Timing of speleogenesis of Las Karmidas Cave (Mexico): first description of pseudokarst developed in ignimbrite

Maria del Pilar Aliaga-Campuzano¹, Rafael López-Martínez², Pablo Dávila-Harris³, Ramón Espinasa-Pereña⁴, Adriana Espino del Castillo⁵, and J. P. Bernal¹*  

¹Laboratorio de Estudios Isotópicos, Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, 76230, Mexico  
²Laboratorio de Carbonatos y Procesos Kársticos, Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria Campus, Coyoacán, C.P. 04510, Mexico City, Mexico  
³División de Geociencias Aplicadas, Instituto Potosino de Investigación Científica y Tecnológica, A.C. 78216, San Luis Potosí, Mexico  
⁴Centro Nacional de Prevención de Desastres (CENAPRED), Mexico City, 04630, Mexico  
⁵Departamento de Procesos y Tecnología, División de Ciencias Naturales e Ingeniería, Universidad Autónoma Metropolitana, Cuajimalpa, Mexico

Abstract: Las Karmidas Cave (Puebla State, Mexico) is an unusual type of pseudokarstic cavity generated by piping and erosive processes within the contact of a diamicton and an overlying Quaternary ignimbrite. Morphological evidence suggests that the cave was developed in two stages: a phreatic stage and a vadose stage. The latter was characterized by the formation of carbonate speleothems. The absolute upper-age limit for the cave (168 ± 7.1/-7.5 ka) was established by U-Th dating of zircons grains extracted from the overlying ignimbrite, whilst a minimum age for the transition from a phreatic to vadose regime (95.6 ± 2.1 ka) was constrained by U-Th dating of carbonate speleothems within the cave. The geochronological results indicate a very rapid evolution of this pseudokarstic system, and suggest that similar systems might evolve and degrade at a very fast pace; consequently, making them hard to be preserved. Despite this, and considering the rather common geological context in which this system was developed, it is likely that similar pseudokarstic systems are yet to be detected worldwide.

Keywords: pseudokarst, cave, speleogenesis, Xaltipan ignimbrite, Las Karmidas Cave

Received 1 December 2016; Revised 5 April 2017; Accepted 6 April 2017

INTRODUCTION

Pseudokarst processes and geoforms have been recently recognized as an important source of landscape modification (Benson & Yuhr, 2016). Despite its ubiquitous occurrence and relevance in geomorphic and geotechnical studies, the formation of pseudokarstic caves where mineral solution is not the driving force modulating cave development, remains to this day poorly understood (Wray, 1997; Doerr & Wray, 2004; Halliday, 2007). Different terminology has been proposed for such non-dissolution caves, based on rock or processes involved (Halliday, 2007; Eberhard & Sharples, 2013). However, some caves fail to fit any of these descriptions as they were formed by more than one process, and within different lithologies.  

A better understanding of pseudokarstic processes can be obtained by applying a multidisciplinary approach that can provide links between stratigraphy, sedimentary facies, and establish geochemical and geochronological constraints on the origin, timing and/or rates of deposition of the different materials. Unfortunately, most pseudokarstic systems display poor conservation of structures, sediments, and passage morphology, and, notably, a systematic lack of authigenic minerals amenable for radiometric dating.

Here, we describe for the first time the Las Karmidas Cave, an extraordinary study site in southern Mexico, characterized by its emplacement at the contact between a diamicton and an ignimbrite, as well as the presence of carbonate speleothems in the cave passages. Because of its well preserved sedimentological structures, we are able to propose an evolution model based on piping and erosion. Moreover, by applying U-Th zircon dating methodologies by LA-MC-ICPMS, we are also able to establish robust geochronological constrains on the evolution and formation of the cave.

