Contributions to understanding volcanic nature, their hazards and geothermal exploration: Personal insights from Mexican volcanism

Gerardo Carrasco-Núñez*

Centro de Geociencias, Universidad Nacional Autónoma de México, Campus UNAM, Juriquilla, 76100, Querétaro, Qro., Mexico.
** gerardoc@geociencias.unam.mx*

ABSTRACT

Extensive studies covering the diversity of volcanoes and eruptive styles have been performed worldwide showing that volcanoes are complex systems that require further investigation to be fully understood. Volcanological research performed in the last decades by my colleagues and myself on a natural laboratory (Eastern Trans-Mexican Volcanic Belt), reveals interesting features that represent important contributions to the understanding of volcanic nature worldwide, their hazards, and geothermal exploration. This paper focuses particularly on some relevant subjects of present interest, such as monogenetic *versus* polygenetic behavior, complex evolution of polygenetic volcanoes (hybrid volcanoes, assembly of caldera systems, unraveling the eruptive history, role of glaciers on the repetitive collapse of volcanoes), eruptive processes (lateral migration of phreatomagmatic activity, syn-eruptive bimodal eruption of contrasting magmas), and petrologic processes and systems (double compositional zonation in magma mixing and mingling in the origin of ignimbrites; polymagmatic multilayered magmatic plumbing systems). Understanding how volcanoes work is necessary to assess volcanic hazards. For this, I focus on uncovering active volcanism, assessing volcanic edifice instability in active and non-active volcanoes, and developing hazard mapping. Multiple contributions to volcanology are applied to improve geothermal exploration, as a case study of Los Humeros volcanic complex and geothermal field. Finally, volcanic geology is considered a key issue to be developed before any geological, geophysical, or geochemical approach.

Keywords: Mexican volcanism; contributions to volcanology; volcanic nature; volcanic hazards; geothermal exploration; volcanic geology; Eastern Trans-Mexican Volcanic Belt.

RESUMEN

Gran cantidad de estudios vulcanológicos han sido realizados a nivel mundial, abarcando toda la diversidad de volcanes y estilos eruptivos. Dichos estudios han mostrado que los volcanes son sistemas complejos que requieren investigaciones adicionales para ser completamente entendidos. La investigación vulcanológica realizada en las últimas décadas por mis colegas y por mí mismo en un laboratorio natural (sector oriental del Cinturón Volcánico Trans-Mexicano) destaca características interesantes que representan importantes contribuciones a la comprensión de la naturaleza volcánica en el mundo, a sus peligros y a la exploración geotérmica. De manera particular, este trabajo resalta la importancia de algunos temas relevantes de interés actual, como son: el comportamiento monogenético versus poligenético, la evolución compleja de volcanes poligenéticos (volcanes híbridos, ensamble de estructuras caldéricas, reconstrucción de la historia eruptiva, papel del glaciar en el colapso repetitivo de volcanes), procesos eruptivos (migración lateral de la actividad freatomagmática, erupción simultánea de magmas de composición contrastante), y procesos y sistemas petrológicos (zoneamiento composicional inusual, mezcla de magmas y sistemas magmáticos complejos). Entender como funcionan los volcanes es necesario para poder evaluar los peligros volcánicos. El enfoque sobre estos temas permite revelar el vulcanismo activo, evaluar la inestabilidad de edificios volcánicos tanto activos como inactivos, y realizar mapas de peligros. Múltiples contribuciones de la Vulcanología son aplicadas para mejorar la exploración geotérmica, como es el caso del complejo volcánico y campo geotérmico de Los Humeros. Finalmente, una sección sobre geología volcánica basada en cartografía digital es considerado como un tema clave, previo a la realización de cualquier tipo de estudio con enfoques geológicos, geoquímicos y/o geofísicos.

Palabras clave: vulcanismo mexicano; contribuciones a la Vulcanología; naturaleza volcánica; peligros volcánicos; exploración geotérmica; geología volcánica; Faja Volcánica Trans-Mexicana (sector Oriental).

INTRODUCTION

Volcanoes are an essential component of Earth. They provide strong evidence that our planet is alive and in constant dynamics. Understanding how volcanoes work is fundamental to learning the evolution of the Earth and the surface environments. With the accelerated growth of the world population, more people are exposed to volcanic hazards and then a better knowledge of the volcanic behavior is needed to forecast the possible impact that volcanic activity may pose in the future. On the other hand, volcanoes provide multiple benefits to society including improving soil quality, source material for infrastructure, geothermal resources to generate electrical energy, tourism, etc. All of these elements show the great importance of learning about volcanoes.

Carrasco-Núñez, G., 2023, Contributions to understanding volcanic nature, their hazards and geothermal exploration: Personal insights from Mexican volcanism: Revista Mexicana de Ciencias Geológicas, v. 40, núm. 3, p. 325-341, DOI 10.22201/cgeo.20072902e.2023.3.1755.

The dramatic increase in research about volcanoes in the last decades has provided extensive scientific information about volcanic behavior (*e.g.* Sigurdsson, 2015) Nevertheless, and contrary to the logical reasoning, the more we study volcanoes, the more we learn they have a complex nature and require a thoughtful approach to being fully understood.

Understanding volcanic nature is challenging. This paper provides a summary of some miscellaneous contributions considered to be interesting in volcanological research, based on the experience obtained from the study of a large natural laboratory: the Eastern Trans-Mexican Volcanic Belt (ETMVB), during the past decades by my colleagues and me. It is, of course, not intended to be a comprehensive review of all volcanological subjects, but instead to expose some particular subjects uncovered from spotted examples of volcanism, highlighting its unusual and sometimes unexpected complex volcanic behavior as compared with the volcanism worldwide. We also explore the hazards associated with active and non- active volcanoes, and the geothermal exploration of volcanic areas. For more details, please check the specific cited references. This paper is a contribution to the special issue of the Revista Mexicana de Ciencias Geológicas to commemorate the 20th anniversary of the Centro de Geociencias (Universidad Nacional Autónoma de México).

I selected some particular topics (and examples) that are of recurrent interest among the volcanological community. In regards to understanding volcano nature, my colleagues and I are interested in: exploring monogenetic *versus* polygenetic nature: uncovering polymagmatic and syn-eruptive contrasting eruptive style; and polygenetic behavior. Deciphering the complex evolution of polygenetic volcanoes: defining hybrid volcanoes (shield-like compound volcanoes); unraveling the complex structure and assembly of caldera volcanoes; reconstructing the eruptive history and deciphering the role of glaciers in the repetitive sector collapse of volcanoes. Understanding special explosive processes: interpreting the controls of lateral migration of phreatomagmatic activity; unraveling syn-eruptive bimodal eruption of contrasting magmas. Exploring special petrologic processes and systems: unraveling double compositional zonation, complex magma mixing and mingling in the origin of ignimbrites, reappraisal of polymagmatic plumbing systems; identifying simultaneous contrasting petrologic processes. Regarding volcanic hazards, I am interested in uncovering active volcanism; assessing volcanic edifice instability in active and non-active volcanoes; and mapping volcanic hazards. I also consider it important to include some volcanological contributions to the exploration of geothermal resources, which may help to improve the knowledge about the key components of a geothermal system (a case study of Los Humeros Volcanic Complex-LHVC) including the heat source (complex configuration), permeability (role of microporosity), cap rock (heterogeneities affecting permeability conditions), and reservoir rocks (heterogeneous subsurface geology).

In addition to those important subjects, I consider that volcanic geology based on detailed cartography and extensive fieldwork are fundamental ingredients that represent a paramount contribution to understanding volcanic nature, with application to hazards and geothermal exploration. Thus, the latter topic is also included in this work.

VOLCANIC GEOLOGY

Geological mapping based on extensive fieldwork and complemented by analytical studies revealing the chemical composition, petrography, and age of the volcanism are the basis to develop any kind of detailed volcanological studies, which are essential to understand the eruptive behavior of volcanoes, their future activity, and associated hazards (in the case of active volcanoes) and/or the possible potential for geothermal energy extraction or any other type of direct use.

Volcanic geology is mainly based on systematic volcanic stratigraphy (Martí *et al.*, 2018), which provides essential information to identify the spatial and temporal relationships between the eruptive products and volcanic processes involved as a first approach to understand the general volcanological evolution of a region. However, on a regional scale, this is a long-lasting task requiring long fieldwork journeys. A cartographic strategy was successfully applied to uncover the volcanism of the Easternmost sector of the Trans- Mexican Volcanic Belt (ETMVB). As a result of several decades of work digital geologic mapping was progressively incremented and updated by using GIS software. This process includes extensive fieldwork with data acquisition and sampling, along with petrographic and geochemical characterization (550 analyses), and support of about 100 isotopic ages, which were integrated with compiled geologic maps from individual volcanic fields (such as Citlaltépetl stratovolcano, Carrasco-Núñez and Ban, 1994; Cerro Grande volcanic complex, Carrasco-Núñez *et al.*, 1997; Cofre de Perote compound volcano, Carrasco-Núñez *et al.*, 2010; Los Humeros caldera, Carrasco-Núñez *et al.*, 2017), in addition to other smaller- scale maps. Integration of the lithostratigraphic framework on a regional scale was challenging, due to the large diversity of landforms, eruptive products, magmatic compositions, and spatio-temporal variations. A proper analysis of these parameters along with stratigraphic information facilitates more precise correlations and define lithostratigraphic units and groups based on the eruptive product, composition, and age, which at the end provide support to obtain a final new regional volcanological map for the ETMVB (Carrasco-Núñez *et al.*, 2021), as depicted in Figure 1.

UNDERSTANDING VOLCANIC NATURE

Despite the continuous advances in the comprehension of volcanic phenomena because of the increasing number of studies worldwide, several topics on volcanology are constantly debated, particularly when new examples are discovered to be exceptional or distinct from the standard models and sometimes off from the so-called "normal" behavior.

In this paper, I will focus on some particular subjects that have been found intriguing, and at the same time are important to be addressed as special cases of study. They are grouped into the following categories: complex monogenetic polygenetic behavior; diversity and complexity in the evolution of polygenetic volcanoes; special eruptive processes, and special petrologic processes and systems.

Complex monogenetic behavior

A simple and practical way to classify volcanoes is based on the size, diversity, and longevity of the eruptive activity. Monogenetic volcanoes were first defined as small-volume volcanic centers that erupted only once, that is, occurring over a brief period (Walker, 2000) having an apparent simple eruptive evolution (meaning no significant changes in composition or eruptive style). Recent works review that term and propose a more adequate definition for a monogenetic volcano: "A small-volume (less than 1 km^3) volcano built by continuous or discontinuous eruptions occurred over a short timescale (typically less than 10 yr) fed from one or multiple magma batches through a feeder dyke system with no association with well-developed magma chambers" (Németh and Kereszturi, 2015). However, volcanoes show a wide and diverse spectrum ranging from simple, small-volume monogenetic volcanoes, which by the way are the most common type

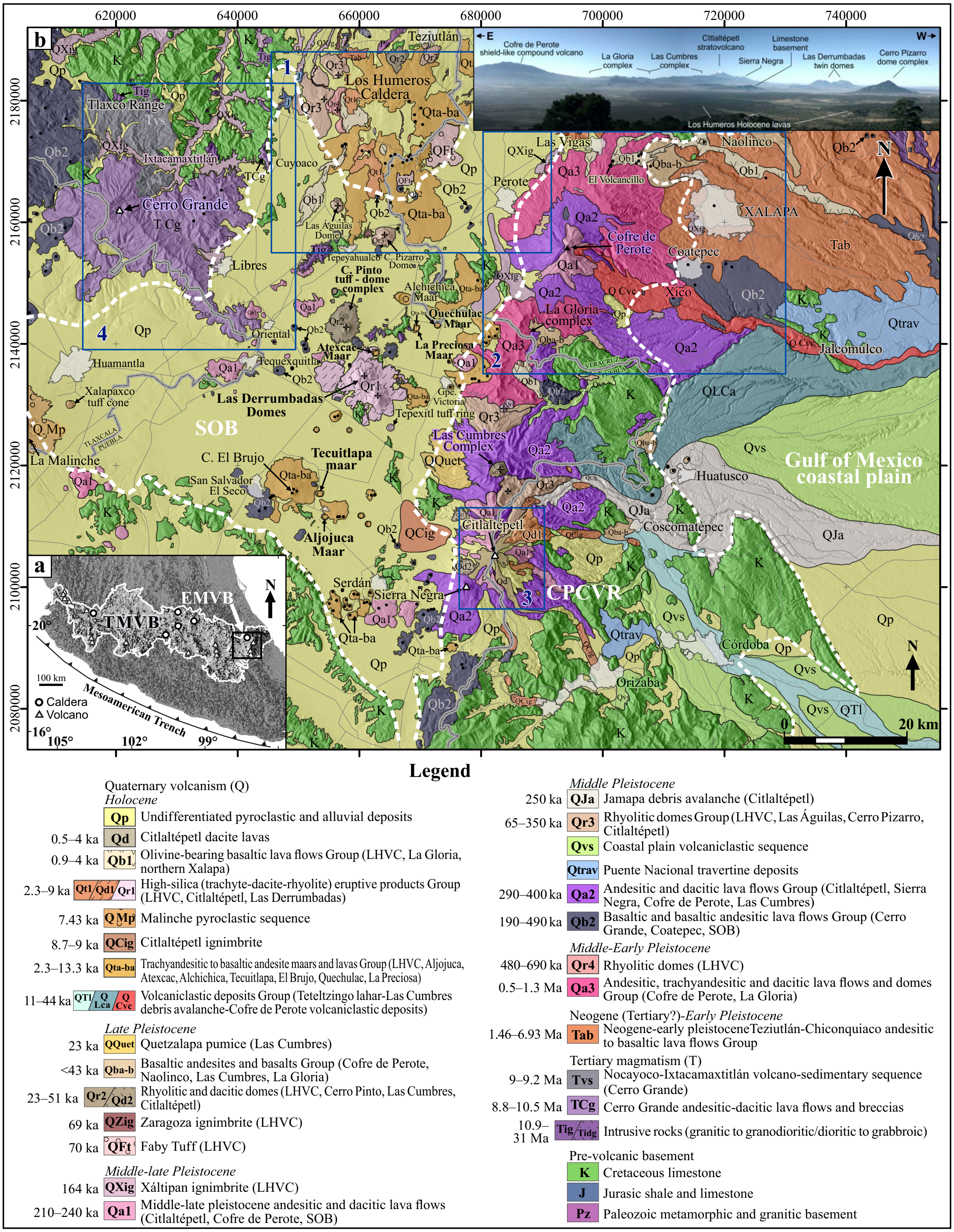

Figure 1. Location of the study area. a) Inset map of the Trans-Mexican Volcanic Belt (TMVB) showing the location (square) of the ETMVB. b) Regional volcanic geology of the ETMVB showing the distribution of the Quaternary volcanism with the main volcanoes (condensed version from Carrasco-Núñez *et al.*, 2021). Blue boxes indicate the coverage area of different compiled maps: 1- Los Humeros caldera (Carrasco-Núñez *et al.*, 2017); 2- Cofre de Perote compound-shield-like volcano (Carrasco-Núñez *et al.*, 2010); 3- Citlaltépetl stratovolcano (Carrasco-Núñez and Ban, 1995); 4- Cerro Grande Volcanic Complex (Carrasco-Núñez *et al.*, 1997). In the upper right corner, there is a panoramic view showing the most important volcanoes of the ETMVB (from Carrasco-Núñez *et al.*, 2021).

of continental volcano (Valentine and Gregg, 2008) to very complex and large-volume polygenetic structures. Transitions occur when volcanoes present different eruptive episodes separated by evident temporal breaks, or erupt from several individual eruptive vents, and/or erupt large volumes of magma (compound), with similar or different magma composition (polymagmatic) and eventually show a more complex eruptive history and a polygenetic behavior (Kereszturi and Németh, 2012; Németh and Kereszturi, 2015). Eruptive styles range from effusive (lava dome, coulee, small-shield, lava flow) to explosive (scoria/spatter cone, tuff cone, tuff ring, maar diatreme), varying from magmatic to phreatomagmatic styles (Murcia and Németh, 2020). Therefore, a simple traditional view to classify volcanism in monogenetic or polygenetic volcanoes fails to explain all the diversity of volcanic structures forming on the Earth's surface, as there will be cases with transitional behavior that are not easy to group into one or other categories.

