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An unusual syn-eruptive bimodal eruption: The Holocene Cuicuiltic Member at Los Humeros caldera, Mexico

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Abstract

The Cuicuiltic Member (CM) at Los Humeros Caldera, eastern Mexican Volcanic Belt is a Holocene (6.4 ka B.P.) succession of alternated fallout deposits of contrasting composition (trachydacite pumice and basaltic andesite scoria). The CM covers approximately 250 km^2 on its proximal facies and its thickness ranges from 1.5 m to of 8.0 m. It postdates two caldera-forming ignimbrites (Xaltipan and Zaragoza) and numerous Plinian successions. It is subdivided in 9 units (C1 to C9) according to its textural and chemical characteristics. Sub-horizontal, topography-draping layers of trachydacite pumice lapilli, andesitic pumice lapilli and basaltic-andesite scoria lapilli with sporadic one-meter blocks are common lithofacies. The base is formed by coarse trachydacite pumice lapilli (C1 and C2), overlain by a layer with banded pumice (C3). Thin layers of ash and ash-tuff are intermittent on lower units, whilst continuous at the base of C4. The middle units, C4 and C6 are basaltic-andesite pumice, and scoria lapilli to blocks; C5 is in-between the two mafic units and it is represented by a layer of pale grey pumice lapilli. Units C7 and C8 are a mixture of white trachydacite

pumice, scoria lapilli and banded pumice. The uppermost layer, C9, is a brown to grey andesitic pumice lapilli. Extensive fieldwork allowed a close and reliable correlation of layers that helps to understand the complexity of stratigraphic relations and sources for those layers. The distribution of these units is varied across the caldera, with the trachydacite layers dispersal from the center towards the NW, whilst the andesitic units have maximum thicknesses over the SE and NE sectors of the caldera. Isopach and isopleth maps, combined with detailed mapping of near-vent spatter facies, orientation of local bomb sags and variation of mean clasts size for some layers were very useful to determine the vent location, particularly for the andesitic-basaltic layers.

The CM represents the last explosive event registered at Los Humeros caldera, combining simultaneously both Plinian and Strombolian activity. The eruption was fed from one central vent and at least two independent but simultaneously active vents up to 6 km apart. The eruption began with a trachydacite explosive eruption depositing pristine white pumice in the centre of the caldera in two stages. After a short repose period, at least two andesitic to basaltic fissure vents erupted ejecting pumice and scoria over the southeast and northeast sector, mainly along a weakness structural plane parallel to the Potreros scarp. These eruptions became less energetic with time until reaching classic Strombolian style with sudden fluxes generating local and discrete pyroclastic currents. Trachydacite pumice kept falling intermittently accompanied by mingling at depth. The end of the Cuicuiltic eruption is marked by the well-graded layer C9, which registers lapilli-sized pumice-fall clasts from a hybridized magma chamber. The CM may represent (a) either a trachydacite magma chamber disturbed by a basaltic intrusion triggering the eruption of the evolved material first or, (b) a heterogeneously zoned magma reservoir tapping the evolved magma first and due to contrasting density and viscosity conditions, the basaltic and andesitic material was extruded through adjacent weakness planes up to the surface.

Keywords: Heterogeneous pumice-fall deposit; Plinian eruptions; Strombolian eruptions; Los Humeros caldera; magma mingling and mixing; bimodal volcanism

1. Introduction

Compositional contrast or heterogeneity in eruptive products from large calderas and composite volcanoes has been well documented in a wide spectrum of volcanic settings. Magma mixing and mingling have been broadly invoked in Iceland (Askja, Torfajokull, Katla, Eyjafjallajokull; Sparks et al., 1977), Italy (Salina, Aeolian islands, Calanchi et al., 1993; Vesuvius, Cioni et al., 1995; Campi Flegrei caldera, Tonarini et al., 2009), New Zealand (Tongariro, Taupo Volcanic Zone; Nairn et al., 1998; Shane et al., 2008), the Andes (Hudson volcano; Kratzmann et al., 2009; Nevado Sabancaya, in southern Peru, Gerbe and Thouret, 2004) and the Phillipines (Pinatubo; Pallister et al., 1996). These processes are also common in products from large calderas, in the United States of America, the San Juan Mountains and other volcanoes like Lassen Peak (Clynne, 1999) and Augustine volcano, in Alaska (Roman et al., 2006). Recent examples from island-volcanoes include ignimbrite-forming eruptions from Las Cañadas in Tenerife (e.g. the Poris and Granadilla Formations; Bryan et al., 2002; Brown and Branney 2004). In Mexico, cases of magma mixing include El Chichón (Tepley et al., 2000), Popocatépetl (Sosa-Ceballos et al., 2012) and widespread ignimbrite sheets from Quaternary calderas (e.g. La Primavera: Mahood, 1980; Walker et al., 1981; Wright, 1981; Amealco: Aguirre-Díaz, 2001; and Los Humeros: Carrasco-Núñez and Branney, 2005; Carrasco-Núñez et al., 2012). However, magma mixing at these eruptions is, in most cases, documented within a single eruptive unit (ignimbrite, lava or pumice-fall deposit) or between a series of eruptive products or eruptive units in a long time span.

In this paper we document an unusual type of bimodal explosive activity that was emplaced in a close time-frame but with vents separated in space by up to 6 km apart within the Los

Humeros intra-caldera sector (Fig. 1). This type of bimodal volcanism from independent vents but coeval is unusual and it has been less documented in both geological and historical eruptions. Examples in the geological record include La Tarta unit at Tenerife's Las Cañadas volcano and NE rift-zone, where contrasting phonolite pumice and scoriae were falling simultaneously from independent vents producing a multi-layered fall deposit (Edgar et al., 2007); another example include the 1256 A.D. Madinah eruption, in Saudi Arabia, comprising magma mixing and simultaneous extrusion of lavas of contrasting chemical compositions from different vents, that erupted along a 2.25 km fissure over a 52 days period (Camp et al., 1987), and the well-documented Lower Pollara Pumice in Salina island, Italy (Calanchi et al., 1993) amongst others. Historical eruptions with magma mixing evolving in space and time include the 1991 Hudson eruption in Chile (Kratzmann et al., 2009) and the 2010 Eyjafjallajokull eruption (Sigmarsson et al., 2011). This phenomenon is probably more common than expected, however documentation of such changes within a single eruptive unit requires pristine exposures like those presented in this study.

The focus of this paper is the characterization of the youngest explosive activity from Los Humeros caldera, the Cuicuiltic Member, based on detailed stratigraphic sections, componentry analysis and geochemical and physical characteristics. Finally, a model for the magmatic trigger, mingling and mixing of magmas that gave rise to the heterogeneously layered Cuicuiltic eruption is discussed. The importance to study this compositionally contrasting layered succession is to document how geographically distinct vents were nearly active simultaneously or in close succession tapping a heterogeneous magmatic reservoir setting. This example demonstrates the complex internal structure of large-volume magmatic systems.

2. Geological background

Los Humeros caldera is located in the Eastern sector of the Mexican Volcanic Belt (MVB; Fig. 1 inset). It is emplaced at the western limits of the Sierra Madre Oriental fold and thrust province and lies roughly 80 km north of a front line of other active andesite stratovolcanoes. The oldest local basement is represented by Palaeozoic intrusive and metamorphic rocks, which are in turn covered by a Jurassic succession of shale, limestone and sandstone. At the vicinity of Los Humeros caldera, the Cretaceous basement is better exposed as folded remnants of limestone and shale. This basement was extensively affected by the Laramide orogeny, with NE-SW compression, faulting and folding of the succession, followed by intrusion of Tertiary granodiorite and syenite. The last pre-caldera events are represented by andesite and rhyolite. The youngest volcanic rocks previous to the formation of the caldera are represented by 3.5 Ma and 1.55 Ma andesite and ferrobasaltic lavas (Yañez and García, 1982; Ferríz and Mahood, 1984).

