity in composition with older deposits found in the whole stratigraphic sequence.

The following sequence is part of the Managua Formation (Kutterolf et al., 2007; "Managua Sequence" in Bice, 1985) which overlies the Late Pleistocene basaltic ignimbrite shield of Las Sierras Formation that partially crops out inside the Southern Nejapa crater underlying the Fontana Tephra (Pérez et al., 2006), the Lower Apoyo Tephra (Bice, 1985), and a thick sequence of debris-flow deposits. The stratigraphic succession from base to top found inside and around the Asososca crater is summarized below (Fig. 7).

4.1. TA-Tephra (TA)

Unit TA (Fig. 8) is composed of two subunits (TA-A and TA-B) with distinct depositional structures and textures. The lower subunit TA-A is a crudely stratified, poorly sorted, matrix-supported, 2 m-thick deposit that crops out at the northern base of Cerro Motastepe. TA-A consists of several bedsets, each one having a basal, massive bed of block-and-lapilli that is 30 to 50 cm thick, with local imbrications of clasts, overlain by a 30 to 15 cm thick, crudely cross-stratified beds of medium to fine lapilli and coarse ash, showing impact sags and dunes. Fragments are subangular fresh juvenile brown, olivine-bearing scoria lapilli and blocks, accidental subangular black andesites to basaltic-andesites lapilli, rounded red

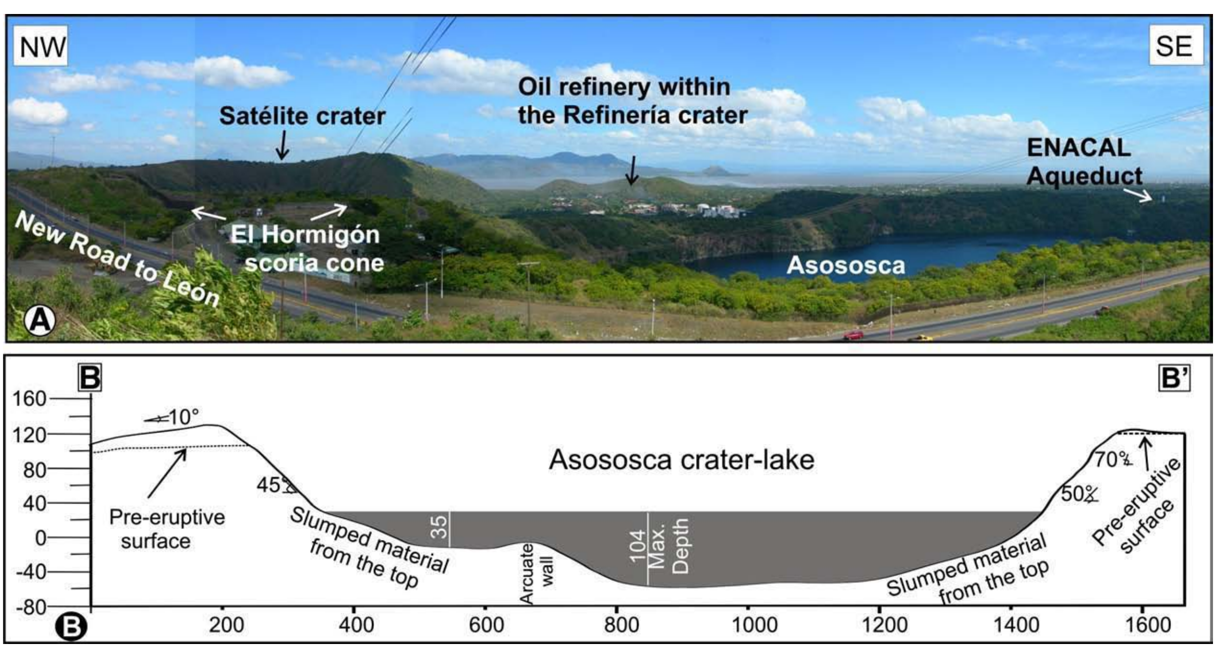

Fig. 6. A. View of Asososca maar and volcanic structures nearby. The oil refinery of Managua is located inside one of the craters and the ENACAL aqueduct is located on the eastern Asososca crater rim. Scoria cone morphologies (e.g. El Hormigón) are modified by construction and quarrying activities. B. Profile where the morphometric parameters of the Asososca maar can be observed: maximum diameter, maximum crater depth, inner and outer slopes as well as maximum wall height are shown.

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Table 1
Radiocarbon ages of buried paleosols inside and around Asososca, determined at the Radiocarbon Laboratory (GeoSIMSLab), of the University of Arizona at Tucson (USA)

Dated paleosol	Lab. no.	Locality	UTM		Conventional Date (yr BP)	Error	$\delta^{13}C$
			N	W			
Ps13	A-14248	A11b	12° 7' 56"	86° 19' 22"	535	±110	−18.3
Ps12	A-4257	A-23	12° 8' 9"	86° 19' 17"	1245	+125/−120*	−26.3
Ps10	A-14243	A-4	12° 8' 7"	86° 19' 22"	3040	±70	−11.7
Ps9	A-14250	A-15	12° 7' 36"	86°19' 26"	6170	±80	−19.7
Ps9	A-14258	A-17	12° 8' 20"	86° 18' 39"	6340	±110	−17.3
Ps9	A-14242	A-1	12° 8' 7"	86° 19' 26"	6375	+270/−260*	−23.9
Ps8	A-14256	A-1	12°8'7.2"	86° 19' 26"	7175	+210/−205*	−24.2
Ps8	A-14246	A-10	12° 7' 57"	86° 19' 24"	7295	+215/−210*	−20.8
Ps5	A-14261	A-17-06	12° 8' 20"	86° 18' 39"	9380	+280/−270*	−22.7
Ps4	A-14259	A-17-06	12° 8' 20"	86° 18' 39"	9715	+345/−335*	−23.2
Ps3	A-14260	A-17	12° 8' 20"	86° 18' 39"	12,435	+380/−365*	−23.5
Ps 1	A-14245	A-10	12° 7' 57"	86° 19' 24"	12,730	+255/−250*	−21.1

Ages are listed in stratigraphic order, being paleosol Ps1 the oldest and paleosol Ps13 the youngest.

scoria lapilli, and red and orange ignimbrite fragments. The structures and textures found in TA-A can be interpreted as typical facies of pyroclastic dry-surges. Subunit TA-B overlies TA-A with sharp contact and consists of a crudely stratified, clast supported, 1 m-thick bed of black, olivine-bearing angular coarse scoria lapilli and blocks. This bed grades upwards into a 70 cm thick ash bed with mm-sized pores and sparse, locally imbricated subrounded scoria blocks and lapilli. These characteristics suggest that TA-B is a scoria fallout deposit partially reworked towards the top.

4.2. TB-Tephra (TB)

TB-Tephra mantles TA-Tephra and consists of a 1 m-thick, clast-supported, well-sorted, massive fallout of juvenile olivine-bearing scoria lapilli. Accidental gray andesitic lithics and altered white dacitic pumice are subordinated. TB-Tephra grades upward into a 10 cm-thick, friable, yellowish silt-sandy paleosol (Ps1) dated at 12,730+255/−250 yr BP, which is the oldest age obtained (Figs. 7 and 8; Table 1). Based on the stratigraphic position and radiometric age, TA and TB tephras represent the oldest stratigraphic units around Asososca.

4.3. Motastepe Tephra (MoT)

This tephra forms the bulk of Cerro Motastepe (Fig. 4) where it consists of a grain-supported, poorly-sorted, 0.7 m-thick, massive bed of coarse angular scoriae lapilli and blocks and less than 5 vol.% of accidental lava fragments. Juvenile scoriae are fresh, dark brown, hypohialine fragments with of 3 to 10 mm spherical vesicles and 5 to 10 vol.% phenocrysts of olivine, plagioclase, and augite. Accidental lithics of the entire deposit consist of plagioclase and clinopyroxene bearing gray lavas, olivine bearing black lavas, and altered red lavas. Motastepe Tephra is interpreted as a proximal scoria fallout originated at Cerro Motastepe. Although Siebert and Simkin (2002) reported Cerro Motastepe as the youngest volcanic vent in the Managua area, its stratigraphic position and the radiocarbon dating of the underlying paleosol Ps1 indicate that it is a ~12,730 yr BP scoria cone (Table 1). In addition, Cerro Motastepe eastern flank is partially overlapped by the Northern-Nejapa crater, and is partially covered by younger stratigraphic units (Figs. 3 and 4).

4.4. Cuesta del Plomo Tuff (CPT)

This tuff crops out on the eastern inner wall of Asososca crater at lake level. It consists of three subunits. The lower subunit (CPT-A) is 1 to 2 m thick, massive at the base and low-angle cross-stratified at the top. The entire subunit is gray, indurated, matrix-supported, poorly sorted, with rounded juvenile dark-brown fresh scoria lapilli and subangular accidental lithic lapilli and fine blocks set in a vesiculated ash matrix with sparse accretionary lapilli. Accidental lithics are altered red and gray scoria fine lapilli, hypocrystalline gray basaltic-andesite coarse lapilli, and red altered aphanitic coarse lapilli and occasional fine blocks. Subunit CPT-B consists of a 20 cm-thick, clast-supported, massive bed of angular, fresh, black juvenile scoria lapilli mantling subunit CPT-A. The upper gray subunit, CPT-C, is erosive above CPT-B. It shows low-angle cross-bedding, dunes (1 m long and 15 to 20 cm high) and lenses of altered accidental white pumice and accidental basaltic to andesitic lithic lapilli. This stratigraphic succession is interpreted as resulting from the deposition of several wet diluted pyroclastic density currents (CPT-A) followed by a scoria fallout (CPT-B), and finally the deposition of dry diluted pyroclastic density currents (CPT-C). The whole unit grades upward into a 10 cm-thick brown paleosol Ps3, dated at 12,435+380/−365 yr BP (Table 1 and Fig. 8). It was not possible to determine the exact provenance of CPT unit. Nevertheless, a 16 m thick succession of laterally discontinuous, indurated beds of lapilli and coarse ash, with crude cross and planar stratification, composed of subrounded juvenile scoria and accidental lava blocks set in an ash and lapilli matrix was observed in the same stratigraphic position at Cuesta del Plomo, North of Asososca (Fig. 9). Local impact sags by accidental blocks up to 60 cm in diameter and soft-sediment deformation structures are also present. These beds underlie the rhyodacitic Upper Apoyeque Tephra, dated at 12,400±100 yr BP by Kutterolf et al. (2007) (Fig. 7). The stratigraphic position, composition, deposit thickness and clasts dimensions of CPT-A and CPT-C suggest that these deposits were originated from Cuesta del Plomo (Fig. 2B). The eroded morphology of that crater is partially collapsed to the East and suggests that it is older than craters located southwards.

