Archaeomagnetic study of five mounds from Upper Mesopotamia between 2500 and 700 BCE: Further evidence for an extremely strong geomagnetic field ca. 3000 years ago

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Article info

Article history:
Received 29 September 2011
Received in revised form 19 June 2012
Accepted 22 August 2012
Editor: DeMenocal

Keywords:
archaeomagnetism
archaeointensity
secular variation
Upper Mesopotamia
Turkey
geomagnetic spikes

Abstract

The distribution of archaeomagnetic data in eastern Europe and the Near and Middle East shows a remarkable gap in Turkey. This study presents the first archaeomagnetic results from five different mounds in southeast Turkey, the northern part of Mesopotamia. The rock magnetic experiments indicate that in the majority of the samples the dominant magnetic carrier is magnetite, which is stable to heating to temperatures of 700 °C. In general, the demagnetization diagrams are single component and all five sets display well-defined characteristic magnetizations and clustered directions. For the period between 2500 and 700 BCE, the declinations are between 350° and 20° while inclinations are in the range of 49–64°. The directional results are compared with the global geomagnetic field models (CALS7k.2, ARCH3k, cst.1 and CALS3k4) and the data from the archaeomagnetic database GEOMAGIA50v2. The results are coherent with both the data and the models except for two near-contemporary sets dating ~2000 BCE, which are offset to the east by more than 20° with respect to CALS7k2. Archaeointensity measurements were made using the microwave and conventional thermal Thellier methods applied to five sets of samples (four furnaces and a mud-brick wall). These yielded comparable and intriguing results. While those from the furnaces are slightly higher than the CALS7k2 model and in agreement with the GEOMAGIA50v2 and the Middle East data, the results from the mud-brick wall suggest a high intensity of 100.8 μT (17.7 × 10−2 Am²) at ~1000 BCE. This result is in excellent agreement with recent claims of extremely high intensity measured in other regions of the Middle East for this time period though less consistent with these being associated with extremely short-lived events. Finally, we discuss our new and other recently published archaeointensity results in terms of geomagnetic intensity versus climate.

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1. Introduction

The recent geomagnetic field is well-known from globally distributed observatories and from satellite observations (Hulot et al., 2002), while for the past few centuries the field has been reconstructed from historical navigational observations (Jackson et al., 2000; Jonkers et al., 2003). Older records of the field can be derived through archaeomagnetism, the study of burnt or fired archeological artifacts. These archaeomagnetic directions and intensities of the field are crucial to furthering our understanding of the behavior of the geodynamo over longer, millennial time scales. A number of global and regional field models have recently been developed based on compilations of archaeomagnetic and lake sediment data like the Continuous Archaeomagnetic and Lake Sediment models CALS3k (Korte and Constable, 2003; Korte et al., 2009) and CALS7k (Korte and Constable, 2005) for the past 3 and 7 kyr, respectively. The most recent model for the past 3000 years CALS3k4 is based on a recently updated and improved data compilation and considered presently to be the best model for Earth surface studies (Korte and Constable, 2011). The model is available through the online database GEOMAGIA50v2 (Donadini...
et al., 2006; Korhonen et al., 2008) (http://geomagia.ucsd.edu). While the CALSNK models are based on both archaeomagnetic and lake sediments data, the ARCH3k1 model is based solely on archaeomagnetic data, and the constrained model ARCH3k_cst.1 additionally uses a set of reliability criteria to minimize uncertainties (Donadini et al., 2009; Korte et al., 2009). The ARCH3k models are certain to be more reliable for the northern hemisphere, especially for Western Europe, since archaeomagnetic data for the southern hemisphere are sparse.

Archaeomagnetic studies in the Levant and Middle East are still scarce (Fig. 1), but recently a number of studies have provided a series of paleointensities from the Levant and Mesopotamia during the past 8000 years. These data come from Syria and Iran (Gallet and Al-Maqdissi, 2010; Gallet et al., 2006, 2008; Gallet and Le Goff, 2006; Genevey et al., 2003) and from Israel and Jordan (Ben-Yosef et al., 2008, 2009; Shaar et al., 2011) (Fig. 1).

Some of these results have produced unusually high virtual axial dipole moments (VADM) of up to $14-18 \times 10^{22} \text{Am}^2$ around 700 and 1000 BCE, twice the present-day value of the field which is already considerably higher than the average of the field during the geological past (Juárez et al., 1998; Selkin and Tauxe, 2000; Valet, 2003; Ziegler et al., 2008).

Periods of rapidly increasing intensities from 3000-0 BCE have been called 'archaeomagnetic jerks' (Gallet et al., 2003). The visual correlation of these short peaks to cooling episodes in the North Atlantic (Bond et al., 1997, 2001) led Gallet et al. (2006) to suggest that the geomagnetic field may have had an impact on climate and therefore perhaps even on the history of ancient civilizations: major cultural crises would occur at the end of cooling cycles – cool implying arid conditions – in turn coinciding with the rapid increase of geomagnetic field intensity, both in Mesopotamia and the Levant, and possibly during Mayan history as well (Gallet and Genevey, 2007). On the basis of this temporal coincidence, Gallet et al. (2005, 2006) argued that there may have been a connection between Earth’s magnetic field and climate. A proposed mechanism involves variations in the geometry of the geomagnetic field resulting in enhanced cosmic-ray induced nucleation of clouds. This speculation has led to heated debates on potential mechanisms causing climate change in the past (Bard and Delaygue, 2008; Courtillot et al., 2008). More recently, even higher intensities were found in copper slag deposits from Jordan (Ben-Yosef et al., 2009; Shaar et al., 2011), fitting in a gap of previously published data. The authors found unprecedented high values, ranging by more than a factor of two ($11-25 \times 10^{22} \text{Am}^2$) over a short time interval of some 200 years ($\sim 1040-860 \text{ BCE}$). This interval of high intensity values coincides well with one of the cooling cycles ($\sim 1115-910 \text{ BCE}$) or, alternatively, with one of the colder periods ($\sim 1055-805 \text{ BCE}$) as derived from the North Atlantic drift ice index (Bond et al., 2001; the stack of 4 records in their Fig. 2) and therefore seems to support the relation between the geomagnetic field and climate (Gallet et al., 2005, 2006). Clearly, there is a need for more reliable paleointensity records to test these hypotheses and to confirm extremely rapid intensity changes.

