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Physics of the Earth and Planetary Interiors 159 (2006) 90–95
PHYSICS OF THE EARTH AND PLANETARY INTERIORS
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# Archaeomagnetic investigations in Greece and their bearing on geomagnetic secular variation

M.E. Evans *

*Institute for Geophysical Research, University of Alberta, Edmonton AB, Canada T6G 2J1*

Received 7 March 2006; received in revised form 11 June 2006; accepted 30 June 2006

**Abstract**

Archaeomagnetic results are presented from kilns and other heated structures on mainland Greece and on the islands of Crete, Delos, Euboea and Thasos. They span the interval from the mid-third millennium BCE to the mid-second millennium CE. The results obtained are in good agreement with the comprehensive dataset from Bulgaria and reveal secular variation with amplitudes of ∼25° in inclination and ∼30° in declination. The sharp inclination low in the first few centuries CE – now recognized at sites ranging from Crete to Britain – is a robust geomagnetic feature reflecting a static flux pulse due to a magnetic source in the outermost core. Another, much more pronounced, inclination low early in the second millennium BCE is tentatively identified. The emerging Greek secular variation curve provides archaeomagnetic dates for five kilns of hitherto uncertain age.


*Keywords:* Archaeomagnetism; Greece; Secular variation; Archaeomagnetic dating

## 1. Introduction

The geomagnetic field undergoes significant fluctuations over a wide spectrum of timescales. In particular, the so-called secular variation – first recognized by Henry Gellibrand early in the 17th Century – has emerged as an important phenomenon in the quest to understand the geodynamo that sustains the Earth's magnetic field (Kono and Roberts, 2002; Aldridge and Baker, 2003). The timescales of interest however extend well beyond the availability of direct instrumental observations, which are limited to the last few centuries (for a comprehensive analysis, see Jackson et al., 2000). This shortcoming has spurred efforts to extend the record backwards by means of suitable archaeological and geological materials (Hongre et al., 1998; Korte and Constable, 2005). Baked archaeological features, such as kilns, are particularly attractive targets because they usually carry a strong, stable thermoremanent magnetization acquired when they were last fired. Furthermore, their chronology is generally known much more accurately than that of their geological counterparts, such as lake sediments and volcanic products. A great deal of work along these lines has been carried out: for example, in Britain (Clark et al., 1988), Bulgaria (Kovacheva et al., 1998), France (Gallet et al., 2002), Germany (Schnepp and Lanos, 2005) and Italy (Evans and Hoye, 2005). Despite its rich archaeological heritage however, no similar survey for Greece has yet appeared.

Belshé et al. (1963) undertook some early investigations in Greece, collecting 131 samples from 31 features, mostly pottery kilns but also including walls and floors burnt by destructive fires. To provide the general reader with an overall assessment of their data Belshé and co-

* Tel.: +1 780 492 5517; fax: +1 780 492 0714.
*E-mail address:* evans@phys.ualberta.ca.

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doi:10.1016/j.pepi.2006.06.005

workers devised a four-fold classification system: good, fair, poor and useless. They regarded only two of their results as “good”. No doubt this discouraged others from following in their footsteps! Indeed, more than 2 decades were to pass before this important line of enquiry was taken up again, in connection with the downfall of the Minoan civilization (Downey and Tarling, 1984). Since then, a handful of results have appeared in conference proceedings and excavation reports but the time is ripe for a systematic overview. Here, I report new results from Greece and collect together earlier data in an attempt to define the pattern of secular variation over the Aegean region for the last four and a half millennia.