4.5. Upper Apoyeque Tuff (UAq)

Inside the Asososca crater and overlying with erosive contact Ps3 (Figs. 7 and 8) there are 10 massive, matrix-supported, poorly sorted beds, <1 m thick each, consisting of rounded fresh, juvenile white pumice lapilli and altered brown, red, and green angular, accidental lithics set in a yellowish ash matrix. The pumice is white or yellowish with quartz and K-feldspar phenocrysts. The uppermost 10 to 20 cm of each bed are highly consolidated and display vertical fractures, marking the top of single depositional units, interpreted as discrete ash-flow deposits. The upper two flow units are capped by well developed, indurated, brownish, silty paleosols (Ps4 and Ps5, Table 1). Considering the small grain size of the deposits, the felsic nature of the juvenile pumice fragments and taking into account that these beds are in the same stratigraphic position as the rhyodacitic Upper Apoyeque Tephra, we correlate the felsic pyroclastic flow deposits found inside

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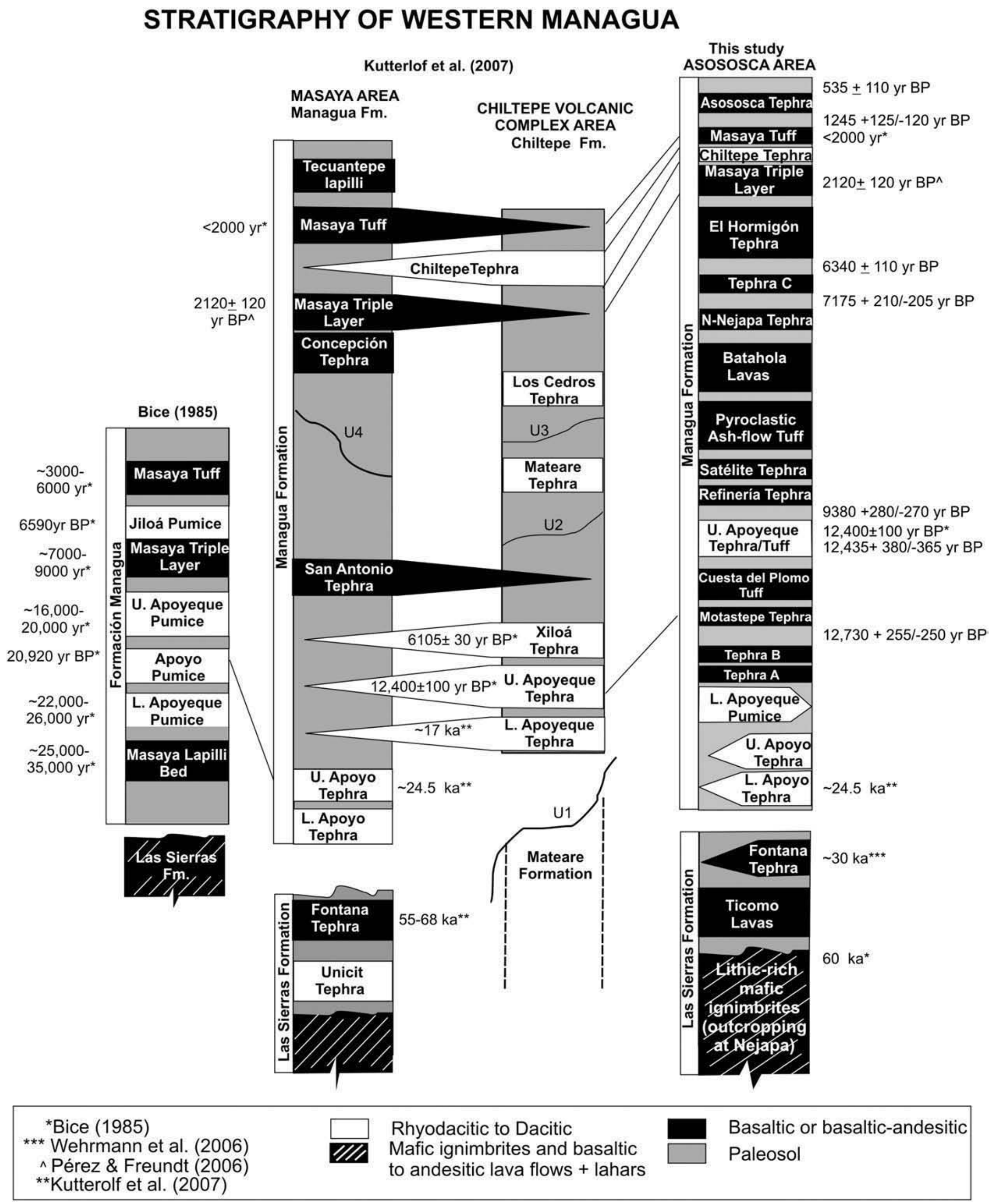

Fig. 7. Comparison of general stratigraphic columns produced by previous studies in the area with the stratigraphic column proposed in this study. This study complements the recently published data by Kutterolf et al. (2007), who reviewed and redefined the classical stratigraphy of Bice (1985). All the units presented here are younger than the Lower Apoyeque Tephra and occur within the Managua Formation.

Asososca to the 12,400±100 yr BP Plinian eruption of Apoyeque stratovolcano reported by Kutterolf et al. (2007).

4.6. Debris flow unit (DFU)

In the western part of Asososca crater a locally distributed,1 m-thick, poorly sorted, matrix-supported deposit consisting of rounded, altered, red, black and green andesitic to basaltic lava and scoria blocks, locally imbricated, and immersed in a sandy-silty matrix with small vesicles, occupies the same stratigraphic position of the Upper Apoyeque Tuff (Fig. 8). The massive appearance, poor sorting, clasts rounding, and the polygenetic nature of its components, suggest that this unit was deposited by a debris flow. The source of this unit is unknown, although similar deposits are also exposed around the Southern Nejapa crater above the plinian fallout “Upper Apoyeque Tephra” and their thickness increases towards the South. Inside the

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Asososca crater, paleosols dated in 9715+345/−335 yr BP (Ps4) and 9380+280/−270 yr BP (Ps5) bracket DFU unit.

4.7. Refinería Tephra (RT)

RT crops out above paleosol Ps5 on the northern crater wall of Asososca (Fig. 9B), where it reaches a maximum thickness of 20 m. It consists of three subunits that are in sharp contact with each other. The lower subunit (RT-A) consists of crude cross-stratified thin beds of subrounded scoria, brown altered lithic lapilli, and scarce andesitic to basaltic–andesitic accidental red and gray lava 10 cm-blocks, followed by a massive gray thin ash bed of the same composition with local impact sags that point to the NNE of Asososca crater.

The middle subunit (RT-B) consists of a massive, well-sorted, grain-supported, and inversely graded 20 cm-thick bed of angular fine scoria and less than 5% of accidental altered brown lapilli.

The upper subunit (RT-C) lies in erosive contact above RT-B and consists of several bedsets varying in thickness between 10 and 30 cm. Each bedset consists of a basal massive to crudely cross-stratified bed of altered rounded brown and accidental red lava coarse-lapilli, and less than 15% of fresh rounded, dark-gray clinopyroxene-bearing scoria lapilli and free olivine and clinopyroxene crystals, set in an abundant gray ash matrix, followed by a massive bed of coarse ash of the same composition, containing accretionary lapilli. This upper subunit grades into a thin brown paleosol (Ps6 in Fig. 8).

The lower and upper subunits can be attributed to the emplacement of several pyroclastic base surges, interrupted by a scoria fallout deposit (subunit RT-B). These events took place around ~9380 yr BP as indicated by the radiocarbon age of the underlying Ps5 (Table 1), which matches the stratigraphic position of the Refinería Tephra.

4.8. Satélite Tephra (ST)

ST crops out inside the Asososca crater above paleosol Ps6 (Figs. 8 and 9B). It consists of multiple 1 to 15 cm thick, indurated, gray, cross-stratified ash beds with sparse gray scoria and altered red and brown hypohialine lithic lapilli. Occasional impact sags are caused by 7–8 cm angular basaltic to andesitic–basaltic accidental bombs and point towards the Satélite crater. All beds are mantled by 5 to 10 cm thick, indurated massive ash beds containing accretionary lapilli. Juvenile clasts consist of gray-brown scoria with olivine, clinopyroxene, and plagioclase phenocrysts; accidental lithics are mainly gray and red lava fragments, as well as white and yellow altered pumices. The succession of beds in ST is interpreted as due to multiple flows of phreatomagmatic pyroclastic surges. Paleosol Ps6 did not contain enough organic matter to be dated. Nevertheless, the stratigraphic position of this unit indicates that the eruption followed a period of quiescence in the area after the emplacement of the Refinería Tuff.

4.9. Pyroclastic ash-flow Tuff (PAT)

PAT is well exposed in the N–NW inner walls of the Asososca crater, in erosive contact above ST (Fig. 8). It was subdivided into three subunits due to the presence of erosive surfaces. The lowermost and uppermost subunits (PAT-A, PAT-C) are yellowish in color, friable deposits varying in thickness between 1 and 5 m consisting, in order of abundance, of sub-rounded, altered, red, brown, and gray accidental aphanitic to porphyritic andesitic lapilli, and juvenile grayish rounded pumice lapilli randomly dispersed in a fine ash matrix with free crystals of pyroxene and plagioclase. The middle subunit (PAT-B) is the thickest deposit (>17 m). It is indurated and consists of rounded juvenile pumice lapilli and altered accidental lava lithics set in a gray ash matrix with scarce free crystals of pyroxene and plagioclase. Juvenile fragments are basaltic–andesitic in composition (Table 2 and Fig. 10). Inside the Asososca crater, the PAT-B and PAT-C subunits are thicker in local relative topographic lows and highs formed by erosion on previous deposits, and locally the Pyroclastic Ash-flow Tuff gradually transforms into a silty red paleosol (Ps7). Based on these characteristics we interpret the whole unit as pyroclastic flow deposits. The only source in the region that could have produced this kind of mafic ash-flows is the Masaya Caldera. Nevertheless, further stratigraphic studies are needed to fully support this hypothesis. In addition, this unit is cut by a N 8W/85 SSE dark greenish-gray basaltic dike on the northern inner wall of Asososca and, together with the Satélite Tephra, is affected by a N–S trending normal fault in the southern wall of the crater.