Polymagmatic and syn-eruptive contrasting behavior

Cinder, scoria, and lava cones are commonly defined as small volume volcanoes with a simple eruptive history. However, there are cases such as El Volcancillo paired cone, located at the northern flank of the Cofre de Perote volcano (Figure 1), which shows interesting features that are not characteristic of a typical simple monogenetic center, but instead, it behaves more like a relatively small complex volcanic system. El Volcancillo consists of two overlapping vents formed in short succession (Figure 2). The SE crater is made of pyroclastic material derived from violent strombolian eruptions followed by the eruption of high-effusion-rate, short duration (about 2 weeks), small volume (0.15 km^3), *aa*-alkaline (hawaiite- Toxtlacuaya) lava flows; in contrast, the NW crater was formed by the eruption of low-effusion-rate, large duration (around 10 years), large volume (1.3 km^3) *pahoehoe*-calc-alkaline (basalt-Río Naolinco) lava flows (Siebert and Carrasco-Núñez, 2002). The latter reached up to 50 km from the source (Figure 2); this high mobility is attributed to a compound lava tube system that inhibited rapid cooling, traveling faster within the lava flow.

Following the schematic spectrum proposed by Németh and Kereszturi (2015), El Volcancillo can be regarded as a polymagmatic compound monogenetic paired volcano (cone), representing the unusual contemporaneous eruption of contrasting lavas in both composition and eruptive style within a continental arc.

Polygenetic behavior

Another interesting example of an apparent monogenetic volcano is Cerro Pizarro. While rhyolitic domes are commonly regarded as monogenetic volcanoes with short-lived eruptions producing pyroclastic material and dome extrusion over a short time span (Fink and Anderson, 2000), on the order of years or up to a few centuries (Duffield *et al.*, 1995; Donnelly-Nolan *et al.*, 1990), Cerro Pizarro shows evidence of complex evolution. Its eruptive history includes alternated effusive (lava domes) and highly explosive eruptions (including episodes of pumice fallout and dilute pyroclastic density currents), separated by long-term repose periods (between 50–80 yr apart), including multiple eruptions of stony rhyolitic (180 ky) and vitrophyre dome extrusion, and cryptodome emplacement (116 ky), debris-avalanche emplacement derived by a flank collapse phase (collapse scar), followed by a final explosive phase at 65 ky, and separated by prolonged erosional periods; in addition to compositional changes recorded during the early and late eruptive phases (Riggs and Carrasco-Núñez, 2004; Carrasco-Núñez and Riggs, 2008) (Figure 3a). All of these features indicate the polygenetic nature of the Cerro Pizarro rhyolitic dome.

Complex evolution of polygenetic volcanoes

Hybrid volcanoes

At the other end of the spectrum are polygenetic volcanoes. Stratovolcanoes are typical examples of this category, showing a long-lived evolution (several hundred thousand years or even more) with alternated periods of construction and destruction by sector collapse episodes, commonly separated by prolonged periods of repose. They usually builts a high-relief cone with a central crater and diverse parasitic activity consisting of small cones and/or domes around or within the main crater. In contrast to stratovolcanoes, Cofre de Perote is defined as a polygenetic volcano built by a dominantly successive emplacement of basaltic andesite, andesite, andesitic-trachyandesitic to dacitic lavas flows, lava domes and associated breccias erupted from different vents to build a compound volcano, without evidence of appreciable explosive activity (Carrasco-Núñez *et al.*, 2010). However,

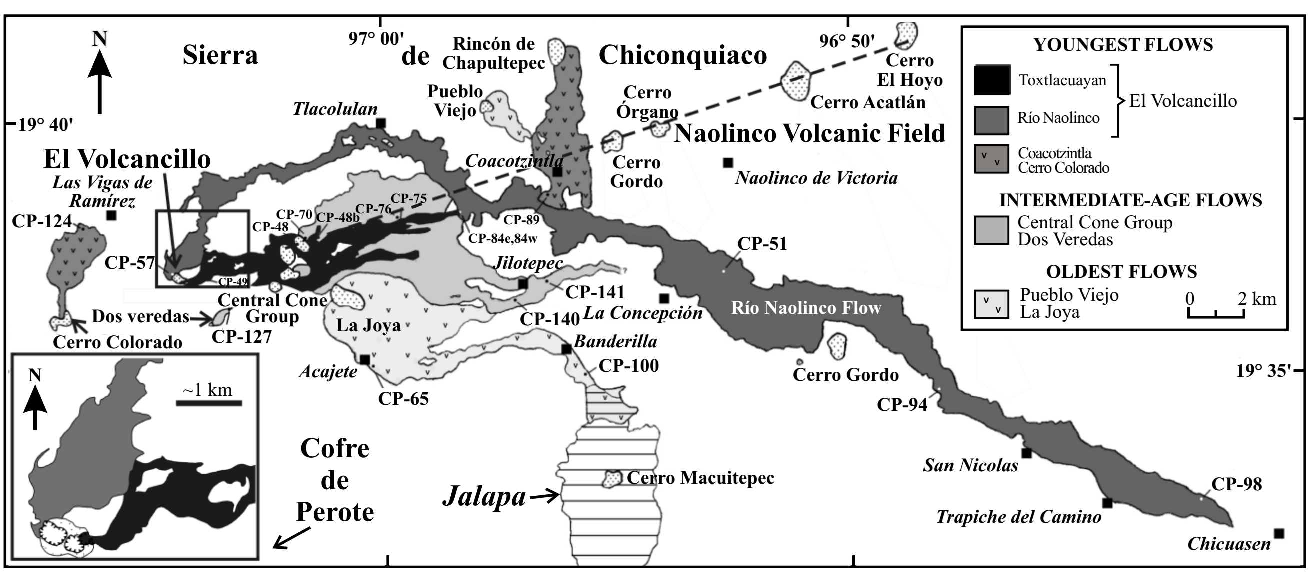

Figure 2. Location of El Volcancillo at the Cofre de Perote's northern flank showing the distribution of the pahoehoe Río Naolinco basalt and the aa Toxtlacuaya hawaiite lava flows (modified from Carrasco-Núñez *et al.*, 2005). The inset map shows the overlapping of the Volcancillo vents.

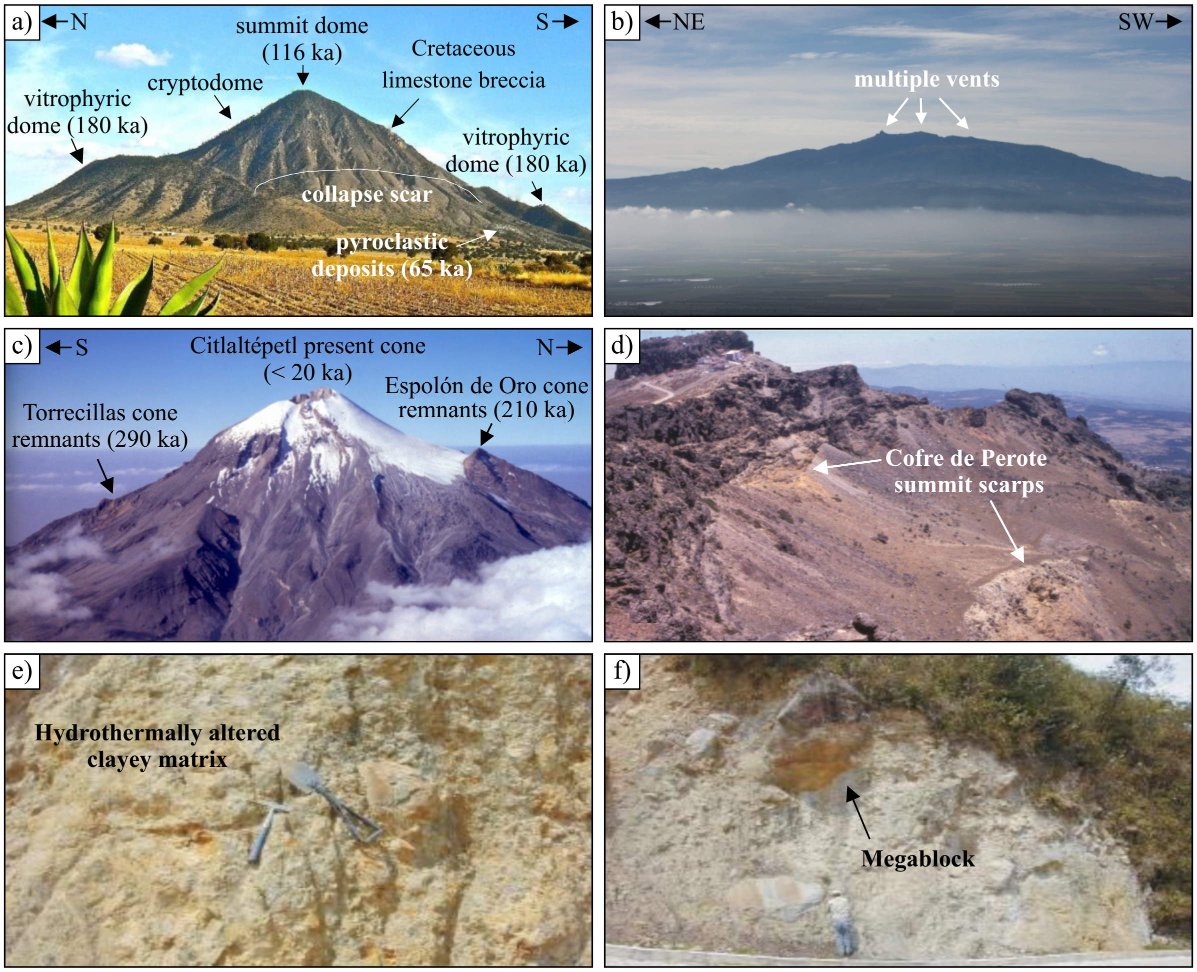

Figure 3. Photographs of selected volcanoes and features. a) WNW view of Cerro Pizarro rhyolitic dome showing the main components used to interpret a polygenetic behavior. See details in text. b) West view of Cofre de Perote compound, shield-like volcano, showing its characteristic gentle morphology with multiple vents. c) North view of Citlaltépetl stratovolcano showing the remnants of the older volcanoes (Torrecillas and Espolón de Oro), and the Citlaltépetl present cone (modified from Carrasco-Núñez *et al*., 2006). d) Cofre de Perote scarps showing some hydrothermally altered zones. e) Texture of the Tetelzingo lahar with clasts within a clayish highly altered matrix. f) Texture of Xico debris avalanche derived from Cofre de Perote showing mega blocks within a highly altered matrix.

Cofre de Perote was constructed as a massive low-angle volcano with gentle slopes that was morphologically modeled as a shield-shaped volcano, in contrast to a typical steep stratocone. Additionally, repeated sector collapse events occurred during its evolution forming high-relief massive horseshoe-shaped scarps that truncated the eastern sector of the volcanic edifice. Considering all these features, Cofre de Perote is not fit in a simple category, instead, it can be regarded as a hybrid polygenetic volcano, defined as a compound shield-like volcano, which evolved into five major evolutionary stages including the emplacement of a multiple-vent dome complex, construction of a basal compound shield volcano with different vents (Figure 3b), followed by the eruption of the summit lavas, and ending with at least two main sector collapse episodes, which were directed towards the Gulf of Mexico coastal plains (Carrasco- Núñez *et al*., 2010). This example of volcanism also shows the necessity to improve the current classification of polygenetic volcanoes and consider the occurrence of new transitional categories within the volcanic realm.

Assembly of caldera structures

Calderas are complex volcanic systems that include a diversity of eruptive styles, volcanic products, and magmatic processes. Catastrophic explosive eruptions produce the sudden evacuation of large volumes of pyroclastic material causing the collapse and formation of large caldera structures (*e.g.* Smith and Bailey, 1968; Lipman 2000; Cashman and Giordano, 2014). The caldera-forming process causes the creation of a complex internal structure during crustal subsidence, reassembly of the magmatic source, and the possible development of a geothermal system. As the occurrence of these events is rare in present times, there are still several uncertainties regarding their origin and evolution. Nevertheless, the advances reached in the study of the caldera volcanoes (*e.g.* Walker, 1984; Lipman, 2000, Kennedy and Stix, 2003; Cole *et al*., 2005; Cashman and Giordano, 2014), understanding of their structure and behavior is still not well-known. The study of calderas exhibiting a complicated long-term eruptive history with multiple collapsing events such as the case of Los Humeros volcanic complex (LHVC), is ideal for unraveling the internal configuration of the caldera framework and its relationship with the evolution of the LHVC (Ferriz and Mahood, 1984; Carrasco-Núñez *et al*., 2018). For that purpose, an integrated approach including high- precision digital elevation models (DEMs), extensive cartographic work, geophysical surveys (MT studies: Corbo-Camargo *et al*., 2020), petrological and subsurface data was recently developed (Carrasco-Núñez *et al*., 2022).