## 2. Methods and results

Samples were collected from the sites indicated in Fig. 1. Most of the structures sampled were kilns, but hearths and burnt walls were also investigated (see Table 1 for details). Small plastic squares (2 cm × 2 cm) were bonded onto each structure at convenient sampling points in order to provide a planar surface to be orientated by solar bearings and bubble-inclinometer. Samples obtained in this way typically have a mass of 10–20 g and are irregular in shape. In the laboratory each sample was set in plaster in a 5-cm diameter cylindrical mould to provide suitably shaped samples for use in a Molspin large sample spinner magnetometer. Magnetic stability was checked by standard alternating field (AF) and thermal demagnetization procedures. Thermal demagnetization curves (Fig. 2) suggest that the magnetic signal is carried mostly by magnetite and/or titanomagnetite. Maghemite is also a possibility, but a comprehensive survey (Evans and Jiang, 1996) indicates that this is not common in archaeomagnetic materials. Fourteen representative samples (from 11 different sites) were subjected to AF treatment up to 180 mT (the maximum achievable in our apparatus). Eight of them (from eight different sites) have median destructive fields ($MDF_{NRM}$) ≤25 mT and only one yielded a value exceeding 40 mT. For the bulk of this study therefore directional stability was tested by AF treatment. In practice, it was found that one or two steps generally suffice to reveal the characteristic remanence direction (Fig. 3).

The results obtained are summarized in Table 1. For the most part, the data are straightforward and yield well-grouped site means. The hearth at site 10 yielded randomly directed magnetic vectors. The reason for this is not clear although it was noted during sampling that

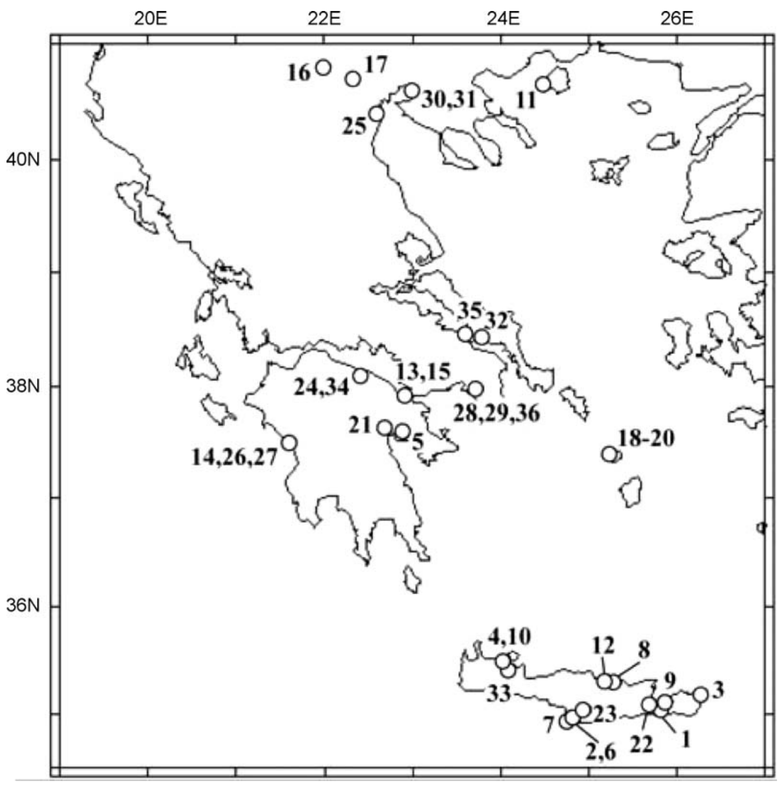


Fig. 1. Sketch map showing the sampling locations.