4.10. Batahola Lavas (BTL)

Five tabular, fresh and massive lava flows lie concordantly on top of the Pyroclastic Ash-flow Tuff (Fig. 11). The basal flow (BTL-A) is a basaltic-andesite (sample A-19-l) with plagioclase, olivine and augite phenocrysts set in an aphanitic black matrix. The second flow (BTL-B) is a basaltic tholeiite (sample A-20-06-1), and is thicker (up to 20 m) in the western Asososca crater wall, where it is found at the lake level while in other sectors it is found above 75 m a.s.l. Between the southern and western crater walls BTL-B displays flow-folds. The uppermost three lava flows (BTL-C, BTL-D, and BTL-E) are well accessible in the northern wall of Asososca. They are high-TiO_2 calc-alkaline basaltic-andesites (samples A-18-06-2, A-18-06-3 and A-7-b) with basal auto-breccias (Figs. 10 and 11), 3 m thick each, and show elliptical, long vesicles (3 to 10 cm) aligned in an E–W direction. Locally, the Batahola lavas overlie a 50 cm thick, red sandy paleosol atop of the Pyroclastic Ash-flow Tuff, which was not useful to obtain a radiocarbon age because it was too oxidized and did not contain enough carbon. It is noteworthy that these lava flows are in a different stratigraphic position compared to the low-TiO_2 tholeiitic basalts that crop out at the Southern Nejapa and Ticomo vents underlying the Fontana Tephra (~25–35 ka in Bice, 1985; Fig. 7).

4.11. Northern-Nejapa Tephra (NNT)

This unit is well exposed along the new road to León, around the Northern Nejapa crater (Figs. 2 and 3), and inside the southern wall of the Asososca crater where it rests concordantly above the Batahola Lavas (Fig. 4). Along this road the tephra consists of three subunits labeled from the base toward the top as NNT-A, NNT-B, NNT-C.

The lower subunit NNT-A is a massive bed with a total thickness of 4 m of juvenile scoria and accidental ignimbrite fragments (from Las Sierras Formation), and andesitic to basaltic-andesite accidental lithic blocks up to 1 m in diameter, supported by a fine matrix. NNT-A grades upwards into multiple bedsets consisting of a basal, 30 to 50 cm thick massive bed of accidental lithic blocks and coarse lapilli, followed by cross-stratified beds of lapilli and ash. Asymmetric dunes are up to 70 cm high and have wavelengths between 2 and 6 m (Fig. 12A-B). U-shaped channels, impact sags pointing towards South and Southeast and lithic concentration lenses were observed along the new road to León.

The middle subunit NNT-B is in erosive contact above NNT-A and is made of two 40 to 50 cm thick bedsets consisting of sub-angular blocks up to 20 cm in diameter randomly distributed in a lapilli-and-ash matrix at the base, followed by 8 to 15 cm-thick thinly stratified beds of lapilli and coarse ash at the top. Asymmetric impact sag points to the ESE and SE, and dune crests migrate towards the W and NW. Toward the top, cross-stratification grades into plane-parallel stratification and single beds are thinner.

The upper subunit NNT-C consists from base to top of three massive, 20 to 100 cm thick beds of accidental andesitic to basaltic–andesitic blocks set in a lithic-rich matrix with few juvenile scoria lapilli clasts. Each massive bed is followed by 10 to 15 cm thick cross-stratified beds, of coarse scoriae lapilli and lava lapilli and ash. Above these massive beds are several crudely cross-stratified beds of coarse lapilli and angular to subrounded blocks set in a finer matrix,

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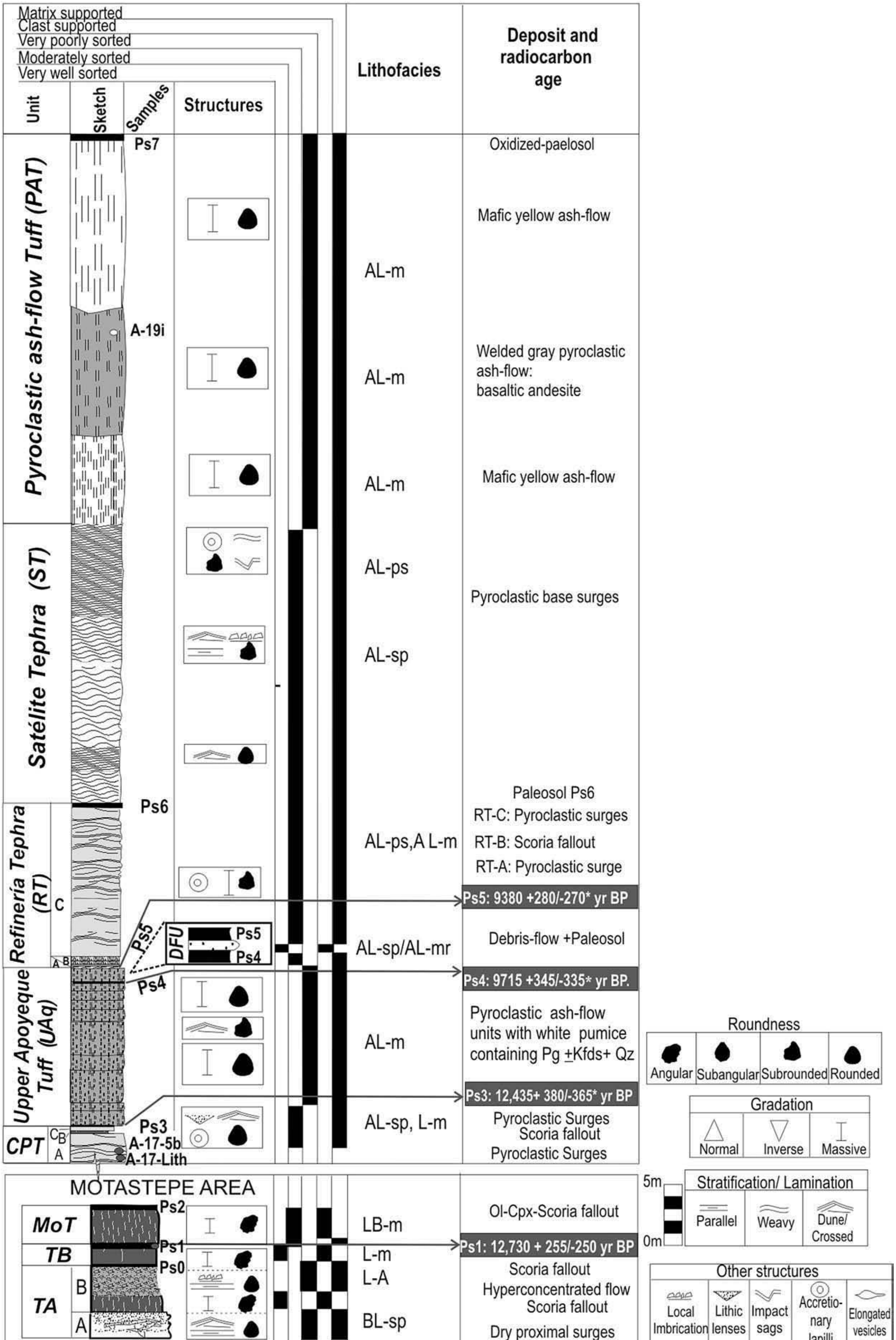
Matrix supported
Clast supported
Very poorly sorted
Moderately sorted
Very well sorted
Unit
Sketch
Samples
Structures
Lithofacies
Deposit and radiocarbon age
Pyroclastic ash-flow Tuff (PAT)
Ps7
Oxidized-paelosol
Mafic yellow ash-flow
AL-m
A-19i
Welded gray pyroclastic ash-flow: basaltic andesite
AL-m
Mafic yellow ash-flow
AL-m
Satélite Tephra (ST)
AL-ps
Pyroclastic base surges
AL-sp
Ps6
Refinería Tephra (RT)
C
B
A
Paleosol Ps6
RT-C: Pyroclastic surges
RT-B: Scoria fallout
RT-A: Pyroclastic surge
AL-ps,A L-m
Ps5: 9380 +280/-270* yr BP
Ps5
DFU
Ps4
AL-sp/AL-mr
Debris-flow +Paleosol
Ps4: 9715 +345/-335* yr BP.
Upper Apoyeque Tuff (UAq)
Pyroclastic ash-flow units with white pumice containing Pg ±Kfds+ Qz
AL-m
Ps3: 12,435+ 380/-365* yr BP
CPT
C
B
A
Ps3
A-17-5b
A-17-Lith
AL-sp, L-m
Pyroclastic Surges
Scoria fallout
Pyroclastic Surges
MOTASTEPE AREA
MoT
TB
TA
B
A
Ps2
Ps1
Ps0
LB-m
L-m
L-A
BL-sp
Ol-Cpx-Scoria fallout
Ps1: 12,730 + 255/-250 yr BP
Scoria fallout
Hyperconcentrated flow
Scoria fallout
Dry proximal surges
Roundness
Angular
Subangular
Subrounded
Rounded
Gradation
Normal
Inverse
Massive
5m
0m
Stratification/ Lamination
Parallel
Weavy
Dune/ Crossed
Other structures
Local Imbrication
Lithic lenses
Impact sags
Accretio-nary lapilli
Elongated vesicles

Fig. 9. A. Older base surge deposits at Cuesta del Plomo outer crater rim. The great thickness and grain sizes involved, as well as the depositional structures such as impact sags and dunes, suggest a proximal vent. These deposits are part of the CPT unit, which underlies the Upper Apoyeque Tephra (UAq). B. The Refinería Tephra (RT) and the Satélite Tephra (ST) crop out inside Asososca, at the northern crater wall. RT overlies a thick paleosol (Ps5) and is separated from ST by paleosol Ps6. Dry pyroclastic surges, ash fallout, and scoria fall deposits compose RT unit.

separated by cross-stratified and laminated coarse ash beds. Dune-crests migrate towards the W–NW and impact-sags point to the SE (Fig. 12C), where the Northern Nejapa crater is located.

A massive, poorly sorted, grain-supported, 3 m thick deposit of blocks and lapilli of angular juvenile scoria, with few altered red scoria, rich in accidental red and gray andesitic to basaltic–andesitic blocks at the base (NNT-D) overlies NNT-C with a sharp contact. Towards the top, NNT-D grades into a yellow paleosol with scoria lapilli in a sandy-silty matrix.

The whole Northern-Nejapa Tephra is composed mainly of accidental lithic fragments of andesitic to basaltic–andesitic lavas, vesiculated red lavas, altered yellow and white pumice, and altered yellow, brown, and red ignimbrite fragments, with subordinate juvenile fragments (basaltic scoria, olivine and augite crystals). Along the new road to León the Northern-Nejapa Tephra is affected by a N–S normal fault (Fig. 12D). Close to the Northern Nejapa crater the matrix is coarser and blocks of andesitic lava fragments and orange-pink ignimbrite fragments are the most common component. The ignimbrite fragments are identical to the lithic-rich, mafic ignimbrites from Las Sierras Formation that crop out inside the Nejapa crater.