The distribution of archaeomagnetic data in eastern Europe and the Near and Middle East shows a remarkable gap in Turkey (Fig. 1), despite the fact that Turkey is extremely rich in archaeological sites from Neolithic times onwards. Turkey has been at the ‘cross-roads’ between Asia and Europe, and has seen many civilizations and migrations (Fig. A1). Only two studies are listed in GEOMAGIA50v2 (Bucha and Mellaart, 1967; Sarıbudak and Tarling, 1993), while a more recent but unlisted study (Sayın and Orbay, 2003) provides directional results from mostly central Anatolian sites ranging from 7900 BCE to 1750 CE. This latter study also reports the results (from 400 BCE to 1800 CE) of an unpublished thesis (Ponat, 1995).

Although the existing data around Turkey and the global field models give a first approximation of the ancient field, the use of archaeomagnetism as a dating tool requires a well established palaeosecular variation (PSV) curve for this large region. The lack of Turkish data combined with the lushness of its archeology

Fig. 1. Map showing the five sampling locations (large white circles) of southeastern Anatolia (Table 1). Red circles refer to locations with data from GEOMAGIA50v2 (Donadini et al., 2006, 2009; Korhonen et al., 2008) within a circle of ~1600 km of Kayseri (black star) which we use as our reference location in Turkey (38.85 N, 35.63 E). Blue circles are locations from Syria, Iran, Israel and Jordan and selected sites from Iraq that we use as an archaeointensity reference for the Levant and Mesopotamia (see for references the text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
makes new archaeomagnetic studies very timely and relevant. We have therefore recently begun a new (Ph.D.) project of which this study presents the first archaeomagnetic results from south-east Turkey (Fig. 1), the northern part of Mesopotamia.

2. Archeological background and sampling

The area known as the ‘Fertile Crescent’ consists of the fertile regions of Mesopotamia and the Levant, delimited by the dry climate of the Syrian Desert to the south and the Anatolian highlands to the north (Fig. 1). The area is important as a ‘land bridge’ between Africa and Eurasia, allowing the Fertile Crescent to retain a great amount of biodiversity and to contribute to the modern distribution of Old World flora and fauna, including the spread of humanity. The southeastern fringe of Turkey forms the northern part of Mesopotamia – (land) between the rivers (Euphrates and Tigris) – widely considered as the cradle of civilization. The indigenous Sumerians and Akkadians (including Assyrians and Babylonians) dominated Mesopotamia from the beginning of written history (ca. 3100 BCE) to the fall of Babylon in 539 BCE, when it was conquered by the Achaemenid Empire.

The sampling sites are located in southeastern Anatolia, along the Tigris and Euphrates rivers (Fig. 1). Archaeomagnetic sampling was carried out in five different mounds with subsets belonging to various time periods. As a rule, a water-cooled electrical drill and generator were used to take cylindrical cores (2.5 cm diameter). If the material was fragile, oriented hand samples were taken and put in plaster of Paris and then drilled in the laboratory, if necessary with air cooling. Brief descriptions of the sites and the sampling are given below (see Table 1 for details). The dating of the sites is based mainly on 14C, as well as on material culture and archeological context referred to as archeological estimate in Table 1. More details about the sites and the basis on which the
structures were dated can be found in the Appendix and figures (Figs. A2–A6, Supplementary information).

2.1. Arslantepe (AT)

The mound Arslantepe is located in Malatya province on the alluvial plain of the Euphrates river. Located in a strategically crucial position, the site was the center of attraction for many civilizations through the ages, from as early as the 5th millennium BCE to the Byzantine period, without any interruptions. The fact that the site has been actively occupied for 6000 years makes it very promising for archaeomagnetic studies. In 2007, a burnt mud-brick fortress wall from a Neo-Hittite (ca. 1200–712 BCE) destruction level was sampled by taking cores. The destruction event is dated to 1200–900 BCE based on pottery comparisons and a well-based stratigraphical sequence. In 2008, we added four near-contemporaneous furnaces from the Early Bronze Age II—Early Bronze Age III transition which was dated to ∼2500 BCE on the basis of a set of radiocarbon analyses (Alessio et al., 1983; Sadori et al., 2006). Furnaces A+C, B and D are from different rooms; furnaces A and C are from a single room and furnace A was built on top of furnace C (Fig. A2, Table 1).

2.2. Zeytinli Bahçe (ZB)

The mound Zeytinli Bahçe lies on the east bank of the Euphrates river, in Şanlıurfa province. It is characterized by a long sequence from the IVth to IInd millennium BCE, and the occupation was dominated by Late Chalcolithic, and Bronze Age periods. Three structures were sampled for this study, including a kiln (ZB1, oriented hand samples) from Early Bronze Age (~2250 BCE) and two different destruction levels (ZB2, burnt mud-brick wall and ZB3, burnt mud-brick pavement) from Middle Bronze Age levels (~2000 BCE) (Fig. A3, Table 1). The chronology of the site is established based on ceramic assemblage and radiocarbon analyses (Di Nocera, 2010). It was observed that ZB3 is stratigraphically younger than ZB2. In the laboratory, we attempted to drill cores from ZB1, but because of the very fragile material we were not successful in obtaining measurable specimens.

2.3. Ziyaret Tepe (ZT)

Ziyaret Tepe (Assyrian Tushhan) was a site situated on the floodplain of the Tigris River on the northern frontier of the Assyrian Empire (Matney et al., 2009). The site was occupied from the Early Bronze Age (ca. 3000 BCE), when it was a modest village settlement, until it became an important center during the Iron Age (ca. 882–610 BCE). Although an important administrative center in the Middle Assyrian period, the site is best known during the Late Assyrian (or Neo-Assyrian) period (Matney et al., 2002). The archaeomagnetic samples used in this study were taken from the baked brick lining of a cremation burial located in the courtyard area of an Assyrian Palace (Operation A/N) from the early VIIIth century BCE, where we sampled baked bricks (Fig. A4, Table 1). Dating is based on three radiocarbon samples excavated from inside the cremation burial which yielded a statistically combined date of 754–613 BCE (Matney et al., 2009; Matney and Rainville, 2005).

