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Influence of Nevado de Toluca's volcanic activity on the karst development of the Cacahuamilpa area, Guerrero, Mexico

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ABSTRACT

Cacahuamilpa Cave, along with several adjacent inactive systems and two lower active river caves, originated in response to Pleistocene volcanic processes associated with Nevado de Toluca, located approximately 50 km to the north. A catastrophic sector collapse of the volcanic edifice generated a large debris avalanche that evolved into the Pilcaya debris flow, which was channeled southward along the paleovalleys of the Chontacoatlán and San Jerónimo rivers. Prior to this event, these rivers converged to form the ancestral Amacuzac river, which incised the Cacahuamilpa limestone range via the Michapa canyon, establishing the regional base level for karst development.

Subsequent remobilization of the volcanic deposits produced the Mogote debris flows, which overtopped the canyon and infilled the upper reaches of the Amacuzac valley, creating the Michapa plain and advancing approximately 20 km further downstream. The resultant depositional surface, convex in a direction transverse to the regional drainage, forced the two rivers to diverge toward the deposit's periphery. The eastern drainage evolved into the San Jerónimo River, which continued to breach the limestone through the original canyon before skirting the western margin of the Mogote deposits across the Michapa plain. Conversely, the western drainage became the Chontacoatlán River, which carved a new course through the limestone massif via a preexisting low saddle.

The increased hydraulic gradient across the limestone range promoted significant river infiltration into the karst aquifer. The combination of substantial discharge and a dense fracture network within the limestone facilitated the formation of extensive vadose and water-table–controlled conduits. A later rejuvenation of the Amacuzac river's gradient resulted in the abandonment of the upper-level caves and the development of younger, currently active river caves at lower elevations. Continued volcanic activity at Nevado de Toluca triggered additional laharic episodes, the deposits of which were emplaced within these younger caves, where they remain preserved as inset terrace remnants. Similar volcanic-derived sediments have also been documented within Cacahuamilpa Cave.

Keywords: Karst geomorphology; Volcanic debris flows; Speleogenesis; Nevado de Toluca; Pleistocene volcanism; Mexico

RESUMEN

La gruta de Cacahuamilpa, varias cuevas inactivas cercanas y dos cuevas fluviales activas a menor altitud deben su origen a la actividad volcánica pleistocénica del Nevado de Toluca, situado aproximadamente 50 km al norte. Un colapso sectorial catastrófico del edificio volcánico desencadenó una gran avalancha que evolucionó hacia el flujo de escombros Pilcaya, desplazándose hacia el sur a lo largo de los paleovalles de los ríos Chontacoatlán y San Jerónimo. Antes de este evento, dichos

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ríos convergían para formar el río Amacuzac, el cual cruzaba la sierra calcárea de Cacahuamilpa a través del cañón de Michapa, estableciendo así el nivel de base regional.

La removilización subsecuente de los depósitos volcánicos generó los flujos de escombros Mogote, que atravesaron el cañón y rellenaron los tramos superiores del valle del Amacuzac, formando la llanura de Michapa y extendiéndose unos 20 km adicionales aguas abajo. La superficie de depósito resultante, convexa en dirección perpendicular al drenaje principal, desvió a ambos ríos hacia los márgenes del depósito. El drenaje oriental se convirtió en el río San Jerónimo, el cual continuó cruzando la sierra calcárea por el cañón original antes de bordear el margen occidental del depósito Mogote sobre la llanura de Michapa. El drenaje occidental, a su vez, dio origen al río Chontacoatlán, que excavó una nueva ruta a través de la sierra calcárea aprovechando un collado preexistente.

El aumento resultante en el gradiente hidráulico a través del macizo calcáreo favoreció la infiltración del agua de los ríos en el sistema kárstico. La combinación de caudales abundantes y una alta densidad de fracturas en la caliza facilitó el desarrollo de extensos sistemas de cuevas en condiciones freático-vadosas. Un descenso posterior del nivel de base del río Amacuzac condujo al abandono de las cuevas del nivel superior y a la formación de las cuevas fluviales activas actuales. La actividad continua del Nevado de Toluca ha generado lahares más recientes que se han depositado dentro de estas cuevas fluviales, dejando restos de terrazas en sus interiores. Depósitos laháricos similares también se han identificado en la cueva de Cacahuamilpa.

Palabras clave: Geomorfología kárstica; flujos de escombros volcánicos; espeleogénesis; Nevado de Toluca; volcanismo del Pleistoceno; México

INTRODUCTION AND PREVIOUS STUDIES

Gruta de Cacahuamilpa is arguably the most renowned show cave in Mexico and has been protected as a National Park since 1936 (Gómez-Aguado de Alba & Palacio Prieto, 2016a, 2016b). Situated in the northern portion of Guerrero State, near the borders with Morelos and the State of Mexico (Figure 1), the cave comprises a single, monumental passage ranging from 20 to 110 m in width and 20 to 70 m in height. The tunnel is profusely adorned with large stalagmites, flowstone accumulations, and other speleothems, which partition the conduit into a succession of expansive chambers. The explored section of the cave extends for nearly 2 km before terminating at a major collapse and speleothem obstruction.

Additional caves are present within the same limestone range, including Carlos Pacheco, Agua Brava, Pedro Asensio, Pilares, and the subterranean sections of the San Jerónimo and Chontacoatlán rivers. The latter two river caves each exceed 5 km in length (Figure 2c) and traverse the range approximately 80 to 100 m below the principal passage of Gruta de Cacahuamilpa.

A further karst system, Gruta de la Estrella, emerges within a nearby hill in the Ixtapan Valley (Figures 2a and 2b). This cave exhibits a tiered morphology with an inactive upper level and an active lower conduit. Owing to its well-preserved stratigraphic and morphological features, Gruta de la Estrella has been used by prior researchers as a genetic model for the larger cave systems in the region and was therefore included in this study.

As one of Mexico's most well-known caves, Gruta de Cacahuamilpa has generated an extensive body of literature, much of which consists of travelogues and descriptive accounts of visits to the show cave (see Gómez-Aguado de Alba & Palacio Prieto, 2016a, 2016b, and references therein). In contrast, rigorous geological and speleogenetic analyses remain comparatively limited. Since the earliest reports, numerous authors have recognized the presence of volcanic agglomerate plains flanking the limestone range to the east and west. Others have noted the occurrence of rounded volcanic boulders within the main passage of the cave—an early indication that it may once have been traversed by a major river (*e.g.*, Bárcena, 1874; Bolívar Pieltain, 1940; Müllerried, 1944; Bonet, 1971). These interpretations generally support the hypothesis that Gruta de Cacahuamilpa represents an abandoned, inactive segment of the ancestral San Jerónimo River's underground course.

A markedly different view was advanced by Bretz (1955), who argued that Gruta de Cacahuamilpa, along with Carlos Pacheco and the upper levels of Gruta de la Estrella, originated as phreatic conduits that predate both the incision of the limestone massif and the emplacement of the volcanic agglomerates. Bretz asserted that these caves bear no geomorphic evidence of former fluvial occupation and instead reflect bathyphreatic conditions associated with a deep, confined aquifer. In his interpretation, only the lower-level caves—such as Chontacoatlán, San Jerónimo, and the active lower level of Estrella—were later modified by epigenetic capture of post-volcanic surface streams, developing predominantly through vadose processes while locally reoccupying pre-existing phreatic voids.

Enjalbert (1964) offered an alternative hypothesis, suggesting that Gruta de Cacahuamilpa was formed prior to the deposition of the volcanic agglomerates. According to his model, a single river—resulting from the confluence of the San Jerónimo and Chontacoatlán rivers within the Ixtapan Valley—originally flowed through the cave. The emplacement of the volcanic agglomerates subsequently blocked and infilled the passage, preserving only its terminal section. In this view, the current subterranean courses of both rivers developed only after the agglomerate deposits were established.

In contrast, Bretz's (1955) visit to Cacahuamilpa—accompanied by the Spanish émigré geologist and speleologist Federico Bonet—led to significantly different conclusions. Over the ensuing 15 years, Bonet conducted intermittent fieldwork aimed at demonstrating the vadose origin of the cave systems. His findings, published in the Boletín del Instituto de Geología (Bonet, 1971), were informed by detailed surveys of regional caves carried out by members of the Grupo Espeleológico Mexicano (GEM). Bonet ultimately argued for a fully vadose origin, asserting that all caves postdate the valley-filling volcanic deposits, and that the inactive and active cave levels represent successive stages of base-level adjustment.

