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# Mayan limekilns as geomagnetic field recorders

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ABSTRACT

We report new results from frontier research that relates the methodology and knowledge of geophysics (geomagnetism) with archeology and the data will represent a valuable contribution to both disciplines. A detailed magnetic survey was performed on limekilns from the northern Yucatan peninsula. We used Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) Spectroscopy to determine the temperature of calcination in order to select limekiln samples that were heated above the Curie temperature for common magnetic minerals. Using rock-magnetism, we identified the main carrier of remanent magnetization to be multi-domain or large pseudo-single domain low titanium titanomagnetite. Alternating magnetic field demagnetizations delivered reliable archaeomagnetic directions. Our summary of 12 limekiln ages shows a large span from 707 to 1900 yr AD. Such a wide time range signifies that Maya used limekilns in the Yucatan peninsula area in the Late Classic period (600 AD), and that some of these limekilns were reused in the Colonial period. From a geophysical point of view, information can be used about the behavior of the Earth's magnetic field in the recent historical past in Mesoamerica. In this context, the hundreds of Mayan limekilns which are distributed in large areas, open great opportunities to contribute to both archeology and geomagnetic field fluctuations during the past two millennia.

## 1. Introduction

Historical variations of the full geomagnetic vector (declination, inclination, and absolute intensity) can be obtained by satellite and geomagnetic observatory measurements, providing invaluable information about the Earth's geodynamo and the deep interior of our planet. However, such data are available only from the last ~1570 yr (Malin and Bullard, 1981), and most of the data are for Europe. Prior to instrumental measurements, burned archaeological artifacts and volcanic rocks that carry stable thermoremanent magnetization, can provide full geomagnetic vector data for at least the last four millennia. Marine and lacustrine sediments provide only relative magnetic intensity and are influenced by inclination flattening and bioturbation effects (Björck and Wohlfarth, 2001; Tauxe; 2006; Panovska et al., 2012). Thus, in practice, only heated archaeological objects together with volcanic rocks are reliable full geomagnetic vector recorders.

The dating of the lime kilns is part of a general project on pyrotechnological knowledge in the Maya area. The studies devoted to the fire as a technology are very scarce in whole Mesoamerica. Novelo Pérez (2016) investigated the ritual approach to the use of fire and its

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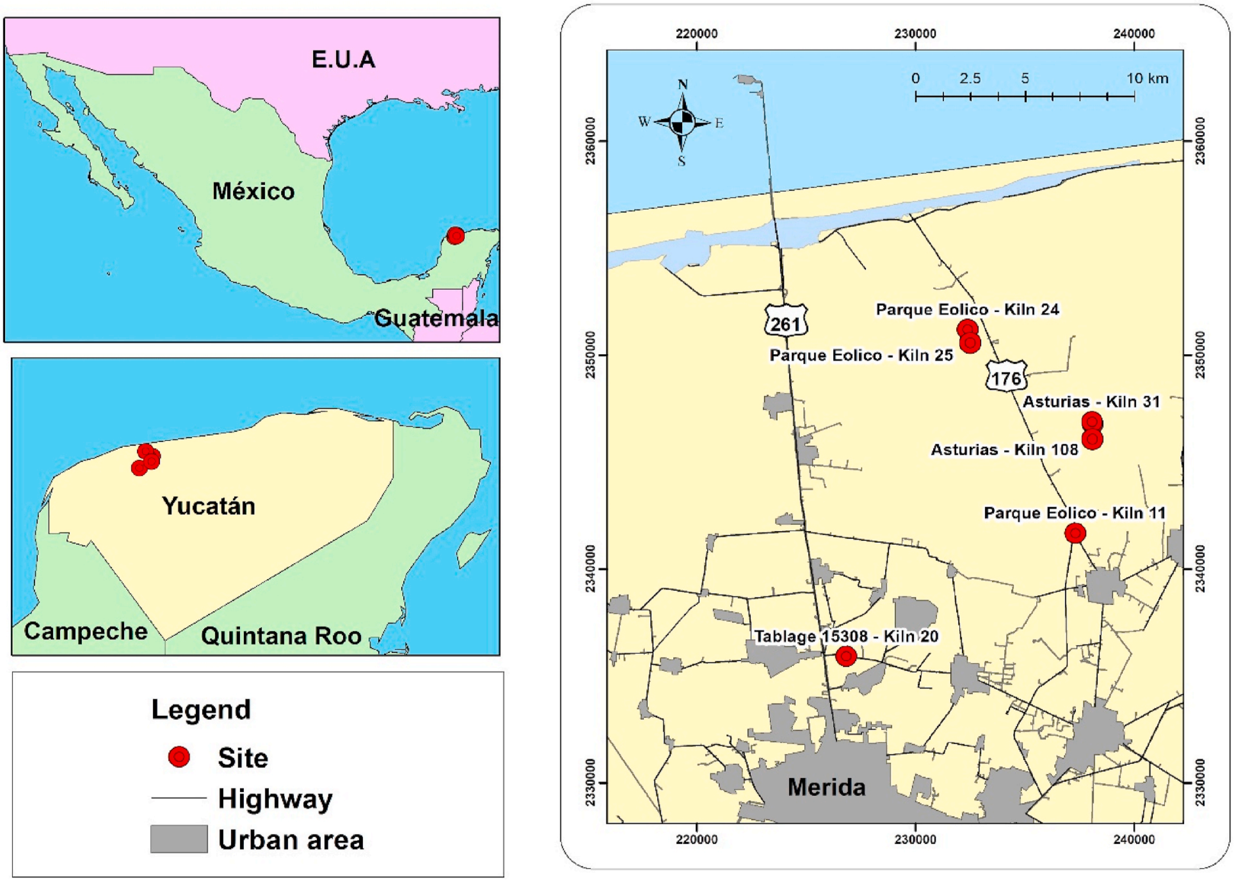

**Fig. 1.** A simplified map of the northern part of the Yucatan peninsula showing the location of limekiln sampling sites.

performance while the use of clay balls for cooking was recently proposed by Simms et al. (2013); Anthropological studies have also been initiated to understand the presence of coal and ash in archaeological contexts, carried out by Dussol et al. (2017) and the study of ovens as structures dedicated to the use of fire (Ortiz Ruiz 2019). In the other hand, surveys on the production of lime in the Maya area are much more extensive including the studies of mortars, the degradation of flattened floors, the origin of production technology, the technological styles used by the pre-Hispanic Mayans and the impact of lime production on the environment (Barba Pingarron 2013; Gillot 2014; Hansen 2000; Russell and Dahlin 2007; Ortiz Ruiz 2014; Schreiner 2002; Seligson 2016; Thibodeau 2013; Villaseñor Alonso 2010; Wernecke 2005).

