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Archeomagnetic dating of Mediterranean volcanics of the last 2100 years: validity and limits

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Abstract

Archeomagnetic dating developed at St. Maur laboratory has been applied to the Mediterranean volcanoes Etna, Vesuvius and Ischia. The method involves samples from lava flows or high temperature emplaced pyroclasts (welded scoriae, pumice, etc.) weighing 0.5–1 kg each, that allows reaching a precision of a few tenths of a degree on the direction of their thermoremanent magnetization, and hence a semi-angle of the Fisher 95% confidence cone between 0.6 and 1.8° for every volcanic unit. Among the factors reducing precision on the mean magnetic direction, the most important appears to be a distortion of the ambient field induced by magnetization of the cooling lava, which means that a number of samples should be collected over a large area. Age determination is based upon similarity between variation curves of the Direction of Earth's Magnetic Field (DEMF) reconstructed in France from 120 well-dated archeological sites, and on Italian volcanoes from historically dated eruptions. A total of 63 lava flows and pyroclastic units, such as cinder cones or nuée ardente deposits, are shown to be dated with an overall precision of ±40 years for the last 1500 years, and ±50 to ±100 years from AD 500 to 150 BC, this lesser precision resulting from both an increasing uncertainty on the shape of the DEMF curve and a smaller variation of the DEMF itself. This irregularity of the DEMF path plus an increasing number of ambiguities, related to similarity of the DEMF at different times further into the past, are the most serious limitations of the method. Though well-dated eruptions are known for the last two millennia, retrieval of their products is often misleading and about 50% of volcanics presumed of known date prior to the 17th century are in fact of older age, discrepancies usually reaching several hundreds of years. Owing to good agreement between the DEMF curves of France and southern Italy, the method may confidently be extended to volcanic materials from the whole of Mediterranean Europe, provided there are firm constraints that they were erupted within the last 2100 years.

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1. Introduction

Archeomagnetism is classically defined as the study of archeological materials whose ages are known with sufficient accuracy for retracing the past variations of the Earth's Magnetic Field, both in direction and intensity ([1–7] and references therein). Alternatively, materials studied can be volcanic rocks that cooled (i.e. acquired their magnetization) during the archeological period of a country, when there are well-dated eruptions that caused significant damage to life and property [7–10]. The volcanoes of southern Italy are particularly suitable in this respect and, for example, we were able to retrace the Direction of the Earth's Magnetic Field (DEMF) for the two last millennia by using lavas from Etna, Vesuvius and Ischia [11]. During that study we demonstrated that the DEMF curves are similar in Sicily, Naples and Paris, provided that change of coordinates is carried out through a method inspired by that used in calculating virtual geomagnetic poles [2,12]. This finding is of paramount importance as it enables us to establish the time dependence of the DEMF from volcanic materials by means of archeological results, especially when imprecise information on the exact location of eruptive centers and lava flows could lead to confusion and spurious dates. Thus, the DEMF at Etna shows good agreement both with instrumental measurements and with archeomagnetic determinations of the DEMF in Paris for the last 350 years. When going back further into the past, however, an increasing number of lavas presumed to have erupted between 1651 and 1284 present paleomagnetic directions away from the curve at their respective dates, most of them having a strong eastern declination consistent with the Middle Ages. Such a bias in mapping Etnean lavas, which are poorly located through historical accounts [13–15], was the main source of error in the pioneering work of Chevallier [8], five of the seven flows he used being incorrectly dated.

For Vesuvius, whose history goes back to the AD 79 eruption which buried the thriving Roman towns of Herculaneum and Pompeii, the DEMF agrees closely with that obtained from the French archeological curve [11]. This is particularly remarkable in the period 787–1139 when intense effusive activity produced numerous lava flows, some of which were erroneously attributed to the large 1631 eruption. Furthermore, very reliable information is given for the year 1302 by the Arso flow from the neighboring island of Ischia, where no further activity occurred in historical times and, therefore, where no confusion between recent lavas could have arisen.

These combined data provide a powerful tool for dating volcanic products of the past 2000 years or so in the central Mediterranean region. The method can be applied either to lava flows or high temperature emplaced pyroclasts, such as cinder cones or pyroclastic flow (nuée ardente) deposits. However, several problems and sources of error must be taken into account in order to achieve reliable results. The purpose of this article is to discuss these questions considering a total of more than a thousand 'big' samples, part of which (Etna, Ischia) were studied 20–30 years ago and reexamined, and another part (Vesuvius, Ischia, Etna) were recently collected and measured, or whose investigations are still in progress.