The evolution of the Los Humeros caldera has been divided into three stages marked by thick and broadly distributed eruption products. The first stage (~460 ka) started with the extrusion of rhyolite lavas and domes, followed by probably the largest Quaternary explosive eruption in México, with the emplacement of the Xaltipan Ignimbrite and the subsidence of Los Humeros caldera (Fig. 1). The second stage (~360 ka to ~240 ka) is marked by the stacked succession of mainly rhyolite pumice-fall deposits separated by paleosols, defined by Ferriz and Mahood (1984) as the Faby Tuff (Faby Formation *sensu* Willcox, 2011). This was accompanied by the emplacement of a small number of domes. No known ignimbrite is related to this eruptive succession. The third stage (60 – 140 ka) is represented by the eruption of the Zaragoza Ignimbrite, which formed the Los Potreros caldera, nested in the central sector of the Los Humeros structure (Fig. 1). Vertical normal-to-reverse compositional zoning has been identified in this eruption (Carrasco-Núñez and Branney, 2005). Numerous pumice and scoria fall deposits overlie the Zaragoza Ignimbrite. These include the rhyolitic Xoxoctic Member pumice-fall deposit, the Tilca lithic-rich layer and finally, the Holocene Cuicuiltic Member; an intercalated, trachydacite to basaltic-andesite pumice-fall layer mixed with scoriaceous proximal layers. Younger scoria cones, basaltic andesites and olivine-bearing basalt lavas represent the latest eruptions and are presumed to be younger than 20 ky (K-Ar age from Ferriz and Mahood, 1984).

3. Stratigraphy and field relations

3.1 Definition of the Cuicuiltic member

The CM was originally called the Cuicuiltic Tuff by Ferríz and Mahood (1984) and described as a "visually striking sequence of interbedded rhyodacitic and andesitic air-fall lapilli tuffs", thought to have originated from the Xalapasco crater (Fig. 1) with an erupted volume of 0.1 km^3. In this study, we provide geological evidence that the Cuicuiltic eruption was a more complex event, where at least 3 different vents were simultaneously active, one ejecting trachydacite pumice and at least 2, producing pumice and scoriae fissure eruptions along a reactivated fault system. However, none of our data suggest the Xalapasco crater as the vent for the Cuicuiltic pumice and/or scoria.

In this study, we keep the original name Cuicuiltic (which means 'snake of very varied colours'), and added the term *Member* instead of *Tuff* for the soil-bounded products of the Cuicuiltic eruption. Although both terms are non-genetic, we prefer to use *Member* as coined in several previous volcanological studies to describe the products of one or more eruptions constrained in units of time (e.g. days to months), paleosols and distribution across a volcanic terrain.

The CM has been subdivided in 9 units, from C1 to C9 on the basis of textural, chemical and stratigraphic characteristics (Fig. 2). The lower units, C1, C2 and C3 correspond to white, highly vesicular trachydacitic pumice lapilli (Fig. 3). The middle units, C4 and C6 are basaltic-andesite pumice, and scoriae lapilli to blocks; C5 is in-between the two mafic units and it is represented by pale grey pumice lapilli. The uppermost units, C7, C8 and C9 preserve contrasting textural and compositional features. They range from a mixture of white trachydacitic pumice, scoria lapilli and banded pumice with sporadic near-vent scoria blocks to intermediate brown to grey andesitic pumice lapilli towards the top (Fig. 3).

3.2 Chemical Characterization

Whole-rock X-ray fluorescence geochemistry for 13 samples was performed at Laboratorio Universitario de Geoquímica Isotópica (LUGIS), UNAM (Table 1). Samples were pumice, scoria, glass and lava from each individual layer of the CM. The rocks were collected in the field with careful constraints on stratigraphic control (see Fig. 4 for sample locations), specimens at the lab were then brushed and rinsed with deionised water, dried, crushed and milled under agate pots to produce the powders and discs, which were then analysed.

The juvenile samples from the CM are sub-alkaline volcanic rocks that range from basaltic andesite to trachydacite (Fig. 3), passing through the intermediate fields and following a nearly linear trend with SiO_2 values ranging from 53.4 wt.% to 68.8 wt.% (Fig. 3). Alkalies ($Na_2O + K_2O$) do not exceed 12.0 wt.% and show a good correlation between high SiO_2 values and high alkalies, for example, the felsic layers (C1, C2 and C5), in contrast low alkalies values for the least evolved layers (C4 and C6). In fact, pumice clasts within C2 have the highest silica values of the CM (Fig. 3). Pumice samples with intermediate compositions, or mixed and mingled layers and clasts within it, like C3, C7, C8 and C9 are mainly trachyandesite. Mingled samples were avoided for whole-rock chemistry, although it was nearly impossible to avoid clasts with at least a low proportion of mingling, for example C7, where most clasts have certain proportion of mingling. For layer C8, a sample of each type of juvenile clast including: felsic pumice, andesitic pumice, scoria, mingled and mixed clasts, were analysed (Fig. 3). These clasts show a variation in SiO_2 from 59.6 wt.% to 67.4 wt.% (trachyandesite to trachydacite). Layer C9 is represented by well mixed trachyandesite pumice clasts with very scarce banding, this can be interpreted as the result of good mixing within the magmatic system by the last phases of the eruption.

The CM exhibit a remarkable chemical zonation at the eruption unit scale (e.g. layers of contrasting compositions bracketed between the same upper and lower paleosol), but also at a conduit or vent-scale, due to the presence of mingled single clasts within independent layers. Zonation also occurs at the geographic scale, represented by the main (felsic) Plinian vent tapping relatively siliceous magma and contemporaneous satellite fissure vents tapping melts under-saturated in silica (mafic). However, small-scale zonation represented by mingling in individual pumice clasts proves mafic and felsic magmas were also interacting before or during the eruption.

3.3 Distribution and stratigraphic relations

The CM is exposed widely across the Los Humeros intracaldera sector, and in lesser extent in the outer flanks south of the caldera. As one of the youngest explosive eruptions it covers most of the inner valleys and smooth hills that comprise the landscape. It has variable lower stratigraphic relationships although at most exposures it overlies a paleosol (Fig. 4), dated by ^{14}C resulting in a 2σ calibrated age of 6,423 years B.P. (99.1%) and 6,032 years B.P (0.8%). Software used for calibration was Calib Radiocarbon Calibration Program (Stuiver and

Reimer, 1993), with *Intcal09.14c* data set curves from Reimer et al. (2009). For sample location see Log 16, transect F, in Electronic Supplementary Material (ESM).

From 68 exposures, 45 sections were logged in detail and transects (fence diagrams) were built to constrain correlation between layers (see ESM), as shown in two principal logs where the most complete stratigraphic sections are exposed, including the type section (Fig. 4). In this paper we depict only the most important transects (Fig. 5), others are included in the ESM. The CM at Los Potreros valley area (Fig. 1), lies on a thin paleosol on top of the lithic-rich Llano Ignimbrite (Fig. 2) and scoria agglomerates. It is also exposed resting unconformably over the Xoxoctic Member (Xoxoctic Tuff *sensu* Ferríz and Mahood, 1984). In the northern sector of Los Potreros caldera, it overlies the Tilca fall deposit, a lithic-rich stratified soil-bounded package of tephras, possibly of phreatomagmatic origin. At the outer southern flank it is exposed over a scoria agglomerate and unconformably over the Xoxoctic Member and several pumice-fall deposits from the Faby Formation (*sensu* Willcox, 2011).

Towards the north and northwest of the caldera, the CM unconformaby drape older lava fields and undifferentiated, phreatomagmatic deposits. Pumice-lapilli from the Cuicuiltic eruption unconformably overlie a spherulitic obsidian dome (the Oyameles Dome, Fig. 1) in the northwest.

3.4 Layer stratigraphy and interpretation

A general description of each of the representative units is shown in Fig. 2, where a composite log mainly based on the type section (Log 1) is depicted. A lithofacies scheme was produced for a systematic description and interpretation of the deposit due to its broad textural variations (Table 2 and Fig. 2).

Layer C1

Layer C1 (Fig. 2), represents the base of the CM, it rests over a well-developed paleosol on top of the Llano lapilli-tuff (Willcox, 2011), other undifferentiated fall deposit, a scoria agglomerate and unconformably over the Xoxoctic and Zaragoza Members. C1 is a white to pale-grey diffusely stratified trachydacite pumice-lapilli layer (Fig. 6a) with thicknesses that range from 0.1 m to 1.3 m. The base is commonly lithic poor, fine lapilli and it is overlain by a coarser lapilli level with abundant oxidized lithics (~15%). The pumices are pale grey, sub-angular, crystal-poor and highly vesicular ranging from coarse-ash to lapilli. Accessory lithic clasts are in order of abundance: hydrothermally altered andesite, fresh andesite, basalt and obsidian. The reddish altered lithics form a subtle layering within the unit.