Subsequent cartographic work by Coons (1976) resulted in the first detailed maps of the subterranean river systems. Since that publication, no major studies have directly addressed the origin of these caves or the broader karst evolution of the area. However,

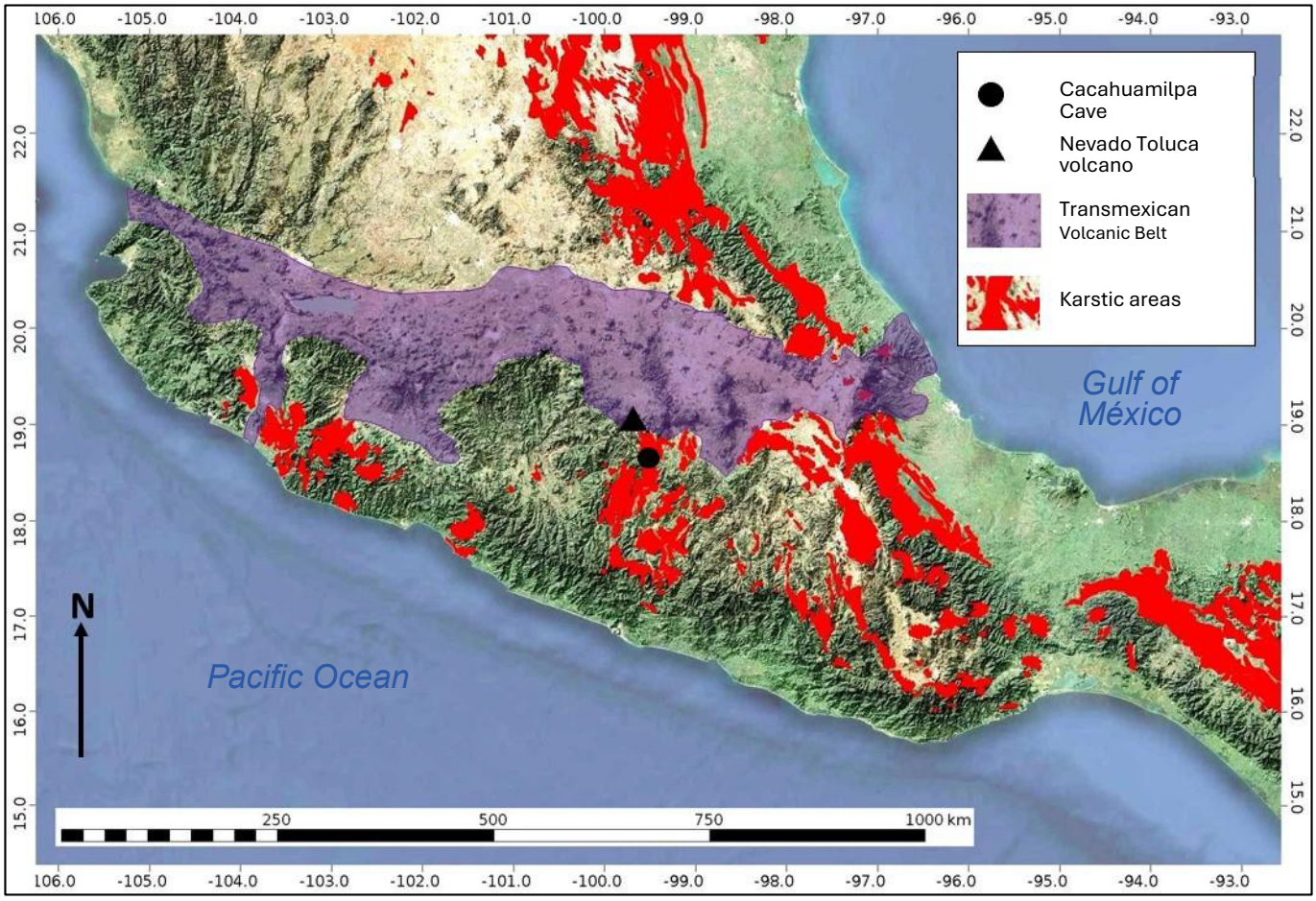


Figure 1. Location map, showing the distribution of the limestone ranges along the Sierra Madre Oriental and Sierra Madre del Sur in Central México, covered by the younger Transmexican Volcanic Belt rocks, and the location of both Cacahuamilpa cave and Nevado de Toluca volcano.

paleoseismological investigations by Garduño-Monroy *et al.* (2011) and Mejean *et al.* (2015) examined seismically disturbed stalagmites within Gruta de Cacahuamilpa, providing insights into the region's neotectonic activity.

This study examines the role of the Pilcaya–Mogote debris flows in reorganizing regional drainage and initiating karst development in the Cacahuamilpa limestone range. It further analyzes the volcaniclastic deposits preserved within active and inactive cave levels to determine their origin, depositional processes, and significance for reconstructing the timing and evolution of speleogenesis in the region.

METHODOLOGY

Surface and subsurface geological and geomorphological investigations were conducted intermittently beginning in 1989. Existing geological maps of the area (Fries, 1960, De Cserna and Fries 1981, Bonet, 1971) were modified through the interpretation of aerial photographs at an approximate scale of 1:50000, acquired in 1990 from Compañía Mexicana de Aerofoto. These were later supplemented and refined using high-resolution imagery from Google Earth and CalTopo.

With the exception of the San Jerónimo and Chontacoatlán river caves, all caves discussed in this study were surveyed or resurveyed by the author and members of the Sociedad Mexicana de Exploraciones Subterráneas (SMES) between 1989 and 2022. Surveys were performed using traditional nylon survey tape and, in later years, a laser rangefinder for distance measurements, alongside Suunto clinometer and compass for inclination and azimuth readings. At each survey station, measurements were collected for station-to-station distance, inclination, and azimuth, as well as transverse dimensions (wall, ceiling, and floor distances) perpendicular to the traverse line. Survey stations were securely marked on cave walls, ceilings, or floors to minimize spatial uncertainty.

This method established a precise polygonal traverse along the principal cave passages. Using COMPASS and CaveXO software, three-dimensional cave models were constructed and georeferenced to the regional topography, enabling spatial comparison with surface geomorphic features. Concurrently, structural characteristics and other geological features within the caves were documented and analyzed.

In February 2010, small stratigraphic trenches were excavated on the floors of both Cacahuamilpa and Carlos Pacheco caves to document their sedimentary sequences. Rounded pumice grains recovered from sand deposits in the Carlos Pacheco trench were collected and submitted for geochemical analysis to the Laboratory of Ultrapure Chemistry (LABQUP) and Mass Spectrometry (ICP-MS) at the Institute of Geology, National Autonomous University of Mexico (UNAM). Analyses were conducted using an Agilent 7500ce

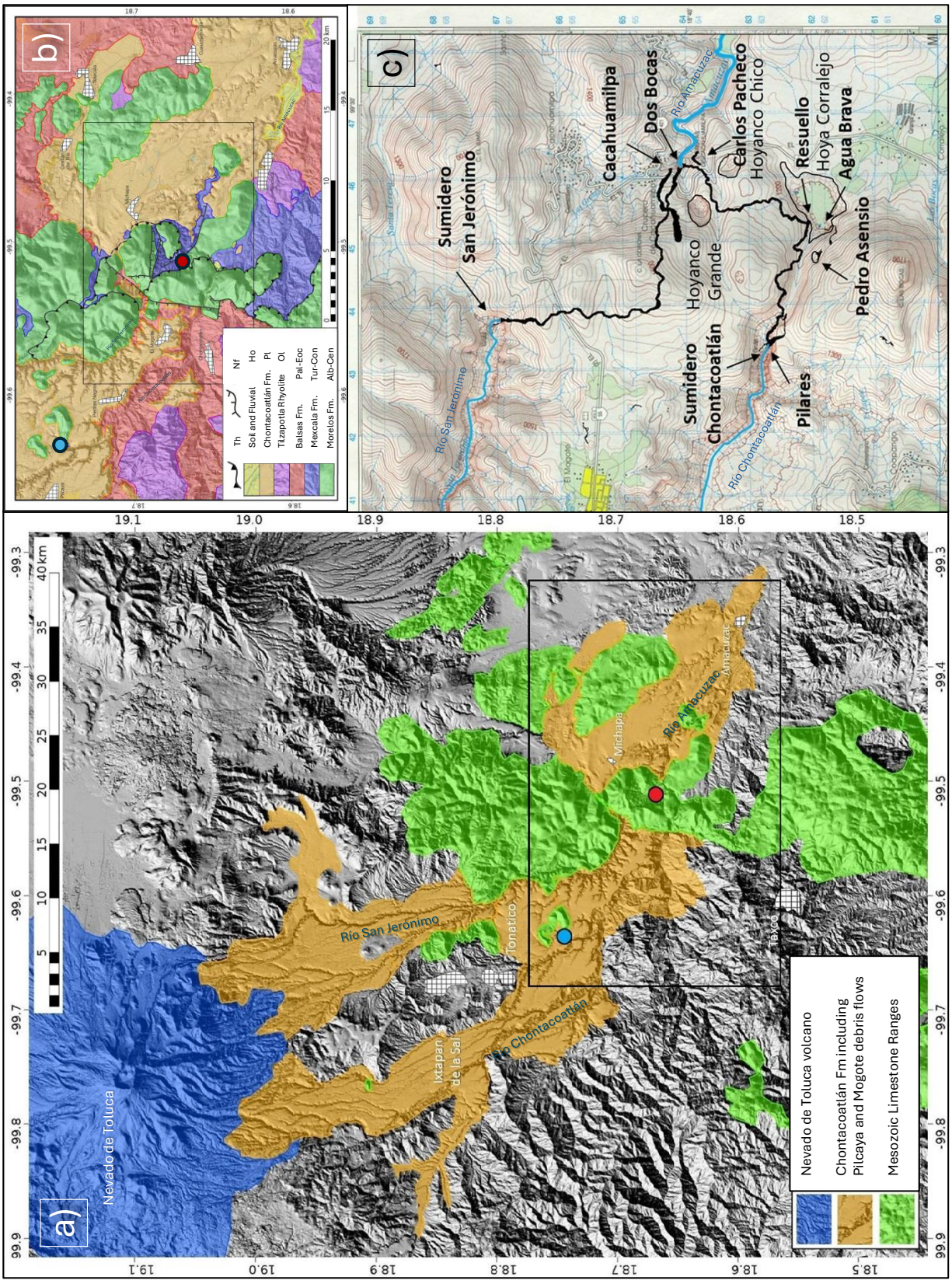


Figure 2. a) Study area showing the limestone ranges and the maximum extent of the debris flows originating from Nevado de Toluca. The red circle marks the location of Cacahuamilpa Cave, and the blue circle marks Gruta de la Estrella. The rectangle shows the area mapped in b. b) Geologic map of the Cacahuamilpa area. The red circle marks the location of Cacahuamilpa Cave, and the blue circle marks Gruta de la Estrella. The rectangle marks the area of Figure 4. c) Segment of the E14A68 INEGI topographic map showing the location of caves in the Cacahuamilpa area.

inductively coupled plasma mass spectrometer (ICP-MS). Sample preparation involved acid digestion following modified procedures based on Eggins *et al.* (1997).