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CAVE LOCATION AND GEOLOGICAL SETTING

Las Karmidas Cave (20° 0’ 20" N 97° 42’ 53" W, 700 m.a.s.l.) is located at Zapotitlán de Méndez, Puebla, Mexico (Fig. 1A, B). The oldest formations exposed in the surrounding areas are mainly Jurassic and Cretaceous shale and limestone. These formations include: Huayacocotla (Jhx), Cahuasas (Jcs), Tepexic (Jtx), Santiago (Jsg), Tamán (Jt), Pimienta (Jp), Lower Tamaulipas (Kti), Upper Tamaulipas (Kts), and Agua Nueva (Kan) (López-Ramos, 1979; López-Ramos, 1982) (Fig. 1C, D). These units comprise mainly marine basin and platform sediments, folded and thrust during Sevier and Laramide orogenies, to conform the Mexican fold and thrust belt (Dickinson & Lawton, 2001; Gray et al., 2001). Towards the south of Zapotitlán de Méndez, the abrupt topography developed on the Mesozoic lithology was covered by a succession of Cenozoic volcanic materials (andesite lava), lacustrine sediments and vast Quaternary volcanic units such as basaltic lava flows and felsic tuffs. Volcaniclastic and epiclastic successions are also commonly exposed in valley bottoms (López-Ramos, 1982; Capra et al., 2003). The study area is also near a well-studied volcanic field, the Libres-Oriental basin, which belongs to the eastern part of the Transmexican Volcanic Belt (TMVB) (Lugo-Hubp et al., 2005; Siebe et al., 2006; Alaniz-Álvarez & Nieto-Samaniego, 2007; Norini et al., 2015).

The Libres-Oriental basin volcanic field is limited on the east by the large (21 x 16 km) Los Humeros Caldera (Ferriz, 1984; Campos-Enriquez & Garduño-Monroy, 1987; Carrasco-Núñez & Branney, 2005), which is located 45 km southeast of Zapotitlán de Méndez (Fig. 1A). After rhyolite dome eruptions a paroxysmal event originated the Xaltipan ignimbrite (Ferriz, 1984), which produced an enormous collapse caldera and more than 115 km³ of pyroclastic flows emplaced radially around the volcano. These partially filled surrounding ravines for tens of kilometers around the caldera, including the already deep valleys of both the Apulco and Zempoala rivers (Ferriz, 1984; Ferriz, 1985; Ferriz & Mahood, 1987; Carrasco-Núñez et al., 2012; Norini et al., 2015). This ignimbrite-forming eruption generated a valley fill which has been progressively incised by river erosion, leaving low and hanging terraces at both valley sides, very prone to landsliding (López-Ramos, 1982; Yañez-García & García-Durán, 1982; Ferriz & Mahood, 1985; Ferriz & Mahood, 1987; Carrasco-Núñez et al., 2012; Norini et al., 2015).
1987; Capra et al., 2003; Lugo-Hubp et al., 2005). The Los Humeros Caldera continued erupting explosively until the Holocene (Dávila-Harris & Carrasco-Nuñez, 2013), although no eruption has been as catastrophic as the one which produced the Xaltipan ignimbrite (Norini et al., 2015).

METHODS

Cave mapping and facies analysis
Underground mapping inside the cave was carried out using compass, clinometers, and tape measure for a UISv1-4-3-A as suggested by Häuselmann (2011). Characteristic features including ponds, waterfalls, rockslides, springs, main galleries, speleothems, and the man-made entrance are indicated in Fig. 2 (map & section). A schematic cross section was also produced with 2x vertical exaggeration, indicating location of main features within the cave, to which we will refer throughout this work. Sample points and other characteristics are also featured in the map and cross section of the cave. Sedimentary facies were classified into diamicton, thalweg, backswamp, channel, and slackwater facies according to the classification of Bosch & White (2004).

Geochemistry and geochronology
Pumice samples (Supplemental Table 1) collected at a quarry (20°00′20.95″ N 97°43′28.68″ W) near the town of Zapotitlán de Méndez, hereafter Zapotitlán Quarry, were analyzed for major elements. Analysis was performed using a WD-XRF on Li-borate/metaborate fused disk following the methodologies of Lozano & Bernal (2005), and trace elements, rare earth elements (REE), using ICP-QMS following Eggins et al. (1997), using BHVO-1, RGM-1, GSR-2 and SDO-1 as calibration standards and the compositions reported by Govindaraju (1994). Both analyses were conducted at the Instituto de Geología, UNAM. Precision and accuracy were assessed by multiple analysis of in-house reference sample IGLa-1 (Lozano & Bernal, 2005). In general, accuracy is better than 95% for major elements, and 90% for trace elements.

