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Physics of the Earth and Planetary Interiors 151 (2005) 155–162

PHYSICS OF THE EARTH AND PLANETARY INTERIORS

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Archaeomagnetic results from southern Italy and their bearing on geomagnetic secular variation

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Received 22 October 2004; received in revised form 31 January 2005; accepted 18 February 2005

Abstract

Archaeodirectional results from kilns and other baked structures in southern Italy are presented. They are generally compatible with the much larger data sets from France and Bulgaria. In particular, a summary of all the results associated with the well-known eruption of Vesuvius that destroyed Pompeii ($n = 9$, $D = 355°$, $I = 58°$, $\alpha_{95} = 1.5°$) provides a reliable archaeomagnetic anchor point supporting the French and Bulgarian master curves. It is extremely well-constrained in time and it comprises independent studies carried out in four different countries. Furthermore, it is derived from a diverse set of features agreement amongst which argues strongly against significant perturbations due to magnetic refraction, structural disturbance, or depositional shallowing. In terms of geomagnetic secular variation, we interpret the western European archaeomagnetic data summarized here in terms of an open loop caused by westward drift, followed by an inclination low spanning the first few centuries CE representing the signal of a static flux pulse that reaches a maximum magnetic moment of a few percent of the earth's main central dipole.

Keywords: Archaeomagnetism; Secular variation; Italy; Vesuvius

1. Introduction

Archaeomagnetic investigations have played – and continue to play – a central role in revealing the long-term behaviour of the geomagnetic field. In France, for example, the subject has reached an advanced stage (Thellier, 1981; Bucur, 1994), and the recent addition of six new data in the first millennium BCE now means that the secular variation curve is reasonably well-constrained for the last 3000 years (Gallet et al., 2002). By contrast, the situation in Italy is far less advanced. Despite the fact that archaeomagnetic investigations were already being carried out in Rome more than a century ago (Folgerhaiter, 1899), there are currently very few published data points derived from dated archaeological features. There are, however, many results based on volcanic material spanning the last two millennia, particularly from Vesuvius and Etna (Hoye,

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0031-9201/$ – see front matter
doi:10.1016/j.pepi.2005.02.002

1981; Incoronato et al., 2002; Tanguy et al., 2003). Although the dates of significant eruptions are usually well-known from historical records, it is often difficult to identify in the field the actual eruptive products of specific events. This means that many excellent results have no independently confirmed age. In this paper, we report directional results from dated archaeological structures (mostly kilns) in southern Italy and discuss their geophysical significance.

2. Methods and results

The locations of the archaeological features we have investigated are shown in Fig. 1. Most of them are kilns (24 out of 31) but burnt walls, funeral pyres, volcanic pyroclastics, an iron smelter, and an oven are also represented (see Table 1). Samples were collected either by drilling or by bonding small plastic squares onto the surface of the item under investigation, orientation being by means of solar bearings and bubble inclinometer. In the laboratory, measurements of remanent magnetizations were made on commercial spinner magnetometers and stability was tested by standard thermal and alternating field (AF) demagnetization procedures. Thermal demagnetization curves exhibit a range of behaviour with some samples having narrow blocking-temperature spectra and others exhibiting a much wider spread (Fig. 2). The dominant mineral species is magnetite and/or titanomagnetite: there is no evidence of significant contributions from hematite. This is borne out by isothermal and thermomagnetic measurements (Fig. 3). For the most part, therefore, we tested stability by means of progressive AF demagnetization: it is quicker and it avoids the risk of mineralogical alteration during laboratory heating. Generally, only one or two AF steps were needed to obtain a well-grouped site mean, but a few samples were demagnetized further to check the median destructive field (MDF) values. Seven samples, from six different sites, yield 16 mT < MDF < 22 mT, again indicating the dominance of magnetite and/or titanomagnetite. Examples of demagnetization behaviour are illustrated in Fig. 4. Often, a small (viscous) component of magnetization is removed in the early stages but thereafter the magnetization decays univectorially to the origin. The majority of samples show this kind of behaviour and yield unambiguous remanence vectors that collectively provide reliable site mean directions. The few exceptions will be discussed individually as they arise.

