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Late Pleistocene Alberca de Guadalupe maar volcano (Zacapu basin, Michoacán): Stratigraphy, tectonic setting, and paleo-hydrogeological environment

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ABSTRACT

The Late Pleistocene (~21,000 yr BP) Alberca de Guadalupe maar is one of the few phreatomagmatic volcanoes occurring within the scoria-cone dominated Plio-Quaternary Michoacán-Guanajuato Volcanic Field. The scarcity of this type of volcano implies that conditions favoring their formation are rarely met in this region. We identify these factors by implementing current methods of investigation with emphasis on hydrogeological conditions. We present the stratigraphy (including a set of $^{40}Ar/^{39}Ar$ and ^{14}C dates) of the SE margin of the Zacapu intermontane tectonic basin, where the maar just forms a hole (~1 km in diameter, ~150 m deep, bearing a ~9 m deep lake) in the otherwise planar topography of the underlying early Pleistocene lava flows of the Cerro Pelón scoria cone. The maar is composed of typical phreatomagmatic surge deposits that are poorly sorted and rich in accidental lithics (>60 wt.% of the deposit) with few juveniles (basaltic andesite, $SiO_2 = 54–58$ wt.%). The entire structure is cut by an ENE–WSW trending normal fault and is underlain by andesite lavas and silicic ignimbrites (partly inferred from xenoliths encountered in the maar deposits) that are Miocene to Early Pleistocene in age. The crater is at the center of a N–S elongated drainage basin surrounded by topographic highlands that channel water with high hydraulic pressure from most directions towards the location of the maar. This geometric configuration was already in existence at the time of the maar-forming eruption, but the climate was different. Colder and more humid conditions during the Last Glacial Maximum (Cw2-climate type, annual precipitation of >1000 mm) favored the saturation of the fractured shallow aquifer system (hydraulic conductivity of 10^{-8} to 10^{-7} m/s) that supplied sufficient groundwater at a high flow rate directed towards the center of the basin. Upon contact near surface (<200 m) with the rising dike of basaltic andesite magma, the continuous supply of both dike-fed basaltic andesite magma and groundwater at an optimal ratio of 0.2 allowed explosive interaction for the entire duration of the eruption (17–57 days) creating a >150 m deep crater with steep inner walls and an underlying shallow diatreme (<300 m). Since then, partial collapse of the walls along listric ring-fractures has reduced crater steepness. The present climate is much drier (Cw1 climate conditions with annual precipitation of 697.5–874.8 mm) and it seems unlikely that a maar would form if these conditions persist. Nonetheless, precipitation is still high enough to sustain a ~9-m-deep lake in the crater with insignificant seasonal water table fluctuations. These findings lend further support to the notion that maars can be used as paleoclimate indicators in central Mexico.

1. Introduction

The Late Pleistocene Alberca de Guadalupe maar volcano is located at the SE margin of the Zacapu lacustrine basin in the Michoacán–Guanajuato Volcanic Field (MGVF) that forms the western–central segment of the Trans-Mexican Volcanic Belt (TMVB). This continental arc stretches across central Mexico for 1200 km in an East–West direction from the coast at the Gulf of Mexico to the Pacific Ocean. It traverses the Mexican Altiplano, a highland characterized by active normal faulting and horst-and-graben structures that result in the formation of basins often occupied by broad (but shallow) lakes (Fig. 1).

The neo-volcanic TMVB is related to the subduction of the oceanic Cocos Plate underneath the continental North American Plate and consists of a large number of Late Tertiary to Quaternary maars, scoria cones, domes, calderas, and strato-volcanoes, the chemical and mineralogical composition of which is largely calc-alkaline (e.g. Demant, 1978; Carmichael, 2002; Ferrari et al., 2012). One feature of the TMVB is the abundance of scoria cones and other types of small monogenetic volcanoes, which outnumber by several orders of magnitude the number of much larger strato-volcanoes. Although the exact causes