2.4. Salat Tepe (ST)

The site lies 5 km to the north of Tigris river, on the western bank of the Salat branch. The earliest settlement in the site is dated to Halaf-Early Ubaid transition in the Chalcolithic period (VIIth millennium BCE). The occupation continued in Middle Bronze Age (MBA), Iron Age and Hellenistic–Roman periods (Ökse, 2010). The sampling was made by taking hand samples from two kilns, one (OY1) belonging to the Iron Age period (~1000 BCE) and the other (OY2) to Late Bronze–Early Iron Age transition (~1200 BCE). Samples from OY1 were very fragile and

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Epoch</th>
<th>Age (BCE)</th>
<th>Dating method</th>
<th>Structure</th>
<th>Material</th>
<th>N</th>
<th>Nspec</th>
<th>Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arslantepe</td>
<td>AT1</td>
<td>Neo-Hittite</td>
<td></td>
<td>AE Fortress wall</td>
<td>Mud-brick</td>
<td>21</td>
<td>21</td>
<td>Cores</td>
</tr>
<tr>
<td>AT-A</td>
<td>Early Bronze</td>
<td>2525 ± 35 14C, AE</td>
<td></td>
<td>Furnace</td>
<td>Baked clay</td>
<td>78</td>
<td>78</td>
<td>Cores</td>
</tr>
<tr>
<td>AT-B</td>
<td>Early Bronze</td>
<td>2525 ± 35 14C, AE</td>
<td></td>
<td>Furnace</td>
<td>Baked clay</td>
<td>2/1</td>
<td>11</td>
<td>Cores/OHS</td>
</tr>
<tr>
<td>AT-C</td>
<td>Early Bronze</td>
<td>2525 ± 35 14C, AE</td>
<td></td>
<td>Furnace</td>
<td>Baked clay</td>
<td>24</td>
<td>24</td>
<td>Cores</td>
</tr>
<tr>
<td>AT-D</td>
<td>Early Bronze</td>
<td>2525 ± 35 14C, AE</td>
<td></td>
<td>Furnace</td>
<td>Baked clay</td>
<td>62</td>
<td>62</td>
<td>Cores</td>
</tr>
<tr>
<td>Zeytinli Bahçe</td>
<td>ZB1</td>
<td>Early Bronze</td>
<td>2250 ± 50 AE</td>
<td>Fire place</td>
<td>Baked clay</td>
<td>–</td>
<td>–</td>
<td>OHS</td>
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<tr>
<td>ZB2</td>
<td>Middle Bronze</td>
<td>2004 ± 24 14C, AE</td>
<td></td>
<td>Mudbrick wall</td>
<td>Mud-brick</td>
<td>3</td>
<td>10</td>
<td>OHS</td>
</tr>
<tr>
<td>ZB3</td>
<td>Middle Bronze</td>
<td>2004 ± 24 14C, AE</td>
<td></td>
<td>Mudbrick pavement</td>
<td>Mud-brick</td>
<td>7</td>
<td>7</td>
<td>Cores</td>
</tr>
<tr>
<td>Ziyaret Tepe</td>
<td>ZT</td>
<td>Late Assyrian</td>
<td>683 ± 70 14C, AE</td>
<td>Mudbrick pavement</td>
<td>Mud-brick</td>
<td>20</td>
<td>20</td>
<td>Cores</td>
</tr>
<tr>
<td>Salat Tepe</td>
<td>ST</td>
<td>Middle Bronze</td>
<td>1630 ± 110 14C, AE</td>
<td>Mudbrick wall and foundation stones</td>
<td>Mud-brick, limestone, travertine</td>
<td>11/1</td>
<td>18</td>
<td>Cores/OHS</td>
</tr>
<tr>
<td>Oylum Höyük</td>
<td>OY1</td>
<td>Iron</td>
<td>1000 ± 200 AE</td>
<td>Kiln</td>
<td>Baked clay</td>
<td>–</td>
<td>–</td>
<td>Cores/OHS</td>
</tr>
<tr>
<td>OY2</td>
<td>Late Bronze–Early Iron</td>
<td>1200 ± 100 AE</td>
<td>Kiln</td>
<td>Red coarse-grained baked clay</td>
<td></td>
<td>4</td>
<td>16</td>
<td>OHS</td>
</tr>
</tbody>
</table>

N is the number of samples (cores/OSH) where OHS denotes oriented hand sample, AE is archeological estimate and 14C is radiocarbon dating.
did not survive sampling in the laboratory; consequently no results are reported. OY2 consisted of a pot-shaped kiln of coarse grained red baked clay from which we were able to extract four hand samples.

3. Rock magnetic properties

For all the sites and for the different materials from each site, we measured thermomagnetic (Curie balance) curves and low field magnetic susceptibilities, and for sites that appeared promising for archaeointensity research we also performed hysteresis loop experiments, including First Order Reversal Curve (FORC) diagrams (Roberts et al., 2000) – the analysis of FORC diagrams may increase the efficiency of paleointensity measurements (Carvallo et al., 2006) – and acquisition of Isothermal Remanent Magnetization (IRM), to characterize the rock magnetic properties.

3.1. Room temperature susceptibility

We measured the low field magnetic susceptibility with a Kappabridge KLY-2. In general, susceptibilities are high as is often the case for burnt material. The burnt mud-bricks (AT1, ZT, ST, ZB2, ZB3) and the red baked coarse material of the OY2 kiln have high susceptibilities ranging from 1 to $16 \times 10^{-3}$ SI, the burned clays of the furnaces of Arslantepe (AT A–D) typically range between 0.5 and $1.0 \times 10^{-3}$ SI, while the limestones and travertines of ST have very low ($15 \times 10^{-6}$ SI) or even negative (diamagnetic) values. We calculated the Koeningsberger ratio ($Q_n$) as the ratio of remanent vs. induced magnetization (Dunlop and Özdemir, 1997), and except for a few samples $Q_n$ is significantly greater than 1 (Fig. A7), which indicates that the remanent magnetization strongly dominates, providing a positive stability test.

