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Jesús Alcalá-Reygosa, José Luis Arce, Irene Schimmelpfennig, Esperanza Muñoz Salinas, Miguel Castillo Rodríguez, Laëtita Léanni, Georges Aumaître, Didier Bourlès, Karim Keddadouche, ASTER Team



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**Revisiting the age of the Jumento volcano, Chichinautzin Volcanic Field (Central Mexico), using *in situ*-produced cosmogenic  $^{10}\text{Be}$**

**Authors:**

Jesús Alcalá-Reygosa

Facultad de Filosofía y Letras

Universidad Nacional Autónoma de México

Ciudad Universitaria, 04510 Ciudad de México

Corresponding Author: jalcalar@ucm.es

José Luis Arce

Instituto de Geología

Universidad Nacional Autónoma de México

Ciudad Universitaria, 04510 Ciudad de México

Email: jlarce@geologia.unam.mx

Irene Schimmelpfennig

Aix Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France

Email: schimmelpfennig@cerege.fr

Esperanza Muñoz Salinas

Instituto de Geología

Universidad Nacional Autónoma de México

Ciudad Universitaria, 04510 Ciudad de México

Email: esperanzam@ownmail.net

Miguel Castillo Rodríguez

Instituto de Geología

Universidad Nacional Autónoma de México  
Ciudad Universitaria, 04510 Ciudad de México  
Email: castillom@geologia.unam.mx

Laëtita Léanni

Aix Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France  
Email: leanni@cerege.fr

ASTER Team\*

Consortium\*: Georges Aumaître, Didier Bourlès, Karim Keddadouche.

Aix Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France  
Email: bourles@cerege.fr

### Abstract

Previous studies on Jumento volcano, based on radiocarbon dating and comparative morphometric analysis, suggest that it could be the youngest volcano of the Sierra Chichinautzin. Here we establish a new chronology of the emplacement of the Late Holocene lava flows of Jumento volcano using *in situ*-produced  $^{10}\text{Be}$  cosmic ray exposure (CRE) dating of quartz xenocrysts to test this hypothesis. Depending on the choice of the cosmogenic nuclide production parameters in the exposure age calculators used, the mean  $^{10}\text{Be}$  CRE ages ranges between  $1.86 \pm 0.68$  ka and  $2.41 \pm 0.97$  ka for the inner lava flow and between  $1.90 \pm 0.29$  ka and  $2.49 \pm 0.41$  ka for the breakout lava flow. These preliminary mean  $^{10}\text{Be}$  CRE ages confirm that the Jumento volcano is one of the youngest volcanoes of the Sierra Chichinautzin although slightly older than the Xitle volcano. This first  $^{10}\text{Be}$  eruption chronology of the Sierra Chichinautzin shows that  $^{10}\text{Be}$  CRE dating represents an alternative approach to date volcanic rocks, not only for the Sierra Chichinautzin but also for other volcanic fields, especially when no charcoal or paleosoils are available for radiocarbon dating. Furthermore, it suggests that *in situ*-produced cosmogenic nuclide dating has considerable potential to throw light on the volcanic history and eruption recurrence of this volcanic field, in order to provide enough data for the mitigation of the hazards and related risks in Mexico City, the city of Cuernavaca and the small towns around the volcanic field.

**Key words:** lava flows, Jumento volcano, Sierra Chichinautzin, *in situ*-produced cosmogenic  $^{10}\text{Be}$  dating, eruptive history, hazards.

## 1. Introduction

Reliable estimation of the ages of volcanic products is essential for a better understanding of the eruptive history of volcanic centers and thus for predicting future eruptions and improving volcanic risk assessment and management. One of the most important volcanic fields worldwide in that sense is the Sierra Chichinautzin because it rises at the southern limit of Mexico City, where ~ 25 million inhabitants live, urbanization continues to expand and government services as well as industrial activity have been developed (Siebe et al., 2004; Siebe and Macias, 2006). Archeological records show that in AD 245-315, the lava flows emitted by the Xitle volcano covered pyramids and other buildings of the Cuicuilco and Copilco archaeological sites to the south of Mexico City (Siebe, 2000). This historical eruption and the recent small-magnitude earthquakes with shallow epicenters around Mexico City (Campos-Enruez et al., 2015) suggest that the Sierra Chichinautzin is tectonically and volcanically active. Therefore, new volcanic activity could be produced with potentially serious volcanic hazard, not only in Mexico City but also in the city of Cuernavaca, Morelos State, and many small towns around the volcanic field.

The Sierra Chichinautzin includes at least 220 overlapping cinder cones, lava flows, tephra sequences and lava domes that cover an area of 2500 km<sup>2</sup> (Siebe et al., 2004). Although the Sierra Chichinautzin is one of the most studied areas in the Trans-Mexican Volcanic Belt, the studies have focused mainly on the geology of the erupted magmas or the eruptive style and geometry of the volcanoes (Martn del Pozzo, 1982; Meriggi et al., 2008; Guilbaud et al., 2009; Agustn-Flores et al., 2011; Roberge et al., 2015). By contrast, detailed chronological information on the volcanic activity is available for only ~10 % of more than 220 volcanic cones; this is based on the use of radiocarbon (Siebe et al., 2004) and <sup>40</sup>Ar/<sup>39</sup>Ar dating (Arce et al., 2013; Jaimes-Viera et al., 2018). As a result of the relatively recent (Late Pleistocene/Holocene) emplacement of many volcanic products, the method most used is radiocarbon dating, which, however, has two drawbacks: (1) organic material is rarely available, especially underneath lava flows; (2) radiocarbon dating is often applied on paleosoils or reworked pyroclastic layers, and thus yields in many cases only minimum ages for the underlying eruptive products (Siebe et al., 2004). The <sup>40</sup>Ar/<sup>39</sup>Ar method is not suitable for dating Holocene volcanic rocks, especially if they have a basic composition, because the <sup>40</sup>Ar concentrations required by this method are below its detection limit (Renne, 2000). Therefore, the chronological data available at the

Sierra Chichinautzin are not yet sufficient to establish a robust pattern of eruption recurrence.