2. Levels of precision required and limitations of the method

Although the DEMF shows considerable changes in Western Europe through the past millennium (about 40° in declination and 20° in inclination), its irregular variation often requires discrimination of only a few degrees for successful archeomagnetic dating, so that the greatest precision is necessary. The classical core drilling methods used on volcanic rocks in paleomagnetism generally fail to reach sufficient accuracy for reconstruction of the DEMF and, therefore, reliable archeomagnetic data. Although some authors (e.g. [9]) obtained fairly good results through core drilling, other published data [16–18] present semi-angles of the 95% confidence cone of the average paleodirections ($\alpha95$) that often exceed 3 or 4°. Even when $\alpha95$ is smaller, this does not necessarily mean that the obtained paleodirection is accurate, as may be seen, for instance, by considering in [17] the Vesuvius flows of 1855, 1906 and 1944, whose paleodirections differ by 5–10° from the observatory instrumental measurements of DEMF at the respective dates. Such low quality results may be related to the small size of the samples which may make difficult their precise orientation both in the field and during laboratory measurements. But another source of error is due to the coring and sawing processes, which produce parasitic magnetizations [19,20]. The largest part of these can be removed through alternating field (AF) cleaning, however problems still remain because of the low AF resistance of the primary thermoremanent magnetization (TRM) in most of the volcanic samples. Finally, it has been observed that some workers take a number of cores all together within the same block 1 or 2 m across. This procedure, though giving sometimes apparently consistent results (low $\alpha95$), must be avoided as the average direction suffers from a systematic error in the case of displacement after cooling of the lava, or if it was magnetized in a locally disturbed region (see below, limitation 3).

For all these reasons we were led to reject all previously published archeomagnetic data which do not satisfy the high degree of precision required to achieve reliable results. At the St. Maur laboratory, our method involves big samples weighing 0.5–1 kg distributed over the tens of meters. Each block is first detached with a hammer and then replaced in its original position. Plaster of appropriate fluidity is poured on to support a plate carrying a spherical spirit level, thus making a horizontal surface 5–7 cm in diameter on which the sun shadow is marked for calculation of the geographical north. In the laboratory, the samples are replastered in square moulds 12 cm in size for measurements using a large rotating induction magnetometer and an AF demagnetization device for big samples [21]. If sawing is necessary for some of the samples, the parasitic magnetization then acquired is limited in extent to a thickness of a few millimeters around the sawing plane [19]. It is negligible, therefore, because of the relatively large size of the sample.

It must be pointed out that this method can also be applied with the same precision to volcanic pyroclasts emplaced at high temperature, such as pyroclastic flow deposits or welded scoriae from cinder cones and spatter ramparts, which are plentiful on Mount Etna and other volcanoes. Such a procedure, either applied to lava flows or pyroclasts, allows one to determine each individual paleodirection within a few tenths of a degree, as may be ascertained when making two independent sun shadow orientations at different times on the same sample, or by making several measurements of a sample on the inductometer.

During measurements, it was checked that the TRM is stable throughout time. The viscous remanent magnetization (VRM) usually represents less than a percent of the whole natural magnetization and is removed during AF cleaning of the sample. Occasional low intensity isothermal remanent magnetization (IRM) was in most cases removed through AF cleaning to 15–20 mT r.m.s. (less than 1° difference between 15 and 20 mT measurements). The retained declination and inclination were determined after the last AF demagnetization. We preferred to stop the AF cleaning processes when the paleodirection becomes stable rather than going to higher AF values because of the often low resistance of TRM which makes it difficult to isolate the primary paleodirection.

Results obtained (Tables 1 and 2, and unpublished data) show that the $\alpha95$ confidence circles range from 0.6 to 1.8° and usually remain around 1°, except for a few cases regarding pyroclasts that were emplaced at low temperature during phreatic or phreatomagmatic activity (not considered here). This high level of precision can sometimes enable us to distinguish between volcanics whose ages differ by only a few decades. Moreover, the archeomagnetic dating is essentially linked to the shape and reliability of the reference DEMF curve and, therefore, is not expressed as a percentage of the result as currently done in other geochronological methods. This means that mate-