Pedogenically altered layer (bed α; Fig. 2): Bed α is a 5-10 cm-thick, brown layer with rounded ≤1 cm pumice clasts and lithics (Fig. 6a). It is horizontally continuous and drapes topography parallel to the bracketing layers (C1 and C2). It has a gradual lower contact and a sharper top contact with C2. It has been interpreted as a very incipient soil from a coarse ash-layer at the top of C1, marking a short repose period during the Cuicuiltic eruption. The hiatus could probably represents a range of months to years within the same eruption, no material suitable for dating was found. It is continuous across all Cuicuiltic exposures within the caldera (see Fig. 4).

Layer C2

Layer C2 consists of massive to diffuse-stratified, clast supported grey trachydacite pumice lapilli. It has a sharp base over bed α. It is a 0.3 m thick pumice layer at the type section although it reaches up to 6 m thick near Los Humeros village. The whole of unit C2 can be in some places subdivided in C2-A and C2-B (see comparison in two locations, Fig. 4), both lapilli layers and bed β, a fine ash layer (Fig. 2).

The unit C2-A has a classic open framework-supported texture formed by lithic-poor, coarse and angular pumice lapilli (Fig. 4b). It is locally overlain by bed β (described below), a white ash, thin bed that percolates between clast open spaces. C2-B is a normal-to-reverse graded, 0.2 m thick pumice lapilli layer. Lithic clasts are slightly platy and fresh; obsidian lithics are more abundant at this level.

In terms of componentry, it is formed mainly by pale-grey trachydacite pumice, angular, micro vesicular, fibrous and with coalesced vesicles. Its mineral assemblage includes plagioclase, clino and orthopyroxenes and scarce K-feldspar in a glassy matrix. The lithic phase is less than 1.6% and it is mainly formed by obsidian, fresh andesite and scarce perlite.

White-ash layer (bed β, Fig. 2): At several localities layer β, a 3 to 8 cm-thick white ash and ash-tuff layer appears at lower parts of C2. It is generally massive ash, with thin laminae; cross-stratification within this laminae could be observed at certain localities. The base passes gradually into the ash from the underlying coarse pumice, the upper contact is sharp with C3 pumice lapilli. It is usually loose but it can also be found indurated by vapour phase processes. It is formed by glass shards, lithic chips and small broken phenocrysts.

Layer C3

Layer C3 is a 0.35 m thick, stratified, grey to black pumice lapilli and scoria respectively, in a coarse ash interclast background; banded pumice is abundant at this level (Fig. 6b). It ranges from 0.3 m to 1.5 meters thick, its base is represented by the first appearance of dark pumice and scoria as a fine-grained (medium ash) layer, the top is sharper, marked by juvenile clasts which are moderately sorted, with grey pumice larger than dark-grey pumice (Fig. 6c). Thin, fine-grained lapilli layers run sub-horizontally through this level. Componentry indicates heterogeneity relative to lower layers; it contains fibrous and angular white pumice and dark-grey to black pumice and scoria, also vesicular and sub-angular. The lithic phase is represented by fresh and oxidized andesite, concoidal black and grey obsidian chips and scattered plagioclase phenocrysts. Small (≤ 2 cm) fine-lapilli agglomerate cemented by fine-ash are common. Towards the top, the proportion of banded pumice increases up to 23% as do the obsidian up to 6% (Fig. 6b).

Layer C4

Layer C4 is sub-divided in two: C4-A and C4-B with two impersistent beds, γ and δ (Fig. 2). As a whole, C4 at the type section is 0.7 m thick, but its thickness ranges from 0.2 m to 3.5 m and with anomalous thickness values near vent. It is a crudely inversely graded black lapilli layer (Fig. 6d). It is generally well sorted but slight diffuse stratification can be observed (Fig 7a). At most places, the base of C4-A displays a thin layer of black sandy scoria (bed γ). It is then overlain by C4-A, scoriaceous dark-grey to black lapilli, brown pumice and accessory white pumice clasts (≤1.6 wt.%). It is a lithic poor layer, with scarce oxidized lithics and red scoria. In some locations C4-A and C4-B are directly in contact (Fig. 4a), or they can be separated by a thin accumulation of white pumices (Figs. 4b and 6d) that generally thickens to up to 10 cm towards the north and represents bed δ, which is not continuous and poorly exposed at the type section (Fig. 3). The upper half of C4 is represented by C4-B, a dark basaltic andesite scoria lapilli layer that also thickens towards the north, and the size and the proportion of block and bomb-sized clasts increases as well. Observations under the microscope show a highly vesicular scoria (see ESM), glassy, dark-grey to black.. Vesicle size range from 0.2 to 1.0 mm, highly coalesced and fibrous, shards produced from broken vesicles are typically elongate and in irregular *x* and *y* shapes. The scoria clasts are fresh and fragile, with no sign of strong alteration. The most vesiculated (scoria) phase, about 10.4 wt.%, resembles typical pumice textures. The mingled pumice phase is absent, although there are some scoria clasts with pumiceous blobs. Accessory lithics are oxidized andesite clasts and sub-rounded red scoria clasts, resembling pre-existent remnants of a cinder cone and agglomerate lava beneath.

*Sandy scoria layer (*bed γ, Fig. 2): Layer γ is a black fine-grained layer very common and traceable across the CM exposures, it is continuous, with constant thickness at southern exposures but can also present abrupt lateral thickness changes towards the center and east of the caldera. It contains fine-grained scoria, black and brown, fine pumiceous lapilli and broken phenocrysts. Obsidian, altered volcanics and andesite (≤2 vol.%) lithics are present in low proportions. Layer γ thickens up to 0.2-0.5 m with maximum anomalous thickness up to 1.5 m at southern Potreros valley (Fig 7b). When this layer is thicker than 10 cm, it commonly exhibits parallel stratification, dunes, low-angle cross bedding and lenses of well sorted scoriaceous sand. Its internal structures are consistent with emplacement from pulsative fully dilute density currents (*surges)* rather than that from only fallout origin.

Layer C5

At the type section (Fig. 2), layer C5 is 10 cm-thick pale grey, massive trachydacite pumice lapilli with abundant brick-red scoria lithics. Its base is sharp over C4-B and its top, although also sharp towards scoriaceous upper C6, it grades into a diffuse stratified fine-lapilli (bed ε; Fig. 2). The thickness interval of layer C5 ranges from 0.1 m to 2.9 m. In general is normal graded, well-sorted but with sporadic larger fresh pumices protruding out of the average fine-lapilli grain size mass (Fig. 7a). It contains abundant fresh white pumice, sub-angular and with phenocrystal phases of plagioclase, biotite, pyroxenes and feldspar. Darker grey pumice is also present (1.4 wt.%) as well as banded pumice (1.6 wt.%). Brown scoria/pumice is ubiquitous. Accessory lithics are mainly obsidian, red-scoria and fresh andesite lava chips.

Bed ε is represented by fine-grained, slightly rounded pumice lapilli and coarse ash displaying low angle cross stratification, fore sets and sub-parallel stratification (Fig. 4). It rests always upon C5, with variable thicknesses, from thin 5 cm thick at the type section, up to 50 cm towards the centre of the caldera. Bed ε may represent reworking of C5 by strong winds during a well identified pause in the eruption, or surface pumiceous material removed and re-deposited by the by-passing of a pyroclastic current.

Layer C6

C6 is a normal-graded, diffuse-stratified scoriaceous pumice lapilli layer 0.8 m thick at the type section (Fig. 4a), with maximum and minimum thickness intervals from 0.15 to 3.5 m. It is generally a lithic-poor layer. The base is a sharp contrasting contact with pumiceous C5, in both colour and texture as the grain size changes dramatically (Fig. 7a). It contains scattered thin layers of pale-grey pumice lapilli and ash (bed λ; Fig. 2), which are slightly richer in lithics. The top is well-stratified scoriaceous lapilli in a diffuse contact with coarser overlying C7 (Fig. 7b). The relative increase of the thickness, and the size of particles, as well as the orientation of ballistic blocks, were used to identify two different sources in opposite directions, which will be shown in the further sections.

Componentry analyses reveal a dominance of black to dark-grey scoria, pumiceous scoria, glassy and micro vesicular angular and fragile lapilli-size clasts. The more vesicular pumiceous scoria is pale-brown whilst the larger the vesicles, more glassy and scoriaceous. The proportion of white pumice is below 1.2 wt.% and banded pumice is ≤0.8 wt.%. The juvenile clasts are rich in phenocrysts, including plagioclase, feldspar and biotite. Accessory lithics comprise fresh, angular andesite and rhyolite clasts, obsidian and red sub-rounded scoria. It contains feldspar phenocryst aggregate, possibly glomerocrysts.