Previous studies, based on  $^{40}\text{Ar}/^{39}\text{Ar}$  dating, indicate that the volcanism at the Sierra Chichinautzin began  $\sim 1.2$  Ma ago (Arce et al., 2013; Jaimes-Viera et al., 2018) and spanned the entire Pleistocene. According to geomorphological characteristics and radiocarbon dating, at least eleven monogenetic volcanoes are younger than  $\sim 10$  ka: Pelado ( $\sim 8550 - 9411 / 10146 - 11414$  cal BP), Tenango lava flow ( $\sim 7073 - 7611 / 7468 - 8282$  cal BP), Tres Cruces ( $\sim 7181 - 7592$  cal BP), Cuauhtzin (6019 - 6438 / 7063 - 7476 cal BP), Tlálóc (4936 - 5353 cal BP), Guespalapa (833 - 1210 / 3323 - 3656 cal BP), Pelagatos and Cerro del Agua ( $> 397 - 844$  cal BP), Jumento ( $\sim 1050 - 2335$  cal BP), Chichinautzin (61 - 266 cal AD) and Xitle (316 - 430 cal AD) (Siebe, 2000; Siebe et al., 2004; Siebe et al., 2005; Agustin-Flores et al., 2011; Arce et al., 2015). These  $2\sigma$  radiocarbon age intervals were calibrated with OxCal v4.3.2 (Bronk Ramsey, 2017) using the IntCal13 calibration curve (Reimer et al., 2013). For the Sierra Santa Catarina, not included in the Sierra Chichinautzin volcanic field, Layer et al. (2009) and Jaimes-Viera et al. (2018) reported young ages in this range although with large uncertainties ( $2 \pm 56$  ka for Tecuatzi cone based on  $^{40}\text{Ar}/^{39}\text{Ar}$  dating), tentatively suggesting a Holocene age. Siebe et al. (2005) suggested that the eruptive average recurrence interval in Sierra Chichinautzin during the Holocene should be 1250 years or less. However, if we consider all of the above Holocene structures, at least one volcano erupts every  $\sim 900$  years.

The radiocarbon ages from the Pelado and Jumento volcanoes reported above are poorly constrained because most of them were obtained from charcoal fragments in reworked paleosoils or pyroclastic layers providing minimum ages. Comparative morphometric analysis has suggested that the Jumento volcano could be younger than the Xitle volcano (Arce et al., 2015). Because the lava flows from the Jumento volcano are very well preserved, are free from vegetation, and contain large quartz xenocrysts, we tested this hypothesis and provided a new chronology of the Jumento volcano using *in situ*-produced  $^{10}\text{Be}$  cosmic ray exposure (CRE) dating for a preliminary set of lava flow surface samples. CRE dating in terrestrial surface rocks is a solid method based on the interaction of cosmic ray derived particles with certain target elements in the minerals of the Earth's surface, resulting in steady accumulation of various rare isotopes (in situ in the crystal lattice), such as  $^{10}\text{Be}$ ,  $^{36}\text{Cl}$ , or  $^3\text{He}$ , with time. One advantage over other methods is the application

to time scales between  $10^2$  and  $10^6$  years (Dunai, 2010). Although CRE dating on the  $10^2$ - $10^3$  year time scale (i.e. Holocene) has long been challenging owing to the difficulty of accurately measuring the small number of nuclides present in the rock, this method has provided consistent Holocene ages of volcanic eruptions (Dunbar and Phillips, 2004; Foeken et al., 2009; Espanon et al., 2014; Fenton and Niedermann, 2014; Alcalá-Reygosa et al., 2018).

## 2. Regional setting

The Sierra Chichinautzin volcanic field is in the central part of the almost 1000 km long E-W-trending Trans-Mexican Volcanic Belt ( $18^{\circ} 30' - 21^{\circ} 30'N$ , central Mexico) whose origin is associated with the oblique subduction of the Rivera and Cocos plates beneath the North American Plate (Wallace and Carmichael, 1999; Ferrari et al., 2012). The Chichinautzin volcanic field is bounded by the Popocatepetl volcano to the east and by the Nevado de Toluca volcano to the west. This volcanic field separates the Basin of Mexico in the north from the valleys of Cuernavaca and Cuautla in the south. Volcanic rocks in the Sierra Chichinautzin are heterogeneous in composition. They vary from alkaline basalts to calc-alkaline basaltic andesites, andesites and dacites (Wallace and Carmichael, 1999; Marquez et al., 1999; Siebe et al., 2004; Meriggi et al., 2008; Straub et al., 2013).

The monogenetic Jumento volcano is situated in the central part of the Sierra Chichinautzin (Fig. 1). It covers an area of  $2.8 \text{ km}^2$  and the volumes of its cinder cone and emitted lavas have been estimated at  $0.04 \text{ km}^3$  and  $0.056 \text{ km}^3$ , respectively, based on an average lava flow thickness of 20 m (Arce et al., 2015). Hence, Jumento is one of the smallest volcanoes in the Sierra Chichinautzin. The cinder cone flanks are steep ( $32^{\circ}$ ) and have been opened to the south by the emission of at least three overlapping lava flows (Fig. 2). These lava flows show steep fronts and levees that are characteristic of a block-lava morphology. The intermediate lava flow overlies the outer and the inner flows and must therefore be the youngest. It is unclear whether the outer or the inner flow was emplaced first. However, since it has been classified as a monogenetic volcano on the basis of its size and morphology, the temporal difference between them must be minimal (less than a decade), as seen in other monogenetic volcanoes such as Parícutín (Luhr et al., 1993). Several breakout lava flows were distinguished on top of the intermediate lava flow (Fig. 2) as a consequence of fissure emissions (Arce et al., 2015). These flows correspond

thus to the last eruption event of the Jumento volcano and they are a calc-alkaline basaltic andesite, with a porphyritic texture owing to phenocrysts of plagioclase, olivine, pyroxene, and Fe-Ti oxides. Anomalous large (2-4 mm in diameter) plagioclase and quartz crystals are common and have been interpreted as xenocrysts (Fig. 3).