3.2. Curie balance curves

Thermomagnetic curves were obtained by measurements in air up to 700 °C using a modified horizontal translation type Curie balance (noise level $5 \times 10^{-9}$ Am$^2$; Mullender et al., 1993). These included cycles of heating and cooling to intermediate temperatures to check for the occurrence of alteration. The applied cycling field varied between 100 and 300 mT for magnetically strong samples and between 20 and 300 mT for weaker samples. For all types of samples, little alteration occurs below the highest Curie temperature ($T_c$), typically ~580 °C (Figs. A8 and 2). In many cases, the heating curves display a slight inflection in the curve, usually in the range of 300–350 °C but sometimes higher (up to 450 °C), which could point to some maghemite (Dankers, 1978), or possibly titanomagnetite or Al substituted magnetite (Dunlop and Özdemir, 1997). In most cases, this is a reversible feature which does not favor maghemite. Except for OY2, $T_c$ is ~580 °C.

![Fig. 3.](https://example.com/fig3.png)

**Fig. 3.** (a) Hysteresis parameters plotted on the Day Plot (Day et al., 1977). The results show a range of mainly PSD magnetite, only some samples from furnace AT-D suggest the presence of MD magnetite. (b) Representative FORC diagrams from clay furnace material from AT-D and mud-brick from AT1, plotted with a smoothing factor (SF) of 3 and contour interval of 10. The central coercivity density maximum is at $+0$ and 10 mT and spreading of contours along the ordinate is 20 mT and 15 mT.
indicating that the dominant magnetic carrier is magnetite. OY2 has a Curie temperature of 620 °C which probably indicates maghemite as the main carrier. For the samples from AT-D there is an additional low \( T_c \) at 120 °C which may imply that furnace D also contains some amount of goethite (Dekkers, 1988). In most cases, the heating and cooling curves are similar indicating that the samples are stable to heating to temperatures of 700 °C.

On the basis of the thermomagnetic measurements, we decided to use the samples from Arslantepe (AT1, AT A–D) for archaeointensity measurements, since these appeared to be most stable upon heating and show no significant alteration and no evidence for maghemite. To determine the magnetic domain state, and hence the magnetic stability of these sites, hysteresis evidence for maghemite. To determine the magnetic domain

\[ B \]

with peak of distribution centered at

\[ 0 \]

are plotted in Fig. 3 b. AT-D displays a symmetrical FORC diagram and indicates that all sets except furnace AT-D fall into the pseudo single domain (PSD) category whereas samples from furnace D are largely in the multi-domain (MD) category.

The IRM acquisition curves show that there is no indication of a high coercivity mineral: all samples are saturated well below 300 mT. The FORC diagrams (Fig. 3b) support the general findings of the hysteresis analysis. Two representative diagrams showing the difference in directions between AF and TH demagnetization.

4. Methods

To determine the characteristic remanent magnetization direction (ChRM), at least 7 (generally more than 10, and occasionally more than 50) specimens per site were demagnetised, both by thermal (TH) and alternating field (AF) demagnetization (Table 2). The demagnetization was performed with small AF or TH increments up to a maximum of 100 mT or 620 °C. The natural remanent magnetization (NRM) was measured on a horizontal 2G Enterprises DC SQUID cryogenic magnetometer (noise level 3 \( \times 10^{-12} \) Am\(^2\)) for TH demagnetization, or on our robotized DC SQUID magnetometer (noise level 10\(^{-12}\) Am\(^2\)) for AF demagnetization, after heating the samples to 150 °C to remove possible high coercivity and low \( T_c \) minerals like goethite, or to remove possible stress in magnetite grains caused by surface oxidation at low temperatures (van Velzen and Zijderveld, 1995). Thermal demagnetization was done with incremental temperature steps of 30–50 °C, in most cases up to 580 °C, while AF demagnetization involved 15 steps with increments of typically 5–10 mT up to 100 mT. The demagnetization results were interpreted via orthogonal projection diagrams (Zijderveld, 1967) and by principal component analysis (Kirschvink, 1980), mean directions were calculated according to Fisher (1953) with uncertainties calculated in VGP space (Deelen et al., 2011). Both for the maximum angular deviation (MAD) of individual directions and \( \alpha_{95} \) of the means we accepted a maximum angle of 10°.

In nearly all cases, a negligibly small viscous component is removed at low temperatures or low alternating field (100 °C or 5 mT), only occasionally a slightly higher temperature or field was required (180 °C or 10 mT). Fig. 4 shows typical examples from all sites. As can be seen from the results (Fig. 4), there is no discernible difference in directions between AF and TH demagnetization.

Archaeointensity measurements were carried out on a total of 54 specimens from the Early Bronze Age furnaces at Arslantepe (AT A–D) and the Neo-Hittite fortress wall (AT1), using laboratory fields ranging from 30 to 100 μT. The microwave technique (Hill and Shaw, 1999; Walton et al., 1996) was primarily used to obtain the archaeointensities. The microwave measurements were performed in the Geomagnetism Laboratory of University of Liverpool using an automated microwave system combined with a Tristan Technologies liquid helium cooled SQUID magnetometer with cryocooler. Conventional thermal Thellier-type (Thellier and Thellier, 1959) experiments method was also used for comparison. These experiments were carried out in Fort Hoofddijk Paleomagnetic Laboratory of Utrecht University using mostly an ASC Model TD48-SC thermal demagnetizer along with an in-built field coil for TRM and pTRM acquisition.

