© 2016 ARQUEOLOGÍA IBEROAMERICANA 30: 23–29. ISSN 1989–4104. http://laiesken.net/arqueologia/.

RESEARCH ADVANCE

ARCHAEOMAGNETIC DATING OF THE ERUPTION OF XITLE VOLCANO, BASIN OF MEXICO: IMPLICATIONS FOR THE MESOAMERICAN CENTERS OF CUICUILCO AND TEOTIHUACAN

Datación arqueomagnética de la erupción del volcán Xitle, cuenca de México: implicaciones para los centros mesoamericanos de Cuicuilco y Teotihuacan

Jaime Urrutia-Fucugauchi,* Avto Goguitchaichvili,** Ligia Pérez-Cruz,* Juan Morales*

* Departamento de Geomagnetismo y Exploración, Instituto de Geofísica, UNAM, México;
** Servicio Arqueomagnético Nacional (SAN), Instituto de Geofísica, UNAM, México

Figure 1. Fragment of the mural paint of the Xitle eruption and impact on Cuicuilco (Artist: Alejandro Linares-García on display at Tlalpan Delegation, Mexico City).

ABSTRACT*. The Cuicuilco archaeological site in southern Basin of Mexico is covered by lava flows from the Xitle volcano. Dating the Xitle eruption and Cuicuilco abandonment has long been attempted.*

Received: 12 April 2016. Accepted: 18 April 2016. Published: 25 April 2016.

Edited & Published by Pascual Izquierdo-Egea. The English text was proofread by Michelle Young.