Four charcoal samples have been obtained from two locations on the Jumento volcano (Arce et al., 2015); at each location, the samples were taken within a basal wet pyroclastic surge deposit overlying a thick, charcoal-rich paleosol. The average dates of the four samples (1177 - 982 cal BP / 2334 - 2154 cal BP / 2042 - 1885 BP / 2042 - 1885 cal BP; Fig. 4) suggest a most probable age of ~2 ka. However, this age could be a maximum age if we consider that the wet pyroclastic surge could erode and incorporate charcoal fragments from the underlying paleosol.

### 3. Material and methods

#### 3.1. *In situ*-produced $^{10}\text{Be}$ CRE dating.

##### 3.1.1. Sampling strategy and analytical methods.

Sampling took place in 2016. Four samples (Table 1) were collected with hammer and chisel from the uppermost ~5 cm of solid rock surfaces. Two of them (June 16-1 and June 16-3) were taken from one breakout lava flow, whereas the other two (June 16-4 and June 16-5) were collected from the inner lava flow (Fig. 2). All sampled surfaces were well preserved, showing no signs of erosion, weathering or boulder toppling. Thus the potential bias in the *in situ*-produced cosmogenic nuclide surface concentrations induced by these post-cooling geomorphological processes are minimized. Moreover, the protruding geometries of the sampled features reduce the risk of surface shielding by snow, tephra fall associated with volcanic activity of surrounding volcanoes and soils.

Physical and chemical samples were prepared and beryllium-10 was measured during 2016 at the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE; France). Lichens, moss and other organic matter were removed from the samples with a brush. Then, the samples were crushed with a roller grinder and sieved to retain the grain size fraction 0.25 - 0.50 mm. The presence of 2-4 mm xenocrystic quartz crystals (Arce et al., 2015), allowed the application of *in situ*-

produced cosmogenic  $^{10}\text{Be}$  dating to determine the emplacement ages of these lava flows (Figures 2 and 3). We decided to use  $^{10}\text{Be}$ , which is routinely measured in quartz and therefore the most applied cosmogenic nuclide; this was in preference to  $^{36}\text{Cl}$ , measured in silicate whole rocks and Ca- and K-rich minerals, or to  $^3\text{He}$ , applied to pyroxene and olivine phenocrysts (e.g. Schimmelpfennig et al., 2011; Alcalá-Reygosa et al., 2018), because the production systematics of  $^{10}\text{Be}$  are simpler and better constrained than those of the other cosmogenic nuclides, usually resulting in a lower uncertainty (Marrero et al., 2016).

The chemical  $^{10}\text{Be}$  protocol was adapted from the procedures used by Brown et al. (1991) and Merchel and Herpers (1999). To isolate these quartz xenocrysts from the bulk rock, the samples went repeatedly through a magnetic Frantz separator until all magnetic minerals were discarded. Then, the non-magnetic fraction underwent successive chemical attacks in a mixture of concentrated hydrochloric and hexafluorosilic acids, which dissolve remaining non-quartz minerals but not the quartz. The sample grains were decontaminated from meteoric  $^{10}\text{Be}$  and potential resistant impurities (e.g. feldspar) through three successive partial dissolutions with concentrated hydrofluoric acid (HF), which dissolved ~30% of the quartz grains. This procedure is a conservative adaption of the finding (Brown et al., 1991) that atmospheric  $^{10}\text{Be}$  is removed by a fractional acid etching that dissolves 10% of the quartz. The purity of quartz was then visually verified under a binocular microscope.

The samples yielded between 6.26 and 8.37 g of purified quartz (Table 2). About 100  $\mu\text{l}$  of a  $^9\text{Be}$  carrier solution with a  $^9\text{Be}$  concentration of 3025 mg/g, prepared in-house from a phenakite crystal (Merchel et al., 2008), was added to the quartz before its complete dissolution in HF. A chemical blank was prepared along with the four samples. Following evaporation of the resulting solution, the samples were recovered in a hydrochloric acid solution and  $\text{Be}(\text{OH})_2$  was precipitated with ammonia before and after elution through an anionic exchange column (Dowex 1X8) to remove iron, and then through a cationic exchange column (Dowex 50WX8) to remove boron and to separate the Be from other elements according to the methods described by Merchel and Herpers. (1999). The solution, which included the purified Be, was evaporated and the resulting  $\text{Be}(\text{OH})_2$  was oxidized to BeO at 700° C. Then, the final BeO was mixed with niobium and loaded on cathodes for measurement of the  $^{10}\text{Be}/^9\text{Be}$  ratios at the French national accelerator mass



spectrometry (AMS) facility ASTER (CEREGE, France) (Arnold et al., 2010). The measurements were calibrated against the in-house standard STD-11, using an assigned  $^{10}\text{Be}/^9\text{Be}$  ratio of  $1.191 (\pm 0.013) \times 10^{-11}$  (Braucher et al., 2015). Sample  $^{10}\text{Be}/^9\text{Be}$  ratios were corrected for the chemical blank background by subtracting the measured chemical blank  $^{10}\text{Be}/^9\text{Be}$  ratio (Table 2). Analytical  $1 \sigma$  uncertainties include uncertainties in AMS counting statistics, the uncertainty in the standard  $^{10}\text{Be}/^9\text{Be}$  ratio, an external AMS error of 0.5% (Arnold et al., 2010), and the uncertainty in the chemical blank measurement. A  $^{10}\text{Be}$  half-life of  $1.387 (\pm 0.01) \times 10^6$  years was used (Chmeleff et al., 2010; Korschinek et al., 2010).

