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How accurate is "paleomagnetic dating"? New evidence from historical lavas from Mount Etna

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[1] In the last years, paleomagnetism has been increasingly used to provide emplacement ages of loosely dated volcanics. Dating is achieved by comparison of paleomagnetic directions with a given reference curve of the paleosecular variation (PSV) of the geomagnetic field. Recently, a debate has developed on the achievable precision (the α_{95} value) of the paleomagnetic directions and hence on the accuracy that "paleomagnetic dating" can yield. At 39 different sites from Etna we paleomagnetically investigated 13 flows (four "test flows" with known age, and nine loosely dated flows), emplaced between 122 B.C. and 1865 A.D. We systematically drilled 12 cores per flow spaced in three (far from each other) sites and demagnetized one specimen per core by alternating field cleaning. Results from the four test flows yield age windows effectively encompassing the respective true flow ages, when dating based on Bayesian statistics at a 95% confidence level is adopted. We find α_{95} values for the flow mean directions ranging between 3.3° and 5.7° (4.5° on average), which translate into accuracies of age determinations of 136–661 years (307 years on average). Such dating uncertainty is likely underestimated, as we disregarded several kinds of errors that might affect both the fidelity of paleomagnetic recording and the PSV reference curve. The strong magnetization of both the underlying terrain and the cooling flow itself and mineral magnetic variations across the flows are the most likely sources for the scatter characterizing the recording process of the magnetic field in volcanic rocks.

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1. Introduction

[2] It is has been known for over two decades that the paleomagnetism of volcanics may yield emplacement age clues, once the paleomagnetic directions retrieved from loosely dated flows are compared to an independently obtained reference curve of the paleosecular variation (PSV) of the geomagnetic field. This approach was attempted at Etna almost a century ago [*Chevallier*, 1925] and was successfully applied more recently to lavas from Vesuvio [*Hoye*, 1981] and Etna [*Tanguy et al.*, 1985; *Rolph and Shaw*, 1986]. This "paleomagnetic dating" method may represent in principle the most powerful dating tool for recent (i.e., up to few thousand years ago) volcanics, where soils (datable by ^{14}C methods) hardly develop if the eruption rate is high. Furthermore, detailing the eruption ages for the last few centuries or millennia is fundamental to constrain the future hazard, as eruptions are often framed into repetitive "volcanic cycles," displaying similar characteristics both in terms of types and timing of eruptions.

[3] Unfortunately, at present there is not an overall consensus above the accuracy of the age determinations that paleomagnetic dating may yield. While some authors suggest that an age accuracy of ±20–30 years can be safely achieved [*Tanguy et al.*, 2003; *Arrighi et al.*, 2004; *Principe et al.*, 2004], others observed a quite large scatter among paleomagnetic directions from the same flow, which may translate into significantly greater uncertainties on the age determinations [*Hagstrum and Champion*, 1994; *Rolph*, 1997; *Quidelleur et al.*, 2005; *Lanza and Zanella*, 2006]. Recently, the disagreement between the paleomagnetic directions retrieved from lava flows emplaced between 1943 and 1946 A.D. at Paricutin volcano (Mexico) and the coeval direction of the geomagnetic field, has even questioned the reliability of this dating method [*Urrutia-Fucugauchi et al.*, 2004].

[4] Etna is an excellent test site to understand if, and to what extent, paleomagnetism may serve as a dating tool of recent volcanics. Because of its almost continuous volcanic activity, and to constant human presence since some millennia ago, it hosts a wealth of flows emplaced during the last two-three millennia which either are exactly dated, or range in well constrained age windows. Furthermore, as

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PSV reference curve for the last three millennia it is possible to use at Etna the relocated French archeomagnetic curve [*Bucur*, 1994; *Gallet et al.*, 2002], which has probably no equals in the world regarding the number of data and precision. Therefore, by paleomagnetically studying the Etna lavas, we should derive (in principle) the maximum accuracy achievable by paleomagnetic dating.

[5] Here we report on the paleomagnetic directions gathered at 39 different sites from 13 Etna flows, 4 "test flows" precisely historically dated between the late 12th century and 1408 A.D., and 9 emplaced in different time windows comprised between 122 B.C. and 1865 A.D. Each flow was systematically sampled at three different sites as far as possible from each other, drilling four cores per site. The flow mean paleomagnetic directions were evaluated systematically retaining all twelve individual directions, isolated by stepwise alternating field magnetic cleaning. The flow mean directions were compared to the relocated French archeomagnetic curve to check the consistency between the historical and paleomagnetically inferred ages (for the 4 test flows), and evaluate the ages (and relative uncertainties) of the remaining nine loosely dated flows.

[6] Our work may serve to better understand the potentiality of the paleomagnetic dating tool on volcanic products, and to try to codify the sampling procedures, laboratory analyses, and data treatment to be used when a given dating accuracy is required.

2. Sampled Flows and Historic-Stratigraphic Age Constraints

[7] Since the 1990s, geological mapping was performed at Mount Etna with the aim of realizing a new 1:50,000 scale geological map, fully based on updated volcanostratigraphic criteria [*Branca et al.*, 2004a, 2004b]. Relying on such detailed and updated volcanic stratigraphy, the geological evolution of the volcano was subdivided in four phases. The lava flows of the last stratovolcano phase, erupted during the last 15 kyr, cover about the 85% of the Etna edifice [*Branca et al.*, 2004c].

[8] Two pyroclastic fallout deposits, widely distributed along the eastern flank of Etna, represent the marker beds constraining the age of the lavas emplaced during the last 15 kyr. Such deposits were generated by a sub-Plinian eruption dated at 3930 ± 60 a BP (FS tephra layer of *Coltelli et al.* [2000]), and by a Plinian eruption in 122 B.C. (FG tephra layer of *Coltelli et al.* [1998, 2000]). The definition of the stratigraphic relationships between the lava flows and the FG tephra layer allowed *Branca et al.* [2004a, 2004b, 2004c] to recognize lava flow fields of unknown age (but younger than 122 B.C.) and to try correlating them with the eruptions reported in the historical sources.

[9] Relying on such updated stratigraphy at Etna, as well as on new geological information gathered by us, we paleomagnetically sampled 13 distinct lava flows (using Etn01 to Etn13 code names) from the post-122 B.C. lava succession (Figure 1 and Table 1). Here we briefly describe all sampled flows, as well as the historic-stratigraphic constraints on their emplacement age.

[10] The Cavolo (Etn01) 8.5-km-long lava flow field reaches the Ionian Sea at the Ognina locality of Catania. Its eruptive fissure includes two small scoria cones (Mount Arsi di Santa Maria and Mount Cicirello), located between the towns of Mascalucia and Gravina, at 450–350 m elevation. In the geological maps of *Sciuto Patti* [1872], *Waltershausen* [1880], *Romano et al.* [1979], *Romano and Sturiale* [1981], and *Monaco et al.* [2000], it was attributed to the 1381 eruption, following the historical accounts from Simone da Lentini [e.g., *Alessi*, 1829–1835].

[11] The Monpeloso (Etn02) lava flow field was generated by the large Monpeloso scoria cone, located at 850 m on the southeastern Etna flank. The frontal portion of the lava flow is well preserved at about 400 m elevation close to Mascalucia, yielding a total flow length of 6.8 km from the vent. It is largely covered by the San Giovanni La Punta (Etn03) lava flow, and by the 1537 lava flow. *Waltershausen* [1880] attributed it to the 252 A.D. eruption relying on historical documents (Acta Sanctorum quoted by *Alessi* [1829–1835]). In the geological maps of *Sciuto Patti* [1872], *Romano et al.* [1979], *Romano and Sturiale* [1981], and *Monaco et al.* [2000] some lava flows located near Catania were associated to the Monpeloso flow and, consequently, assigned to the 252 A.D. eruption. Our new stratigraphic data exclude that such flows are related to the 252 A.D. eruption, since they underlie the 122 B.C. pyroclastic deposit. This geological datum is in agreement with several historical sources, stating that in 252 A.D. a lava flow only threatened Catania, without getting closer to it.

[12] The San Giovanni La Punta (Etn03) ~12-km-long and 4.5-km-wide lava flow field is located on the lower southeastern Etna flank, between ~1000 and 310 m (Figure 1). Besides overlying the Monpeloso (Etn02) flow, this great lava flow field partially underlies the 1408 A.D. (Etn04) lava flow, and other more recent lava flows (1537 and 1634–38 A.D.). It was attributed to the 1408 eruption (after the historical sources from Simone da Lentini as quoted by *Alessi* [1829–1835]) in the geological maps of *Waltershausen* [1880], *Romano et al.* [1979], and *Romano and Sturiale* [1981]. This attribution of the above authors is inaccurate, since the lava flow field reported in their maps does not correspond to the restricted area destroyed by the 1408 eruption (the Pedara village and the cultivated fields located just NW of it, e.g., Simone da Lentini, as quoted by *Alessi* [1829–1835]). Moreover, an age older than 1408 A.D. is confirmed by the age of the towns of San Giovanni La Punta and Viagrande, founded during the 13th century A.D. on the San Giovanni La Punta lava flow.

[13] The 1408 A.D. (Etn04) 7-km-long and up to 2-km-wide lava flow field is located on the lower southeastern Etna flank, between ~1050 m and 500 m. Its eruptive fissure is covered by recent lava flows (e.g., 1634–1638 and 1766 A.D. eruptions). In the geological maps of *Romano et al.* [1979] and *Romano and Sturiale* [1981] it was attributed to the 1444 A.D. eruption, relying on historical accounts from Pietro Ranzano as quoted by *Fazzello* [1558]. Such age attribution is incorrect, since Pietro Ranzano does not provide any information for the geographic location of this event. Conversely, the location of the Etn04 lava flow field is in good accordance with the localities destroyed by the 1408 eruption, as reported in the detailed source of Simone da Lentini as quoted by *Alessi* [1829–1835].