Table 2

<table>
<thead>
<tr>
<th>Site</th>
<th>Treatment</th>
<th>N</th>
<th>n/N (TH)</th>
<th>n/N (AF)</th>
<th>Dec</th>
<th>Inc</th>
<th>Dec</th>
<th>Inc</th>
<th>dDec</th>
<th>dInc</th>
<th>k</th>
<th>( \alpha_{95} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT1</td>
<td>AF</td>
<td>17</td>
<td>–</td>
<td>15/17</td>
<td>356.0</td>
<td>64.0</td>
<td>1.3</td>
<td>64.3</td>
<td>7.2</td>
<td>4.0</td>
<td>118.1</td>
<td>3.5</td>
</tr>
<tr>
<td>AT-A</td>
<td>TH, AF</td>
<td>74</td>
<td>32/40</td>
<td>28/34</td>
<td>351.4</td>
<td>48.2</td>
<td>–4.2</td>
<td>48.9</td>
<td>1.1</td>
<td>4.9</td>
<td>388.8</td>
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<tr>
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<td>AF</td>
<td>9</td>
<td>–</td>
<td>8/9</td>
<td>352.4</td>
<td>48.7</td>
<td>–3.2</td>
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<td>4.9</td>
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<td>TH, AF</td>
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<td>9/11</td>
<td>9/10</td>
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<td>50.2</td>
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<td>21/25</td>
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n/N, number of samples accepted over measured; Dec, mean declination; Inc, mean inclination; k, precision parameter; dDec, deviation in declination; dInc, deviation in inclination; \( \alpha_{95} \), 95% confidence cone of mean directions.
4.1. Microwave experiments

To avoid the potentially widespread problem of multidomain (MD)-type behavior biasing the palaeointensity results (see e.g. Biggin, 2010), we adopted two protocols in the microwave experiments specially designed to detect and minimize this behavior, while simultaneously allowing thermally-induced alteration to also be detected. The first was the IZZI protocol (Tauxe and Staudigel, 2004) used in conjunction with an applied field directed exactly antiparallel to the NRM of each sample. This protocol acts as a very sensitive detector of MD-like behavior by producing strongly zigzag shaped Arai plots if pTRM tails are present (Biggin, 2006; Yu and Tauxe, 2005). The other protocol applied in the microwave experiments is the one that minimizes these effects (Biggin and Böhnel, 2003): the Aitken–Walton (Aitken et al., 1988; Walton, 1979) protocol whereby the infield (I) step is performed prior to the zero-field (Z) step at each double-treatment and the field is applied parallel to the NRM of the sample. In both types of experiment, the use of pTRM tail checks and the extra microwave treatments that these would

Fig. 4. Representative examples of stepwise thermal (TH) and alternating field (AF) demagnetization diagrams and equal area projections of the characteristic remanent magnetization direction of the sites from this study (Table 2) along with their ±95 cone of confidence (red transparent circles). N is the number of samples, k is precision parameter and D/I is the declination/inclination. Closed (open) symbols in the demagnetization diagrams represent the projection of the vector end-points on the horizontal (vertical) plane; values represent temperature or alternating field in °C or mT. Normalized intensity decay plots are shown on the lower left or right corner. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
require are rendered unnecessary. Furthermore, since the field is applied (anti)parallel to the NRM it also minimizes the effects of any magnetic anisotropy on the palaeointensity experiments. To monitor chemical alteration, pTRM checks were performed after every two double-treatments in both protocols.

4.2. Thermal Thellier and Thellier experiments

Once the behavior of the samples to IZZI antiparallel protocol is found to be considerably well-behaved in the microwave experiments, the rest of the thermal experiments are carried out using the IZZI protocol with field applied parallel to the samples NRM. Since the direction of the oven field is either parallel or antiparallel to the sample holder, to be able to attain the desired field direction, a custom-built orientation tray was used where each sample can separately be oriented with respect to the oven field. From each set, half of the samples were measured with pTRM checks in every two double-treatment heating steps. The other half of the samples was measured with one pTRM check at the very end of the experiment.

The data from both experiments are interpreted using Arai plots (Nagata et al., 1963) (Fig. 5). The acceptance criteria for the linear fit are adapted from Coe et al. (1978) and Selkin and Tauxe (2000), where the number of points (N) is greater than or equal to 5, and the ratio of standard error of the slope to absolute value of the slope (β) is smaller than 0.1. The lower acceptance limit for the NRM fraction (f) is increased from 0.15 to 0.4 (though most results had f ≥ 0.5). We chose not to apply the f ≥ 0.7 criterion recently recommended by Biggin (2010) for results produced with no checks for MD behavior. We therefore cannot unequivocally rule out MD effects causing certain results to be biased. As will be shown, however, results from sister samples, in which checks were employed, suggest that any such effects are small. The acceptance criterion for quality factor (q) was set to 3. The directional aspects are analyzed by principle component analysis (Kirschvink, 1980). The upper acceptance limits for maximum

**Fig. 5.** Representative Arai plots (Nagata et al., 1963) with pTRM checks and associated orthogonal vector plots showing single component directions in core coordinates. Solid blue (open red) symbols are vertical (horizontal) planes. Diagrams are normalized to initial NRM intensity. The open (closed) circles are the IZ (ZI) steps. MW denotes microwave and TT stands for standard Thellier and Thellier technique. The direction of the applied field is indicated as P or AP (parallel or antiparallel to NRM). For TT measurements, the temperature steps are shown on the side of the data point. ThellierTool4.0 (Leonhardt et al., 2004) was used to plot the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
angular deviation (MAD) and $z$ are taken as 10%. pTRM checks were deemed positive if the ratio of difference between the check and the relevant TRM value to the length of the selected NRM–TRM segment (DRAT) was smaller than 10% (Selkin and Tauxe, 2000). The acceptance limit for the minimum number of successful pTRM checks is taken as three. However, some of the thermal Thellier and Thellier experiments were carried out with just one pTRM check at the end of the experiment. In that case, the sister samples are taken as reference and the lowest temperature step that an alteration has occurred (if any) became the highest acceptable temperature threshold for the samples with one pTRM check.

In addition to thermally-induced alteration and MD-type behavior, two other potential sources of bias to palaeointensity experiments are described below.

4.3. Anisotropy of TRM

The manufacturing process of baked archeological materials often results in magnetic anisotropy (Rogers et al., 1979). The effect of anisotropy can be corrected by determining the TRM anisotropy tensor or largely avoided by aligning the laboratory field with the NRM (Aitken et al., 1981; Chauvin et al., 2000; Veitch et al., 1984). In this study, the latter method is used to minimize the anisotropy bias. In addition, if the first step of the protocol is a zero-field step, then the applied field direction is determined according to the zero-field direction. This enables any viscous component to be removed and the applied field will align with the ChRM direction (Böhnel et al., 2003). For the samples in this study, using the original NRM direction would not cause erroneous results since the influence from the viscous remanent magnetization (VRM) is negligible, and has approximately the same direction as the ChRM (Figs. 4 and 5).