Table 1
Summary of archaeomagnetic results

| Site | Lat | Long | $N$ | Dec | Inc | $k$ | $\alpha_{95}$ | a.s.e. | Date | Chronology |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Vassiliki | 35.07 | 25.82 | 8 | −0.6 | 53.4 | 839 | 1.7 | 1.0 | −2550 | −2900/−2200 |
| 2. Phaistos | 34.97 | 24.84 | 8 | 6.5 | 38.5 | 332 | 2.7 | 1.6 | −1850 | −2000/−1700 |
| 3. Palaekastro | 35.20 | 26.28 | 13 | 5.9 | 49.3 | 305 | 2.4 | 1.4 | −1550 | −1675/−1425 |
| 4. Hania A | 35.50 | 24.04 | 10 | 1.4 | 54.0 | 147 | 3.6 | 2.1 | −1500 | −1600/−1425 |
| 5. Berbati | 37.60 | 22.90 | 10 | 1.2 | 63.3 | 490 | 2.0 | 1.2 | −1400 | −1450/−1350 |
| 6. Agia Triada | 34.99 | 24.81 | 10 | −4.2 | 56.6 | 320 | 2.7 | 1.6 | −1350 | −1600/−1070 |
| 7. Kommos | 34.95 | 24.76 | 8 | 0.6 | 61.4 | 199 | 3.5 | 2.0 | −1230 | −1390/−1070 |
| 8. Gouves | 35.31 | 25.29 | 10 | 9.0 | 60.3 | 403 | 2.4 | 1.4 | −1230 | −1390/−1070 |
| 9. Kavousi | 35.12 | 25.88 | 17 | 16.2 | 57.7 | 154 | 2.7 | 1.6 | −1130 | −1190/−1070 |
| 10. Hania B | 35.50 | 24.04 | 10 | – | – | – | – | – | −1130 | −1190/−1070 |
| 11. Phari | 40.65 | 24.49 | 11 | −4.7 | 63.7 | 1197 | 1.3 | 0.8 | −475 | −550/−400 |
| 12. Knossos | 35.32 | 25.20 | 17 | −8.5 | 58.4 | 171 | 2.7 | 1.6 | −385 | −400/−370 |
| 13. Corinth A | 37.92 | 22.92 | 16 | −7.2 | 60.1 | 538 | 1.6 | 0.9 | −365 | −400/−330 |
| 14. Olympia C | 37.50 | 21.61 | 7 | −5.2 | 56.4 | 566 | 2.5 | 1.5 | −325 | −350/−300 |
| 15. Corinth B | 37.92 | 22.92 | 11 | −6.4 | 57.2 | 1726 | 1.1 | 0.6 | −315 | −330/−300 |
| 16. Evropos | 40.80 | 22.00 | 8 | −4.7 | 60.8 | 532 | 2.2 | 1.2 | −200 | −330/−70 |
| 17. Pella | 40.70 | 22.33 | 10 | −5.2 | 62.5 | 183 | 3.6 | 2.1 | −200 | −330/−70 |
| 18. Delos A | 37.38 | 25.29 | 8 | −5.5 | 55.2 | 476 | 2.5 | 1.4 | −69 | −69 |
| 19. Delos B | 37.38 | 25.29 | 10 | −7.9 | 47.1 | 373 | 2.5 | 1.4 | −69 | −69 |
| 20. Delos C | 37.38 | 25.29 | 5 | 1.9 | 51.9 | 998 | 2.4 | 1.4 | −69 | −69 |
| 21. Argos | 37.63 | 22.70 | 17 | −1.4 | 54.8 | 776 | 1.3 | 0.8 | 100 | 0/200 |
| 22. Khalo Chorio | 35.10 | 25.71 | 20 | −2.3 | 43.0 | 304 | 1.9 | 1.1 | 150 | 0/300 |
| 23. Gortys | 35.05 | 24.95 | 13 | −2.4 | 45.0 | 222 | 2.8 | 1.6 | 150 | 100/200 |
| 24. Aegira A | 38.10 | 22.42 | 30 | −2.3 | 50.5 | 142 | 2.1 | 1.2 | 200 | 100/300 |
| 25. Louloudia | 40.40 | 22.80 | 5 | −3.8 | 51.0 | 1099 | 2.3 | 1.3 | 300 | 200/400 |
| 26. Olympia A | 37.50 | 21.61 | 7 | 2.8 | 48.6 | 540 | 2.6 | 1.6 | 350 | 300/400 |
| 27. Olympia B | 37.50 | 21.61 | 7 | 0.7 | 47.2 | 1571 | 1.5 | 0.8 | 350 | 300/400 |
| 28. Athens A | 37.98 | 23.73 | 11 | −6.5 | 45.4 | 330 | 2.5 | 1.4 | 400 | 375/425 |
| 29. Athens B | 38.00 | 23.67 | 27 | −3.0 | 51.7 | 220 | 1.9 | 1.1 | 400 | 375/425 |
| 30. Thessaloniki A | 40.60 | 23.00 | 9 | 19.1 | 52.7 | 101 | 5.2 | 3.0 | 1250 | 1200/1300 |
| 31. Thessaloniki B | 40.60 | 23.00 | 10 | 12.5 | 60.2 | 196 | 3.5 | 2.0 | 1450 | 1400/1500 |
| 32. Eretria | 38.44 | 23.79 | 5 | 0.6 | 58.0 | 406 | 3.1 | 1.8 | – | – |
| 33. Stylos | 35.42 | 24.10 | 14 | 3.5 | 55.1 | 293 | 2.3 | 1.3 | – | – |
| 34. Aegira B | 38.10 | 22.42 | 9 | 10.4 | 65.6 | 91 | 5.4 | 3.2 | – | – |
| 35. Avlis | 38.50 | 23.67 | 6 | −6.9 | 62.5 | 226 | 4.5 | 2.6 | – | – |
| 36. Athens C | 38.00 | 23.70 | 11 | −6.9 | 58.7 | 209 | 2.9 | 1.7 | – | – |