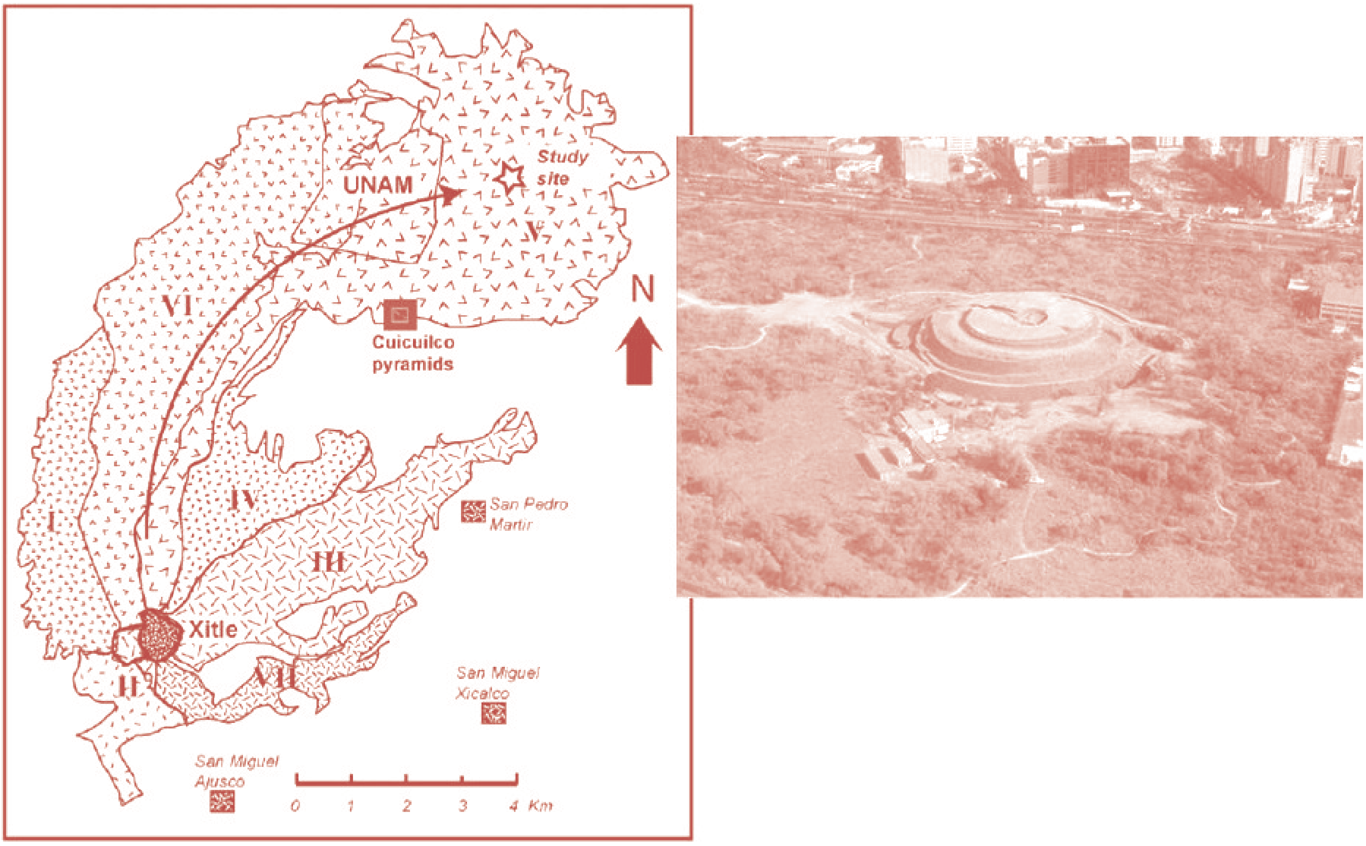

Figure 2. Schematic map of Xitle lava flows, southern Basin of Mexico (Delgado-Granados *et al.* 1998). Arrows indicate flow directions. Location of the Cuicuilco archaeological center is indicated (inset aerial view of Cuicuilco sector-A and the circular-cross section pyramid, surrounded by lava flows; Siebe 2000). The UNAM National University campus is built on the Xitle lava field.

Contrasting results with radiocarbon dates around 2000 and 1670 yr BP have been reported, with implications for the development of the Mesoamerican centers of Cuicuilco and Teotihuacan. Here, we analyze radiocarbon dates and paleomagnetic data for the Xitle lava flows. New age estimates for the eruption are determined from correlating full vector data with the geomagnetic secular variation reference model. The revised archaeomagnetic data give ages correlating with the radiocarbon chronology, with a mean of 2086 cal yr BP and 95% confidence interval from 1995 to 2177 cal yr BP. Bootstrap analysis of the calibrated radiocarbon and archaeomagnetic dates gives mean dates and confidence intervals of 2041 and 1968–2041 cal yr BP and 2035 and 1968–2073 cal yr BP, respectively. The interval estimated of ~90 BC to ~AD 20 supports a possible link between the abandonment of Cuicuilco and the early development of Teotihuacan.

***KEYWORDS**: Cuicuilco, Teotihuacan, Xitle volcano, Archaeomagnetism, Mesoamerica.*

***RESUMEN**. La zona arqueológica de Cuicuilco, en el sur de la cuenca de México, está cubierta por flujos de lava del volcán Xitle. Se ha intentado la datación de la erupción y el abandono del centro de Cuicuilco aplicando diferentes métodos. Se han propuesto fechas contrastantes alrededor de 2000 y 1670 años AP, con implicaciones para el desarrollo de los centros urbanos mesoamericanos Cuicuilco y Teotihuacan. A continuación, analizamos las fechas de radiocarbono y los datos paleomagnéticos para los flujos de Xitle. Se presentan nuevas estimaciones de la edad de la erupción usando datos del vector completo con el modelo geomagnético de referencia. Los datos paleomagnéticos revisados dan edades con una media de 2086 años AP e intervalo de confianza del 95 % entre 1995–2177 años AP. El análisis* bootstrap *de las edades radiocarbónicas y arqueomagnéticas proporciona edades medias e intervalos de confianza de 2041 y 1968–2041 años AP y 2035 y 1968–2073 años cal AP, respectivamente. El intervalo estimado de ~ 90 a.C. a 20 d.C. es compatible con una posible relación entre el abandono de Cuicuilco y el desarrollo de Teotihuacan.*

PALABRAS CLAVE: *Cuicuilco, Teotihuacan, volcán Xitle, arqueomagnetismo, Mesoamérica.*

INTRODUCTION

Xitle is a monogenetic cinder cone located in the southern Basin of Mexico, on the northern slope of the Ajusco volcanic complex. It forms part of the Chichinautzin monogenetic volcanic field developed in the arc front zone of the Trans-Mexican volcanic belt (Urrutia-Fucugauchi & Martin 1993). Xitle is one of the youngest volcanoes and its lava flows cover the Cuicuilco archaeological center (Figs. 1, 2). Cuicuilco represents an early urban settlement in the Basin of Mexico (Heizer & Bennyhoff 1958). The eruption of Xitle volcano has been linked to the abandonment of the site, which was covered by tephra and lava flows. Beginning with the initial excavation projects, determining the age of the eruption has attracted considerable interest. Arnold and Libby (1951) reported a date of 2422 ± 250 yr BP, as part of the first date set obtained with the radiocarbon method (Libby 1955). Since then, more than 30 radiocarbon dates for samples from the Xitle lavas and Cuicuilco archaeological site have been reported, which present a wide multimodal ~4000 to ~1500 yr BP distribution (Urrutia-Fucugauchi 1996).