Bed λ (Fig. 2), is a mixture of dark andesitic pumice and white pumice lapilli with sharp lower contact and diffuse upper contact with the top of C6. It slightly thickens towards the north although the mixture between components continues. There is no absence of the andesitic component, just an influx of white trachydacite pumice lapilli and banded pumice forming this layer. It is 5 cm thick at the type section and rather diffuse, whilst almost 15 cm towards the north of the caldera and much better constrained (Fig. 7b).

Layer C7

Layer C7 is heterogeneous, with diffuse boundaries and thickness intervals of 0.7 m to 2.3 m. It is a buff grey, massive to diffuse-stratified pumice lapilli (Fig. 7b). Juvenile clasts are angular to sub-angular with black scoriaceous lapilli. It is a lithic poor layer, with scarce oxidized andesitic chips. It is normal graded and the top is defined by fine-grained (sandy) layers of dark-grey pumice and scoria.

Layer C7 is a mixed deposit comprising dark grey to white pumice clasts, sub-angular, vesicular, fibrous and fresh, and also brown pumiceous scoria (31.6 wt.%). These scoria clasts are also angular, glassy and fragile and some appear banded with lighter pumice lines. Banded pumice proportion is relatively high, ≤2.4 wt.% (Fig. 7d). The lithic phase is formed by rhyolite, andesite, obsidian and red scoria. Phenocryst content includes plagioclase, feldspar, pyroxene, ilmenite, magnetite, hornblende and oxidized minerals.

Layer C8

C8 is the most heterogeneous layer. It is a diffuse-stratified, clast-supported pumice and scoria lapilli layer with scattered amoeboid blocks that ranges in thickness from 0.5 to 3.0 m thick (Fig. 7b). The base is formed by facetted grey, white and brown pumice with abundant black scoria lapilli and scattered blocks and bombs. Mingled juvenile pumice is also abundant at this layer, in both lapilli and block size clasts. Fresh basalt, andesite, red scoria and hydrothermally altered (and oxidized) volcanic lithics are present. Obsidian and glassy clasts are ubiquitous. The whole of layer C8 is inversely graded marked by the presence of highly angular scoriaceous blocks and prismatic-jointed blocks. Ballistic blocks (juvenile and lithic) are common in outcrops located towards the south of the caldera (Fig. 7b), and they range in size from 0.3 m to 2.0 m, with a maximum size in log 50 with 1.6-2 m. At least 4 sub-horizontal layers of white pumice lapilli clearly appear across the deposit at this level (Fig. 4a). Towards the north of the caldera, the proportion of large basaltic clasts in C8 decreases dramatically, leaving only thin diffuse layers of basaltic-andesite lapilli within a pale-grey pumice layer (Figs. 4b and 7c).

Layer C9

Layer C9 is poorly exposed and mainly eroded as it represents the top of the CM (Fig. 2). It is a normal-graded brown to buff grey pumice lapilli deposit (Fig. 4a). Although it is not widely exposed, it preserves a thickness interval of 0.15 to 1.6 m. It is well sorted, with scattered outsized juvenile clasts and it grades usually into a paleosol or it is found with an eroded top and composed by sub-rounded pumice in a fine-grained matrix due to weathering.

4. Physical parameters

4.1 Grain size analysis

Granulometry analyses were performed on 19 samples mainly from the type section of the CM. Samples were dry sieved at the Centro de Geociencias (UNAM), over 1 Φ intervals. The grain size parameters were obtained using the SFT software (Wohletz et al., 1989).

Variable clast sizes through all its vertical section were observed, with median diameters (Md Φ) that range from -5.5 to 2.5 Φ (Fig. 8; granulometry data in the ESM). The vast range of granulometries within the CM reflects the heterogeneity of the eruptions, with moderately to well-sorted pumice and scoria fall layers (C1, C2, C3, C4 and C6) and coarser grain layers like C8. In contrast, fine-grained layers bracketed between well-sorted lapilli beds occur commonly at C2, C4 and C6. The finest layer in the CM is the white ash bed β within C2, with a Md Φ of 2.45 and σ Φ of 0.47 (Fig. 8).

The two basal layers of the CM (C1 and C2) show common Gaussian curves for pyroclastic fall deposits, with median diameters (Md Φ) in the range of -1.6 and -2.3 Φ. The bed α shows a bimodal arrangement caused by the excess of fine-grained material, probably silts and clays product of incipient paedogenesis. Layer C2 has two main clast types: a coarse pumice lapilli component and a white fine ash layer (β). The fine-grained layer has Md Φ of 2.45 Φ whilst the upper lapilli layer is -2.3 Φ. The scoriaceous thin layers within C3 are fine-grained, with Md Φ of -1.7. The base of C4 is a black thin layer of coarse ash with median diameter of 2.05 and a sorting coefficient of 1.68. The middle and top of C4 is coarser grained (Md Φ of -3.0) and moderately sorted (σ Φ of 1.35). Locally, near to fissure vents from the Cuicuiltic eruption, scoria clasts and ballistics can exceed 30 cm in diameter (Fig. 8). In contrast, C5 contains fine lapilli clasts (Md Φ -0.65) and is poorly sorted (σ Φ 2.38). The top scoria layer is C6, coarse-grained scoria lapilli with median diameter of -2.95 and 1.68 of standard deviation coefficient. It is commonly normal graded, with fine-grained lapilli layer at the top showing Md Φ of 1.65 and an σ Φ of 1.95 (Fig. 8). C7 is a coarse deposit with a moderately sorted distribution, with median diameter of -2.35 Φ and a sorting coefficient of 1.60 Φ. From C7 upwards, the CM contains coarse pumice lapilli and scoriaceous breccias. Layer C8 starts with MdΦ of -3.75 Φ and the clast size continues increasing up to -5.55 Φ, being this last sample the coarsest one within the non-ballistic analyses (Fig. 8). C8 is moderately sorted, with σ Φ ranging from 0.95 to 1.5. Layer C9 shows MdΦ of -2.3 with a sorting coefficient of 1.35 (Fig. 8), resulting in moderately to well sorted deposits.

4.2 Componentry analysis

Seventeen samples were collected for componentry analyses from the distinct layers of the CM and one from the underlying Llano ignimbrite, using the medium to coarse intervals (1Φ to -6Φ), 300 points were counted for each grain size phase. Totals were averaged by its wt.% and normalized. The samples were washed with deionised water and dried overnight to free the surface from clays and soil to facilitate its classification. After careful observations, 12 main components were identified (Table 3).

Most of the clasts from the CM are juvenile (>60 wt.%), the base, represented by C1 contains more than 60 wt.% of felsic pumice clasts (P, pumice), but also a high proportion of lithics (L, >25 wt.%). An anomalous proportion of oxidized altered lithics (Oxi), that stain the fresh pumice clasts around them characterizes layer C1 (Fig. 8). It has also a large amount of other white hydrothermally altered lithics (AL). No mafic juvenile clasts appear within C1 and C2, only very low (<0.5 wt.%). In contrast, by layer C2 above 98 wt.% comprises fresh trachydacite pumice (P), with lithics mainly formed by obsidian and perlitic glass (perl). C3 marks a change on the components, the pumice proportion lowers down to 65 wt.% and andesite pumice and scoria (Sc) begins to appear in large amounts (20 wt.%), towards the top of C3, mingled pumice is abundant (bp, ~15 wt.%; Fig. 8). A significant change occurs at the base of C3, with more than 20 wt.% of phenocrysts (pxls), lithic clasts remain scarce. Layer C4 is formed almost entirely by basaltic andesite scoria (Sc, 55 to 80 wt.%). Another significant change is the influx of brown scoria/pumice (brSc) into the deposit, which from this layer upwards it represents an important component (>20 wt.%). Banded pumice and obsidian (Obs) are also abundant. Layer C5 marks an abrupt change in the proportion of components (Fig. 8). It is formed mainly by pale-grey trachydacite pumice (>80 wt.%), with very infrequent scoria and a distinctive red scoria (rSc) component that has been regarded as a lithic component. C6 resembles C4 in its componentry; with mainly black scoria (Sc), brown scoria (brSc) and andesite lava lithics (And), an increase in obsidian chips (Obs) is also significant. C7 shows an increase on trachydacite pumice and banded pumice marking a return to a more silicic influx within the Cuicuiltic eruption. Scoria and brown scoria/pumice are also ubiquitous. The top layer, C8 is formed mainly by scoria, banded pumice, grey pumice and brown scoria, with very little obsidian and other lithic clasts. No quantitative componentry data was able to collect from layer C9.