Here we evaluated the reliability of six limekilns excavated north of the city of Merida on the Yucatan peninsula to record geomagnetic field elements (declination, inclination, and absolute intensity) at the time of last heating (Fig. 1). We used Attenuated Total Reflection Fourier Transfer Infrared (ATR-FTIR) Spectrometry to obtain an infrared spectrum of absorption or emission of a solid sample to ensure its thermoremanent origin of magnetization. Lime production typically requires temperatures above 700 °C (Ortiz Ruiz, 2019), which makes limekilns an adequate target to accurately record the Earth's magnetic field during their last heating. Most archaeomagnetic studies of limekilns have been done in Europe (Hus and Geeraerts, 1998; Borradaile et al., 2001; Tema and Lanza, 2008; Donadini et al., 2010; Casas et al., 2014; Carrancho et al., 2016). Recently, hundreds of annular kilns were reported on the Yucatan peninsula (Ortiz Ruiz, 2019). Although Hernandez-Alvarez et al. (2017) and Pantoja et al. (2020) reported preliminary archaeomagnetic results, only one systematic archaeomagnetic study in the region exists today (Goguitchaichvili et al., 2020).

### 1.1. Archaeological context and sampling

The region that was occupied by the Mayan civilization is located in the states of Yucatan, Campeche, and Quintana Roo in Mexico, in Guatemala, in Belize, and in parts of Honduras and Salvador. We sampled in the northern part of the Maya area, in Ichkaantijoo, the ancient capital city of Yucatan, 12 km north of Merida (Fig. 1). There are many world famous archaeological sites in the region (Dzibilchaltún, Tamanché, Komchén, ~~Dzibilchaltún~~). Góngora Salas (2015) and Maldonado Cardenas et al. (2012) suggested that the northern Ichkaantijoo region was one of the Mayan settlement centers. A continuous occupation of the northern Ichkaantijoo region has been reconstructed based on the pottery style (Góngora Salas et al., 2015) from the Middle Preclassic period (1000–400-300 B.C.) to the Colonial period.

Seligson et al. (2019) proposed that the production of lime in the Maya area was essentially for construction purposes. The regional network was extended along the whole Maya lowlands. The study of limekilns in the last ten years has largely contributed to the knowledge of pre-Hispanic pyrotechnological technology. However, the age framework of the limekilns is still not well defined; there exist only four radiocarbon dates (Seligson, 2016) and eight previous archaeomagnetic dates (Ortiz Ruiz et al., 2015; Hernandez-Alvarez et al., 2017; Pantoja et al., 2020; Goguitchaichvili et al., 2020); these studies estimated the use of and the lifespan of kilns in the early age of lime production when the Maya area played an important role. Hypothetically, the Maya area was the cradle of lime production technology in Mexico (Barba Pingarron, 2013).

Our study sites are located north of Merida, the capital city of the Yucatan peninsula. In the last two years, numerous annular limekilns have been excavated during the archaeological rescue campaign headed by the *Instituto Nacional de Antropologia e Historia*. These excavations

**Table 1**

Archaeomagnetic results in Yucatan: n is the number of samples used in the calculation of the site mean direction, N is the total number of samples measured; $\alpha_{95}$ and k are the confidence cone (degrees) and the precision parameter that correspond to the Fisher statistics. Inc (Dec) refer to geomagnetic inclination (declination); Int is the absolute intensity of the geomagnetic field. Previously published archaeomagnetic data from Hernandez-Alvarez et al. (2017), Pantoja et al. (2020), and Goguitchaichvili et al. (2020) are included.

| Archaeomagnetic study sites | UTM (m) | UTM (m) | n/N | Inc (°) | Dec (°) | k | $\alpha_{95}$ (°) | Int (μT) | Archaeomagnetic dates (years A.D.) | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Dzoyilá | 230,023 | 2,317,636 | 12/14 | 30.7 | 350.6 | 214 | 3.4 | 44.1 ± 2.6 | 932-1019/1189-1281 | Goguitchaichvili et al. (2020) |
| Vicente Guerrero | 185,130 | 2,269,632 | 7/10 | 29.9 | 351.8 | 426 | 3.2 | | 934-1047/1213-1273 | Goguitchaichvili et al. (2020) |
| Santa Barbara | 800,758 | 2,290,606 | 9/11 | 24.8 | 348.7 | 405 | 2.7 | 32.5 ± 2.5 | 912–979 | Goguitchaichvili et al. (2020) |
| Federal Road 180 Kiln 2 | 193,808 | 2,283,580 | 8/10 | 33.8 | 5.5 | 236 | 3.6 | | 1498–1622 | Goguitchaichvili et al. (2020) |
| Material Bank Proser Kiln 1 | 189,657 | 2,278,236 | 8/11 | 28.1 | 357.4 | 325 | 4.1 | | 707–938 | Goguitchaichvili et al. (2020) |
| Material Bank Proser Kiln 1 | 192,103 | 2,282,959 | 6/10 | 37.1 | 5.8 | 158 | 4.2 | | 1459–1644 | Goguitchaichvili et al. (2020) |
| Sitpach | 236,572 | 2,326,340 | 7/12 | 37.9 | 354.9 | 429 | 2.9 | | 1279–1455 | Pantoja et al. (2020) |
| San Pedro Cholul | 234,907 | 2,327,586 | 4/8 | 47.9 | 7.1 | 1332 | 2.5 | | 1835–1896 | Hernandez et al. (2017) |
| Tablage 15,308 (Site 1) | 226,831 | 2,335,905 | 8/10 | 44.1 | 6.1 | 248 | 3.3 | | 1719–1862 | This study |
| Asturias 108 (Site2) | 238,113 | 2,346,777 | 8/9 | 30.6 | 9.6 | 165 | 4.3 | | 1532–1610 | This study |
| Parque Eolico 25 (Site 4) | 232,378 | 2,351,196 | 7/9 | 45.2 | 7.8 | 192 | 4.2 | | 1729–1900 | This study |
| Chixchulub 11 (Site 6) | 237,303 | 2,341,671 | 7/9 | 32.7 | 9.8 | 95 | 6.3 | | 1498–1622 | This study |