The site mean directions obtained and their associated statistics are summarized in Table 1. Three results (6, 9, and 11) are statistically random. At Heraclea (6), the structure investigated appeared to be an excellent

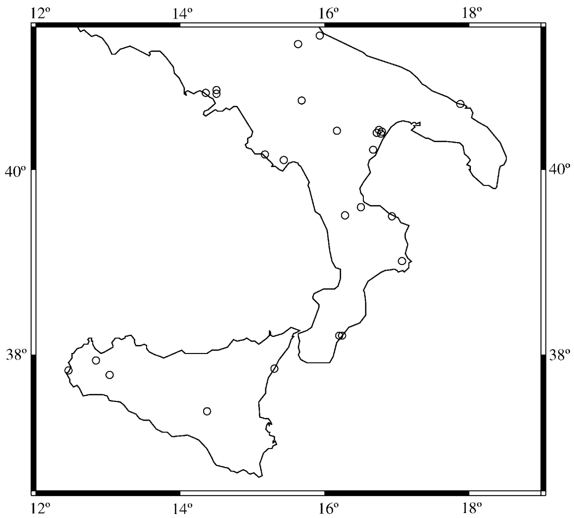

Fig. 1. Sketch map showing the locations we have sampled.

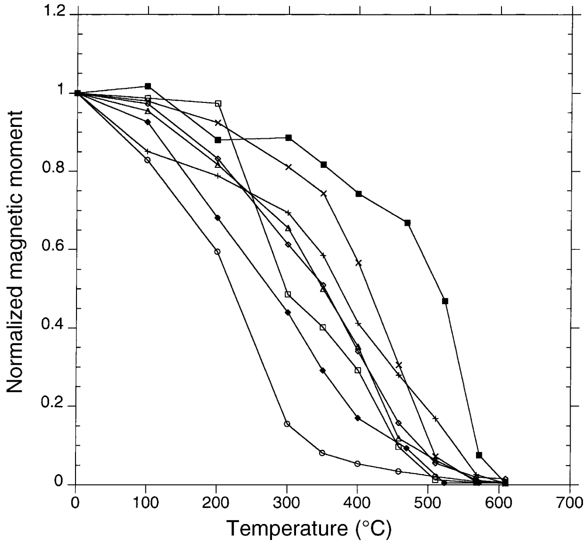

Fig. 2. Thermal demagnetization curves showing the wide range of blocking-temperature spectra and the absence of significant hematite contributions. Symbols correspond to numbered entries in Table 1 as follows: triangle, 3; plus sign, 7; cross, 10; open square, 12; closed diamond, 16; circle, 20; open diamond, 22; closed square, 27.

Table 1
Summary of archaeomagnetic directions

Feature	Latitude	Longitude	Chronology	Date	Dec	Inc	N	k	a95	A.S.E.
1. Salapia[a]	41.41	15.93	−900/−700	−800	7.1	63.5	10	121	4.4	2.5
2. Naxos[a]	37.85	15.30	−575/−525	−550	5.6	60.3	7	1233	1.7	1.0
3. Metaponto (Tempio)	40.42	16.75	−550/−500	−525	0.6	66.4	10	711	1.8	1.0
4. Poggioreale[a]	37.48	13.02	−500/−430	−465	4.3	60.7	6	293	3.9	2.3
5. Locri[a](A)	38.21	16.24	−500/−400	−450	0.7	61.3	9	98	5.2	3.0
6. Heraciea[a]	40.21	16.67	−400/−350	−375	–	–	–	–	–	–
7. Motya (#3)	37.83	12.50	−400/−350	−375	352.2	61.3	7	737	2.2	1.3
8. Sant'Angelo Grieco[a]	40.40	16.79	−400/−300	−350	3.2	63.4	10	273	2.9	1.7
9. Metaponto[a] (pyre)	40.42	16.75	−400/−300	−350	–	–	9	7	–	–
10. Metaponto (Kerameikos)	40–42	16.75	−350/−325	−338	347.0	62.0	12	251	2.7	1.6
11. Roccagloriosa[a] (pyre)	40.10	15.43	−350/−300	−325	–	–	7	4	–	–
12. Bisignano[a]	39.51	16.28	−350/−250	−300	9.4	64.3	10	333	2.7	1.6
13. Locri[a] (B)	38.21	16.24	−300/−250	−275	358.5	58.6	7	807	2.1	1.2
14. Velia[a]	40.16	15.17	−300/−250	−275	355.6	60.2	8	271	3.4	2.0
15. Metaponto (Insula)	40.42	16.75	−300/−250	−275	348.7	61.4	8	499	2.5	1.4
16. Sant'Angelo Vecchio	40.39	16.72	−200/−100	−150	358.3	57.9	13	617	1.7	1.0
17. Ordona[a]	41.32	15.63	−150/−50	−100	4.8	63.0	60	115	1.7	1.0
18. Metaponto[a] (iron smelter)	40.42	16.75	−200/0	−100	353.1	58.0	11	120	3.9	2.3
19. Bassento Destra[a]	40.41	16.17	−200/0	−100	353.6	61.5	10	652	1.9	1.1
20. Apani	40.72	17.90	−100/−50	−75	356.7	58.0	7	1203	1.7	1.0
21. Morgantina[a]	37.38	14.37	−100/0	−50	5.1	60.0	5	188	4.6	2.7
22. Capocolonna[a]	39,02	17.07	−80/20	−30	357.1	59.8	10	980	1.5	0.9
23. Pizzica[a]	40.38	16.78	−50/50	0	356.4	51.4	14	367	2.1	1.2
24. San Giovanni	40.73	15.68	0/100	50	350.5	58.8	106	232	0.9	0.5
25. Pompeii[a]	40.80	14.50	79	79	355.0	59.1	13	581	1.6	0.9
26. Herulaneum	40.81	14.35	79	79	351.9	57.0	20	212	2.2	1.3
27. Sibari	39.60	16.50	300/400	350	0.3	55.1	10	224	3.2	1.9
28. Segesta[a]	37.94	12.83	300/500	400	359.9	63.3	5	769	2.8	1.6
29. Ottaviano[a]	40.84	14.50	472	472	357.5	58.2	5	260	4.8	2.8
30. Santa Maria[a]	39.50	16.93	400/600	500	359.4	57.6	6	318	3.8	2.2
31. Ruoti[a] (F446)	40.73	15.68	460/540	500	0.6	58.1	16	67	4.2	2.4