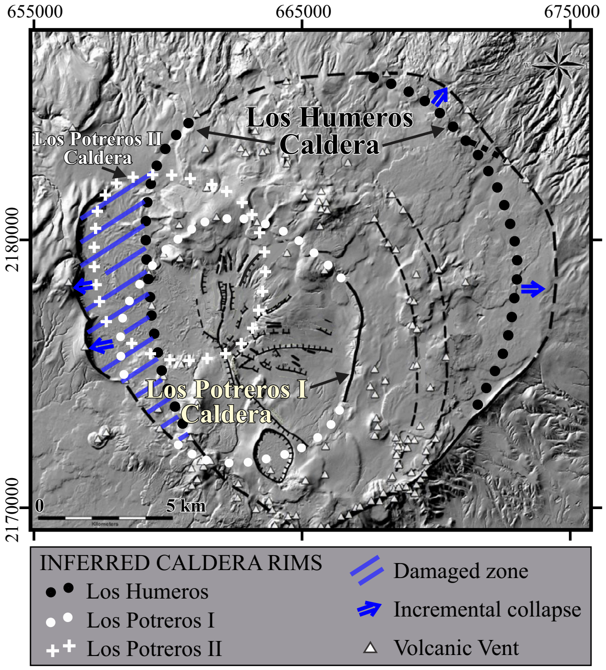

Figure 4. Digital Elevation Model map showing the inferred configurations of the caldera rims: single for Los Humeros and multiple (I and II) for Los Potreros caldera structures (modified from Carrasco-Núñez *et al.*, 2022), which serve to support the intricate assembly of the LHVC.

An interpretative reconstruction of the proposed configuration for the main caldera structures associated with the LHVC is presented in Figure 4. It is noteworthy to see the inferred caldera rims continuing the trace of the main scarps; one for Los Humeros (the largest and older caldera) and two for Los Potreros (the smaller and youngest caldera), creating a damage zone in the overlapping of the two calderas, as a result of incremental collapse processes (Carrasco-Núñez *et al.*, 2022). The two caldera-forming episodes inferred for Los Potreros caldera are based on the configuration of the present caldera scarps, and geologic evidence of at least two co-ignimbrite breccia deposits found within the single massive Zaragoza ignimbrite unit, confirming the sequential collapse that formed at least two inferred caldera structures (Willcox, 2011; Carrasco-Núñez *et al.*, 2022).

Unraveling the eruptive history

Reconstruction of the eruptive history of a volcano is vital, particularly for large polygenetic volcanoes due to the complexity of their behavior, reflecting a diversity of eruptive products, composition, and magmatic processes. Alternated periods of construction and destruction of the main volcanic edifice, separated for long repose periods are common stages associated with a relatively standard behavior of stratovolcanoes (composite volcanoes), such as Citlaltépetl volcano (also known as Pico de Orizaba), which is the highest North American active volcano (5675 m a.s.l.). Nevertheless, the identification of the volcanic structures and vents, including the remnants of former stratocones, is not a trivial job, and requires extensive fieldwork, complemented with interpretation using detailed air photos and satellite imagery, and supported by analytical work (petrography, geochemistry, and geochronology), which altogether are integrated to define the structural architecture of Citlaltépetl volcano (Carrasco- Núñez and Ban, 1994; and Carrasco-Núñez, 2000). The picture depicted in Figure 3c indicates the location of the remnants of older cone structures corresponding to Torrecillas (0.29 ky) and Espolón de Oro (0.2 ka) main stages, which were partially destroyed by successive sector collapse events, producing large debris avalanches and cohesive lahars. The present cone was built in the last 20 ky erupting andesitic-dacite lava flows followed by a period of repetitive Plinian eruptions at 13 ky and 8.5–9.0 ky, showing an interesting eruptive dynamics of alternated fall and flow deposits forming the Citlaltépetl pumice (Rossotti *et al.*, 2006), followed by dome-growth activity with explosive phases producing radially-dispersed block-and-ash flows (4.2 ky, Carrasco-Núñez, 1999).

An important parameter to characterize volcanoes is the longevity of large magmatic systems, such as the case of caldera volcanoes, where precise geochronologic determinations are required to evaluate their thermal conditions. A reappraisal of the evolution of the geothermally active LHVC was made based on combined U/Th zircon and $^{40}Ar/^{39}Ar$ dating. Using these two geochronometers a new age for the beginning of the caldera formation was obtained (164 ± 4.2 ky, Carrasco-Núñez *et al.*, 2018), which is much younger than the previously reported (K-Ar: 460 ± 40 ky; Ferriz and Mahood, 1984). Ages for other important eruptive events were also obtained (70 ky for the intracaldera Plinian activity; and 0.69 ky for the Los Potreros caldera, nested within the larger Los Humeros caldera; as well as younger post-caldera resurgent phase), allowing a complete reconstruction of the eruptive history of the LHVC. A substantial reduction in the time interval for the complete caldera development as compared with previous works varies from 410 ky to 85 ky stage (shaded area in Figure 5).

Role of glaciers on the repetitive sector collapse of volcanoes

Volcano's edifice instability can be attributed to several factors including magmatic activity (Elsworth and Voight, 1996) and/or external processes such as hydrothermal alteration (Reid *et al.*, 2001), gravitational spreading (Van Wyk de Vries and Francis, 1997), steepening slopes (Béget and Kienle, 1992) or tectonic setting (Francis and Self, 1987).

Multiple edifice-collapse events were identified along the Citlaltépetl-Cofre de Perote volcanic range (CCPVR), which forms a remarkable physiographic divide separating the Central Altiplano (2500 m a.s.l.) from the Gulf coastal plain (1300 m a.s.l.). It has been proposed that the abrupt eastward drop in relief (more than 1 km) as well as the sloping substrate due to the irregular configuration of the Mesozoic basement rocks (Figure 6) played a fundamental role in promoting unstable conditions that caused the large catastrophic sector collapses of all major volcanoes along the CCPVR, which include different volcanic structures such as: Citlaltépetl stratovolcano, Las Cumbres caldera, La Gloria complex, Cofre de Perote compound-shield like volcano, all directed towards the coastal plains (Figure 6) (Carrasco-Núñez *et al.*, 2006). In some cases, like Citlaltépetl and Cofre de Perote volcanoes, multiple edifice collapses occurred, producing large debris avalanches and transformed debris flows with exceptional long runouts that reached the Gulf of Mexico's coast, traveling more than 80 km from their source. A remarkable example is the so-called Teteltzingo debris avalanche and lahar deposit derived from the sectorial collapse of the ancestral edifice of Citlaltépetl volcano (Espolón de Oro). It is a clay-rich (cohesive) lahar formed (Figure 3e) by the rapid transformation of a proximal avalanche originated as a sector collapse of hydrothermally altered rock (Carrasco-Núñez *et al.*, 1993). The high degree of hydrothermal alteration is enhanced by the presence of a glacier (Figure 3c); the larger the glacial ice coverage area, the higher intensity and/or are covered by hydrothermal alteration (Figure 7), which provides an intermittent but constant source of water that interact with the ascending gases generating large volumes of hydrothermally altered rock that weaken the volcanic edifice and leave it prompt to collapse and flow as saturated, liquified debris with abundant clay comprising secondary alteration minerals (Zimbelman, 1996).

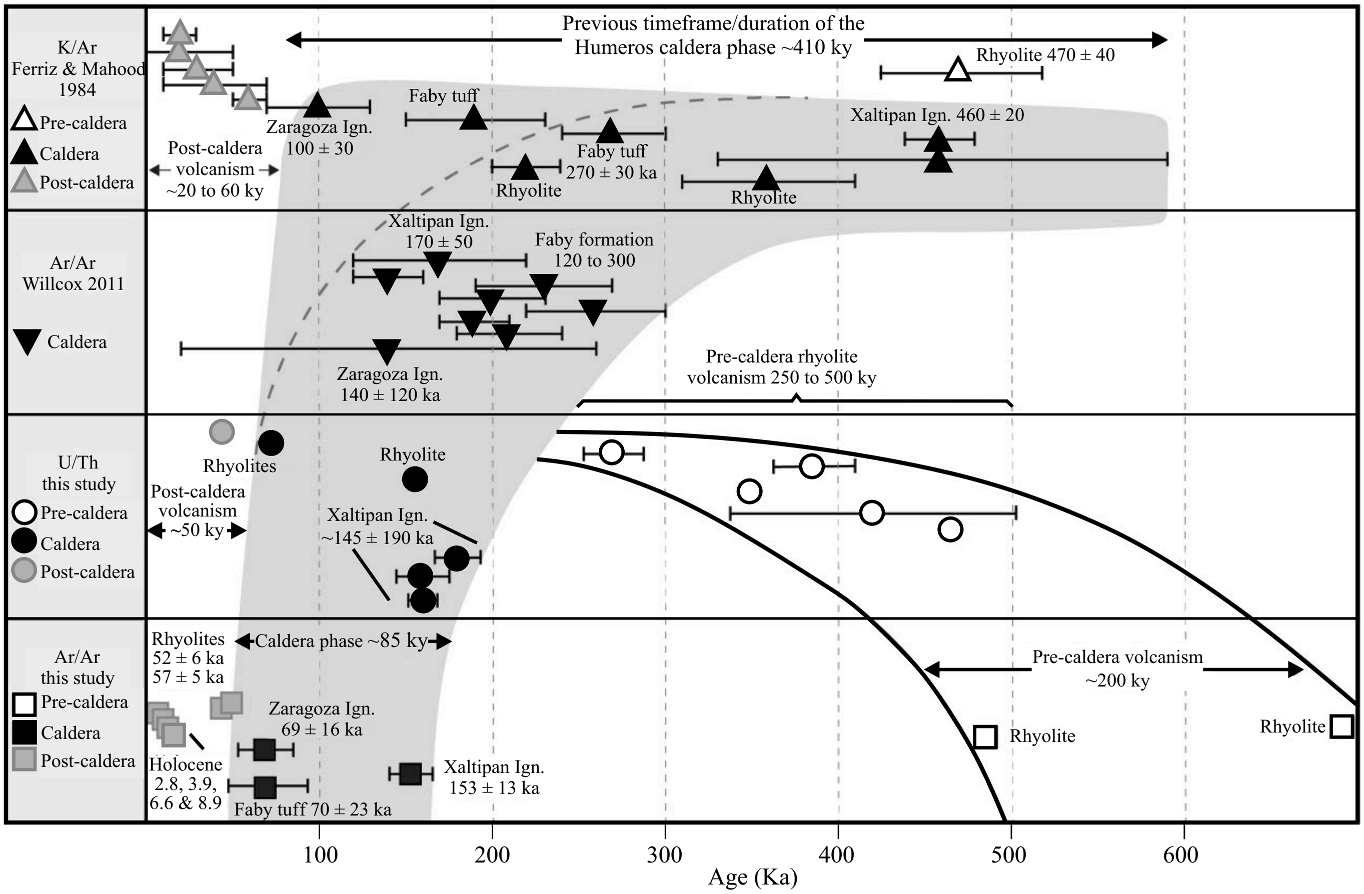

Figure 5. Comparative plot of reported ages for the different stages of LHVC (pre-caldera: open, caldera: black, post-caldera: gray symbols) by different authors and methods (modified from Carrasco-Núñez *et al.*, 2018).

The abundance of clay in the cohesive lahars allows them to travel and carry large boulders for long distances without lateral transformation. Although this kind of cohesive lahars has occurred in some other volcanoes such as Mt. Rainier (Crandell, 1971; Vallance and Scott, 1997) and Nevado de Toluca (Capra and Macías, 2000), this was the first case reported in Mexico.

In the case of Cofre de Perote, two large-volume volcanoclastic deposits have been identified on the eastern lower flanks of the volcano, which are associated with the horseshoe-shaped amphitheater that characterizes the eastern sector of the Cofre de Perote summit área (Figure 3d), as a clear evidence of the multiple sector collapse events that have affected the configuration of the volcanic edifice through time (Carrasco-Núñez *et al.*, 2010). These two deposits (named Los Pescados and Xico) present features of both debris avalanche (*e.g.* hummocks and jigsaw structures) and debris flow deposits and include moderate amounts of hydrothermally altered clay minerals in the matrix (Figure 3f), suggesting that they originated from catastrophic edifice collapses that partially transformed downstream to debris flows (Carrasco-Núñez *et al.*, 2006). As in the case of Citlaltépetl volcano,

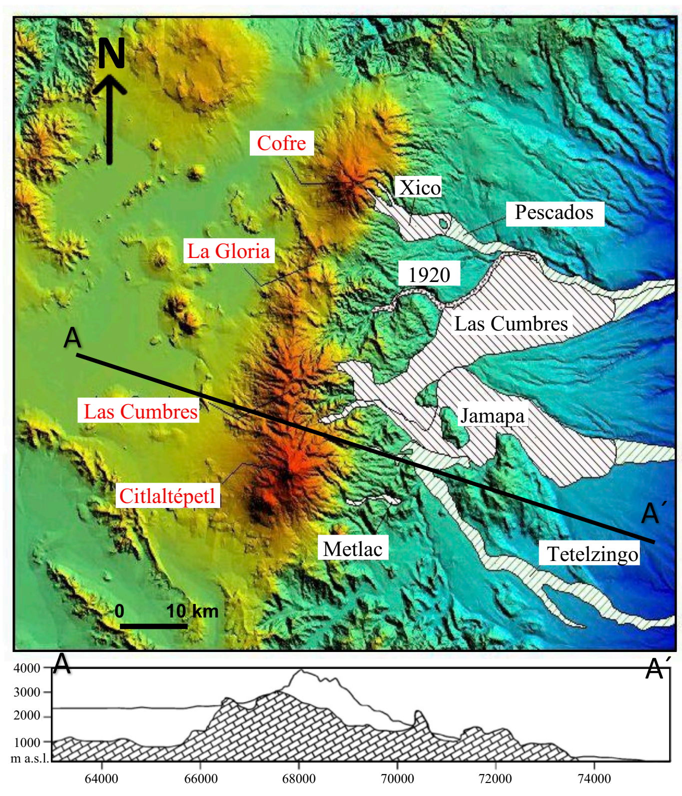

Figure 6. Colored Digital Elevation Model indicating the distribution of the main debris avalanche (black lines pattern) and associated downstream-transformed debris flow deposits (green lines pattern), all of them emplaced towards the eastern CCPVR to the coast (from Carrasco-Núñez *et al.*, 2010). Section A-A´ shows a general eastward slopping substrate of the limestone basement (from Carrasco-Núñez *et al.*, 2006).