### 3.1.2. $^{10}\text{Be}$ CRE age calculations

Although the equation for calculating a CRE age from an in situ-produced  $^{10}\text{Be}$  concentration is consensually accepted, various parameters that govern the production of cosmogenic nuclides are still under discussion. Among these, there is particular controversy regarding the spatial scaling of the production rate and its temporal variability both of which depend mainly on the intensity of the Earth's magnetic field. Many combinations of the different parameters presented in the literature are possible and proposed in the available online calculators (Balco et al., 2008; Marrero et al., 2016; Martin et al., 2017).

When the default parameter settings are used, the highest  $^{10}\text{Be}$  CRE ages (Table 3) are obtained with the online calculator for exposure age CREp (Martin et al., 2017; <http://crep.cprg.cnrs-nancy.fr/#/init>) using the time-dependent “Lm” scaling method of Lal/Stone (Lal, 1991; Stone, 2000; Nishiizumi et al., 1989; Balco et al., 2008) together with the ERA40 atmosphere model (Uppala et al., 2005) and the geomagnetic database proposed by Muscheler et al. (2005), and in combination with the worldwide mean of the sea level/high latitude (SLHL)  $^{10}\text{Be}$  spallation production rate of  $4.13 \pm 0.20$  atoms  $\text{g}^{-1} \text{yr}^{-1}$ , as calibrated in the ICE-D production rate database linked to CREp. The lowest  $^{10}\text{Be}$  CRE ages (Table 3) are obtained with version 3 of the “online calculator formerly known as the CRONUS-Earth online calculator” (Balco et al., 2008; [https://hess.ess.washington.edu/math/v3/v3\\_age\\_in.html](https://hess.ess.washington.edu/math/v3/v3_age_in.html)) based on the time-independent “St” scaling (Stone, 2000) in combination with the ERA40 atmosphere model and the

default global SLHL  $^{10}\text{Be}$  spallation production rate inferred from the ICE-D production rate database.

The two methods of calculation differ in that the former takes into account the dependence of the production rate on the variability of the geomagnetic field strength, whereas the latter does not. Over short exposure durations of a few thousand years, the resulting age difference can be pronounced, because the variability of the geomagnetic field strength is less averaged out than for longer time scales. In both cases, a rock density of  $2.7 \text{ g cm}^{-3}$  is applied. The shielding factors were calculated with the Topographic Shielding Calculator v1.0 provided by CRONUS-Earth Project (Marrero et al., 2016). Considering the good state of preservation of the surfaces sampled, no corrections for erosion were applied. Similarly, considering that today the snow pack does not usually remain for longer than a few days, the influence of snow cover on the production rates when integrated over the past thousands of years is assumed to be insignificant.

#### 4. Results

The individual  $^{10}\text{Be}$  CRE ages of the lava flow samples of the Jumento volcano are shown in Figure 2 and Table 3, together with their  $1 \sigma$  uncertainties that include the analytical errors only (internal uncertainty) and those that also include the uncertainty in the SLHL  $^{10}\text{Be}$  production rate (external uncertainty). The external uncertainties are relevant when comparing the  $^{10}\text{Be}$  ages with ages derived from other dating methods; when the  $^{10}\text{Be}$  ages are compared among them, only the internal uncertainties are of importance.

Considering the CRE ages and their analytical uncertainties calculated with the CREp exposure age calculator, i.e. the highest results, the two CRE ages from the inner lava flow are  $3.09 \pm 0.78 \text{ ka}$  and  $1.73 \pm 0.74 \text{ ka}$ , whereas the two CRE ages from the breakout lava flow are  $2.77 \pm 0.71 \text{ ka}$  and  $2.21 \pm 0.52 \text{ ka}$  (fig. 2). The considerable analytical uncertainties, of the order of 25% (and 43% for sample June 16-5), are due to the relatively young ages and the small amounts of quartz we obtained from the available rock material, leading to low measured  $^{10}\text{Be}/^9\text{Be}$  ratios that are only between 2 and 5 times that of the chemical blank (Table 2). For future studies, it should be possible to reduce these analytical uncertainties to as low as ~3% by extracting the  $^{10}\text{Be}$  from a larger amount of quartz (~40 g in the case of samples from Jumento volcano).

Within uncertainties, these four  $^{10}\text{Be}$  CRE ages from the two lava flows are not significantly different. They lead to an arithmetic  $^{10}\text{Be}$  CRE mean age and standard deviation of  $2.41 \pm 0.96$  ka for the inner lava flow and of  $2.49 \pm 0.40$  ka for the breakout lava flow. Taking into account the uncertainty in the SLHL  $^{10}\text{Be}$  production rate by calculating the square root of the sum of squared standard deviation and squared production rate error, the ages are  $2.41 \pm 0.97$  ka for the inner lava flow and  $2.49 \pm 0.41$  for the breakout lava flow.

Considering the results computed with the “calculator formerly known as the CRONUS-Earth online calculator”, i.e. the lowest CRE ages and their analytical uncertainties, the two CRE ages from the inner lava flow are  $2.33 \pm 0.59$  ka and  $1.38 \pm 0.51$  ka, whereas the two CRE ages from the breakout lava flow are  $2.09 \pm 0.52$  ka and  $1.71 \pm 0.36$  ka (Fig. 4). Within uncertainties, these four  $^{10}\text{Be}$  CRE ages are not significantly different. They lead to an arithmetic  $^{10}\text{Be}$  CRE mean age of  $1.86 \pm 0.67$  ka for the inner lava flow and of  $1.90 \pm 0.27$  ka for the breakout lava flow. Taking into account the uncertainty in the SLHL  $^{10}\text{Be}$  production rate, the ages are  $1.86 \pm 0.68$  ka for the inner lava flow and  $1.90 \pm 0.29$  ka for the breakout lava flow. Since age uncertainties are very similar whether or not the production rate uncertainty is included, we discuss in the following text only the ages with their full uncertainties.