The first date of Arnold and Libby (1951) was obtained from a soil sample recovered beneath the lava. Subsequent studies have dated samples from soils and charcol from outcrops and from archaeological excavations in different sectors of the lava field and in the Cuicuilco site. Dates around 2000–1960 yr BP and younger dates around 1530–1630 yr BP have been proposed for the Xitle eruption (e.g. Fergusson & Libby 1963; Cordova *et al.* 1994; Urrutia-Fucugauchi 1996; Siebe 2000; Gonzalez *et al.* 2000). Older or younger dates present archaeological implications for the abandonment of the site, population migration and relationships to the development of the Teotihuacan urban center (Nichols 2016). Discussion on the age of the eruption has focused on the stratigraphic context and nature of the samples dated, with arguments for and against its temporal relation to the tephras and lavas (Cordova *et al.* 1994; Gonzalez *et al.* 2000). In this study we present an analysis using paleomagnetic data retrieved from the lava flows. For the archaeomagnetic dating we use full vector data with the remanent magnetization directions and paleointensities and the recently developed archaeomagnetic reference curve.

ARCHAEOMAGNETIC AND RADIOCARBON DATING

The basaltic flows of the Xitle eruption cover an extensive > 80 km^2 area on the Ajusco volcano slope and into the adjacent plain, where the Cuicuilco center was built and nowadays is occupied by the urban development of Mexico City (Fig. 2). The flows have long been studied, with several distinct flow and tephra units mapped (Delgado-Granados *et al.* 1998). Paleomagnetic studies have been conducted, reporting remanent magnetization directions and paleointensities from different sites in the lava field (e.g. Nagata *et al.* 1965; Urrutia-Fucugauchi 1996; Morales *et al.* 2001, 2006; Alva-Valdivia 2005).

The paleomagnetic directions present northward declinations and downward inclinations with small within-site angular dispersion. The mean-site inclinations mainly cluster around the dipolar direction, with some showing shallower inclinations (Urrutia-Fucugauchi 1996). The overall mean direction determined for 26 sites is Dec = 359.8°, Inc = 32.8°, k = 167 and α_{95} = 2.2°. The mean direction for the shallow inclination group is N = 7, Dec = 1.5°, Inc = 26.7°, k = 338 and α_{95} = 3.3°. The mean direction for the dipolar inclination group is N = 19, Dec = 359.0°, Inc = 35.1°, k = 247 and α_{95} = 2.1°. Paleointensities were determined for some sites, using the Thellier double-heating and Shaw methods, giving a mean of N = 20, 60.5 + 9.2 μT (a subset group gives a mean N = 13, 56.5 + 6.2 μT). Alva-Valdivia (2005) reported data for 10 sites, with a mean direction of Dec = 1.1°, Inc = 34.1°, k = 531 and α_{95} = 2.1°. In this study, a larger set of paleointensities determined with the Thellier method was obtained. The paleointensities range from 48.6 to 73.9 μT, with mean of N = 9, 59.9 ± 7.7 μT. For this study, the site mean directions and paleointensities reported in Urrutia-Fucugauchi (1996) and Alva-Valdivia (2005) are referred to the archaeomagnetic reference curve by Pavón-Carrasco *et al.* (2014). Inclusion of full vector data improves analysis, considering three variables with higher-resolution age estimates.