Table 1
Magnetic directions and ages of volcanics from the present to AD 800

Volcanic units (E = Etna, V = Vesuvius)	*N*	α95 (°)	*k*	*I* (°)	*D* (°)	Magnetic age (years AD)	Given eruption (years AD)
E 1910 flow on south flank	10	1.35	1070	51.3	−7.5		
E 1865 flow on NE flank, Citelli road	14	1.3	824	51.5	−10		
E 1843 flow on W flank, 2 km south of Bronte	12	1.12	1552	53.2	−14.2		
E 1792 flow on SE flank (three sites)	18	1	1099	56.1	−15.1		
E 1780 flow on south flank (four sites)	32	0.97	651	56.6	−16.2		
V 1754 or 1767 flow near Boscotrecase (S flank)	8	1.32	1412	56.9	−15.9		
E 1763 flow near cable car lower station	9	1.08	1861	57.7	−13.1		
V 1701 flow on east flank (Pozzelle alta)	11	0.6	4870	64.1	−11.6		
E 1669 flows on the lower south flank (four sites)	30	0.71	1310	62.5	−3.3		
E presumed 1689 flow above Fornazzo (two sites)	16	1.17	891	63.3	−2.2	1660 ± 20	1651
E 1646 flows on north flank (two sites)	15	0.84	1856	61.5	−1.9		
E presumed 1566 flow on N flank (*Sciara Nuova*)	13	1.02	1458	59.9	2.3	1610 ± 20	1614
E 1610 flow on SW flank	10	1.61	750	60	3.5		
E presumed 1536 A flow on the upper NW flank	6	1.67	1172	59.4	4.8	1600 ± 30	1607
E 1536 flow on south flank (two sites)	21	1.04	855	56.5	8.7		
E 1408 flow above Pedara village (SE flank)	15	1.23	863	48.5	9.3		
E presumed 1408 A flow, contrada Ragalà (three sites)	26	1.1	621	46.4	7.5	1360 ± 30	1381?
E 1329 cinder cone of Monte Rosso, E flank	10	1.04	1824	45.1	7.1		
Ischia 1302 Arso flow (three sites)	22	1.07	771	44.8	9.3		
E presumed 1444 flow east of Tre Monti, SE flank	16	1.2	850	45.3	12	1270 ± 20	1284
E presumed 1536 B flow west of Mt. Vetore	11	0.91	2139	45.4	13.7	1250 ± 20	1250?
E presumed 1595 A flow on SW flank (upper Gallo Bianco flow)	10	1.2	1351	48.9	15.1	1200 ± 30	1197 or 1222?
E presumed 1566 flow at Linguaglossa (two sites)	19	1.4	525	49.7	17.7	1180 ± 30	1194 or 1197?
E presumed 1381A flow at Gravina on south flank	12	1.41	815	51.1	18.6	1160 ± 30	1169?
V P17 Middle Age flow at Passanti, eastern base of Vesuvius	7	1.48	1284	54.1	18.7	1140 ± 50	1139
V P04 flow on south flank, 170 m elevation	13	1.33	853	54	16.4	1140 ± 40	1139
E presumed 1595 B flow (lower Gallo Bianco flow)	16	1.44	591	56	17	1060 ± 30	1062

Table 1 (*Continued*).

Volcanic units (E = Etna, V = Vesuvius)	*N*	α95 (°)	*k*	*I* (°)	*D* (°)	Magnetic age (years AD)	Given eruption (years AD)
V P01 upper flow at Villa Inglese, southern base	15	1.18	943	56.9	19.3	1050 ± 30	1037?
E presumed 1329 Mt. Ilice cinder cone and large flow at sea near Stazzo (four sites)	37	0.86	720	57.2	16.2	1040 ± 20	
E presumed 1651 east flow (Scorciavacca)	15	1.44	627	57.5	15.1	1030 ± 40	
V P09 cinder cone of Fossa Monaca, S flank	7	1.3	1650	57.7	18	1020 ± 40	999?
V P02 lower flow at Villa Inglese	9	1.45	1040	57.9	16	1010 ± 50	999?
V P14 flow at sea near Villa Balke (Scogli di Prota)	10	1.76	634	57.9	18.2	1010 ± 50	999?
V P03 flow at sea near Torre Scassata	14	1.08	1199	58.1	15.2	1000 ± 30	999?
E presumed 812 or 1169 cinder cone of Mt. Sona and large flow towards Paterno, SW flank (three sites)	25	0.9	883	58.1	14.6	1000 ± 20	
V P26 presumed 1697 flow above Torre del Greco	10	1.66	711	58.4	16.9	980 ± 50	1006-07?
E presumed 1536 C lower flow on NW flank (Sciara del Pomiciaro)	16	1.23	809	60.5	17	950 ± 30	
V P15 flow at Torre Bassano, lower SW flank	14	1.01	1385	60.8	16.2	940 ± 30	968
V P23 flow, Masseria Bosco del Monaco, S Base	9	1.2	1523	59.9	13.1	920 ± 30	
V P18 flow at sea, Scogli della Scala, SW flank	14	1.64	520	61.7	12.8	900 ± 40	
V P28 Oncino flow at Torre Annunziata	11	1.1	1484	61.4	11.7	900 ± 30	
V P16 flow at sea, S. Vincenzo Postiglione	10	1.16	1454	64.7	11.2	870 ± 30	
V P06 flow, Terrioni quarry, upper E flank	5	1.24	2563	64.4	6.4	850 ± 40	
E presumed 1408 B flow, Trecastagni North	11	1.23	1176	66.6	3.8	800 ± 30	

The volcanic units include lava flows, cinder cones or pyroclastic flow deposits. The results are presented in order of increasing magnetic ages determined using both the FAMC and SIVC curves (see text – note that the error bars do not take into account uncertainty on reference curves). Presumed ages of Etna lavas are from [15], which compiles data from [13,14,28]. For discussion regarding the ages of given eruptions (last column), see [29]. Ages of Vesuvius and Ischia lavas are from [32–34]. All the magnetic directions are reduced to the coordinates of Etna (37.75°N, 15.00°E of Greenwich).

rials several thousand years old could, at least theoretically, be dated with this same precision of a few tens of years as well as the more recent ones. Practically, however, it is clear that the reference curve is known with increasing uncertainty when going back further into the past, and we will see below (Section 4) that there is considerable deterioration in the quality of information for the period older than about AD 500.

In addition to this fundamental problem of accurate knowledge of the DEMF in the distant past, other limitations to archeomagnetic dating are of several kinds.