*Notes*: All the results tabulated here were obtained at the University of Alberta Petromagnetism Laboratory. They all come from pottery kilns, except numbers 1 and 20 (burnt walls), 4, 7, 10 and 19 (hearths), 21 and 23 (baths) and 25 (a metal smelter). Dates are the midpoints of the ranges, given in the chronology column, obtained from the available archaeological ages (either from published sources or in consultation with the appropriate experts): positive (negative) dates are CE (BCE). Cretan chronology follows Arthur Evans's classic scheme, as tabulated in Huxley (2000). Dec: declination in degrees east (+) or west (−) from north. Inc: inclination in degrees below the horizontal. $N$: number of samples. $k$: Fisher's precision parameter. $\alpha_{95}$: semi-angle of 95% confidence cone, a.s.e.: angular standard error (both in degrees).

the material involved was extremely fragile. Perhaps the excavated surface represents a somewhat deeper level to which the heat did not effectively penetrate (see the discussion of cremation pyres in Evans and Hoye, 2005). The remaining sites yielded acceptable site mean directions, with an average value of 476 for the Fisher precision parameter. For the kiln at site 5 the underlying characteristic remanence direction was extracted by the method of demagnetization great circles (Bailey and Halls, 1984). Three features (18–20) were investigated on the island of Delos, all of them last heated at, or near, the time of the general destruction that took place in 69 BCE. They are a kiln (18 = A), a restaurant kitchen facility (19 = B) and the burnt walls of a house (20 = C). The latter two are made entirely of strongly foliated slabs of gneiss, the ubiquitous bedrock in this part of the island. Since the slabs are disposed horizontally one suspects *a priori* that the measured inclinations may be too shallow, as is, in fact, observed (see Table 1). In principle it should be possible to make a first-order correction for the resulting angular deflection, but this requires that the anisotropy of each sample be determined. Unfortunately, this is not possible because the irregular shapes of the samples are likely to adversely affect such mea-