The radiocarbon dates range from 4690 ± 70 to 1430 ± 200 yr BP, with four groupings around 4000, 2400, 2000 and 1500 yr BP. Production of radioactive carbon varies with the strength of the geomagnetic field, which changes through time (Ramsey *et al.* 2006). Correcting the dates using the dendrochronologic reference curve provides calendar years ranging from about 3500 BC to AD 640, which spans a rather long interval. Radiocarbon dates ranging

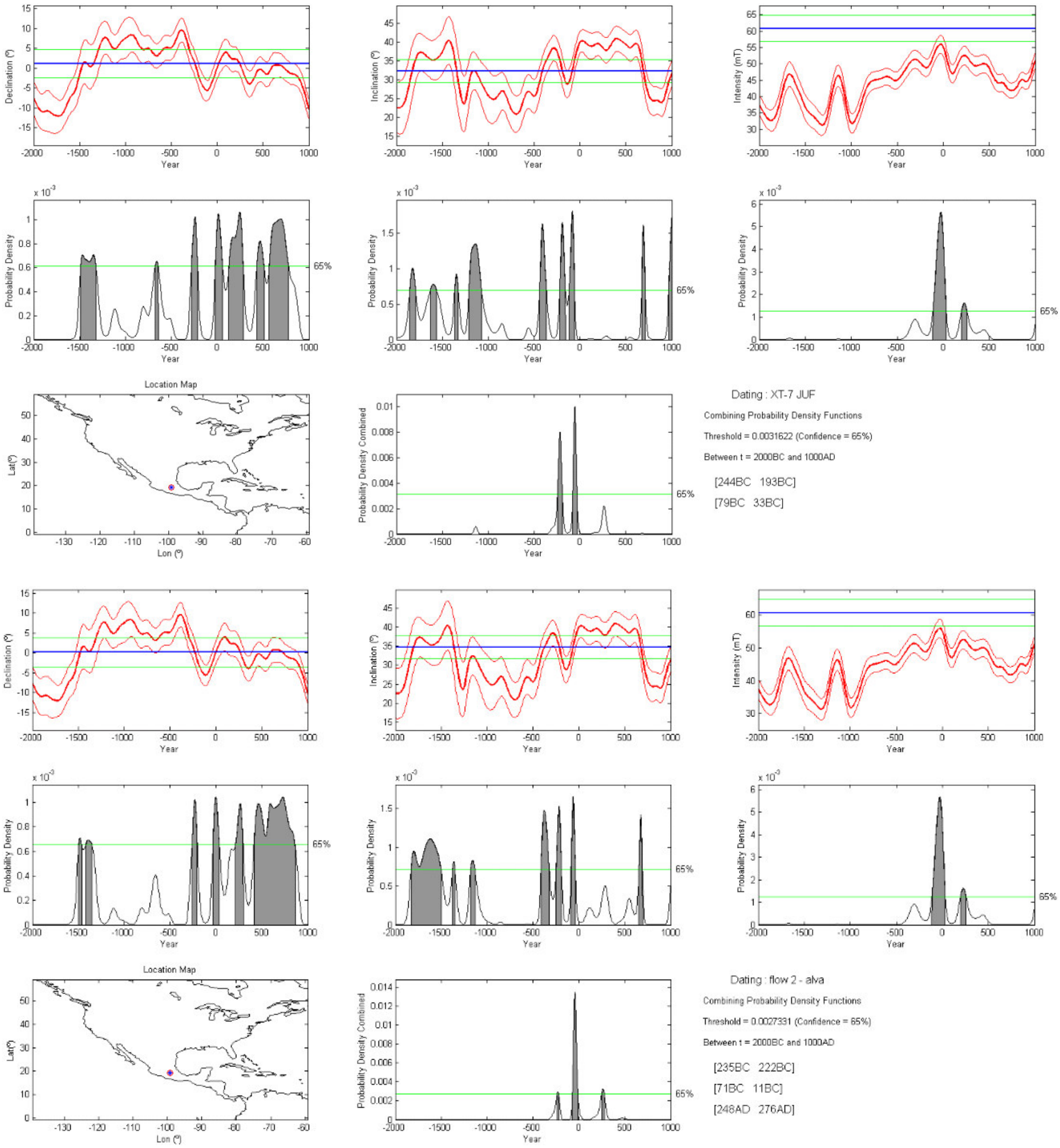

Figure 3. Archaeomagnetic dating of Xitle lavas. Diagrams show in red the master reference archaeomagnetic curves with uncertainty ranges for declination, inclination, and intensity (Pavón-Carrasco *et al.* 2014 geomagnetic model); and in blue the Xitle paleomagnetic data. Green lines give the cutoff values at a given probability level. Probability density functions from the secular variation curve analysis are shown in the lower diagrams. The combined analysis of full vector paleomagnetic data is given in the summary diagram with the reference geographic map. Results for sites XT-7 (Urrutia-Fucugauchi 1996, see above) and 6 (Alva-Valdivia 2005, see below).

from 1950 to 2100 yr BP result in calendar years around 100 BC to AD 60, which correlate with the expansion of Teotihuacan. Younger radiocarbon ages of about 1670 yr BP (Siebe 2000) imply that Cuicuilco inhabitants, if migrating to Teotihuacan, were not involved in the center expansion (Nichols 2016; Cordova *et al.* 1994; Gonzalez *et al.* 2000). For this study, radiocarbon dates are recalibrated to the dendrochronologic curve and re-analyzed using bootstrap statistics.