To establish geochronological constrains on the deposition of the ignimbrite, thus the emplacement rock hosting the cave, zircons were extracted from samples collected at the Zapotitlán Quarry using standard heavy-mineral extraction techniques, and dated using U-Th systematics (Schmitt, 2011). Additionally, to verify the age and origin of the ignimbrite, zircons from a sample collected at Las Minas, Puebla (19°41′32″ N 97°8′57″ W), which is generally recognized to be part of the Xaltipan ignimbrite (Ferriz & Mahood, 1984), were also analyzed. U-Th dating of zircons (Supplemental Table 2) was carried out using a Neptune-plus MC-ICP-MS coupled to a Resonetics L-50 laser-ablation workstation (Müller et al., 2009; Solari et al., 2010) following the methodology of Bernal et al. (2014). Precision and accuracy was continuously assessed by analyzing two zircon samples known to be at secular equilibrium: standard zircon 91500 with a U/Pb age = 1,065 ± 0.6 Ma (Wiedenbeck et al., 2004), and our laboratory internal standard, Panchita zircon, with an U/Pb age = 959 ± 1.4 Ma, which are expected to be in

Fig. 2. Top: Map of Las Karmidas Cave. Bottom: Schematic cross section with 2x vertical exaggeration. Characteristic features such as ponds (blue), waterfalls (blue arrows), rockslides (grey semicircular shapes), man-made entrances, springs (dot with blue arrow), main galleries, and speleothems (yellow triangle-like shapes) are indicated. The sectors described in the cave morphology section are also shown here.
secular equilibrium, i.e., \((230\text{Th}/238\text{U}) = 1.00\); note that all ratios between brackets represent activity ratios. Results from more than 400 independent analyses for each zircon obtained, during 20 different analytical sessions, attest to the long-term high-reproducibility and precision of the methodology used here, with \((230\text{Th}/238\text{U}) = 1.0006 \pm 0.0031\) (2xSE, n = 370, MSWD = 1.105) for 91500 zircon, and \((230\text{Th}/238\text{U}) = 1.005 \pm 0.0022\) (2xSE, n = 340, MSWD = 2.05) for Panchita zircon. The \(238\text{U}/232\text{Th}\) and \(230\text{Th}/232\text{Th}\) composition of the magma was estimated from the U and Th concentrations obtained from the whole-rock ICP-MS analysis, assuming secular equilibrium (i.e., \(230\text{Th}/238\text{U} = 1.00 \pm 0.05\)) (Schmitt, 2011).

Carbonate samples from the cave (Supplemental Table 2 in electronic supplement) were dated by isotope-dilution MC-ICPMS, using a Thermo Finnigan Neptune Plus at Centro de Geociencias, UNAM, following methodologies described elsewhere (McCulloch & Mortimer, 2008; Hernández-Mendiola et al., 2011). For zircon and carbonate dating, U-Th activity ratios and ages were calculated using the half-lives from Jaffey et al. (1971) Audi et al. (1997); activity ratios and ages were calculated using the isotope-dilution MC-ICPMS, using a Thermo.

RESULTS AND DISCUSSION

Cave Stratigraphy

The general stratigraphy of the cave (Fig. 3) begins with (a) a Quaternary diamicton (fines-rich talus breccia) that unconformably rests upon unexposed Mesozoic carbonate rocks (Fig. 1D), followed by (b) a Quaternary rhyolitic ignimbrite, in both welded and non-welded facies (Fig. 4A); (c) an heterolithic breccia that post-dates the ignimbrite, and (d) Holocene unconsolidated sand, silt and clays. Detailed stratigraphic logs through the internal units were used to describe the local stratigraphic relationships.

Diamicton: It is a brown, massive and matrix-supported unconsolidated to poorly consolidated deposit formed by sub-angular blocks of limestone, shale and scarce volcanics, supported in a clayey to silty matrix (Fig. 4B). It is at least 5 m thick, massive and non-stratified. The upper contact of the diamicton is sharp and in places shows a slight pink color change that resembles a 'baked' contact by the overlying volcanic unit (Fig. 3). It is interpreted as formed by talus, slope or local cohesive debris-flow events, due to the abrupt local topography.