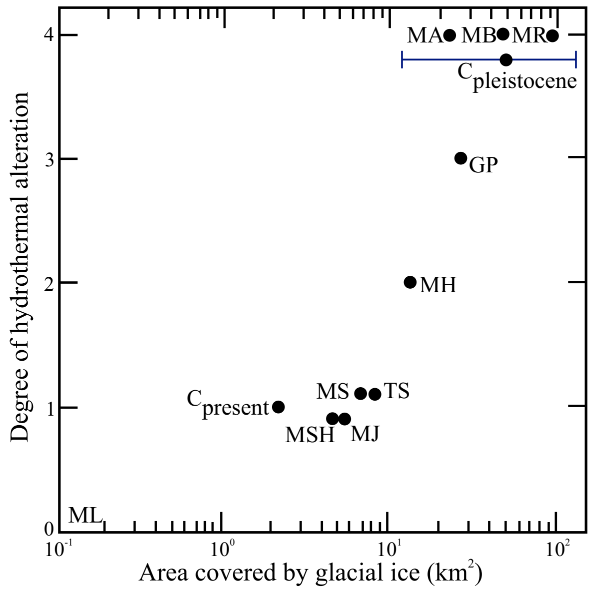

Figure 7. Relation of the degree of hydrothermal alteration *versus* the area covered by glacial ice for the Citlaltépetl and some Cascade volcanoes (from Carrasco-Núñez *et al.*, 1993). Key for degree of alteration: 0- no alteration; 1- small areas of moderate alteration; 2- moderate alteration; 3- large areas of moderate alteration; 4- large intensely altered rocks. Labels for volcanoes: C- Citlaltépetl, MA- Mount Adams; MB- Mount Baker; MR- Mount Rainier; GP- Glacier Peak; MH- Mount Hood; MS- Mount Shasta; TS- Three Sisters; MSH- Mount St. Helens; MJ- Mount Jefferson; ML- Mount Lassen.

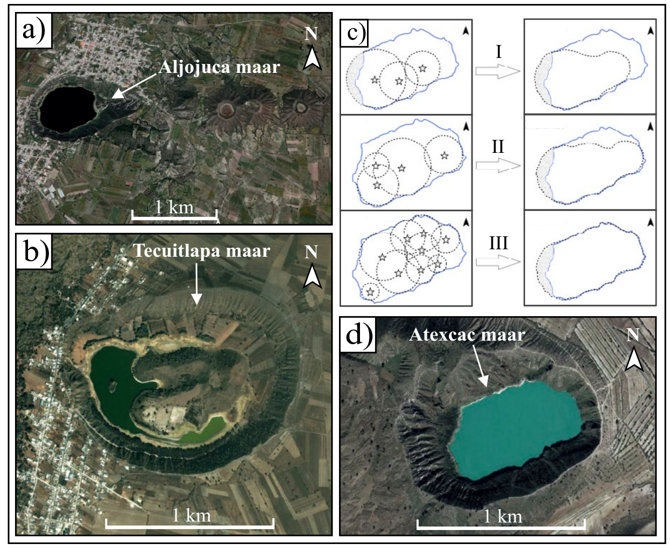

Figure 8. Google Earth satellite images of selected maar volcanoes of the Serdán-Oriental Basin showing E-W crater elongation and/or cone alignments for a) Aljojuca and b) Tecuitlapa; c) Atexcac successive eruptive locus migration grouped into 3 main stages (modified from López-Rojas and Carrasco-Núñez, 2015); and d) a NE-trending elongated crater for Atexcac.

it is very likely that water originated from melting of a glacier in association with the hydrothermal system enhancing the process of alteration. The presence of an ancestral glacier is supported by different glacial features, such as: U-shaped valleys, lateral moraines, cirques, etc., which were identified in many localities on the upper parts of the mountain (Carrasco-Núñez *et al*., 2010). Capra *et al*. (2013) present strong evidence of how climatic variations during the Late Pleistocene could have promoted sector collapses of these volcanoes and enhanced the mobility and transformation of debris avalanches into debris flows.

Special explosive processes

Controls of the lateral migration of phreatomagmatic activity

Maar volcanoes are formed by the interaction of ascending magma with phreatic or superficial water by repeated phreatomagmatic explosions leading to the formation of 1–2 km diameter craters. These explosions are attributed to molten fuel-coolant interactions (MFCI; Zimanowski, 1998) producing punctuated explosions and discrete, instantaneous, and repetitive deposits. Craters formed by phreatomagmatic activity commonly have a circular shape, but they also frequently produce elongated or quite irregular-shaped craters due to lateral vent migration during the maar formation (Graettinger and Bearden, 2021). However, this is not commonly a simple and systematic process, as in the case of Atexcac crater, where the irregular, and shallow pre-maar country rock led to the overlapping of a large number of eruptive locus during its evolution, which can be grouped into 3 main eruptive stages (Figure 8c), although producing at the end a general NE-SW trending elongation (Figure 8d) (Carrasco-Núñez *et al*., 2007; López-Rojas and Carrasco-Núñez, 2015). In fact, a recent study compiling the shape of more than 200 maar craters reveals that at least three different explosion locations are involved but do not always follow the trend of the dike that commonly feeds the eruption (Graettinger and Bearden, 2021). Other examples like Aljojuca and Tecuitlapa craters show both an elongated crater and vent alignment of associated cones, which are oriented parallel to the E-W regional trend (Figure 8a, 8b), indicating a structural control in their formation. Aljojuca evolved into two main eruptive phases, producing first a circular crater by intense phreatomagmatic activity with subordinated strombolian eruptions, followed by a sequence of directed phreatomagmatic explosions and then by the subsequent flank collapse of the eastern sector of the main crater (De León *et al*., 2020). In the case of Tecuitlapa, it is interesting that an initial migration of the eruptive locus occurred from East to West during the development of the phreatomagmatic crater, but it was followed by the successive construction of cinder and small lava cones aligned in the reverse order, from West to East within the crater (Ort and Carrasco-Núñez, 2009) (Figure 8b). The way to explain this special behavior is attributed to lateral migration of the initial phreatomagmatic eruptions within a shallow subsurface formed by water-saturated tuff and sediments unit. These eruptions dried out when the water of this unit exhausted, so the eruptive locus migrated downwards, and the following eruptions were dominantly magmatic and effusive through a principal E-W trending dike favoring the construction of the inner cones (Ort and Carrasco-Núñez, 2009). This case shows the influence of the country rock on the migration of eruptive locus and availability of water for the initial phreatomagmatic activity following with the regional structural trends. The presence of scoria (magmatic) tephra derived from strombolian activity at the upper part of the stratigraphic column in the Tecuitlapa maar confirms the progressive loss of water upwards.

Some other interesting features of maar volcanoes can be explored such as: Alchichica (rapid transition from strombolian to phreatomagmatic activity, Chako Tchamabe *et al*., 2020), Tepexitl tuff ring: unusual rhyolitic phreatomagmatism, Austin-Erickson *et al*., 2011; Cerro Pinto dome and tuff complex: alternated effusive and explosive phases, Zimmer *et al*., 2010).

Syn-eruptive bimodal eruption of contrasting magmas

Bimodal volcanic activity from independent eruptive vents but contemporaneous is unusual and has been poorly documented in

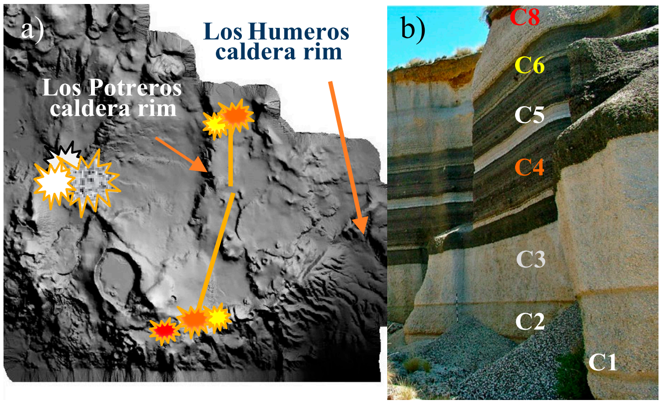

Figure 9. a) Digital elevation model showing the location of the inferred vents associated with the eruption of the 7.4 ky Cuicuiltic activity at LHVC: white and grey stars for the felsic fallout layers (C1, C2, C3, and C5), while the yellow, orange, and red stars indicate the vents for the mafic fallout layers (C4, C6), mixed deposit (C8) as indicated in "b". The orange line suggests the position of a possible fracture connecting the north and southern vents. b) Stratigraphic succession showing intercalations of felsic and mafic layers forming the Cuicuiltic sequence (modified from Dávila-Harris and Carrasco-Núñez, 2014).

the geological record (*e.g.* Tenerife's Las Cañadas volcano, Edgar *et al.*, 2007; 1256 A:D: Madinah eruption in Saudi Arabia, Camp *et al.*, 1987) or in historical eruptions (*e.g.* 1991 Hudson eruption in Chile; Kratzmann *et al.*, 2009; Eyjafjalllajokull, Sigmarsson *et al.*, 2011). An example of this unusual syn-eruptive bimodal activity is represented by the Holocene (7.3 ky) Cuicuiltic member, which corresponds to the last major explosive activity recorded for Los Humeros caldera. It is an alternated sequence of fallout layers covering the inner part of the caldera (Figure 9), showing a contrasting composition from basaltic andesite: 53 % SiO_2 to trachydacite: 69 % SiO_2 with lesser intermediate compositions (trachyandesites). A complete characterization of this member was performed by Dávila-Harris and Carrasco-Núñez (2014) based on detailed stratigraphic sections, component analysis, isopach and isopleths maps, physical characteristics, petrography and geochemistry. The distribution of the trachydacitic (felsic) layers show a dispersal from the central part of the caldera, which can be associated with relatively high Plinian columns; while the basaltic andesite layers have maximum thicknesses towards the SE and NE sectors, suggesting contemporaneous Strombolian activity from at least two distinct vents (Figure 9). The simultaneous eruption of highly contrasting compositions (basaltic andesite and trachyandesite) and eruptive styles (Plinian and Strombolian) from different vents forming an episodic synchronous succession is exceptional in active caldera environments, and may confirm the existence of a heterogeneous zoned magmatic reservoir that first tapped the felsic magma due to contrasting density and viscosity conditions, and subsequently erupts mafic magma near weakness planes up to the surface, as proposed by Dávila-Harris and Carrasco-Núñez (2014).

Special petrologic processes and systems

Complex compositional zonation, magma mixing and mingling in the origin of ignimbrites

Vertical compositional zonation is a relatively common pattern in large-volume ignimbrite deposits, showing an upward trend from silica-rich pumice at the base to more mafic pumice at the top. This zonation is interpreted to record progressive eruption withdrawal beginning from the upper part of a density-stratified magma chamber, tapping first a silica-rich zone and then a deeper, denser, and more mafic part of the magma chamber with time (*e.g.* Bacon and Druitt, 1988; Freundt and Schmincke, 1992), during a relatively continuous process of progressive aggradation (Branney and Kokelaar, 1992).

A detailed study of the stratigraphy and sedimentology of the Zaragoza ignimbrite documents the compositional zonation of the single massive pyroclastic layer (Carrasco-Núñez and Branney, 2005).

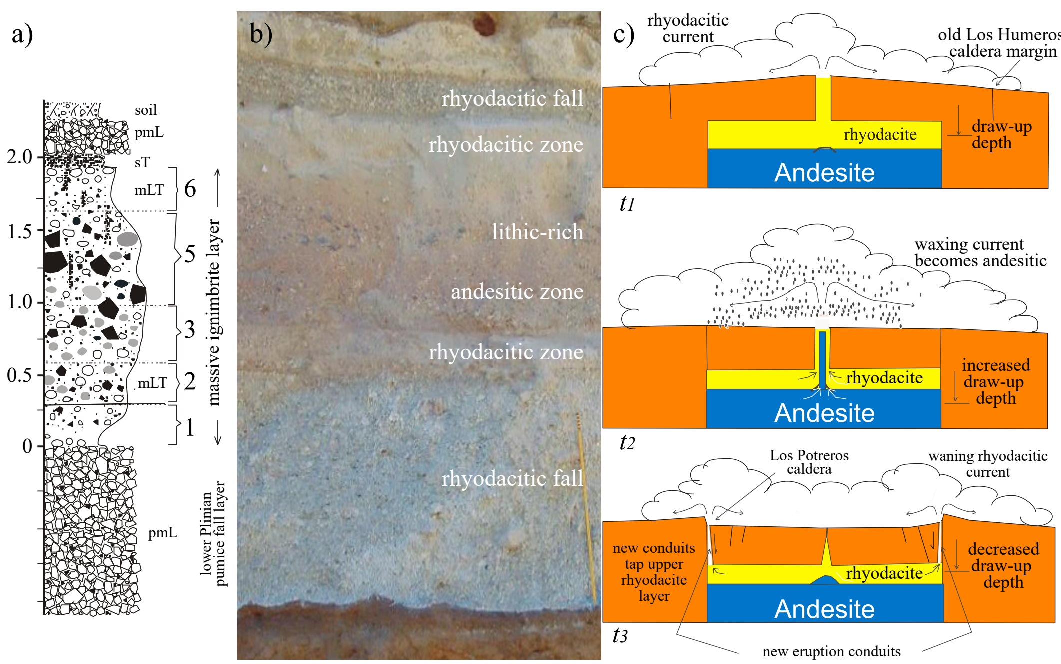

Figure 10. Composite figure for the Zaragoza ignimbrite derived from Los Potreros caldera at LHVC. a) Stratigraphic type section of the Zaragoza ignimbrite. b) Photograph showing the compositional zones. c) Interpretation of the double compositional zonation in 3 different times emplaced by progressive aggradation (modified from Carrasco-Núñez and Branney, 2005).