Notes: all the results tabulated here were obtained at the University of Alberta Petromagnetism Laboratory. All but seven come from kilns, the exceptions being numbers 4 (burnt walls), 9 and 11 (funeral pyres), 18 (iron smelter), 26 and 29 (pyroclastics), and 31 (oven). Dates used for plotting Figs. 5 and 6 are the mid-points of the ranges given by the available archaeological evidence as summarized in the "chronology" column; positive (negative) dates are CE (BCE). Results from the volcanic products of Vesuvius (26 and 29) have precise dates. Dec: declination in degrees measured clockwise from north; Inc: inclination in degrees below the horizontal; N = number of independently oriented samples; k: Fisher's precision parameter; a95: semi-angle of the cone of 95% confidence; A.S.E.: angular standard error of the mean (both in degrees).

[a] Previously unpublished or newly updated results.

in situ kiln. However, closer inspection during sampling revealed a great deal of modern cement indicating that the structure had been considerably restored. The general form of the kiln is no doubt correct, but the actual re-assembly evidently incorporated numerous misplacements; some bricks even had stable negative inclinations suggesting that they had been inverted during reconstruction. This is a hazard that is perhaps rare for an entire collection from an archaeomagnetic structure, but it may explain the odd widely discordant vector that is occasionally found at otherwise well-behaved sites.

Results 9 and 11 come from cremation pyres that we were asked to investigate by way of feasibility studies. In both cases, all bones and ash had been removed during excavation. The wide dispersion of the directions obtained suggests that the underlying bedrock that we sampled had not been sufficiently heated to acquire a coherent thermoremanence. This is consistent with the observations of Canti and Linford (2000) who deployed buried thermocouples to monitor the heat flux under experimental fires and found that significant heating does not penetrate deeper than a few centimetres.