4.4. Cooling rate dependence

The difference between the actual cooling time and the laboratory cooling may lead to erroneous results since the blocking temperature of TRM is a function of time (Dodson and laboratory cooling may lead to erroneous results since the influence from the viscous remanent magnetization (VRM) is negligible, and has approximately the same direction as the ChRM (Fig. 4a) indicating that there is no high coercivity mineral like goethite or hematite. Samples from AT-A and AT-C show the presence of only magnetite magnetization (Fig. 4b and d). The thermal decay curves of samples from furnace D show a very slight inflexion around 300 °C (Fig. 4e) similar to that which is observed in the Curie balance curves. This and the observation that the remanence has not been fully removed at 580 °C could indicate a small amount of maghemite in these samples. This may also be consistent with the AF demagnetisations and decay curves of samples from furnace B, where there is a rapid decay until 30–50 mT followed by a gradual decay to the highest fields (100 mT), but there is still some remanence left (Fig. 4c).

5. Results

5.1. Demagnetization and ChRM directions

5.1.1. Arslantepe (AT)

For the furnaces AT-A, AT-C and AT-D, half of the samples were demagnetized thermally and the other half by using alternating fields. AT1 and AT-B were too fragile for thermal treatment, and specimens of these sites were carefully glued into perspex sample holders and demagnetized only by AF. The results are straightforward: a single component decays straight to the origin. Samples from AT1 are completely demagnetized at 100 mT (Fig. 4a) indicating that there is no high coercivity mineral like goethite or hematite. Samples from AT-A and AT-C show the presence of only magnetite magnetization (Fig. 4b and d). The thermal decay curves of samples from furnace D show a very slight inflexion around 300 °C (Fig. 4e) similar to that which is observed in the Curie balance curves. This and the observation that the remanence has not been fully removed at 580 °C could indicate a small amount of maghemite in these samples. This may also be consistent with the AF demagnetisations and decay curves of samples from furnace B, where there is a rapid decay until 30–50 mT followed by a gradual decay to the highest fields (100 mT), but there is still some remanence left (Fig. 4c).

5.1.2. Zeytini Bahçe (ZB)

The samples taken from a mud-brick wall (ZB2) were treated by both AF and TH demagnetization whereas the stratigraphically younger fragile mud-brick pavement (ZB3) was demagnetized only by AF. The demagnetization results are typical of a single component magnetite magnetization (Fig. 4f). Although an inflexion in the decay curve could suggest some possible presence of maghemite, Tc's higher than 580 °C are not observed, while AF demagnetization removes nearly all remanence at 80 mT. The number of successful samples from ZB3 is low: of the 7 cores only 4 survived demagnetization treatment, but a value of $k > 1000$ testifies to the excellent stability of the samples (Fig. 4g).

5.1.3. Ziyaret Tepe (ZT)

The samples taken from a baked brick structure, i.e., kiln-fired mud-bricks used to construct a pavement surrounding the cremation burial (denoted as ‘baked’ in Fig. 4), provide some interesting results. From the 20 cores we were able to take, 10 were either fully or partially heated by the last burning event of the level ('burnt' in Fig. 4) and showed either a 'fully-burnt' and consistent single magnetite component (Fig. 4h), or a 'partially burned' low-temperature component that could be resolved (Fig. 4i). When the mud-bricks were not fully burnt, we were able to determine a high-temperature component that originated from the kiln-firing of the mud-bricks: they typically show random groups of directions in terms of declinations (Fig. 4, ZT baked) according to their original baking position within the kiln. Interestingly, the shallow inclinations of these groups suggest that they were baked in a (near) vertical position.

5.1.4. Salat Tepe (ST)

The site at Salat Tepe yielded burnt samples from a mud-brick wall and travertine foundation stones – with good results (Fig. 4j) – and from its limestone foundation stones with weak and random results (Fig. 4k). Obviously, the limestone foundation stones of the wall were not the ideal carriers of magnetization. The mud-brick and travertine samples, however, gave a consistent well-clustered direction with a high k-value of 525.

5.1.5. Oylum Höyük (OY)

Unfortunately, the samples from the Iron Age kiln (OY1) did not survive laboratory sampling of specimens. From OY2, the 16 specimens we extracted from 4 hand samples gave puzzling results. The demagnetization results are excellent, straight lines going to the origin (Fig. 4l), but the specimens from the 4 hand samples cluster in 3 distinct groups (A, B, C+D, Fig. 4). An
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*Table 3*

The archaeointensity estimates and associated statistics for all samples.

- **Site:** Name of the site
- **n/N:** Number of samples
- **Sample:** Sample number
- **Tr.** and **Pr.:** Treatment and Procedure
- **Field direction:** Field direction
- **Lab field:** Laboratory field
- **$T_{\text{min}}$** and **$T_{\text{max}}$:** Minimum and maximum temperatures
- **$N_{\text{tr}}$:** Number of trials
- **$\beta$, $f$, $g$, and $q$:** Parameters
- **Mad anch:** Madan anch
- **Mad free:** Madan free
- **Drat:** Drat
- **$p_{\text{TRM}}$:** Probability of TRM
- **PI:** Probability Index
- **SD:** Standard Deviation
- **$V\text{ADM} \times 10^{22}$** and **$\Delta V\text{ADM} \times 10^{22}$:** Values of $V\text{ADM}$ and $\Delta V\text{ADM}$
- **Cooling rate:** Cooling rate
- **Remarks:** Remarks on the results

Table 3 (continued)

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<th>Tr., treatment</th>
<th>Pr., protocol</th>
<th>Field direction</th>
<th>Lab field</th>
<th>Paleointensities</th>
<th>Beta Values (IZZI anti-parallel excluded)</th>
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Note: n, number of samples accepted over measured; Tr., treatment; Pr., protocol; Field direction = parallel or antiparallel with respect to samples NRM; MW, Microwave; TT, Thellier and Thellier; Tn, magnetic moment; Tn adj., magnetic moment adjusted; Tn free, magnetic moment unadjusted; Δf, quality factor; MAD (anch.), maximum angular deviation (anchored to the origin); DRat, the difference ratio; γpTRM, number of successful measurement steps; ΔT, difference ratio; γpTRM, number of successful measurement steps.

