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▶ **To cite this version:**

Evdokia Tema, Ian Hedley, Philippe Lanos. Archaeomagnetism in Italy: a compilation of data including new results and a preliminary Italian secular variation curve. Geophysical Journal International, 2006, 167 (3), pp.1160-1171. 10.1111/j.1365-246X.2006.03150.x . insu-00266626

HAL Id: insu-00266626
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Submitted on 6 Jul 2017

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Geophys. J. Int. (2006) **167,** 1160–1171 doi: 10.1111/j.1365-246X.2006.03150.x

Archaeomagnetism in Italy: a compilation of data including new results and a preliminary Italian secular variation curve

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Accepted 2006 July 20. Received 2006 July 19; in original form 2006 March 13

SUMMARY

Published Italian archaeomagnetic data are combined with new data from the Genève and Torino laboratories. A total of 74 directional data is presented with age estimates falling between 1300 BC to 1600 AD, including results from volcanic deposits of unquestionable age. The data set has been analysed using the Bayesian stochastic approach for curve building to produce a preliminary Italian secular variation (SV) curve. Comparison with the French SV curve shows a general agreement but some significant differences are also observed. The new Italian SV curve can be used for archaeomagnetic dating of Italian artefacts, even though caution must be paid for the period 9th–12th century AD and times older than 8th century BC, when only few data are available and error envelopes are large.

Key words: archaeomagnetism, Bayesian statistics, Italy, secular variation.

INTRODUCTION

During the last few decades archaeomagnetic studies have attempted to establish the variation of the Earth's magnetic field prior 16th century, when the earliest direct measurements started. Although Italy has a rich archaeological heritage, Italian archaeomagnetic data are still sparse in comparison to those of other countries where the quantity and quality of archaeomagnetic data allow the construction of reliable secular variation (SV) curves; e.g. France (Thellier 1981; Bucur 1994; Gallet *et al.* 2002), Bulgaria (Kovacheva 1997), United Kingdom (Clark *et al.* 1988; Tarling & Dobson 1995; Batt 1997), Hungary (Márton 1996, 2003; Márton & Ferencz 2006) and Germany (Schnepp *et al.* 2004; Schnepp & Lanos 2005). Clearly the acquisition of new data from Italian sites is needed to enrich the Italian database and to establish a SV curve for Italy before 1640 AD, when Athanasius Kircher made the first direct measurement of both declination and inclination of the Earth's field in Rome (Cafarella *et al.* 1992).

This paper presents 28 new directional results from archaeological sites in Italy (Fig. 1) that have been investigated in recent years by the Torino and Genève laboratories. They have been added to a compilation of the existing Italian archaeomagnetic data and a preliminary SV curve derived by Bayesian statistical modelling is proposed.

NEW ARCHAEOMAGNETIC RESULTS

Torino laboratory

During the last 2 yr, samples have been collected from three sites in southern Italy (Vagnari, Ascoli Satriano, Canosa—Nos. 24, 25 and 15, respectively, Table 1) and two in central Italy (Foro Traiano situated in the centre of Rome—Nos. 3 and 14, Table 1). In all cases the material sampled consists of bricks and tile fragments collected *in situ* from the main structure of the kilns (Fig. 2). Hand samples were oriented in the field using an inclinometer and both magnetic and sun compass whenever possible. In the laboratory the samples were cut into cylindrical specimens of standard size (diameter = 25.4 mm, height = 22 mm). For all structures a well-constrained age was available based on archaeological evidence.

All magnetic measurements were carried out at the palaeomagnetic laboratory of Torino. The natural remanent magnetization (NRM) was measured for all specimens using a JR-5 spinner magnetometer and the characteristic remanent magnetization (ChRM) was isolated using both thermal and alternating field (AF) stepwise demagnetization. The demagnetization diagrams (Fig. 3) for all the structures studied show the presence of only one very stable component of magnetization with no or very minor secondary components of probably viscous origin that are easily removed at low temperature ($<200^{\circ}$C) or in weak applied field (<20 mT). The ChRM is well defined and can be taken as representative of the primary remanence acquired during the last firing of the structure. As a standard routine, three specimens were stepwise demagnetized from each independently oriented sample and their ChRM directions were obtained by principal component analysis using the PaleoMac program (Cogné 2003). They were used for the calculation of the sample's and subsequently the site's mean direction using Fisher statistics (Fisher 1953).

Magnetic mineralogy was investigated by isothermal remanent magnetization (IRM) measurements (Fig. 4a) and thermal demagnetization of IRM components (Lowrie 1990) (Fig. 4b). In most cases saturation is reached in low fields (200–300 mT) and almost

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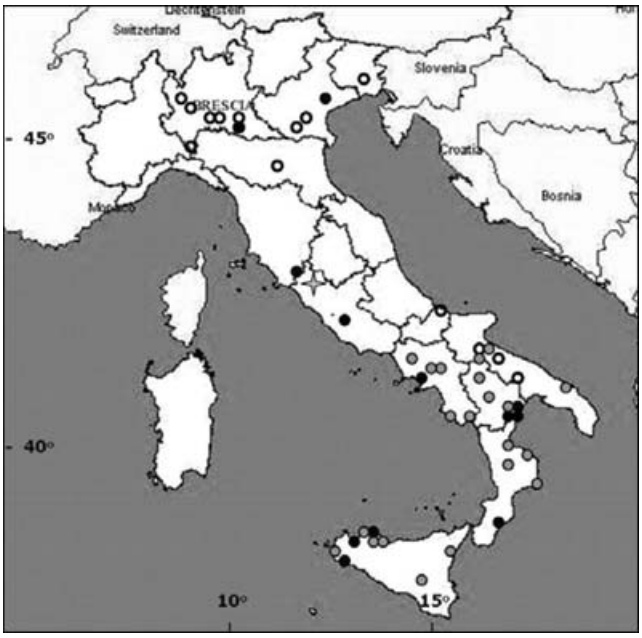


Figure 1. Locations of Italian archaeomagnetic sites. Symbols: open dot = new site studied in the present paper; full dot = site from literature: black dot = site where more than one independent structure have been studied, grey dot = one structure studied; grey star = Viterbo reference site.

all magnetization is erased at temperatures between 520–580°C, indicating a soft, low-coercivity mineral as the dominant remanence carrier; accordingly a magnetite near mineral with impurities or maghemitization.

Genève laboratory

As part of an on-going research project in archaeomagnetism 23 burnt structures have been sampled in Italy over a period of 12 yr. They consist mainly of hearths and kilns.

At the first site (San Vincenzo, Galliano—No. 12, Table 1) large samples were taken (6 × 6 × 4 cm) moulded in plaster of Paris, but subsequent structures were sampled using the glued plastic disc method established by Clark *et al.* (1988). The remanence of the resulting small (18 mm diameter) cylinders of baked clay was measured using a Digico/Minispin fluxgate magnetometer. In the case of three of the large kilns (Massinigo and Carlino—Nos. 74 and 19, 20, Table 1) pieces of tiles were taken, which were later cored to give standard 25 mm diameter cylinders. In calculating the mean direction for the entire kiln the hierarchy of specimens from samples was maintained. All samples were oriented in the field using a magnetic compass and an electronic inclinometer, and wherever possible the orientation was also checked with a sun compass. Most specimens were subjected to a viscosity test (Thellier & Thellier 1959) and some of the structures were treated using AF or partial thermal demagnetisation. The Thellier type viscosity test consisted of inverting the specimen with respect to its original orientation in the field and leaving it for one month in the laboratory field. Specimens that changed their remanence more than 10 per cent were rejected.

A description of the archaeological structures studied is given in the appendix.

ITALIAN ARCHAEOMAGNETIC DATABASE

Evans & Hoye (2005) have recently published a summary of the archaeomagnetic investigations they carried out in Italy over the last 20 yr. This included 29 sites from southern Italy and is the only systematic account in the literature. Around 10 other papers dealing with single sites have been published by various authors in a variety of national and international journals. Other data are still confined to excavation reports.

