

Tracking large volcanic eruptions and their regional variability

José Luis Macías*

Instituto de Geofísica, Unidad Michoacán, Universidad Nacional Autónoma de México, Campus-Morelia, Morelia, 58090, Michoacán, México

In order to understand the hazards and risks posed by active volcanoes to modern societies, it is imperative to reconstruct their geologic, historic, and modern records. This information is crucial to decipher volcano behavior over time and the way volcanic unrest may occur. The analysis of all this volcanological data provides the basis to estimate recurrence periods of activity, develop computer models to simulate volcanic processes, and generate volcanic hazards maps. These maps are used by the authorities to mitigate the risk posed by volcanic activity.

As stated, it may seem like a straightforward procedure to unravel the behavior of volcanoes; however, our understanding is hindered by the variable preservation of volcanic deposits due to local conditions. Volcanoes are located in diverse tectonic environments, altitudes, and climates, and so are subjected to contrasting conditions for deposit preservation, soil formation, and reworking after deposition. Even at a specific geographic location and tectonic environment, a single long-lived volcano may have experienced periods of global cooling and/or warming. For example, most active volcanoes today were formed during the Pleistocene or late Pleistocene and thus have experienced periods of glaciation during which large amounts of melt water would have been available to facilitate remobilization of debris and reduce the availability of organic material. These conditions would negatively impact on the preservation of deposits and the amount of organic material for dating past eruptions.

For volcanoes located near the tropics, it could be difficult to track deposits of a single eruption from near-vent facies to distal facies due to dense vegetation, and because the proximal and distal deposits may not look the same. Distal facies could be deposited by vertical eruptive columns that dispersed fine ash over extended areas far away from the volcano. Nooren et al. (2017, p. 175 in this issue of *Geology*) report an exceptional example of this type of explosive eruption attributed to El Chichón Volcano, located in Chiapas in southern Mexico, that disrupted the Maya civilization during the 6th century (A.D. 540) and that had a global cooling effect on the planet. The authors reconstructed the stratigraphic record of this deposit by using proximal data (Espíndola et al., 2000), distal tephra deposits (Nooren et al., 2009, 2017), and the Holocene beach ridge plain along the Gulf of Mexico. These studies, and careful use of ¹⁴C data, enabled them to propose a major explosive eruption of El Chichón with a prominent volcanic sulfur spike in bipolar ice core records dated at 540 CE. This eruption is important because it could have had a severe environmental impact on Maya societies, causing temporary cultural decline, site abandonment, and migrations. The eruption is one of at least 11 eruptions that occurred during the past 8000 years of activity of El Chichón volcano, including the famous A.D. 1982 event (Espíndola et al., 2000; Scolamacchia and Capra, 2015). These 11 eruptions represent large events that left a stratigraphic record around the volcano. Although several studies have contributed to refining the stratigraphy of El Chichón, it is quite plausible that parts of its volcanic record have been under-recorded, because they have not been yet discovered or because minor eruptions did not produce traceable deposits.

This lack of preservation is a common characteristic of active volcanoes; for instance, Popocatepetl in central Mexico has produced large

Plinian eruptions during the last 23 k.y. (Siebe et al., 1996; Panfil et al., 1999; Arana et al., 2010; Sosa-Ceballos et al., 2012) and has an important historic record (Martin del Pozzo et al., 2016). However, its ongoing eruption that started in December 1994 has emplaced and destroyed 38 lava domes inside the crater (Gómez-Vazquez et al., 2016) but has rarely emplaced pyroclastic deposits outside the crater (Siebe and Macías, 2006). So far, this behavior is related to magma availability at depth and therefore small volumes have been erupted.

Thus, volcanic records are always incomplete. In order to understand the impact of such a lack of information for volcanoes worldwide, Sheldrake and Caricchi (2017, p. 111 in this issue of *Geology*) used the LaMEVE database of Crosweller et al. (2012), which provides a record of large-magnitude explosive eruptions throughout the Quaternary, to estimate the recurrence rate of large-magnitude eruptions ($M \geq 4$). In their study, they describe biases in the volcanic records that impact their data completeness and their analysis. To overcome such biases, they used a hierarchical Bayesian method to characterize the common frequency-magnitude (f - M) behavior for different groups of volcanoes. In their approach, the proportion of eruptions of different magnitude is quantified considering groups of volcanoes associated by a common behavior (e.g., arc volcanoes). To account for systematic under-recording (deposits not studied or preserved in nature) in the volcanic record, they calculate global recurrence rates for large-magnitude eruptions during the Holocene. The Bayesian statistics is important to understand the dynamic analysis of a sequence of data to obtain the posterior distribution of model parameters.