Quaternary rhyolitic ignimbrite: Lies directly and unconformably above the diamicton (Fig. 4C), as a pale-cream to grey, non-welded tuff to lapilli-tuff. The contact can be clearly observed at the man-made entrance to the cave. The tuff preserves a minimum thickness of 3 to 50 m near and within the cave, but with thicker exposures (near 200 m) at the outskirts of Zapotitlán de Méndez. The base of the tuff is finely laminated to cross-laminated, with thin lithic trails and sporadic larger lithic clasts protruding. It grades upwards into a massive pumice and lithic poor lapilli-tuff. The material that forms the tuff matrix is mainly rhyolitic glass shards needles and ash (Fig. 4D); lithic clasts and phenocrysts are scarce but include quartz, biotite, feldspar and plagioclase. The juvenile component is represented by altered, rounded and slightly fibrous rhyolitic pumice lapilli, relatively crystal-poor. Lithics include limestone, shale, andesite, basalt and rhyolite. The tuff contains lateral and vertical facies changes (Fig. 5), the most contrasting one is exposed at the narrow-flooded entrance, where the welded facies can be observed, resembling a vitric tuff with spherulites and lithophysae (devitrification) structures and fiamme-like pumices. Under the microscope, eutaxitic texture is clearly defined within this lithofacies. Per these features, this unit, which postdates the diamicton, is defined as a variously welded, rhyolitic pyroclastic flow deposit (ignimbrite), that would have infilled the Zempoala River valley at the time of its emplacement; from which only eroded terraces are preserved today. The geomorphology of the region is in an active stage and the remains of the ignimbrite are prone to landslides due to the unconsolidated nature of the material (Capra et al., 2003; Lugo-Hubp et al., 2005; Hernández, 2008).

Breckia: This unit is exposed at the cave ceiling and is placed unconformably above the ignimbrite (Fig. 4E). It is a heterogeneous deposit formed by large, angular clasts in a lithic-rich matrix. The breccia presents an erosive lower contact, either formed by scours and channels or just sharp fractured contacts. Its lithology comprises limestone and shale blocks and large clasts from the underlying welded and non-welded tuff. It is mainly massive and ungraded, although showing levels of finer grained sediments. This unit is interpreted as a locally-derived collapse breccia of the upper parts of the cave, and suggests that parts of the cave ceiling might have collapsed at least once, during the cave's evolution.

Detrital cave facies: The youngest deposits inside the cave comprise a succession of fine-grained, brown silts and sands that range from 0.5 to 4 m thick (Fig. 4F). This unit rests unconformably on top of the cave walls, unconformably over the diamicton, the ignimbrite and locally on top of the breccia (Fig. 3). They comprise thalweg, channel, slack water, and backswamp facies. Although this unit has not been directly dated, it is considered a continuous deposit which could be Holocene in age.

Thalweg (TW): Formed by well-winnowed material, mainly boulders and some cobble; the majority of the fragments are ignimbrite and, in less quantity, limestone. This facies sensu Bosch & White (2004) is the result of the winnowing of the fine material of the diamicton and collapses, remaining only the coarse sediments.

Channel facies (CH): Are mainly composed of limestone and ignimbrite fragments embedded within a sand to gravel matrix. Imbrication and cross bedding in a chaotic fabric are the most common sedimentary structures.

Slack-water facies (SLW): Fine grained clays and silts with parallel lamination. These facies appear almost horizontally in the upper part of the sequence.
Fig. 3. Schematic section and stratigraphic logs of Las Karmidas Cave, showing the internal lithological variations at the contact between the diamicton (facies mCg) and the overlying rhyolitic ignimbrite, including the following lithofacies: massive tuff (mT), massive lapilli-tuff (mLT), diffuse-stratified lapilli tuff (dsLT), cross-stratified lapilli tuff (xsLT). Location of logged sections (K2 to K5) indicated in cave sketch; K6 and K7 out of diagram. Sketch is not to scale and it represents sectors 3 and part of section 4. Vertical scale in logs is schematic and horizontal scale depicts grain sizes.
Backswamp facies (BSW): Composed of clays, with no clear stratification or any other sedimentary structures.

**Cave geomorphology by sectors**

*Sector 1: waterfall and spring*

Sector 1 in Fig. 2 consists of a narrow and very low passage (Fig. 5A), which becomes wider at the base of a small waterfall of ~12 m (Fig. 5B). Beyond the waterfall, the passage becomes smaller again until joining the artificial entrance (Fig. 5C). The sediments here are a succession of thalweg, channel and slackwater deposits, covered and cemented by flowstones (Fig. 5D).