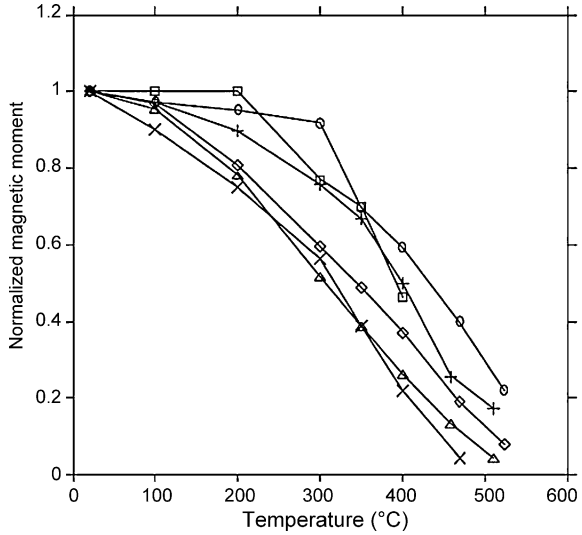


Fig. 2. Stepwise thermal demagnetization curves for samples from sites 3 (plus sign), 8 (cross), 13 (diamond), 20 (square), 21 (circle) and 22 (triangle). Numbers correspond to entries in Table 1. The curves terminate at the temperature beyond which directional fidelity is lost.

surements. However, three approximately equidimensional samples were checked on a Bartington susceptibility meter, using an 18-position measurement protocol. They indicate that anisotropy of magnetic susceptibility (AMS) varies widely: two samples from B have AMS values of 31% and 46%, whereas the single sample from C yields a value of only 9%. It would appear that the observed shallowing (∼8° between the A and B means, ∼3° between A and C) could well be due to magnetic fabric (for example, see Dunlop and Özdemir, 1997, p. 487), but more comprehensive data would be required to perform an acceptable correction. The B and C data are generally supportive of the kiln result, but in the absence of complete information, only the A result is used hereafter. Finally, it will be noted that Table 1 gives no chronological information for sites 32–36. The structures involved (all kilns) are either poorly constrained in time or have dates that are subject to some controversy; they are discussed in more detail in following section.

## 3. Discussion

The results given in Table 1 are conveniently summarized in the inclination and declination magnetograms of Figs. 4 and 5, where they are compared with the comprehensive data from nearby Bulgaria. The agreement is generally good bearing in mind the limitations that still plague the Greek dataset, in particular, the gap in the first half of the first millennium BCE and the poor coverage of the post-Roman period. Nevertheless, the evidence for some important geomagnetic features now seems to be robust. For inclination (Fig. 4), these are: (1) low values in the first few centuries CE, (2) high values in the second half of the second millennium BCE, and (3) a deep minimum in the early second millennium BCE. Concerning this last feature it is interesting to note that Tarling and Downey (1990) report a very similar result (declination = 6.0°, inclination = 41.5°, $\alpha_{95}$ = 3.5°, $N$ = 5) for a kiln at Phaistos (the same kiln that I sampled in 1990 before learning of their result). An independent "blind" check of this kind lends support to the reality of the observed deep inclination low, but there is a pressing need for more data. For declination (Fig. 5), the major features to note are the strong easterly extrema (4) at ∼1000 BCE and (5) around the end of the first millennium CE. The strong westerly swing in Bulgaria at 300–400 BCE is rather muted in the Greek results, but is supported by the Italian data of Evans and Hoye (2005, see their Fig. 6). The rapid decrease following feature (4)