1. The path of the DEMF appears to be quite irregular with time. In some cases, the DEMF does not change significantly for periods reaching a century or more (see Section 4, early Roman period).
2. This particular path of the DEMF means that in the past there are a number of cases where it was nearly identical. Thus an increasing number of ambiguities is to be expected, for dating purposes, when going back further into the past. For example the DEMF was quite similar around AD 1650 and AD 600–700 (Figs. 1 and 2). There is actually no concern for these dates because of the evidently fresh morphology of lava flows or pyroclasts only 350 years old, but the problem cannot easily be resolved for historically ancient volcanic outcrops, samples showing indistinguishable paleodirections possibly belonging to various epochs. For these older lavas, however, other means can be used for avoiding uncertainty such as stratigraphy, archeology or radiochronology. In the Etna case, a new method based on Ra–Th disequilibria is being developed [22], which is suitable for very young rocks (last 8000 years) from this volcano. Though less precise than archeomagnetism, this method is of the greatest interest for resolving the uncertainties mentioned above.
3. The Earth's Magnetic Field within a cooling lava flow may be affected by a distortion owing to the magnetization of underlying lavas and also to the earlier magnetized parts of the cooling flow itself [23]. Our study shows that this latter effect seems predominant and that the total magnetic effect of the volcanic pile is generally negligible. The best results were obtained on samples taken near the interface between surficial scoriae and the massive part of the lava flow which acted at the time of cooling as a magnetic insulator between the already magnetized upper part and the still hot main body. Similarly, instrumental measurements of the present Earth's Magnetic Field performed on various archeomagnetic sites distributed over the whole area of Mount Etna, by using a three-component flux gate magnetometer (Tanguy and Le Goff, in preparation), revealed a generally weak distortion of the field provided measurements are carried out at least 30 cm away from the lava surface.

Taking in mind these considerations, we were led to collect our samples over a distance of at least several tens of meters, and whenever possible at several sites for the same eruption. This procedure ensures the accuracy of the results and offers also a guarantee against possible movements of the lava during cooling. Indeed it is not always easy to be sure in the field whether the rock was in its final position during or after cooling, nor whether the outcrop had not been upset by the effects of the last movements during emplacement of the flow.

3. The French Archeological Magnetic Curve (FAMC)

The French archeomagnetic curve was drawn by using 120 well-dated archeological structures (kilns), selected over a total of more than 200 sites thoroughly sampled and measured during the pioneering work of Emile Thellier [1], followed in the same manner by Ileana Bucur [2]. Precision on selected results is of the same order as described above, with $\alpha 95$ usually between 0.3 and 2° and only rarely exceeding this latter value. The sites are distributed over the whole area of France and neighboring Western Europe, so that, for almost every site, change of coordinates was necessary in order to gather the data at a unique place chosen as the city of Paris (48.9°N, 2.3°E). This change of coordinates was made through the method of the virtual geomagnetic pole. Such a calculation introduces an additional error estimated to be less than 2° [2]. Although small, this correction implies that the overall precision on each archeological site is not so good as that obtained from samples on a single volcano, where changes of coordinates between the various sites are negligible. Uncertainties coming from archeological dating range between 0 and ±120 years. Although the studied sites are distributed in a span of time going from about 560 BC to AD 1830, their distribution is rather irregular and almost half of them can be considered as clustered within

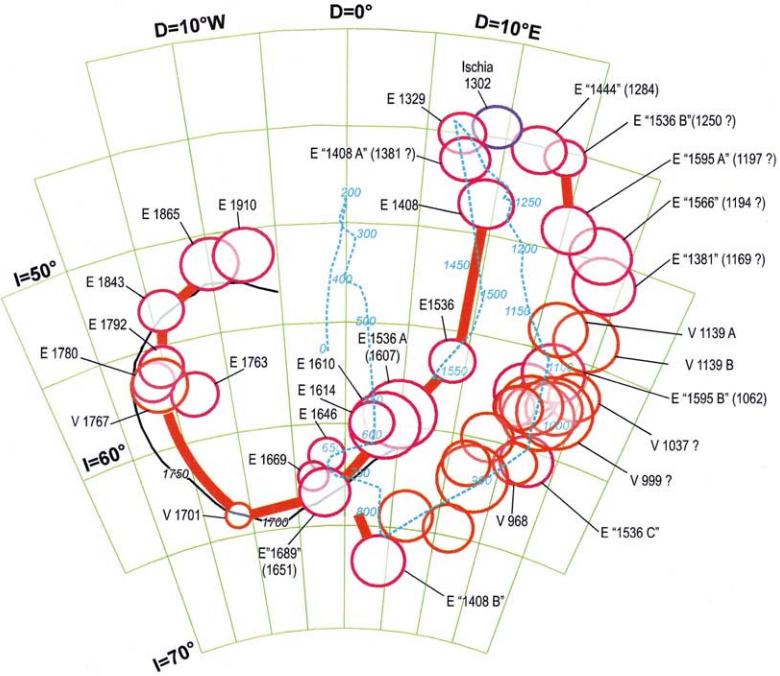

Fig. 1. SIVC from the present to AD 800 (thick red line, E = Etna, V = Vesuvius lavas, see Table 1). The thin solid line represents a synthesis of instrumental measurements from the last four centuries for Western Europe [1] and Paris [27], reduced to the coordinates of Etna. Dates with quotation marks indicate Etna lavas of presumed age, with the new suggested ages within brackets (see text). The blue dashed line represents the French archeomagnetic curve reduced to the coordinates of Etna.