VOLCANIC RECORDS: THE CASE OF DEPOSIT PRESERVATION AT EL CHICHÓN

El Chichón volcano belongs to a volcanic complex formed by craters and peripheral domes. Its magmatism began at ca. 370 ka with the emission of lava domes forming a large andesitic dome complex between 209 and 276 ka (Layer et al., 2009). This complex was destroyed by an eruption of unknown age that left a 1.5-km-wide Somma-type crater. The activity continued with the extrusion of peripheral domes: a southwest dome at 217 ka, Cambac at 168–187 ka, Capulín at 152 ka, and a northwest dome at 80–97 ka. Some deposits emplaced by pyroclastic density currents associated with these domes have been dated between 48 and 102 ka. These dates were obtained with the ⁴⁰Ar/³⁹Ar method. Younger deposits correspond to Holocene explosive eruptions that occurred at an inner crater excavated within the older Somma crater (e.g., the crater formed during the A.D. 1982 eruption). As summarized, the volcanic record of El Chichón is still incomplete. The Holocene stratigraphy is based on mapping, correlation of deposits, and ¹⁴C dating of organic material (Tilling et al., 1984; Espíndola et al., 2000; Macías et al., 2003). However, late Pleistocene stratigraphy is based on ⁴⁰Ar/³⁹Ar geochronology of whole rocks (Layer et al., 2009; Macías et al., 2010), which has some problems due to excess argon (Layer et al., 2009) and subsequent alteration. Recently, Pack et al. (2016) used ²³⁰Th/²³⁸U disequilibrium (U-Th), and U-Pb geochronology in zircons crystals that aided in the understanding of both late Pleistocene and Holocene chronology of events of the volcano.

*E-mail: macias@geofisica.unam.mx

Since the 1982 catastrophic eruption of El Chichón volcano, the slopes have been revegetated, making it quite difficult to recognize the deposits of this event. The volcano is located in a region of abundant vegetation and water that favors the rapid growth of vegetation and development of soils. Thirty-five years after the 1982 eruption of El Chichón, a thin soil began to form on top of the deposits around the volcano, and now it has become a significant unit masking information about the eruption. Evidence of past eruption-soil formation is common at El Chichón, attesting to repose periods in the late Holocene activity of the volcano (Solleiro et al., 2007) and human occupation during the past 2400 years (Espíndola et al., 2000). Distal preservation of tephra is mostly eroded, and is only preserved in selected environments. In this sense, the careful analyses by Nooren et al. (2017) of distal tephra-fall deposited ~140 m northeast of the volcano depicts these problems, but also shows how a deposit from an explosive eruption can be traced back to the volcanic source. The authors used new accelerator mass spectrometry ¹⁴C analysis of organic material of the distal tephra-fall deposits in the Usumacinta-Grijalva delta, and the magnetite enrichment in deposits of the beach ridge to further refine the age of the eruption. These results allowed them to match the El Chichón proximal and distal tephra to the 540 CE sulfur spike in the bipolar ice-core data (Zielinski et al., 1997).

SUMMARY

Volcanological studies are based on field reconnaissance of erupted products aided by modern techniques and methods such as Geographic Information System, satellite, and drone-based imagery; geochemistry; petrology; and geochronology. A synthesis of this information provides a faster and more precise means to understand the past records of active volcanoes on a global scale. An increased number of geochronological and other isotopic methods are available for refining near-vent volcanic stratigraphy and distal subaerial or subaquatic tephrochronology. This information, combined with microanalytical techniques used in juvenile material (e.g., EPMA or SIMS in glass shards) of volcanic deposits, becomes a powerful instrument to correlate single explosive eruptions that had far-reaching effects, as Nooren et al. (2017) show. Global events such as glaciations, droughts, meteoric impacts, or extreme weather conditions drastically reduced the probability of preserving the complete eruptive record of volcanoes around the world. The record is inevitably incomplete in different parts of the stratigraphic column, in regions around the volcano, or in proximal versus distal areas from the vent. However, by improving the stratigraphic volcanic record of volcanoes across different tectonic and depositional environments, we can construct a more robust worldwide data set and provide the basis to statistically analyze regional and global volcanic hazards using approaches such as that presented by Sheldrake and Caricchi (2017).

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