We interpret the basal subunit NNT-A as the opening phase of a phreatomagmatic eruption that ejected a coarse breccia made of accidental-blocks, and later shifted to a more effective mode of fragmentation of pre-existing material with the production of dry pyroclastic base surges (NNT-B and NNT-C).

Considering the geometry of impact sags and the direction of dune-crest migration, the most likely source for these surges was the Nejapa crater (Figs. 2 and 3). In fact, close to the Northern Nejapa crater, impact sags point toward the South and the matrix consists of coarse lapilli and blocks. NNT-D is a scoria fallout that reflects a change towards a final magmatic activity and grades into a friable, dark yellow to pale brown, sandy paleosol Ps8 (Fig. 13). The stratigraphic position of the Northern Nejapa Tephra suggests that this unit is younger than the Batahola lavas (BTL unit) and younger than the underlying paleosol Ps8 (7295+215/−210 yr BP; Table 1).

4.12. Undistinguished Masaya Lapilli (UML)

UML is a grain-supported, well-sorted, massive lapilli bed exposed along the new road to León (Fig. 3), where it is laterally interfingered with the Northern-Nejapa Tephra. It consists of angular, highly vesiculated mafic pumice with mm-sized, elongated vesicles, and subordinated accidental andesitic to basaltic lava lapilli with plagioclase, pyroxene, and olivine, and altered white pumice. This Undistinguished Masaya Lapilli unit is interpreted as a distal mafic fallout deposit of unknown age from Masaya caldera, although its stratigraphic position suggests that it was deposited contemporarily with the Northern-Nejapa Tephra.

4.13. TC-Tephra

TC-Tephra is a 2 m thick unit well exposed along the new road to León in sharp contact with a dark yellow to pale brown sandy paleosol (Ps8) (Fig. 13). It consists of a grain-supported, massive bed of angular scoria lapilli and blocks, with constant thickness. Scoriae are poorly vesiculated, with 1 cm vesicles and clinopyroxene phenocrysts. Accidental lithics are <5 vol.%, and consist of basaltic-andesites and basalts with clinopyroxene, olivine, and plagioclase phenocrysts in different proportions. TC-Tephra is interpreted as a proximal scoria fallout, partially transformed into a sandy paleosol (Fig. 13). The radiocarbon age of the underlying paleosol Ps8 is 7175+210/−205 yr BP, in good agreement with TC-Tephra stratigraphic position (Table 1).

4.14. El Hormigón Tephra (HT)

A sequence of red, thick, massive scoria beds is well exposed on the SW inner walls of Asososca and at the El Hormigón quarry above paleosol Ps9 (Figs. 2 and 3). The beds are grain-supported, poorly sorted and consist of juvenile scoria and bombs, and <10 vol.% of accidental olivine-bearing and clinopyroxene-plagioclase-bearing lava blocks up to 50 cm in diameter. Juvenile scoria is basaltic in composition (Fig. 10). El Hormigón Tephra becomes stratified towards the top and grades into an orange 50 cm-thick bed of scoria lapilli embedded in a sandy matrix, corresponding to paleosol Ps10 (Fig. 14). This unit is interpreted as a proximal scoria fallout at El Hormigón quarry where it reaches a maximum thickness of 30 m (Fig. 14). This quarry probably represents part of a pre-existing scoria cone that erupted 6340±110 yr BP as indicated by the radiocarbon age of the underlying paleosol Ps9 (Figs. 4 and 13). To the East of Asososca there are two additional scoria cones (La Embajada cones) consisting of clast-supported, massive beds of scoria blocks and bombs intersected by basaltic dikes that become concordant with the cone's topography

Fig. 8. Composite stratigraphic section of lower (i.e. older) depositional units. Radiocarbon data indicate that the studied deposits around and inside Asososca are all younger than 13,000 yr BP. MoT: Motastepe Tephra; CPT: Cuesta del Plomo Tuff. A: Ash; L: Lapilli; B: Blocks; m: massive; s: sandwave; p: planar; sp: sandwave>planar; ps: planar>sandwave.

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Table 2
Major element chemical analyses of different stratigraphic units

A

Sample	A-4-05-2	Hormigón	A-6-lava	A-7-b	A8-05-1	A-17-5-b	A-17-Lit	A18-6-02	A18-6-3	A-18b-d	A-19-l	A-19-i
Unit	HT	HT	BTL	BTL-E	BTL-B	CRT	CRT-Lith	BTL-C	BTL-D		BTL-A	PAT-B
Locality	El Hormigón	El Hormigón	La Embajada	North of Asososca		NE-inner wall of Asososca		N-inner wall of Asososca			NW-inner wall of Asososca	
Lat-N	12° 8' 7"		12° 8' 33"	12° 8' 30"		12° 8' 20"		12° 7' 46"			12° 8' 20"	
Long-W	86° 19' 24"		86°18' 49"	86° 18' 50"		86° 18' 38"		86° 18' 31"			86° 19' 11"	
Rock-type	Scoria	Scoria	Lava	Bomb	Lava	Bomb	Lava	Lava	Lava	Dike	Lava	Pumice
SiO_2	46.81	45.98	47.14	54.19	46.49	49.21	46.47	53.87	54.01	46.10	54.27	48.43
Al_2O_3	18.02	15.09	17.98	15.23	15.11	17.19	15.83	15.13	15.33	15.19	15.28	13.76
Fe_2O_3(T)	11.88	12.65	11.90	10.05	11.10	11.03	12.37	10.38	10.29	10.84	10.24	10.47
MnO	0.199	0.189	0.198	0.159	0.183	0.186	0.186	0.184	0.164	0.180	0.165	0.186
MgO	6.37	10.75	6.31	5.41	10.14	6.19	9.47	5.54	5.30	9.60	5.30	3.40
CaO	12.00	10.63	12.01	8.07	14.71	11.67	11.41	8.45	8.35	14.90	8.40	7.14
Na_2O	1.96	2.05	2.00	3.15	1.54	2.25	2.12	3.04	3.18	1.54	3.17	1.85
K_2O	0.33	0.15	0.26	0.60	0.25	0.51	0.19	0.55	0.58	0.21	0.64	1.26
TiO_2	0.765	1.077	0.771	1.704	0.654	0.849	1.104	1.740	1.688	0.657	1.674	0.981
P_2O_5	0.10	0.09	0.10	0.22	0.11	0.14	0.10	0.23	0.23	0.10	0.22	0.29
LOI	0.04	0.17	−0.14	0.005	−0.51	−0.21	−0.32	−0.09	−0.27	−0.55	−0.12	11.15

B

Sample	A20-06-1	T-11-l1	T-11-l2	T-11-sc	N10-06	N-17a	Asososca**
Unit	BTL-B	Ticomo Lavas			NNT	NNT-Lithic	ASOT
Locality	W-inner wall of Asososca	Ticomo	Ticomo	Ticomo	Nejapa	N-Nejapa	Motastepe
Lat-N	12° 8' 11"	12° 5' 45"			12° 08' 0"	12° 07' 42"	12° 8' 9"
Long-W	86° 19' 16"	86° 19' 20"			86° 19' 20"	86° 19' 20"	86° 19' 17"
Rock	Lava	Lavas			Bomb	Lava	Glass shards
SiO_2	47.87	53.03	53.42	49.63	48.66	47.96	48.21
Al_2O_3	15.72	15.04	14.86	16.21	18.12	16.03	13.86
Fe_2O_3(T)	12.40	11.03	10.94	11.02	10.49	11.69	14.55
MnO	0.189	0.165	0.163	0.183	0.175	0.180	0.296
MgO	9.18	6.16	6.12	6.96	6.46	7.17	6.11
CaO	10.80	8.48	8.49	12.06	12.06	12.37	13.30
Na_2O	2.37	2.93	3.00	2.05	2.20	2.35	2.01
K_2O	0.21	0.49	0.44	0.44	0.46	0.17	0.50
TiO_2	1.153	1.882	1.890	1.036	0.869	1.234	0.993
P_2O_5	0.12	0.22	0.21	0.16	0.14	0.13	0.17
LOI	−0.51	−0.23	−0.16	0.02	−0.07	−0.44	_

Data obtained in samples from units older than ASOT were processed at Actlabs (Ontario, Canada). **For ASOT an average of 17 ion-microprobe analyses is shown. These latter were performed at LUP-Instituto de Geofísica-UNAM (Mexico). Sample A 19 l, which is highly hydrated, is a juvenile pumice in the Pyroclastic ash-flow Tuff (subunit PAT-B).

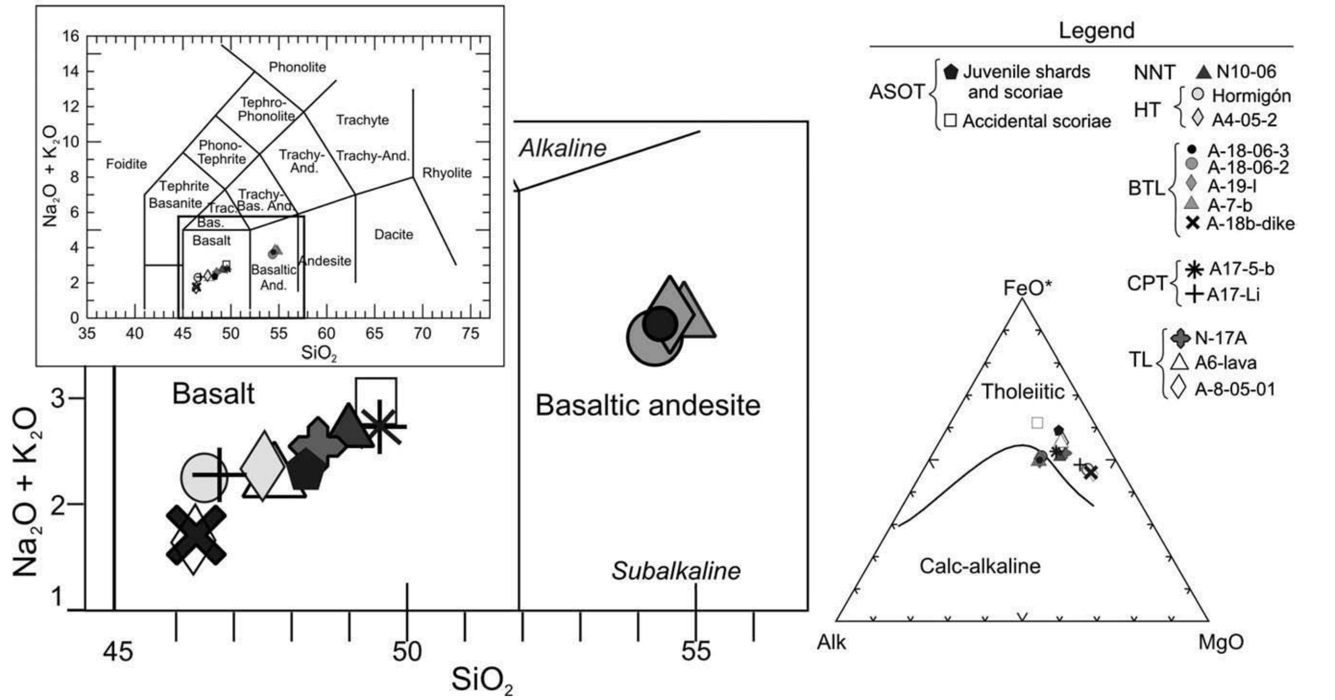

Fig. 10. Plots of products related to the Nejapa–Miraflores fault eruptions showing that in this area those have been mainly tholeiitic basaltic to basaltic–andesitic in composition.

upwards. These scoria layers overlie the Batahola lava flows, but unfortunately we could not find any paleosol with enough carbon content to constrain their age.