Fig. 6. Comparison of the results from the two techniques, microwave and thermal Thellier and Thellier, for individual measurements (in diamonds and circles) and for the site means and standard deviations (as histograms). For all sites, the results are in excellent agreement, further supporting the equivalence of the two methods in most cases (Hill et al., 2002). (b–d) One-to-one plots comparing site mean averages of the palaeointensities and β values using different subsets of results. Error bars are one standard deviation.

5.2. Archaeointensity results

Out of 54 measurements, 37 are considered to be reliable and site mean intensities and statistical parameters are reported in Table 3. Representative Arai plots and orthogonal plots from each set are shown in Fig. 5 and the plots from all measurements are presented in Fig. A9. The results from the furnaces (A, C, D) are very consistent and intensities range from 56.3 to 60.6 μT. Only from furnace B all samples except one failed the criteria probably because of their very low initial NRM. The one sample that passed has an intensity of 57.9 μT, but since we cannot calculate a reliable mean, we refrain from plotting this result. Samples from AT1 produced intriguing results with a mean archaeointensity value as high as 100.8 μT. For all the sites, microwave and thermal Thellier results are in excellent agreement, further supporting the equivalence of the two methods in most cases (Hill et al., 2002). Arai plots produced by IZZI experiments generally displayed only minor or no zig-zagging despite the choice of an antiparallel field to exaggerate these effects. Therefore MD-type effects were not considered problematic for these samples. Only one site (AT-D) gave even a modestly different (~14%) mean palaeointensity measurement in the microwave and thermal experiments (Fig. 6b) which further supports our confidence in these results. Though comprising a dataset too small to make robust inferences about the efficacy of the two methods, subtle differences are nonetheless consistent with the conclusions of
Biggin (2010). The β values are marginally higher (indicating more noise in the Arai plots) for the results from the microwave experiments (Fig. 6c) but this difference disappears when the subset of microwave IZII experiments were excluded (Fig. 6d). These measurements are indeed expected to be the noisiest because the lab field was applied antiparallel to the NRM and mostly with a much lower applied field intensity than the palaeointensity. This supports that the specific protocol is more important than the choice of microwaves versus conventional thermal treatments in determining the quality of results (Biggin, 2010).

The results of the cooling rate experiment show a difference of minimum 2% and maximum 10% between TRM1 and TRM2 but TRM1 and TRM3 differ by at least 10% indicating significant alteration. Since we do not have any control on the moment the alteration has started (e.g., it could have been already in the second heating), the cooling rate experiment is deemed inconclusive and no correction is made in the intensity results. Since nearly all samples are in the PSD range, cooling rate effects are likely negligible (Yu, 2011).

6. Discussion and conclusions

6.1. Directions

The directional results from this study, corrected for local declination at the time of sampling, are relocated to Kayseri as the approximate center of Turkey (lat: 38.85°N, long: 35.63°E), and plotted against the data from GEOMAGIA50v2 (countries within ~1600 km radius), the Turkish data (Sarbakudak and Tarling, 1993; Sayın and Orbay, 2003) and the global geomagnetic field models CALS7k.2, CALS3k.4 and ARCH3k_cst.1 at Kayseri (Fig. 7a and b). The Turkish data from the literature are kept ‘as is’ since there is no information as to whether any correction for local declination has been made. The data points with z_{95} > 15° or precision parameter k < 50 are rejected. The original database of Sayın and Orbay (2003) is provided in the Appendix (Table A2).

The declination values of all sites are broadly consistent with CALS7k.2, with the exception of ZB2 and ZB3 which are off to the east by more than 20° (Fig. 7a). The consistency of the two sites – nearly contemporaneous, but from different levels – support the validity of the measured points. In addition, these easterly directions fit well with the records from Sayın and Orbay (2003) and Kovacheva et al. (1998). We note, however, that the number of data points between 2300 and 1500 BCE is very scarce, and the model (CALS7k) therefore is poorly constrained. At present, such a global field model cannot adequately represent small scale but possibly important variations. The swing is relatively small anyway, compared to historical observations which document 60° swings in declination and 20° swings in inclination for the past 4 kyr in the United Kingdom (Zanarini et al., 2007). Nevertheless, it is clear that additional data from this period is required to improve the resolution and to substantiate this easterly swing.

The declination from ZT is far to the west of ARCH3k_cst.1 but within error of CALS3k.4, while the site has very well constrained age but a large error in direction. This larger error is likely the consequence of partial burning of some of the mud-bricks (see Fig. 4), causing fewer points for calculating the best fit line and a partial overlap in blocking temperatures. Once age and inclination uncertainties are taken into account, the inclinations of almost all sites fit with the predictions of the models (Fig. 7b).

We assessed the (near) contemporaneous burning of the furnaces from Arslantepe, by applying a common true mean direction (CTMD) test (McFadden and McElhinny, 1990). We use Monte Carlo simulation, thereby effectively applying the (Watson, 1983) χ² statistic test. We determine γ, the angle between the means, and γ*, the critical angle in the test. If γ < γ*, the test is positive and the distributions share a common true mean direction. The quality of the test is expressed as A, B, C or indeterminate, depending on the value of γ* (McFadden and McElhinny, 1990). Furnaces A and B share a CTMD with classification A (γ*<5°) and furnaces B and C also share an A classification CTMD, whereas A and C do not share a CTMD. Since we know that furnace A is younger than C (it was built on top of C), we may safely assume that furnace B was built between the construction of C (oldest) and A (youngest). Furnace D does not share a CTMD with any of the other furnaces. Since we know the order in which the three furnaces were constructed (from old to young C→B→A), we can deduce a slight steepening trend while declinations become more westerly. We plot the results in stratigraphical (age) order, arbitrarily taking an age difference of 10 yr (older for C and younger for A) with respect to B, and adjust the error bars to fall into the age error of the site. The relative age of furnace D is unknown.