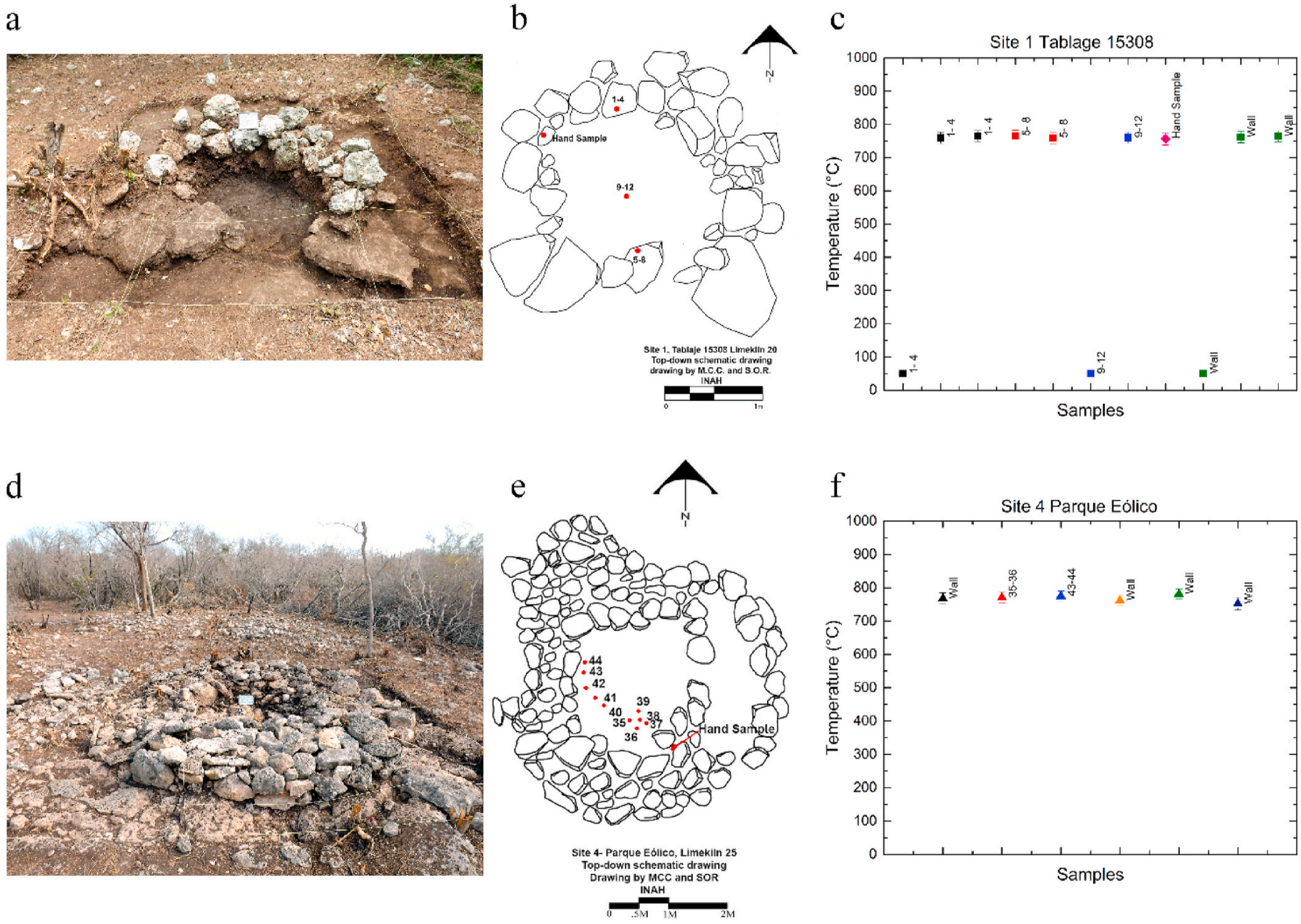

**Fig. 2.** Photos and schemes of two studied limekilns with sampling spots indicated. Calcination temperatures were determined with attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy: a-c - site 1, d-f - site 4.

unearthed lime concretions, burned stones, and calcified limestone walls and floors.

We sampled six limekilns for archaeomagnetic dating (Fig. 1). Four of them yielded successful archaeomagnetic directions. Their names and Universal Transverse Mercator (UTM) coordinates are summarized in Table 1. Nine to ten standard paleomagnetic cores were drilled at each site using a portable Pomeroy drill (ASC Scientific). The drilling was done in different parts of the kilns. The cores were oriented using both magnetic and sun compasses. We took a few hand samples at each site to compare the results obtained from the hand samples and the drilled cores. Small cubic specimens (2 × 2x2 cm) were cut from each hand samples using non-magnetic saw.

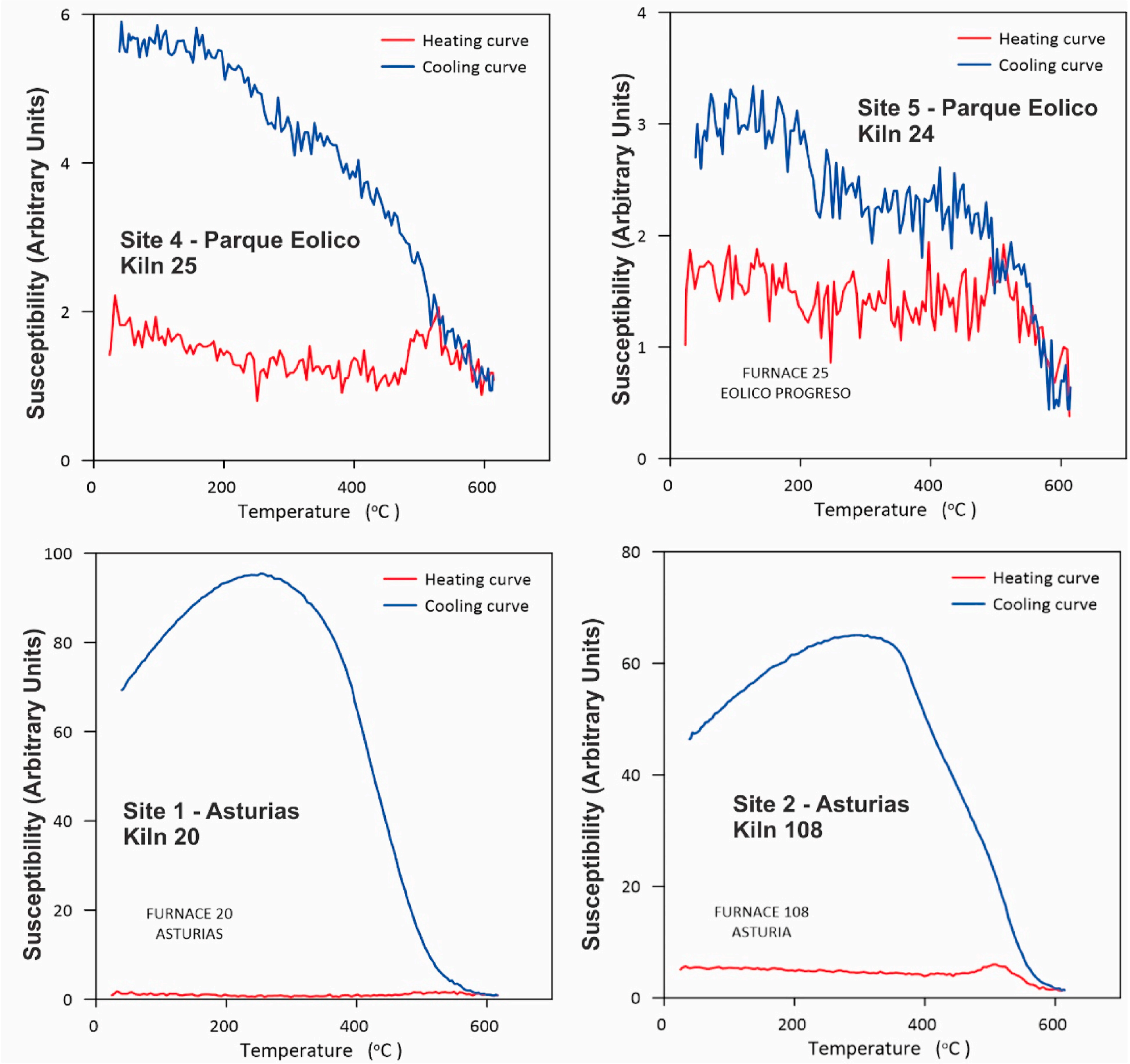

**Fig. 3.** Representative examples of magnetic susceptibility vs. temperature curves recorded up to 620 °C. Heating and cooling curves are shown in red and blue, respectively.