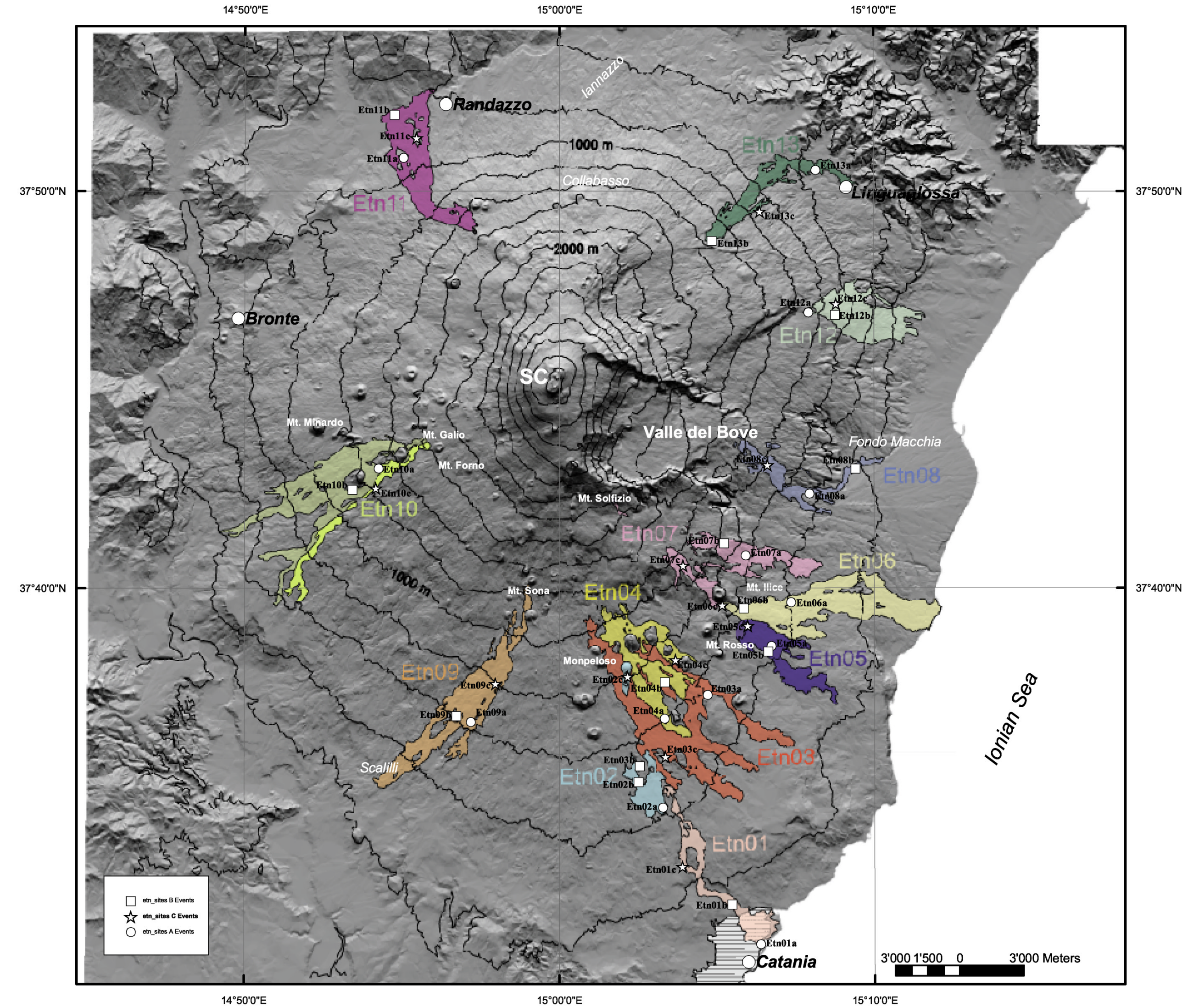

Figure 1. Digital elevation model of Etna and location of the studied flows and sampling sites. SC are the summit craters. Sites A (circles), B (squares), and C (stars) indicate the sites where we sampled the cores 01–04, 05–08, and 09–12, respectively, from each flow (see text and Table 1).

[14] The 1329 A.D. (Etn05) 5.5-km-long lava flow field is located on the lower eastern Etna flank, and reaches an altitude of ~240 m. Its eruptive fissure is formed by the large coalescent scoria cones of Mt Rosso, located at ~520 m, close to the village of Fleri. The 1329 lava flow field was incorrectly attributed to the 1334 eruption in the geological maps of *Waltershausen* [1880], *Romano et al.* [1979], and *Romano and Sturiale* [1981]. In fact the 1334 eruption is a false event, not reported in the historical sources [*Tanguy*, 1981]. The 1329 age proposed by *Tanguy* [1981] is based on well-documented eyewitness reports (N. Speciale as quoted by *Alessi* [1829–1835]).

[15] The Fleri (Etn06) 10-km-long lava flow field is located on the lower eastern Etna flank, and reaches the Ionian Sea close to the village of Pozzillo (Figure 1). Its eruptive fissure (at ~750 m) dissects the Mt Ilice scoria cone, and is formed by a small spatter rampart. This long lava flow is partially covered by the 1329 lava flows. It was wrongly attributed to the 1329 eruption in the geological maps of *Waltershausen* [1880], *Romano et al.* [1979], and *Romano and Sturiale* [1981].

[16] The Mount Solfizio (Etn07) 10-km-long lava flow field is located on the eastern Etna flank, and reaches an elevation of 310 m. Its eruptive fissure is formed by the small scoria cone of Mount Solfizio, located at about 1800 m elevation south of the Valle del Bove (Figure 1). This huge lava flow field is partially covered by the 1634–1638 and 1792–1793 A.D. lava flows.

[17] The 1284 A.D. (Etn08) 8-km-long lava flow field is located on the lower eastern Etna flank, between ~1100 and 160 m. In the Valle del Bove (where its eruptive fissure was located) it is covered by several recent lava flows, datable to the 19th and 20th century A.D. It was attributed to the 1284 eruption by *Recupero* [1815], who localized the Byzantine church of Santo Stefano surrounded by the lava flow of this eruption, as described in the historical sources (e.g., Nicolò Speciale as quoted by *Recupero* [1815]).

Table 1. Location of the Outcrops Sampled at Etna Flows and Original Age Constraints[a]

Code	Flow	Age Low	Age Up	Method	Sample	Locality	Altitude, m asl	Latitude N	Longitude E
Etn01	Cavolo	122 B.C.		strat	01-04	Catania, Piazza Europa	13	37°31'02″	15°06'24″
					05-08	Catania, Leon. da Vinci	130	37°32'02″	15°05'29″
					09-12	Barriera del Bosco	280	37°33'00″	15°03'54″
Etn02	Monpeloso	122 B.C.	Flow Etn03	strat	01-04	Mascalucia	416	37°34'29″	15°03'18″
					05-08	Massa Annunziata	500	37°35'07″	15°02'31″
					09-12	Monpeloso	805	37°37'47″	15°02'10″
Etn03	San Giovanni La Punta	Flow Etn02	1408 A.D.	strat	01-04	Trecastagni	565	37°37'19″	15°04'43″
					05-08	Villaggio Inchiuso	363	37°35'31″	15°02'33″
					09-12	Torre del Grifo	525	37°35'46″	15°03'22″
Etn04	1408 A.D.	1408 A.D.	1408 A.D.	strat hist	01-04	Pedara	600	37°36'43″	15°03'21″
					05-08	Cozzarelli	700	37°37'38″	15°03'21″
					09-12	Tre Monti	710	37°38'12″	15°03'41″
Etn05	1329 A.D.	1329 A.D.	1329 A.D.	strat hist	01-04	Contrada Collegio	425	37°38'33″	15°06'44″
					05-08	Contrada Collegio	425	37°38'25″	15°06'38″
					09-12	Mount Rosso	510	37°39'04″	15°05'58″
Etn06	Fleri	122 B.C.	1329 A.D.	strat	01-04	Lineri	380	37°39'39″	15°07'22″
					05-08	Fleri	550	37°39'30″	15°05'51″
					09-12	Mount Ilice	700	37°39'35″	15°05'10″
Etn07	Mount Solfizio	122 B.C.	1634 A.D.	strat	01-04	Sarro	615	37°40'50″	15°05'55″
					05-08	Zafferana	930	37°41'08″	15°05'14″
					09-12	Contrada Cicirello	1110	37°40'35″	15°03'55″
Etn08	1284 A.D.	1284 A.D.	1284 A.D.	strat hist	01-04	Monacella	420	37°42'23″	15°07'57″
					05-08	Macchia	200	37°43'01″	15°09'24″
					09-12	Caselle	770	37°43'07″	15°06'36″
Etn09	Mount Sona	2nd century A.D.	1536 A.D.	strat	01-04	Pennina di lupo	620	37°36'38″	14°57'12″
					05-08	Feza	620	37°36'47″	14°56'44″
					09-12	Sciara Gallifi	800	37°37'36″	14°57'58″
Etn10	Mount Gallo	122 B.C.	1607 A.D.	strat	01-04	Case Corsaro	1310	37°43'01″	14°54'16″
					05-08	Mount Turchio	1160	37°42'58″	14°53'26″
					09-12	Mount Gallo	1450	37°42'29″	14°54'23″
Etn11	Murazzo Rotto	122 B.C.	1614 A.D.	strat	01-04	Rivaggi	935	37°50'51″	14°55'03″
					05-08	Murazzo rotto	855	37°51'56″	14°54'47″
					09-12	Santa Caterina	883	37°51'21″	14°55'27″
Etn12	Scorciavacca	122 B.C.	1865 A.D.	strat	01-04	Cannizzaro	840	37°46'57″	15°07'55″
					05-08	Scorciavacca	675	37°46'53″	15°08'46″
					09-12	Vena	657	37°47'10″	15°08'47″
Etn13	Linguaglossa	late 12th century A.D.	late 12th century A.D.	hist	01-04	Linguaglossa	560	37°50'32″	15°08'09″
					05-08	Piano Pernicana	1285	37°48'45″	15°04'51″
					09-12	Manica	860	37°49'30″	15°06'21″

[a]Age low and Age up, age lower and upper boundary, respectively. Method, method of dating (strat, stratigraphic, hist, historic). The codes of the test flows (with known age) are in bold.

[18] The Mt Sona (Etn09) 11-km-long lava flow field is located on the lower southwestern Etna flank, and reaches an elevation of about 290 m close to the Paternò town. Its eruptive fissure dissects the large Mt Sona scoria cone at about 1250 m elevation. The Mt Sona lava flow breaks off the Roman aqueduct dated at about the II century A.D. at Scalilli (Figure 1), and it is partially covered by the 1536 lava flows. It was doubtfully attributed to the 812 or 1169 A.D. eruption in the geological maps of *Romano et al.* [1979]. However, the 812 eruption is a false event not reported in the historical sources, while during 1169 only summit activity is documented at Etna [*Tanguy*, 1981].

