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

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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.

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.
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, reappaisal 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 km³) 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 Keresztrúti, 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- Citaláltépetl stratovolcano (Carrasco-Núñez and Ban, 1993); 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 (Kereszthuri and Németh, 2012; Németh and Kereszthuri, 2015). Eruptive styles range from explosive (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 Kereszthuri (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 alternating 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 built 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,

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**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.
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. Catas-

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 Espólón 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.
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 scarp; 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 scarp, 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 Cítaltépetl 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 Cítaltépetl 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 Cítaltépetl 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 ⁴⁰Ar/³⁹Ar 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, nestled 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 Cítaltépetl-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: Cítaltépetl 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 Cítaltépetl 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 sectoral collapse of the ancestral edifice of Cítaltépetl volcano (Espolón de Oro). It is a clay-rich (cohesive) lahar formed (Figure 3c) 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).
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 area (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,
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., 1993). 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 crater 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
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; Eyjafjallajökull, Sigmarsson et al., 2011). An example of this unusual syn-eruptive bimodal activity is represented by the Holocene (7.3 ky) Cuicuitic 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 9. a) Digital elevation model showing the location of the inferred vents associated with the eruption of the 7.4 ky Cuicuitic 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 Cuicuitic sequence (modified from Dávila-Harris and Carrasco-Núñez, 2014).

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).
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 zonation 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 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).
Uncovering active volcanism

In the past decades, the only reported active volcano on the ET-MVB was Cítaltepétl 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 C¹⁴ ages at 3.8 ky and 2.8 ky (Carrasco-Núñez et al., 2018). Also at LHVC, the already mentioned Cuicuilict member has an age of 7.3 ky, and some lavas within Los Humeros caldera are dated at 8.9 ky. The Cuicuilict 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 (Chédéville 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 sloping 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-quietescent 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 Cítaltepétl 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 Cítaltepétl 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).
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...
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 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 Xáltipan 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 (μCT) 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 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 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. Tecomatlá-Atezca-Ajouca maars); uncovering unusual syn-eruptive bimodal eruption of compositionally contrasting magmas (Cuicuilco 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).

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