To ensure analytical reliability, four certified reference materials (BHVO-1, RGM-1, GSR-2, SDO-1) were analyzed in parallel, with accepted reference values from Govindaraju (1994). In addition, the syenite standard IGLa-1 was analyzed as an independent control for assessing analytical accuracy, precision, and reproducibility (Lozano & Bernal, 2005).

During through-trips of the Chontacoatlán River cave in April 2017 and the San Jerónimo River cave in March 2018, volcaniclastic deposits were described in situ and subsequently plotted onto the existing cave maps of Coons (1976).

REGIONAL GEOLOGY

The regional stratigraphy of the Cacahuamilpa area was initially described by Fries (1960) and subsequently refined by De Cserna and Fries (1981). In addition to the geological map published by Bonet (1971), broader regional surveys including the Cacahuamilpa region were later provided by Morán-Zenteno *et al.* (1998, 2007), though these maps lack detailed resolution due to their small scale. The maps presented here were based on aerial photo interpretation and field work (Figures 2a and 2b).

The carbonate rocks that constitute the Cacahuamilpa mountain range belong to the Morelos Formation, as originally defined by Fries (1960). Based on fossil assemblages, this unit has been assigned an Albian–Cenomanian age. The formation is composed of very pure limestones and dolomites, typically thick- to massively bedded, frequently recrystallized, and with a cumulative thickness exceeding 1000 m (De Cserna and Fries, 1981).

Overlying the Morelos Formation in conformable contact is the Mexcala Formation, also described by Fries (1960). This unit consists of a flysch-like succession of thinly bedded calcareous shales, sandstones, and argillaceous limestones, deposited during the Turonian to Coniacian stages of the Late Cretaceous. Both formations were significantly deformed during the Laramide orogeny at the close of the Cretaceous.

The Balsas Group unconformably overlies all preexisting lithologies in the region (Fries, 1960). Within the study area, this unit is predominantly represented by conglomerates composed of limestone and sandstone clasts—derived from the underlying Morelos and Mexcala formations—set within a clay-rich matrix enriched in red iron oxides and cemented by calcite. Based on its stratigraphic position, the Balsas Group is interpreted to be of Eocene age (De Cserna and Fries, 1981), and marks the onset of post-orogenic continental deposition in the region. Locally, these deposits primarily correspond to talus accumulations at the base of a prominent escarpment formed by a major normal fault that delineates the western margin of the limestone range.

Immediately south of the mapped area, resting atop the Balsas Group with slight angular discordance, is the Tilzapotla Rhyolite. This unit comprises a substantial sequence of ignimbrites and rhyolitic pyroclastic density current deposits. The stratigraphy and structural relationships of the Tilzapotla Rhyolite and its contact with the Balsas Group have been comprehensively investigated by Morán-Zenteno *et al.* (1998), Alaniz-Álvarez *et al.* (2002), and Morán-Zenteno *et al.* (2007).

North of the study area lies the prominent Nevado de Toluca volcano, which underwent a complex and well-documented eruptive history during the Late Pleistocene (Bloomfield & Valastro, 1974, 1977; Cantagrel *et al.*, 1981; García-Palomo *et al.*, 2000, 2002; Arce *et al.*, 2003, 2005; Capra *et al.*, 2006, 2008). Of particular relevance to this study is a voluminous volcaniclastic sequence that was emplaced southward along two graben-bound valleys, extending as far as the Cacahuamilpa region. These deposits were originally mapped by De Cserna and Fries (1981) as components of the Chontacoatlán Formation. Subsequent work by Capra and Macías (2000) distinguished the uppermost units as the Pilcaya and El Mogote volcanic debris flows deposits (Figure 3). According to Capra & Macías (2000), intense hydrothermal alteration weakened the southern flank of Nevado de Toluca, promoting gravitational instability. This culminated in a sector collapse, generating a large volcanic debris avalanche. As the debris avalanche descended, it incorporated water and rapidly transformed into a cohesive debris flow—the Pilcaya deposit. High water content, combined with the abundance of fine altered material, allowed the flow to behave as a plastic mass capable of long runout. The flow followed the tectonically controlled Coatepec Graben. After emplacement of the Pilcaya deposit, intense rainfall and surface runoff remobilized its unconsolidated upper portions. This process generated two additional deposits known as the Mogote debris flows, which followed the ancestral Amacuzac drainage system, overfilled the limestone canyon and extended onto the Michapa plain, reaching near present-day Amacuzac.

PHYSIOGRAPHY AND KARSTIC GEOMORPHOLOGY

Cacahuamilpa Cave, along with several associated systems, is developed within a north–south-oriented limestone massif situated immediately south of the Trans-Mexican Volcanic Belt. The Nevado de Toluca stratovolcano lies 56 km to the northwest (Figure 2a). The southwestern, southern, and southeastern flanks of the volcano drain into two principal rivers, the Chontacoatlán and the San Jerónimo, which occupy tectonically controlled grabens. Upstream of the limestone range, both rivers are entrenched within deep canyons that dissect a conspicuously planar surface formed by extensive volcaniclastic sequences of debris-flow deposits (Figure 3). This geomorphic surface and the mountain ranges that bound it to the east and west was termed the Ixtapan Valley by Bonet (1971) after the principal settlement located within its bounds, to refer to the paleo-valley that was infilled by the volcaniclastic deposits.

Upon reaching the southeastern margin of the valley, where it contacts the limestone uplands, both rivers are captured by large, well-developed swallow holes (*sumideros*) (Figure 2c). Their former surface courses are preserved as dry valley remnants incised into the limestone (Figure 4; De Cserna & Fries, 1981). Both rivers reemerge approximately 100 m apart at the upper end of the Dos Bocas ("two mouths") canyon, situated immediately below Cacahuamilpa Cave.

The limestone range is characterized by a series of relatively uniform, rounded hills, punctuated by four prominent collapse dolines, which are described in detail below (Figure 4). At the eastern margin of the massif, where the limestone contacts the Mexcala flysch, lies the flat-floored Hoya de Corralejo, a marginal polje that hosts the resurgence cave Agua Brava. The resurgence waters transit the polje before sinking again into the *Resolladero* of the Chontacoatlán River (Figure 5). Small, isolated outcrops of the Mogote cohesive debris flow southeast of the polje confirm that its formation postdates the emplacement of this volcaniclastic unit (Figures 2b and 4).

Within the Ixtapan valley, another notable cave system—Gruta de la Estrella—was formed by a tributary of the Chontacoatlán river (Figures 2a and 2b). The system comprises inactive upper passages and an active lower level that transects a limestone hill entirely surrounded

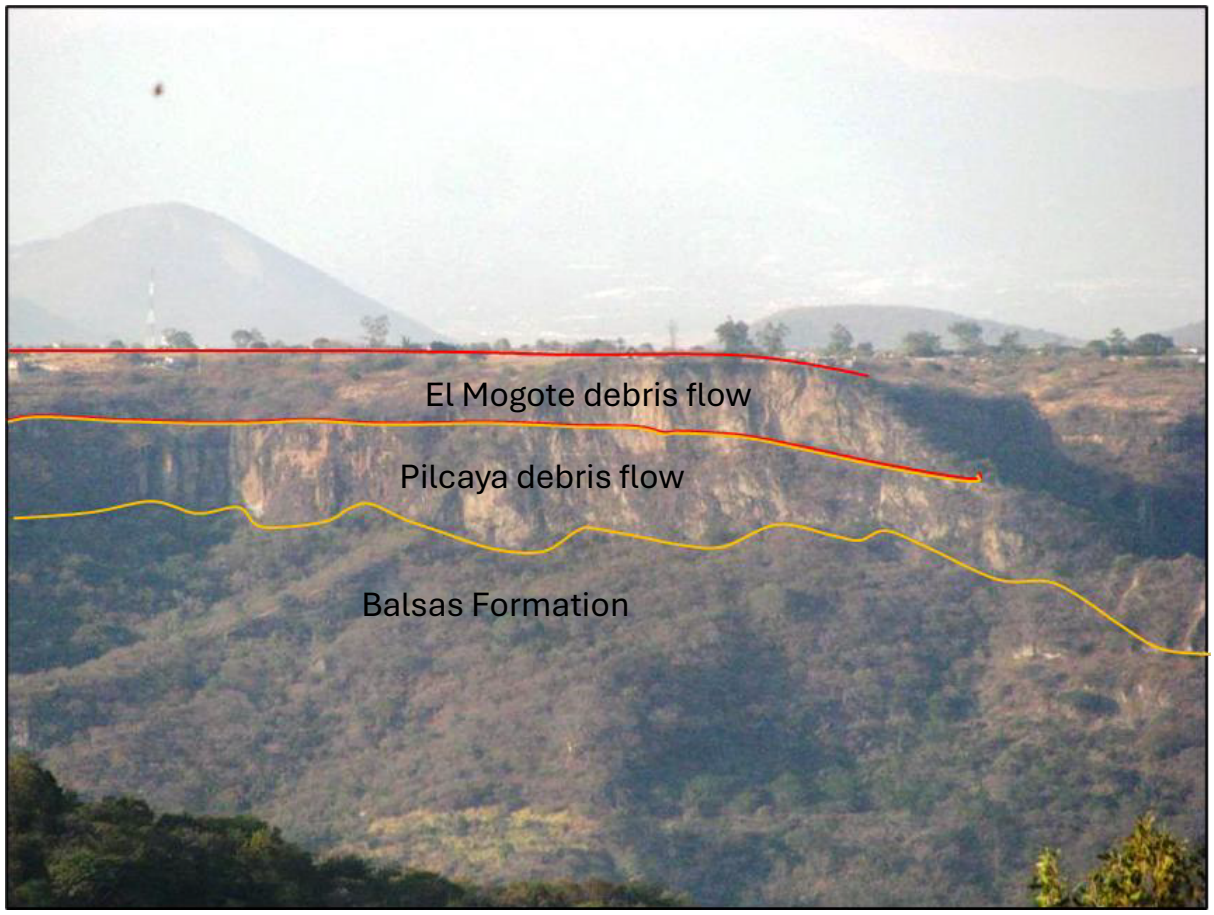


Figure 3. View of the wall of the Chontacoatlán River canyon, capped by the Pilcaya and Mogote debris flow deposits. Note the nearly flat surface left by these deposits. In the distance, the rounded limestone hills of the Cacahuamilpa range can be seen.

by volcaniclastic deposits. Gruta de la Estrella has been widely used as a conceptual model for the speleogenesis of the nearby cave systems (Bretz, 1955; Bonet, 1971).