At least one level of horizontal thalweg-channel facies points to a paleoflood that completely filled the conduit (Fig. 5E). Later, these deposits were eroded and a new lower conduit was formed. All sediments are cemented by relatively more recent flowstones (Fig. 5A, B).
**Sector 2**

Sector 2 in Fig. 2 is a curved passage carved within the rhyolitic tuff. All along this sector there is a continuous flow of water, which is sensitive to rain variability outside the cave. Here, water flux often blocks the passage during the peak of the rainy season (August-September), particularly when hurricanes reach the area.

**Sector 3**

Sector 3 in Fig. 2 is characterized by a rectilinear steep tunnel with a N 0-10° E direction. In cross section, the passage shows keyhole morphology (Fig. 6A), indicating a two-stage formation: phreatic, evidenced by an elliptical cross section elongated in the direction of the diamicton/ignimbrite contact, which was followed by a vadose erosive stage incising the diamicton. Additionally, this sector presents some tributary phreatic conduits with circular cross section and orientated in the direction S 50° E (Fig. 6B). Channel, thalweg and slack water facies deposits are present in this sector (Fig. 6C, D), covered by flowstone, suggesting abundant sediment supply, followed by an abrupt change in deposition conditions that allowed the precipitation of calcite with significantly less clastic sediment contribution (Fig. 6E, F).

**Sector 4**

This sector is the widest part of the cave, ~30 m, produced by the junction of three different streams (Fig. 2). This chamber formed mostly by erosion of the diamicton, as evidenced by the nearly flat roof at the inception horizon (the contact between the ignimbrite and the underlying diamicton) (Fig. 7A), and by the formation of incisive channels at the passage junctions (Fig. 7B). This sector can be divided into three different subsectors based on their current hydrological function; we also identify two distinct levels in the cave A (upper level) and B (lower, presently active level).

- **Laguna Encantada** (level A₄): This is a small pond formed in the contact between the ignimbrite and the diamicton (Fig. 7C), and is highly decorated with different speleothems. The passage is approximately 8 m above the lower level, and is a relict from the first stage of the formation of the cave -in which the diamicton was not yet eroded, as it coincides with the inception level of the main cave (contact between diamicton and ignimbrite).

- **Salón de los Recuerdos** (level A₃): This passage presents a similar morphology to that of the level A; here it is possible to observe the initial stage of the development of the cave, consistent with the inception horizon and posterior incision of the river eroding the diamicton (Fig. 7D).

- **Tunel del Silencio** (level A₃): This section is currently non-active and its entrance is nearly blocked by flowstone. The passage has a phreatic morphology, elongated in the direction of the inception horizon. An incipient conduit, epiphreatic, is shown in the ceiling (Fig. 7E). The sediments in the roof only include backswamp facies.

**Level B**: Corresponds to the actual stream in the bottom of the cave, with incisive morphology eroding the diamicton (Fig. 7B). In the main room, the inception horizon is clear, and the incision of the river created a passage with keyhole morphology. Facies are similar to those described in sectors 1 and 2.
Geochemical characterization of the tuff

The elemental composition of the ignimbrite at the Zapotitlán Quarry, together with previously reported data for the Xaltipan ignimbrite from Los Humeros Caldera (Ferriz & Mahood, 1987; Willcox, 2012) and the Acoculco rhyolite (Verma, 2001) are shown in Fig. 8. The major element composition of the Zapotitlán Quarry tuffs shows that these are highly acidic, rhyolitic, with SiO₂ contents ranging between 70 and 78% (Fig. 8A and Supplemental Table 3), and have similar compositions to those previously reported for the Xaltipan ignimbrite from Los Humeros Caldera and the Acoculco rhyolite. The REE composition for the ignimbrites (Fig. 8B) are all characterized by a significant enrichment of LREE over HREE (Supplemental Table 4), with La/Lu = 8.2 ± 1.16 (Ferriz & Mahood, 1987; Verma, 2001; Willcox, 2012). However, the rhyolitic deposits from the Xaltipan ignimbrite show the most pronounced negative Eu anomaly (Eu*), 0.19 ± 0.16, with other deposits from Los Humeros showing only slight Eu depletions. Fig. 8B shows the chondrite-normalized (McDonough & Sun, 1995) REE diagrams for the Zapotitlán Quarry and Los Humeros and Acoculco calderas rhyolites; and shows that both the Zapotitlán and Xaltipan ignimbrites have identical REE composition, with La/Lu = 8.7 ± 1 and Eu* = 0.16 ± 0.02, while the Acoculco Caldera has a notorious lower REE composition.