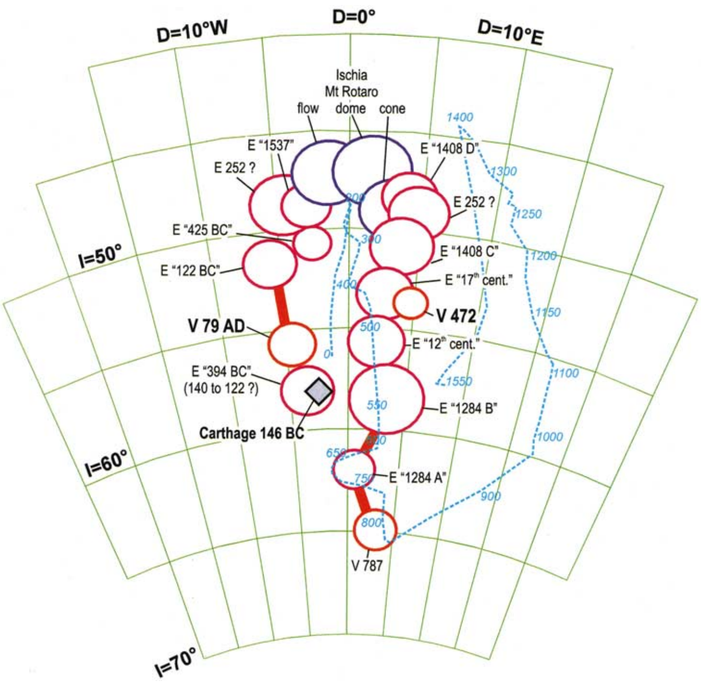

Fig. 2. SIVC from AD 800 to 150 BC (see Table 2). Data on the 146 BC archeological site are taken from [1].

the first six centuries AD. Only a few sites were studied belonging to the last four centuries and, paradoxically, the FAMC is less certain for the recent period than for the Middle Ages.

Thanks to the large number of sites generally available, the DEMF curve has been established by calculation of the bivariate mean vector [24] of the directions contained within an 80 year window, displaced through steps of 25 years each (see fig. 4 in [2]). This method minimizes the disturbing effect of some poorly reliable sites and gives larger weight to the average of all sites over periods of 80 years and, therefore, a better precision of the resulting DEMF curve. An improved procedure is being developed [25] which takes into account the irregular time distribution of the results. By using the same results as above, a new curve is obtained which shows a similar path in a spherical projection, however with some slight differences related to the dates which are unevenly distributed owing to the variability of the sliding windows with time.

4. The South Italian Volcanic Curve (SIVC)

In contrast to the FAMC which involves archeological objects whose ages are more or less uncertain, the SIVC considers well-known eruption dates for which, however, the objects (i.e. the lavas) are often misidentified. This is because lava flows and eruptive centers older than a few centuries were obviously not mapped, and sometimes not even located by contemporaneous historians. Thus a large part of the following discussion deals with the various degrees of confidence regarding identification of the studied lavas.

4.1. Period from the present to AD 800 (Table 1 and Fig. 1)

The SIVC can confidently be retraced backwards to AD 1300 by using historically dated lavas that are identified by means of sufficiently precise sources of information [10,11]. These lavas come from Etna (37.75°N, 15.00°E), Vesuvius (40.83°N, 14.42°E) and Ischia island in the Gulf of Naples. The SIVC thus obtained is in close agreement with the FAMC [2], when recalculated to Sicily by assuming a purely dipolar geomagnetic field [2,12]. It compares well, also, with instrumental field measurements which are available for the last four centuries [26,27]. Regarding the most ancient instrumental measurements, it must be pointed out that their precision is subject to caution, and uncertainty may reach as much as 7° [26]. With respect to these instrumental results, however, the constantly lower inclination shown by volcanic and archeological materials (1–2°) could be the result of some magnetic distortion effect owing to their relatively high magnetization [23]. This deflection is not subsequently a problem because archeomagnetic dating is basically a comparison between various archeomagnetic curves and does not take into account instrumental measurements.

As previously demonstrated for Mount Etna [10,11], several flows presumed to have erupted within the period from 1651 to 1284 present in fact magnetic directions which are consistent with dates in the Middle Ages. Their spurious assigned dates result from the poor quality of old topographical descriptions and also from incorrect interpretations of the primary documents by later authors, mostly writers from the past two or three centuries. These writers had no geochronological method at their disposal to distinguish, in the entanglement of morphologically recent flows, those which genuinely correspond to eruptions reported by historians. For example, the 'Scorciavacca' flow on the eastern flank of Etna, which appears undated on the earlier maps [13,14], was ascribed to '1651' only by Chaix [28] and subsequent authors [15]. Actually, reexamination of a contemporary account [29] shows the 'true' 1651 east flow to lie about 5 km southwards, where it has been confused with that of another eruption occurring in 1689 (see also Table 1).