Downstream of the limestone range, the combined Chontacoatlán and San Jerónimo rivers form the Amacuzac river, which follows a deeply incised valley carved in the Mesozoic rocks, capped by volcaniclastic sequences.

MORPHOLOGY OF THE CAVES

Cacahuamilpa

This renowned cave comprises a single, exceptionally large, slightly sinuous passage, measuring between 20 and 110 m in width and 20 to 70 m in height, with a total surveyed length of 1907 m (Figure S1, of the Supplementary Material). The entrance is partially obstructed by breakdown material derived from the weathering of the overlying cliff. The cave interior is richly adorned with monumental stalagmites—some reaching up to 40 m in height—and extensive flowstone deposits (sheet-like speleothems formed when thin films of mineral-rich water flow over cave walls or floors and precipitate layers of calcite as carbon dioxide degasses (Hill & Forti, 1997; Palmer, 2007)). The floor is predominantly flat, gently sloping toward the entrance, and mantled by speleothems and clay. The passage terminates at a zone of collapse and speleothem deposits. Throughout its course, the passage trends approximately parallel to, and at an elevation of about 80 m above, the final segment of the San Jerónimo River cave.

Volcaniclastic deposits are preserved in two distinct areas of the cave, consisting primarily of subrounded andesitic clasts up to 1 m in diameter, lacking imbrication and cemented within a matrix of andesitic pebbles and sand, with occasionally discrete sand lenses exhibiting crossbedding (Figure 6).

Along much of the first half of the passage, a prominent "bathtub ring" or horizontal waterline is visible on the cave walls and covering stalactite formations, marking a late-stage episode during which the cave was partially flooded nearly to the elevation of the entrance breakdown deposits (Figure S1).

Carlos Pacheco

Slightly smaller in diameter than Cacahuamilpa and located at approximately the same elevation, this cave consists of a single passage with a surveyed length of 487 m, ranging from 12 to 25 m in width and 10 to 27 m in height. The entrance occurs at a ceiling collapse located at a right-angle bend in the tunnel (Figure S2, of the Supplementary Material). The upstream segment of the passage, extending to the southwest, runs parallel to the terminal section of the Chontacoatlán river cave. It is nearly obstructed midway by a massive speleothem accumulation and contains several large stalagmites. Nevertheless, much of the floor is covered by a relatively flat, clay-rich fill. The upstream passage terminates abruptly where the ceiling and floor descend, marking what is interpreted as the downstream side of a

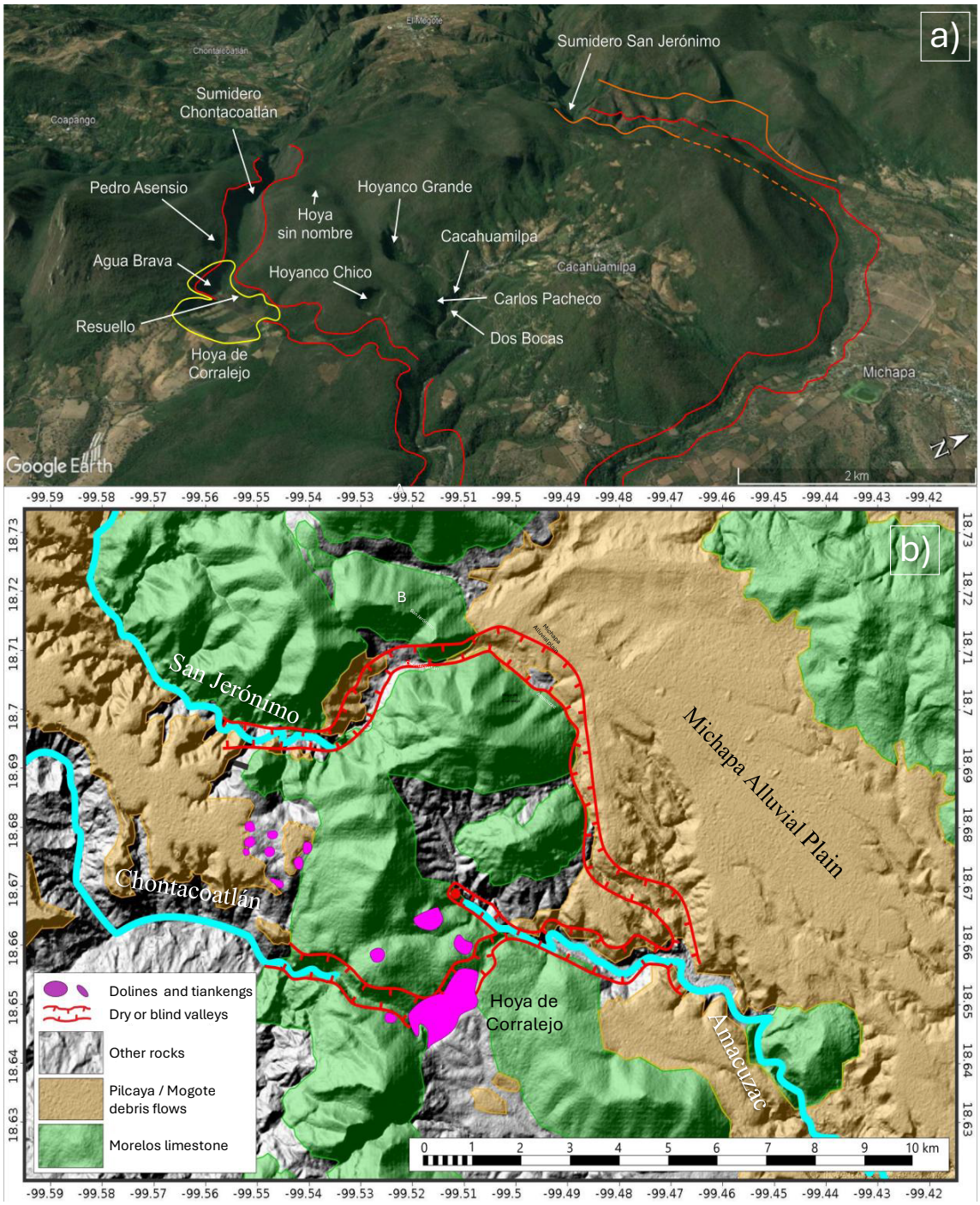


Figure 4. a) Interpreted oblique Google Earth image showing dry valleys (marked in red) used by the San Jerónimo and Chontacoatlán rivers after emplacement of the Pilcaya/Mogote debris-flow deposits and before underground capture. The canyon carved by the Amacuzac river prior to emplacement of the debris flows is marked in orange. Terraces composed of debris-flow material are also visible. The Hoya de Corralejo developed after the Chontacoatlán River was captured underground. b) Map of the same area showing the surface karst features.

sediment-choked sump. The downstream passage, trending southeast, averages approximately 10 m in width and 20 m in height, ending against a flowstone wall.

In the large chamber of the southwest passage, just before the sump, a trench was excavated into the floor, exposing a sequence of fluvial sands and clay layers, including a distinctive bed of cross-bedded sand containing rounded pumice pebbles (Figure 7).