Tuff and calcite geochronology

The ²³⁰Th/²³²Th and ²³⁸U/²³²Th composition of the zircons extracted from the Zapotitlán Quarry ignimbrite is shown in Fig. 9A (Supplemental Table 5). In general, the zircons form two isotopically distinct groups: one in secular equilibrium plotting over the isoleine (i.e., age > 350 ka), and a second group forming an isochron that yields an age of 168 ± 7.7 / - 7.5 ka. (n = 8, MSWD = 0.95, probability 0.47), and in perfect agreement with the U-Th composition of the magma. In Fig. 9A we also compare the U-Th composition of the zircons from the Zapotitlán ignimbrite with that from zircon grains extracted from a sample collected at Las Minas, Puebla (19°41′32″N 97°8′57″W), which is generally recognized to be part of the Xaltipan ignimbrite (Ferriz & Mahood, 1984). Both samples have identical compositions, providing strong evidence that the ignimbrite hosting the cave corresponds to the Xaltipan ignimbrite, emplaced ~168 ka ago as
a result from pyroclastic flows associated with the collapse of Los Humeros Caldera. This result is in stark contrast to the previously K-Ar age of 400 ka reported by Ferriz (1984), but in excellent agreement with more recent \(^{40}\text{Ar}/^{39}\text{Ar}\) dating by Willcox (2012) who obtained an age of 170 ± 50 ka for basal fall of the Xaltipan tuff. The difference between the new results and the previously accepted age can stem from the presence of unrecognized inherited radiogenic \(^{40}\text{Ar}\) in certain zones of the ignimbrite, a problem commonly found in volcanic tuffs with prolonged magma residence times (Bachmann et al., 2007; Phillips & Matchan, 2013). These results provide quantitative evidence supporting previous interpretations by several authors that linked the origin of the ignimbrite at Zapatitlán to Los Humeros Caldera on the basis of volcanic stratigraphy (Capra et al., 2003; Lugo-Hubp et al., 2005; Hernández-Madrígual et al., 2007).

**Carbonate geochronology**

To obtain a minimum age for speleogenesis, we sampled and dated several flowstones found embedded between unconsolidated tuff or sediments. Because their occurrence generally implies the presence of voids where calcite-saturated water can degas CO\(_2\), leading to the precipitation of calcite, these are interpreted to represent the early stages for the system migrating from phreatic aquifer to the current vadose stage as a result from a drop in the local base level.

Unfortunately, most flowstone samples collected contained significant amounts of detrital material, with very low \(^{238}\text{U}/^{232}\text{Th}\) ratios, hence hampering U-Th dating (Ludwig & Paces, 2002), and only few samples proved amenable for dating with reasonably high \(^{238}\text{U}/^{232}\text{Th}\) ratios, thus resulting in precise and meaningful ages (Table 1). The oldest flowstone sample (Fig. 9B), collected at the entrance of Sector 4, is sample KAR-fs-core which yields an \(^{230}\text{Th}\)-age of 95.6 ± 2.1 ka. We interpret this result to represent a minimum age for the appearance of voids in the host rock where calcite can precipitate from the percolating solution and, thus, the minimum age for the phreatic-vadose transition *sensu-stricto*. Other
well preserved conduit morphologies; good
goecronomological constraints; and well preserved
clastic facies that provide information about
paleohydrogeological evolution.

A simplified speleogenetical diagram of Las
Karmidas Cave shows the main steps of cave
formation (Fig. 10): firstly, deposition of the
diamicton upon the hill slopes of the valley
carved by the Zempoala River (Fig. 10A). During
the caldera collapse event previously described
(Ferriz & Mahood, 1984), the valley was filled
by pyroclastic flows that deposited the Xaltipan
ignimbrite 168 ± 7.7 / - 7.5 ka ago (Fig. 10B).
The contrasting hydraulic conductivity between
the recently deposited ignimbrite and the clay-based
diamicton allowed for the transmission of meteoric
water through the ignimbrite into the vadose zone,
leading to the formation of a perched aquifer that
flowed through the contact between the diamicton
and the ignimbrite towards the discharge area
and, consequently, forming the first phreatic
conduits (Fig. 10C).