4.15. Masaya Triple Layer unit (MTL)

This unit is partially exposed in Managua as documented by Williams (1983), Bice (1985), and Pérez and Freundt (2006). Around Asososca crater the Masaya Triple Layer consists of two gray, laminated fine ash layers bracketed by thin, friable, sandy, brownish paleosols (Ps10 and Ps11). It is well exposed along the new road to León, at the base of the northern flank of Motastepe hill, and inside the southern inner wall of the Asososca crater. Each ash layer is 1 to 2.5 cm thick, finely laminated and consists of rounded coarse ash particles embedded in a fine ash matrix. Fragments are mostly scoria containing olivine, clinopyroxene, and plagioclase phenocrysts, as well as accidental red and black accidental aphanitic lithics with plagioclase and clinopyroxene. The two ash layers are separated by a yellow, massive deposit with rounded lithic clasts in a sandy matrix (Fig. 15). The whole unit corresponds to the distal laminated ash tuffs of the Masaya Triple Layer described by Kutterolf et al. (2007) and Pérez and Freundt (2006) originated from Masaya Caldera, 24 km to the SE of Asososca. Its age, determined by Pérez and Freundt (2006) at 2120±120 yr BP is concordant with the stratigraphy described in the present work (Fig. 13).

4.16. Chiltepe Tephra unit (CT)

A poorly sorted massive deposit, with rounded lithic clasts and grain-supported pumice lenses embedded in a yellow silty matrix with small pore spaces, overlies the Masaya Triple Layer around Asososca and in western Managua. White, highly vesiculated pumices are angular and up to 1.5 cm in diameter, containing abundant plagioclase and clinopyroxene phenocrysts. Bice (1985) described this deposit as a pumice fallout at Chiltepe Peninsula gradually changing into a lahar southward because of a subsequent reworking. Based on its characteristics and stratigraphic position, this unit correlates with the <2100 yr BP dacitic Chiltepe Tephra of Kutterolf et al. (2007).

4.17. Masaya Tuff (MT)

The Masaya Tuff rests above the Chiltepe Tephra with an erosive contact. It crops out in the upper inner walls of Asososca crater and can be followed all over southwestern Managua and around the Nejapa and Ticomo craters to the South. It consists of a yellowish-brown, massive, highly altered, and lithified ash layer with abundant orange, brownish, and gray altered lithics. It is discontinuous in thickness (10–20 cm) with occasional accretionary lapilli and leaf-casts. Around Asososca the Masaya Tuff is laterally discontinuous and made of indurated angular blocky fragments of yellowish ash with accretionary lapilli, set in a finer matrix. Its thickness decreases towards the NW where it changes laterally to a poorly sorted, massive deposit with subangular ash-tuff blocks, pumice lapilli, altered lava and scoria lithics in a silty vesiculated matrix. Towards the top it grades into a yellowish paleosol Ps12 (Figs. 13 and 15).

The Masaya Tuff unit corresponds to the last phreato-plinian eruption of Masaya caldera according to Bice (1985) or as a wet pyroclastic surge that travelled 35 km from its source, according to Pérez and Freundt (2006). Around Asososca this unit is partially remobilized. Its age was estimated at ca. 1000 yr BP by Pérez et al. (2006) and younger than 2000 yr BP by Pérez and Freundt (2006), and Kutterolf et al. (2007).

4.18. Asososca Tephra (ASOT)

This unit (Figs. 13–16) overlies the Masaya Tuff or is in erosive contact above paleosol Ps12 that crops out in the inner rim of Asososca crater. The Asososca Tephra extends asymmetrically around the crater being absent to the North, thinner to the East, and thicker to South and West.

In the southwestern inner rim, this unit is 20 m thick and is composed from the base towards the top by a 50 cm-thick basal massive, poorly sorted, lithic-rich bed with angular accidental lithic blocks set in a fine highly-altered argillaceous matrix, overlain by thin, laterally discontinuous, gray, green, and yellowish, highly altered ash beds with accretionary lapilli and incipient cross lamination and

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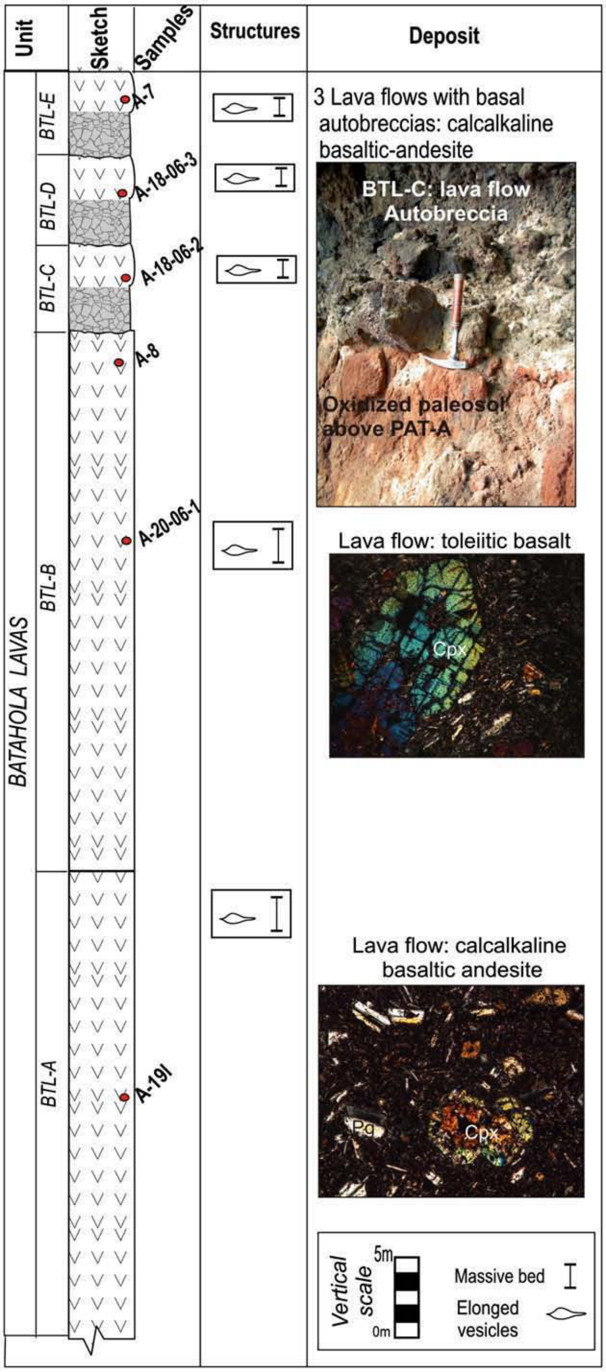

Fig. 11. Continuation of the stratigraphic section shown in Fig. 8. The greatest part of the stratigraphic record cropping out inside Asososca is composed of basaltic to basaltic–andesitic lava flows, named here the Batahola lavas. Plagioclase, augite, and olivine are the main mineral phases.

plastic deformation. This succession suggests an opening phase with ballistic ejection of country-rocks followed by the emplacement of several flows of wet base surges (Figs. 16 and 17). In sharp or local erosive contact above this basal sequence there are multiple, friable bedsets consisting of a basal 30 cm-thick, massive to crudely stratified, inversely graded beds of coarse ash and lapilli with few blocks followed by 5–10 cm-thick, cross-to plane-parallel stratified ash and fine lapilli beds. All these bedsets dip outward from the Asososca crater at angles lower than 15°, becoming horizontal at distance of ca. 100 m towards the South and Southwest. These bedsets change from dominantly dune-like and cross-stratified beds with a few planar and massive beds near the crater to dominantly planar beds, with some massive beds and a few dunes at distances of 500 from the crater.

Southwest of the crater, on the northern flank of Motastepe scoria cone, the Asososca Tephra unit becomes thicker with scarce bomb sags, and consists of predominant planar beds and massive beds with blocks up to 30 cm, and few cross-stratified beds with dune-crests migrating towards the South and Southwest. In this position impact sags point towards the North and Northeast (Fig. 16 and 17). To the South of Motastepe these friable bedsets are better sorted, thinner and finer-grained. To the West, the Asososca Tephra lies above paleosol Ps10 and El Hormigón scoria cone deposits, where dunes are well developed, dune-crests migrate towards the Southwest and West, and impact sags point towards the East (Asososca lake). Dune structures have wavelengths from 2 m to 20 m and amplitudes from 30 cm to 10 cm between the crater and at distance of 800 m, after which plane-parallel beds prevail. On the eastern inner wall of Asososca crater, similar but indurated deposits with accretional lapilli dip inward at 35° and are plastered to the crater inner wall, or collapsed from the top of the rim, as reported in other crater rims (Stoppa and Principe, 1997; Heiken and Fisher, 2000). These observations indicate as the most likely source for ASOT the crater of Asososca.

At outcrop scale, the Asososca Tephra consists of accidental lithics (subangular black and gray basaltic–andesitic to basaltic lava fragments, rounded pre-Asososca scoriae and ignimbrite fragments) immersed in a fine-grained matrix composed of smaller rounded scoria lithics and crystal fragments. No juvenile material was recognized at this scale. Accidental lithics of subrounded gray olivine-pyroxene bearing scoriae, olivine-bearing lavas, plagioclase-clinopyroxene bearing lavas, red scoriae and lavas, white and yellow altered pumice, together with red, yellow and grey altered ignimbrite fragments predominate also in fractions <-1 phi. Poorly vesiculated brown to black fresh basaltic glass particles with blocky, moss-like and fused shapes, indicative of phreatomagmatic fragmentation (Heiken, 1972; Dellino et al., 2001), were identified in proportions <25 vol.% in fractions smaller than -1 phi. The accidental lithic composition resembles the pre-Asososca stratigraphy observed inside the crater (from Cuesta del Plomo Tuff to Masaya Tuff units).