The present paper presents a total of 74 directional results from archaeological material (Table 1) derived from a systematic compilation and supplemented by the new results presented in the previous section. The table includes:

(1) Site name and geographical coordinates. The coordinates, when missing in the original publication, refer to the town or village nearest to the archaeological site. The location error is no more than few kilometres and is negligible in relocating the data to the reference site. The geographical distribution of the sites (Fig. 1) shows that they are concentrated in southern Italy, whilst central and northern Italy are only poorly represented. In fact, no data from northern and central Italy have been published previously.

(2) The age of the sampled structure, mainly based on archaeological evidence. Only four thermoluminescence and three ^{14}C ages are available; all of them from the new sites. From the age uncertainty of each structure, a mean age was calculated that is used as the time coordinate to draw the declination and inclination plots. Data from a few sites with uncertain or no age have also been included; these do not contribute to the SV curve, but could be useful for future studies.

(3) Type of material studied. In most cases this was kilns, furnaces, and *in situ* fragments of tiles and bricks from fired structures. In some cases mural paintings or small hearths have also been studied. The results from sets of bricks, which only give the inclination value, have also been included in Table 1. A structure/context number is included when available.

(4) Number of independently oriented samples, N . The number of specimens measured from each structure (n) is given within brackets. However, in the majority of the original papers information regarding the distinction between specimens/ samples is not clear or even lacking.

(5) The technique used to derive the archaeomagnetic direction, usually AF or thermal stepwise demagnetization. In some cases only NRM measurements and Thellier viscosity tests (Thellier & Thellier 1959) have been performed.

(6) The site mean archaeomagnetic direction (D, I), together with the values of the α_{95} and k parameters of Fisher's statistics, and the direction relocated to the Italian reference station at Viterbo (D_r, I_r). Relocation was performed using the virtual geomagnetic pole (VGP) method (Noel & Batt 1990) in which the site D, I values are used to calculate the VGP position (inclined geocentric dipole) and the VGP is then used to calculate the relocated values to a common reference point, in this case D_r, I_r. Lanza & Zanella (2003) proposed a point near Viterbo (lat. 42° 27′N, long. 12° 02′E) as the most suitable reference site for Italy, as it gives the smallest relocation error both in D and I (less that 1°), wherever the original site is situated in Italy.

(7) The original reference.

In additional to the archaeological remains, the Italian active volcanoes can contribute to the SV curve, particularly when the eruptions are described in written sources; the most famous being the two

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Table 1. Italian archaeomagnetic directions from archaeological sites.

No.	Site	Lat (°)	Long (°)	Age (years)	Mean Age	Method	Material	Code	(n)	N	Treatment	D (°)	I (°)	α_{95}(°)	k	D_r (°)	I_r (°)	Reference
1	Rome, Bibliotheca Apost.	41.90	12.45	1610–1615 AD	1612	A	Mural painting	D- Paul	(10)	10	AF	0.8	67.4	2.4	414	0.9	67.8	Chiari & Lanza (1999)
2	Castelseprio	45.72	8.85	1506–1574 AD	1540	A	Hearth	US1020		7	Tv	7.8	59.0	3.1	365	7.9	56.3	this study
3	Rome, Foro Traiano	41.90	12.45	1480–1520 AD	1500	A	Kiln		(33)	11	AF, Th	359.0	62.4	2.8	258	359.0	62.9	this study
4	Dosso Castello, Cremona	45.13	10.37	1120–1270 AD	1195	TL	Hearth	H		7	Tv	22.0	56.0	5.0	145	21.6	54.0	this study
5	Monreale, Palermo	38.07	13.29	1172–1185 AD	1178	A	Bricks from building			17	Th	*	51.2	2.3	*	_	_	Tanguy *et al.* (1985)
6	Dosso Castello, Cremona	45.13	10.37	1080–1250 AD	1165	TL	Hearth	C		10	Tv	19.1	55.5	5.7	72	18.8	53.3	this study
7	Cefalu, Sicily	38.03	14.07	1132–1148 AD	1140	A	Bricks from church			17	Th	*	53.2	1.8	*	_	_	Tanguy *et al.* (1985)
8	Palazzo Reale, Palermo	38.11	13.33	1130–1150 AD	1140	A	Bricks from building			47	NRM	*	50.5	1.3	*	_	_	Tanguy *et al.* (1985)
9	St.Salvatore d'Alunzio, Sicily	38.73	14.70	1105 AD	1105	A	Bricks from church			31	NRM	*	51.8	1.7	*	_	_	Tanguy *et al.* (1985)
10	Santa Maria di Mili, Sicily	38.13	15.49	1092 AD (or 1542?)	_	A	Bricks from church			25	NRM	*	60.7	2.1	*	_	_	Tanguy *et al.* (1985)
11	St Pietro e Paolo di Agro	37.96	15.32	1000–1060 AD	1030	A	Bricks from church			41	AF	*	53.0	1.4	*	_	_	Tanguy *et al.* (1985)
12	San Vincenzo, Galliano	45.73	9.13	700–1200 AD	950	A	Hearth	US24		7	NRM	14.9	62.6	2.6	508	14.3	60.4	this study
13	Dosso Castello, Cremona	45.13	10.37	750–950 AD	850	TL	Hearth	E		10	Tv	27.3	62.2	2.2	463	26.4	60.6	this study
14	Rome, Foro Traiano	41.90	12.45	600–800 AD	700	A	Bricks from limekiln		(26)	8	AF, Th	8.4	61.8	2.3	573	8.5	62.2	this study
15	Canosa, Puglia	41.22	16.07	500–600 AD	550	A	Bricks from kiln		(26)	9	AF, Th	359.4	51.3	3.1	279	358.6	52.7	this study
16	Ruoti	40.73	15.68	460–540 AD	500	A	Oven	F446		16	AF, Th	0.6	58.1	4.2	67	0.5	59.6	Evans & Hoye (2005)
17	Pioppi, Pratola Serra	40.98	14.85	400–600 AD	500	A	Bricks from a furnace		(18)	6	AF	1.6	56.7	3.6	363	1.4	58.0	Nardi *et al.* (1995)
18	Santa Maria	39.50	16.93	400–600 AD	500	A	Oven			6	AF, Th	359.4	57.6	3.8	318	359.2	60.3	Evans & Hoye (2005)
19	Carlino, Aquileia	45.80	13.22	380–430 AD	405	A	Kiln	kiln 1		10	NRM	359.4	58.5	3.0	255	359.3	55.3	this study
20	Carlino, Aquileia	45.80	13.22	380–430 AD	405	A	Kiln	kiln 2		7	NRM	357.7	55.8	3.1	357	357.6	52.4	this study
21	Segesta, Sicily	37.94	12.83	300–500 AD	400	A	Kiln	SG2	(8)	8	Th	2.1	62.3	3.7	222	2.4	65.9	Márton *et al.* (1992)
22	Segesta, Sicily	37.94	12.83	300–500 AD	400	A	Kiln			5	AF, Th	359.9	63.3	2.8	769	0.0	66.8	Evans & Hoye (2005)
23	Sibari, Cavallero	39.60	16.50	300–400 AD	350	A	Fired structure			10	AF, Th	0.3	55.1	3.2	224	359.9	57.8	Evans & Hoye (2005)
24	Vagnari, Puglia	40.83	16.27	300–400 AD	350	A	Tiles from kiln		(23)	9	AF, Th	2.1	50.8	2.8	343	1.3	52.4	this study
25	Ascoli Satriano, Puglia	41.21	15.56	350–400 AD	375	A	Bricks from kiln		(16)	5	AF, Th	2.3	54.4	2.9	701	1.9	55.5	this study
26	Cassano	41.10	14.50	50–300 AD	175	A	Kiln		(7)	7	AF	6.4	51.6	9.2	33	6.0	52.8	Chiosi *et al.* (1998)
27	Lonato, Brescia	45.47	10.48	146 AD–74 BC	36	TL	Tile kiln	A		20	NRM	355.8	55.2	1.7	369	356.3	52.0	this study
28	Pompei, Porta Nocera	40.80	14.50	79 AD	79	A	Kiln			13	AF, Th	355.0	59.1	1.6	581	354.8	60.7	Evans & Hoye (2005)
29	Pompei, Thermae Stab.	40.80	14.50	62–79 AD	70	A	Mural painting		(18)	18	AF	1.2	58.0	5.5	40	1.1	59.5	Zanella *et al.* (2000)
30	San Giovanni	40.73	15.68	0–100 AD	50	A	Kiln			106	AF, Th	350.5	58.8	0.9	232	350.1	60.7	Evans & Hoye (2005)
31	Pizzica	40.38	16.78	50 AD–50 BC	0	A	Kiln			14	AF, Th	356.4	51.4	2.1	367	355.5	53.8	Evans & Hoye (2005)
32	Segesta, Sicily	37.90	12.80	50 AD–50 BC	0	A	Kiln	SG1	(5)	5	AF	355.5	58.2	7.0	120	355.2	62.2	Márton *et al.* (1992)
33	Marzabotto, Bologna	44.35	11.20	20 AD–50 BC	−15	A	Furnace	A		7	pTD, 0v	356.8	63.4	2.7	498	356.9	61.8	this study
34	Capocolonna	39.02	17.07	20 AD–80 BC	−30	A	Kiln			10	AF, Th	357.1	59.8	1.5	980	357.1	62.9	Evans & Hoye (2005)
35	Morgantina	37.38	14.37	0–100 BC	−50	A	Kiln			5	AF, Th	5.1	60.0	4.6	188	5.7	64.0	Evans & Hoye (2005)
36	Apani, Brindisi	40.72	17.90	50–100 BC	−75	A	Fired structure			7	AF, Th	356.7	58.0	1.7	1203	356.4	59.8	Evans & Hoye (2005)
37	Ordona	41.32	15.63	50–150 BC	−100	A	Kiln			60	AF, Th	4.8	63.0	1.7	115	5.2	63.7	Evans & Hoye (2005)
38	Metaponto	40.42	16.75	0–200 BC	−100	A	Iron smelter			11	AF, Th	353.1	58.0	3.9	120	352.7	60.2	Evans & Hoye (2005)
39	Bassento Destra	40.41	16.17	0–200 BC	−100	A	Kiln			10	AF, Th	353.6	61.5	1.9	652	353.6	63.4	Evans & Hoye (2005)