[19] The Mount Gallo (Etn10) lava flow consists of two distinct lava flow fields located on the western Etna flank. The oldest one, 9.3 km long, reaches an elevation of about 570 m near the town of Adrano (Figure 1). Its eruptive fissure is in the coalescent scoria cones of Mts. Gallo and Testa, located at 1500–1600 m of altitude. This lava flow field (sampled by us at Mount Turchio and Mount Gallo, Table 1 and Figure 1) is in partial overlap with the flow generated by the Mount Forno scoria cone, located at 1600 m of altitude. The Mount Forno lava flow field (sampled by us at Case Corsaro, Table 1 and Figure 1) is 8.8 km long, reaches an elevation of 610 m uphill of the Adrano town, and is partly covered by the 1607 lava flow. The Mount Gallo-Testa and Mount Forno lava flows were incorrectly attributed to the 1595 eruption in the geological maps of *Waltershausen* [1880] and *Romano et al.* [1979]. In fact, the 1595 eruption is a false event not reported in the historical sources [*Tanguy*, 1981].

[20] The Murazzo Rotto (Etn11) 7-km-long and up to 2-km-wide lava flow field is located on the northern Etna flank, and reaches an elevation of about 800 m close to the Randazzo town (Figure 1). Its eruptive fissure is formed by a small scoria cone located at about 1550 m elevation, partially covered by the 1614–1624 lava flow. It was inexactly attributed to the 1536 eruption in the geological maps of *Romano et al.* [1979]. In fact, the 1536 eruption (well reported by several sources quoted by *Recupero* [1815]) occurred through the formation of several eruptive vents in the southern and southwestern Etna flanks. Only one source [*Fazzello*, 1558] reports

lava flows in the northern Etna flank, but this can be related to lava overflows from the summit crater of the volcano. Conversely, this source does not describe any eruptive fissure opened in the northern Etna flank.

[21] The Scorciavacca (Etn12) 5.7-km-long lava flow field is located on the lower northeastern Etna flank, and reaches an elevation of ~90 m close to the Santa Venera village. Its eruptive fissure is covered by the 1865 lava flow. In the geological maps of *Romano et al.* [1979], it was wrongly attributed to the 1651 eruption, which is described in the historical sources reported by *Recupero* [1815]. Such sources document the occurrence in 1651 A.D. of a lava flow in the locality "Fondo Macchia," located in fact ~6 km south of the Scorciavacca lava flow field.

[22] The Linguaglossa (Etn13) 8-km-long lava flow field is located on the northeastern Etna flank, and reaches an elevation of about 475 m in correspondence of the Linguaglossa town (Figure 1). Its eruptive fissure is formed by a small spatter rampart located at 1370 m. It was incorrectly attributed to the 1566 A.D. eruption in the geological maps of *Waltershausen* [1880], *Romano et al.* [1979], *Romano and Guest* [1979], and *Branca* [2003], relying on the historical sources reported in the catalogue of *Recupero* [1815]. In fact, the localities Collabasso and Jannazzo (destroyed by the 1566 eruption) described in the source of Ribizzi [e.g., *Recupero*, 1815] are located about 7 km west of Linguaglossa. Conversely, a document preserved in the municipality of Linguaglossa clearly reports that this town was threatened by a lava flow some years after its foundation (1145 A.D.).

3. Paleomagnetic Sampling and Measurements

[23] Samples were collected by drilling 2.5-cm-diameter cores using a petrol-powered portable drill cooled by water. Within each flow we systematically drilled 12 cores in three different sites (localities), collecting four cores per site (Figure 1 and Table 1). The sites were selected as far as possible from each other, in order to try to gather a well-averaged, representative paleomagnetic direction for each flow. The cores were oriented in-situ by both a magnetic and a Sun compass. The local field declination values (i.e., the difference between the magnetic and Sun compass readings) are generally similar for samples from the same site, though differences of 10°–15° can even be observed for close samples. Values are predominantly negative and range between 9° and −17°, but for the core 02 from the Linguaglossa (Etn13) flow a declination of 93° (likely due to strong magnetization induced by lightening) was observed.

[24] The cores were cut into standard cylindrical specimens and the remanent magnetization of a specimen per core was measured in the shielded room of the paleomagnetic laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (Rome) by a 2G DC-SQUID cryogenic magnetometer. For all specimens, alternating field (AF) cleaning effected by three perpendicular coils in-line with the magnetometer was systematically adopted, using 10–12 demagnetization steps per specimen, up to a 150 mT maximum AF field. Twin specimens from 12 cores were also thermally demagnetized in 9 steps up to 550°C, and measured by a Molspin spinner magnetometer at the paleomagnetic laboratory of Istituto di Scienze Marine, Consiglio Nazionale delle Ricerche (Bologna, Italy).

[25] Demagnetization data were plotted on both orthogonal demagnetization diagrams [*Zijderveld*, 1967] and on equal-area projections, and the magnetization components were isolated by principal component analysis [*Kirschvink*, 1980]. Flow mean paleomagnetic directions were computed using *Fisher's* [1953] statistics.

[26] The hysteresis loop (up to a maximum applied field of 0.5 T) of a small (~1 mm^3) rock fragment from each flow was measured with a MicroMag 2900 alternating gradient magnetometer. The magnetization and coercivity parameters were plotted according to *Day et al.* [1977] to compare mineral magnetic properties of the different flows.

4. Paleomagnetic Directions

[27] In all specimens, a characteristic remanent magnetization (ChRM) could be isolated in a field interval variable from 10–150 mT (Figure 2b) to 40–150 mT (Figures 2a and 2c). Twin specimens from the same cores yielded a ChRM in a temperature interval varying from 100–550°C (Figure 2e) to 280–550°C (Figures 2d and 2f) during thermal demagnetization. Most of the magnetic remanence is annulled at 80 mT and 550°C, pointing to low-Ti titanomagnetite as main magnetic carrier. However, in some samples a high-coercivity fraction representing 10–15% of the natural remanent magnetization is removed between 80 and 150 mT (Figures 2a and 2b). Both the low- and high-coercivity fractions are almost completely demagnetized at 550°C, and yield identical magnetization directions. A high-coercivity fraction demagnetized below 550°C might be carried by deuterically oxidized titanomagnetite [e.g., *Dunlop and Ozdemir*, 2001]. The ChRM directions gathered by AF and thermal cleaning from twin specimens are not identical, and display differences varying from 5° (Figures 2b and 2e) to 17° (Figures 2a and 2d). Such discrepancies are in the range of those observed among close cores from the same site (Figure 3). Therefore they likely reflect variations of paleomagnetic directions recorded in adjacent rock fragments, instead of being related to the different demagnetisation/measurement methods adopted.

[28] The α_{95} values relative to the mean paleomagnetic directions evaluated for each flow vary from 3.3° to 5.7° (4.5° on average, Figure 3 and Table 2). At flow Etn03 (San Giovanni La Punta), the four cores sampled at the first site (Trecastagni, Figure 1 and Table 1) yielded low-inclination ChRM directions lying ~40° apart from the remaining eight samples (Figure 3e). This suggests that either the lava sampled at Trecastagni does not belong to the San Giovanni La Punta flow sampled at the other two sites, or that the Trecastagni outcrop was significantly tilted after cooling. Consequently, for flow Etn03 we calculated two different paleomagnetic directions, one for the Trecastagni site (Etn03a in Table 2), and another one (Etn03b) for the remaining two sites.

[29] To calculate the site-mean directions, we systematically retained all the 12 ChRM directions from the cores drilled in each flow and did not eliminate any scattered specimen. Only for the Linguaglossa (Etn13) lava flow, we considered as an outlier (and eliminated) the specimen Etn13-05 (D = 48.7°, I = 38.4°), which lies at 21.4° (i.e.,

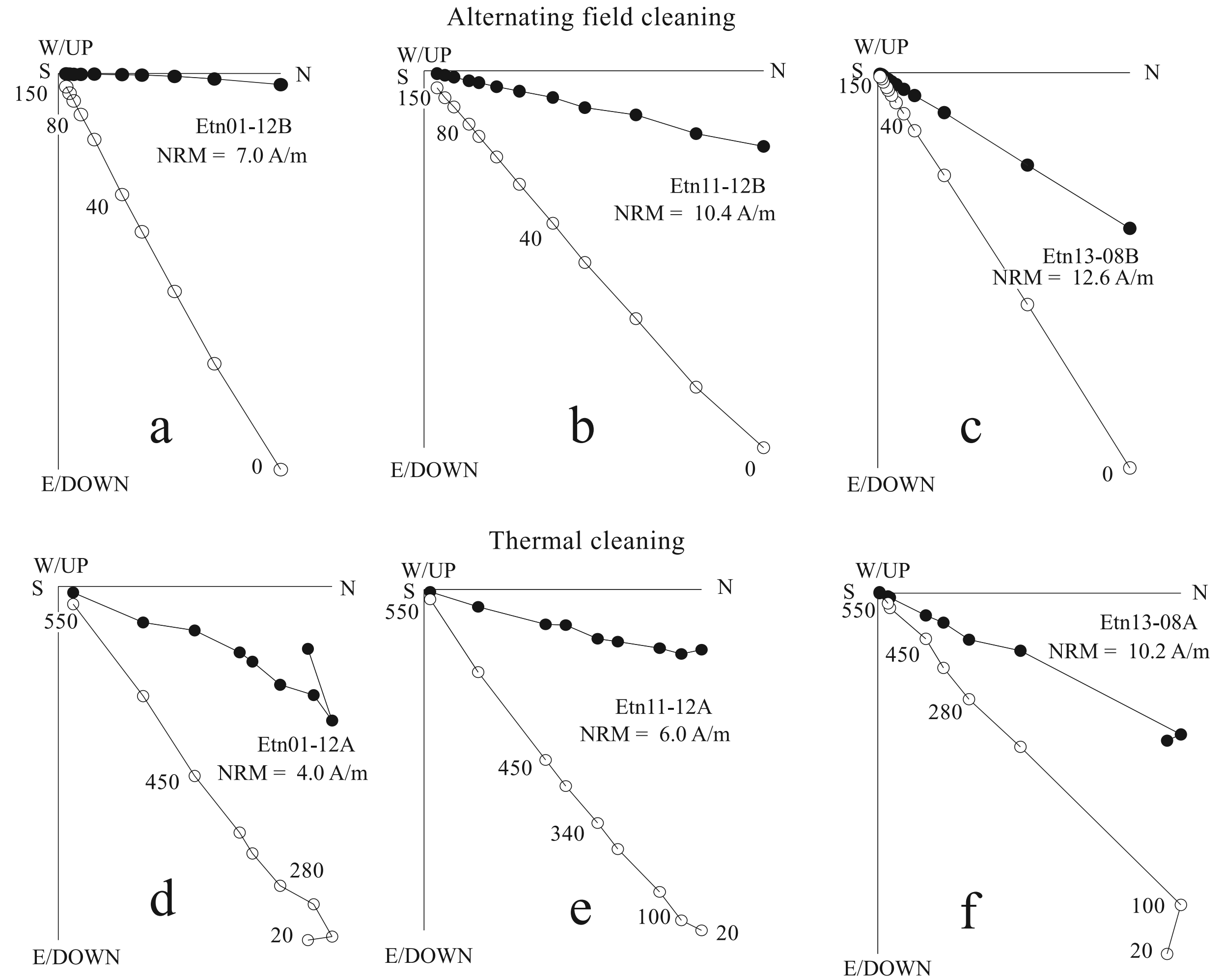

Figure 2. Orthogonal vector diagrams of typical demagnetization data, in situ coordinates. Open and solid dots represent projections on the vertical and horizontal planes, respectively. Figures 2a/2d, 2b/2e, and 2c/2f are from twin specimens obtained from the same cores. (a, b, c) Alternating magnetic field and (d, e, f) thermal cleaning is used for specimens (see text). Demagnetisation step values are in mT (Figures 2a, 2b, and 2c) and °C (Figures 2d, 2e, and 2f).

more than 5 α_{95} values, Table 2) from the mean direction computed with the other eleven specimens.