A second example is provided by the '1595' flow, which in fact corresponds to two magnetically and chemically distinct flows. These are similarly undated in documents published before the middle of the 19th century. The date of '1595' appears for the first time in the Sartorius Atlas of Etna [13] although this author himself does not

Table 2
Magnetic directions and ages of volcanics from AD 800 to 150 BC

Volcanic units (E = Etna, V = Vesuvius)	*N*	α95 (°)	*k*	*I* (°)	*D* (°)	Magnetic age (years AD or BC when specified)	Given eruption (years AD or BC when specified)
V P21 flow at Masseria Galassi, lower southern flank	15	0.98	1374	65	3	800 ± 20	787
E presumed 1284A flow on eastern flank, north of Zafferana	12	0.87	2158	62	0.7	700 ± 50	
E presumed 1284B flow above Zafferana	7	1.7	971	58.5	3.3	550 ± 50	
E presumed 12th century flow downslope Mt. Ciacca, S flank	9	1.3	1358	55.7	2.2	520 ± 50	
V AD 472 pyroclastic flow at Pollena quarry, non-welded large pumice clasts	13	0.76	2596	53.7	4.7		472
E presumed 17th century flow near Bronte, W flank	8	1.3	1504	53.3	2.7	450 ± 50	
E presumed 1381B flow, Catania circonvallazione	8	0.9	2839	52.8	2.1	420 ± 40	
E presumed 1408 C flow above S. G. La Punta (two sites)	14	1.42	697	50.9	3.7	350 ± 50	
E presumed 252 flow at the southern base of Monpeloso cinder cone, S flank	13	1.3	833	49.2	4.7	300 ± 100	252?
E presumed 1408 D flow 3 km downslope of Monpeloso	8	1.22	1633	48.4	4	300 ± 100	252?
Ischia cinder cone of Mt. Rotaro, second–third century	15	1.58	520	49.4	3.1	300 ± 100	
Ischia lava dome of Mt. Rotaro, second–third century	7	1.82	849	47.2	1.3	250 ± 100	
Ischia, lava flow from Mt. Rotaro at Casamicciola, second–third century	11	1.71	607	47.2	−1.5	200 ± 100	
E presumed 1537 flow below the cable car station	9	1.09	1835	48.9	−2.9	200 ± 100	
E presumed 252 flow at Cibali, NW part of Catania	11	1.5	780	48.8	−4.4	200 ± 100	252?
E presumed 425 BC flow at sea via Rotolo, Catania	10	0.84	2792	50.8	−2.6	150 ± 100, or prehistoric	
E presumed 122 BC flow at Piazza Goieni, N Catania	7	1.2	1952	51.7	−5.7	100 ± 100, or prehistoric	
V AD 79 pyroclastic ash flow including large pumice clasts, Herculaneum excavations	11	1.06	1573	55.8	−4.6		79
E presumed 394 BC flow NE of Mt. Gorna cinder cone on SE flank	14	1.19	985	58.1	−3.5	100BC ± 50	140–122 BC?

Same caption as Table 1. See text for discussion regarding the presumed AD 252 lava flow(s) of Etna.

mention any eruption for this particular year in his further compilation [14]. Furthermore, contemporaneous witnesses pointed out that Etna had been inactive for 30 years before 1603 [30]. As no historical document alludes to this phantasmal eruption, we suggested ([31], p. 136) that 1595 was misleadingly read and printed instead of 1535, when another lava flow is sometimes reported in the same region [14].

Such misconceptions are clearly inevitable. For a volcano which has been strongly active during the past millennia, it is difficult to be precise about the exact locality of its eruptive products. It is relevant to note that modern historians ascribed most of the morphologically recent flows to dates beginning in 1284, because it was merely at the end of the Middle Ages that reports of eruptions became available. A full discussion regarding the complicated history of Etna is given elsewhere [29,31].

These erroneously dated historical lavas of Etna are nevertheless used here to reconstruct the shape of the SIVC beyond 1300 into the past (Fig. 1), making the assumption that their fresh morphology precludes them being older than the Middle Ages. Some of these flows are tentatively attributed to other eruptions mentioned in history, although their location remains unspecified (1250, 1222, 1197, 1194), or the eruptions themselves are doubtful (1169). For the other medieval volcanics only an approximate date is given, the ± values on the magnetic ages being a mere indication obtained by extending the $\alpha95$ circles to the nearest part of the FAMC. For the 1150–1400 period, however, the SIVC curve is preferred because of several well-dated eruptions (1139 at Vesuvius, 1302 at Ischia, 1329 and 1408 at Etna) whose products are clearly identified and define a more reliable reference curve.