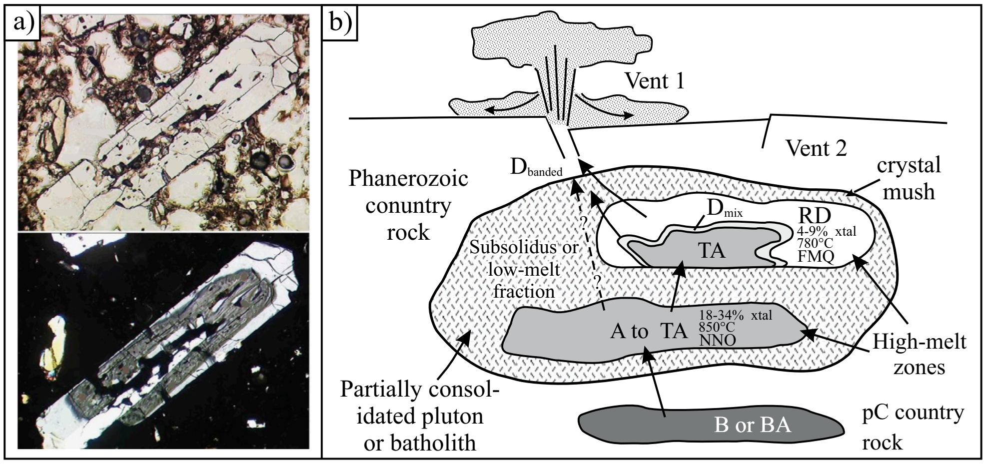

Figure 11. Petrologic processes involved in the formation of the Zaragoza ignimbrite. a) Photomicrograph showing zonation of a plagioclase phenocryst inferring 2 different magmas (gray central-rhyolite and white outer-andesite, in polarized light, lower photo). b) Conceptual model of the complex magmatic reservoir (after Carrasco-Núñez *et al.*, 2012).

This layer represents an intraplinian event bounded by two pumice fall layers (Figure 10a). This ignimbrite is associated with the formation of Los Potreros caldera (at 69 ky; Carrasco-Núñez *et al.*, 2018), which is part of the Los Humeros caldera complex. What is relevant is that it exhibits an unusual double compositional zonation with a basal rhyodacite zone grading up to a mixed central andesitic zone (normal zoning), which grades up into another rhyodacite zone (reverse zoning) (Figure 10b). This zonation is also observed in the vertical variations of the lithic clasts, presenting a lithic-rich layer at the lower middle part of the ignimbrite unit, which represents the point where Los Potreros caldera collapse occurred. The double zonation is interpreted to record an initial tapping of the rhyodacite top of the magma chamber (Figure 10c, t3) followed by eruption waxing (increasing the draw-up depth and tapping now the andesitic magma) (Figure 10c, t2), continuing with a waning stage of the pyroclastic current when the rhyodacite pumice was deposited in the upper part. This final reverse zoning may have been the result of the conduit geometry modification during the collapse of Los Potreros caldera, where the draw- up decreases and new conduits tap the upper rhyodacite magma again as proposed by Carrasco-Núñez and Branney (2005) (Figure 10c, t3).

Further investigations helped to unravel the complex nature of the magmatic processes that occurred during the formation of Los Potreros caldera. Petrographic and microprobe analyses of coexisting phenocrysts (Figure 11a) and glass revealed disequilibrium conditions in the different magmas identified by the diversity of pumice clasts formed during the eruption. The results indicate that the Zaragoza eruption was not associated with a simple density-stratified magma reservoir, but more likely to a complex magmatic system dominated by rhyodacite zones possibly arranged as semi-connected high-melts lenses within a crystal mush, in which hybridized andesitic magmas intruded to produce mixing and mingling with the rhyodacite reservoir (Figure 11b) (Carrasco-Núñez *et al.* 2012), which are contrary to assumptions supporting a simple process of replenishment, tapping, and crystal fractionation systems, as there is not a record of evolved rhyolites related to the Zaragoza magmatic system.

Reappraisal of complex magmatic plumbing systems

Characterization of the magmatic plumbing system is challenging, particularly in large and complex caldera systems hosting a geothermal reservoir for a proper assessment and modeling of the heat source. The standard model considers a single large bowl-shaped magma reservoir where a diversity of petrological processes of differentiation, crystal fractionation, and assimilation occur (*e.g.* Hildreth 1979; Hildreth and Wilson, 2007). However, more recent innovative conceptual models propose a more complex irregularly-shaped geometric configuration with variable interconnected zones of magma accumulation hosted in largely crystallized and vertically extensive mush zones with partially active melt zones (*e.g.* Bachman and Bergants, 2004; Cashman and Giordano, 2014; Cashman *et al.*, 2017).

A standard model was originally proposed for the magmatic reservoir of LHVC, so the heat source was constrained by the caldera's geometry, the volume and mass balance calculations of the caldera-forming ignimbrites (*e.g.* Ferriz and Mahood, 1984, 1987; Verma, 1983), which consider a single magma body installed at about 5 km depth. However, a recent geothermobarometric study (Lucci *et al.*, 2020) performed for the post-caldera Holocene volcanism of the LHVC provides support for an innovative heterogeneous magmatic plumbing system model, consisting of multiple interconnected and stagnated small reservoirs installed at different depths, ranging from 3 km up to 30 km (Lucci *et al.*, 2020) (Figure 12). This magmatic system feeds the compositionally heterogeneous volcanism featuring the southern caldera ring-fracture volcanic field emplaced during the Holocene, which is characterized by compositionally heterogeneous lava flows including olivine basalts, basaltic andesites, trachyandesites, and trachytes.

Coeval contrasting magma compositions derived from a homogeneous mantle source

Contemporaneous eruption of alkaline and calc-alkaline volcanoes has been reported in different places in Mexico, such as western Mexico (*e.g.* Lange and Carmichael, 1990), Colima (Luhr and Carmichael, 1985), and Chichinautzin volcanic fields (Wallace and Carmichael, 1999), and other sites like Cascades (Leeman *et al.*, 1990), and the Andes (Hildreth and Moorbarth, 1988). The coeval eruption of magmas showing contrasting compositions has been generally explained by the existence of a heterogeneous sub-arc mantle consisting of a mixture of depleted, enriched, and subduction-modified reservoirs. However, the case of El Volcancillo, described already in the previous sections, is unusual for volcanic arcs, because here the contemporaneous occurrence of alkaline and calc-alkaline volcanism is explained by variable degrees of melting from a similar isotopically homogeneous largely depleted source, as demonstrated by Carrasco-Núñez *et al.* (2005).

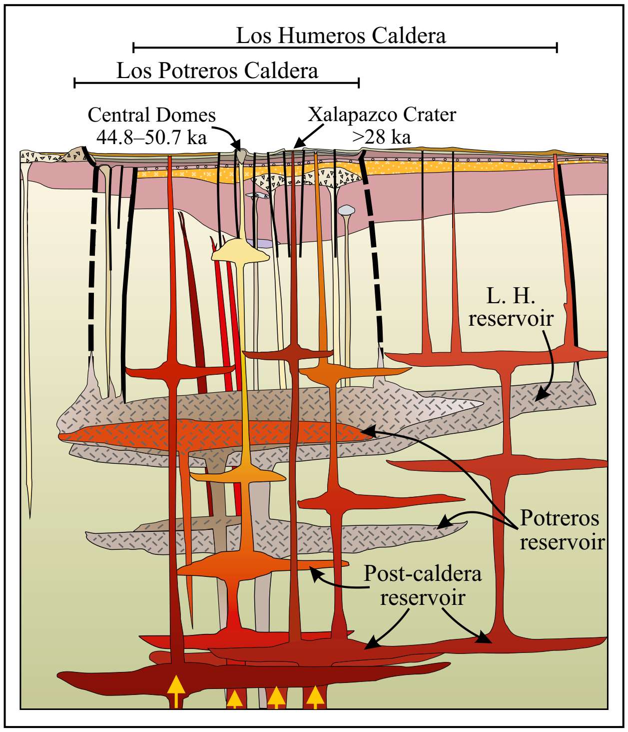

Figure 12. Cartoon showing the synthesized evolution of the LH magmatic reservoir. The caldera-forming large reservoirs (Los Humeros -1.64 ky and Los Potreros -0.69 ky) are depicted in gray color, while the red, orange, and yellow zones represent all the Holocene post-caldera magmatic plumbing system (modified from Carrasco-Núñez *et al.*, 2022).

VOLCANIC HAZARDS

Uncovering active volcanism

In the past decades, the only reported active volcano on the ET-MVB was Citlaltépetl volcano, located to the front of the arc. However, different studies performed in the last years reveal the Holocene age of many other volcanic centers. The location of this recent volcanism shows no systematic patterns, instead it is randomly distributed along the entire area (Carrasco-Núñez *et al.* 2021), which is contrary to the general appreciation that the volcanic front of the TMVB tends to migrate trenchward.

To the north of the ETMVB, there are several occurrences of Holocene activity. The compositionally heterogeneous ring-fractured volcanic field associated with the post-caldera volcanism of LHVC has C^{14} ages at 3.8 ky and 2.8 ky (Carrasco-Núñez *et al.*, 2018). Also at LHVC, the already mentioned Cuicuiltic member has an age of 7.3 ky, and some lavas within Los Humeros caldera are dated at 8.9 ky. The Cuicuiltic member is particularly important for hazards as this activity implies the simultaneous activation of different vents showing contrasting composition and eruptive style. In addition to this volcanism, El Volcancillo represents one of the youngest pre-hispanic volcanoes erupted in Mexico (870 yr BP, Siebert and Carrasco-Núñez, 2002; 780 yr BP, Jacome-Paz *et al.*, 2022), which it is surrounded by other Holocene cones, some of them forming a NE-trending alignment of more than ten vents (Figure 2), which is in turn parallel to the main regional stress regime. This could show that this is a volcanically active zone.

Other reports of Holocene volcanism occurred in the middle (Alchichica crater, 6.8–11.8 ky, Chako Tchamabe *et al.*, 2020), or in the southern parts of the Serdán Oriental Basin (Aljojuca, 3.3–4.1 ky, De León *et al.*, 2020; Tecuitlapa, Ort and Carrasco-Núñez, 2009). New ages reported recently (Chédeville *et al.*, 2019) confirm these young ages and also Holocene ages are reported for Las Derrumbadas domes, Cerro Pinto, Tepexitl, and some other places, revealing that the ET-MVB, in general, is a volcanologically active region with very random distribution, which is highly relevant for future hazard assessments.

Furthermore, volcanoes such as the Cerro Pizarro rhyolitic dome, which behaves as a polygenetic volcano as described previously, involve long periods of repose during its evolution, and although this is not regarded as an active volcano, the possibility of future awakening cannot be discarded at all.

Edifice Instability assessment

As described before, the volcano's edifice instability of the CCPVR is strongly controlled by the abrupt drop in relief, and the eastward slopping basement substrate (Figure 6), where hydrothermal alteration contributes to generating weak and unstable conditions (Zimbelman, 1996), which can be enhanced in the presence of a glacier.

Cofre de Perote shows a gentle morphology with apparent stable conditions of a long-quiescent edifice; however, the occurrence of repetitive sector collapse events strongly supports the significant hazard that this volcano may pose even if is not currently active (Carrasco-Núñez *et al.*, 2010).

So far, it has not been yet reported compelling evidence that magmatic activity caused any of the large edifice collapse of the CCPVR. Instead, other triggering mechanisms such as seismic activity, strong hydrothermal alteration, very high rainfall, and intense fracturing must be considered.

Hazard maps

Mapping volcanic hazards is a prime product to show the areas that can be potentially impacted by hazardous volcanic events, including debris avalanches, lahars, pyroclastic flows, fallout ash, and ballistic deposits, and lava flows. They are based on volcanological information revealing the eruptive history of the volcano, spatial and temporal distribution, and frequency of events and include scenarios from other volcanoes with similar eruptive conditions. Even though Citlaltépetl is the only volcano having a hazard map within the ETMVB (Figure 13) (Sheridan *et al.*, 2001, there are some hazard approaches including: a regional assessment for debris flows for three different levels of hazard for the whole CCPVC (Carrasco-Núñez *et al.*, 2006), in addition to some specific assessments for Cofre de Perote on potential worst-case scenario for the formation of debris avalanches derived from edifice collapse events (Figure 14), and a comparison of different methodologies for debris flows from Citlaltépetl volcano (Hubbard *et al.*, 2007).

GEOTHERMAL EXPLORATION

Long-lived volcanic systems provide heat for hundreds of thousands of years and even up to millions of years (*e.g.* Wilson and Charlier, 2009). The younger ages reported for the caldera-forming volcanism (described above) are an important finding because they represent enhanced thermal conditions of the system envisaging more heat and favoring longer and higher geothermal potential (Figure 15) (Carrasco-Núñez *et al.*, 2018). Equally important for the application of heat conduction models to geothermal systems is the evidence and timing of rejuvenation of the system due to the recharge of magmas, which is evident from the short time scales (<5 ky) of magma assembly occurred before Los Humeros caldera-forming eruption as proposed by Carrasco-Núñez *et al.* (2018).