San Jerónimo river cave

The entrance to this cave is located at the contact between the Balsas Conglomerate and the underlying Morelos Limestone, at the base of a gorge incised into the floor of the dry Michapa canyon, which marks the former surface course of the San Jerónimo–Amacuzac rivers (Figures 2c and 4). The cave consists of a large tunnel, generally 30–50 m wide and 40–60 m high, with a floor composed of fluvial

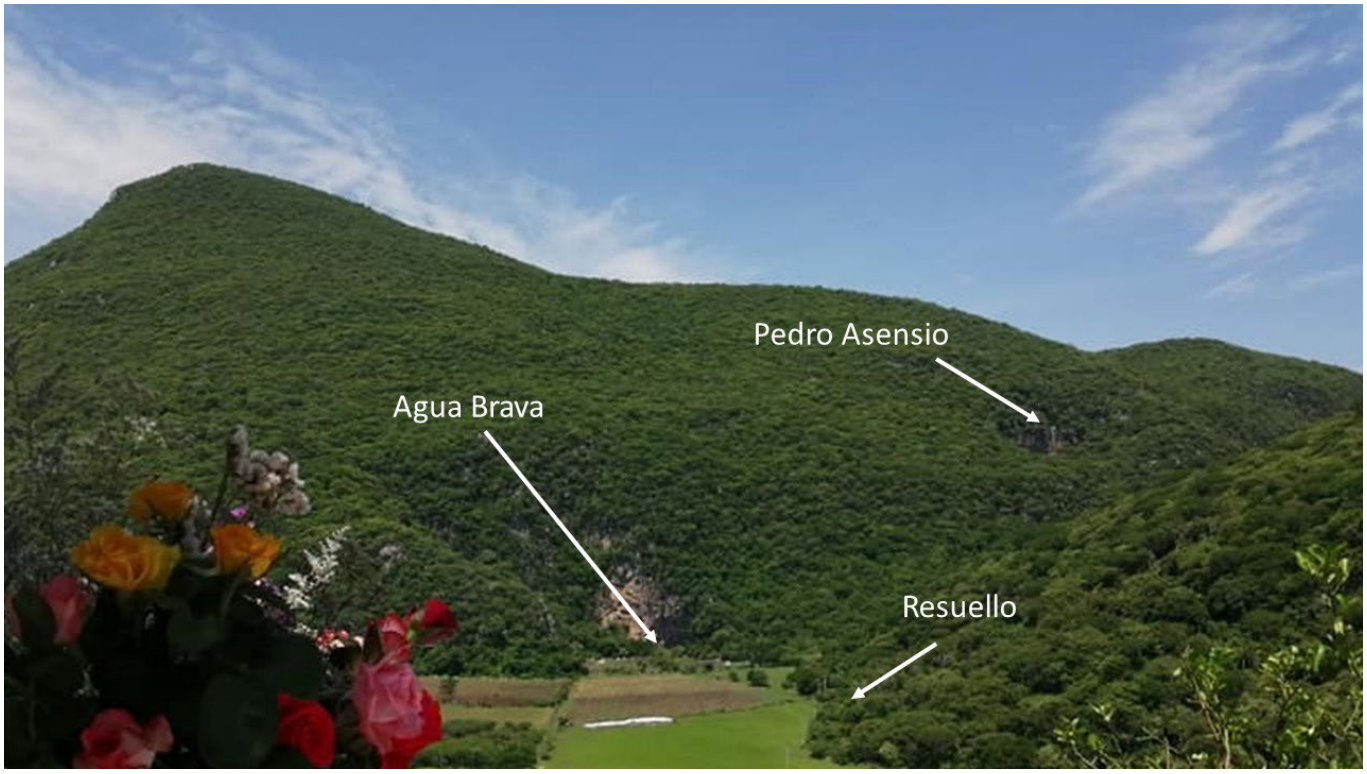


Figure 5. Corralejo polje with Cerro Temasol in the background. Cave entrances are marked.

deposits. These include large, imbricated andesitic boulders up to one meter in diameter, sand and gravel deposits, and, in certain sections, exposed and polished limestone bedrock.

Seepage from the cave walls has produced extensive flowstone formations along portions of the tunnel. These deposits are continually undercut by the active river, resulting in episodic collapses. The largest flowstone structure, known as Fuente Monumental, is fed by a stream emerging from a small lateral passage. Formerly around 60 m high and over 300 m long, its central portion collapsed during the early 1980s. The total surveyed length of the main passage is approximately 5.6 km (Figure S3, Supplementary Material).

Almost every bend in the passage, as well as many walls and ledges, contains volcaniclastic deposits several meters thick, in some cases partially covered by flowstone. These deposits are composed of large subrounded to subangular clasts, some up to one meter in diameter, lacking imbrication and set within a matrix of gravel and sand of similar lithology. Other layers are formed by angular andesitic clasts a few centimeters in diameter in a matrix of silt size particles of similar composition (Figures 8 and 9).

Chontacoatlán River Cave and Cueva de los Pilares

The Chontacoatlán river is diverted underground near the stratigraphic contact between the El Mogote debris-flow deposit and the underlying limestone. Prior to this capture point, the river has incised a canyon approximately 700 m in length into the limestone bedrock; its dry, suspended continuation represents the abandoned surface course of the river (Figures 2c and 4).

An upper-level inactive passage, known as Cueva de los Pilares, lies at the cave entrance, approximately 20 m above the active river level. This passage, which receives minor inflow from a small tributary containing substantial flowstone deposits, begins as a broad gallery measuring approximately 20 m in width and height and contains abundant stalagmites. After extending for roughly 200 m, the passage constricts into a low, sinuous tunnel only 1–2 m in height and width. The floor of this constricted section is entirely composed of well-cemented volcaniclastic debris-flow deposits, over which the limestone ceiling remains intact. This tunnel continues for nearly 500 m, terminating in a large chamber—Sala Urquijo—measuring approximately 20 m in both height and width. The chamber is almost completely filled with the aforementioned debris-flow deposit, which has subsequently been re-excavated by the tributary stream. The exposed floor surface corresponds to the upper surface of this volcaniclastic deposit. The inlet stream emerges from a small, still-unexplored conduit formed between the debris fill and the overlying limestone ceiling (Figure S4, Supplementary Material).

The main passage of the Chontacoatlán River cave is slightly smaller in scale than that of the San Jerónimo system, generally measuring 20–40 m in width and height. The passage floor is composed of coarse fluvial deposits, including large imbricated andesitic boulders and sand. Flowstone accumulations are common throughout the cave, with the most substantial deposits typically issuing from small, impenetrable or unmapped tributary passages. As in the San Jerónimo system, collapsed remnants of once-massive flowstone aprons are frequently observed.

Volcaniclastic deposits are conspicuously present along nearly every bend, wall, and ledge, forming accumulations several meters thick and occasionally overlain by a flowstone caprock. These deposits consist of subrounded to subangular clasts, some reaching up to one meter in diameter, set within a matrix of smaller pebbles and sand of comparable composition. Other layers are formed by angular andesitic clasts a few centimeters in diameter in a matrix of silt size particles of similar composition.

Approximately midway through the cave, the ceiling height increases abruptly at a collapse entrance known as El Resolladero,



Figure 6. Volcaniclastic deposits inside Cacahuamilpa Cave. Left: several layers with a total thickness exceeding 15 m. Right: detail of the base of the deposit, consisting of rounded to subrounded andesitic boulders in an unconsolidated sand and silt matrix. A large, incorporated limestone block is visible in both photographs (upper left).

situated at the base of the Hoya de Corralejo polje. Water emerging from Cueva de Agua Brava crosses the flat floor of the polje and sinks into El Resolladero, generating an impressive flowstone cascade. Unstratified volcaniclastic debris-flow deposits are adhered to the southwestern wall of this chamber to an elevation approximately 70 m above the present river level and 40–50 m above the ceilings of both the upstream and downstream passages (Figure 10). This exceptional deposit likely overtopped the cave and spilled into the Corralejo polje.

The surveyed length of the main tunnel is approximately 5.6 km. Including the Pilares upper-level passage system, the total mapped extent of the cave reaches 6475 m (Figure S5, Supplementary Material).

Hoyanco Grande, Hoyanco Chico, and Cueva de Pedro Asensio

Two prominent collapse dolines are situated above the subterranean courses of the regional rivers and are locally referred to as Hoyanco Grande and Hoyanco Chico. These features are located on the eastern flank of Cerro La Corona, almost directly above Cueva Carlos Pacheco. Hoyanco Grande measures approximately 460 × 320 m, while Hoyanco Chico spans 370 × 240 m. Both depressions exhibit vertical to subvertical walls and may be classified as *tiankengs* according to the criteria outlined by Waltham (2006) (Figures 2c and 4). A third, unnamed and significantly degraded collapse doline is present near the summit of Cerro La Corona, although none of these features currently provides direct access to cave passages.

A fourth collapse structure, Cueva de Pedro Asensio, measuring 140 × 115 m, is located on the northern slope of Cerro Temasól, above the upstream sector of the Chontacoatlán river cave. The northern margin of this doline forms a gently inclined slope, whereas the southern margin is characterized by a vertical to overhanging wall. At its base, the collapse allows entry to a short segment of phreatic passages situated approximately 70 m below the surface. These passages occupy an elevation comparable to that of the Corralejo polje floor, the distal reaches of the Los Pilares branch of the Chontacoatlán river cave, and the majority of conduits within Cueva de Agua Brava (Figure S6, Supplementary Material). All accessible passages terminate in clay-rich sediment fill, indicating cessation of active karstification at this level.

Cueva de Agua Brava

Situated within the flat-floored Corralejo polje, Cueva de Agua Brava serves as a seasonal resurgence during the rainy months. The outflowing stream traverses the length of the polje before cascading into El Resolladero, the large collapse skylight that opens into the Chontacoatlán river cave. The entrance passage of Agua Brava is relatively low-ceilinged and heavily coated with mud, suggesting intermittent submergence during high-flow conditions. After several hundred meters, the conduit abruptly increases in size, attaining widths of more than 20 m and heights exceeding 10 m, and terminates in a deep freshwater lake. Beyond this point, a network of smaller passages connects to a broad but low-ceilinged chamber, known as Sala Federico Bonet, which marks the current limit of exploration (Figure S7, Supplementary Material).

Gruta de la Estrella

Located within the Ixtapan Valley (Coatepec structural depression), Gruta de la Estrella is developed in a limestone hill entirely encircled by the Pilcaya–Mogote debris-flow deposits (Figure S8, Supplementary Material). The cave captures a surface stream that has incised predominantly into these volcaniclastic deposits, draining a catchment area of approximately 8 km². The entrance opens at the lithologic contact between the volcanic agglomerate and the



Figure 7. Trench excavated on the floor of the final chamber of Carlos Pacheco Cave, showing sandy clays containing rounded pumice clasts.