The Vesuvius eruptions prior to 1631 were less frequent than those of Etna and often very powerful, so that they had a large impact in a region highly civilized since the Roman epoch. The cataclysmal outbursts of AD 79 and 472 produced thick fallout and pyroclastic flow (nuée ardente) deposits that cannot be confused with products of other activities. Indeed the famous 'Letters' from Pliny the Younger represent the oldest true volcanological document, but other historical accounts exist for the entire period 79–1631 [32,33]. Most of the volcanics described in these documents overlie the 79 and/or 472 deposits on the southern side of the volcano, and this confirms that they were necessarily erupted from the Middle Ages onwards. However, for the same reasons of poorly known topographical details, the medieval Vesuvius flows are not precisely mapped, and today the intensively urbanized area preserves only rare outcrops. Therefore, we have shown in Table 1 a selection of representative sites, some of them probably belonging to the same eruption because of their statistically identical paleodirections. Conversely, owing to the rapid succession of effusive eruptions (e.g. 968, 991, 999, 1006–0707, ...), some volcanic units, whose error bars on paleodirections exceed the time span considered, are suitable candidates for several different eruptions, although only the most likely one (followed by a question mark) is indicated in Table 1. A comprehensive discussion of the stratigraphical and volcanological arguments leading to this choice is presented in [33].

In conclusion, there is excellent agreement between France, Etna and Vesuvius for reconstructing the DEMF during the periods 800–1150 and 1400 to the present (Fig. 1). The small, but significant (3 ± 1.5°) discrepancy shown for the period 1150–1400 could be attributed to the poor quality of some archeological data used in building the FAMC (for instance, had some archeological sites between 1400 and 1450 dated only 100 years earlier, this would affect the shape of the curve because of the strong variation in inclination at that time, see discussion in [11]). Investigations which are now in progress indeed show that the FAMC should be displaced eastwards for the period 1150–1300.

4.2. Period from AD 800 to 100 BC (Table 2 and Fig. 2)

For the period prior to AD 800 the reliability of historical accounts becomes very poor, except at Vesuvius for the large Plinian outbursts of 472 and 79. A Vesuvius lava flow suspected to have occurred in 685 is actually inaccessible to sampling because it is buried beneath the present foundations of the town of Torre del Greco. On Ischia island the ages of several outcrops are constrained by archeological data, the most consistent of which being referred to the Mt. Rotaro complex (second to third century [34]). At Mount Etna the only eruption recorded by history with a reasonable degree of confidence is that which occurred a year after St. Agatha had been martyred in Catania, i.e. in February 252. However the original report (Acts of Saints from the Bollandists) does not specify the exact location of the flow. Following this uncertainty, two sites were attributed by Sartorius to this eruption [14]: the large Cibali flow west of Catania and the Monpeloso cinder cone and flow on the lower south flank. Although the lavas from both sites are magnetically consistent with a late Roman epoch, their respective averaged paleodirections differ by more than 8° (Fig. 2) and this means, therefore, that they could not have resulted from the same eruption.

As with the period 1300–1000, the shape of the SIVC may be traced between AD 800 and 100 BC by making the assumption that some of the wrongly dated historical Etnean lavas belong to this period (e.g. presumed 1284 flows near Zafferana, Table 2). The curve thus defined represents a coherent path passing through the points corresponding to the Vesuvius pyroclasts from 472 and 79, and finishing with the exceptionally well-dated archeological site of Carthage in 146 BC [1]. This site is also of particular interest because of its proximity to Sicily, needing only a small correction for change of coordinates.

Compared to the FAMC, the SIVC shows significant discrepancy between AD 100 and 400, a fact already explained [11] by the up and down motion of inclination with small variation of declination, leading to a poor discriminative power for archeological materials whose ages are known with an error bar sometimes exceeding a century. Indeed the FAMC, while in relatively good agreement with the 472 paleodirection at Vesuvius, then deviates from the SIVC and finally differs by about 60 years from the direction given by the AD 79 Pompeii eruption. Whatever the cause(s) of these discrepancies, the result is that the precision of archeomagnetic dating for the period from 100 BC to 500 AD is much lower, probably on the order of ± 100 years. This is the consequence of both imprecise archeological dating and restricted variation of the DEMF during the period considered.

5. Dating volcanics from the Mediterranean area

Archeomagnetic dating is the reverse application of the direct problem of reconstruction of the DEMF curve and is strongly dependent, therefore, on the state of advancement of this primary research. Particularly, the same careful and precise methods of sampling and measurement must be carried out for materials that are to be dated, and all the possible limitations listed in Section 2 must be taken into account. Although it is well known that the DEMF shows a very different path all around the Earth, the remarkable agreement between the FAMC and SIVC curves leads us to suggest that these reference curves may be used within a radius of about 2000 km around Sicily, i.e. for the whole Mediterranean area, which is the right order of magnitude for the typical spatial correlation length of secular variation.

For Etna, we have already shown that lava flows previously ascribed, on entirely inconclusive grounds, to eruptions occurring in 1689, 1651 (east flank), 1595, 1566, 1537, 1536 (particularly NW flank), 1444, 1408, 1381, 1329, 1284, 1169 or 812, are in fact of different, usually older ages (see Fig. 1). These volcanics represent more than 80% of the dated Etnean products in the span of time considered (Table 1), and discrepancies currently reach several centuries, sometimes more than a millennium. For the period between AD 800 and 150 BC (Fig. 2) the situation is still worse, and only two eruptions (AD 252 and 122 BC) may have lava flows that fit the reference curve, though at least one of these must be discarded because of the significantly different paleomagnetic directions of the two presumed 252 lavas. Other flows or cinder cones presumed to have erupted in 122, 394 (or 396) and 425 BC show paleodirections clearly inconsistent with these dates, as most of the related flows could either belong to the late Roman epoch, or be older than 3000 years [6]. Conversely, it appears evident that many eruptions from the 100 BC to 800 AD period went unnoticed by historians, as testified by the numerous morphologically recent lavas whose magnetism is compatible with the Roman and Middle Age times. Most of these latter cases are not taken into consideration here, and a comprehensive paper on archeomagnetic results regarding the history of Etna will be published later.