The bulk of the Asososca Tephra sequence is interpreted as the result of the emplacement of dry pyroclastic base surges generated at Asososca maar. Sedimentary structures such as plane-parallel and cross-stratified beds at different scales, dunes, and local U-shaped channels formed by the erosion of subsequent flows, indicate a lateral turbulent transport (Chough and Sohn 1990; Cole 1991). In addition, small obstacles such as accidental blocks up to 50 cm in diameter favored the formation of some of the dune structures down-flow.

In summary, the Asososca eruption excavated previous topography exposing all the units described above, from TA-Tephra (>12,700 yr BP) to the Masaya Tuff (<2000 yr BP; Kutterolf et al., 2007) which marks the top of the pre-eruptive surface. Asososca has the best-preserved crater along the Nejapa–Miraflores fault, it is not faulted and its well-defined inner walls contrast with the smoothed morphology of the other older aligned craters (Figs. 2–6). We propose that the Asososca eruption produced diluted pyroclastic density currents that were mainly dispersed to the West, South and Southwest (Figs. 3 and 4). To the West, these flows encountered the El Hormigón and Motastepe scoria cones that acted as topographic barriers partially blocking the density currents. Some flows were unable to surmount the 355 m high Cerro Motastepe and were forced to move around it, depositing the material to the West. The coarsest material inside the stratified density currents (Valentine, 1987; Dellino and La Volpe, 2000) was blocked by the Northern slope of Cerro Motastepe resulting in thicker Asososca Tephra deposits at the base of the scoria cone. The fine-grained material (above the density currents streamline, Valentine, 1987) was able to surmount Cerro Motastepe to be deposited to the South.

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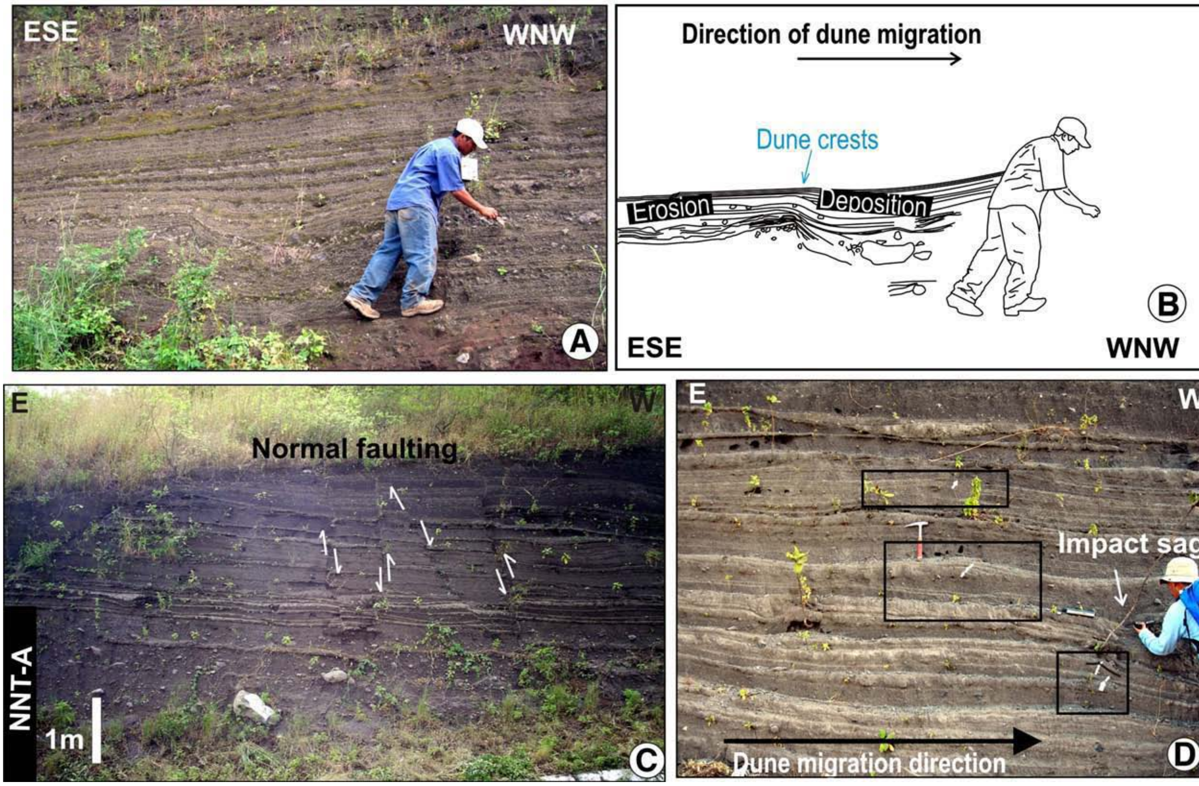

Fig. 12. Northern-Nejapa Tephra (NNT) is well exposed along the new road to León, between Asososca and Motastepe. A–B. Dune crests and impact sags were used as indicative of transport direction and source provenance. All of these structures coincide with a source located south of Asososca, probably at the northern 500 m crater of Nejapa. C. Basal massive and poorly sorted NNT-A subunit which grades into a cross-stratified deposit; NNT-A is affected by N–S normal faulting south of Asososca. D. The bulk of NNT is well-stratified, displaying bedsets with parallel and crossed-stratified beds. Dunes and impact sags are common.

The stratigraphic position of Asososca Tephra above the Masaya Tuff unit suggests that it is the youngest phreatomagmatic unit related to the volcanic vents along the Nejapa–Miraflores fault. Furthermore, it is bracketed between paleosols Ps12 and Ps13, dated at 1245+125/−120 yr BP and 535±110 yr BP, respectively (Table 1), suggesting that the Asososca eruption took place around ~1245 yr BP.

5. Revision of Western Managua volcanic stratigraphy and eruptive history

The stratigraphy exposed inside and around the Asososca crater records part of the volcanic activity occurred in western Managua since the Late Pleistocene. The sequence of deposits described here is younger than 12,730+255/−250 yr BP, and is part of the Managua Formation (Kutterolf et al., 2007) that overlies the Las Sierras Formation (partially exposed inside Nejapa and around Ticomo vents). The stratigraphic record evidences a complex superposition of deposits that originated from explosive and effusive magmatic eruptions and explosive phreatomagmatic eruptions, mostly related to the volcanic activity generated at Nejapa–Miraflores aligned vents, and to a lesser extent to Masaya Caldera to the South, and Chiltepe Volcanic Complex to the North.

The oldest units found in the area (TA-Tephra, TB-Tephra, and Motastepe Tephra), record eruptions that produced base surge sand scoria fallouts, probably related to vents located south of Asososca and at the Motastepe scoria cone, as well as phreatomagmatic eruptions that emplaced wet pyroclastic base surges (Cuesta del Plomo Tuff) from a northern, partially collapsed and faulted vent (Cuesta del Plomo). Paleosol Ps3 indicates a short period of quiescence, after which volcanic activity occurred to North, at the Chiltepe Volcanic Complex, characterized by the emplacement of several ash-flows around 12,435+380/−365 yr BP. Resultant deposits have the same stratigraphic position and a similar acid composition as the Upper Apoyeque Tephra, a plinian fallout that constitutes a regional stratigraphic marker. The Upper Apoyeque Tephra was originated from the northern Apoyeque stratocone in the Chiltepe Peninsula (Bice, 1985; Kutterolf et al., 2007), therefore the ash-flow deposits that crop out inside Asososca (Upper Apoyeque Tuff) were probably generated by associated column collapses. After a period of reworking, indicated by lahars generation and soil formation (Ps 5), the area was affected by renewed explosive volcanic activity from eruptive vents located along the Nejapa–Miraflores fault ca. 9380+280/−270 yr BP (Refinería Tephra). Phreatomagmatic eruptions generated both pyroclastic surges and ash fallouts with accretionary lapilli, and were interrupted by minor strombolian activity. The eruptive sources seems located to the N of Asososca. Since the Refinería crater overlaps the Cuesta del Plomo crater, and considering that a thick unit composed of base surge deposits overlies the Upper Apoyeque Tephra near to Cuesta del Plomo sector, the Refinería crater is the most plausible candidate for the origin of the Refinería Tephra. The Satélite Tephra records an additional phreatomagmatic eruption occurred to the W of Asososca after a short period of quiescence attested by the Ps6 paleosol. Dry base surges were probably generated at the Satélite vent, the only vent located to the W of Asososca, which overlaps the northern Refinería vent (Figs. 2 and 3). Afterwards, the Pyroclastic Ash-flow Tuff that crop out inside the Asososca crater confined into previous topographic lows, records the beginning of a different type of volcanic activity in the area, characterized by the emplacement of mafic pyroclastic ash-flows. These deposits were with all probabilities generated from Masaya Caldera because it is the only Holocene source in the area able to produce deposits of mafic composition. The region between the Satélite crater and the Embajada scoria cones was affected by N–S normal faults that involved all the units already mentioned and later, covered with basaltic to andesitic–basaltic lava flows which accommodated to the pre-existing faulted topography forming an extended shield. These lava flows (Batahola lavas unit) have a