Tablaje 15,308 (site 1), also known as limekiln 20 in the archaeological documents is the closest to the Merida study site. Limekiln 20 is the largest and best preserved of the three limekilns at the site. About 500 m to the north we found a *Puuc style* architectural feature with an L shape platform and an apparent water storage structure. Limekiln 20 has a circular wall made up of large and medium sized coarsely cut boulders; the fill was made up of small and medium size stones (known as *Chich*) mixed with sediment that partially collapsed inside the kiln. The diameter of the kiln was 2.4 m N–S by 3.7 m E-W and the depth was 0.7 m.

Asturias kiln 108 (site 2) is located in the town of Chicxulub, about 100 m from limekiln 31 (site 3), and 50 m from a residential complex. A single circular wall of the limekiln at site 2 was constructed at the western and northern sides of the kiln while the southern and eastern sides were constructed with several vertical rows of boulders. The basement of the kiln is bedrock, 2.42 m in depth, with an average diameter of 2.69 m. The excavation contained a mix of brown soil with greyish sediment and burned stones with lime crust. The walls of the kiln exhibited darker colors and bedrock fractures, suggesting several burnings (Góngora Salas and Canché Canché, 2019a).

Limekiln 31 (site 3) is circular, 3 m in diameter and 0.6 m in depth. The floor of the limekiln is bedrock and the walls are two rows of large and medium sized boulders (Góngora Salas and Canché Canché, 2019).

Parque Eolico limekiln 25 (site 4) and limekiln 24 (site 5) are located along Federal Road 261, 7 km north of Merida. The kiln (site 4) has an annular shape, the double ring wall is 5.3 m N–S by 5.0 m E-W, the diameter of the central pit is 2.5 m E-W by 3.0 m N–S. The double ring wall at the eastern and northern sides of the limekiln were filled with boulders between two rings and then modified to a small bench. The wall was built with horizontal and vertical rows of boulders placed on the top of the bedrock (Gongora Salas and Cepeda, 2019).

Four small structures and another water collector are situated near limekiln 24 (site 5) which is located 20 m north of site 4. The limekiln has a double ring wall 5.5 m N–S by 4.8 m E-W, and central pit dimensions of 3.1 m N–S by 2.7 m E-W with 2.4 m depth. The kiln contains burned rocks mixed with dark brown soil (Gongora and Cepeda, 2019).

Parque Eolico limekiln 11 (site 6) is located in the town of Chicxulub about 25 km northeast of Merida. It has a quadrangular central pit shape and a semicircular double ring. The wall is built as a vertical row of boulders placed on the top of the bedrock. The diameter of the

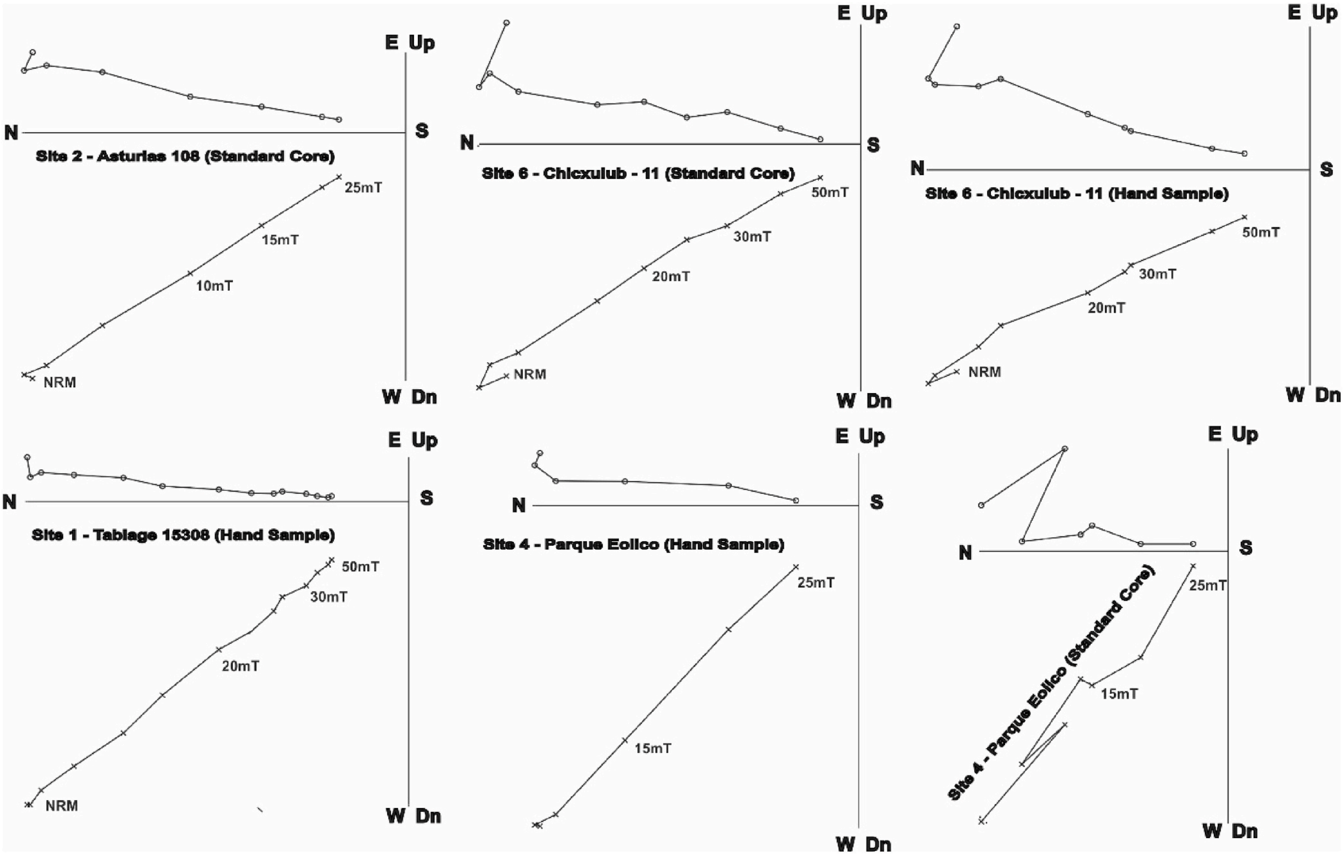

**Fig. 4.** Representative examples of orthogonal projection plots illustrating alternating magnetic field treatments. Although maximum available laboratory alternating filed was 100 mT, great majority of samples were almost completely demagnetized applying 50 mT. Hand samples and standard paleomagnetic cores yielded very similar demagnetization trends (please see text for more details).