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Table 1. (*Continued.*)

No.	Site	Lat (°)	Long (°)	Age (years)	Mean Age	Method	Material	Code	(n)	N	Treatment	D (°)	I (°)	α_{95} (°)	k	D_r (°)	I_r (°)	Reference
40	St Angelo, Vecchio	40.39	16.72	100–200 BC	−150	A	Fired structure			13	AF, Th	358.3	57.9	1.7	617	358.1	59.9	Evans & Hoye (2005)
41	Insula, Metapontum	40.42	16.75	250–300 BC	−275	A	Fired structure			8	AF, Th	348.7	61.4	2.5	499	348.5	63.6	Evans & Hoye (2005)
42	Velia	40.16	15.17	250–300 BC	−275	A	Kiln			8	AF, Th	355.6	60.2	3.4	271	355.5	62.3	Evans & Hoye (2005)
43	Locri	38.21	16.24	250–300 BC	−275	A	Kiln	B		7	AF, Th	358.5	58.6	2.1	807	358.5	62.3	Evans & Hoye (2005)
44	Bisignano	39.51	16.28	250–350 BC	−300	A	Kiln			10	AF, Th	9.4	64.3	2.7	333	10.6	66.1	Evans & Hoye (2005)
45	Roccagloriosa	40.10	15.43	300–350 BC	−325	A	Funeral pyre			7	AF, Th	_	_	_	4	_	_	Evans & Hoye (2005)
46	Metapontum, Kerameikos	40.42	16.75	325–350 BC	−338	A	Fired structure			12	AF, Th	347.0	62.0	2.7	251	346.8	64.2	Evans & Hoye (2005)
47	St Angelo Grieco	40.40	16.79	300–400 BC	−350	A	Kiln			10	AF, Th	3.2	63.4	2.9	273	3.9	64.8	Evans & Hoye (2005)
48	Metapontum	40.42	16.75	300–400 BC	−350	A	Funeral pyre			9	AF, Th	_	_	_	7	_	_	Evans & Hoye (2005)
49	Motya	37.83	12.50	350–400 BC	−375	A	Kiln			7	AF, Th	352.2	61.3	2.2	737	351.6	65.0	Evans & Hoye (2005)
50	Heraciea	40.21	16.67	350–400 BC	−375	A	Kiln			_	AF, Th	_	_	_	_	_	_	Evans & Hoye (2005)
51	Locri	38.21	16.24	400–500 BC	−450	A	Kiln	A		9	AF, Th	0.7	61.3	5.2	98	1.2	64.7	Evans & Hoye (2005)
52	Poggioreale	37.48	13.02	430–500 BC	−465	A	Burnt walls			6	AF, Th	4.3	60.7	3.9	293	4.8	64.7	Evans & Hoye (2005)
53	Pozzuolo del Fruili, Udine	45.97	13.20	500–550 BC	−525	A	Oven	No. 8		4	Tv	359.9	74.8	11.7	63	0.5	72.6	this study
54	Metapontum, Temple Area	40.42	16.75	500–550 BC	−525	A	Kiln			10	AF, Th	0.6	66.4	1.8	711	1.7	67.8	Evans & Hoye (2005)
55	Chiesa St Francesco, Udine	46.03	13.14	500–600 BC	−550	A	Hearth	TRA/a, US6		7	Tv, AF	6.5	71.1	2.4	642	6.3	68.6	this study
56	Treglia, Pontelatore	41.25	14.17	500–600 BC	−550	A	Furnace		(9)	6	AF	353.3	53.7	5.8	79	352.9	55.1	La Torre *et al.* (1998)
57	Naxos	37.85	15.30	525–575 BC	−550	A	Kiln			7	AF, Th	5.6	60.3	1.7	1233	6.3	63.9	Evans & Hoye (2005)
58	Este-Casa di Ricovera	45.42	11.88	600–625 BC	−612	A	Hearth	US169		8	Tv, AF	352.7	63.9	9.6	34.3	353.1	61.5	this study
59	Salapia	41.41	15.93	700–900 BC	−800	A	Kiln			10	AF, Th	7.1	63.5	4.4	121	7.5	64.0	Evans & Hoye (2005)
60	Arcora, Campomarino, Molise	41.95	15.05	700–900 BC	−800	A	Hearth	US2		22	Tv	18.1	62.9	1.0	888	18.3	62.7	this study
61	Montagnana, San Zeno	45.23	11.47	700–900 BC	−800	A	Hearth	US137		6	AF	36.6	60.1	4.7	200	35.3	58.3	this study
62	Scarceta, Manciano	42.57	11.57	1000–1300 BC	−1150	A	Hearth	1, D5–3		16	pTD	11.5	62.9	1.5	578	11.5	62.9	this study
63	Scarceta, Manciano	42.57	11.57	1000–1300 BC	−1150	A	Hearth	2, D5–4		20	Tv	5.4	61.5	1.7	393	5.4	61.4	this study
64	Scarceta, Manciano	42.57	11.57	1000–1300 BC	−1150	A	Hearth	3, D6–3		10	Tv	9.9	59.7	3.6	177	9.9	59.6	this study
65	Grotta dell' Edera di Aurisina	45.75	13.70	2500–4300 BC	−3400	^{14}C	hearth	2		6	Tv	3.9	60.6	2.9	524	3.6	57.6	this study
66	Laghetti del Crestoso	45.85	10.44	5900–5480 BC	−5690	^{14}C	hearth	5		10	0v	4.5	65.7	11.6	18.3	4.2	63.1	this study
67	Laghetti del Crestoso	45.85	10.44	5900–5480 BC	−5690	^{14}C	hearth	1		6	Tv, 0v	346.0	64.7	17.7	15.2	346.8	61.8	this study
68	Selinunte, Sicily	37.60	12.80	_			Kiln	SB2		6	Th	356.8	55.9	2.4	328	356.6	60.4	Abdeldayem *et al.* (1992)
69	Selinunte, Sicily	37.60	12.80	_			Kiln	SB2		9	AF	350.4	60.5	4.1	158	349.7	64.5	Abdeldayem *et al.* (1992)
70	Selinunte, Sicily	37.60	12.80	_			Kiln	SB3		12	Th	4.5	59.1	5.2	165	4.9	63.2	Abdeldayem *et al.* (1992)
71	Selinunte, Sicily	37.60	12.80	_			Kiln	SB3		9	AF	7.2	65.0	5.7	82	8.1	68.5	Abdeldayem *et al.* (1992)
72	Castelgoffredo, Piazza Gonzaga	45.30	10.45	_			Hearth	H 1226		14	Tv	16.8	62.5	1.8	500	16.1	60.5	this study
73	Castelgoffredo, Piazza Gonzaga	45.30	10.45	_			Hearth	H 1205		10	Tv	18.0	56.0	2.0	567	17.7	53.6	this study
74	Massinigo, S. Margherita di Staffora	44.77	9.25	_			Kiln			8	Tv, 0v	355.6	63.1	1.7	966	355.8	61.1	this study