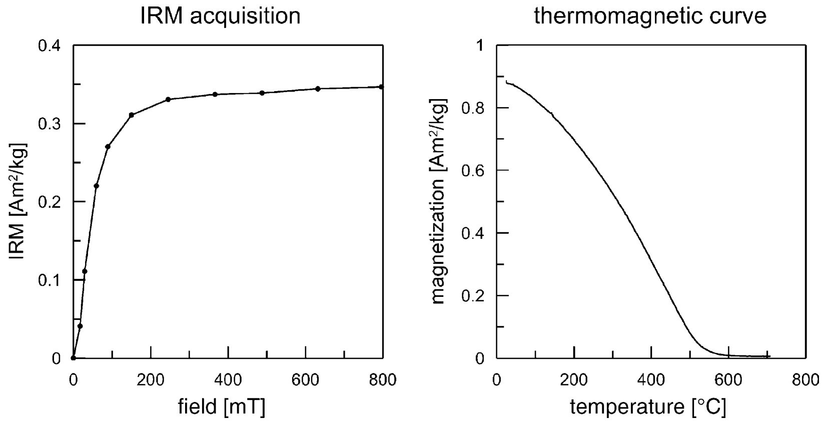

Fig. 3. Isothermal remanence and thermomagnetic curves for a baked brick sample from Pompeii. A Curie point of 530 °C is derived by the method of Moskowitz (1981), indicating a titanomagnetite composition of $Fe_{2.91}Ti_{0.09}O_4$. Hysteresis parameters were also determined: $M_{rs}/M_s = 0.39$ and $B_{cr}/B_c = 2.06$, suggesting that single-domain grains are dominant. Measurements were made on a variable field translation balance.

The remaining sites yield good results, with a mean value of 448 for the Fisher precision parameter (k). However, two structures (18 and 31) yielded initially scattered directions that did not improve during demagnetization. Rather, their demagnetization trajectories yielded the diverging paths indicative of magnetic overprinting caused by modest heating to temperatures significantly lower than the Curie point. The samples at site 18 come from a structure thought to have been used for smelting iron. In retrospect, it appears that we took our samples at some distance from the main furnace (which could not be identified among the partially preserved remains). To obtain the site mean, we used the well-known method of Bailey and Halls (1984), which extracts the underlying Fisherian statistical parameters from the intersection pattern of the great circles defined by the demagnetization trajectories. Site 31 (feature F446 in the villa at San Giovanni di Ruoti described by Small and Buck, 1994) is a simple kitchen oven made from re-used tile fragments surrounded by several large field stones. The floor tiles were previously studied by Evans and Mareschal (1986), to whose data we have now added six remanence vectors obtained from the field stones.

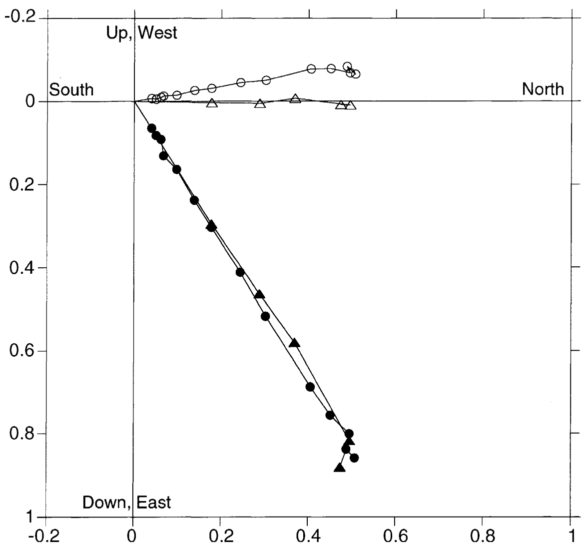

Fig. 4. Two examples of orthogonal vector plots obtained from stepwise demagnetization. Circles represent AF treatment of a sample from site 25: steps are 0, 2.5, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 140, and 180 mT. Triangles represent thermal demagnetization of a sample from site 31: steps are 20, 100, 200, 250, and 300 °C. Closed (open) symbols are in the vertical (horizontal) plane. Values are normalised to the total NRM.

3. Discussion

Since the Italian database is still rather sparse, we discuss the results summarized in Table 1 by comparing them to the excellent – and much more numerous – data from France. To make this comparison, allowance must be made for the geographic separation of the sampling sites. There has been considerable discussion of this problem, but most practitioners agree that the so-called VGP method gives the best results. The procedure is first to calculate the virtual geomagnetic pole (VGP) corresponding to the archaeomagnetic direction observed at a site and then to calculate the corresponding magnetic field direction at the chosen reference location. A recent example – germane to the present discussion – is that described by Tanguy et al. (2003) who use this procedure to transfer the French Archaeological Magnetic Curve (FAMC) to the coordinates of Mount Etna in order to compare it to their south Italian volcanic curve (SIVC). There is, of course, doubt concerning the geographic extent over which the VGP method can be employed, but a posteriori the results of Tanguy et al. suggest that the distance from Sicily to Paris is not too great. Our experience is the same, as will become evident shortly, but first it is perhaps worth pointing out that the alternative procedure of reducing the observations to a common reference location on the assumption of a geocentric axial dipole (GAD) field makes very little difference. The inclination adjustments obtained from the two methods differ by more than 1.5° in only two cases (2.3° and 2.4°). For declinations, there are three cases where the adjustments obtained from the two methods differ by more than 3° (3.1°, 3.9°, 4.1°), the discrepancies being larger because of the greater sensitivity of declination changes at steep inclinations (at 60° – typical of our observations – this amounts to a factor of 2, i.e. 1/cos 60°). The overall message is that the VGP method is preferred, but that the precise procedure used to allow for geographic spread is not critical. In what follows, we discuss only the VGP-corrected data.