## 5. Discussion

In this study, we present a preliminary test of the application of  $^{10}\text{Be}$  CRE dating of quartz xenocrysts extracted from four samples from two lava flows of Jumento volcano in the Sierra Chichinautzin volcanic field. Independent of the exposure age calculator and the cosmogenic nuclide production parameters used, the arithmetic  $^{10}\text{Be}$  CRE mean ages determined from the inner lava flow (from  $1.86 \pm 0.68$  to  $2.41 \pm 0.97$  ka) and breakout lava flow (from  $1.90 \pm 0.29$  to  $2.49 \pm 0.41$  ka) are indistinguishable from each other and thus suggest that the corresponding effusive eruptive emissions occurred within a relatively short time of each other. In addition, the spatial position of the intermediate lava flow shows that it must have been emitted between the two dated flows. This new chronology does not support the tentative hypothesis put forward by Arce et al. (2015) that the breakout lava flows could have been emitted significantly later than the outer, intermediate and inner lava flows; however, more precise measurements are necessary to definitively confirm this finding. The vegetation is less dense on the breakout flows than

on the outer, intermediate and inner lava flows; this might suggest that the breakout flows are younger, but can probably be explained by the fact that they are not overlaid with tephra or ash like the other lavas, suggesting that the tephra was emitted before the formation of the breakout flows. The arithmetic  $^{10}\text{Be}$  CRE mean ages obtained from the inner lava flow and the breakout lava flow, independent of the calculation method used, are in agreement with the  $\sim 2$  ka radiocarbon age reported by Arce et al. (2015) (Fig. 4). Therefore, both methods suggest consistently that the Jumento volcano is one of the youngest volcanoes of the Sierra Chichinautzin, but the Xitle volcano (316 - 430 cal AD) (Siebe, 2000) might still be the youngest known volcanic edifice of this monogenetic field. However, the uncertainties in our  $^{10}\text{Be}$  CRE ages prevent us from drawing a final conclusion on this question. In addition, because only a few of the cones have been dated, more dating efforts are needed to confirm this hypothesis.

The mineralogy of lava flows usually precludes the determination of their ages by  $^{10}\text{Be}$  CRE dating. Although quartz is rare in basaltic andesites, in these flows on the Jumento volcano the presence of large quartz crystals, considered as crustal xenocrysts (Arce et al., 2015), allowed the use of  $^{10}\text{Be}$  dating. To our knowledge, the Jumento volcano is the second place worldwide where this method has been applied, the first being the Kula volcanic field (western Turkey) (Heineke et al., 2016); hence,  $^{10}\text{Be}$  CRE dating can be useful to date Holocene volcanic rocks if the mineralogical composition allows it. In fact, crustal xenocrysts are common in the Sierra Chichinautzin (Meriggi et al., 2008; Arce et al., 2013) and  $^{10}\text{Be}$  CRE ages could thus potentially be obtained on other volcanic edifices where traditional methods such as K/Ar,  $^{40}\text{Ar}/^{39}\text{Ar}$  or radiocarbon dating cannot be used. Moreover, Late Holocene lava flows are particularly well suited for cosmogenic surface dating because their exposure history is simple and the effects of erosion and exhumation on the nuclide production *in situ* are generally negligible (Dunai, 2010; Dunai et al., 2014; Espanon et al., 2014; Fenton and Niedermann, 2014; Alcalá-Reygosa et al., 2018). Therefore, if quartz is present in volcanic rocks,  $^{10}\text{Be}$  CRE dating constitutes a consistent method to determine the eruptive history, not only in the Sierra Chichinautzin but also in other volcanic areas; this could improve the mitigation of the hazards and related risks in densely populated areas.

## 6. Conclusions

For the first time,  $^{10}\text{Be}$  CRE ages were obtained for four quartz xenocryst samples extracted from two lava flows of Jumento volcano. The  $^{10}\text{Be}$  CRE mean ages of these two lava flows, constrained between  $1.86 \pm 0.68$  and  $2.41 \pm 0.97$  ka and between  $1.90 \pm 0.29$  and  $2.49 \pm 0.41$  ka, confirm that the Jumento volcano is one of the youngest volcanoes of the Sierra Chichinautzin. They also suggest that the Xitle volcano is likely the youngest known volcanic edifice of this monogenetic volcanic field, although more precise  $^{10}\text{Be}$  ages are needed to confirm this hypothesis. In future studies, lower analytical uncertainties could be achieved by using larger amounts of quartz for the  $^{10}\text{Be}$  extraction, but the present preliminary results already show the potential of  $^{10}\text{Be}$  CRE dating when quartz xenocrysts are present in volcanic rocks. In such cases, the  $^{10}\text{Be}$  CRE dating method not only offers an alternative method to date lava flow surfaces that are not suitable for the radiocarbon and/or  $^{40}\text{Ar}/^{39}\text{Ar}$  dating methods, but it also has the potential to supplement the volcanic history and eruption records of volcanic areas, in order to improve the mitigation of the hazards and related risks in densely populated areas.