[30] The relatively large α_{95} values obtained for each flow are predominantly due to the distance of ChRM directions from samples gathered at different sites (Figure 3), though a difference up 15°–20° may exist between ChRMs from cores from the same site. A greater distance between ChRMs obtained at different sites seems to characterize the flows showing the largest (>5°) α_{95} values (Figures 3c and 3d).

5. Comparison With the PSV Reference Curve

[31] Independent historical and stratigraphic age constraints indicate that the paleomagnetically studied flows were emplaced in the 122 B.C. to 1865 A.D. age window (Table 1). Therefore the retrieved paleomagnetic directions should be compared to coeval PSV reference curves in order to infer paleomagnetically consistent ages of emplacement. Since reliable historical measurements of the geomagnetic field are available for Europe only since the 17th century A.D. [*Cafarella et al.*, 1992; *Alexandrescu et al.*, 1996], reference data for the flows sampled by us at Etna can uniquely be provided only by archeomagnetism. There are several valuable archeomagnetic data sets from the last three millennia gathered from several European countries, i.e., United Kingdom [*Clark et al.*, 1988], France [*Bucur*, 1994; *Gallet et al.*, 2002], Germany [*Schnepp et al.*, 2004; *Schnepp and Lanos*, 2005], and Bulgaria [*Kovacheva et al.*, 1998]. Among them, we selected the French data set, which is based on a greater number of data than the others and has been also already compared to paleomagnetic data collected from several Italian volcanoes [*Tanguy et al.*, 2003; *Arrighi et al.*, 2004; *Principe et al.*, 2004]. The validity of the French archeomagnetic curve for the Mediterranean region has been also confirmed by the agreement with a recent compilation of archeomagnetic data gathered in southern Italy [*Evans and Hoye*, 2005], the SV record from marine and lacustrine sediments collected in central Italy [*Rolph et al.*, 2004], and the available results from historical lava flows from Etna and Vesuvius [*Vigliotti*, 2006].

[32] We considered French directional archeomagnetic data from 400 to 50 B.C. (sliding windows of 160 years

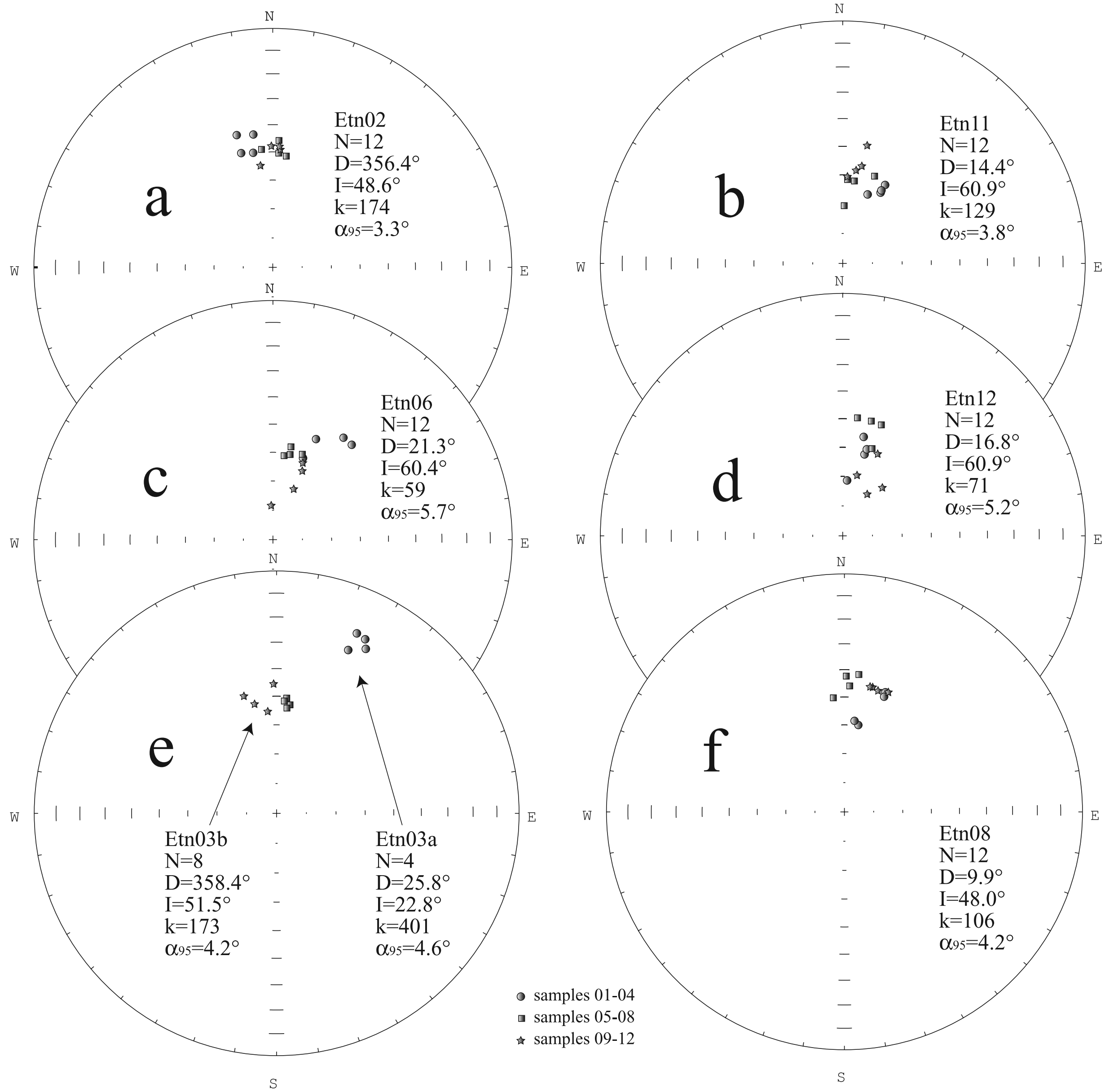

Figure 3. Equal-area projection (lower hemisphere) of the characteristic remanent magnetization directions gathered from the specimens from six Etna flows.

with step of 50 years [*Gallet et al.*, 2002]), and from 0 to 1600 A.D. [*Bucur*, 1994] (the mean directions computed using sliding windows of 80 years with step of 25 years were downloaded from the IAGA Global Paleomagnetic Database at ftp://ftp.ngdc.noaa.gov/Solid_Earth/Paleomag/access/ver3.5/secvrasc/). All data were relocated to Etna coordinates (latitude 37.5°N, longitude 15°E) via the virtual geomagnetic pole method [*Noel and Batt*, 1990].

[33] As a first attempt, we visually evaluated the overlap between our paleomagnetic directions and the relocated French reference directions (considering the relative confidence cones of both data sets, Figure 4). All paleomagnetic directions from Etna flows lie over the PSV reference curve, but the directions from flows Etn03a and Etn13 (Figure 4). The direction for flow Etn03a (Trecastagni site of San Giovanni La Punta flow) lies $\sim$20° off the reference curve.

[34] Considering the four "test" flows (with precisely known historical age), two (1284 and 1329 A.D.) agree with the respective age windows indicated by the reference curve; the 1408 A.D. flow direction is consistent with ages $\geq$1425 and $\leq$1325 A.D., while the Linguaglossa (Etn13) flow direction is located definitely off the reference curve (Table 3 and Figure 4). However, if one takes into account the westward drift of the nondipole field (0.38°/yr for the last 2 millennia according to *Merrill et al.* [1996]), and the longitude difference between France and Etna, the original ages of the French archeomagnetic curve should be reduced at Etna by some 30–40 years. By doing that, even the direction of the 1408 A.D. flow becomes consistent with the reference data.

[35] The French PSV data set has been recently reevaluated using Bayesian hierarchical modeling [*Lanos et al.*, 2005]. The use of such curve and the program REN-

Table 2. Mean Paleomagnetic Directions From Etna Flows[a]

Code	Flow	D, deg	I, deg	k	α_{95}, deg	Dev, deg
Etn01	Cavolo	17.1	54.4	81	4.9	0.8±5.7
Etn02	Monpeloso	356.4	48.6	174	3.3	0.7±5.1
Etn03a	Trecastagni	25.8	22.8	401	4.6	−4.9±1.8
Etn03b	San Giovanni La Punta	358.4	51.5	173	4.2	−2.8±5.9
Etn04	**1408 A.D.**	**12.4**	**50.0**	**113**	**4.1**	**−1.0±3.5**
Etn05	**1329 A.D.**	**5.5**	**44.6**	**108**	**4.2**	**0.8±4.2**
Etn06	Fleri	21.3	60.4	59	5.7	−8.1±7.5
Etn07	Mount Solfizio	2.8	62.5	79	4.9	−4.0±5.7
Etn08	**1284 A.D.**	**9.9**	**48.0**	**106**	**4.2**	**−9.5±20.4**
Etn09	Mount Sona	6.0	58.6	62	5.6	−4.5±5.3
Etn10	Mount Gallo	14.0	57.0	95	4.5	−1.7±6.4
Etn11	Murazzo Rotto	14.4	60.9	129	3.8	−2.7±2.2
Etn12	Scorciavacca	16.8	60.9	71	5.2	−0.7±8.9
Etn13	**Linguaglossa**	**21.8**	**48.0**	**135**	**3.9**	**−8.2±4.5**

[a]All flow mean directions (but the direction of flow Etn13) are calculated systematically retaining all characteristic remanent magnetization directions from the twelve cores sampled in each flow. The direction of flow Etn13 was calculated discarding one sample (see text). Etn03a and Etn03b refer to samples 01–04 and 05–12, respectively, collected in the San Giovanni La Punta flow (see text). Data from the test flows (with known age) are in bold. Dev is the flow mean field declination, i.e., the average (and relative standard deviation value) of the local field declinations calculated for each core by the differences between magnetic and Sun compass readings. For the flow Etn13, we discarded the local field declination from core 02, yielding a 93° value.