At Vesuvius almost all the prospected lavas or pyroclasts, whose stratigraphy is well constrained between the AD 79 and 1631 deposits, fall within the 750–1150 period (Figs. 1 and 2 and Tables 1 and 2). As for Etna, the archeomagnetic results show that several eruptions went unrecorded, but the better availability of historical documents enables us to ascribe several outcrops to the well-defined eruptions of 787, 968, 999, 1006–1007, 1037 and 1139 [33]. Conversely, two lava flows believed to be of Middle Age times were found to date from the 18th century, their paleodirections being consistent with those expected for the 1701 and 1767 eruptions. No lava flow was found belonging to the 79–787 and 1139–1631 inter-eruptive periods, and it appears that volcanic activity at these times was either uniquely explosive or very weak. It is definitely concluded that the large 1631 eruption did not produce any noticeable lava flow, as already stated from reexamination of the many historical sources pertaining to this awful event [35].

Investigations are in progress on the Aeolian Islands (Vulcano, Lipari, Stromboli) and only one surprising result will be given here. It deals with the Rocche Rosse obsidian flow, which represents the last historical eruption in the island of Lipari [36]. This flow issued through a breach on the northern side of the Mt. Pilato pumice cone, and is classically related to the end of an explosive eruption that built the cone. The pumice eruption was perhaps that witnessed by the monk St. Willibald in AD 729, although reports in Vitae Willibaldis relate more probably to eruptions of the neighboring island of Vulcano (Keller, personal communication). On the other hand, tephrochronology and ^{14}C dating on wood carbonized by the pumice fall indicate a later date, around AD 800 [37]. Archeomagnetic data from the obsidian flow samples distributed over three different sites ($I_{Etna}=47.8°$, $D=15.6°$, $\alpha95=1.8°$) give a still more recent date of AD 1220 ± 30 years, well constrained between the 1302 flow from Ischia and the 1139 flow from Vesuvius. This result would mean that the major eruption building Mt. Pilato was followed by another one about 400 years later, which produced the obsidian flow. The gentle character of this effusive stage would explain the lack of historical information at a time of political trouble in Sicily.

Other geologically recent volcanics from southern Italy and Greece may be investigated through the archeomagnetic method presented here. In fact, it must be pointed out that results previously published on this matter by other authors ([16–18,38,39] and references therein) suffer from a lack of precision or/and matching the obtained results with the wrong part (in time) of their reference curve. This latter point is mainly because of erroneous ages attributed to the presumed '1697' and '1631' Vesuvius flows, which actually erupted during the Middle Ages (see our Table 1, VP 26 and VP 14, 16, 28). Such a misconception led some authors to confuse the AD 1600–1300 period with that of AD 1300–900 [18,38]. Moreover, the same authors recently adopted a new secular variation curve [39] with a most unlikely 15° change between '1169' and '1284', and then a further eastward trend for accounting to the presumed '1631' flows which actually never existed [35].

6. Conclusion

Lava flows and high temperature pyroclasts from the last 1500 years in the Mediterranean area can be dated with an excellent precision (± 40 years) through the 'big sample' archeomagnetic method developed at St. Maur laboratory. This method involves collection of samples weighing 0.5–1 kg, whose magnetization can be determined with an accuracy of a few tenths of a degree by means of the rotation inductometer and AF cleaning device specially designed for measuring objects 12 cm across. Age determination is based on a comparison between the secular variation of the direction of Earth's Magnetic Field in France (well-dated archeological sites) and southern Italy (historically dated volcanics from Etna and Neapolitan volcanoes). The quality of dating crucially depends on a careful magnetic study of each site, with samples distributed over at least several tens of meters, and on the reliability of the reference curve at the epoch considered. Because of increasing uncertainty on the knowledge of secular variation and owing also to its smaller change during Roman times, volcanics from the period AD 400 to 150 BC are likely to be dated with a lesser precision (± 50 to ± 100 years). Dating further into the past is hindered by greater ambiguity owing to the fact that the

Earth's Magnetic Field presents more cases of identical or very similar direction. However, useful information may be obtained when the age of each individual case is ascribed to a defined time span by means of traditional geochronological methods such as archeology, stratigraphy, and radioactive disequilibria. Finally, high precision archeomagnetic dating of volcanic materials which are widely distributed over Mediterranean Europe has evident implications not only for the succession of eruptions and understanding of volcanic hazards, but also from a fundamental research standpoint to obtain a better knowledge of the Earth's Magnetic Field [40,41].

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