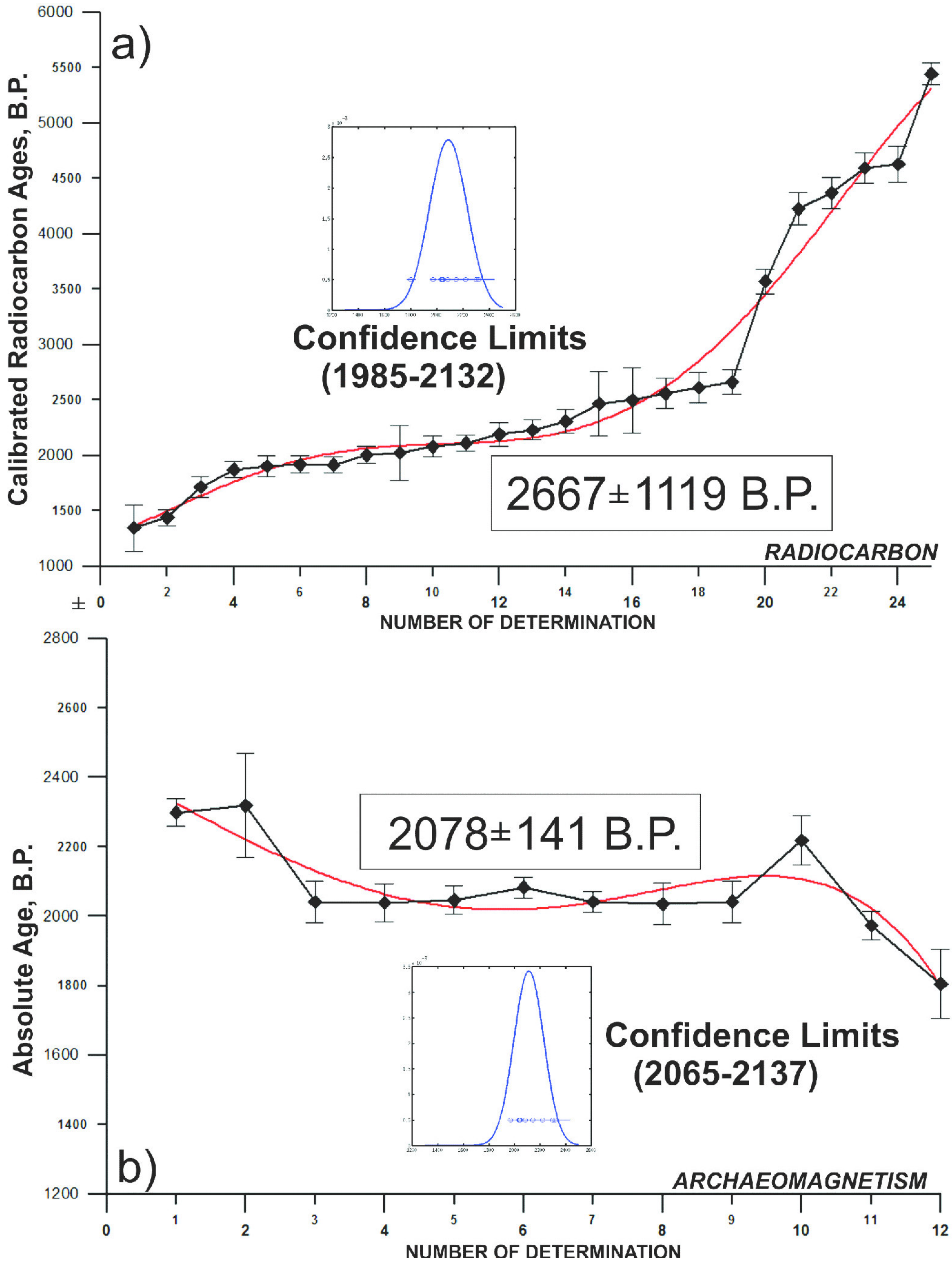

Figure 4. Distribution of radiometric (a) and archaeomagnetic dates (b). Mean dates and confidence limits derived from bootstrap analysis. Insets show Gaussian function fits (see text).