DATE (developed by P. Lanos and downloaded at http://www.meteo.be/CPG/aarch.net/rendate_en.html) yield another set of inferred ages for our paleomagnetic directions from Etna, once a given probability significance level is previously selected (Table 3). By systematically adopting a 95% significance level, we find that all test flows yield age windows encompassing the respective true flow ages, i.e., are now consistent with the reference curve (Table 3). This may suggest that the use of Bayesian statistics is preferable when using paleomagnetism as a dating tool. The ages of the remaining (loosely dated) nine flows were inferred by both visually verifying the overlap between the confidence cones relative to our and the reference directions (Figure 4) and relying on Bayesian statistics (Table 3). For some flows two different age intervals can be derived. However, some of these ages (bracketed in Table 3) are not consistent with historical accounts at Mount Etna (see chapter below). The data of Table 3 imply that by adopting our sampling, measurement, and analysis strategy, and relying on Bayesian statistics, the ages of Etna flows can be determined with uncertainties of 136–661 years (307 years on average, Table 3).

5.1. Paleomagnetically Inferred Ages of the Studied Flows

[36] Our new paleomagnetic data, after comparison with the relocated PSV reference curve, allow better constraining the age windows for the lava flows emplaced at Etna after 122 B.C. (Table 3). Here we systematically discuss the age windows gathered by the use of Bayesian statistics, as the analysis of the test flows has shown that such dating methodology yields sound results. For the Cavolo (Etn01) flow, the inferred 953–1229 A.D. age interval rules out that such lava flow field was produced by the 1381 eruption, as it has been previously suggested relying on Simone da Lentini quoted by *Alessi* [1829–1835]. The paleomagnetic data show that this eruption occurred in a historical period (the Middle Age) characterised by a lack of well-documented sources on the eruptive activity on Etna [*Tanguy*, 1981].

[37] The 90–391 A.D. age interval obtained for the Monpeloso (Etn02) flow is in agreement with historical-stratigraphic data, and seems to confirm its attribution to the 252 A.D. eruption. The Roman age (90–501 A.D.) inferred for the San Giovanni La Punta (Etn03b) flow is also in accordance with the stratigraphic data, showing that this flow at some places directly rests on the 122 B.C. pyroclastic deposit. Therefore its previous attribution to the 1408 A.D. eruption can be excluded. The paleomagnetic direction from the Trecastagni outcrop (Etn03a) is definitely off the post-122 B.C. PSV reference curve, and ~40° from the paleomagnetic direction gathered at the other two sites from the San Giovanni La Punta flow (Figure 4 and Table 2). Since the Trecastagni site was sampled in a huge (several tens of cubic meters) lava block located in the middle of a quarry, we infer that such block was tilted by ~40° during excavation.

[38] The Medieval ages inferred for the Fleri (Etn06) and Mt Solfizio (Etn07) lava flows (898–1106 and 522–914 A.D., respectively) are in agreement with their stratigraphic position. Concerning the Mt Sona (Etn09) flow, we find two paleomagnetically compatible age intervals (356–1017 and 1479–1681 A.D.), yet we exclude the latter because no historical source reports lava flows occurring in the lower southwestern Etna flank during such age window [see *Tanguy*, 1981]. The Low Medieval (910–1188 A.D.) age interval paleomagnetically inferred for the Mount Gallo (Etn10) flows (Table 3) is potentially in agreement with field data. Conversely, the younger (1477–1591 A.D.) age window is solely compatible with the Mount Forno lava flow, but not with the Mount Gallo-Testa flow. In fact the Mount Forno flow could be attributed to the 1536 eruption, which also affected the western flank of Etna uphill the Adrano town, and is reported to occur not far from the large Mount Minardo scoria cone (Figure 1 (e.g., Archivio di Stato di Catania, Trattato del fuoco soccesso nell'anno 1536 cavato dallo libro delli privilegij del Reverendo Monasterio di San Nicolò la Rena della Clarissa, vol. 7, paragraphs 12–14, Benedettini, Catania, Italy, 18th century A. D.)).

[39] The Low Medieval (854–1065 A.D.) age gathered for the Murazzo Rotto (Etn11) flow is not in conflict with historical-stratigraphic data, while the 1535–1605 A.D. interval can be excluded on the same grounds. Similarly, the 856–1119 A.D. age inferred for the Scorciavacca (Etn12) flow is compatible with historic-stratigraphic information, while the 1527–1597 A.D. age window is not in agreement with historical accounts.

[40] Our data from Mt Etna confirm that paleomagnetism cannot be used alone as a dating tool, but needs substantial support from other methods, such as historical investigation, archaeological research, and radiometric dating.

5.2. Comparison With Previous Paleomagnetic Results From Etna Lavas

[41] Almost all the flows studied by us were already paleomagnetically investigated in the past (Figure 5 and Table 4), but the name and age attribution of most of the

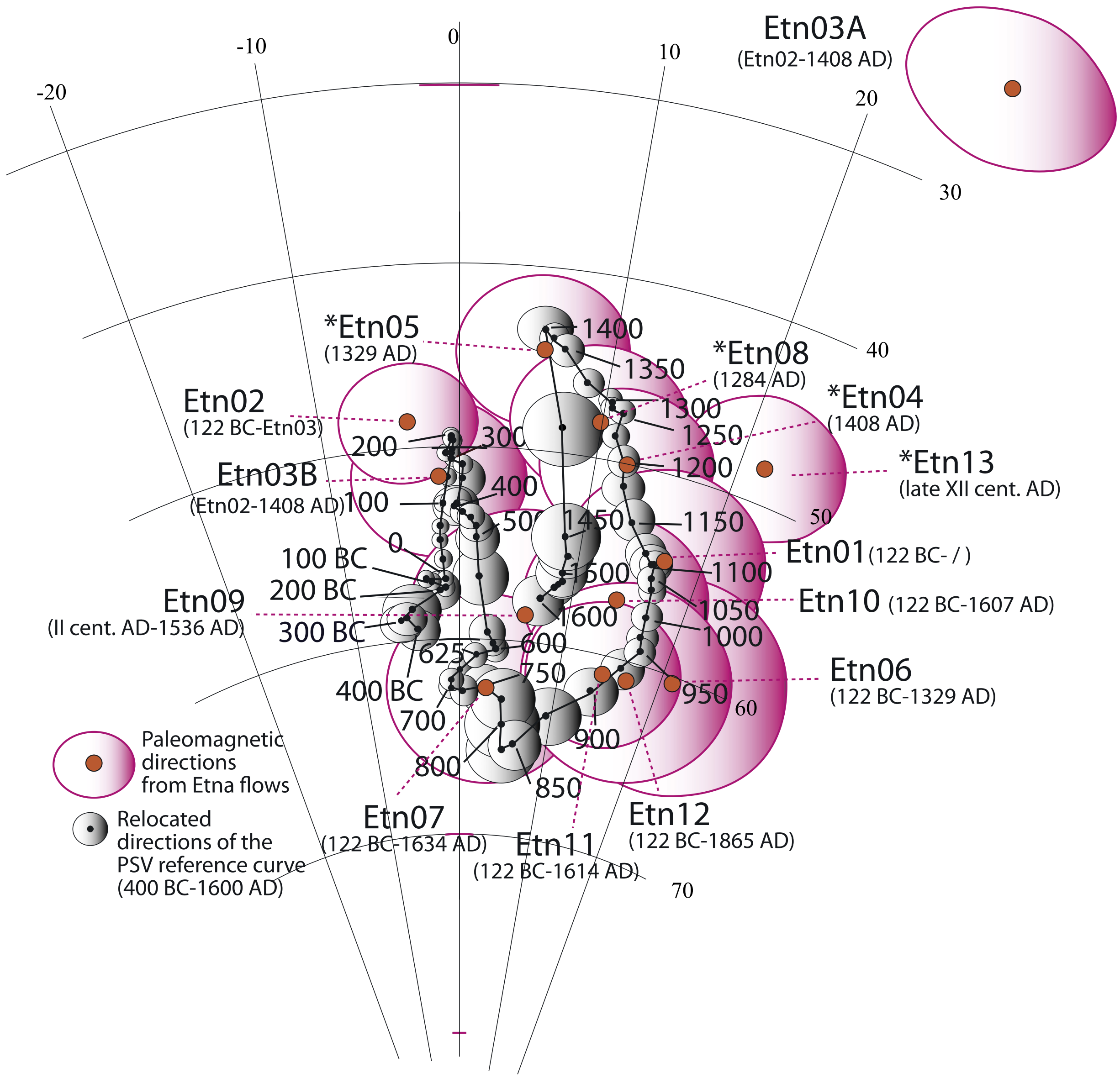

Figure 4. Equal-area projection (lower hemisphere) of the mean paleomagnetic directions from Etna flows and of the reference curve of the paleosecular variation of the geomagnetic field (from 400 B.C. to 1600 A.D.) reported to Etna coordinates (latitude 37.5°N, longitude 15°E). Data of the reference curve (the French archeomagnetic curve) are from *Gallet et al.* [2002] for data from 400 to 50 B.C. (sliding windows of 160 years with step of 50 years) and from *Bucur* [1994] for data from 0 to 1600 A.D. (sliding windows of 80 years with step of 25 years). Numbers adjacent to the reference curve indicate ages (the A.D. suffix is omitted). Ellipses are the projections of the α_{95} cones about the individual mean directions. Age windows of the flows are according to historical-stratigraphic data (see text and Table 1). Test flows with known ages are indicated with an asterisk.

flows has considerably changed in the last years. We have been able to find the correspondence between flows sampled by us and by other authors thanks to the fundamental help given by T. Rolph and J.-C. Tanguy, who kindly showed us the exact location of their sampling localities (the site coordinates were absent in all papers cited in Table 4). As a rule, there is a first-order agreement (considering the respective confidence cones) between paleomagnetic directions retrieved by us and by previous authors from the same flow. Few directions are very far one from another (i.e., site Etn03a with respect to "presumed 1408B" of *Tanguy et al.* [2003], or site Etn04 compared to "1444" of *Rolph and Shaw* [1986]), suggesting that in these cases the flow correspondence indicated in Table 4 may be wrong.