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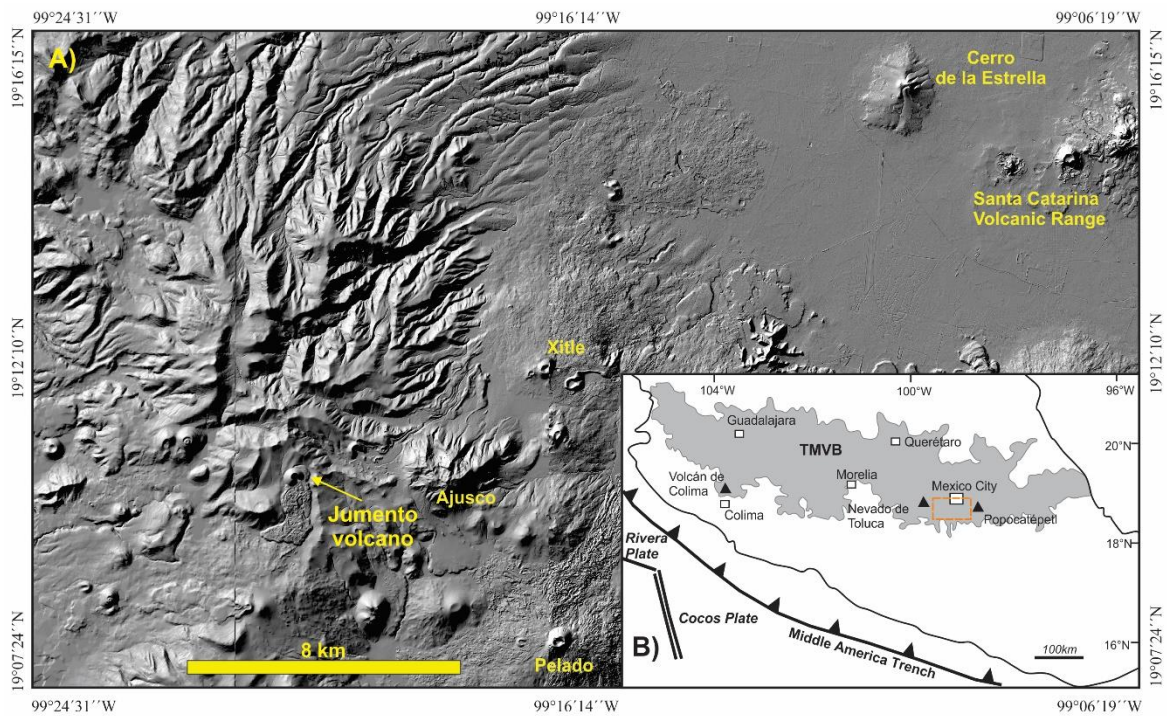
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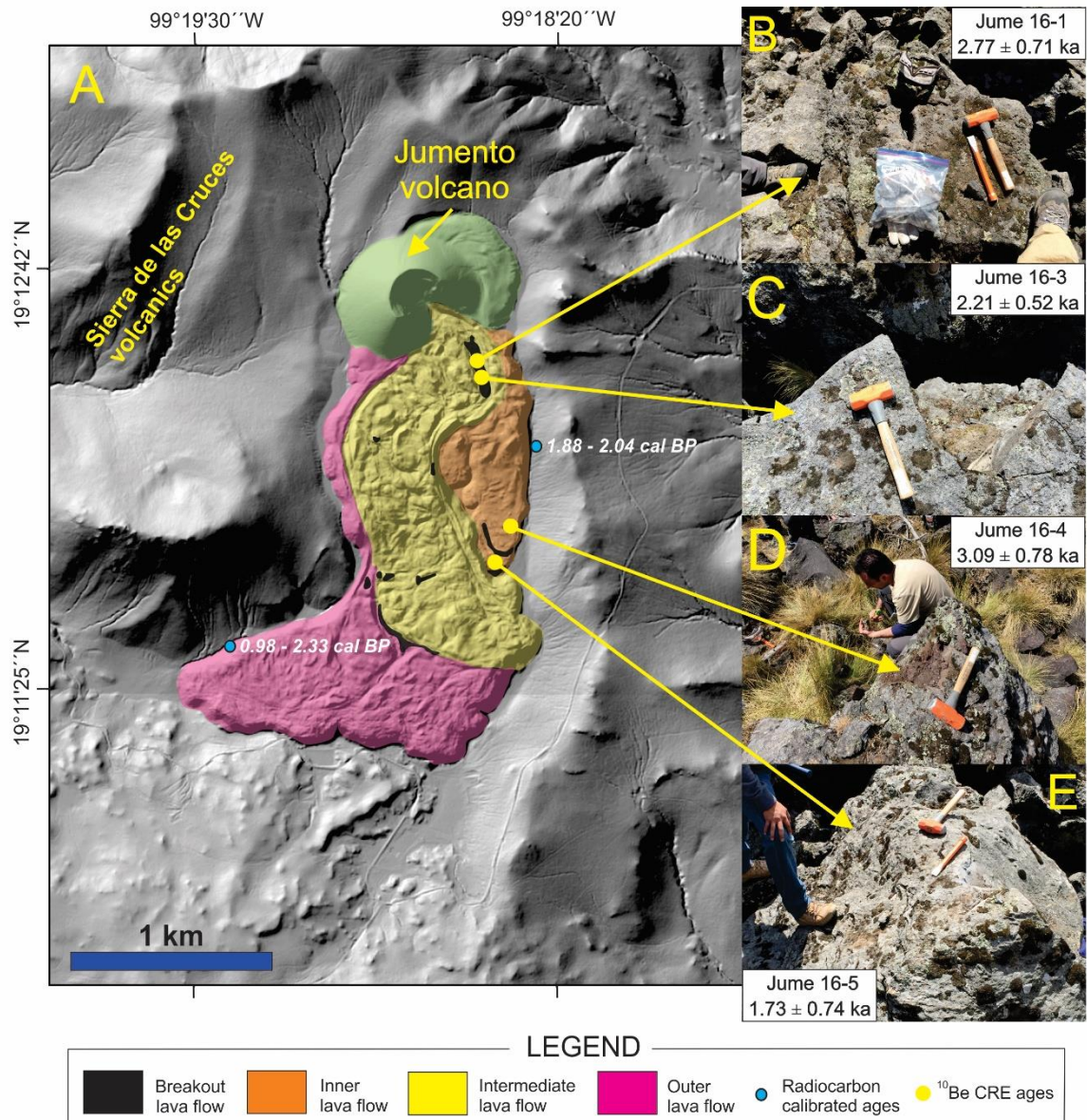
## FIGURES

**Figure 1.** Location of Jumento volcano. A) Digital Elevation Model (DEM) to show the proximity of the study area to Mexico City. B) General map of the Trans-Mexican volcanic belt in central Mexico showing the location of some active Mexican volcanoes and some important cities. The orange rectangle represents the area of A).