Columns: No. = site reference number; Location of the sampling sites; Lat/Long = site latitude /longitude; Age range; Mean age; Method of dating (A: archaeological estimate, TL: thermoluminescence, ^{14}C: radiocarbon); Material studied; Code name of the structure; (n)/N = (number of specimens)/number of independently oriented samples; laboratory treatment (AF: alternating field demagnetization, Th: thermal demagnetization, pTD: partial thermal demagnetization, Tv: Thellier viscosity test, 0v: zero field viscosity test); D, I = declination, inclination; α_{95} = 95 per cent semi-angle of confidence; k = Fisher's precision parameter; D_r, I_r = declination, inclination relocated to Viterbo (42.45°N, 12.03°E); Reference.

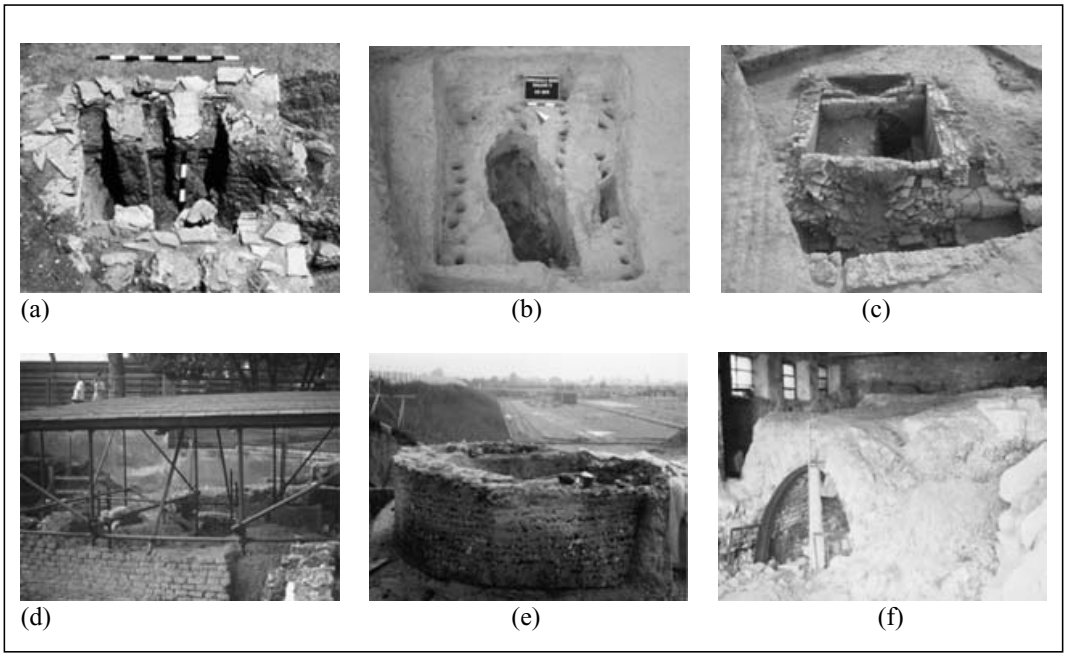


Figure 2. Pictures of some of the new studied structures (a) Vagnari (No. 24), (b) Ascoli (No. 25), (c) Canosa (No. 15), (d) Roma (No. 3), (e) Lonato (No. 27) and (f) Massinigo (No. 74). (Numbers within parenthesis refer to Table 1).

letters of Pliny the younger with the account of the 79 AD eruption of Vesuvius which destroyed the Roman cities of Pompeii and Herculaneum. However, combination of volcanological and rock-magnetic investigations (Tanguy *et al.* 2003; Principe *et al.* 2004) has shown that the age traditionally attributed to lava flows on the ground of written reports is in several cases inconsistent with the archaeomagnetic direction of the rocks. Many lava flows have thus been assigned a new, archaeomagnetic age on the grounds of comparison with the French SV reference curve. These data are, therefore, not used to construct the Italian SV curve. On one hand, introducing archaeomagnetically dated values in an archaeomagnetic reference curve would be a circular reasoning; on the other hand they would bias any comparison between the Italian and French curves, having their new ages actually derived from the French SV curve. As a cautionary criterion, we only use the data from volcanic rocks of undisputed, certain age, i.e. those of the Mt. Vesuvius 1631 AD (pyroclastic flow), Mt. Arso (Ischia) 1302 AD, Pollena (Vesuvius) 472 AD and Pompeii (Vesuvius) 79 AD eruptions (Table 2).

DISCUSSION ON THE ARCHAEOMAGNETIC DATA

The Italian archaeomagnetic data relocated to Viterbo (D_r, I_r) are presented in Table 1 and plotted in Fig. 5. Results from volcanic rocks emplaced by eruptions of certain age (Table 2) have been used as time markers as previously discussed. The plots also show the SV curve for the last four centuries drawn from direct measurements (Lanza *et al.* 2005), derived from the historical Italian catalogue (Cafarella *et al.* 1992) and the Jackson *et al.* (2000) global database. The irregular time distribution of Italian archaeomagnetic data is clearly visible (Fig. 5). The majority of data are concentrated in the period from 600 BC to 600 AD with a two centuries gap from 100 to 300 AD. Outside of this period, data are scarce and for some centuries (e.g the 9th century BC and 14th century AD) are absent. For the periods for which more data are available, they are generally consistent with each other, even if some discrepancies do occur. It is interesting that in some cases the mean direction seems to be in very good agreement with the other data from the same time period even when characterized by high measurement errors (e.g. structure 53, Table 1, with angle $\alpha_{95} = 11.7^\circ$). The directions from the volcanic rocks with no age uncertainty represent reference points and are in excellent agreement with the coeval archaeomagnetic data. Data for the last centuries (14th–15th century AD) seem to follow the general trend of the SV of the geomagnetic field as indicated by historical measurements of the last 400 yr, although declination values from data of 15th century are slightly lower than expected.

The Italian data have been relocated to Paris using the VGP method and plotted (Fig. 6) against the French SV curve (data set from Gallet *et al.* 2002, treated with Lanos algorithm, Lanos 2004). The French SV curve is shown with its 95 per cent error envelope while for the Italian data the time and measurement errors are not shown for legibility reasons. The data fit well to the French curve and most of them are inside its error bars. However, some points fall far from the curve. Such discrepancies may be due to various reasons such as uncertainty in the age of the structures, measurement errors, anisotropy effects etc. It is interesting to observe (Fig. 6) that the declination values of the new sites of Vagnari, Ascoli, Canosa and Rome fit very well to the French curve, whilst their inclination values are lower than expected for their archaeological age. Systematic measurements of the anisotropy of magnetic susceptibility (AMS) have been done for all specimens; anisotropy of isothermal (AIRM) and anhysteretic (AARM) remanent magnetization have been studied for selected specimens. Equal area projections of the three principal anisotropy axes show a well-developed magnetic foliation (Fig. 7a) with the maximum and intermediate susceptibility axes lying in the tile/brick plane and the minimum axis perpendicular to this plane (Fig. 7b). As in most cases the tiles and bricks sampled were in a horizontal position in the kilns, these anisotropy results suggest a possible systematic shallowing of the inclination values. The inclination values of these five structures (Table 1) could, therefore, be slightly underestimated. Nevertheless, there are still some