6. Discussion

6.1. Extent of Scatter of Paleomagnetic Directions Retrieved From Volcanic Rocks, Fidelity of Paleomagnetic Recording, and Reliability of PSV Reference Curves

[42] A lively debate has developed during the last years over the precision (the α_{95} value) associated to paleomag-

Table 3. Paleomagnetically Inferred Ages for the Flows Paleomagnetically Studied at Etna[a]

Code	Flow	Inferred Ages	
		Confidence Cones	REN-DATE
Etn01	Cavolo	950–1200 A.D. (1450–1575 A.D.)	953–1229 A.D. (1472–1537 A.D.)
Etn02	Monpeloso	125–350 A.D.	90–391 A.D.
Etn03a	Trecastagni		
Etn03b	San Giovanni La Punta	125–500 A.D.	90–501 A.D.
Etn04	**1408 A.D.**	**(1125–1325 A.D.) (1425–1450 A.D.)**	**(1088–1335 A.D.) 1381–1517 A.D.**
Etn05	**1329 A.D.**	**1275–1425 A.D.**	**1241–1463 A.D.**
Etn06	Fleri	875–1050 A.D.	898–1106 A.D.
Etn07	Mount Solfizio	525–900 A.D. (1600–1634 A.D.)	522–914 A.D. (1575–1701 A.D.)
Etn08	**1284 A.D.**	**1175–1350 A.D. (1425 A.D.)**	**1178–1486 A.D.**
Etn09	Mount Sona	450–1000 A.D. (1450–1536 A.D.)	356–1017 A.D. (1479–1681 A.D.)
Etn10	Mount Gallo	900–1150 A.D. 1450–1607 A.D.	910–1188 A.D. 1477–1591 A.D.
Etn11	Murazzo Rotto	775–800 A.D. 875–1000 A.D. (1600–1614 A.D.)	854–1065 A.D. (1535–1605 A.D.)
Etn12	Scorciavacca	775–1050 A.D. (1500–1600 A.D.)	856–1119 A.D. (1527–1597 A.D.)
Etn13	**Linguaglossa**		**1047–1260 A.D.**

[a]Paleomagnetically inferred ages are after comparison with the relocated French archeomagnetic curve. The inferred ages are gathered by (1) visually evaluating the overlap of the confidence cones relative to the paleomagnetic directions from Etna lavas with the confidence cones relative to the directions of the French archeomagnetic curve relocated at Etna and (2) using the French archeomagnetic curve reevaluated using Bayesian hierarchical modelling [*Lanos et al.*, 2005] and the program REN-DATE (developed by P. Lanos and downloaded at http://www.meteo.be/CPG/aarch.net/rendate_en.html), systematically adopting a 95% significance level. The oldest age of flow Etn03b (San Giovanni La Punta) is inferred considering the oldest age of flow Etn02 (Monpeloso), stratigraphically underlying flow Etn03b. Inferred ages not consistent with historical accounts are in parentheses. Data from the test flows (with known age) are in bold.

netic directions gathered from volcanics, and the subsequent age accuracy that ‘‘paleomagnetic dating’’ can yield. Researchers from the St. Maur Observatory (France) suggest that paleomagnetic directions from volcanics should be determined with α_{95} values <2°, and show that values even <1° can be obtained [*Tanguy et al.*, 2003; *Arrighi et al.*, 2004; *Principe et al.*, 2004]. These very low α_{95} values were obtained at several Italian volcanoes by using the large sample method (LSM), which relies on hand sampling of kilogram-sized blocks and ‘‘blanket’’ magnetization measurements with a rotating induction magnetometer [e.g., *Tanguy et al.*, 2003; *Arrighi et al.*, 2004, 2005].

[43] On the other hand, studies carried out on the same rocks using the classical paleomagnetic method (core drilling and systematic stepwise magnetic cleaning) typically yielded 2°–5° confidence cones [*Rolph and Shaw*, 1986; *Carracedo et al.*, 1993; *Lanza and Zanella*, 2003; *Speranza et al.*, 2004; *Quidelleur et al.*, 2005]. Relying on the very small α_{95} values they gathered, *Tanguy et al.* [2003], *Arrighi et al.* [2004], and *Principe et al.* [2004] suggest that (after comparison with a PSV reference curve) paleomagnetic dating may be achieved with an age accuracy of even ±20–30 years. This conclusion has been recently questioned by *Lanza and Zanella* [2006], who suggested that *Principe et al.* [2004] did not consider several factors causing the misalignment between the paleomagnetic direction frozen in lavas and the regional geomagnetic field at the time of cooling. Such mismatch in turn would significantly increase the age uncertainty associated with paleomagnetic dating. Furthermore, *Speranza et al.* [2005] argued that the use of partial demagnetization techniques (the ‘‘blanket’’ method) and the unjustified rejection of scattered samples from a volcanic flow may yield a fictitious improvement in statistical uncertainty of results provided by using the LSM.

[44] In order to test the efficiency of paleomagnetic dating, *Lanza et al.* [2005a] have compared the paleomagnetic directions (and associated confidence cones) gathered from Etna flows emplaced during the last four centuries to coeval directions of the geomagnetic field defined by historical measurements. They show that most of the remanence directions defined by an α_{95} <2.5° deviate from the coeval expected field direction by an angle larger than the paleomagnetic α_{95} value. This discrepancy is observed for data gathered by several authors using both the classical paleomagnetic method, and the LSM [*Tanguy et al.*, 2003]. *Principe et al.* [2006] and *Arrighi et al.* [2005] have replied to the comments provided by *Lanza and Zanella* [2006] and *Speranza et al.* [2005], respectively. Moreover, *Tanguy et al.* [2005] have questioned the validity of the findings by *Lanza et al.* [2005a], and *Lanza et al.* [2005b] have provided a further reply.

[45] Our work cannot resolve the above controversies, but may add further elements of discussion for this tricky debate: first we can compare the directions gathered from the four test flows (of known age) by the classical and the LSM method to the PSV reference curve, and check for consistency. Second we can establish which α_{95} values (and hence which dating accuracy) are to be expected by a paleomagnetic study carried out with the classical drilling method, by sampling twelve cores per flow spaced in three distinct (and distant) sites.

[46] As discussed above, all four paleomagnetic directions gathered by us from the four test flows are consistent with the coeval field directions expected by the relocated French archeomagnetic curve, when dating based on Bayesian statistics is adopted (Table 3). *Tanguy et al.* [1985, 2003] sampled five sites in the test flows, two in the 1408 A.D., one in the 1329 A.D., one in the 1284 A.D., and one in the Linguaglossa flow (Table 4 and Figure 5). When the paleomagnetic directions from these flows are considered, all four directions from *Tanguy et al.* [2003] yield age windows encompassing the respective true flow ages, while the direction from the 1284 A.D. flow [*Tanguy et al.*, 1985] gives two ages windows do not containing the 1284 A.D age (Table 4). Finally, considering also the previous results obtained by the classical sampling measurement methodol-

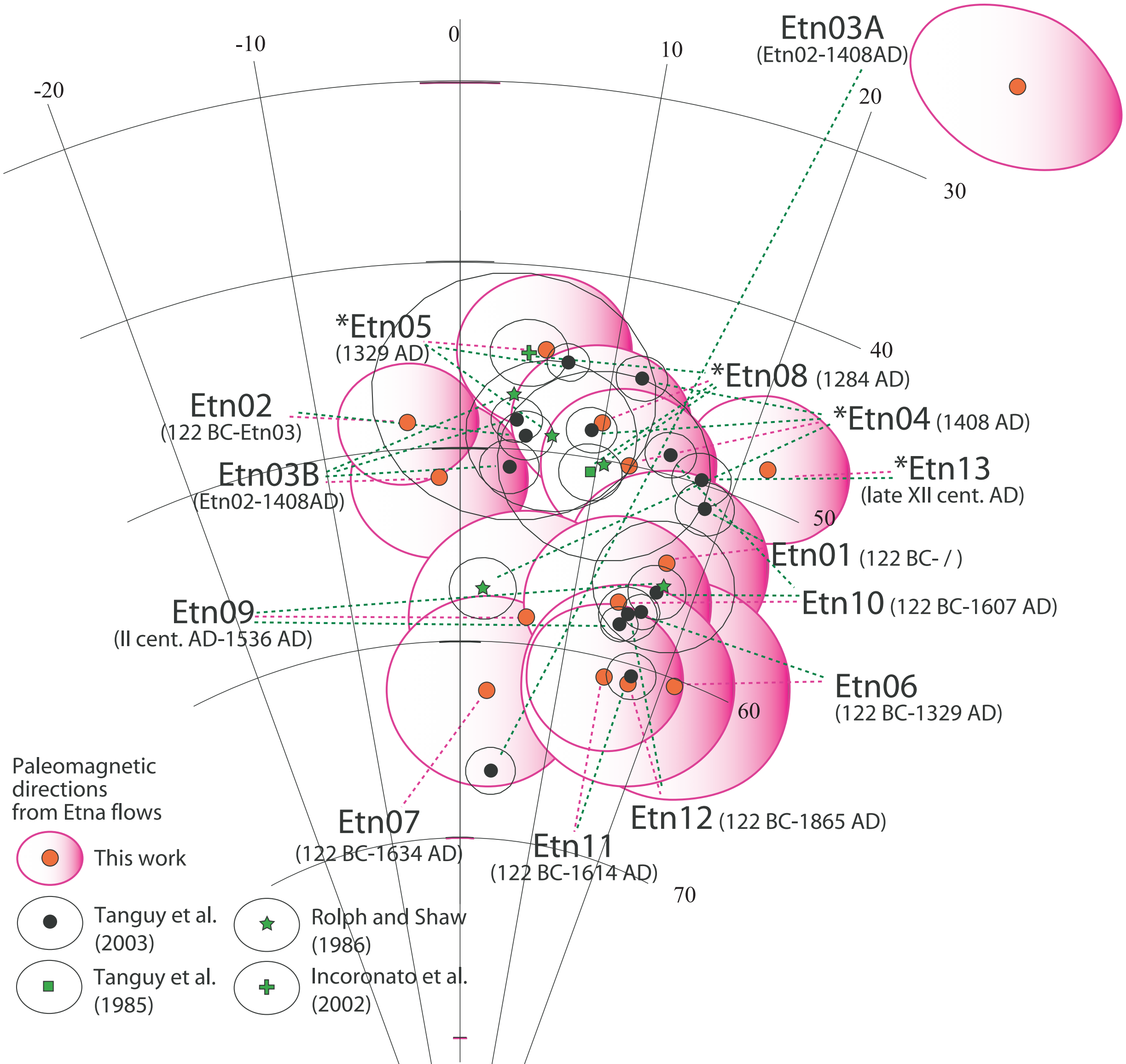

Figure 5. Comparison between paleomagnetic directions gathered by us (as in Figure 4) and by other authors (see text and Table 4 for details) from the same Etna flows. Legend is as in Figure 4; the reference curve is omitted for simplicity.

ogy, two out of the three directions from *Rolph and Shaw* [1986] gathered from the test flows yield consistent ages, while the sole result from *Incoronato et al.* [2002] for the 1284 A.D. flow translates into a 1323–1430 A.D. age window (Table 4).