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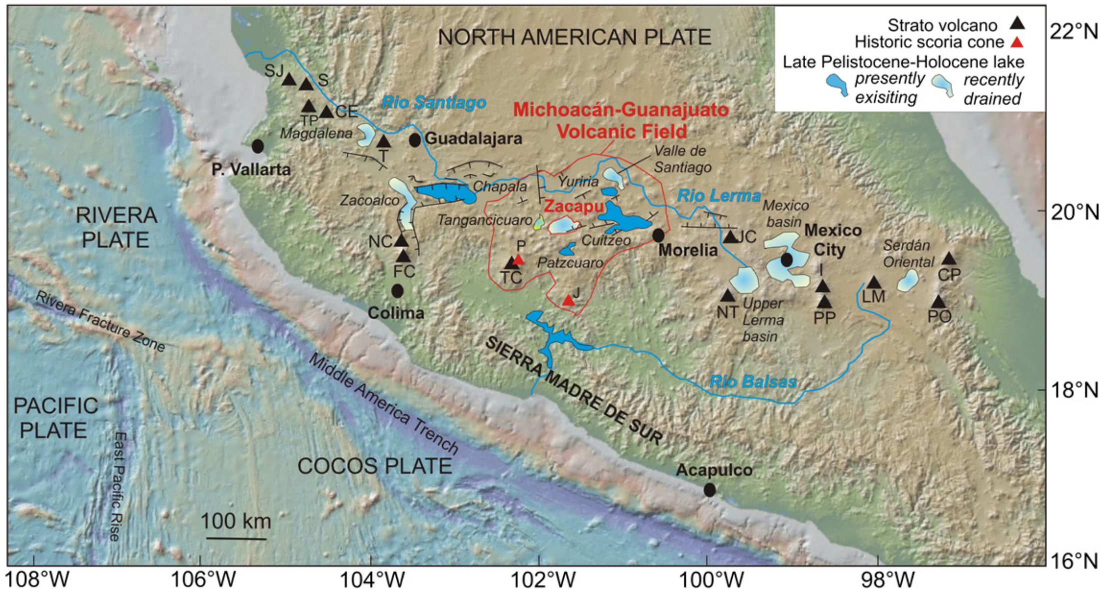

Fig. 1. Map of central Mexico showing major tectonic features and the Trans-Mexican Volcanic Belt (TMVB) with main strato-volcanoes San Juan (SJ), Sangangüey (S), Tepetiltic (TP), Ceboruco (CE), Tequila (T), Nevado de Colima (NC), Fuego de Colima (FC), Tancítaro (TC), Jocotitlán (JC), Nevado de Toluca (NT), Iztaccíhuatl (I), Popocatépetl (PP), La Malinche (LM), Cofre de Perote (CP), and Pico de Orizaba (PO). Major neo-tectonic grabens (black lines with dip direction) generally occupied by Late Pleistocene–Holocene lakes (outlined in blue). Rivers Santiago, Lerma, and Balsas (blue lines) bounding the Michoacán–Guanajuato Volcanic Field (outlined in red) are also indicated. Historic monogenetic scoria cones Paricutin (P) and Jorullo (J), and the Zacapu basin (study area) are highlighted in red.

for their great number (>3000) are still poorly understood, their high frequency of occurrence may be related to the unique geometric configuration of the subduction zone (Pardo and Suárez, 1995; Gómez-Tuena et al., 2003; Blatter and Hammersley, 2010; Kim et al., 2012) that control the location and size of magma generation areas and the magnitude of crustal extension.