6.2. Archaeointensity

For the period from 3000–0 BCE, archaeomagnetic studies in the Levant and Middle East have provided a series of data with unusually high VADMs up to more than 20 × 10^{22} Am², not observed elsewhere. Periods of rapidly increasing intensities during this time span have been called ‘archaeomagnetic jerks’ (Gallet et al., 2003), with time characteristics intermediate between ‘geomagnetic jerks’ and magnetic excursions, i.e. typically a few hundreds of years. In addition, Shaar et al. (2011) provided a high-resolution archaeointensity curve of the Levant that displays two exceptionally high and very short-lived (< 30 yr) spikes in geomagnetic intensity in excess of 20 × 10^{22} Am². Shaar et al. (2011) argue that their archaeomagnetic record places new constraints on maximum geomagnetic intensity as well as on its rate of change, but concede that it is not yet clear whether the geomagnetic spikes are local non-dipolar features or a geomagnetic dipolar phenomenon.

Our archaeointensity experiments have a success rate of 69% which is remarkably high. The results are coherent between samples and methods and in good agreement with existing data from the Middle East. Although the cooling rate experiment was deemed inconclusive, the agreement between microwave (cooling time of 10–100 s) and thermal Thellier-type experiment’s (cooling time of 10–100 min) results suggest that the cooling rate effects are minimal.

The mean intensity values obtained from three clay furnaces and the mud-brick fortress wall (AT-A, AT-C, AT-D and AT1) were converted into virtual axial dipole moments (VADM). The results are plotted against the Middle East data (Ben-Yosef et al., 2008, 2009; Gallet and Al-Maqdissi, 2010; Gallet et al., 2006, 2008; Gallet and Le Goff, 2006; Genevey et al., 2003; Shaar et al., 2011) and the field models CALS7k.2, CALS3k.4 and ARCH3k_cst.1 (Fig. 7c). The results from the furnaces are coherent with the Middle East data points around ~2500 BCE, and the intensities of furnaces A and C especially are very consistent with one another (10.57 and 10.65 × 10^{22} Am², respectively), in agreement with the directional results and a near-contemporaneous construction of the furnaces. They have slightly higher intensities than the previously published Middle East data and prolong the increasing trend earlier observed by Gallet et al. (2008). They are also significantly higher than CALS7k.2 and the compilation of Genevey et al. (2008). Furnace D, on the other hand, is clearly different from the other two furnaces (VADM of 9.90 × 10^{22}), which is supported by the conclusions from the directional data (Tables 2 and 3).
Our result from mud-brick wall AT1 is in excellent agreement with the data from Ben-Yosef et al. (2009) and Shaar et al. (2011) in the sense of producing a very high mean VADM value of \( \sim 18 \times 10^{22} \text{ Am}^2 \) combined with a date \( (1050 \pm 150) \) placing it potentially in the same age range \( (\sim 1040–860 \text{ BCE}) \) as the Israel-Jordan data. The high quality of the data and the fact that the...
results are obtained using different techniques (microwave and Thellier–Thellier) and that they are coming from a material (mud-brick) different from the copper slag used in the previous studies strengthens the existence of very high intensities during this interval. However, we realize that we seemed to have been 'lucky' to observe an allegedly very short-lived phenomenon (<30 yr, Shaar et al., 2011), considering the large error range of the age (300 yr interval). Alternatively, high intensities may be longer-lived and are perhaps not as transient as suggested. It is difficult to say whether these geomagnetic spikes are possibly local/regional features (Shaar et al., 2011) if reliable and high quality records are not available from elsewhere. And if indeed these spikes are very short-lived, it is statistically unlikely that they are picked up in any record.

Gallet et al. (2005, 2006) correlated the archaeomagnetic jerks with climatic cooling trends obtained from the drift ice index curve of Bond et al. (2001) and speculated on a causal relation between the intensity peaks and the major cooling periods, leading Gallet et al. (2005, 2006) and Courtillot et al. (2007) to argue for a possible connection between Earth's magnetic field and climate. More recent archaeointensity studies on copper slag deposits from Israel and Jordan (Ben-Yosef et al., 2009; Shaar et al., 2011) argued that the field intensity may not only rapidly increase but may also show significant fluctuation at very short time scales (geomagnetic spikes). In Fig. 7c we do not show the periods of the cooling trend (positive first derivative of the Bond et al. (2001) curve), as e.g. in Gallet et al. (2006, 2009), but we follow the suggestion of one of the reviewers (Yves Gallet, pers. comm.) to show the colder periods according to the same index, where the intervals are determined by arbitrarily taking an index value higher than 6 percent. For details on ages of cooling trends and colder periods, see Fig. A10 (Supplementary information).

Our new results from the furnaces at Arslantepe (~2500 BCE) fill in a data gap in the results obtained by Gallet et al. (2006) in which they originally suggested a decrease in geomagnetic intensity. However, after the cooling trend from ~2950 to 2630 BCE associated with a geomagnetic intensity increase from approximately 7 to 10 × 10^(-22) Am^-2, our data show a prolonged (by a century, to 2525 ± 35 BCE) trend to higher values (10.7 × 10^(-22) Am^-2) and plot on the graph with an intensity peak exactly between two cooling cycles. However, if we consider not the cooling cycle but the colder period (~2780–2480 BCE), it appears that the interval of higher and increasing intensities matches very well. We also note that the period of high intensities in the Middle East data (~1040–860 BCE) correlates well – within age errors – with a colder period (1055–805 BCE). Also the interval of increasing intensities 1450–1225 BCE seems to agree quite well with a colder period (1495–1215). On the contrary, no such relation is seen between intensity and climate in the colder period 2295–1965 BCE: instead, intensities are decreasing during this period. The presently existing dataset for the Middle East thus raises a number of important questions that seriously require confirmation.

Acknowledgments

We are grateful to the teams of the archeological sites who were at all times very helpful. In particular, we thank Francesca Balossi at Zeytini Bahe for her help.

Yves Gallet provided a manuscript with relevant data, while he and an anonymous reviewer provided critical comments that greatly helped to improve the original manuscript. Nurettin Kaymakci has been an indispensable help in the field, carefully and unrelentingly drilling with expertise the fragile archeological material. The late Tom Mullender has been indispensable for his help in the laboratory and his never-ending interest and support.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2012.08.039.

References