[47] To sum up, the great majority of the paleomagnetic directions from the test flows (both those gathered by the classical method and by the LSM) yield age windows consistent with the respective true flow ages. Moreover, the direction documented by *Rolph and Shaw* [1986] for the 1408 A.D. flow (reported name "1444" in Table 4) is very far (~10°) from the field direction expected during 1408 A.D. (Figures 4 and 5), implying that (very likely) their result was not obtained from the 1408 A.D. flow. As a rule, the age windows derived by paleomagnetic directions produced by the LSM are much smaller than those inferred by directions obtained using the classical paleomagnetic methodology.

[48] The inconsistency of the paleomagnetic directions from few test flows from Etna with the directions expected from the PSV reference curve might cast doubts over the reliability of the curve itself. Moreover, it has been demonstrated that the relocation of French data to Italy via the virtual geomagnetic pole method [*Noel and Batt*, 1990] introduces direction errors of 1°–3° [*Lanza et al.*, 2005a], and this is related to the not completely dipolar nature of the geomagnetic field.

[49] However, as stated above, the first-order validity of the archeomagnetic data set from France (when relocated to the central Mediterranean domain) is confirmed by recent archeomagnetic and paleomagnetic results gathered in Italy [*Rolph et al.*, 2004; *Evans and Hoye*, 2005; *Vigliotti*, 2006]. Furthermore, the relocation errors should be minimized

Table 4. Previous Paleomagnetic Results From the Same Etna Flows of Tables 1–3[a]

Code	Flow	Reported Name	Ref	D, deg	I, deg	k	α_{95}, deg	Inferred Ages (REN-DATE)
Etn01	Cavolo (s. 09–12)	presumed 1381A	A	18.6	51.1	815	1.41	1066–1200 A.D.
Etn02	Monpeloso (s. 09–12)	presumed 252 flow, Monpeloso	A	4.7	49.2	833	1.3	226–380 A.D. (1387–1501 A.D.)
Etn03a	Trecastagni	presumed 1408B	A	3.8	66.6	1176	1.23	754–867 A.D.
Etn03b	San Giovanni La Punta	presumed 1408C	A	3.7	50.9	697	1.42	(115–183 A.D.) 222–468 A.D. (1447–1497 A.D.)
		presumed 1408D	A	4	48.4	1633	1.22	162–344 A.D. (1383–1483 A.D.)
		1408	B	3.7	47.1		6.6	69–470 A.D. (1190–1514 A.D.)
Etn04	**1408 A.D. (s. 05–08)**	**1408 flow.Pedara**	**A**	**9.3**	**48.5**	**863**	**1.23**	**(1204–1312 A.D.) 1382–1478 A.D.**
	(s. 09–12)	**presumed 1444**	**A**	**12**	**45.3**	**850**	**1.2**	**1249–1408 A.D.**
		1444	**B**	**2.0**	**57.3**		**1.6**	**(451–617 A.D.) (1564–1635 A.D.)**
Etn05	**1329 A.D.**	**1329, Mount Rosso**	**A**	**7.1**	**45.1**	**1824**	**1.04**	**1306–1420 A.D.**
		1334	**B**	**6.5**	**49.1**		**4.0**	**(136–388 A.D.) 1166–1525 A.D.**
Etn06	Fleri	presumed 1329	A	16.2	57.2	720	0.86	959–1096 A.D.
Etn07	Mount Solfizio							
Etn08	**1284 A.D.**	**1284(?)**	**C**	**9.7**	**50.7**	**468**	**1.52**	(1159–1253 A.D.) (1420–1512 A.D.)
		1284–E28	**D**	**4.5**	**44.8**	**1789**	**1.8**	**(1323–1430 A.D.)**
		1284	**B**	**10.6**	**50.2**		**5.0**	**1076–1543 A.D.**
Etn09	Mount Sona	presumed 812 or 1169, Mount Sona	A	14.6	58.1	883	0.9	936–1056 A.D.
		1169	B	17.4	55.6		3.4	961–1172 A.D.
Etn10	Mount Gallo (s. 01–08)	presumed 1595A	A	15.1	48.9	1351	1.2	1148–1259 A.D.
	(s. 09–12)	presumed 1595B	A	17	56	591	1.44	910–990 A.D.
Etn11	Murazzo Rotto	presumed 1536C	A	17	60.5	809	1.23	916–995 A.D.
Etn12	Scorciavacca	presumed 1651	A	15.1	57.5	627	1.44	947–1034 A.D.
Etn13	**Linguaglossa**	**presumed 1566, Linguaglossa**	**A**	**17.7**	**49.7**	**525**	**1.4**	**1096–1226 A.D.**

[a]Abbreviations: s, samples; Ref, references: A, *Tanguy et al.* [2003]; B, *Rolph and Shaw* [1986]; C, *Tanguy et al.* [1985]; D, *Incoronato et al.* [2002]. The reported name is the flow name originally reported in the tables from the references listed. The inferred ages were gathered by using Bayesian statistics and the program REN-DATE (see Table 3). Data from the test flows (the same as in Tables 1–3) with known age are in bold. Inferred ages not consistent with historical accounts are in parentheses.

because the French curve takes into account data collected from several French localities, and averaged over sliding windows of 80–160 years. We conclude that the PSV reference curve used at Etna is valid, at least at first approximation. This implies that the few paleomagnetic directions from Etna test flows, which are at odds with the PSV reference curve, did not faithfully record the geomagnetic field directions present at Etna when the lavas were emplaced.

6.2. Why the Recording of the Geomagnetic Field in Volcanic Rocks May Be Unfaithful?

[50] There may be several causes affecting the fidelity of the paleomagnetic recording process (a recent synthesis is provided by *Lanza and Zanella* [2006]). The more important factor seems to be the local perturbation of the geomagnetic field due to the strongly magnetized volcanic edifice and the cooling lava flow. This is likely very important at Etna, where we observed that the natural remanent magnetization of the specimens may even exceed 20 A/m, and is confirmed by the comparison between Sun and magnetic compass readings, yielding significant deviations (up to 9° and −17° in declination) of the magnetic needle. This is fully confirmed by field measurements carried out at Hawaii [*Baag et al.*, 1995] and Canary islands [*Valet and Soler*, 1999], where field deflections up to 15°–20° with respect to the expected values were observed, and subsequently modelled by *Knudsen et al.* [2003]. Conversely, *Tanguy and Le Goff* [2004] documented much smaller (<3°) field deviations at a dozen measurement sites at Etna.

[51] Although our flow mean paleomagnetic declinations from Etna display predominant positive values (Figure 4 and Table 2), the local field declinations evaluated by the comparison between magnetic and Sun compass readings yield mainly negative values (Table 2). The three flows characterized by mean paleomagnetic declination values greater than 20.0° (Etn03a, Etn06, and Etn13), show negative average field declination values, comprised between −4.9° and −8.2° (Table 2 and Figure 4). We suggest that this coincidence is not fortuitous, and is related to the (southwestward directed) strength lines generated by the lava flows hosting a northeastward directed remanent magnetization. In fact we normally sampled these huge (i. e. tens of meters thick and several kilometers wide) flow fields above or laterally to them, where the direction of the strength lines of the magnetic field generated by the flows themselves is expected to be roughly antipodal to that hosted by the flow body. If our hypothesis is correct, it follows that the magnetic field at the flow outcrops is primarily influenced by the remanent magnetization hosted by the flow itself, instead of being controlled by the underlying terrain. This in turn implies that (1) by our local field declination measurements we cannot gather any information about the field characterizing that area of the volcano once the flow was emplaced, and (2) the magnetic field acting within a cooling flow is expected to be significantly influenced by the remanence hosted by the flow located just below of it.

[52] The geomagnetic field deflection due to local magnetic sources, i.e., related to the rugged topography made of

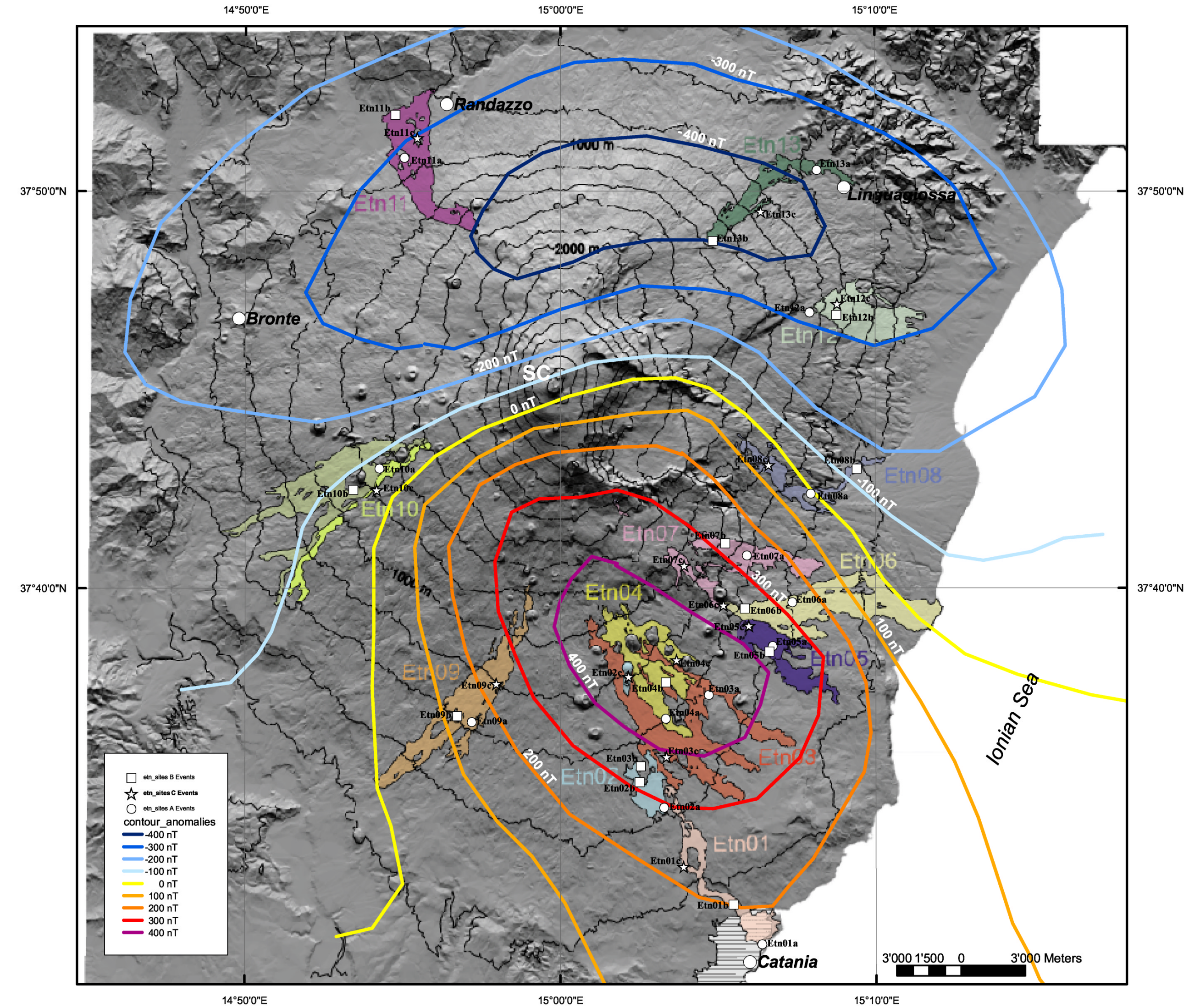

Figure 6. Same digital elevation model of Etna as in Figure 1, and magnetic anomaly values from airborne surveys, reduced to 2500 m of altitude [*Caratori Tontini et al.*, 2004].