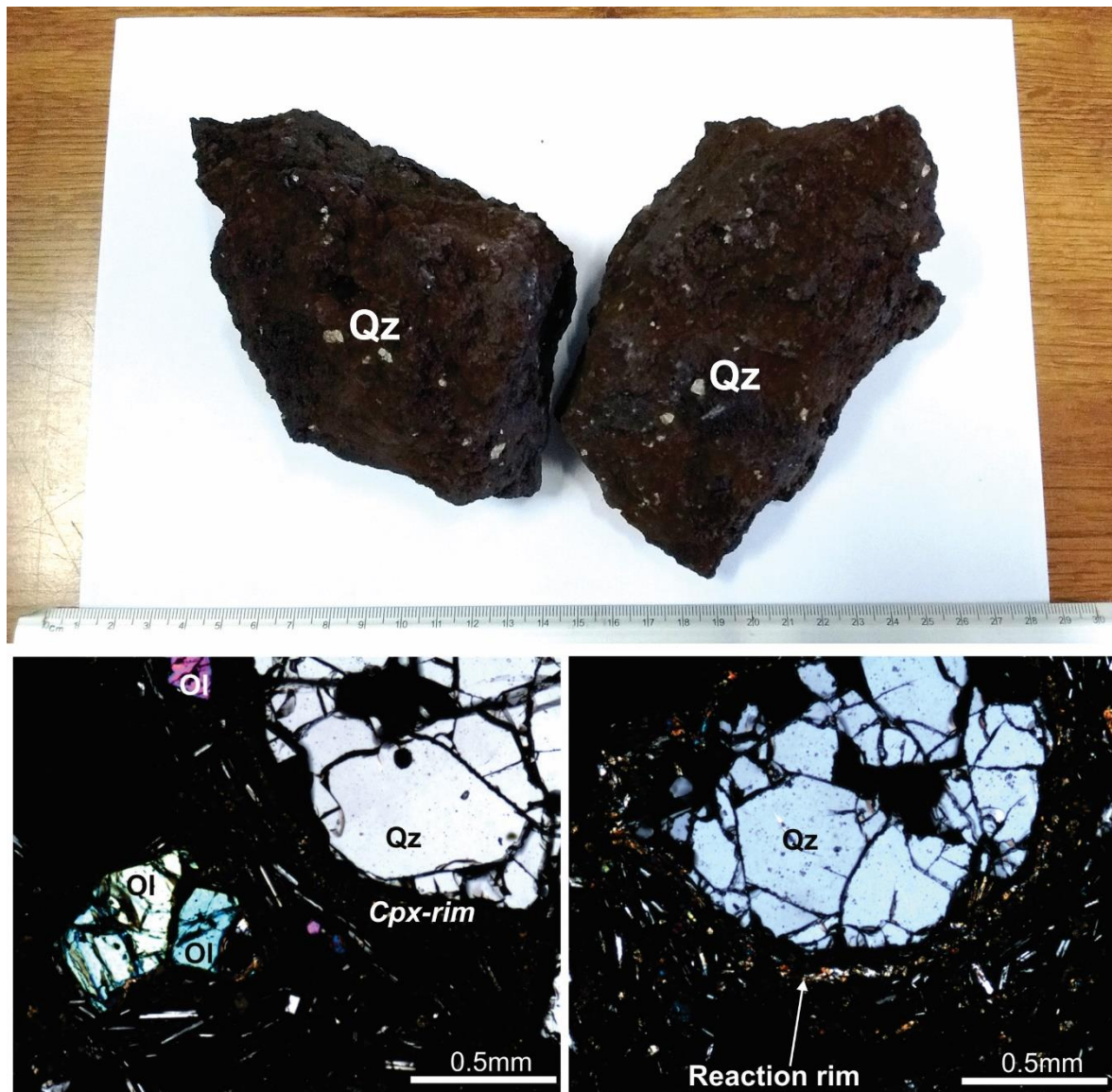
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**Figure 2.** Sample sites. A) Digital elevation model showing the morphology of Jumento volcano, and the sampled lava flows. B-E) Photographs and  $^{10}\text{Be}$  CRE ages of the sampled geomorphic features on Jumento volcano based on the online exposure age calculator CREp.