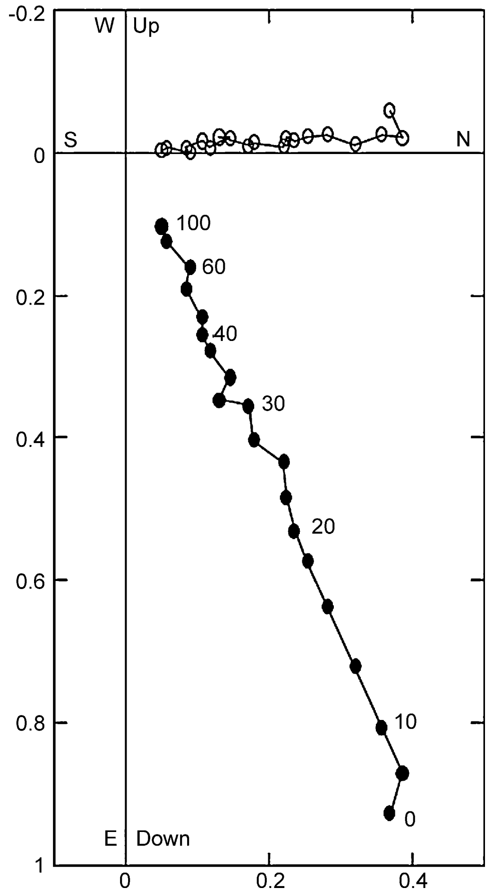


Fig. 3. AF demagnetization vector orthogonal plot (normalized to the total NRM) for a sample from site 17 (steps are 0, 8, 10, 13, 15, 18, 20, 22, 25, 27, 30, 32, 35, 37, 40, 45, 50, 60, 80 and 100 mT). Open (closed) symbols are on the horizontal (vertical) plane.

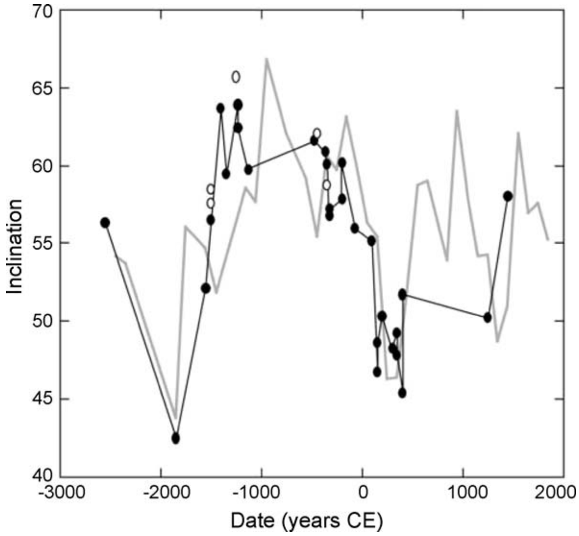


Fig. 4. Inclination magnetogram for the Greek data listed in Table 1. To allow for the geographic spread of the sampling sites all results have been transformed to their corresponding values at Athens by means of the so-called VGP method (Noël and Batt, 1990), but the differences between this method and the alternative procedure based on a geocentric axial dipole (GAD) never exceed 1°. The thick grey line represents the Bulgarian data of Kovacheva et al. (1998) shifted downwards 4.2° (i.e. GAD corrected) to allow for the latitude difference between Athens and Sofia. The open symbols represent sites 32–36 chronologically placed as explained in the text.

seen in the Bulgarian data falls in the previously mentioned data gap in Greece. However, it fits very nicely with corresponding data from France (Gallet et al., 2002, see their Fig. 4).

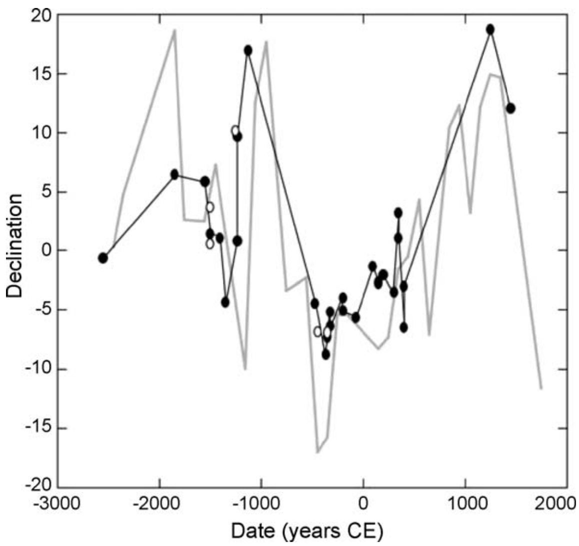


Fig. 5. Declination magnetogram corresponding to Fig. 4. The Bulgarian data have not been adjusted. The open symbols represent sites 32–36 chronologically placed as explained in the text.