Vesicularity contrasts

The range of vesicularities across juvenile fragments of the CM is very wide. The white ash layer β is formed by highly microvesicular, cuspate and bubble-wall glass shards, in the order of 50 µm across (SEM images at ESM). Scoriaceous layers (C4 and C6) comprise particles with typical bubble wall vesicles with limited coalesced texture, whilst more evolved layers (SEM images at ESM) present rounded vesicles. C8 contains two main types of vesicularity, typical pumiceous sub-angular clasts, and highly angular to irregular scoria glass with stretched vesicles in the shape of strings and elongated vesicles (SEM images at ESM).

4.3 Distribution of the Cuicuiltic Member: Isopach and Isopleth maps

The distribution of the CM is mainly within the internal walls of the Los Humeros caldera, where the best exposures occur, although thin veneers have been recognized in the outer slopes. Exposures are usually good, mainly those at deep narrow gullies, like the type section and other logged sections (Fig. 4). The tephra deposit lies at the top of Los Humeros stratigraphy and for this reason, erosion has hindered its complete preservation, causing a non systematic distribution of outcrops, and in some cases a minimum thickness is registered. It is evident that not all layers are well exposed and the data were not sufficiently precise to complete isopach and isopleth maps for all the CM layers. After a careful and extensive collection of field data from all available logs, we were able to construct isopach maps for layers C1, C2, C4B, C5, C6, and one part of C8 (Fig. 9). Layers C3, C7, and C9 have diffuse limits, and are somewhat difficult to recognize its boundaries in the field or are strongly affected by erosion (e.g. C9). A similar situation occurs for the isopleth maps and only layers C1, C2 and C5 were constructed (Fig. 10).

Isopach interpretation: Individual thickness data was collected from exposures mainly around the intra-caldera sector of Los Humeros caldera (see isopach and isopleth data in the online resource). At most exposures, the individual thickness of each layer was measured.

The results show variations within dispersal axes, areas of distribution, thicknesses and configuration of the isolines between most layers, mainly between chemically distinct layers. Trachydacite layers behave similar in terms of thicknesses and areas, but not exactly for dispersal axes. For layer C1, the thickest value recorded is near 1.6 m, towards the northwest of Los Humeros village, with lowest values of 0.1 m towards the southeast, still within the caldera limits. This configuration generates a dispersal axis for the isopach map towards the southeast, with little or no exposures found towards the north and west (Fig. 9a). The absence of data towards those areas could be caused, in addition to less deposition, to the presence of younger lava fields, thicker vegetation and broad successions of volcaniclastic aprons.

For layer C2, the most voluminous trachydacite layer, the dispersal axis is clearly bilobate towards the ENE and SSW, although thicknesses vary widely. Layer C2 is the most broadly distributed, with evidence of lapilli tephra deposited nearly 3 km outside the caldera margins. The thickest exposure corresponds to a 6.2 m layer just north of Los Humeros village (Fig. 9b). The thinnest values recorded range from 0.05 to 0.2 m towards the southeast of the caldera. Layer C3 has not formed good coherent isopach lines, and therefore is not considered in figure 9.

Layer C4 (the lower pervasively andesitic layer) has complex isopach distribution, with a rather odd configuration of two apparent isopach curves that suggest at least two different vents. As described earlier C4 show two layers (C4A and C4B), separated by a felsic layer in some locations, but in other sites it appears as an apparent continuous merged layer where it is difficult to identify the boundary between both layers (Fig. 9c). Although we were able to construct only a reliable isopach map for the upper layer C4B, we suspect that layer C4A come from a vent located to the southern caldera rim, across the Vigía Alta road section, based on a relative increase in thickness and grain size towards that area where near-vent facies consisting of very thick exposures of alternatively scoria lapilli, glassy lava, ballistic blocks, fusiform bombs and rootless flows, depositing thick agglomerate and agglutinated breccias with scoria lapilli. Isopachs for C4-B show a progressive increase in thickness towards the NNE of the Los Potreros scarp with values around 2.1 m in the north and minimums of 0.15 m in the south. In addition to that, the number and size of spatter and ballistic bombs increases towards the same area, confirming the source for C4B, and the dispersal axis towards the southwest (Fig. 9c).

Isopach for layer C5 shows maximum thicknesses north of Los Humeros village (3.4 m) and a minimum of 0.15 m towards the SE. The dispersal axis is not well-defined due to the absence of data from the NE sector; however, a lobe towards the SW appears to be slightly dominant (Fig. 9d). Abrupt thickness changes at exposures around Los Potreros scarp could be the result of deposition over steep slopes and thus, the less smooth configuration of the curves towards the 0.5 and 1.0 m isopach in the southeast. Isopachs for layer C6 are also complex and are in good agreement with the eruption of at least two fissure vents (Fig. 9e). According to the correlated sections, logs and transects, and several observations such as the orientation of ballistic blocks, relative increase in mean grain-sized clasts, proximity of spatter and large ballistic blocks towards the vent areas, and confirmed by the isopach maps, all indicate that the vents that produced C6 layers are located at two different sites, to the north with a dispersal axis to the SW, similar to C4B, and other to the south, with a dispersal axe to the NW (Fig. 9e). A rough configuration of isopachs was made for layer C8 (Fig. 9f), which is supported on the abundance and size of spatter and ballistic bombs distributed around the vent area formed by a large quarry just north of the Maztaloya village (Fig. 1), from where bombs and ballistic blocks were fed into the unit. At reasonable distances from Maztaloya, C8 looses its large blocks and basaltic material and it is represented mainly by lapilli-sized clasts and banded pumices. Finally, C9 is the least exposed layer from all the CM, with very few good exposures (<6), recording thicknesses of less than 1.6 m. C9 records the final stages of the Cuicuiltic eruption but was probably eroded soon after deposition and preserved only at key localities.

The distribution and overall configuration of the isopach maps from the CM support the hypothesis of one trachydacite explosive vent area towards the north to northwest of Los Humeros village (thickest isopach lines of C1, C2 and C5; Fig. 9a, 9b and 9d), and the contemporaneous activation of basaltic-andesite fissure vents at the caldera rim fracture (S and SW), others probably over the north-south Los Potreros scarp lineament in the east and southerly at Maztaloya village area (at least 2 discrete vents, Fig. 9e and 9f.

Isopleths: We compare the average of the three and five largest clasts for both pumice/scoria clasts and lithic clasts selected from each individual layer at selected logs, and considering the methods proposed by Rosi et al. (2001) and Hernández et al. (2009), we choose the three clasts method to calculate the isopleth maps. Care was taken to distinguish between layer limits, and from each clast set, the two largest axis of each clast were recorded and averaged. Ballistic blocks within lapilli-sized scoria layers were not recorded to avoid mixing of data between clasts affected by wind or plume dispersal and ballistic trajectories from proximal fissure vents (outliers). Ballistic data was recorded in separate plots as evidence of the proximity of a vent. Isopleth maps were constructed only for layers C1, C2, and C5 (Fig. 10) because of the scarcity of data and poor correlation, particularly for many locations of the andesitic-basaltic layers C4 and C6, and the upper mixed layers C7, C8 and C9.

The isopleth map for pumice and lithics of layer C1 is, in general, similar and in agreement with the isopach maps for C1 with a dispersal axis to the SE, particularly for lithics (Figs. 10 a and b), while for pumice it shows a ESE direction. It shows dispersal axis towards the southeast, with largest values 2 to 3 km towards the N-NW of Los Humeros village. Refining data for layer C2 allows a general configuration for the isopleths with a bilobate shape that is better defined for the lithics clasts (Figs 10 c and d), which is also in agreement with the isopach configuration depicted in figure 9b. Isopleths for layer C3 are not depicted due to less confidence on discrimination between stratigraphic boundaries of C3 at distal localities. Clast data for layer C5 shows a general trend similar to C1 and C2, supporting the isopach map. Although the shape for the isopach map is bilobate, it shows a dominant tendency to the SSE, which is similar to that shown for both isopleths (Figs. 10e and f). In fact, the isopleths map for pumice is slightly bilobate (Fig. 10e), but clearly dominant to the NW-SE direction.

As we can see, the isopleth data for layers C1, C2 and C5 (Fig. 10) is in general terms consistent with the isopach maps (Fig. 9). C5 follows a very similar pattern and distances to C1 and C2, even though it is bracketed between two basaltic-andesite layers demonstrating evidence that C5 represents a second (or third) pulse within the trachydacite erupting magma. The data from the two mafic layers (C4 and C6), and the basaltic C8 influx, shows that eruptions were acting simultaneously from independent vents; the first towards the south and southwest caldera rim, and subsequently near the trace of the eastern Los Potreros scarp (from north to south), and northeast of the same scarp but in the outside, towards Las Chapas village (Fig. 1).