Looking first at the inclination plot (Fig. 5), we see that the Italian data (open circles) are in good agreement with the French data (all the other symbols) and improve the coverage of the first millennium BCE. The two most divergent results are from Pizzica (23) and Segesta (28), dated at 0 and 400 CE, with I (Paris) = 60.5° and 70.3°, respectively. In both cases, the magnetic results favour dates some two or three centuries younger than those currently suggested, but it remains to be seen if the archaeological evidence can accommodate such revisions. Further archaeomagnetic study might also help, particularly at Segesta where limited time allowed us to collect only five samples. As it happens, Màrton et al. (1992) have independently studied this kiln (although, at the time, neither team

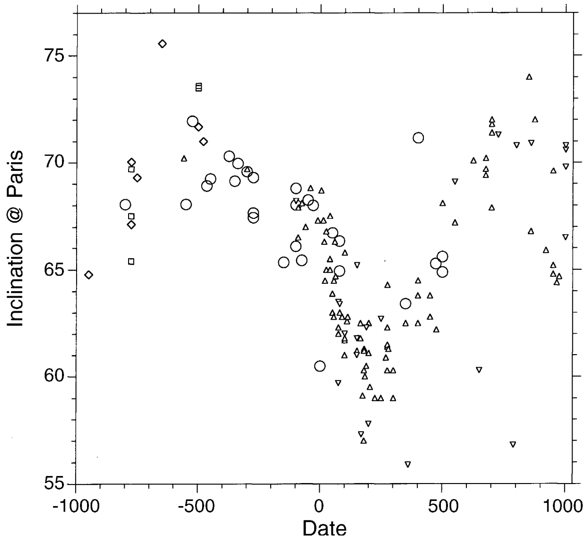

Fig. 5. Inclination magnetogram of Italian (◯) and French data (diamonds from Moutmir (1995), squares from Gallet et al. (2002), and triangles from Bucur (1994)). The inverted triangles were excluded by Bucur due to age uncertainties or because they represent “abnormal values”. The Italian data have been transferred to Paris by the VGP method (see text). Negative dates refer to years BCE.

knew of the other’s work) and obtain a result that is statistically indistinguishable from ours. Combining their eight samples with our five yields $D = 1.2°$, $I = 62.4°$, $k = 316$, and $\alpha_{95} = 2.2°$ (this is the result plotted in Fig. 5). Nevertheless, in view of the problems associated with the Pizzica and Segesta results, they should be used with caution. Indeed, Bucur (1994) classifies such points as “abnormal values” and omits them entirely from the French secular variation curve (examples are the three low-inclination values in Fig. 5 dated 360, 650, and 790 CE).

Turning now to the declination data (Fig. 6), we see broad consistency between the Italian and French data, but prior to zero there is considerable scatter. As far as the Italian data is concerned, the three main problems are the easterly declinations of results 12, 17, and 21 (Bisignano, 300 BCE; Ordona, 100 BCE; Morgantina, 50 BCE: D (Paris) = 13.5°, 6.5°, and 7.3°, respectively). Bisignano is poorly dated and at Morgantina, we were only permitted to remove five small samples, which leads to a large cone of confidence, but Ordona is a puzzle. It is well-dated and thoroughly studied (60 independently oriented samples; it is a very large kiln!). In view of these difficulties, we adopt the cautious ap-