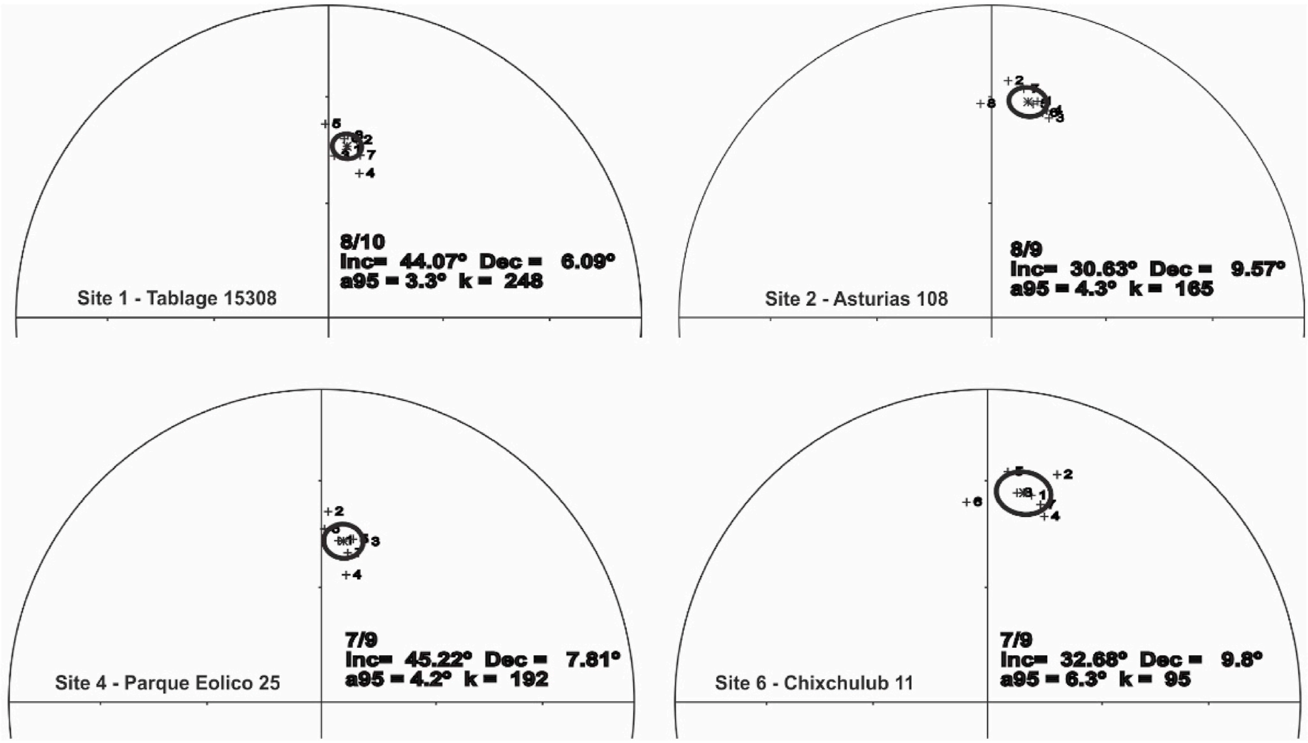

**Fig. 5.** Equal area projection of site-mean paleodirections for four limekilns (see the text for more details).

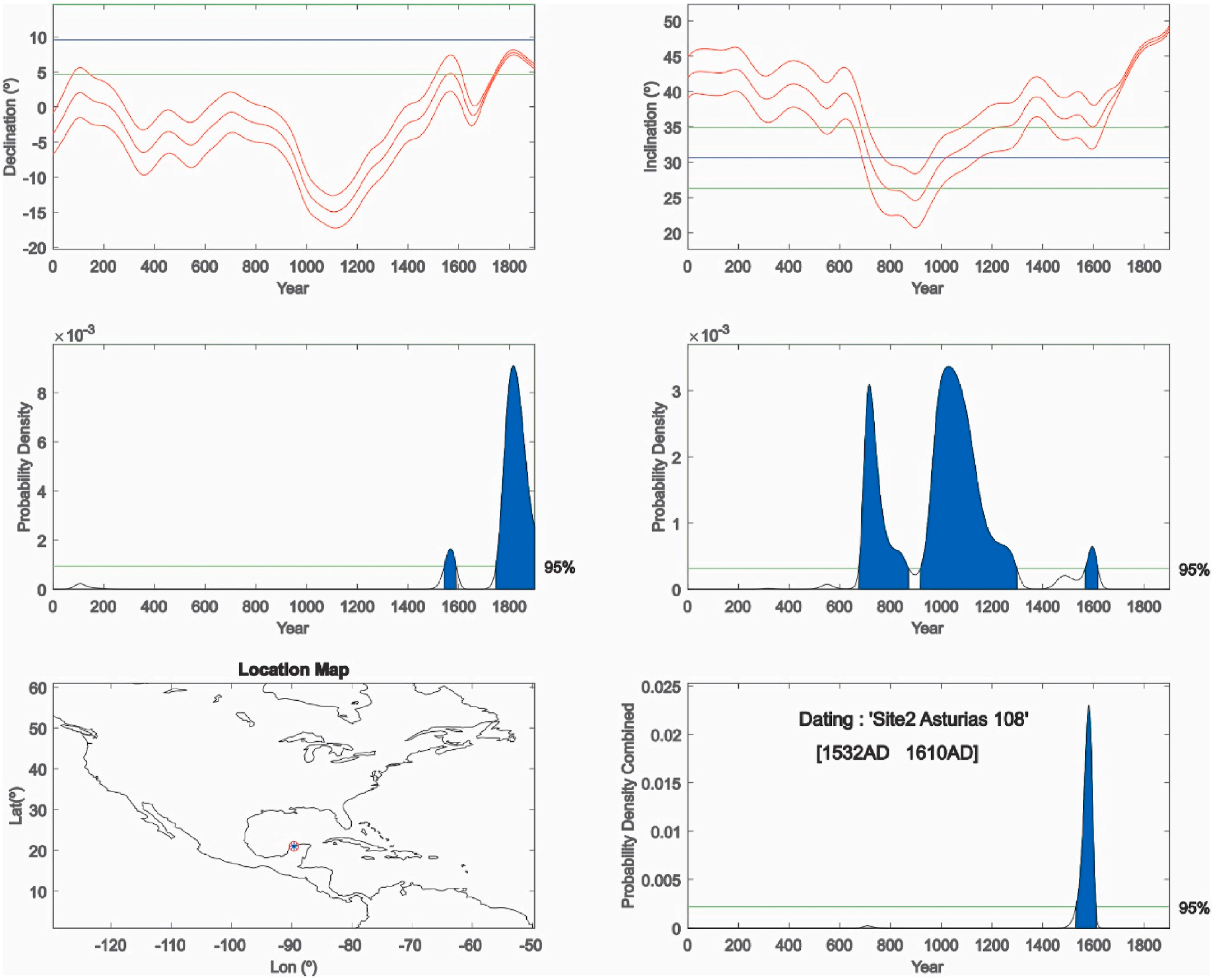

**Fig. 6.** Archaeomagnetic dating results for limekiln Aaturias 108; the MATLAB tool used was provided by Pavón-Carrasco et al. (2011, 2014).

semicircular double ring is 6.5 m and the central pit dimensions are 2.9 m N–S by 2.2 m E-W with 0.54 m depth.