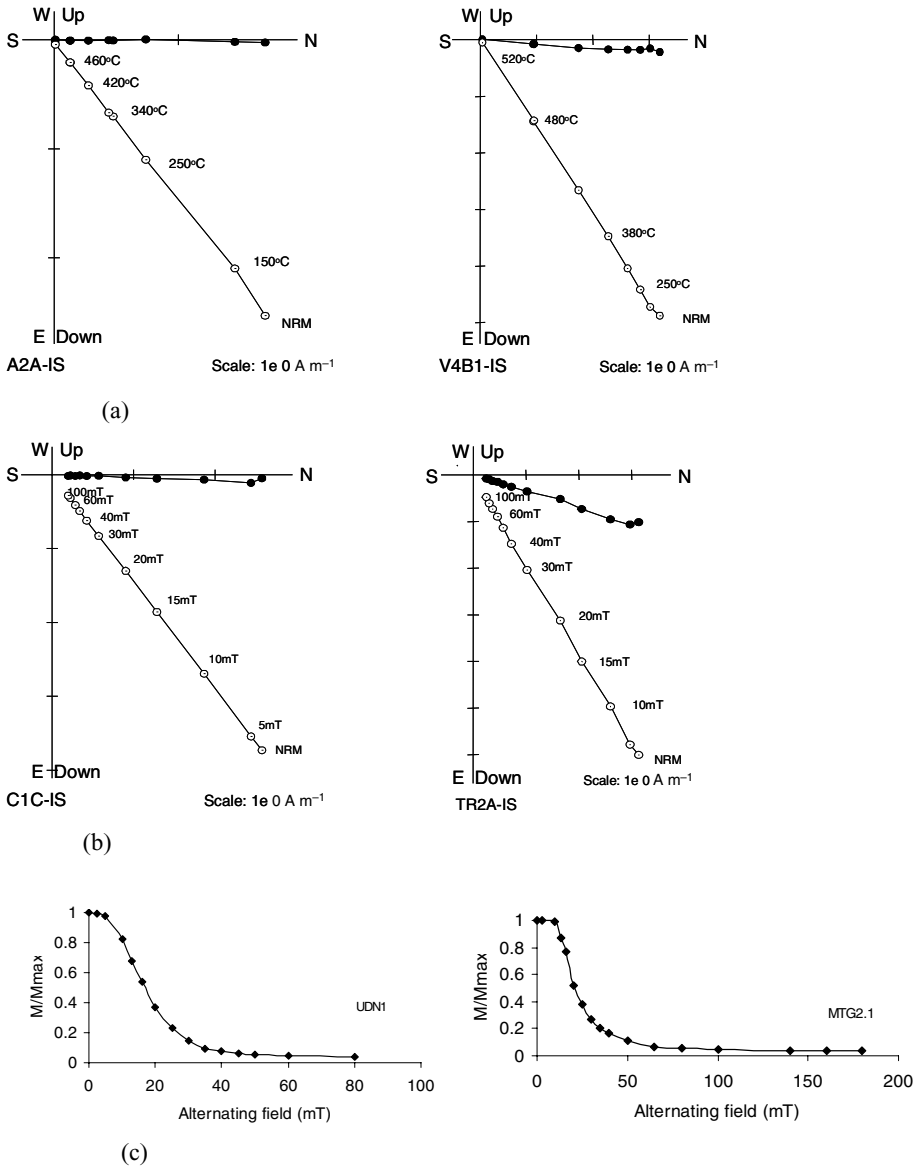


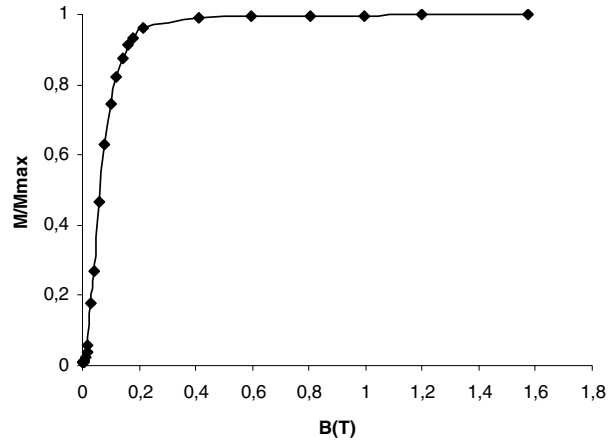
Figure 3. (a), (b) Zijderveld diagrams from stepwise thermal (a) and AF (b) demagnetization of specimens from the kilns at Ascoli (No. 25), Vagnari (No. 24), Canosa (No. 15) and Roma (No. 14), respectively. Symbols: full dot = declination; open dot = apparent inclination; figures: peak-field (mT) or temperature (°C) values. (c) Normalized intensity decay during AF demagnetization of specimens from the hearth at Chiesa San Francesco (UDN1- No. 55) and Montagnana (No. 61).

data that show incompatible inclination values even when there is no evidence for important anisotropy effects (e.g. structures Nos. 21, 22 Table 1). As discussed by Evans & Hoye (2005), these data come from the same structure independently studied by two different groups, both obtaining very similar results that are nonetheless far from the curve. A possible explanation for such a deviation could be a younger age than suggested by archaeological evidence currently available (Evans & Hoye 2005).

BAYESIAN FRAMEWORK FOR THE CONSTRUCTION OF CALIBRATION CURVES: A PRELIMINARY ITALIAN SECULAR VARIATION CURVE

In order to build a SV curve for a given region, a long sequence of numerous and well-dated data should be available. However, in archaeomagnetism, it is often the case that the data are unevenly distributed in time and space and characterized by varying precisions depending on measurement errors as well as on errors related to the dates used as reference points. In such a case, the aim is to consider the given data and their potential errors and find the best-corresponding statistical model to describe their variations in a smoothed way. To achieve this goal different methods have been used; the moving window technique (Kovacheva & Toshkov 1994; Kovacheva *et al.* 1998; Batt 1997), the bivariate Le Goff statistics (Le Goff *et al.* 1992; Daly & Le Goff 1996; Le Goff *et al.* 2002), the Bayesian statistical framework (Buck *et al.* 1996; Lanos 2004; Lanos *et al.* 2005). In the present paper, in order to obtain a smooth SV curve for Italy, the hierarchical Bayesian modelling based on roughness penalty has been used (Lanos 2004). This model compares data from different methods, prior dates and parameters, and relative chronology (stratigraphy) information and

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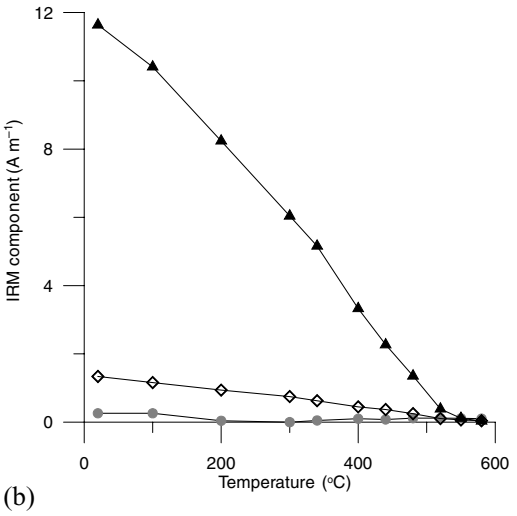


Figure 4. (a) Isothermal remanent acquisition (IRM) curve (b) thermal demagnetization of IRM components (specimens from the structures Nos. 14 and 3—Table 1). Symbols: black triangle = low-; open diamond = intermediate-; grey dot = high-coercivity component.

the use of penalized maximum likelihood from smoothing univariate, spherical or 3-D time-series data allows representation of the SV of the geomagnetic field over time. The smoothed curve obtained (which takes the form of a penalized natural cubic spline) provides an adaptation to the effects of variability in the density of reference points over time. Since the model takes into account all the known errors in the archaeomagnetic calibration process, a functional highest-posterior-density envelope on the new curve can be obtained.

For the construction of the SV curve for Italy, referred to Viterbo, 65 directional results ranging in time from 1300 BC to 1700 AD have been used, i.e all those with complete information: declination, inclination and age (Table 1) and data from volcanic rocks of certain age (Table 2). No cut-off criterion based on the α_{95} angle of confidence has been applied; however, all data used for the construction of the curve have precision parameter $k > 30$. Historical measurements for the last four centuries have not been included in the construction of the curve with the Bayesian model as their high precision would bias the calculation of the curve, but they have been plotted together with the final curve in Fig. 8. This figure shows the obtained declination and inclination curves together with their 95 per cent error envelope from Bayesian calculations and the raw data. In general, almost all

Table 2. Italian archaeomagnetic directions from historical eruptions.