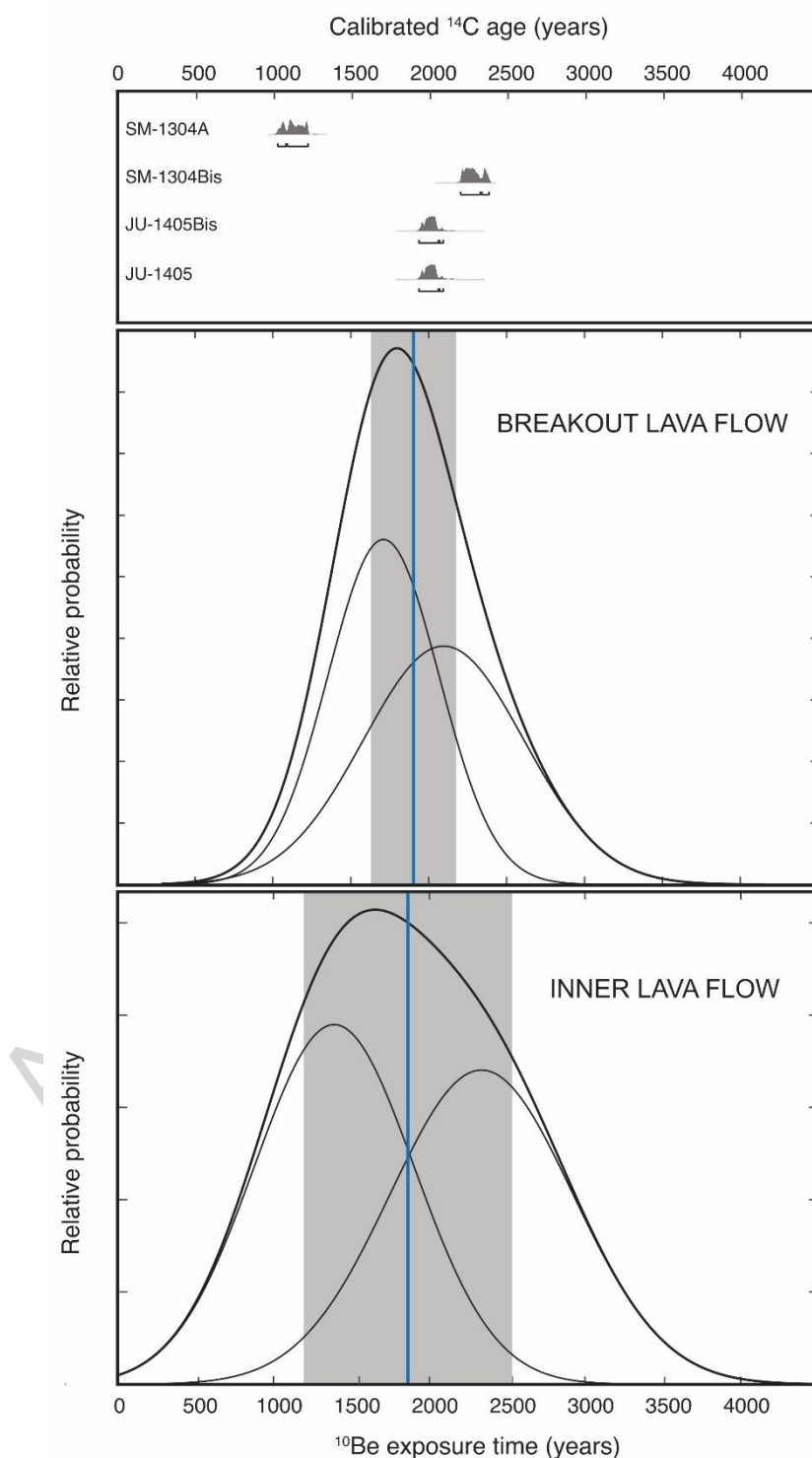




**Figure 3.** Photographs of untreated mafic rock pieces, and photomicrographs of thin sections of the lava samples from Jumento volcano, showing the large quartz (Qz) xenocrysts (> 1 mm) that allowed *in situ*-produced cosmogenic  $^{10}\text{Be}$  dating.



**Figure 4.** Probability plots of  $^{10}\text{Be}$  CRE ages of the Inner and the Breakout lava flows, based on the “calculator formerly known as the CRONUS-Earth online calculator” (this work) and  $^{14}\text{C}$  ages (Arce et al., 2015) from Jumento volcano. Individual  $^{10}\text{Be}$  ages with their analytical uncertainties are shown as thin gaussian bells, while the thick curve represents their summed probability function; vertical lines represent the arithmetic mean ages and grey bands their  $1\sigma$  uncertainties.  $^{14}\text{C}$  ages are calibrated and plotted using OxCal v4.3.2 (Bronk Ramsey, 2017) with the IntCal13 atmospheric curve (Reimer et al., 2013);  $2\sigma$  age intervals are shown for each of the four individual measurements.



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## TABLES

Table 1. Field data and sample characteristics of  $^{10}\text{Be}$ -dated samples from lava flows of Jumento volcano.

Sample	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Thickness (cm)	Shielding factor
June 16-1	19.20697	-99.31033	3654	6	0.98219
June 16-3	19.20669	-99.31018	3664	4.5	0.99452
June 16-4	19.19676	-99.30778	3563	6	0.99502
June 16-5	19.19576	-99.30917	3580	4.5	0.99337

Table 2. Analytical data of  $^{10}\text{Be}$  dated samples from lava flows of Jumento volcano.

Sample	Quartz (g)	$^{10}\text{Be} / ^9\text{Be}$ ( $10^{14}$ )	AMS measured error ( $10^{14}$ )	$^{10}\text{Be}$ (at.g-1) ( $10^3$ )	Error $^{10}\text{Be}$ (at.g-1) ( $10^3$ )
June 16-1	7.25	1.73	0.43	56	14
June 16-3	8.37	1.58	0.33	47.2	9.8
June 16-4	7.85	2.10	0.53	61	15
June 16-5	6.26	0.98	0.36	37	14
Blank		0.45	0.13	-	-



Table 3.  $^{10}\text{Be}$  CRE exposure ages from Jumento volcano derived from (1) CRE Cosmic Ray Exposure Program  $^{10}\text{Be}$  CRE and (2) v3 CRONUS-Earth online exposure age calculator ([https://hess.ess.washington.edu/math/v3/v3\\_age\\_in.html](https://hess.ess.washington.edu/math/v3/v3_age_in.html)) based on St scaling.

Sample	$^{10}\text{Be}$ CRE age (ka)	External uncertainty	Internal uncertainty	$^{10}\text{Be}$ CRE age (ka)	External uncertainty	Internal uncertainty
	(1)	$1\sigma$ (ka) (1)	$1\sigma$ without PR error (1)	(2)	$1\sigma$ (ka) (2)	$1\sigma$ without PR error (2)
Jume 16-1	2.77	0.73	0.71	2.09	0.54	0.51
Jume 16-3	2.21	0.54	0.52	1.71	0.38	0.35
Jume 16-4	3.09	0.79	0.78	2.33	0.61	0.58
Jume 16-5	1.73	0.75	0.74	1.38	0.52	0.51

## Highlights

>We provide a new chronology of Jumento volcano (Sierra de Chichinautzin, Mexico). > We used *in situ*-produced  $^{10}\text{Be}$  cosmic ray exposure (CRE) dating. > Jumento volcano is one of the youngest volcanoes of the Sierra de Chichinautzin. >  $^{10}\text{Be}$  cosmic ray exposure (CRE) dating has considerable potential to date volcanic products worldwide.

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