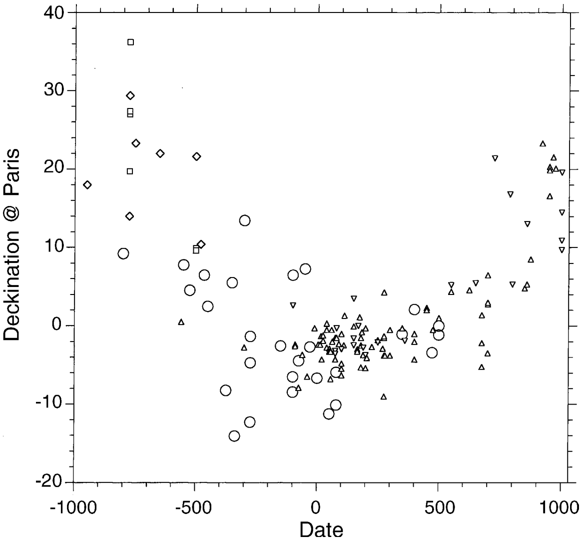

Fig. 6. Declination magnetogram. The symbols are the same as in Fig. 5.

proach of giving less weight to these three results. The Italian data then suggest a small westerly swing culminating at about 300 BCE, following naturally from the strong easterly swing suggested by the French data. As Gallet et al. (2002) point out, the most extreme declination they obtained came from a hearth that had been disturbed by the emplacement of a post. Nevertheless, they show that the swing is supported by the British lake sediment data (Turner and Thompson, 1982). We return to this point below in connection with a broader assessment of European secular variation.

A particularly important set of results relates to the famous Plinian eruption of Vesuvius in 79 CE. Our first result (Evans and Mareschal, 1989) from Pompeii was obtained from nine samples collected from a well-preserved kiln in an oil-lamp workshop near the Porta Nocera. To these, we can now add data from four samples collected from another kiln in Pompeii near the Porta Ercolano to obtain the combined result given in Table 1. This modification is minor, but coherent data from two kilns provides extra confidence in the overall reliability. Further support is provided by Zanella et al. (2000) who obtain what they refer to as a pictorial remanent magnetization from the hematite-based red paint used in mural paintings at the Stabian Baths in Pompeii. Although their result lies more than 3° from our kiln average, the severe demands of their technique generally lead to more scatter than is usually found in archaeomagnetic work. In the case of the Stabian Baths, $k = 40$ and $\alpha_{95} = 5.5°$, so their error cone easily encompases our kiln result. In addition to these two results from Pompeii, there are now seven published archaeomagnetic results from the volcanic products that engulfed Herculaneum during the disaster. Six of them are summarized by Zanella et al. (2000), to which we now add the excellent result of Tanguy et al. (2003). Combining all these leads to a grand overall mean of $D = 355.0°$, $I = 58.0°$, $n = 9$, $k = 922$, $\alpha_{95} = 1.5°$. This represents one of the best archaeomagnetic results available — it is extremely well-constrained in time and it comprises independent work from four laboratories (in Canada, France, Italy, and USA). Furthermore, it involves magnetic vectors derived from thermoremanent magnetization (TRM) in kilns, from partial TRM (pTRM) in lithic fragments (of various compositions) embedded in pyroclastic flows, from depositional remanence (DRM) in the encompassing pyroclastic flows, and from pictorial remanent magnetization (PiRM) in mural paintings. The agreement observed between these diverse sources argues strongly against significant distortion by any of the mechanisms that have been put forward from time to time (e.g. magnetic refraction due shape and/or fabric anisotropy, depositional inclination shallowing, and structural problems such as kiln wall fall-out).

A persistent problem in archaeomagnetic work is that of chronology. In Figs. 7 and 8, the Vesuvian result is compared to the secular variation curves for France and Bulgaria. There is at least one fixed point where the three independent data sets are in excellent agreement! For the first millennium CE, the French and Bulgarian curves are in phase and during the first half of the millennium, they are characterised by a prominent inclination minimum that involves no significant declination change. This feature has been recognised since the seminal work of Emile Thellier and is clearly visible on published declination–inclination plots (e.g. Fig. 1 of Gallet et al., 2002). We interpret it as the signature of a so-called static flux bundle (Bloxham and Gubbins, 1985) (or standing anomaly (Yukutake and Tachinaka, 1969)). In the present case, a shallowing of the inclination by some 12° is observed (see Figs. 5 and 7). Data from a single site cannot yield a unique solution, but a simple model indicates that this is readily explained by perfectly acceptable parameters. For example, a flux patch vertically beneath the site can be