Site	Lat (°)	Long (°)	Age	Material	N	D (°)	I (°)	α_{95}(°)	k	Treatment	D_r(°)	I_r(°)	Reference
Vesuvius (Villa Inglese)	40.50	14.80	1631 AD	Pyroclastic flow	6	2.1	65.2	1.9	1237	AF, Th	2.7	66.6	Carracedo *et al.* (1993)
Ischia (3 sites)	40.74	13.94	1302 AD	Lava flow	22	9.3[a]	48.2[a]	1.1	771	AF	9	49.9	Tanguy *et al.* (2003)
Ischia (2 sites)	40.74	13.94	1302 AD	Lava flow	12	4.9[a]	51.3[a]	1.8	606	Th	4.6	53.0	Incoronato *et al.* (2002)
Vesuvius, Pollena quarry	40.83	14.42	472 AD	Pumice clasts	13	4.8[a]	56.7[a]	0.8	2596	AF	4.8	58.1	Tanguy *et al.* (2003)
Vesuvius, Herculaneum	40.83	14.42	79 AD	Pyroclastic flow	11	355.2	58.7	1.1	1573	AF	355.0	60.3	Principe *et al.* (2004)
Vesuvius, Herculaneum	40.83	14.42	79 AD	Pyroclastics	14	353.6	59.9	2.5	258	AF	353.4	61.5	Zanella *et al.* (2000)
Vesuvius, Herculaneum	40.83	14.42	79 AD	Pyroclastics	12	348.3	56.8	2.1	423	AF	347.8	58.6	Zanella *et al.* (2000)
Vesuvius (8 sites)	40.83	14.42	79 AD	Lithic fragments	87	354.4	57.2	2.7	433	Th	354.1	58.8	Cioni *et al.* (2004)
Vesuvius, Herculaneum	40.83	14.42	79 AD	Lithic fragments	6	359.2	56.8	4.2	251	Th	359.0	58.3	Kent *et al.* (1981)
Vesuvius, Herculaneum	40.83	14.42	79 AD	Pyroclastic flow	20	351.9	57.0	2.2	212	AF	351.5	58.7	Hoye (1981)

Columns as in Table 1. [a]Directions relocated at Etna in the original paper.

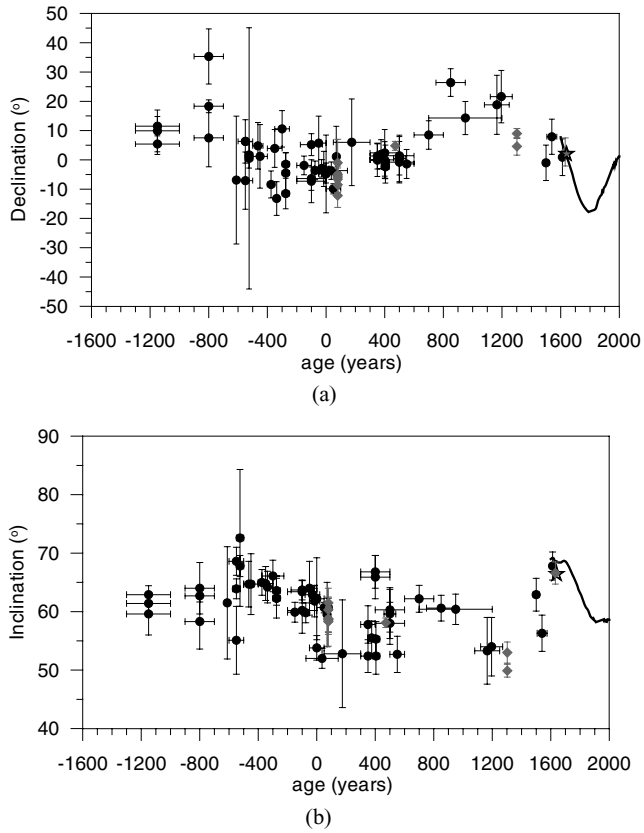


Figure 5. Declination (a) and inclination (b) values of Italian archaeological sites and volcanic rocks plotted versus age together with measurement errors (dD, dI) and age uncertainties. All directions are reduced to the reference site Viterbo (42.45°N, 12.03°E). Symbols: black dots = archaeomagnetic data; grey diamonds = volcanic data; star = 1640 measurement in Rome by Kircher; black line = secular variation curve for Italy during last four centuries (see text for explanation).

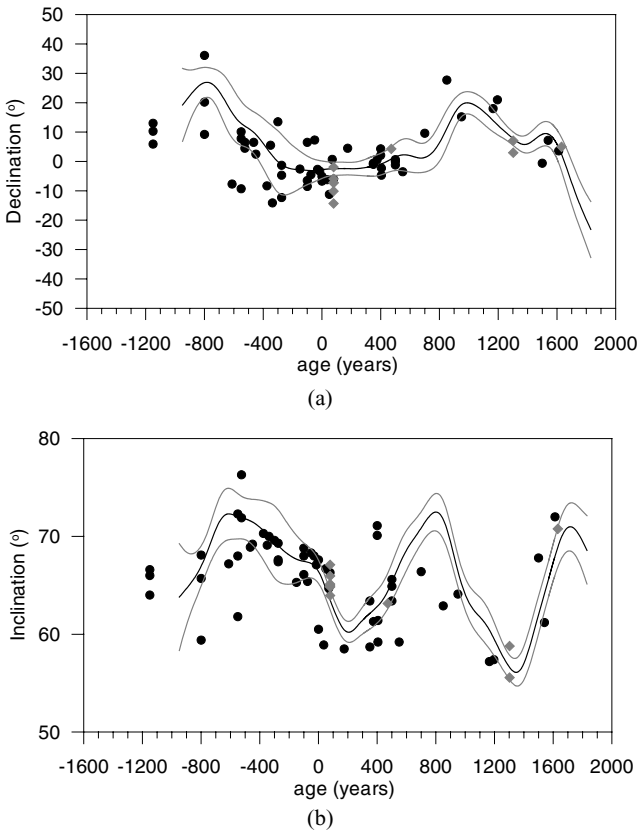


Figure 6. Declination (a) and inclination (b) values of Italian data (same as in Fig. 5) plotted versus the French SV curve (black line surrounded by the 95 per cent error envelope in grey colour—data set Gallet *et al.* 2002). All directions are reduced to Paris. Symbols: black dots = archaeomagnetic data; grey diamonds = volcanic data.

data are well represented by the smoothed curves. As expected for the periods for which many data exist (e.g. 79 AD), the curves are better defined with narrow error envelopes while for those time periods with few or no data the curves are more roughly estimated. As Bayesian calculations take into consideration both the measurement and time uncertainties, it is probable that for those periods poorly covered by the data the curve is affected by an over-smoothing effect. Historical measurements seem to fit the curve within its error envelope but for both declination and inclination they tend to coincide with the upper error margin. Inclination measurement done by Kircher at Rome in 1640 is around 2° lower than that derived from Jackson's model (Jackson *et al.* 2000) for the same period. This coincides better with the trend of the curve for the beginning of the 17th century suggesting that the inclination for this time period maybe over estimated by Jackson's model, as already discussed by Lanza *et al.* (2005).

In Fig. 9 the Italian reference SV curves for declination and inclination are plotted together with the French reference curves (data set from Gallet *et al.* 2002, relocated to Viterbo). Comparison of the curves shows an agreement in the general features taking into consideration the error limits. However, some differences are apparent, mainly in the inclination values. The Italian curve has less abrupt maxima and minima and more smoothed changes compared with the French curve. The inclination maxima at around the 7th century BC and the 8th century AD shown at the French curve are also observed in the Italian curve but about 5° lower. Furthermore the Italian inclination curve shows a minimum around the 13th century AD while in the French curve it is more abrupt and occurs over a century later. Such differences could be due to the smoothing effect of Bayesian interpretation on the Italian data in particularly for those periods with a small number of data, such as 10th–14th century AD. However, similar, less abrupt changes in inclination have been also noticed in the German SV reference curve (Schnepp & Lanos 2005) when compared to the French SV curve.