5. Discussion

5.1 Eruptive history and physical volcanology

In addition of the information derived from the isopach and isopleths maps, detailed field observations and mapping of near-vent spatter facies, data derived from the orientation of local ballistic blocks and impact bomb sags combined with data obtained from the observed variations of mean clasts size for some layers, were all together used to define with more precision the location of vent areas for the andesitic-basaltic layers C4B, C6 and C8, which resulted in a more complicated distribution of the tephra associated with those layers. As for example in the case of layer C4B (Fig. 11), coarse spatter scoriaceous partially welded clasts (Fig. 11b) as well as the abundance of large ballistic bombs (Fig. 11c), are good indicators of the proximity of the vent area, which reinforces what is also indicated by the isopach maps for that layer (Fig. 9c).

With all the available data, we are able to reconstruct the eruptive history of the CM as follows: The CM started with the emplacement of a trachydacite Plinian eruption column after a repose period smaller than 30 kyr after the last explosive eruptions: the Llano ignimbrite and the Xoxoctic Plinian eruption (Willcox, 2011). The opening phase was characterized by the eruption of pumice lapilli and ash that blanketed most of the intracaldera floor over an incipient ~6,400 years B.P. paleosol. The thickest exposures (1.2 m) reveal deposition of pumice lapilli over the relatively plain topography of the caldera and partially in the outer margins. Abundant hydrothermal alteration in lithic clasts within this layer may represent strong fumarole activity prior to the onset of the eruption (Fig. 6a). C1 at most exposures grades into layer α, regarded as a short pause (hiatus) within the Cuicuiltic eruptive unit inferred on less than a couple of years.

We consider that the magmatic system (depicted in Fig. 12) was re-activated in the central part of the caldera causing the extrusion of the most voluminous layer of the Cuicuiltic eruption, C2. This layer represents steady Plinian pumice-fall deposits in a quasi-radial distribution across the caldera, only interrupted by the emplacement of a fine ash fallout layer directed towards the SE, which represents a slight change within the column dynamics between the first steady pulse and a more pulsating column afterwards, which was possible affected by changes in wind direction that created an apparent bilobated configuration of both the isopach and isopleths maps. The fine-ash bed β could represent either a short pause on pumice lapilli fallout during emplacement of C2, or the result of a directed eruptive phase that deposited ash towards the southeast. The low proportion of lithics within C2 may be the result of high mass-flux eruption tapping trachydacite magma through the conduit after most of the first phase (C1; Fig. 12a), had already eroded the conduit walls (lithic supply). C3 marks the entrainment of banded and andesitic pumice within the eruption (Fig. 6c and 6d). The contact marked by the influx of less evolved pumice is sharp, however, the lack of variation in the granulometry and the continuation of the diffuse-bedded attitude between C2 and C3 could be interpreted as felsic material that was still depositing whilst andesitic and banded pumice was added into the plume from the same central vent, representing C3 (Fig. 12a).

The eruption of C4 represents a dramatic change in the eruptive sequence of the CM, with the simultaneous activation of more than one fissure vent producing a Strombolian basaltic-andesite eruption just after the first felsic pulses. Due to the complexity of how this layer was assembled, only one isopach was obtained for layer C4B; nevertheless field data comprising relative thickening and clasts coarsening, distribution of proximal spatter and detailed field logging, all indicate that at least 2 mafic vents were active from a unconfirmed southern area near the caldera rim followed by other to the north, from a vent located towards the north of the eastern Los Potreros scarp (Las Chapas, Fig. 1 and 11), forming the well-configured C4B

(Fig. 12b). C4 is characterized by the presence of a sandy grade black ash (bed γ; Fig. 2), that at some localities show cross stratification. It has been interpreted as deposits from proximal, dilute density currents and its correlative distal ash deposit. It is still unknown from which vent this layer is derived although the thickest exposures appear at the south of Potreros scarp. However, as depicted in Fig. 4b, between the layers (A and B) forming C4 is layer δ, a thin white pumice layer that may represent a small pulse of trachydacite pumice expelled during a very short repose interval between eruptions forming C4 (Fig. 11a, 11c). The thin, discontinuous character of this layer (δ) and the fact it thickens towards the north may indicate dispersion from the center of Los Humeros towards the N-NE. This may also suggest trachydacite pulses were not fully ceased while basaltic andesite material was erupting through the fissure vents.

Eruption from the Strombolian fissure vents had probably discontinued whilst evidence shows the trachydacite vent re-activated depositing layer C5. This layer represents explosive products from the central vent. This layer is an important marker bed due to its very well constrained and bracketed stratigraphic position. C5 marks the reactivation of the trachydacite vent showering pumice lapilli from a high eruptive column under relatively steady conditions. However, the presence of layer ε (Fig. 2) could represent either re-working after its emplacement due to strong winds or water remobilised surface lapilli. An alternative interpretation may be that it represents the products of pumice-rich, bypassing density currents deposited elsewhere, however, no ignimbrite has been identified that correlated with the CM.

After the emplacement of C5, a second reactivation of basaltic fissure vents took place, this time it deposited composite layer C6 from possibly the same vents and probably a new one. Firstly, we infer material was erupted by andesitic vents from close to the southern caldera rim and afterwards from the north of the Potreros scarp, following a cryptic lineation of older vents (probably a buried fault; Fig. 1). These two vents were identified by using proximal spatter agglomerates and large blocks overlying C5 layer as evidence.

The last phase of the Cuicuiltic eruption was characterized by abundant mingling and mixing within the main magmatic system. Trachydacite magma eruptions were taking place ejecting well fragmented pumice lapilli with evidence of incomplete mixing of magma batches at the chamber and conduit, as recorded by ubiquitous banded pumices in layer C7 (Fig. 7d). The limit with the overlying layer C8 is marked by the entrainment of andesitic pumice and large scoria blocks mixed with pumice and banded lapilli. Layer C8 represents lapilli fallout from the umbrella cloud whilst local fissure eruption was taking place from a new vent located at the south of Potreros scarp (where it is now a scoriae quarry at Maztaloya village; Fig. 1). Configuration of the C8 isopach map combined with the abundance and increase of oversize blocks towards the quarry location confirm the location of the vent area. Out of the dispersal axis of this small scoria vent, C8 is represented by trachydacite and banded pumice lapilli (Fig. 7c). The last products from the Cuicuiltic eruption are recorded by layer C9, which represents deposition of trachyandesite pumice lapilli fallout, when efficient mixing (hybridization) had apparently occurred at depth. This is based on the scarcity of mingled pumices and the few within show very delicate strings of intermediate chemical composition. Vent location for C9 has not been constrained due to the paucity of exposures, although according to the well-classified aspect of this lapilli layer, our thoughts favour its origin from the central vent rather than from a secondary fissure vent.

5.1 Multiple vents

Evidence based on field data, stratigraphic correlations, isopach and isopleth maps and compositional variations supports the existence of contemporaneous or sequential vent opening phases of at least two magma batches during the Cuicuiltic eruption (Fig. 12). The absence of hiatus or significant repose periods between eruptions such as palaeosols is consistent with the almost continuous emplacement of deposits. After careful and detail logging of the CM across the caldera, changes in thickness of individual layers were recorded, for example, thinning and then thickening again of individual basaltic andesite correlated layers (e.g. C4) towards a given direction. Such behaviour as well as the presence of large ballistics and lava blocks near the thickest correlative scoria lapilli layers (Fig. 11) led us to the hypothesis of multiple active vents erupting nearly simultaneously. Isopach and isopleth data plotted over the caldera also corroborated this interpretation. Finally, chemical variations between the products from independent vents (trachydacite vs. basaltic andesite) also proved the existence of a chemical zonation that cannot be explained by common tapping of stratified magma reservoirs considering changes are often sharp between compositions.

In summary, our interpretations support the existence of one major trachydacite vent towards the north of Los Humeros village that produced layers C1, C2, C3, C5 and parts of C7, C8 and C9; and at least three fissure vents (Fig. 1) producing basaltic-andesite Strombolian eruptions either in short pauses from the main felsic eruption or simultaneously, represented by layers C4, C6 and basaltic components of C8.

Examples of multiple vents acting simultaneously or at least sequentially over a short time lapse are not common. Well-documented cases in the literature include the Pahoka-Manganate sequence at Tongariro Volcanic Centre, New Zealand (Nairn et al., 1998), the 1991 Hudson volcano eruptions in Chile (Kratzmann et al., 2009) and more recently the 2010 Eyjafjallajökull eruption in Iceland (Sigmarsson et al., 2011). In all these cases, including the CM a common feature is the heterogeneous composition of the magmas involved.