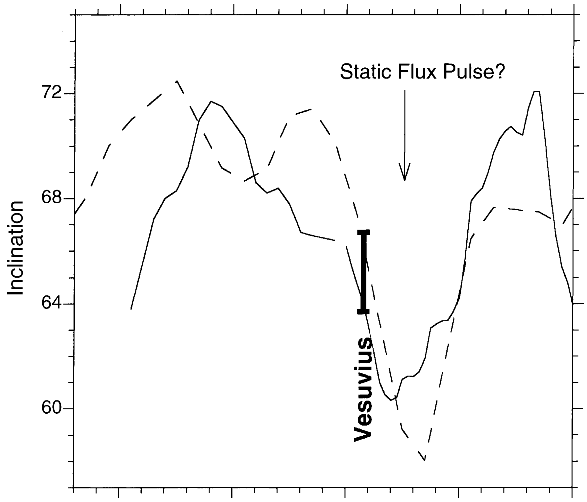

Fig. 7. Comparison of the Vesuvius 79 CE combined inclination result (see text) and its 95% error limits with the smoothed French (—) (Daly and Le Goff, 1996; Gallet et al., 2002) and Bulgarian (- - -) (Kovacheva et al., 1998) secular variation curves. All data have been corrected to Paris using the VGP method.

modelled as a small dipole just inside the core. The curves of Figs. 7 and 8 can then be explained as the signal of such a source that, starting about zero CE, grows to a maximum radially outward strength about 3% of that of the earth's central dipole before decaying away over the next few centuries. Such an outward (reversed flux) source will reduce the amplitude of the net field at the site and this is hinted at by the (extremely sparse) archaeointensity data available from Italy. A third century BCE kiln yields an ancient field value of 80 μT, whereas three others from the first century CE (one of them Pompeii) yield values in the range 68 ± 7 μT (Evans, 1986, 1991). This tentative conclusion based on Italian data is put on a firmer footing by the much more extensive Bulgarian results. These indicate a pronounced minimum (62 μT, following a peak of 83 μT) spanning the first half of the first millennium CE (see Fig. 9 of Kovacheva et al., 1998).

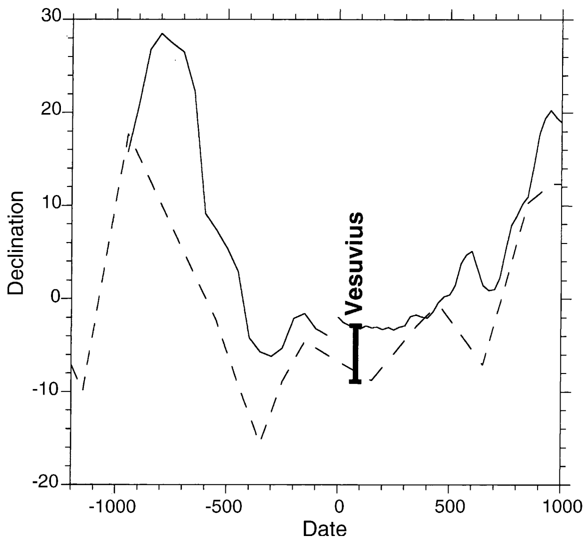

Fig. 8. Declination plot corresponding to Fig. 7.

Prior to the establishment of the standing anomaly proposed above, the French and Bulgarian curves are not in phase. But in the early part of the first millennium BCE they are consistent with westward drift. Following Runcorn's Rule (Runcorn, 1959), this would give rise to a clockwise secular variation loop as, indeed, is seen in the French data (see Fig. 1 of Gallet et al., 2002).

4. Concluding remarks

Compared to the extensive results from France and Bulgaria (gathered over several decades), the Italian data are still rather sparse. Nevertheless, the three sets of results are mutually compatible and are critically confirmed at least at the one fixed cornerstone provided by the 79 CE data garnered from various volcanic and archaeological elements at Pompeii and Herculaneum. Over western Europe during the first millennia BCE and CE, geomagnetic field behaviour can be described – in a nutshell – as a loop and a low. First the clockwise loop so clearly defined by Gallet et al. (2002) due to westward drift (similar to historical observations covering the last 400 years), followed by an inclination low due to a pulse from a static flux bundle (rather like the one currently under Mongolia, but with the opposite sign).

Acknowledgements

Financial support from the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged. We are indebted to David Krása of the Institut für Geophysik, Ludwig-Maximilians-Universität, Munich for essential help in acquiring the variable field translation balance data of Fig. 3. This paper is dedicated to the memory of Marianne Mareschal, whose unfailing support and cheerful collaboration was a constant source of inspiration.

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