CONCLUSIONS

These new directional results from Italian archaeological sites are a significant contribution to the Italian archaeomagnetic database as they cover time periods, for example, 1300–700 BC and 600–1600 AD, that were previously poorly studied, as well as geographical areas, for which no data have been previously published (northern Italy). Compilation of the data shows that they range in time from 1300 BC to 1700 AD but with several periods that need further study. Their geographical distribution covers almost the entire Italian peninsula, although most of data are far more concentrated in the south, emphasizing the need for obtaining new results from central and northern Italy. The total number of data, even though not as numerous as those from France, Bulgaria or UK, can now be considered sufficient for a preliminary Italian SV curve for the

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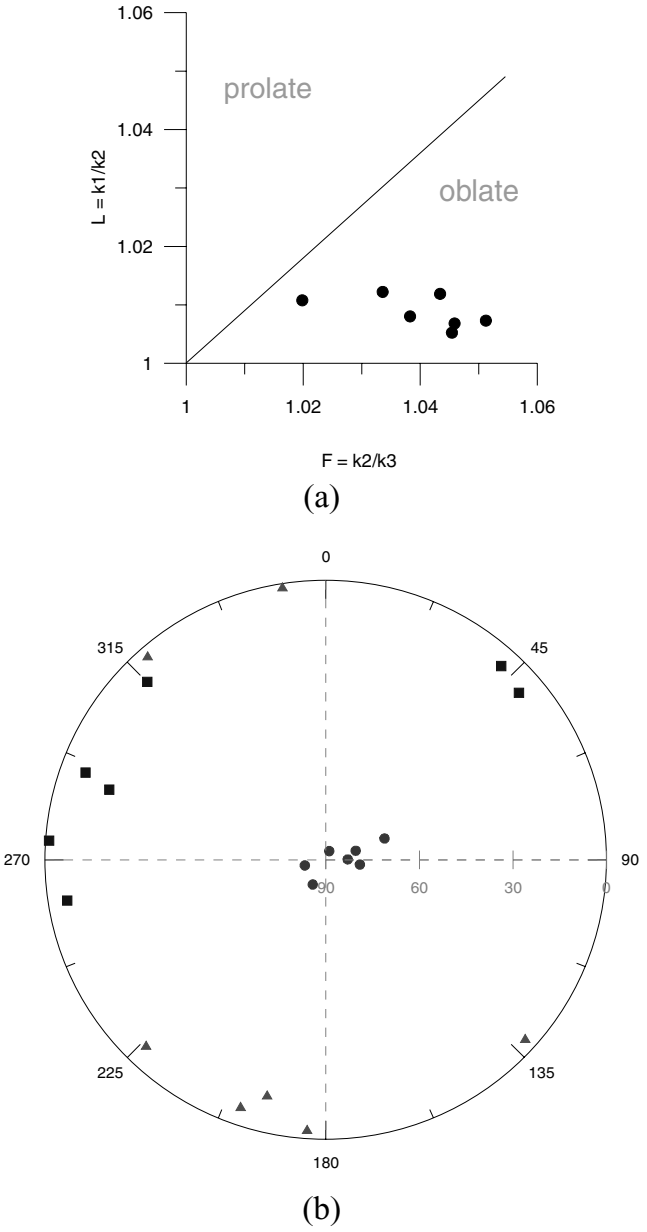


Figure 7. (a) Flinn-type plot of the degree of lineation (L) and foliation (F), (b) equal-area projection of the principal axes of magnetic susceptibility ellipsoid (Vagnari kiln). Symbols: square = maximum; triangle = intermediate; dot = minimum axis of susceptibility.

last three millennia. The SV curve obtained using Bayesian modelling compared with the French SV curve shows a similar trend but also some important differences. The two curves do not completely coincide in the whole period examined but there is no clear indication of a westward or eastward drift. The preliminary SV curve succeeds in describing the variations of the Earth's magnetic field in the past. However, the large error envelope obtained for certain time periods indicates that caution is needed if used for archaeomagnetic dating, when the maximum precision is required. Undoubtedly more data are still required in order to be able to draw a more detailed SV curve for Italy that will be necessary for improved dating reliability as well as further defining the geomagnetic variation properties.

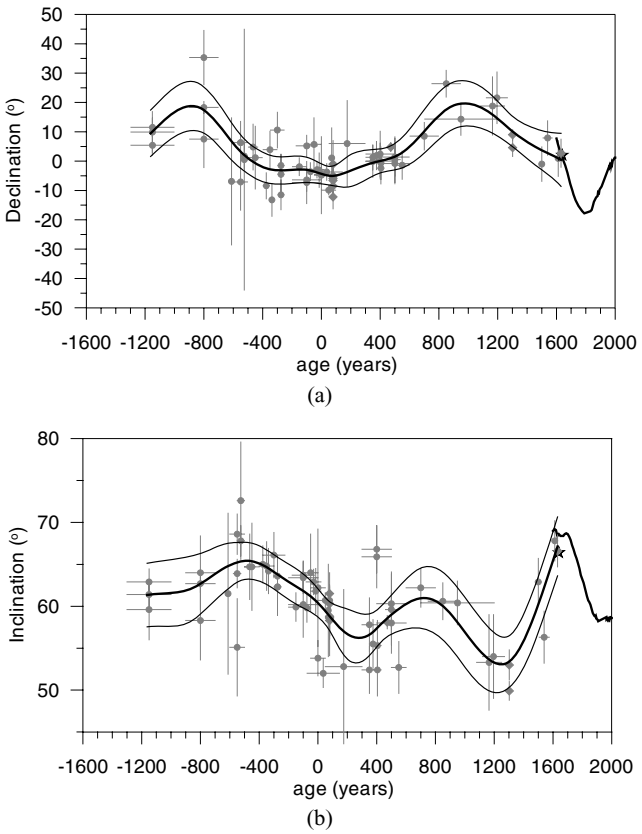


Figure 8. Smoothed SV curves for (a) declination and (b) inclination for Italy surrounded by the 95 per cent error envelope as obtained from the Bayesian modelling. Together are plotted the raw data and the historical measurements for the last four centuries. All directions are reduced to the reference site Viterbo (42.45°N, 12.03°E).

ACKNOWLEDGMENTS

We thank all archaeologists for sampling permission, their collaboration and helpful discussions. R. Lanza is greatly thanked for precious advice and constructive comments on the manuscript. The paper benefited from the reviews of D. Tarling, E. Schnepp and H. Soffel. ET acknowledges a fellowship from the European AARCH Network (Archaeomagnetic Applications for the Rescue of Cultural Heritage), Contract EU: HPRN-CT-2002-00219. The Genève laboratory was supported by FNRS grants: 2.756-0.87, 20-30288.90, 2-0056.43.

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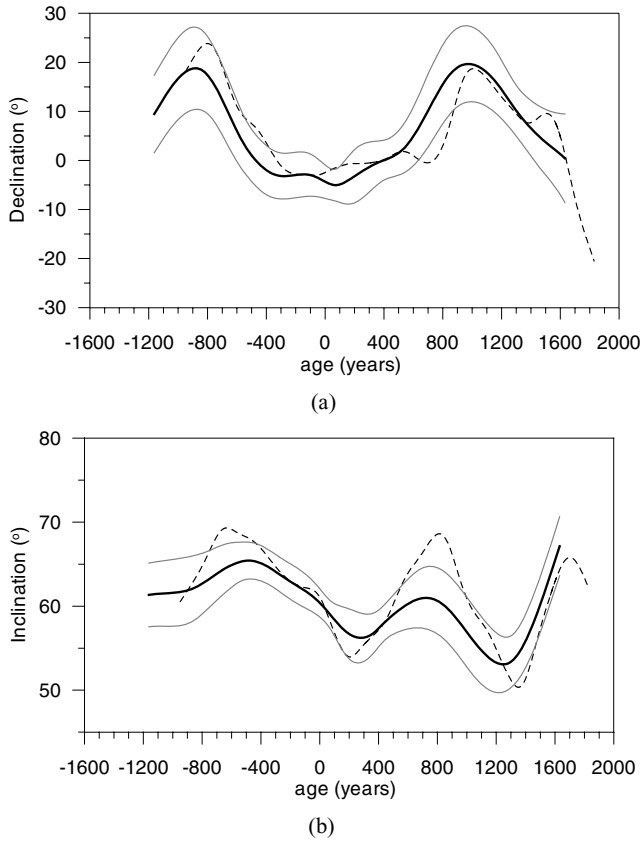


Figure 9. Declination (a) and inclination (b) of the obtained Italian SV reference curves as in Fig. 8 compared with the French SV curves reduced to Viterbo station (dashed line—data set Gallet *et al.* 2002).