The sharp inclination low in the first few centuries CE has been widely recognized; it is seen clearly in the Bulgarian data (Fig. 4) and is also present in the British, French and German results. It is regarded as the signature of a magnetic flux bundle emanating from the outer core. Since little or no change in declination occurs, the suggestion is that the flux bundle remains fixed geographically but undergoes a growth and decay cycle lasting a few centuries—what Evans and Hoye (2005) refer to as a static flux pulse. The deeper inclination trough centred early in the second millennium BCE, followed by the maximum in the later part of the millennium is accompanied, in Bulgaria, by equally rapid declination changes. It is more likely, therefore, to have been caused by a drifting source. In terms of the observed amplitude, it is perhaps worth noting that such rapid changes are by no means out of the question. In mid-latitudes, a secular change of a few tens of nT/year (if appropriately directed) can cause a 20° shift in ∼500 years. Much higher annual rates of change are currently present over large areas of the Earth's surface.

The results from sites 32–36 provide potentially useful chronological information. Result 32 is a unique example of archaeomagnetic data obtained from a kiln that had been rescued from below the water table and removed bodily to an outdoor storage facility at the local museum. Orientated samples were taken in the normal way and then corrected to the original alignment of the kiln indicated on the excavation plans. The result obtained suggests that this kiln ceased operation in Late Helladic I/II times (∼1500 BCE). The kiln at Stylos (33) has yielded a thermoluminescence date of 1878 ± 270 BCE (Liritzis and Thomas, 1980), but Davaras (1973) regards it as Late Minoan (LMIIIB, i.e. ∼1300 BCE). The archaeomagnetic result favours something in between, most probably ∼1500 BCE (LMIA). At Aegira samples were taken from kilns of two distinct periods, the one located on the acropolis (34) being much the older; its high inclination and easterly declination imply that it belongs to the earliest remains known at this site (LH IIIA = ∼1250 BCE). At Avlis (35) the result from the small potter's kiln investigated agrees well with the fifth century BCE date of other nearby buildings at the site. Finally, considering inclination and declination together, the age of the Athens C kiln (36) is assigned to the fourth century BCE.

## 4. Concluding remarks

Ancient kilns and other heated structures on the Greek mainland and on the islands of Crete, Delos, Euboea and Thasos provide archaeomagnetic directional results reaching back to the mid-third millennium BCE. Collectively, the entire dataset is in good agreement with previously published data from Bulgaria. Prominent features of the secular variation are the inclination minima in the early part of the second millennium BCE and in the first few centuries CE. The latter has been widely reported in European datasets and is interpreted as a static flux pulse due to the rapid growth and decay of a stationary magnetic source in the outer core. The former is based on very few results from Greece, but it is clearly seen in Bulgaria. There, it is associated with strong declination changes and is therefore more likely due to a drifting source. For the archaeologist, it is the possibility of obtaining chronological information that is of interest. In this context, the emerging secular variation curve for Greece permits archaeomagnetic dates to be proposed for five kilns whose chronologies were hitherto in doubt. Such results demonstrate that archaeomagnetism could contribute to the problem of correlating the separate chronologies that have evolved for different regions (e.g. Minoan on Crete versus Helladic on the mainland), or to the continuing question of what caused the downfall of the Minoan civilization. But many more results will be required!

## Acknowledgements

I am very grateful to the Greek authorities for permission to carry out this project and for all the help they provided; nothing could have been achieved without their willing cooperation. I am also deeply indebted to numerous institutions (American, Austrian, British, Canadian, French, German, Italian, Swedish and Swiss) and to the many archaeological experts who offered advice and assistance at every stage of the fieldwork. Financial support from the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

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