ANALYSIS AND DISCUSSION

Archaeomagnetic dating relies on the spatio-temporal variations of the geomagnetic field and the record of remanent magnetization in volcanic and archaeological materials. Remanent magnetization, directional and paleointensity data, which record the geomagnetic field at time of magnetization acquisition, are correlated to a reference curve independently dated from the directional and intensity changes of the geomagnetic field. Resolution depends on the fidelity of the remanence recording and precision of the reference geomagnetic secular variation curve. For this study, the paleomagnetic data for the Xitle lavas have small angular dispersion at the within- and between-site levels. The mean directions determined in Urrutia-Fucugauchi (1996) and Alva-Valdivia (2005) are statistically indistinguishable, with small 2.1° α_{95} overlapping confidence cones. Site-mean directions show northward declinations and inclinations close to the dipolar inclination, which are referred to the geomagnetic reference SHA.DIF.14k model of Pavón-Carrasco *et al.* (2014). We consider full vector data, adding the paleointensities in the correlation. The paleointensities present higher dispersion at the between site level, which has been analyzed, incorporating determinations with cooling rate corrections (Morales *et al.* 2006; Alva-Valdivia 2005).

For this study, the archaeomagnetic correlations are performed at site level (Fig. 3), to take into account the dispersion. The results show internal consistency, with small standard deviations. Assuming a Gaussian probability distribution, mean is 2068.5 cal yr BP with sigma of 143 and 95% confidence interval from 1995.4 to 2177.4 cal yr BP (Fig. 4). Analysis of radiocarbon dates in the 1200–2600 cal yr interval gives 12 dates with mean of 1916.8 cal yr BP and sigma of 227, with 95% confidence interval from 1772.2 to 2061.3 cal yr BP (Fig. 4). The mean radiocarbon date is younger than the archaeomagnetic date.

To analyze the difference in age estimates, we carried out a bootstrap analysis to constrain the best date estimates. Confidence limits are determined for each date and used to generate random series of 100 vectors. For the radiometric dates, the resulting matrix then has 12 x 100 elements and for the archaeomagnetic dates it has 9 x 100 elements. Vectors are fitted using splines and mean and confidence intervals calculated. The resulting mean for the archaeomagnetic dates is 2035 cal yr BP, with a 95% confidence interval from 1968 to 2073 cal yr BP. The corresponding mean for the radiometric dates is 2041 cal yr BP, with 95% confidence interval from 1968 to 2041 cal yr BP (Fig. 4).

These estimates can be refined by deleting data points that fall off from the confidence interval in the probability density distributions. In this analysis, one archaeomagnetic and two radiometric dates are deleted. The resulting mean for the archaeomagnetic dates is 2101 cal yr BP with confidence interval of 2065–2137 cal yr BP. For the radiocarbon dates the mean is 2061 cal yr BP with a confidence interval of 1985–2132 cal yr BP.

CONCLUSIONS

The age of the Xitle eruption is determined from correlating paleomagnetic full vector data with the recently constructed geomagnetic secular variation reference model. The revised archaeomagnetic dates have a mean age of 2086 cal yr BP with 95% confidence interval from 1995 to 2177 cal yr BP. Bootstrap analysis of the calibrated radiocarbon and archaeomagnetic dates gives mean ages and confidence intervals of 2041 cal yr BP and 1968–2041 cal yr BP and 2035 cal yr BP and 1968–2073 cal yr BP, respectively. These estimates are internally consistent, with overlapping calendar intervals of 91 BC to AD 18 and 83 BC to 18 AD, respectively. Results support a possible link between the Xitle eruption and collapse of Cuicuilco center and the early development of Teotihuacan.

Acknowledgments

Authors are grateful to Rafael Garcia for the bootstrap analysis. Financial support from Conacyt-252149, DGAPA-PAPIIT IN105214 and IG101112.