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APPENDIX: ARCHAEOLOGICAL REFERENCES OF THE NEW STUDIED SITES

2: Castelseprio, Varese. Baked clay hearth, US1020, House VI, room 2. TL date Milan, Mi89-Ca4: 1540 ±4 A. D. E. S. Sibilia, L. D. Della Torre, 1989, Notiziario Soprintendenza archeologica Lombardia, 183. (Sampled 1988/7)

3: Rome, Foro Traiano. Brick kiln. Archaeological information suggests that below the structure sampled there is another kiln, probably of a circular shape. Meneghini, R., 1999. Roma- Interventi per il Giubileo del 2000 scavo del monastero di S. Urbano al Foro di Traiano. Archeologia Medievale XXVI, 43–66. (Sampled 2004/5)

4,6,13: Dosso Castello, Piadena. Three horizontal baked clay hearths sampled in the same section exposed in a trench. Based on stratigraphy, from oldest to youngest: E, C, H. TL dates from Milan TL laboratory. M. Martini, E. Sibilia, G. Spinolo. 1985, Notizario Soprintendenza archeologica della Lombardia. p216. (Sampled 1985/7)

12: San Vincenzo, Galliano, Cantu, Como. Hearth inside the church that could possibly be a bell mould. Large samples (6 × 6 × 4 cm) taken embedded in plaster of Paris. (Sampled 1981/9)

14: Rome, Foro Traiano. Limekiln. Archaeological dating based on the characteristic shape of the structure and also on the later backfill of the kiln missing 'vetrina pesante' potsherds. Meneghini, R., 1998. Roma- Nuovi dati sul medioevo al foro e ai Mercati di Traiano. Archeologia Medievale XXV, 127–141., (Sampled 2004/5)

15: Canosa, Puglia. Kiln for the production of bricks, probably used for the construction of the nearby well-dated church of Saint Sabino. Excavation responsible: Prof. Giuliano Volpe, Universita di Foggia. (Sampled 2003/10)

19, 20: Carlino, Aquileia. Large rectangular kilns in poor state of preservation, so only 7 tiles sampled from kiln 2. Estimation of effect of magnetic anisotropy made but not applied. Luisa Bertacchi. 1976. La ceramica invetriata di Carlino. Aquileia Nostra, p 182–194. (Sampled 1982/6)

24: Vagnari, Puglia. Small kiln in Trench 5. Prof. Alastair Small, University of Edinburgh, Prof. Giuliano Volpe, Universita di Foggia. *Vagnari: Il villagio, l'artigianato, la proprietà imperiale. Lo scavo e le strutture, I.* Eds. Alastair Small & Carola Small, in press. (Sampled 2003/7)

25: Ascoli Satriano, Puglia. Archaeological excavation of Faragola. Kiln probably used for the production of tiles and bricks for the construction of a nearby Roman villa. Volpe G., De Felice G., Turchiano M., 2004. *I rivestimenti marmorei, i mosaici e i pannelli in opus sectile vitreo della villa tardoantica di Faragola (Ascoli Satriano Foggia),* in atti del X Colloquio dell' associazione Italiana per lo Studio e la Conservazione del Mosaico (AISCOM) (Lecce 18–21 febbraio 2004), Roma, c.s. (Sampled 2003/7)

27: Lonato, Brescia. Very large circular kiln, 9 m in diameter, the only one sampled of the several excavated at this workshop. Filli Rossi, 1986. Lonato (Brescia), Località "Fornace dei Gorghi", fornaci romane. Notizario Soprintendenza archeologica della Lombardia, pp. 188–190. Filli Rossi, 1987. Lonato (Brescia), Località Fornace dei Gorghi. Notizario Soprintendenza archeologica della Lombardia, pp. 59–65. (Sampled 1987/10)

33: Marzabotto, Bologna. Large rectangular (6.9 × 2.5 m) kiln (Fornace A) protected by metallic roof. Magnetic viscosity estimated using zero field store. All specimens thermally demagnetized but only to 120°C because of plastic disc support.Archaeological date is that found in first reference (p391) for kiln B. S. De Maria, G. Sassatelli, D. Vitali. 1976. Studi Etrusci, vol XLIV, ser III, p389–391. S. De Maria, 1978. Atti della Accademia nazionale dei Lincei, anno CCCLXXV, Notizie degli scavi di Antichità, ser. 8, vol. 32, pp. 82–91. (Sampled 1982/6)

53: Pozzuolo del Fruili, Udine. The baked clay from this oven (No. 8) has an important viscosity, so only 4 of the 8 specimens accepted. A.-M. Adam, P. C. Guida et S. Vitri. L'insediamento protohistorico di Pozzuolo del Friuli (Udine). Bollettino della Societa Adriatica di Scienze LXIX, 67–75, 1986/87. (Sampled 1988/7)

55: Chiesa San Francesco, via Beato, Odorico da Pordenone, Udine. Well baked hearth (TRA/α), US6.under pavement inside church. (Sampled 1988/7)

58: Este-Casa di Ricovero, Padova . US 169, square I40 near tomb 98. Baked clay from this structure has a high magnetic viscosity and probably has not been heated to a high enough temperature and this is responsible for the large dispersion of directions. Sampled 1988/9)

60: Arcora, Campomarino, Molise. Remarkable thick well-baked clay hearth. US 2, square E VIII.13. A.di Niro, 1991. Il villagio protohistorico di Campomarino. In Samnium, Archeologia del Molise, Roma, pp. 35–47. (Sampled 1993/7)

61: Montagnana, - Borgo San Zeno. Two hearths sampled in protohistoric village but only US137 (G.885/C3) gives an acceptable result. (Sampled 1988/8)

62, 63, 64: Scarceta, Manciano-Grosseto, Toscane. Hard baked clay hearths, late Bronze Age. Trincea D5–3, 1: well-preserved flat hearth exposed in trench. Some evidence of bronze working. One specimen AF demagnetised, rest heated to 120°C. Square D 5–4, 2: flat hearth with broken surface. Square D 6–3, 3: smaller flat hearth, poorly preserved. (Sampled 1982/8)

65: Grotta dell'Edera di Aurisina, Trieste. Structure 2. Only one hearth was sampled of the many visible in section of sedimentary deposit inside cave. Archaeological age: Neolithic to Chalcolithic. C_{14} 4680 ± 325 BP Geochron GX-19019 (Sampled 1993/9)

66, 67: Laghetti del Crestoso, Bovegno, Brescia. When sampled in October 1988 these were the only Mesolithic hearths known in the Alps. C_{14} 6790 ± 120 BP (HAR 887–1). Hearths are made up of sandy sediment. Specimens generally have a low remanence and some have appreciable magnetic viscosity. Baroni *et al.* 1987, Scavi di età preistorica e protohistorica. Notizario Soprintendenza archeologica della Lombardia, 15–17. Baroni *et al.* 1990. Laghetti

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72, 73: Castelgoffredo, Piazza Gonzaga, Mantova. Flat baked clay hearths exposed in the wall of a deep trench. US 1226, settore A/sezione N. US 1205, settore A/sezione W. Koenigsberger ratio Qn and viscosity measurements indicate that 1226 has been heated more than 1205. A. Breda, 1986. Castelgoffredo (Mantova) Piazza Gonzaga. Edificio altomedievale. Notiziario Soprintendenza archeologica della Lombardia, pp. 94–96. (Sampled 1986/4)

74: Massinigo, San Margherita di Staffora, Pavia. Large kiln 4 m in diameter protected inside a building. Sun compass used for orientation of 4 of the 8 practically horizontal tiles removed from the kiln. N. Cuomo di Caprio. 1971–1972 Proposta di classificazione delle Fornaci. Sibrium XI pp. 423–425. (Sampled 1981/9)

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