Relation with the Xalapasco crater

Previous publications (Ferriz and Mahood, 1984; 1987) referred to the Xalapasco crater (Fig. 1), as the explosive source for the CM. However, here we present an alternative interpretation for the origin of this structure, relative age and its possible products. None of the isopach and isopleth data sets point out to the Xalapasco or nearby areas as the source of the CM. We propose that the Xalapasco eruption and collapse occurred prior to the emplacement of the Cuicuiltic eruption and after the deposition of the Xoxoctic Member (Fig. 2). The following lines of evidence support this assumption: (1) The nearest active vent was the small Strombolian fissure located at Maztaloya village, which deposited the coarse basaltic products of C8, including a 2-m horizon that crops out only on the north rim of the Xalapasco crater; (2) No other pyroclastic material has been found on the other sectors of the crater or within the Xalapasco crater floor, although it is filled with apparently post-Cuicuiltic lavas; (3) Cuicuiltic pyroclastics, if preserved, would be at the base of the crater (and would now be buried by younger lava), and the walls are too steep and no preservation there is to be expected; (4) The Xalapasco inner crater walls are formed by andesitic to dacitic altered lava, with banding and discrete brecciation, no pyroclastics have been reported within the walls; (5) In the outer margins of the crater, exposures of the CM are not anomalous, thicknesses are consistent with the isopach configurations and the scarce ballistics present do not appear to be derived from that direction, but from basaltic C8 vent at Maztaloya. Finally (6), below the paleosol at the base of the CM there are a couple or merging paleosols and a thin white ash overlying a brown, lithic-rich and dark pumice-rich tuff, informally named the Llano ignimbrite (Figs. 2; Willcox, 2011). The lithic-rich facies of the llano ignimbrite contains identical lithologies that the inner crater walls of the Xalapasco, and its distribution form lobes towards the north, east and southern slopes of the Xalapasco crater and into Los Potreros scarp (Fig. 1). No detailed work has been done on the genesis and eruption of the Xalapasco volcano, although some interpretations suggest it was formed at the final stages of the Arenas volcano (Fig. 1; Ferriz and Mahood, 1984). Our hypothesis suggests collapse was probably originated due to the rapid explosive tapping of magma below the structure and its sudden collapse, with no further activity related apart from local scoria-flow and lithic-rich pyroclastic flow pulses depositing the Llano Ignimbrite.

5.2 Magma mingling/mixing

The process of magma mixing and mingling within pyroclastic deposits has been documented broadly within various volcanic environments (Sparks et al., 1977; Calanchi et al., 1993; Cioni et al., 1995; Tonarini et al., 2009; Nairn et al., 1998; Shane et al., 2008; Kratzmann et al., 2009; Gerbe and Thouret, 2004; Pallister et al., 1996; Clynne, 1999; Roman et al., 2006; Bryan et al., 2002; Brown and Branney 2004; Tepley et al., 2000; Sosa-Ceballos et al., 2012; Walker 1981; Aguirre-Díaz, 2001; Ferríz and Mahood, 1987; Carrasco-Núñez and Branney, 2005; Carrasco-Núñez et al., 2012). Magma mingling occurring at Los Humeros caldera has been also reported within ignimbrites and pumice-fall deposits (Ferríz and Mahood, 1987; Carrasco-Núñez and Branney, 2005; Carrasco-Núñez et al., 2012). More recent works had been focused on the zoning and mixing from voluminous pumice fall layers (Willcox, 2011).

The occurrence of magma mixing and mingling in tephra clasts of the CM reported in this study comprises a singular type directly related with the timing and geographic distribution of vents and its compositions. The first evidence of mingling within the CM occurs in layer C3. Below this, layers C1 and C2 are fully formed by pale-grey homogenous pumice glass with no megascopic evidence of banding. However, by layer C3 a large proportion of banded pumice clasts and 90% andesitic (dark grey) clasts with light grey (trachydacitic) blobs were introduced into the eruptive column and deposited as thin-layered C3. Upwards into layers C4, C5 and C6, banded pumice are scarce or even absent at least in layer C5 which is formed by pale grey pumice lapilli. In contrast, C7 records the onset of magma mixing and mingling again with ubiquitous banded pumice lapilli at most of the thickness of this layer. Whilst at the lower mingled layer (C3) there is no evidence of efficient mixing, by C7 stripes of different compositions are thinner and resemble a lower viscosity state while mixing was occurring. Upwards, a mixture of banded, grey and dark pumice and scoria blocks are present, suggesting different materials were falling simultaneously by the time C8 was depositing. Finally, C9 is formed by buff grey homogenous pumice lapilli in which some of the clasts show very thin threads of lighter grey glass.

A different type of magma mixing is also occurring at the Strombolian stages, where evidence of fresh pumiceous glass is present in black andesitic scoria clasts, common at proximal sites like C4 at Vigia Alta caldera rim vents and the northern C4B vent (Fig. 11). These pumice 'xenoliths' are not altered but have more vesicular edges than the rest of the interior glass. This texture may suggest both materials were viscous at the moment of contact, with the basaltic magma hotter than the silicic one causing the enhancement and exsolution of volatiles from the silicic melt and thus the expansion of vesicles at the contact.

Layer C5 is formed only by pale grey pumice lapilli, it has no andesitic nor mingled pumice clasts and thus, it suggests that mixing processes at this moment in the eruption stopped temporarily or mingled material was not available at the time when C5 was emplaced. However, immediately after, in layer C6 andesitic scoria lapilli predominates over thin discontinuous layers of white pumice (bed λ). No evident mixing is present in layer C6. Upwards, layer C7 marks the onset of a high proportion of mingled juvenile clasts.

This alternation of layers with and without mingling processes inside the same eruptive unit represents an unusual case where magma is not mixing. The presence of compositionally contrasting magmas could be related to a simple chemical zonation in the magmatic reservoir (Ferriz and Mahood, 1987) or a more complex model involving two magma chambers: a zoned major one tapping first homogeneous trachydacite magma with subsequent episodes of mingling and the presence of probably deeper and coeval basaltic-andesite reservoir tapping magma through re-activated faults generating fissure-fed vents. In this regard, Carrasco-

Núñez and Branney (2005) proposed that the double compositional zonation exhibited for the Zaragoza ignimbrite records the progressive tapping of a compositionally-stratified magma chamber (andesite at lower levels and rhyodacite at the top), with the upper, reverse-zoned part of the ignimbrite reflecting a late-stage resumption in the tapping of shallower, felsic upper parts of the magma chamber caused by a decrease in draw-down depth due to post-climactic waning mass-flux and a modified fracture-conduit geometry following caldera subsidence. However, in a more recent study, Carrasco-Núñez et al. (2012) proposed a new model for the Zaragoza eruption involving an isotopically homogeneous but chemically heterogeneous magma reservoir, possibly arranged as semi-connected high-melt lenses or zones within a partially consolidated crystal mush. Perhaps a similar model can be inferred for the CM, assuming the existence of a single but heterogeneous magma reservoir tapping compositionally different magmas through distinct conduits first (Fig. 12), and then mixing at depth to produce mingling at both type of vents (i.e. trachydacite tephra from main central vent and andesitic scoria and lapilli from the Strombolian fissure vents).

5.3 Role of faults re-activation

Faulting is ubiquitous in the CM, and because of the contrasting colours of the unit, these structures are very well exposed and pristine (Fig. 6d and Log 17 at Fig. 5). At least 7 faults have been recorded within the CM across the caldera (Fig. 1); most of them correspond to normal faults with little vertical displacement ($\leq$ 30 cm) and at some localities they present lateral components. A small number appear to be listric faults related to slump of material deposited on steep slopes of the Potreros scarp. Faulting is a common process during any explosive eruption, at most granular pyroclastic deposits these faults are poorly preserved or cryptic due to the lack of contrast within pumice fallout layers or ignimbrites, however, the case of the CM is ideal for documenting syn-eruptive faulting and reactivation of volcano-tectonic structures. From the set of faults documented in this study, some were produced during the eruption, for example those that do not continue towards the upper layers of the member (Fig. 6d), and those that occurred by reactivation of major structures and affect the entire CM, after deposition of the entire sequence. Willcox (2011) provided a detailed morpho-structural map of faulting within Los Humeros caldera revealing a piecemeal configuration with multiple faults that were active in different times and occasionally coeval. Identifying which faults were produced by reactivated structures could be of importance to detect currently active faults and places to prospect for geothermal resources and volcano risk management.