### 1.2. Laboratory methods

To investigate the range of calcination temperatures for each sample (Fig. 2) we applied attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy. ATR-FTIR enables temperature range identification by measuring how much of a beam of light with many frequencies is emitted by the sample (Regev et al., 2010; Toffolo and Boaretto et al., 2014, Teoffolo et al., 2017). The maximum paleotemperatures of samples from different parts of the limekilns were determined; for temperatures above the Curie temperature (the temperature above which magnetic materials lose their permanent magnetic properties) for magnetic minerals, the thermoremanent origin of the primary magnetization was determined (Ortiz-Ruiz, 2019; Goguitchaichvili et al., 2020). The temperature range was identified by comparing the measured spectra of the limekiln samples with the reference samples SRM 88b and SRM 1D from the National Institute of Standards and Technology, following procedures described in Chukanov (2014), Aldeias et al. (2019), and Weiner (2010). The calcination temperatures are the highest temperatures in the limekilns; the calcination temperature could be higher or lower than the Curie temperature of magnetite. If the calcination temperature in a sample was higher than the Curie temperature, the measured magnetization was considered to be primary and thermoremanent. The temperature analysis was performed using the methodology proposed in Chu et al. (2008) and Regev et al. (2010).

All magnetic measurements were carried out at the facilities of the National Archaeomagnetic Service at the Universidad National Autonoma de Mexico in Morelia, Mexico. To remove viscous remanent magnetization before laboratory measurements were taken, the samples were stored for 20 days in a five-layer magnetic shield with a residual magnetic field of less than 15 nT.

To determine the nature and thermal stability of the minerals responsible for magnetization, we measured magnetic susceptibility vs. temperature from room temperature to 620 °C using an AGICO MFK1A susceptibility bridge. To determine characteristic paleodirections, alternating field (AF) demagnetization was applied using an LDA3 (AGICO) demagnetizer with maximum available peak fields of 100 mT. Magnetic remanence was measured using an AGICO JR-6a spinner magnetometer. Paleodirections for each sample were computed using linear regression (Kirschvink, 1980); associated statistical parameters were calculated using Fisher statistics (Fisher, 1953).

## 2. Results, discussion, and concluding remarks

Paleotemperatures of samples, i.e. the temperature to which the kiln

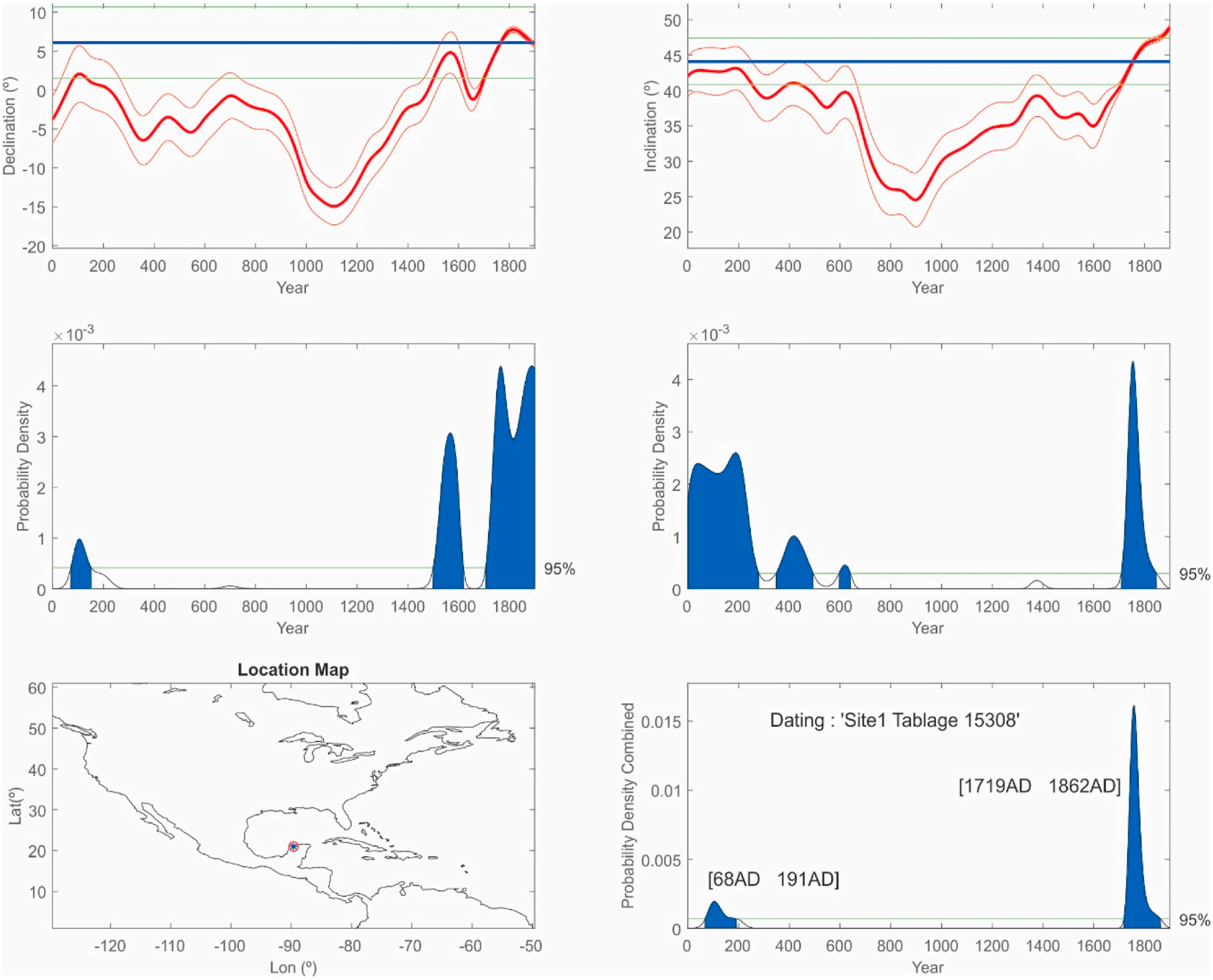

**Fig. 7.** Archaeomagnetic dating results for limekiln Tablage 15,308; the MATLAB tool used was provided by Pavón-Carrasco et al. (2011, 2014). The early interval from 68–191 AD seems unviable because of the local archaeological context.