A recent inventory of monogenetic phreatomagmatic volcanoes (maars, tuff-rings, tuff-cones) in the TMVB, revealed the occurrence of only 88 such volcanoes within the entire arc (Siebe and Salinas, 2014). According to these authors, maars are scarce (3% of all monogenetic vents in the TMVB) and 47% of them are concentrated in the Tuxtla Volcanic Field (a littoral setting near the Gulf of Mexico, Sieron et al., 2014). Most of the remaining 53% are found clustered in only few of the many intermontane basins in the Mexican Altiplano (e.g. Serdán-Oriental and Valle de Santiago). Maars are the second most common type of volcanic vent encountered on Earth and their formation requires two basic ingredients: water (surficial or ground) and a small batch of magma (Lorenz, 2007). From the above it becomes clear that optimal conditions for maar formation are usually not met in the TMVB, despite of the relative availability of ground water (abundance of lacustrine basins) and ascending low volume magmas required to fuel this type of eruptions. Hence, maars such as Alberca de Guadalupe can be considered a rare occurrence.

In this paper we outline the special conditions, namely the tectonic setting and hydrogeological environment that favored the formation of Alberca de Guadalupe. We first introduce the regional geologic framework of the MGVF, discussing the relevance and distribution of maar volcanism, and then describe the geology, tectonics, archeology, paleoclimatology, and hydrogeology of the Zacapu basin. Subsequently, the volcanic-stratigraphy of the eastern part of the basin where the maar is located is defined. In addition, we discuss the sedimentological characteristics (e.g. sorting, grain-size distribution, and componentry) of the maar deposits, as well as the petrography and geochemistry of juvenile clasts, xenoliths, and surrounding lava flows. From these, the sub-surface stratigraphy and associated hydrogeological parameters (e.g. permeability) are inferred which, along with available climatic data from the present day and existing paleoclimatic studies, allow us to discuss the conditions of formation of a maar at that specific time and location.

2. The Michoacán–Guanajuato Volcanic Field

The largest concentration of monogenetic volcanoes in the TMVB occurs in the MGVF, where the arc reaches a maximum width of ~300 km (Fig. 1). This ~40,000 km^2 area hosts more than 1000 monogenetic vents, 90% of them scoria cones that include the historical Jorullo (1759–1774) and Paricutin (1943–1952), ~300 medium-sized volcanoes (shields and domes), fewer viscous flows and lava domes, and rare maars (Hasenaka and Carmichael, 1985, 1987; Guilbaud et al., 2011, 2012). There are only two true strato-volcanoes in the MGVF: Tancítaro (3845 m) that is believed to be extinct (Ownby et al., 2007), and Patamban (3450 m) that has never been studied in detail.

Prominent structural and physiographical zones (Johnson and Harrison, 1989, 1990; Pasquaré et al., 1991; Suter et al., 2001; Garduño-Monroy et al., 2009; Guilbaud et al., 2011, 2012; Siebe et al., 2014) mark the boundaries of the MGVF (Fig. 2). It is limited by the Tzitzio anticline in the east, a noticeable embayment at the front of the TMVB (Blatter and Hammersley, 2010), while to the west it is restricted by a similar indentation, here called the “Mazamitla gap”. Its northern boundary coincides with the Lerma river valley that drains the central basins of the TMVB and flows westward into Lake Chapala. While the Lake Chapala basin is structurally controlled by the E–W-trending Chapala-Tula Fault System (Fig. 2), the Cuitzeo and Zacapu lake basins are controlled by faults of the ENE–WSW trending Cuitzeo Fault System. The MGVF terminates to the south on the steep slopes leading from the highland (>2000 m asl) down into the Balsas river depression (<600 m asl), which is fed by several tributaries including the Tepalcatepec (Fig. 2). This limit can also be linked to the NW–SE Chapala-Oaxaca Fault System. Furthermore, towards the NE the MGVF is delimited by the NNW–SSE trending Querétaro–Taxco Fault System.

Within the boundaries of the MGVF, the surface topography is dominated by andesitic Plio-Quaternary volcanic landforms. Intense recent volcanic activity conceals most of the older rocks; hence the underlying basement can only be inferred from outcrops located beyond the limits of the MGVF.

Recent studies near the eastern limit of the MGVF revealed that the Plio-Quaternary eruptive products are emplaced unconformably over Miocene volcanics exposed extensively to the southeast of Lake Cuitzeo. The Miocene volcanics include voluminous ignimbrite successions