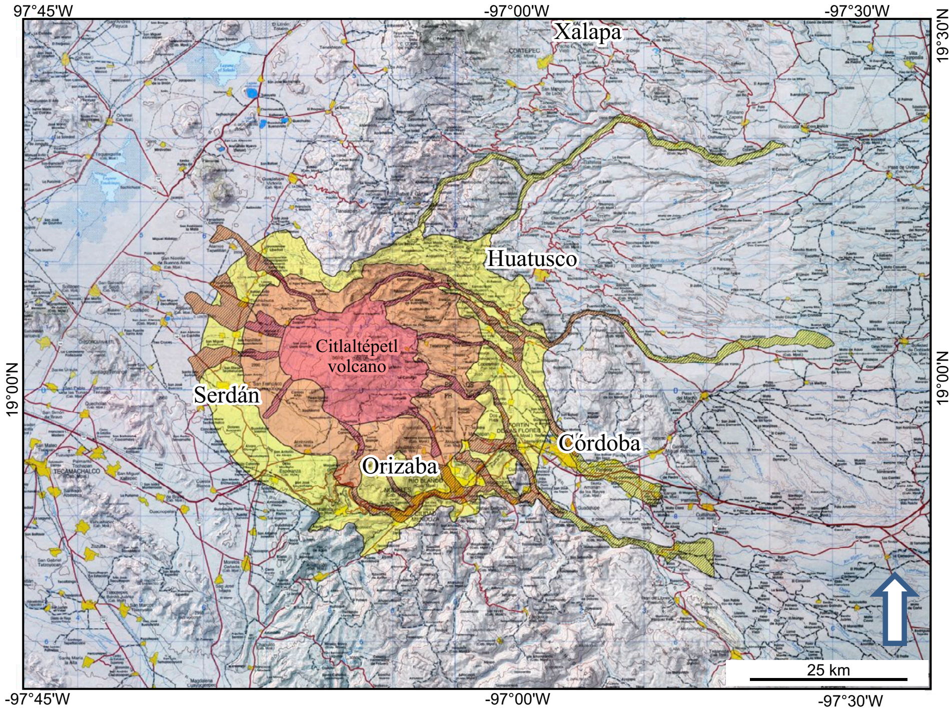

Figure13. Hazard map of the Citlaltépetl (Pico de Orizaba) volcano, showing the three main levels of hazard degree: red-high; orange-intermediate, and yellow-low. The narrow arm-shaped areas indicate extended hazards from the three main zones, which are mainly for debris and pyroclastic flows. Modified from Sheridan *et al.* (2001). A copy of the original map is hosted on this journal's server and can be downloaded from <http://www.rmcg.unam.mx/index.php/rmcg/article/view/1755> or by *clicking here* (For the electtronic version of this paper).

Multidisciplinary projects on LHVC (CemieGEO and GEMEX research consortiums) have provided new elements to improve the knowledge about the geothermal system, particularly on the reconfiguration of the heat source, lithofacies variations affecting permeability of the cap rock, role of microporosity on permeability, and some other aspects such as the complex internal structure derived from the reappraisal of the subsurface lithostratigraphy (Peña Rodríguez, 2021), which is beyond the scope of this review and thus has not been considered.

Reappraisal of the heat source configuration

The standard model of a large geothermal magmatic heat source associated with large caldera systems considers a classical melt-dominated, single, voluminous, long-lived magma chamber (*i.e.* the Standard Model in Gualda and Ghiorso, 2013) that has been envisaged so far at LHVC (*e.g.* Verma *et al.*, 2011). This model is perfectly valid for the caldera stage, and most of the current thermal models of the heat source consider it; however, it is possible that the two caldera-forming eruptions depleted largely this magma chamber from the melt phase, and that the crystallized part of the large magma chamber of the caldera stage has not been recharged and is presently cooling (Figure 12). In contrast, during the post-caldera stage (particularly during the Holocene) scattered small-volume magma batches intruded at various times and depths, configuring a much more complex geometry for the magmatic heat source(s), as described earlier (Lucci *et al.*, 2020). This multilayered magmatic system may include stagnation levels locally, very shallow to be intruded within the geothermal reservoir and caprocks (Urbani *et al.*, 2020).

Lithofacies variation in the cap rock affects permeability

The Xáltipan ignimbrite, associated with the formation of Los Humeros caldera, represents the largest eruption of the TMVB, with a Dense Rock Equivalent-volume of 291 km^3 (Cavazos-Álvarez and Carrasco-Núñez, 2020). It has been commonly regarded as a homogenous unit with low to null permeability that acts as the caprock of the system of the Los Humeros geothermal field (*e.g.* Cedillo, 2000). However, recent geological characterization of the outer and intracaldera deposits of this ignimbrite revealed abrupt lithofacies variations caused mainly by welding processes and secondary mineralization (Cavazos-Álvarez *et al.*, 2020). They usually vary from highly welded (with evident pore reduction by compaction of 5–6 % and practically

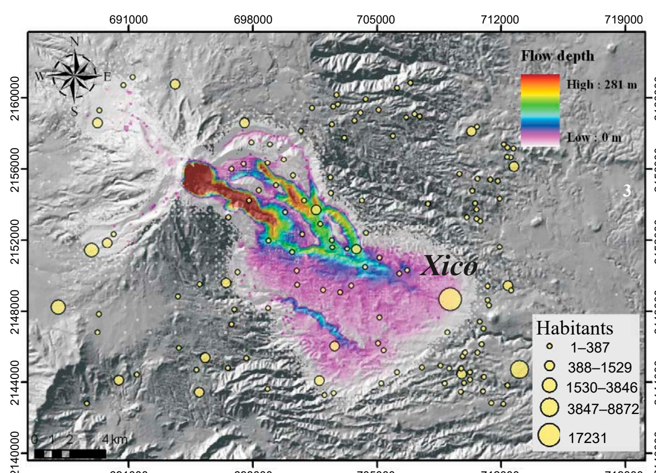

Figure 14. Worst-case scenario obtained by TITAN2D simulations to define hazard zonation for Cofre de Perote debris avalanche events. The colors correspond to the flow depth distribution as indicated in the vertical bar scale (modified from Carrasco-Núñez *et al.* 2010).

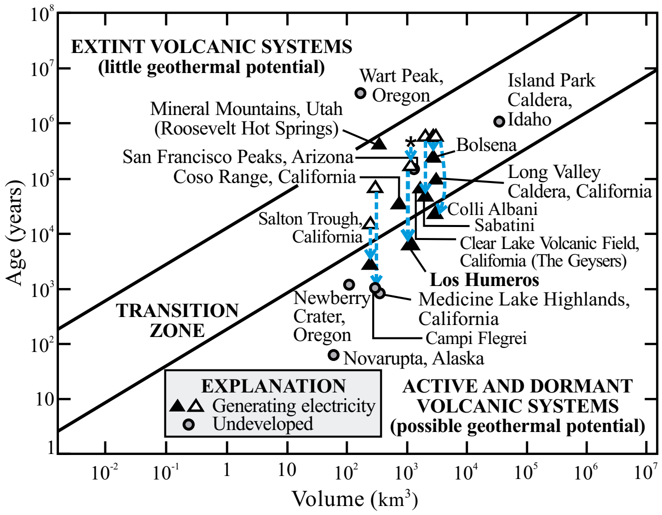

Figure 15. Age of most recent rhyolitic volcanism *versus* erupted volume. The younger age obtained for LHVC allows it to move from the transitional to the active volcanic systems (marked with blue dashed lines) (after Carrasco-Núñez *et al.*, 2018).

null permeability) at the base of the stratigraphic sequence, to moderate and non-welded (with low to moderate permeability) to the top, but this trend is not laterally continuous (Figure 16). This highly heterogeneous configuration at Los Humeros subsurface geology may cause strong lateral and vertical changes in permeability.

These observations are consistent with geophysical studies that show spatial resistivity anomalies along the Xáltipan deposits, and that are interpreted as occur due to zones of high conductivity (Corbo-Camargo *et al.*, 2020). These observations contradict the conventional idea that suggests that the Xáltipan ignimbrite is spatially homogeneous and that acts as caprock of the geothermal system. Therefore, these results (lateral and vertical variations in the welding lithofacies for the Xaltipan ignimbrite) must be strongly considered to anticipate strong variations in permeability within the LH geothermal reservoir.

Role of microporosity on permeability

Permeability in geothermal systems is usually attributed to secondary processes including faults and fractures, particularly in volcanic units where macroporosity (< 1 μm) is commonly low or not connected and thus its contribution to permeability is commonly underestimated. However, microporosity studies performed in andesite lava samples from a production well at Los Humeros geothermal field using X-ray Micro-Computed Tomography (uCT) demonstrate that microporosity can act as a link between the macropores, enhancing pore network connectivity, reaching in some cases more than 70 % of connected pores (Cid *et al.*, 2021). Results from this study show a relatively higher porosity in samples ranging between 1600 and 2200 m depth, which coincides with the permeable zone (reservoir) proposed by the field operator CFE (Comisión Federal de Electricidad). Precise absolute permeability simulations were used to identify a peak in permeability in the zone between 2000 and 2100 m depth. In general, a good correlation can be observed between the computed porosity permeability and the well-logs, indicating that porosity associated with the micropore fraction provides effective flow pathways that enhance reservoir permeability (Figure 17). It seems like microchannels allow the flow of highly pressured water steam of the vapor-dominated reservoir, with effective traveling through small cavities. Therefore, in addition to fractures and faults, primary microporosity in the reservoir volcanic rocks has a remarkable contribution to the permeability of Los Humeros geothermal reservoir. These analyses are necessary during the exploration stage for an accurate permeability model.

CONCLUDING REMARKS

This paper joins a collection of examples of Mexican volcanism (ETMVB) representing interesting contributions derived from a diversity of case studies reported in the last three decades, highlighting unusual and/or characteristic peculiarities, and uncovering their hazards and geothermal applications.

This research confirms the complex nature of volcanism, in particular, some important issues are uncovered, such as: a) Complexity of monogenetic volcanism exhibiting polymagmatic and/or polygenetic

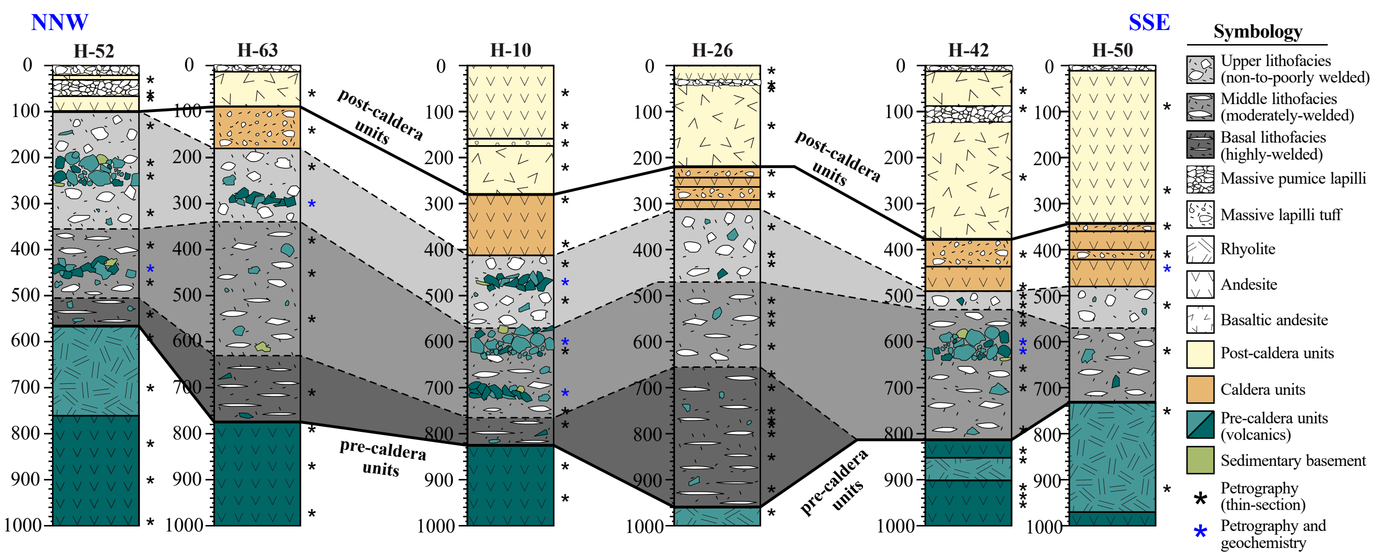

Figure 16. NNW-SSE trending subsurface profile of selected geothermal wells for Los Humeros geothermal field showing the discontinuous lateral distribution of the three main welding lithofacies identified within the Xaltipan ignimbrite, with different grey color intensities (after Cavazos-Álvarez *et al.*, 2020).

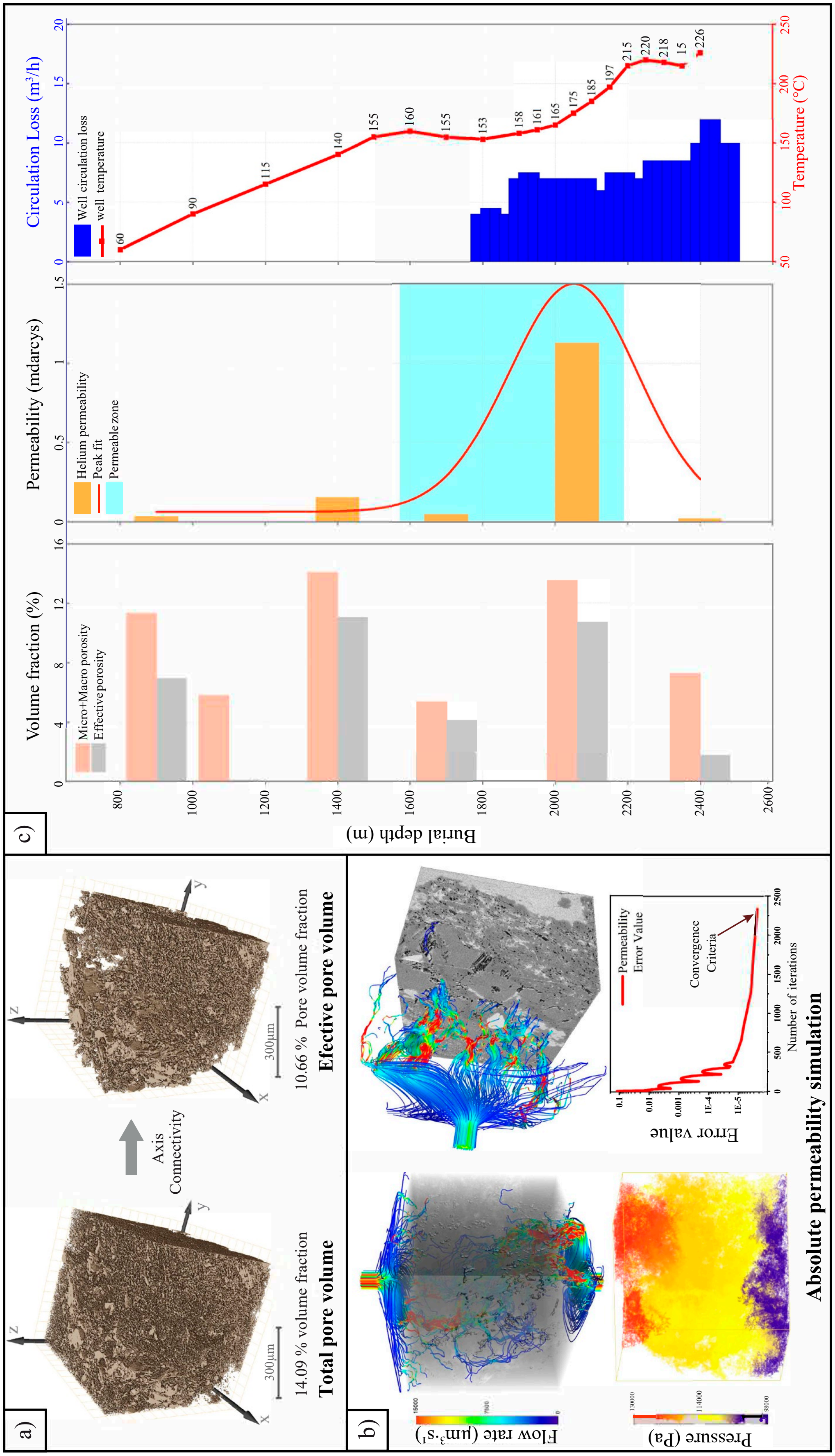

Figure 17. Summarized Micro-CT studies to determine microporosity in samples of the LHVC geothermal wells revealing the role of pores smaller than 1 µm (microporosity) as the main responsible of void volume connectivity. a) 3D images showing the total pore volume and effective porosity of an andesite geothermal core. b) Absolute permeability simulation showing the connected porosity. c) Plots of the volume fraction for micro-macro and effective porosity, permeability, and circulation loss (provided by CFE), showing a good correlation with the temperature, permeability, and fluid circulation logs. (modified from Cid *et al.*, 2021).