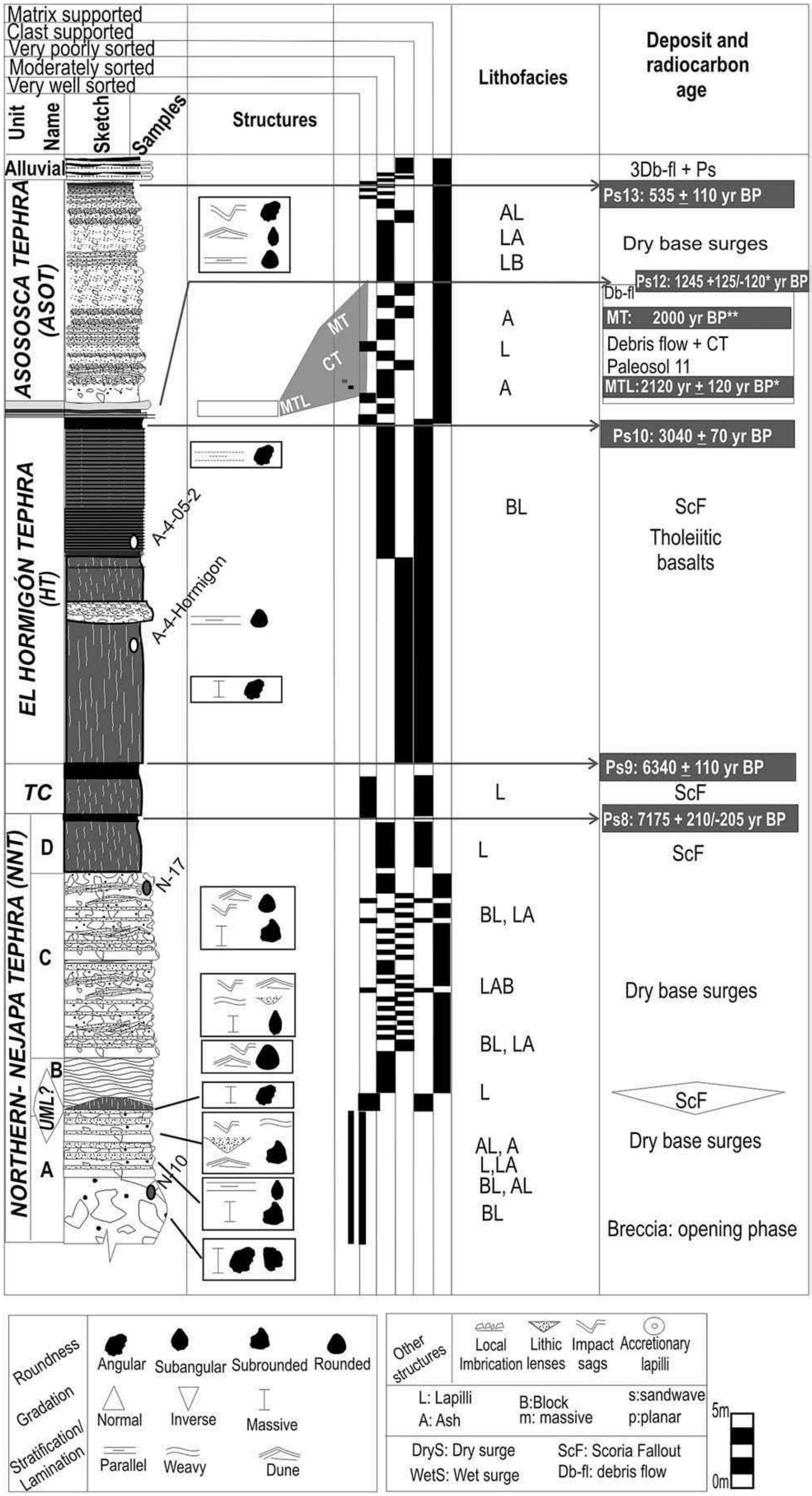

Fig. 13. Composite stratigraphic section showing the upper (younger) depositional units that occur in the Asososca area above the Batahola lavas. Seven eruptions <9000 yr BP were identified. Four of them are related to NMF vents, two were generated at Masaya Caldera and one originated at the northern Chiltepe Volcanic Complex. The Asososca Tephra is the youngest unit with an age close to 1245 + 125/−120 yr BP data obtained on the underlying paleosol Ps12 UML: Undistinguished Masaya Lapilli; TC: C-Tephra; D: Schmincke et al. (1973).

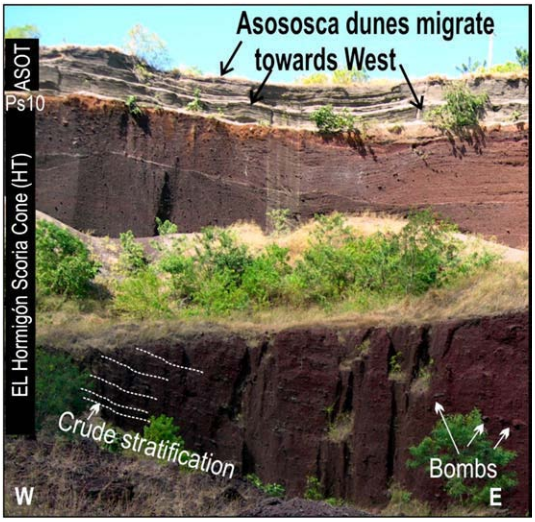

Fig. 14. The El Hormigón Tephra (HT), composed of scoria fallouts, is well exposed West of Asososca crater and characterized by blocks and bombs in a clast-supported, unsorted matrix. Clast-size and thickness suggest a proximal source likely located at the Hormigón quarry.

composition similar to the N–S trending dikes that crop out inside Asososca crater and at La Embajada scoria cones, and were probably erupted during a fissural activity along the Nejapa–Miraflores fault. Similar lavas are also found inside the southern Ticomo craters, but in a lower stratigraphic position, indicating that periods of effusive activity regularly occurred along the fault, as proposed by McBirney (1955).

After the emplacement of lava flows, new phreatomagmatic eruptions took place at the N-Nejapa crater, excavating previous units. The opening phase is indicated by the abundance of accidental lava blocks at the base of the Northern-Nejapa Tephra, followed by subsequent dry pyroclastic base surges that were emitted forming a small crater with a diameter of 500 m, nested with the older Southern-Nejapa crater. Conduit obstruction and reopening with the emission of base surges are recorded by the upper part of this unit, as the result of a normal process of crater widening and deepening (Lorenz and Kurszlaukis, 2007), until the eruption ended with the deposition of a scoria fallout. This eruption must be older than 7175+210/−205 yr BP but younger than the formation of the Batahola lavas.

After a quiescence period of paleosol formation, at least two younger scoria cones generated basaltic tholeiitic scoria fallout deposits, ca. 7175+210/−205 yr BP and 6340±110 yr BP. Subsequently, the dominant activity following the Northern-Nejapa eruption in the surroundings of Asososca was of Strombolian type. The source of the youngest fallout was the El Hormigón scoria cone, located at the present Hormigón quarry. The next eruptions were generated from Masaya Caldera and Chiltepe Volcanic Complex, producing the Masaya Triple Layer at 2120±120 yr BP (Pérez and Freundt, 2006), the plinian dacitic Chiltepe Tephra (Kutterolf et al., 2007), and finally, the phreatoplinian Masaya Tuff (Pérez and Freundt, 2006).

The youngest deposits registered in the research area are represented by the Asososca Tephra, which dates back 1245+125/−120 yr BP, and indicate that the Asososca maar progressively excavated the previous topography with the emission of wet and dry pyroclastic base surges. The high efficiency of phreatomagmatic interaction is suggested by the comminution of country rock with subordinated juvenile basaltic ash. Most of the material was distributed to the South and West, infilling the adjacent craters, such as Satélite and N-Nejapa, or blocked by surrounding obstacles, such as Cerro Motastepe, affecting the area occupied today by Managua city. Subsequent reworking occurred as indicated by debris-flow deposits that overlie a 535±110 yr BP paleosol, and that contain abundant clasts picked up from the underlying Asososca Tephra.

6. Discussion and hazard implications

Magmatic effusive eruptions probably related to fissural vents, strombolian eruptions related to scoria cones, as well as phreatomagmatic eruptions from maars and tuff rings, have been common

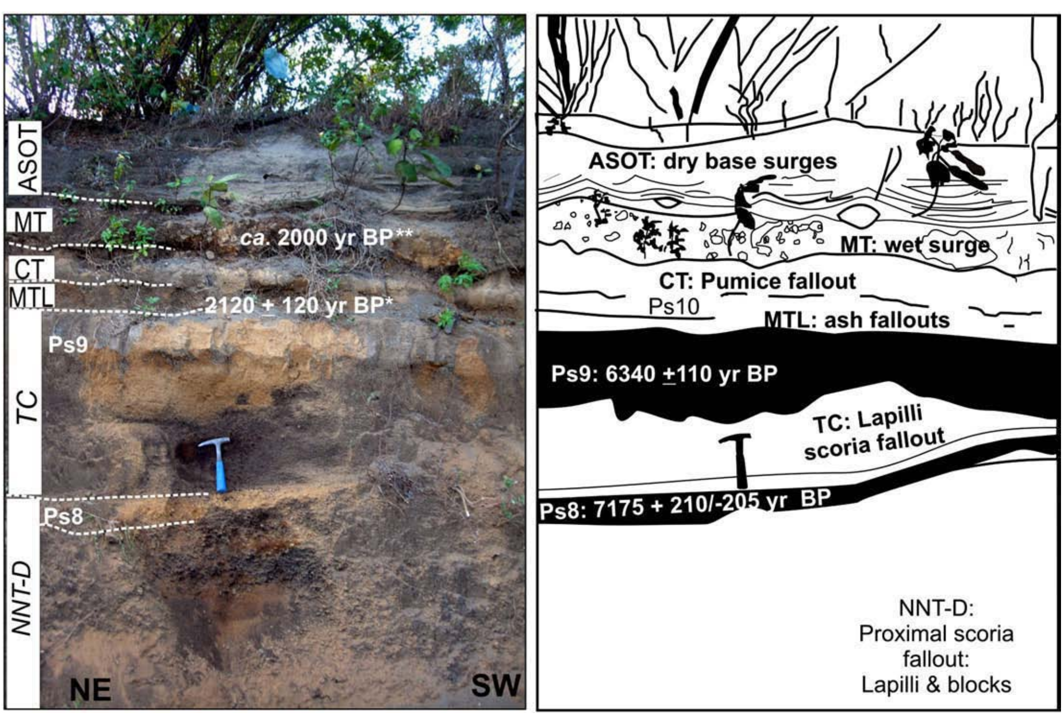

Fig. 15. Upper subunit of the Northern-Nejapa Tephra (NNT-D) and el Hormigón Tephra (HT) are overlain by the Masaya Triple Layer (MTL), the Chiltepe Tephra (CT), and the Masaya Tuff (MT). These units are exposed along the new road to León and inside the Asososca crater. All of them are covered by Asososca Tephra. *Published by Pérez et al., 2006 **Published by Kutterolf et al. (2007).