6. Conclusions

A careful documentation of the stratigraphy and volcanology of the CM is presented in this article. The Cuicuiltic member represents an unusual eruptive succession derived from a persistent contemporaneous alternation eruptive activity producing both highly explosive Plinian to sub-Plinian scale eruptions of trachydacite magma derived from a vent area located in the central part of the caldera structure, and less explosive Strombolian-style eruptions derived from at least three different fault-related fissure vents located to the eastern sector of the caldera structure between Los Potreros and Los Humeros scarps. The succession records incomplete mixing at the first stages erupting mostly pure trachyandesitic and basaltic andesite magmas followed by a more efficient mixing at the final eruptive stages. Due to the complexity to unravel the eruptive history of the CM involving the coeval eruption of compositionally contrasting magmas, a combination of extensive field work including detailed log mapping, unit correlation, isopach and isopleths maps, field data including indicators of proximal vent facies (variations in size and abundance of spatter blocks, ballistic bombs, impact structures, etc.) were used to refine and confirm vent areas and provide support to the multivent configuration of the eruptive model proposed here. This work supports the existence of one major trachydacite vent towards the north of Los Humeros village that produced layers C1, C2, C3, C5 and partial input into layers C7, C8 and C9; and at least three fissure vents (Fig. 1) producing basaltic-andesite Strombolian explosive paroxysms in short pauses from the main felsic eruption and simultaneously, recorded by layers C4, C6 and basaltic components of C7 and C8.

The nearly simultaneous eruption or in short succession of magmas of contrasting composition is not a common eruptive behavior, rather reveals the complexity of the magmatic system, which can be associated to the activation of high melt zones within a largely heterogeneous magmatic reservoir as it has been proposed in previous eruptions of Los Humeros caldera. The significance of recognizing the multiple vent nature for the CM eruption translates on a much better understanding of the Los Humeros caldera magmatic behavior over time and the importance of structural control on intra-caldera eruptions. This eruptive event corresponds to the last recorded explosive phase from Los Humeros caldera, in the eastern sector of the Trans Mexican Volcanic Belt, which occurred at least ~6,400 years B.P., and therefore represents an important hazard for the future.

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Tables

Table 1. Bulk rock geochemistry data of the Cuicuiltic Member. Major elements analysed from whole-rock pumice samples using XRF; values reported in wt. %, volatile free and normalised to 100%, showing LOI values. For location of samples see logs in Fig. 5.

Table 2. Summarised non-genetic lithofacies codes and abbreviations for the Cuicuiltic Member (modified from Branney and Kokelaar 2002 and Brown and Branney 2004).

Table 3. Clast componentry of tephra layers within the Cuicuiltic Member.

Figures

Fig. 1. Landsat image of Los Humeros caldera and main structural features. Eruptive vents are depicted with white symbols (dacitic) and red stars (basaltic-andesite). Lithic ballistic blocks (> 64 mm) are shown in white triangles and juvenile scoria/pumice blocks are shown in red triangles. Insets show regional location of Los Humeros caldera within Mexico and the Mexican Volcanic Belt.

Fig. 2. Composite log of the Cuicuiltic Member showing vertical distribution of main layers and beds, descriptions and interpretations are synthetized. For lithofacies codes and abbreviations see Table 2.

Fig. 3. Whole-rock compositional variation within the Cuicuiltic Member juvenile clasts. Pumice clasts from the lowermost layers (C1, C2) and C5 are the most evolved, followed by mixed and mingled compositions including C3, C7, C8 and C9. Less evolved clasts (basaltic andesite) comprise those from layers C4 and C6. TAS plot after Le Bas (1986) with fields modified from Le Maitre (1989).

Fig. 4. a) Type section of the Cuicuiltic Member south of Los Potreros valley showing most layers identified within the deposit. b) Thick exposure at the north of Los Potreros scarp showing variations in specific layers and beds within the Cuicuiltic fall deposit. Inset DEM with location of exposures. Scale bar is 1 m with 10 and 1 cm intervals.

Fig. 5. Selected Cuicuiltic Member stratigraphic logs forming transects D and E. Transect D runs N-NE from the type section towards the northern sector of Los Potreros scarp (see inset map). Transect E is distributed northbound across Los Potreros scarp. Vertical scale in logs is schematic. Lithofacies codes are defined in Table 2 and in the inset key. Correlation lines: thick solid line indicates base or top was recorded; thick dashed line, base or top not exposed; thin dashed lines refer to well correlated layers. For other log transects see Online Resource.

Fig. 6. Photographs of the lower layers of the Cuicuiltic Member: a) Top of C1 overlain by pedogenically altered bed α. b) Layer C2 grading into C3 stratified lapilli with influx of dark grey and banded pumice. c) Detail of layer C3 with white trachydacite pumice, black basaltic-andesite and mingled clasts. d) Normal fault affecting layers C2 to C7 at the west of Los Potreros scarp. Scale ruler is 1 meter with 10 and 1 cm intervals.

Fig. 7. Photographs of the middle to top layers of the Cuicuiltic Member. a) Top of C4, two-fold C5 and C6. b) Scoriaceous layers (C4 & C6), note 1.5 m thick fine-grained scoria tuff bed γ. C8 at the top is also scoriaceous. c) Layer C8 at the north of Los Potreros scarp, grading to a paleosol, note low proportion of andesitic scoriaceous lapilli and bombs at this exposure. d) Mingled pumice clasts in layer C7, scale shows 10 and 1 cm intervals.

Fig. 8. Grain size distribution histograms and frequencies from 18 samples of the Cuicuiltic Member. Right hand side panel shows componentry data across the fall deposits.

Fig. 9. Isopach maps for selected layers of the Cuicuiltic Member (data in cm). a) Layer C1 showing main dispersal axis towards the SE. b) Bilobate shape of the isopach for layer C2. c)

Isopach configuration within layer C4B, showing the vent area NE of the Potreros scarp. d) Trachydacite layer C5 with a partially bilobate shape and sispersal axis to the SE. e) Basaltic andesite scoria vents for layer C6 in the southern caldera rim, and north of Los Potreros. f) Basaltic andesite scoria facies of C8 layer with a dispersal axe to NE.

Fig. 10. Isopleth maps for selected layers within the Cuicuiltic Member, values in cm. a) Pumice isopleth for layer C1; b) Lithic isopleth for layer C1; c) Pumice isopleth for layer C2; d) Lithic isopleth in layer C2; e) Pumice isopleth for layer C5; f) Lithic isopleth for layer C5. Abbreviations: C1 P, stands for layer C1 maximum pumice values; C1 L, stands for layer C1 maximum lithic clasts sizes, respectively.

Fig. 11. Log and pictures of C4-B vent area at Las Chapas quarry. a) Detailed log of the Cuicuiltic exposure there. b) The base of the exposure shows cross-stratified facies (xsT) of C3 scoria tuff layer and coarse spatter material indicating near-vent facies. c) Proximal scoria agglomerate with ballistic bombs deforming underlying beds of the Cuicuiltic Member. Scale bar is 1 m with 10 and 1 cm intervals, field notebook is 20 cm tall.

Fig. 12. Schematic section of Los Humeros caldera with proposed eruptive model: a) An heterogeneous magma chamber beneath Los Humeros caldera with two high-melt zones, one trachydacite (TD) and the other basaltic to basaltic-andesite (B-BA) erupted explosively at ca. 6.4 ka. This generated a Plinian plume that deposited felsic layer C1. After a short repose period, the largest Plinian pulse deposited up to 6 m thick pumice-fall layer C2 (Phase A). This was followed by the emplacement of layer C3 (Phase B) with evidence of magma mingling. b) The next phases record contemporaneous eruptions from the central vent and satellite basaltic fissure vents. Phase C is marked by the eruption of basaltic layer C4 from the southern caldera rim and C4-B towards the north of Potreros scarp. A pause on basaltic eruptions and onset of trachydacite magma produces a third Plinian pulse depositing layer C5

(Phase D). Reactivation of fissure vents with basaltic magmas deposited layer C6 at the south and north of the caldera (Phase E). The major mingling phase is recorded by layer C7 including banded pumice lapilli with on-going pumice fall deposition (Phase F), and eruption of a new basaltic vent producing proximal scoria agglomerates near Maztaloya village, this partially produced heterogeneous layer C8. The last phase (Phase G) is marked by the emplacement of layer C9 from a probably hybridized section of the magma chamber.