was heated, were estimated by comparing the measured data with the calcination temperature calibration curve for limestone materials (Aldeias et al., 2019). Fig. 2 shows that the temperature range was between 760 °C and 790 °C for the majority of the samples. This temperature range corresponds to the usual temperatures during lime production (Ortiz-Ruiz, 2019). The temperatures shown in Fig. 2 are above the Curie temperatures for magnetic minerals and indicate that thermoremanent magnetization was acquired during the last cooling below the Curie temperature. A few samples from site 1 were heated below 100 °C (Fig. 2) and therefore might not have thermoremanent magnetization; such samples were exempted from further analyses. In summary, here we illustrate the representative examples of calcination temperatures. Remained limekilns yielded essentially similar behavior. This means that most samples yielded temperatures around 775 °C while some few samples, especially those collected at the peripheral part of the kilns provide calcination temperatures between 50 and 95 °C.

The magnetic susceptibility (MS) of our samples was demonstrated by heating up to 620 °C and cooling. Minimum MS values occurred between 550 and 575 °C, which is just below the Curie temperature of magnetite (578 °C) (Fig. 3). Such temperatures are typical for low-titanium magnetite. The MS vs. temperature curves were not reversible, indicating the formation of new magnetic minerals during heating above 610 °C and then cooling to room temperature (Fig. 3). Such curve behavior demonstrates that the study samples are unsuitable for thermomagnetic analysis to obtain the absolute geomagnetic intensity values; therefore, we used alternating field demagnetizations to acquire archaeomagnetic directions for the samples.

The majority of samples exhibited linear segments in the demagnetization diagrams demonstrating a single component trending toward the origin of the orthogonal projection diagrams (Fig. 4). The present day overprint is removed by an alternating magnetic field of 5 mT or less. The high field characteristic component of the remanent magnetization was almost completely removed by an alternating magnetic field of 50 mT with the median destructive field (MDF) ~ 20 mT. Such MDF indicates that the remanent magnetization is most likely carried by low-coercivity, probably multi-domain or large pseudo single domain, ferrimagnetic grains, as demonstrated in Dunlop and Ozdemir (1997). Low coercivity and irreversible curves in the MS vs. temperature experiments made determinations of absolute intensity unfeasible.

In any modern, high standard, paleomagnetic or archaeomagnetic survey, the origin and quality of remanent magnetization should be estimated and discussed. Namely, the remains that have been previously heated must carry primary thermoremanent magnetization acquired during cooling from high temperatures to qualify for archaeomagnetic investigation (Goguitchaichvili et al., 2020). The geomagnetic validity of the present archaeomagnetic data is supported by the fact that

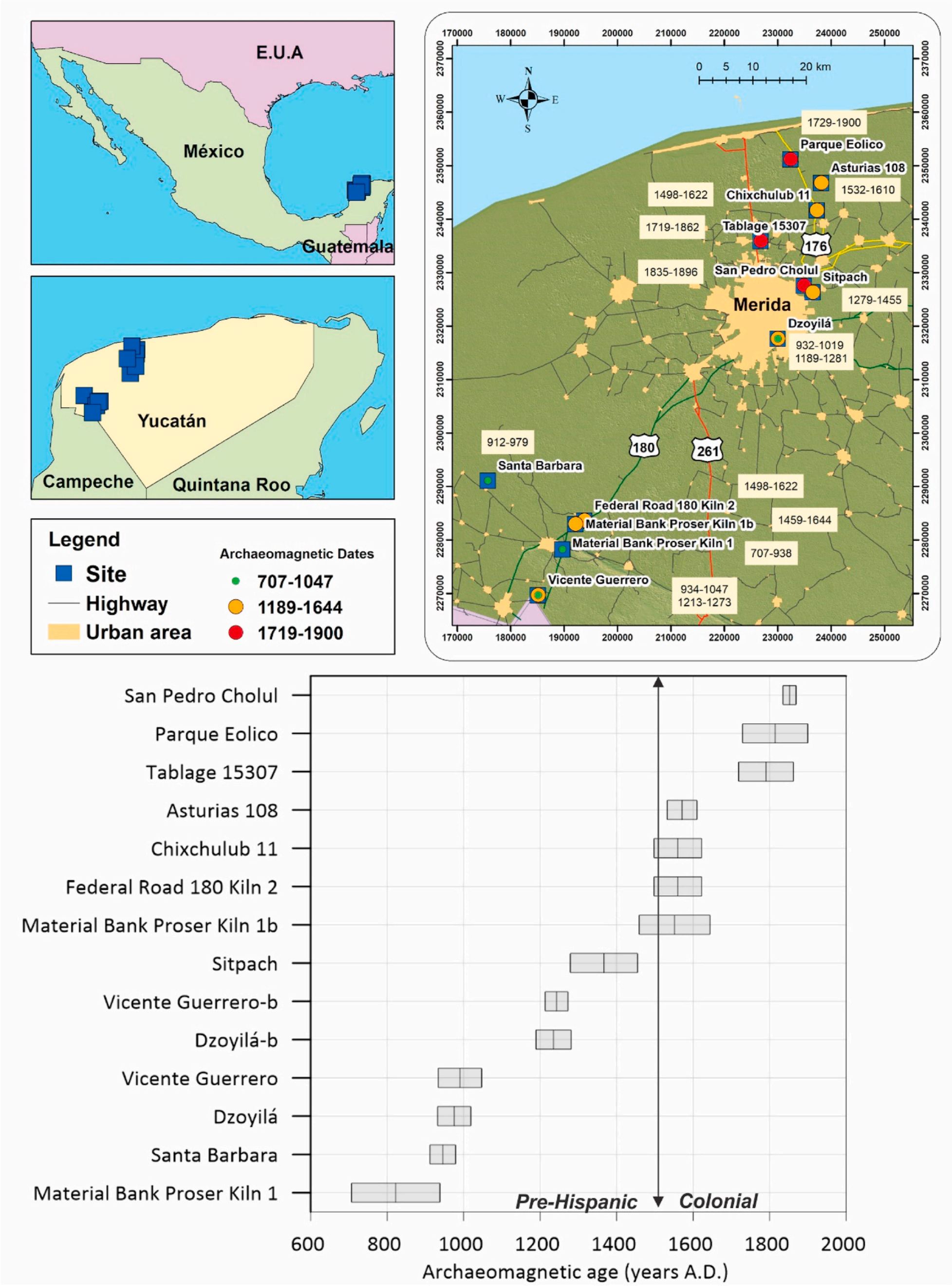

**Fig. 8.** Summary of archaeomagnetic dates obtained in this study and in previous studies.

infrared spectroscopy yielded calcination temperatures above 700 °C. In addition, the studied limekilns are essentially built by sedimentary rocks that initially carry detrital magnetization but thermoremanence is acquired during the lime production process involving temperatures as high as 750 °C in average. In this context, the direction deviation due to refraction or anisotropy is less probable. The main reason of failure to determine the primary, characteristic paleodirections is the fact that the samples probably do not carry full thermoremanence. As already observed by Goguitchaichvili et al. (2020), some samples appeared to have enough thermal footprint; ATR-FTIR analysis indicates their temperatures to have been below 100 °C.