Figure 8. Volcaniclastic deposits exposed on the south wall at Boca del San Jerónimo, one of the most accessible outcrops. At least nine distinct debris-flow deposits filled the 20 m-high tunnel to within 3 m of the ceiling and were partially eroded before emplacement of the tenth flow. The river later eroded most of the fill.



Figure 9. Detail of a typical volcaniclastic deposit along the passage in San Jerónimo Cave, composed of angular to subrounded andesitic blocks embedded in a sand and silt matrix of similar composition.

underlying limestone bedrock. Above the entrance, the remnant of an abandoned dry valley marks the former course of the stream prior to its subterranean capture. The cave has been partially modified and is currently accessible as a show cave.

The active entrance passage measures ~10 m in width, with the stream entrenched into the passage floor and descending through a series of short cascades into a canyon-shaped gallery 10–20 m wide and up to 20 m high. This segment can be followed for 364 m before the stream resurges at the base of the hill, approximately 100 m above the Río Salado, a tributary of the Chontacoatlán river.

Approximately 60 m from the upper entrance, just before the stream descends into the lower active conduit, the tourist path ascends a constructed ladder through a vertical chimney on the left, providing access to an inactive upper level. Upon entry, this upper passage extends briefly back toward the entrance before becoming obstructed by speleothem deposits and breakdown blocks, features consistent with an older, abandoned phreatic or shallow vadose conduit. Directly above the chimney, a conglomerate of stream-rounded cobbles cemented by flowstone is exposed (Figure 11), providing compelling evidence of former fluvial activity at this higher elevation.

Following a descending trend, the upper inactive passage forms a broad, ancient meander loop that reconnects with the active stream passage within a few meters of the chimney. At this junction, additional cemented cobbles are visible adjacent to the modern tourist pathway (Figure 11). Two short side passages diverge from the meander loop but terminate in speleothem-choked chambers. A separate, small-diameter tunnel branches from the active stream passage and narrows into impassable fissures (Figure S8, Supplementary Material).

SPELEOGENESIS OF THE CACAHUAMILPA CAVE SYSTEM

Capra and Macías (2000) attribute the catastrophic flank collapse of the southern sector of Nevado de Toluca volcano during the Pleistocene to extensive hydrothermal alteration of the edifice. The resulting sector failure mobilized as a large debris avalanche which, owing to syn-event water saturation and the mechanical weakness of the altered lithologies, rapidly transformed into a cohesive debris flow (the Pilcaya deposit; Table 1). This lahar was funneled along a narrow tectonic depression—the Coatepec Graben (García-Palomo *et al.*, 2000)—which coincides with the paleo-valley of the Chontacoatlán river. The debris flow traveled approximately 40 km before emerging onto a low-gradient alluvial plain, ultimately reaching distances of up to 55 km from the volcanic edifice.

A key geomorphic transition occurs east of Pilcaya and south of Tonatico, where the paleo-Chontacoatlán valley intersects the Villa Guerrero graben (García-Palomo *et al.*, 2000), which is the paleo-valley of the San Jerónimo river. At this confluence of the two paleo-rivers, a marked change in valley width and gradient—from ~5° to <1°—induced a rapid deceleration of the debris flow. This decrease in transport efficiency facilitated substantial flow thickening and deposition. The Pilcaya deposit increases in thickness from roughly



Figure 10. Three images inside *El Resolladero* of the Chontacoatlán River Cave. Left: southern wall covered by two volcaniclastic debris-flow deposits. The flowstone in the foreground was deposited by water emerging from Cueva de Agua Brava. The red rectangle marks the area of the center photograph. Center: upper debris flow composed of subangular to subrounded andesite blocks in a sand matrix. Right: lower debris flow with smaller subangular clasts and a higher proportion of fine sand and silt.

15 m upstream to over 40 m in this area and contains isolated megaclasts up to 15 m in diameter (Capra and Macías, 2000). The surface morphology of this zone is characterized by a hummocky topography typical of cohesive debris-flow terminal deposits.

Following the emplacement of the Pilcaya debris flow, intense post-event rainfall and associated surface runoff partially reworked the uppermost portions of the deposit, mobilizing two secondary cohesive debris flows. These events, known as the Mogote debris flows (Capra and Macías, 2000), traveled an additional ~25 km along the ancestral course of the paleo-Amacuzac river—formed by the confluence of the paleo-Chontacoatlán and paleo-San Jerónimo drainages. They crossed the Cacahuamilpa limestone range and spread onto the modern Michapa alluvial plain, eventually reaching the area of the present-day town of Amacuzac (Figure 2a).

The catastrophic emplacement of the combined Pilcaya–Mogote deposits led to the complete infilling of the former Ixtapan valley. The resulting depositional surface was likely convex in a direction transverse to the original drainage axis, forcing both river systems to bypass the central axis of the deposits. The eastern drainage was redirected and evolved into the modern San Jerónimo river, which maintained its original incised course through the limestone range before being deflected along the western margin of the deposit near Michapa. Conversely, the western drainage was captured by a previously undeveloped low saddle in the limestone, forming the new course of the Chontacoatlán river. The traces of both paleochannels are still discernible in the modern landscape (Figure 4).

The diversion of the Chontacoatlán river onto a lower elevation along the eastern flank of the limestone range increased the hydraulic gradient and triggered a regional lowering of the water table. This hydraulic reorganization induced a significant shift in subsurface flow, drawing groundwater from both the Chontacoatlán and San Jerónimo drainages toward the new confluence point and accelerating infiltration into the underlying carbonate strata (Figure 12).

Throughout the Cacahuamilpa system, cave morphology is dominated by relatively straight, single-conduit passages, with minor anastomotic development confined to Gruta de la Estrella. This pattern is characteristic of conduit systems fed by sinking allogenic streams originating in non-karstic terrain (Palmer, 2007). The combination of substantial discharge and the presence of a well-developed joint and fracture network in the limestone facilitated the formation of extensive vadose/water-table–level conduits, consistent with Stage IV in the speleogenetic model proposed by Ford and Williams (1989), which represents mature cave development under mixed vadose-water table conditions.

Subsequent downcutting by the Amacuzac river further rejuvenated local base levels, leading to the abandonment of upper-level conduits and the entrenchment of the lower, presently active river caves (Figure 13).

The comparable elevations of the main conduit in Cueva de los Pilares, the lower phreatic passages of Cueva de Pedro Asensio, and the surveyed galleries of Agua Brava and Carlos Pacheco suggest that these caves may represent inactive or partially reoccupied remnants of a former speleogenetic level of the Chontacoatlán River's subterranean course. By analogy, Cacahuamilpa Cave appears to record an abandoned level of the San Jerónimo system, reflecting a broader pattern of multi-level karst development governed by shifts in regional base level and fluvial incision.

Gruta de la Estrella, which transects a limestone ridge in the center of the Ixtapan valley, documents a comparable sequence of geomorphic evolution. As the stream incised its valley, it was deflected against a resistant limestone spur, creating a saddle that remains topographically distinguishable. Paleo-meanders preserved in the upper-level passages, combined with fluvial deposits incorporating large, rounded volcanic boulders, demonstrate the allogenic and fluvial origins of these now-abandoned conduits.

Volcanic activity at Nevado de Toluca persisted synchronously



Figure 11. Upper: stream cobbles cemented by flowstone in the uppermost level of Gruta de la Estrella; the largest boulder on the left is 30 cm high. Lower: stream cobbles in the upper level above the junction with the active tunnel.

with the development of the karstic system. Volcaniclastic deposits have been identified at multiple sites within the principal conduit of Cacahuamilpa Cave. These sediments could only have been emplaced via transport by a high-energy debris flow or lahar while the cave was still hydrologically active.

In the Chontacoatlán river cave, the upper-level passage known as Pilares is almost entirely occluded by fine-grained volcaniclastic sediments, whose upper surface lies approximately 40 m above the modern stream level. The morphology and sedimentology of the Pilares passage suggest that it represents a former active level of the main river cave that was later overwhelmed and infilled by a single, large lahar event.

At El Resolladero, also within the Chontacoatlán system, debris-flow deposits reach elevations up to 70 m above the present stream floor, indicating complete infill prior to significant re-excavation by fluvial processes. In the San Jerónimo River Cave, the outcrop shown in Figure 8 is exposed within daylight below the lower entrance and is observable from the tourist trail. Along both caves, volcaniclastic deposits are preserved as benches and ledges on walls, bends, and projections, marking former sediment surfaces. Their characteristics indicate emplacement by mudflows or debris flows (lahars).

In Carlos Pacheco Cave, excavation of a trench in the floor of the primary passage revealed fine-grained fluvial sediments containing rounded pumice clasts. Geochemical analyses indicate these pumices exhibit compositional affinities with eruptive products from Nevado de Toluca (Table 2, Figure 14), providing the first direct evidence that this cave also formed within a fluvial environment and further corroborating the volcanic provenance of the sedimentary infill.

AGE OF KARST DEVELOPMENT

The stratigraphic and geochronological evidence constrains the onset of karst development in the Cacahuamilpa region to a time period younger than approximately 1.3 Ma. This lower boundary is defined by the K–Ar age of 1.3 Ma reported by García-Palomo *et al.* (2002) for a dacitic clast entrained within the Pilcaya–Mogote debris-avalanche deposits, themselves derived from flank collapse of Nevado de Toluca volcano. The oldest volcanic rocks comprising the Nevado de Toluca edifice have been independently dated to 2.6 Ma (García-Palomo *et al.*, 2002), establishing a maximum window for both volcanic and geomorphic processes in the region.