About the authors

Jaime Urrutia-Fucugauchi (juf@geofisica.unam.mx) is a Researcher at the Geophysical Institute, UNAM, Mexico City. Avto Goguitchaichvili is a Researcher at the Geophysical Institute and Chair of the National Archaeomagnetic Service, UNAM, Morelia. E-mail: avto@geofisica.unam.mx. Ligia Pérez-Cruz is a Researcher and Chair of the Department of Geomagnetism and Geophysical Exploration, UNAM, Mexico City. E-mail: perezcruz@geofisica.unam.mx.

Juan Morales (jmorales@geofisica.unam.mx) is a Researcher at the Geophysical Institute and Co-Chair of the National Archaeomagnetic Service, UNAM, Morelia.

REFERENCES

Alva-Valdivia, L. 2005. Comprehensive paleomagnetic study of a succession of Holocene olivine basalt flow: Xitle Volcano (Mexico) revisited. *Earth Planets Space* 57: 839–853.

Arnold, J.T., W.F. Libby. 1951. *Radiocarbon dates*. *Science* 113: 111–120.

Cordova, C., A.L. Martin, J. Lopez. 1994. Palaeoland forms and volcanic impact on the environment of prehistoric Cuicuilco, southern Basin of Mexico. *Journal of Archaeological Science (J. Archaeol. Sci.)* 21: 585–596.

Delgado-Granados, H. *et alii*. 1998. Geology of the Xitle volcano in southern Mexico City—A 2000-year-old monogenetic volcano in an urban area. *Revista Mexicana de Ciencias Geológicas (Rev. Mex. Ciencias Geol.)* 15: 115–131.

Fergusson, G.J., W.F. Libby. 1963. UCLA radiocarbon dates 11. *Radiocarbon* 5: 1–22.

Gonzalez, S., A. Pastrana, C. Siebe, G. Duller. 2000. Timing of the prehistoric eruption of Xitle Volcano and the abandonment of Cuicuilco Pyramid, Southern Basin of Mexico. *Geological Society, London, Special Publications (Geol. Soc. London Sp. Pub.)* 171: 205–224.

Heizer, R., J. Bennyhoff. 1958. Archaeological investigations of Cuicuilco, Valley of Mexico, 1956. *Science* 127: 232–233.

Libby, W.F. 1955. *Radiocarbon Dating*. Chicago: Chicago University Press.

Morales, J., A. Goguitchaichvili, J. Urrutia-Fucugauchi. 2001. A rock-magnetic and paleointensity study of some Mexican volcanic lava flows during the Latest Pleistocene to the Holocene. *Earth, Planets and Space* 53/9: 893–902.

Morales, J., L.M. Alva-Valdivia, A. Goguitchaichvili, J. Urrutia-Fucugauchi, 2006. Cooling Rate Corrected Paleointensities From the Xitle Lava Flow: Evaluation of Within-Site Scatter for Single Spot-Reading Cooling Units. *Earth, Planets and Space* 58/10: 1341–1347.

Nagata, T., K. Kobayashi, E.J. Swarz. 1965. Archaeomagnetic intensity studies of South and Central America, *Journal of Geomagnetism and Geoelectricity (J. Geomag. Geoelectr.)* 17: 399–405.

Nichols, D.L. 2016. Teotihuacan. *Journal of Archaeological Research (J. Archaeol. Res.)* 24: 1–74.

Pavón-Carrasco, F.J., M.L. Osete, J.M. Torta, A. De Santis. 2014. A geomagnetic field model for the Holocene based on archaeomagnetic and lava flow data. *Earth and Planetary Science Letters (Earth Planet. Sci. Lett.)* 388: 98–109.

Ramsey, C.B. *et alii*. 2006. Developments in radiocarbon calibration for archaeology. *Quaternary Science Reviews (Quaternary Sci. Rev.)* 25: 783–798.

Siebe, C. 2000. Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico-City. *Journal of Volcanology and Geothermal Research (J. Volcanol. Geoth. Res.)* 104: 45–64.

Urrutia-Fucugauchi, J. 1996. Paleomagnetic study of the Xitle-Pedregal de San Angel lava flow, southern basin of Mexico. *Physics of the Earth and Planetary Interiors (Phys. Earth Planet. Int.)* 97: 177–196.

Urrutia-Fucugauchi, J., A.L. Martin. 1993. Implicaciones de los datos paleomagnéticos sobre la edad de la Sierra de Chichinautzin, Cuenca de México. *Geofísica Internacional (Geof. Int.)* 32: 523–533.