While the Zempoala River started to incise
the new riverbed, the perched aquifer started to
drain to the discharged area through the Tunel
del Silencio (A3). During this stage, cave evolution
seems to have been mostly driven by piping,
as suggested by the absence of channel and
associated facies in this part of the cave (Fig. 10D).
Lowering of the Zempoala River, and the increase
of the hydraulic gradient, lead to the start of the
incisive stage with the erosion of the diamicton,
evidenced by channel and thalweg facies in

**Speleogenesis of Las Karmidas Cave**

Las Karmidas Cave displays a series of features that
allow a well-supported speleogenetical reconstruction:
sector B. This rapid erosion and entrenchment separated sectors A1, A2, and A3 from B, and led to the development of a main channel, as well as the abandonment of the higher levels (level A). At this stage, the hydrologic dynamics of the cave were substantially altered to a more direct and rectilinear discharge channel. Precipitation of carbonate speleothems started as soon as cave passages were partially drained.

**CONCLUDING REMARKS**

This study is the first report of a pseudokarstic cave developed between ignimbrite and a diamicton, with calcite speleothems decoration. Its peculiarity allowed us to apply several geomorphological, sedimentological, geochemical and geochronological methodologies to establish a robust evolution model.

U-Th dating of zircon grains from the Xaltipan ignimbrite, in which Las Karmidas Cave is emplaced, constrain the maximum age of the speleogenetical process at 168 ± 7.7 / -7.5 ka, and is in perfect agreement with more recent ⁴⁰Ar/³⁹Ar dating. The inception horizon, located at the contact between the ignimbrite and the previously deposited diamicton, favored the formation of the earliest phreatic conduits forming the upper level. During this stage, piping initiated the enlargement of conduits, as suggested by the absence of high-energy facies deposits in this level. The lowering of the Zempoala riverbed changed the conditions from phreatic to vadose, with an important entrenchment of one preferable channel. At least in some parts of the cave, this initiated subaerial conditions and the precipitation of the oldest carbonates (95.6 ± 2.1 ka).

Considering the rather common geological context upon which Las Karmidas Cave evolved, it is likely that similar systems can be found elsewhere; however, due to very fast rate of evolution, long-term preservation in the stratigraphic record seems unlikely.

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**Table 1. Carbonates detrital-corrected U-series ages and compositions.**

<table>
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<td>±</td>
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**Fig. 10. Proposed Speleogenetic model for Las Karmidas Cave.**
A) The diamicton covered part of the valley carved by the Zempoala River within the Pimienta Formation; B) The valley was filled by the Xaltipan ignimbrite; C) The cave began to form within the contact of the diamicton and the ignimbrite while the Zempoala River eroded the valley again; D) The aquifer drained throughout the Tunel del Silencio (A3); E) As the Zempoala River eroded the valley, level B formed disconnecting level A.
ACKNOWLEDGEMENTS

The authors would like to thank the Editor Bogdan P. Onac, Paolo Forti, and two anonymous reviewers that kindly suggested improvements in the original text, their comments, suggestions, and constructive criticism lead to an improved manuscript. We also thank the people from Zapotitlán de Méndez (Puebla) for all their support and kindness. Special thanks to Herminio Rojas and his family, for facilitating access to the cave and helping us in any possible way; the Nieto Family, for their support and warm meals and shelter at the end of the day in the cave, and Mr. Ernesto Manzano for granting access to the cave. We thank Elena Louniejeva, Rufino Lozano Santa-Cruz, and Carolina Muñoz Torres for analytical support, Bernardino Rodriguez (CGEO) for infrastructure support and maintenance, and Vicente Loreto, Miguel A. Hernández Patricio and Marisol Vega Orijuela for fieldwork support. This research was funded by projects CONACyT (grant #78828); PAPIIT/UNAM IN112008 and IN105713 (JPB) and National Geographic Society W418-15 (RLM), MPA-C was supported by a CONACyT scholarship #61009. The authors would like to thank Dr. Gerardo Carrasco Núñez for kindly providing the Xaltipan ignimbrite sample from Las Minas, Veracruz.

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