The Pilcaya–Mogote debris flows, which represent key geomorphic agents in redirecting surface drainage and promoting karst initiation, are stratigraphically older than 37 ka B.P., as they are overlain by a gray block-and-ash flow dated by Macías *et al.* (1997) and Capra

Table 1. Composite stratigraphic column of Nevado de Toluca volcano (after Macías *et al.*, 1997). The Pilcaya/Mogote debris-flow deposits form the uppermost members of the Chontacoatlán Formation (marked in pale rose). Units shaded in pale brown indicate other eruptive events that may have produced the lahars preserved within Cacahuamilpa and the river caves, as well as the pumice deposits in Carlos Pacheco.

Thickness	Age	Description
1.5 m	~3.3 ka	Grey, cross stratified surge and brown ash deposits with disseminated charcoal.
20 m	10.5 ka	Upper Toluca Pumice — Three fall deposits interbedded with thick pyroclastic flow and surge beds.
20 m	~12. 1 ka	White pumice flow deposit, rich in subrounded dacitic pumice and crystals, with thin pumice-fall and surge horizons at the base.
5 m	~ 14 ka	Grey, massive block-and-ash flow deposits. Ash flows and surge layers with accretionary lapilli; the deposit includes juvenile dacitic clasts and pumice.
3 m	24.5 ka	Lower Toluca Pumice, Inversely graded fallout rich in yellow pumice with some schist fragments derived from the local basement, capped by surge beds.
10 m	~26.5 ka	Grey, massive block-and-ash flow deposits, scarce outcrops.
>10 m	~28 ka	Blue-Grey Lahar deposits, massive block-and-ash flow deposits in at least three units, interbedded with surge beds; contains juvenile dacitic clasts and pumice, and red altered dacite clasts.
5 m	~32 ka	Pale brown ash flow deposits in several flow units interbedded with surge deposits; some pyroclastic flow deposits contain disseminated charcoal.
>10 m	~37 ka	Grey block-and-ash flow deposit, three main massive units and minor flow and surge layers; composed of juvenile dacitic clasts, red altered dacite clasts and rarepumice fragments.
3.5 m	36 to 39 ka	Ochre Pumice Fall deposit, three airfall layers interbedded with surge deposits and capped by a massive pyroclastic flow deposit rich in pink pumice fragments and charcoal.
~4 m	~42 ka	Pink Pumice Flow deposits — Multiple flow units composed of subrounded dacitic pumice clasts with minor andesitic fragments set in a sandy matrix.
>20 m		Chontacoatlán Formation — Mogote Debris Flow deposits — Two heterolithic, cohesive debris-flow deposits composed of dacitic clasts and exotic lithologies (basalt, limestone, rhyolite, and sandstone) embedded in an indurated sandy matrix.
>40 m		Pilcaya Debris Flow deposits — Heterolithic, cohesive debris-flow deposit composed of dacitic clasts and exotic lithologies (basalt, limestone, rhyolite, and sandstone) embedded in an indurated sandy matrix.
>15 m		Monolithic Debris-Avalanche Deposit — Breccia composed of angular dacitic clasts set in a sandy matrix.
~200 m		Older volcaniclastic Sequence of Nevado — Interbedded sequence of debris-flow, runout-lahar, fluviatile, and lacustrine deposits.
>150 m	1.2 to 1.6 Ma	Primitive Andesitic–Dacitic Lava Flows of Paleo–Nevado de Toluca — Andesitic to dacitic lava flows forming the oldest volcanic units of the edifice.
100 m	2.6±0.2 Ma	Light-grey porphyritic lavas.

and Macías (2000). García-Palomo *et al.* (2002) further suggested that these debris-flow deposits predate the oldest radiocarbon-dated eruptive products at Nevado de Toluca, which have an age of 42.03 +3.53/–2.45 ka B.P., although the absence of a direct stratigraphic contact introduces some uncertainty.

Complementary radiometric evidence is provided by speleothem dating. In Carlos Pacheco Cave, a speleothem overlying fluvial sediments yielded a basal U–Th age of 72 ka B.P. and an upper age of approximately 52 ka B.P. (M. S. Lachniet, unpublished data, pers. comm.). Similarly, a stalagmite sampled from the upper fossil level of Gruta de la Estrella produced an age of 38.75 ± 1.58 ka B.P., while a younger specimen from the same locality indicates active speleothem deposition between approximately 10 ka and 5 ka. These findings collectively indicate that cave development was well underway by at least the late Pleistocene and continued into the Holocene.

Mejean *et al.* (2015) reported additional U–Th speleothem ages from Cacahuamilpa Cave, clustering at 950 ± 20 yr B.P., 28.8 ± 0.2 ka B.P., and 88 ± 0.7 ka B.P. The latter two dates are consistent with those obtained in the present study, whereas the youngest likely represents late Holocene or modern speleothem growth. Given that dated speleothems from this cave are relatively small and capture only a limited portion of its developmental timeline, it follows that the Pilcaya–Mogote debris flows must significantly predate 88 ka B.P., and therefore also the onset of karst development in the Cacahuamilpa region

Of particular interest is the 28.8 ka B.P. speleothem age, which coincides with one of the major block-and-ash flow events at Nevado de Toluca. This temporal agreement suggests a possible correlation between this eruptive phase and the volcaniclastic deposits observed in the subterranean segments of the San Jerónimo and Chontacoatlán river caves. Although García-Palomo *et al.* (2002) reported that these pyroclastic units extended only to approximately 30 km north of Cacahuamilpa, the apparent lack of correlative deposits at the surface south of this limit may be attributable to post-depositional erosion. Subsurface preservation in the river caves could have shielded these materials from such removal. Alternatively, the volcaniclastic deposits within the caves may be related to other eruptive or remobilization events of Nevado de Toluca documented by Macías *et al.* (1997) (Table 1).

CONCLUSIONS

Volcanic activity at Nevado de Toluca exerted the primary control on the initiation and evolution of karst development within the Cacahuamilpa limestone massif. Prior to major volcanic disruption,

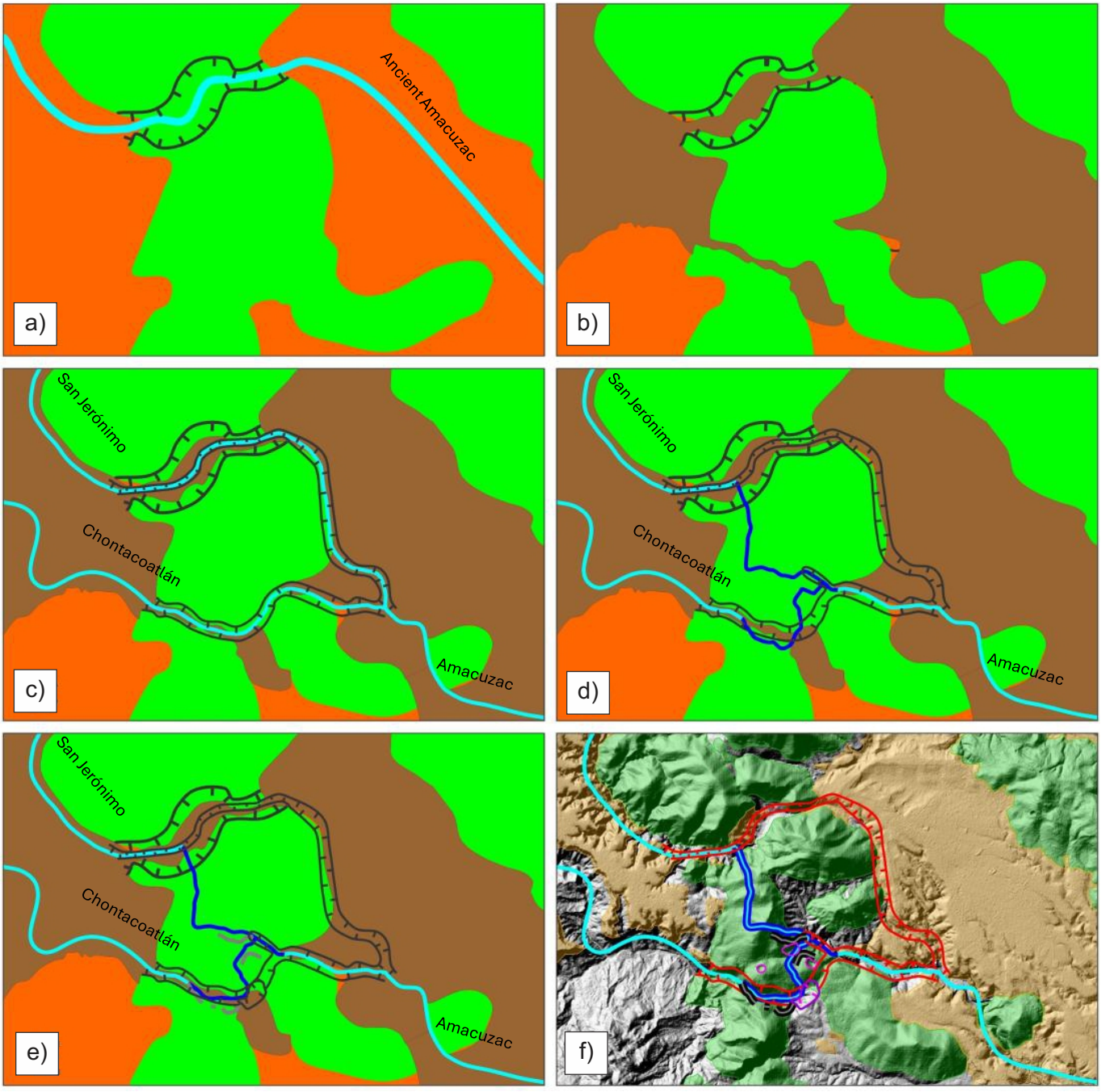


Figure 12. Development of the Cacahuamilpa cave system. The area represented is the same as in Figure 4b. The Amacuzac river, formed by the junction of the Chontacoatlán and San Jerónimo rivers within the Ixtapan Valley, crosses the Cacahuamilpa range through a surface canyon and continues into the Michapa valley. Emplacement of the Pilcaya/Mogote debris-flow deposits sometime after 1.4 Ma but substantially earlier than 88 ka B.P. The San Jerónimo River, forced toward the eastern edge of the debris-flow deposits, continues to cross the Cacahuamilpa range along the original canyon and then follows the western edge of the new Michapa plain. The Chontacoatlán River, diverted along the western margin of the deposits, finds a new course through a low saddle across the range. The new course of the Chontacoatlán reached the eastern flank of the limestone range at a lower altitude than the previous one. The resulting increase in hydraulic gradient facilitated the infiltration of water from both rivers into the limestone, forming through-river caves whose remnants correspond to Cacahuamilpa (ancient San Jerónimo) and Pilares, Pedro Asensio, Agua Brava, and Carlos Pacheco (ancient Chontacoatlán). A subsequent lowering of the Amacuzac base level led to the abandonment of the earlier caves and the development of the presently active river caves. The Hoya de Corralejo polje also formed during this stage. Present-day digital elevation model (DEM) showing in red the dry paleovalleys, in black and blue the presently active river courses, and in black and gray the fossil upper-level caves. Green shading represents limestone outcrops; brown shading shows the extent of the Pilcaya/Mogote debris-flow deposits.