behavior with contrasting contemporaneous eruptive styles (*e.g.* El Volcancillo cone, Cerro Pizarro dome); b) diversity and complexity of polygenetic volcanoes such as: hybrid volcanoes, shield-like compound volcano (Cofre de Perote); assembly of caldera structures (Los Humeros); unravelling the eruptive history by geochronologic reappraisal and/or structure analyses (*e.g.* Los Humeros volcanic complex, Citlaltépetl); highlighting the role of glaciers enhancing hydrothermal alteration and weakening volcanic edifices, which in turn promote repetitive collapsing events involving large volume, avalanche-induced cohesive lahars on large composite and compound volcanoes (*e.g.* Citlaltépetl, Cofre de Perote); c) special explosive processes: identifying the controls on lateral migration of phreatomagmatic activity (*e.g.* Tecuitlapa-Atexcac-Ajojuca maars); uncovering unusual syn-eruptive bimodal eruption of compositionally contrasting magmas (Cuicuiltic member-Los Humeros caldera); d) special petrologic processes and systems: reporting unusual double compositional zonation, magma mixing and mingling in the origin of ignimbrites (*e.g.* Zaragoza ignimbrite); development of polymagmatic multilayered plumbing system model (Los Humeros post-caldera activity), in contrast with the traditional simple reservoir; discovering a coeval eruption of compositionally heterogenous magmas from an isotopically mantle source (El Volcancillo paired cone).

Contributions to understanding the volcanic nature are fundamental to assessing volcanic hazards. Firstly, stressing the relevance of the results from the reappraisal of the LHVC geochronology providing younger ages for the caldera formation meaning greater geothermal potential. Then, uncovering the active volcanism (Holocene) within the EMVB with a random distribution, assessing volcanic edifice instability in active and non-active volcanoes (along the CCPVR), and developing hazard mapping (Citlaltépetl and Cofre de Perote) to show the different degrees and types of potentially hazardous events. Furthermore, several contributions of volcanology are applied to improve geothermal exploration strategies, particularly in the case of Los Humeros volcanic complex and geothermal field, where a thoughtful reappraisal of the heat source configuration was made. Also, a detailed analysis of the lithofacies variation in the so-called cap rock (Xaltipan ignimbrite) reveals important changes affecting the permeability conditions of the system. An additional finding is the research on the role of microporosity of the reservoir volcanic rocks on the permeability of the LHGF, which represents a relevant issue for future consideration in the exploration of geothermal fields. Last but not least important, I want to highlight the relevance of volcanic geology studies as a fundamental and compulsory base for further investigations.

APPENDIX

For a better appreciation of the Figure 13, a copy of the original map by Sheridan *et al.* (2001) is hosted on this journal's server and can be downloaded from <http://www.rmcg.unam.mx/index.php/rmcg/article/view/1755> or by *clicking here* (For the electronic version of this paper).

ACKNOWLEDGEMENTS

This work was supported by PAPIIT project IN108823 (DGAPA, UNAM). CFE provided samples and data useful for Los Humeros geothermal field. Centro de Geociencias (UNAM) provided logistic support for more than two decades since its foundation, this is a tribute to the institution. Several projects funded by CONACYT, including those of the Mexican Energy Sustainability CONACYT-SENER (CemieGeo and GEMEX) were involved in the publication of several cited papers. This review paper was possible through the participation of many academics, students, and supporting people who provided strong input to support all the investigations made over the last 30 years. Thank you to the collaborations with: Mike Branney, Guido Giordano, Federico Lucci, Gianluca Norini, Michael Ort, Nancy Riggs, Lee Siebert; as well as: Masao Ban, Marco Bonini, Brian Jicha, Mike McCurry, Kevin Righter, Bill Rose, Mike Sheridan, Jim Vallance, Surendra P. Verma, David Zimbelman; Jorge Aranda, Jorge Arzate, Juan Pablo Bernal, Harald Böhnel, Lucia Capra, Fernando Corbo, Luca Ferrari, Arturo Gómez, Javier Hernández, Penélope López, Vlad Manea, Adrián Ortega, Juan Vázquez, Sandra Vega; Fidel Cedillo, Pablo Dávila, Jaime Cavazos, Laura Creon, Boris Chako, Bernard Hubbard, Andrea Rossotti; Alison Austin, Héctor Cid, Lorena De León, Rodolfo Díaz, Mario López, José Luis Rodríguez, Claudia Romero, Víctor Vargas, Brian Zimmer and many other academics, administrative supporters, and students. Special thanks to Javier Hernández and Jaime Cavazos who did an excellent work drawing and modifying most of the figures. I thank two anonymous reviewers, Rafael Torres, and the invited editor, Susana Alaniz, for critical and useful observations that helped to improve this paper, as well as Jesús Silva for his very efficient technical editing job. I miss special people like Víctor Vargas and Fidel Cedillo, who unfortunately are no longer with us. I dedicate this work to my wife, my daughters, and all my family for unconditional support and continuous motivation.

REFERENCES

Austin-Erickson, A., Ort, M., Carrasco-Núñez, G., 2011, Rhyolitic phreatomagmatism explored: Tepexitl tuff ring (Eastern Mexican Volcanic Belt): Journal of Volcanology and Geothermal Research, 201, 325-341.

Bacon, C.R., Druitt, T.H., 1988, Compositional evolution of the zoned, calc-alkaline magma chamber of Mount Mazama, Crater Lake, Oregon: Contribution to Mineralogy and Petrology, 76, 53-59.

Bachmann, O., Bergantz, G.W., 2004, On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes: Journal of Petrology, 45, 1565-1582.

Begét, J.E., Kienle, J., 1992, Cyclic formation of debris avalanches at Mount St. Augustine volcano: Nature, 356, 701-704.

Branney, M.J., Kokelaar, B.P., 1992, A reappraisal of ignimbrite: progressive aggradation and changes from particulate to non-particulate flow during emplacement of high-grade ignimbrite: Bulletin of Volcanology, 54, 504-520.

Camp, V.E., Hooper, P.R., Roobol, M.J., White, D.L., 1987, The Madinah eruption, Saudi Arabia: Magma mixing and simultaneous extrusion of three basaltic chemical types: Bulletin of Volcanology, 49, 489-508.

Capra, L., Macías, J.L., 2000, Pleistocene cohesive debris flows at Nevado de Toluca Volcano, central Mexico: Journal of Volcanology and Geothermal Research, 102, 149-168.

Capra, L., Bernal, J.P., Carrasco-Núñez, G., Roverato, M., 2013, Climatic fluctuations as a significant contributing factor for volcanic collapses. Evidence from Mexico during the Late Pleistocene: Global and Planetary Change, 100, 194-203.

Carrasco-Núñez, G., Vallance, J., Rose, W.I., 1993, A voluminous avalanche-induced lahar from Citlaltépetl Volcano, Mexico: Implications for hazard assessment: Journal of Volcanology and Geothermal Research, 59(1/2), 33-46.

Carrasco-Núñez, G., Ban, M., 1994, Geologic map and structure sections of the summit area of Citlaltepetl Volcano, Mexico, with summary of the geology of the Citlaltépetl volcano summit area: Instituto de Geología., Universidad Nacional Autónoma de México (UNAM), Cartas Geológicas y Mineras # 9.

Carrasco-Núñez, G., Gómez-Tuena, A., Lozano, V.L., 1997, Geologic map of Cerro Grande volcano and surrounding area, Central Mexico: The Geological Society of America Bulletin, Map Chart Series, MCH, 081, 10 pp.

Carrasco-Núñez, G., 1999, Holocene block-and-ash flows from summit dome activity of Citlaltépetl Volcano: Journal of Volcanology and Geothermal Research, 88(1/2), 67-75.

Carrasco-Núñez, G., 2000, Structure and proximal stratigraphy of Citlaltépetl Volcano (Pico de Orizaba), Mexico: Special paper "Cenozoic Volcanism and Tectonics of Mexico" of the Geological Society of America Special Paper, 334, 247-262.

Carrasco-Núñez, G., Righter, K., Chesley, J., Siebert, L., Aranda-Gómez, J.J., 2005, Contemporaneous eruption of calc-alkaline and alkaline lavas in a continental arc (Eastern Mexican Volcanic Belt): chemically heterogeneous but isotopically homogeneous source: Contributions to Mineralogy and Petrology, 150, 423-440.

Carrasco-Núñez, G., Branney, M., 2005, Progressive assembly of a massive layer of ignimbrite with normal-to-reverse compositional zoning: the Zaragoza ignimbrite of central Mexico: Bulletin of Volcanology, 68, 3-20.

Carrasco-Núñez, G., Díaz-Castellón, R., Siebert, L., Hubbard, B., Sheridan, M. F., Rodríguez, S. R., 2006. Multiple edifice-collapse events in the Eastern Mexican Volcanic Belt: the role of sloping substrate and implications for hazard assessment, *in* Tibaldi, A., Lagmay, A., (eds.), The effects of basement structural and stratigraphic heritages on volcano behaviour: Journal of Volcanology and Geothermal Research, 158, 151-176.

Carrasco-Núñez, G., Ort, M., Romero, C., 2007, Evolution and hydrological conditions of a maar volcano (Atexcac crater, Eastern Mexico), *in* Martin, U., Németh, K., Lorenz, V., White, J. (eds.), Maar-diatreme volcanism and associated processes: Journal of Volcanology and Geothermal Research, 159, 179-197.

Carrasco-Núñez, G., Riggs, N., 2008, Polygenetic nature of a rhyolitic dome and implications for hazard assessment: Cerro Pizarro volcano, Mexico: Journal of Volcanology and Geothermal Research, 171, 307-315.

Carrasco-Núñez, G., Siebert, L, Díaz-Castellón, R., Vázquez-Selem, L., Capra, L., 2010, Evolution and hazards of a long-quiescent compound shield-like volcano: Cofre de Perote, Eastern Trans-Mexican Volcanic Belt: Journal of Volcanology and Geothermal Research, 197, 209-224.

Carrasco-Núñez, G., McCurry, M., Branney, M.J., Norry, M., Willcox, C., 2012, Complex magma mixing, mingling, and withdrawal associated with an intraplinian ignimbrite eruption at a large silicic caldera volcano: Los Humeros of central Mexico: Geological Society of America Bulletin, 124, 11-12, 1793-1809, doi: 10.1130/B30501.1.

Carrasco-Núñez, G., Hernández, J., De León, L., Dávila, P., Norini, G., Bernal, J. P., Jicha, B., Navarro, M., López-Quiroz, P., 2017, Geologic Map of Los Humeros volcanic complex and geothermal field, eastern Trans-Mexican Volcanic Belt: Terradigitalis, 1, 1-11.

Carrasco-Núñez. G., Bernal, J. P., Dávila, P., Jicha, B., Giordano, G., Hernández, J., 2018, Reappraisal of Los Humeros volcanic complex by new U/Th zircon and $^{40}Ar/^{39}Ar$ dating: Implications for greater geothermal potential: Geochemistry, Geophysics and Geosystems, 19, 132-149.

Carrasco-Núñez, G., Hernández, J., Cavazos-Alvarez, J., Norini, G., Orozco-Esquivel, T., López-Quiroz, P., Jaquez, A., De León-Barragán, L., 2021, Volcanic geology of the easternmost sector of the Trans-Mexican Volcanic Belt, Mexico: Journal of Maps, 17(2), 474-484.

Carrasco-Núñez, G., Cavazos-Álvarez, J., Dávila-Harris, P., Bonini, M., Giordano, G., Corbo-Camargo, F., Hernández, J., López, P., Lucci, F., 2022, Assembly and development of large active calderas hosting geothermal systems: insights from Los Humeros Volcanic Complex (Mexico): Journal of South American Earth Sciences, 120, 104056.

Cashman, K.V., Giordano, G., 2014, Calderas and magma reservoirs: Journal of Volcanology and Geothermal Research, 288, 28-45.

Cashman, K.V., Sparks, R.S.J., Blundy, J.D., 2017, Vertically extensive and unstable magmatic systems: a unified view of igneous processes: Science, 355, 3055.

Cavazos-Álvarez, J., Carrasco-Núñez, G., 2020, Anatomy of the largest (ca. 285 km^3)eruption of the Trans-Mexican Volcanic Belt, the Xáltipan ignimbrite from Los Humeros Volcanic Complex, Mexico, implications for greater geothermal conditions: Journal of Volcanology and Geothermal Research, 392, 106755.