No significant difference was found between the demagnetization behavior of drilled cores and hand samples; each yielded identical directions in the majority of cases (Fig. 4 shows samples from site 6 as an example). However, when the initial remanent magnetization was relatively low (in the order of $10^{-4}$ A/m, as in samples from site 4, shown in Fig. 4), the hand samples exhibited less scattering behavior. Likely the drilling-induced some magnetization in the cored samples; such effect has been reported in other paleomagnetic studies (Audmundson and Levi, 1989). The study conducted by Audunsson and Levi (1989) is probably not adequate to judge the drilling induced remanent magnetization because the sampling procedures are quite different. However, Lauer (1978) observed same phenomena during the cylindrical sample preparation under laboratory conditions while Genevey et al. (2002) found strong evidence of drilling effects on magnetization.

All individual, characteristic remanent magnetization determinations are based on at least five aligned (towards the origin) point yielding the maximum angular deviation (MAD) values whithin 2.9° while most MAD values are found less than 1.8°. The site mean archaeomagnetic directions are reasonably well defined for four out of six of the studied sites (Table 1, Fig. 5) with a cone of confidence $\alpha_{95}$ between 3.3° and 6.3°. For archaeomagnetic dating we used the model SHADIF14k and MATLAB software from Pavón-Carrasco et al. (2011, 2014). The archaeological dating interval was chosen between 0 and 1900 AD, based on general archaeological considerations (Fig. 6 and Fig. 7).

Detailed magnetic studies of limekilns worldwide are scarce, and the quality of these studies varies. So-called quicklime kilns with known ages were studied by Hus and Geeraerts (1998) to construct a palaeosecular variation curve for Belgium. Borradaile et al. (2001) reported unstable thermal and magnetic behavior in ancient limekilns in the U.K. Sixth century Italian limekilns were archaeomagnetically dated in Tema and Lanza (2008) using Italian and French archaeomagnetic reference curves. Numerous Roman limekilns were archaeomagnetically studied in Bulgaria (Donadini et al., 2010). Casas et al. (2014) combined archaeodirectional and thermoluminiscence techniques to date two 19th century limekilns in northeastern Spain. Carrancho et al. (2016) carried out comprehensive archaeomagnetic dating based on a full geomagnetic field vector of a limekiln excavated at the Pinilla del Valle archaeological site close to Madrid, Spain. To our knowledge, our study is the first archaeomagnetic study to apply paleotemperature estimations using ATR-FTIR to study ancient limekilns.

Our summary in Table 1 of published results pertaining to Mayan limekilns suggests that limekilns were used in the area of Yucatan, Mexico, continuously from ~700 AD to the Colonial period and even in more recent times until ~1900 AD (Fig. 8). Previous archaeomagnetic studies in the Maxcanú area placed the earliest date of the use of limekilns on the Yucatan peninsula between the Late Classic period (707–938 AD) and the Colonial period (1600 AD). We place the limekilns in the Ichkaantijoo region between 1400 and 1900 AD. Based on the wide range of the archaeomagnetic ages we suggest a continuity of limekiln use in the northern plains populated by the Mayan culture. Limekilns were used in pre-Hispanic lime production for construction and crafts and in the technology of the Colonial period of Spain for the construction of towns in the Yucatan region.

Limekilns dated between 1400 and 1900 AD in the Ichkaantijoo region are located in archaeological sites 15, 26, and 161, which present evidence of colonial occupation, as recorded in the *Regional Archaeological Atlas* (Garza Tarazona and Kurjack, 1980). Site 15 is associated with the Chacxulubchen, which corresponds to the first colonial settlement. Site 26 corresponds to the Maxtunil, a Spanish *encomienda*. Site 161 presents evidence of pre-Hispanic structures converted to fortresses with palisades and the presence of an open chapel (Góngora Salas, 2017). Radiocarbon ages from Kiuc in the Puuc area indicate the presence of limekilns in the Late-Terminal Classic period between 658 and 892 AD (Seligson, 2016). These dates correspond to the 707 and 1047 AD dates obtained archaeomagnetically in the Maxcanú area by Goguitchaichvili et al. (2020) (Table 1). In some case (the Site 1 is a good example), dual ages were obtained. This is very common during the archaeomagnetic dating procedure. However, the first age interval does not match the general archaeological context of the site.

The present study should be considered as an example of frontier research that relates the methodology and knowledge of geophysics (geomagnetism) with archeology and the results will represent a valuable contribution to both disciplines. From a geophysical point of view, if alternative radiometric ages are available, information can be obtained about the behavior of the Earth's magnetic field in the recent historical past in Mesoamerica while the same results can be potentially used as a dating tool to determine the age of the burned archaeological artifacts carrying stable thermoremanent magnetization. Currently, there are global models of the Earth's magnetic field based on records retrieved from archaeological artifacts (mainly exposed to the fire), volcanic lava flows and lacustrine sediments (Korte et al., 2009). Specific regional models of secular variation have also been developed based exclusively on thermoremanent magnetization (Pavón-Carrasco et al., 2011, 2014). Although some efforts were done during the last year to build the absolute geomagnetic intensity variation curve (Goguitchaichvili et al., 2018; Mahgoub et al., 2019), still no directional record is available for whole Mesoamerica. Because no local (or regional) directional reference curve is available, the SHADIF.14K model proposed by Pavon-Carrasco (2014) emerges as the best estimation of the geomagnetic field variation in terms of both intensity and directions. The use of this model provided expected age intervals not only in Mesoamerica but also in South America (see for instance Gogorza et al., 2021; Garcia et al., 2021). In this context, the numerous Mayan limekilns which are distributed in large areas, often containing charcoal remains inside of ovens, open great opportunities to contribute to both archeology and geomagnetic field fluctuations during the past two millennia.

The ancient limekilns studied here demonstrate the well preserved thermoremanent magnetization acquired during their cooling from temperatures as high as 750 °C. Most likely, titanium-poor titanomagnetites carry most of remanence and show clearly unstable thermal behavior. Natural remanent magnetization is carried by low coercivity multidomain or large single domain magnetic grains, which impede the determination of absolute geomagnetic intensities. Archaeomagnetic dating attests to the continuous use of limekilns in pre-Hispanic and Colonial period from about 700 to 1900 AD.

## Author contribution

We explicitly declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all co-authors. We further confirm that the order of authors listed in the manuscript has been approved by all authors. This work is leaded by Soledad Ortiz. All authors participated either in the field trip, laboratory measurements or data analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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