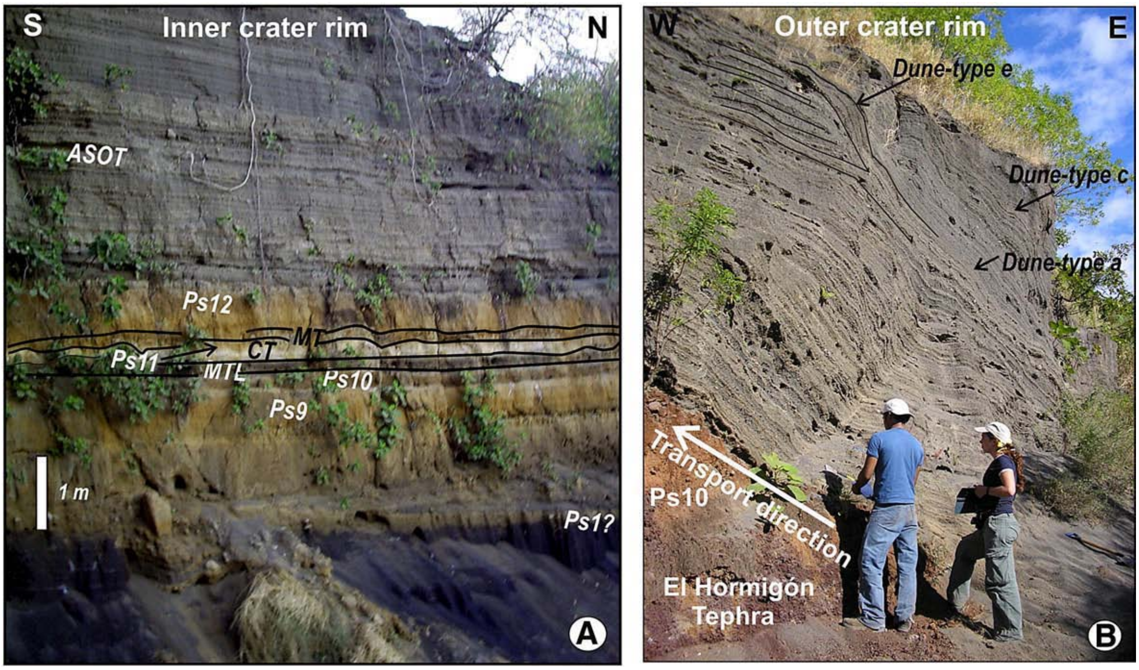

Fig. 16. Proximal outcrops of the Asososca Tephra: A (outcrop inside the crater), and B (outcrop outside the crater). A shows the stratigraphic position of ASOT over the Masaya Triple Layer, the Chiltepe Tephra and the Masaya Tuff. ASOT begins with a massive, poorly sorted, lithic rich, and highly altered layer, followed by well stratified, finer grained deposits with planar and cross-stratified beds. B shows ASOT covering the El Hormigón Tephra with dunes. Dune-types were identified following Cole (1991) and they indicate a transport direction from E to W, that is from Asososca towards the W (See also Fig. 14).

phenomena along the Nejapa–Miraflores fault. Based on the stratigraphic record exposed inside and around the Asososca maar, supported by radiocarbon dating, petrographic and chemical analyses, and aided by geological mapping, we identified 18 depositional units, 16 of which are younger than 12,730+255/−250 yr BP. Among these 18 units, at least three originated from the southern Masaya Caldera (Undefined Masaya Lapilli, Masaya Triple Layer, and Masaya Tuff), two originated from the northern Chiltepe Volcanic Complex (Upper Apoyeque Tefra/Tuff and the Chiltepe Tephra) and the rest are related to the aligned vents close to Asososca, at the western Managua outskirts. The stratigraphic record exposed inside the Asososca maar is younger than the deposits exposed inside the Nejapa vent, where the Plinian Apoyeque pumice was found on top of a thick sequence of Plio-Pleistocene lithic-rich ignimbrites of Las Sierras Formation, and is capped by lahar deposits. Younger wet base surges, pyroclastic flows, basaltic to basaltic–andesitic lava flows, dry pyroclastic base surges, and scoria fall deposits form the bulk of the stratigraphic record found inside and around Asososca. Older deposits were mainly the product of vents located to the south of Asososca, probably at the southern-Nejapa crater and Motastepe scoria cone. Afterward, the eruptive activity was centered to the North and West of Asososca, at Cuesta del Plomo, Refinería, and Satélite vents, except for the pyroclastic flows (Upper Apoyeque Tuff and Pyroclastic Ash-flow Tuff), probably generated at the Chiltepe Volcanic Complex (felsic) to the North, and the Masaya Caldera (mafic) to the Southeast. Subsequent effusive eruptive activity probably related to fissural vents, produced lavas that covered the whole area (Batahola lavas), and explosive eruptions were concentrated to the south and Southeast of Asososca, at the Northern-Nejapa crater and el Hormigón scoria cone. After that, the Masaya Triple Layer (2120 yr BP; Freundt et al., 2006a) and the Masaya Tuff (*ca.* 1000 yr BP; Pérez et al., 2006 and 2000 yr BP estimated by Kutterolf et al., 2007), record a further influence of Masaya caldera activity in Managua. At the end, a sequence of pyroclastic surge deposits, named here the Asososca Tephra (ASOT) was generated by the Asososca maar and dates back to 1245+125/−120 yr BP, recording to the youngest phreatomagmatic eruption along the fault.

The variety of identified deposits, including phreatomagmatic and magmatic tephras, is consistently related with the formation of maars and tuff rings (Wohletz and Sheridan, 1983; Fisher and Schmincke, 1984; Cas and Wright, 1987; Lorenz and Kurszlaukis, 2007), or scoria and cinder cones (Fisher and Schmincke, 1984; Cas and Wright, 1987) along the NMF. It should be expected that the former volcanic vents occur wherever a local potential for explosive interaction between the rising magma and external water, at low hydrostatic pressures, exists (Lorenz and Kurszlaukis, 2007). If groundwater or other water bodies are not available, or if they are at high hydrostatic pressure, the eruptions will more likely result in lava fountaining with the formation of scoria cones and lava flows (Lorenz and Kurszlaukis, 2007). In summary, the overall spatial and temporal distribution of maars and tuff rings or scoria and cinder cones depends on the local hydrogeological conditions (Siebe, 1986; Abrams and Siebe, 1994; Németh et al., 2001; Guttmann, 2002). In Managua this conditions are strictly determined by the Nejapa–Miraflores fault, minor NW and NE faults (Frischbutter, 2002), and by the geometry of the Managua and Las Sierras Aquifers (Johansson et al., 1999).

This work complements the Holocene stratigraphic record of the Managua Formation (Bice, 1985; Kutterolf et al., 2007), reinforcing the conclusions about a prominent volcanic hazard for the city, as indicated by numerous eruptions recorded during the last 13,000 yr BP and the recent age of the Asososca eruptive event. Even if single aligned volcanic structures are mainly monogenetic, short-lived vents represent a structural-controlled, and apparently long-lived volcanic field that should be active up to several thousands years or more, as reported in other studies (Connor and Conway, 2000; Walker, 2000; Schmincke, 2004; Melnick et al., 2006; Barnett and Lorig, 2007; Lesti et al. in press). Radiocarbon data obtained in this work are consistent with the relative stratigraphic position of single units, and match other published data on Masaya caldera deposits (Pérez and Freundt, 2006; Kutterolf et al., 2007).

This area is being increasingly urbanized with paved roads communicating Managua with industrial, touristic and commercial centers such as Ciudad Sandino, Granada, and León. In addition, an oil-

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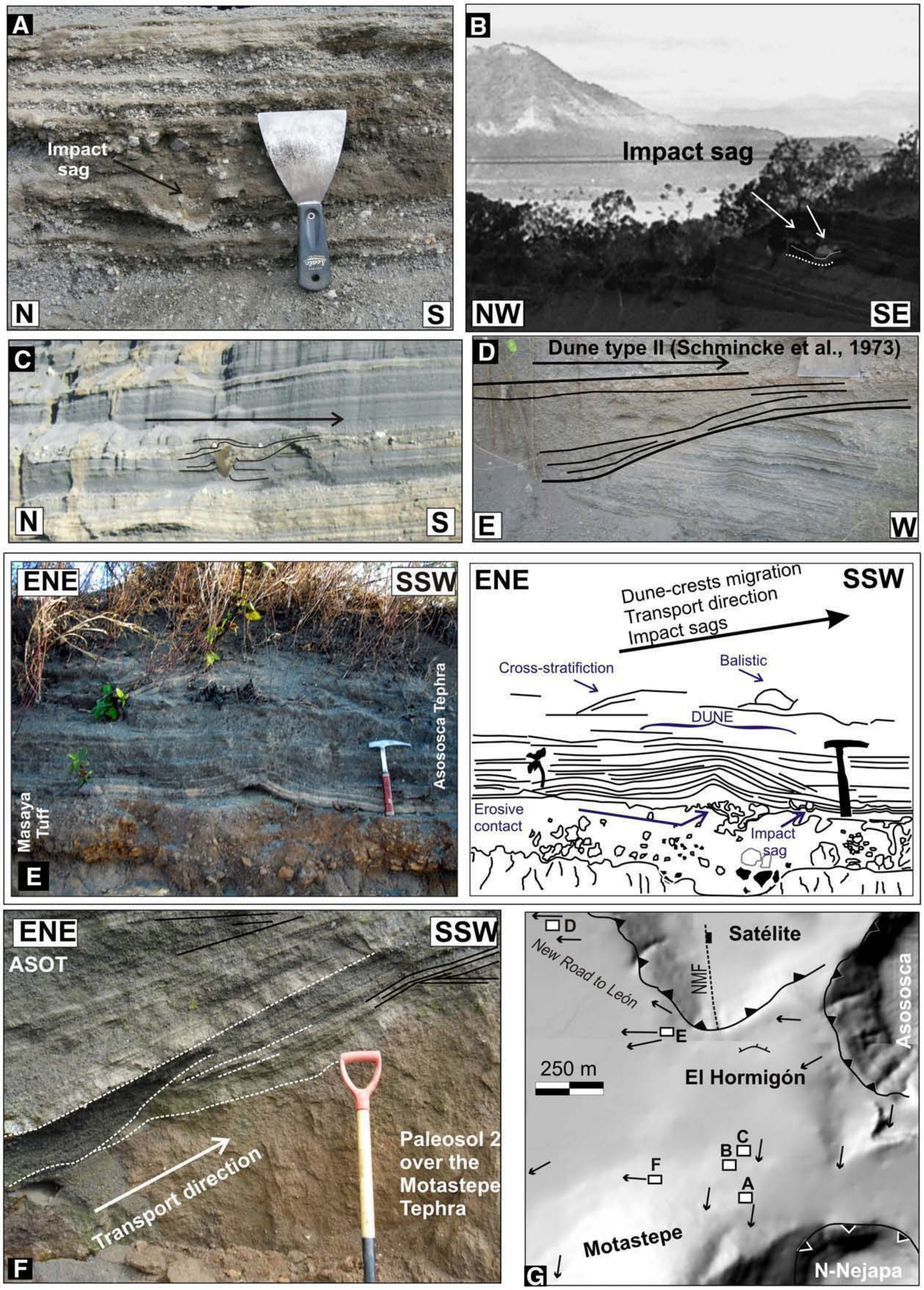

Fig. 17. ASOT mid-distance facies, south and Southwest of Asososca, particularly at Cerro Motastepe, where plane-parallel stratified and massive beds are dominant with respect to cross-stratified beds. Sedimentary structures such as bomb sags and dunes are consistent with a source located at Asososca. Arrows show transport direction inferred from local sedimentary structures. A to G are located in H.

refinery is located inside the Refinería crater and an aqueduct and water pumping system inside the Asososca maar. The high frequency of recent eruptions and seismic activity along the NMF, represent a considerable hazard to more than 1.3 million inhabitants and important infra-structures. Future work should focus on the estimation of recurrence periods of the eruptions in the whole volcanic field. Seismic monitoring, gas emissions and crater lakes geochemical fluids studies (e.g. In Asososca, Apoyeque, and Xiloá lakes) are needed in agreement with urgent urban planning.

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