Cavazos-Álvarez, J.A., Carrasco-Núñez, G., Dávila-Harris, P., Peña, D., Jáquez, A., Arteaga, D., 2020, Facies variations and permeability of ignimbrites in active geothermal systems, case study of the Xáltipan ignimbrite at Los Humeros Volcanic Complex: Journal of South American Earth Sciences, 104, 102810.

Cedillo, F., 2000, Hydrogeologic model of the geothermal reservoirs from Los Humeros, Puebla, Mexico *in* Proceedings World Geothermal Congress 2000: Kyushu – Tohoku Japan, 1639-1644.

Chako Tchamabe, B., Carrasco-Núñez, G., Miggins, D.P., Németh, K., 2020, Late Pleistocene to Holocene activity of Alchichica maar volcano, Eastern Trans-Mexican Volcanic Belt: Journal of South American Earth Sciences, 97, 102404.

Chédeville, C., Guilbaud, M.N., Siebe, C., 2019, Stratigraphy and radiocarbon ages of late_holocene Las Derrumbadas rhyolitic domes and surrounding vents in the Serdán- Oriental basin (Mexico): implications for archeology, biology, and hazard assessment: The Holocene, 30(3), 1-18.

Cid, H., Carrasco-Núñez, G., Manea, V.C., Vega, S., Castaño, V., 2021, The role of microporosity on the permeability of volcanic-hosted geothermal reservoirs: A case study from Los Humeros, Mexico: Geothermics, 90, 102020.

Cole, J.W., Milner, D.M., Spinks, K.D., 2005, Calderas and caldera structures: a review: Earth Sciences Reviews, 69 (1-2), 1-26.

Corbo-Camargo, F., Arzate, J., Fregoso, E., Norini, G., Carrasco-Núñez, G., Yutsis,V., Herrera, C., Hernández, J., 2020, Shallow structure of Los Humeros (LH) caldera and geothermal reservoir from magnetotellurics and potential field data: Geophysical Journal International, 223(1), 666-675.

Crandell, D.R., 1971, Postglacial lahars from Mount Rainier volcano, Washington: United States, Geological Survey Professional Paper, 677, 75 pp.

Dávila-Harris, P., Carrasco-Núñez, G., 2014, An unusual syn-eruptive bimodal eruption: The Holocene Cuicuiltic Member at Los Humeros caldera, Mexico: Journal of Volcanology and Geothermal Research, 271, 24-42.

De León, L., Carrasco-Núñez, G., Ort, M.H., 2020, Stratigraphy and evolution of the Holocene Aljojuca Maar volcano (Serdán-Oriental basin, Eastern Trans-Mexican Volcanic Belt), and implications for hazard assessment: Journal of Volcanology and Geothermal Research, 392, 106789.

Donnelly-Nolan, J.M., Champion, D.E., Miller, C.D., Grove, T.L., Trimble, D.A., 1990, Post-11,000-year volcanism at Medicine Lake volcano, Cascade Range, Northern California: Journal of Geophysical Research, Solid Earth, 95, 19693-19704.

Duffield, W.A., Richter, D.H., Priest, S.S., 1995, Physical volcanology of silicic lava domes as exemplified by the Taylor Creek rhyolite, Catron and Sierra counties, New Mexico: United States Geological Survey, Map I-2399, 1:50,000.

Edgar, C.J., Wolff, J.A., Olin, P.H., Nichols, H.J., Pittari, A., Cas, R.A.F., Reiners, P.W., Spell, T.L., Martí, J., 2007, The late Quaternary Diego Hernández Formation, Tenerife: Volcanology of a complex cycle of voluminous explosive phonolitic eruptions: Journal of Volcanology and Geothermal Research, 160, 59-85.

Elsworth, D., Voight, B., 1996, Dike intrusion as a trigger for large earthquakes and the failure of volcano flanks: Journal of Geophysical Research, Solid Earth, 100, 6005-6024.

Ferriz, H., Mahood, G.A., 1984, Eruption rates and compositional trends at Los Humeros volcanic center, Puebla, Mexico: Journal of Geophysical Research, Solid Earth, 89, 8511-8524.

Ferriz, H., Mahood, G.A., 1987, Strong compositional zonation in a silicic magmatic system: Los Humeros, Mexican Neovolcanic Belt: Journal of Petrology, 28, 171-209.

Fink, J., Anderson, S., 2000, Lava domes and coulees. Encyclopedia of Volcanoes: Academic Press, 307-319.

Francis, P.W., Self, S., 1987, Collapsing Volcanoes: Scientific American, 256(6), 90-97.

Freundt, A., Schmincke, H.U., 1992, Mixing of rhyolite, trachyte and basalt magma erupted from a vertically and laterally zoned reservoir, composite flow P1, Gran Canaria: Contribution to Mineralogy and Petrology, 112, 1-19.

Graettinger, A.H., Bearden, A.T., 2021, Lateral migration of explosive hazards during maar eruptions constrained from crater shapes: Journal of Applied Volcanology, 10(3), 1-14.

Gualda, G.A.R., Ghiorso, M.S., 2013, The Bishop Tuff giant magma body: An alternative to the Standard Model: Contributions to Mineralogy and Petrology, 166(3), 755-775.
Hildreth, W., 1979, The Bishop Tuff: Evidence for the origin of compositional zonation in silicic magma chambers: Geological Society of America Special, 180, 43-75.
Hildreth, W., Wilson, C.J., 2007, Compositional zoning of the Bishop Tuff: Journal of Petrology, 48, 951-999.
Hildreth, W., Moorbath, S., 1988, Crustal contributions to arc magmatism in the Andes of Central Chile: Contribution to Mineralogy and Petrology, 98, 455-489.
Hubbard, B., Sheridan, M.F., Carrasco-Núñez, G., Díaz, R., Rodríguez, S., 2007, Comparative lahar mapping at volcán Citlaltépetl, Mexico using SRTM, ASTER, and DTED-1 Digital topographic data: Journal of Volcanology and Geothermal Research, 160, 99-124.
Jácome-Paz, M., Torres-Orozco, R., Espinasa-Pereña, R., De la Fuente, J.R., Ruiz, J.O., Delgado, H., 2022, Review of geology and geomorphology of the Xalapa Monogenetic Volcanic Field, eastern Trans-Mexican Volcanic Belt: Journal of Volcanology and Geothermal Research, 432, 107689.
Kennedy, B., Stix, J., 2003, Igneous rock associations 1. Styles and mechanisms of caldera collapse: Geoscience Canada, 30(2), 59-72.
Kereszturi, G., Németh, K., 2012, Monogenetic basaltic volcanoes: genetic classification, growth, geomorphology and degradation, *in* Németh, K. (ed.), Updates in Volcanology - New Advances in Understanding Volcanic Systems: Rijeka, Croatia, Intech Open, 3-88.
Kratzmann, D.J., Carey, S., Scasso, R., Naranjo, J.A., 2009, Compositional variations and magma mixing in the 1991 eruptions of Hudson volcano, Chile: Bulletin of Volcanology, 71, 419-439.
Lange, R.A., Carmichael, I.S.E., 1990, Hydrous basaltic andesites associated with minette and related lavas in western Mexico: Journal of Petrology, 31, 1225-1259.
Leeman, W.P., Smith, D.R., Hildreth, W., Palacz, Z.A., Rogers, N.W., 1990, Compositional diversity of late Cenozoic basaltic magmas of the southern Washington Cascades: Journal of Geophysical Research, Solid Earth, 95, 19561-19582.
Lipman, P.W., 2000, Calderas, *in* Sigurdsson, H. (ed.), Encyclopedia of Volcanoes: Academic Press, 643-662 pp.
López-Rojas, M., Carrasco-Núñez, G., 2015, Depositional facies and migration of the eruptive loci for Atexcac axalapazco (Central Mexico): implications for the morphology of the crater: Revista Mexicana de Ciencias Geológicas, 32(3), 377-394.
Lucci, F., Carrasco-Núñez, G., Rossetti, F., Theye, T., White, J.C., Urbani, S., Azizi, H., Asahara, Y., Giordano, G., 2020, Anatomy of the magmatic plumbing system of Los Humeros Caldera (Mexico): implications for geothermal systems: Solid Earth, 11,125- 159.
Luhr, J.F., Carmichael, I.S.E., 1985, Contemporaneous eruptions of calc-alkaline and alkaline magmas along the volcanic front of the Mexican Volcanic Belt: Geofísica Internacional, 24(1), 203-216.
Martí, J., Groppelli, G., Brum da Silveira, A., 2018, Volcanic stratigraphy: a review: Journal of Volcanology and Geothermal Research, 357, 68-91.
Murcia, H., Németh, K., 2020, Effusive monogenetic volcanism: *in* Németh K., Updates in Volcanology Transdisciplinary Nature of Volcano Science: Intech Open, 1-15.
Németh, K., Kereszturi, G., 2015, Monogenetic volcanism: personal views and discussion: International Journal of Earth Sciences, 104(8), 2131-2146.
Ort, M., Carrasco-Núñez, G., 2009, Lateral Vent Migration during Phreatomagmatic and Magmatic Eruptions at Tecuitlapa Maar, East-Central Mexico: Journal of Volcanology and Geothermal Research, 181, 67-77.
Peña Rodríguez, D., 2021, Reevaluación de la litoestratigrafía del subsuelo del Campo Geotérmico de los Humeros, Puebla, México: Querétaro, Qro, México, Posgrado Ciencias de la Tierra, Universidad Nacional Autónoma de México, Master thesis, 115 pp.
Reid, M., Sisson, T., Brien, D., 2001, Volcano collapse promoted by hydrothermal alteration and edifice shape Mount Rainier, Washington: Geology, 29, 779-782.
Riggs, N., Carrasco-Núñez, G., 2004, Evolution of a complex, isolated dome system, Cerro Pizarro, central México: Bulletin of Volcanology, 66, 322-335.
Rossotti, A., Carrasco-Núñez, G., Rosi, M., Di Muro, A., 2006, Eruptive dynamics of the "Citlaltépetl Pumice" at Citlaltépetl volcano, Eastern Mexico: Journal of Volcanology and Geothermal Research, 158, 401-429.
Siebert, L., Carrasco-Núñez, G., 2002, Late-Pleistocene to precolumbian behind-the-arc mafic volcanism in the eastern Mexican Volcanic Belt; implications for future hazards: Journal of Volcanology and Geothermal Research, 115,179-205.
Sigmarsson, O., Vlastelic, I., Andreasen, R., Bindeman, I., Devidal, J.L., Moune, S., Keiding, J.K., Larsen, G., Höskuldsson, A., Thordarson, Th., 2011, Remobilization of silicic intrusion by mafic magmas during the 2010 Eyjafjallajökull eruption: Solid Earth, 2, 271-281.
Sigurdsson, H., 2015, The Encyclopedia of Volcanoes: Second edition. Elsevier, 1422 pp.
Smith, R.L., Bailey, R.A., 1968, Resurgent cauldrons: Geological Society of America Memoir, 116, 613-662, https://doi.org/10.1130/MEM116-p613.
Sheridan, M., Carrasco-Núñez, G., Hubbard, B., Siebe, C., Rodríguez, S., 2001 Mapa de peligros volcánicos del Volcán Citlaltépetl (Pico de Orizaba): Universidad Nacional Autónoma de México, Gobiernos de los Edos. de Puebla y Veracruz, esc. 1:250000, 1 map.
Urbani, S., Giordano, G., Lucci, F., Rossetti, F., Acocella, V., Carrasco-Núñez, G., 2020, Estimating the depth and evolution of intrusions at resurgent calderas: Los Humeros (Mexico): Solid Earth 11, 527-545.
Vallance, J.W., Scott, K.M., 1997, The Osceola mudflow from Mount Rainier; sedimentology and hazard implications of a huge clay-rich debris flow: Geological Society of America Bulletin, 109, 143-163.
Valentine, G.A., Gregg, T.K.P., 2008, Continental basaltic volcanoes- Processes and problems: Journal of Volcanology and Geothermal Research, 177(4), 857-873.
Van Wyk de Vries, B., Francis, P.W., 1997, Catastrophic collapse at stratovolcanoes induced by gradual volcano spreading: Nature, 387, 387-390.
Verma, S.P., 1983, Magma genesis and chamber processes at Los Humeros caldera, Mexico- Nd and Sr isotope data: Nature, 302, 52-55.
Verma, S.P., Gómez-Arias, E., Andaverde, J.,2011, Thermal sensitivity analysis of emplacement of the magma chamber in Los Humeros caldera, Puebla, Mexico: International Geology Review, 53(8), 905-925.
Walker, G.P., 1984, Downsag calderas, ring faults, caldera sizes, and incremental caldera growth: Journal of Geophysical Research, Solid Earth, 89 (B10), 8407-8416.
Walker, G.P.L., 2000, Basaltic volcanoes and volcanic systems, *in* Sigurdsson H, (eds.), Encyclopedia of Volcanoes: San Diego, Academic Press, 283-290.
Wallace, P.J., Carmichael, I.S.E., 1999, Quaternary volcanism near the Valley of Mexico: implications for subduction zone magmatism and the effects of crustal thickness variations on primitive magma compositions: Contribution to Mineralogy and Petrology, 135, 291-314.
Willcox, C., 2011, Eruptive, Magmatic and Structural Evolution of a Large Explosive Caldera Volcano: Los Humeros México: U.K., University of Leicester, Ph.D. Thesis, 326 pp.
Wilson, C.J.N., Charlier, B.L.A., 2009, Rapid rates of magma generation at contemporaneous magma systems, Taupo Volcano, New Zealand: insights from U–Th model-age spectra in zircons: Journal of Petrology, 50 (5), 875-907.
Zimanowski, B., 1998, Phreatomagmatic explosions, *in* Freundt, A., Rosi, M. (eds.), From Magma to Tephra: Developments in Volcanology 4: Amsterdam, Elsevier, 25-54.
Zimbelman, D.R., 1996, Hydrothermal alteration and its influence on volcanic hazards: Mount Rainier, Washington, a case history: University of Colorado at Boulder, Ph thesis, 384 pp.
Zimmer, B., Riggs, N.R., Carrasco-Núñez, G., 2010, Evolution of tuff ring-dome complex: the case study of Cerro Pinto, eastern Trans-Mexican Volcanic Belt: Bulletin of Volcanology, 72, 1233-1240.

Manuscript received: June 22, 2023
Corrected manuscript received: September 14, 2023
Manuscript accepted: September 18, 2023