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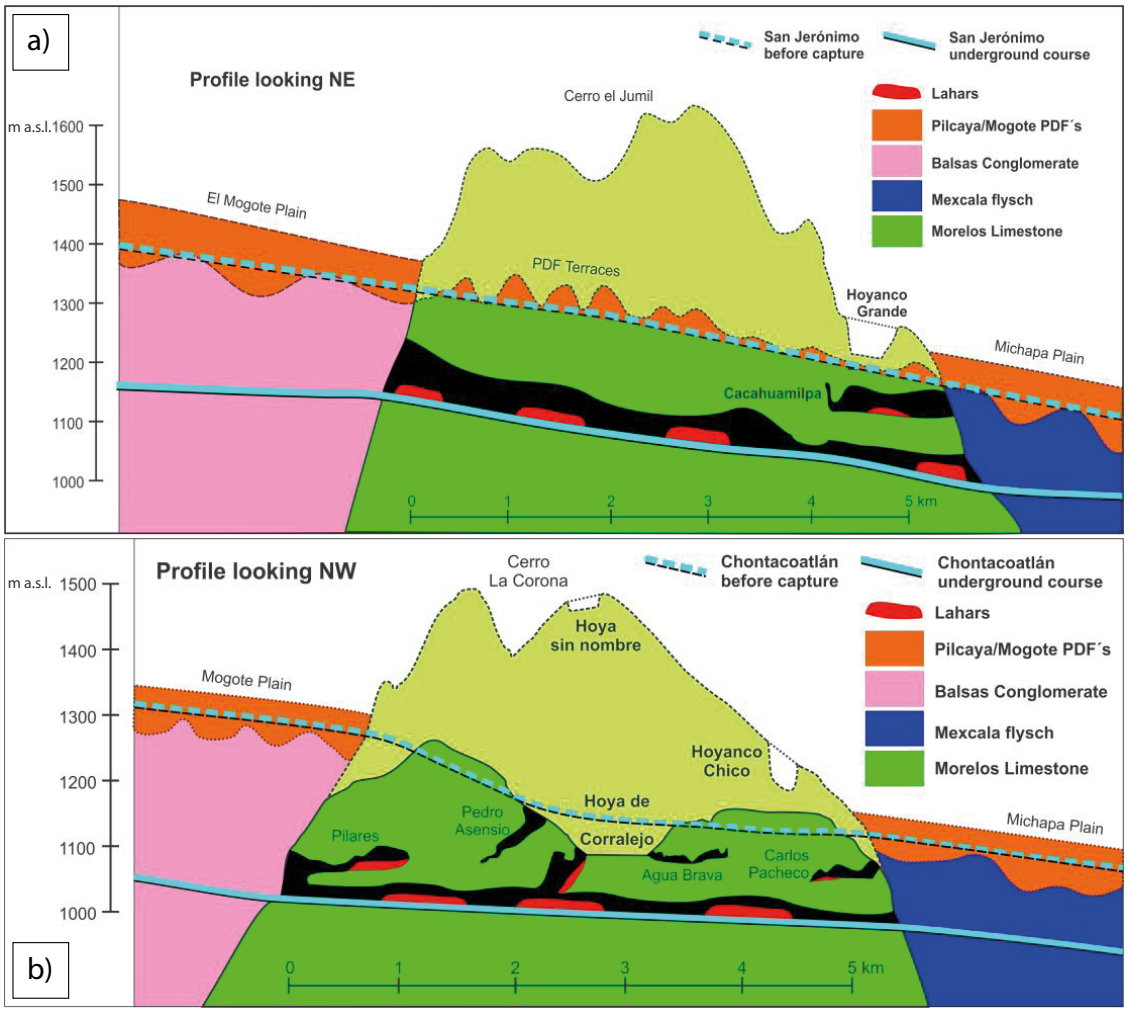


Figure 13. a) Sketch profile of the San Jerónimo and Cacahuamilpa caves. b) Sketch profile of the Chontacoatlán River and related caves. These profiles were assembled from multiple longitudinal sections extracted from Google Earth data.

Table 2. Analytical results for the major element composition of two pumice samples from Gruta Carlos Pacheco.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	TOTAL
GCP-1a	61.605	0.584	15.815	3.986	0.063	1.836	4.785	4.149	1.97	0.161	94.954
GCP-1b	61.542	0.589	15.748	3.972	0.061	1.884	4.822	4.041	1.964	0.158	94.781

the ancestral Amacuzac river crossed the range through a surface canyon and established the regional base level, preventing significant speleogenesis.

A catastrophic sector collapse after 1.3 Ma generated the Pilcaya debris flow, later remobilized as the Mogote debris flows, which completely infilled the ancestral graben valleys. This event reorganized the regional drainage network, diverted both the San Jerónimo and Chontacoatlán rivers, and fundamentally modified base-level geometry. The resulting increase in hydraulic gradient across the limestone massif promoted rapid infiltration of large volumes of allogenic water, triggering the development of extensive linear vadose–water table conduits that now form the core of the Cacahuamilpa Cave system.

Subsequent eruptive episodes continued to influence cave evolution by introducing laharic sediments into both active and inactive passages, locally filling conduits to near-roof level. Later fluvial incision and base-level lowering reactivated and entrenched the system, abandoning upper levels and establishing the modern river caves.

Speleogenesis in the Cacahuamilpa region was not an autonomous karst process but a direct geomorphic consequence of large-scale volcanic construction, sector collapse, debris-flow emplacement, and continued eruptive activity at Nevado de Toluca. The cave system therefore represents a volcanically forced karst system in which volcaniclastic sedimentation governed both its initiation and subsequent evolution.

SUPPLEMENTARY MATERIAL

The supplementary figures S1 to S9 can be found on the abstract's preview page of this paper at www.rmcg.unam.mx

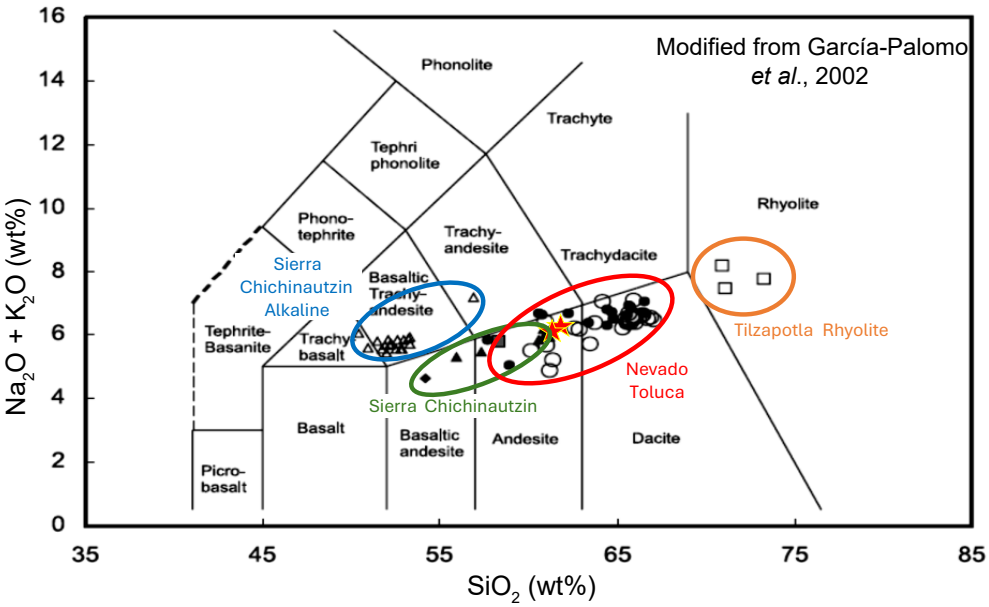


Figure 14. Composition of pumice samples from Carlos Pacheco Cave (red stars) compared with compositions of other volcanic rocks in the study area compiled by García-Palomo *et al.* (2002), demonstrating their affinity to the Nevado de Toluca suite.

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Author contributions. The only author contributed all the research and writing of the manuscript.

Data availability statement. The author confirms that all data supporting the findings of this study are available in this article or its supplementary materials.

Declaration of competing Interests. The author declares that he is not aware of any financial conflicts of interest or personal relationships that could have influenced the work reported in this article.

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