strongly magnetized volcanics, is greatly variable. Conversely, a more regular deflection over large areas should be due to the long-wavelength magnetic anomaly produced by the (exposed and buried) volcanic structure as a whole. To gather an estimate of this, magnetic anomaly maps obtained by ground station or airborne data are needed. At Etna, local magnetic field disturbances are so great that a ground station magnetic anomaly map could not be elaborated [see *Chiappini et al.*, 2000]. On the other hand, *Caratori Tontini et al.* [2004] have provided an updated aeromagnetic map of Italy (revising the *AGIP SpA Italia* [1981] original data set), which includes also Etna. In Figure 6 we have superimposed the magnetic anomaly isolines (projected to an altitude of 2500 m) from *Caratori Tontini et al.* [2004] to the digital elevation model of Etna. It appears that most of the flows (as well as the 1408, 1329, and 1284 A.D. test flows) are located in a domain characterized by positive (up to 400 nT) magnetic anomalies. Conversely, the Linguaglossa (Etn13) test flow, (yielding a mean paleomagnetic direction ~10° far from the PSV curve, though not significantly different using Bayesian statistics), is entirely located in a region characterized by negative magnetic anomalies exceeding the −400 nT value (Figure 6). This may suggest that larger deflections of the local magnetic field in a volcano occur where the magnetic anomaly values are negative, i.e., where the strength lines of the large-scale magnetized volcanic body are roughly antipodal to the local geomagnetic field direction. This hypothesis has never been put forward. Yet we argue that it should be tested elsewhere, to find whether the misaligned geomagnetic field recording of lavas is systematically associated with long-wavelength negative magnetic anomalies. Alternatively, extrapolating our evidence of local magnetic field declinations and their relation with paleomagnetic declinations, the anomalously great (21.8°) mean declination gathered from the Linguaglossa flow might be due to the influence (when the lava cooled) of underlying flow(s) hosting a northwestward directed magnetization. Yet the volcanics located below the Linguaglossa flow have not been paleomagnetically investigated so far, and this hypothesis cannot be tested.

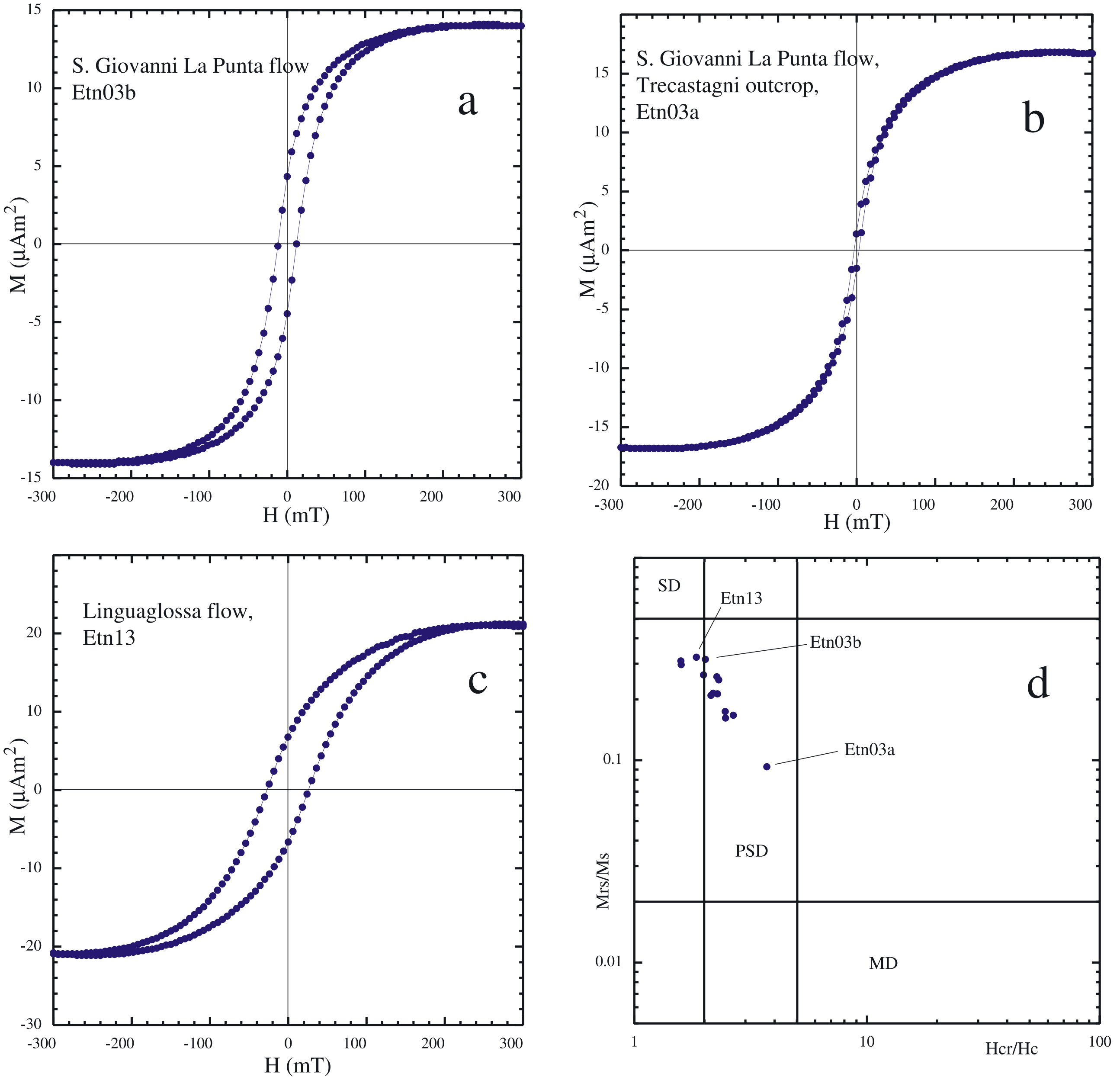

Figure 7. Hysteresis loops for three representative specimens (Figures 7a–7c) and hysteresis ratios as plotted on a *Day et al.* [1977] diagram (Figure 7d). (a) Typical hysteresis loop, (b) specimen from the Trecastagni outcrop (Etn03a) of the San Giovanni La Punta Flow, and (c) specimen from the Linguaglossa flow (Etn13).

[53] Another factor producing a bias of geomagnetic field recording in volcanic rocks may be represented by magnetic mineralogy changes occurring within the same volcanic unit. In fact, it has been recently demonstrated that the great variability of the paleointensity retrieved from a single lava flow [*Biggin et al.*, 2003] requires a number of paleointensity estimates larger than previously thought. It is suggested that the variation in cooling rate through the flow may play a dominant role to produce paleomagnetic scatter, but also gradients in the ambient field and nonthermal components of magnetization may be important. This concurs with the findings by *Rolph* [1997] and *Wilson et al.* [1968], who studied the changes of the paleomagnetic direction retrieved from samples collected across single flows. *Rolph* [1997] documented that significant variations in both rock magnetic characteristics and the paleomagnetic vector occur across two flows from Etna. This evidence is confirmed by the scatter of the paleomagnetic directions we observed in close cores (up to ∼20°, Figure 3), and even in twin specimens from the same core (5°–17°, Figure 2).

[54] The hysteresis measurements we have made on rock fragments from the studied flows document rather homogeneous magnetization/coercivity parameters (Figure 7). Superimposed over a *Day et al.* [1977] plot, such parameters are typical of pseudosingle-domain magnetite. The elongation of the data distribution points to a mixture of single-domain and multidomain (or superparamagnetic) grains. A sample from the Trecastagni outcrop (Etn03a) of

the San Giovanni La Punta flow shows significantly different M_{rs}/M_s and H_{cr}/H_c values with respect to the other samples (Figures 7b and 7d). This may suggest that its anomalous paleomagnetic direction with respect to the other two outcrops from the San Giovanni La Punta flow is due to peculiar magnetic mineralogy, besides possible tilting during quarrying. Conversely, a specimen from the Linguaglossa (Etn13) test flow shows magnetic parameters similar to those of the other samples (Figures 7c and 7d).

[55] Measurements of the anhysteretic remanent magnetization in a pyroclastic flow succession revealed an inclination shallowing up to 10° [*Gattacceca and Rochette*, 2002], showing that magnetic anisotropy may cause a significant deviation of the recorded field toward the plane of maximum alignment of the magnetic grains. This concurs with several reports of paleomagnetic investigations in volcanic rocks yielding paleoinclinations significantly smaller than the expected values [*Urrutia-Fucugauchi et al.*, 2004; *Lanza and Zanella*, 2003]. However, this effect seems to be predominant in pyroclastic successions, and definitely less important in lava flows. Both *Rolph and Shaw* [1986] and *Lanza et al.* [2005a] have consistently shown that at Etna the inclinations paleomagnetically retrieved from flows emplaced during the last four centuries are no more than ~2° smaller than the coeval field inclinations gathered from direct observations.

[56] Our data from the four test flows show a first-order consistency (considering the respective confidence cones) of the paleomagnetic inclinations with the inclinations expected by the reference archeomagnetic curve (Figure 4 and Table 3). The Linguaglossa flow (Etn13) shows a mean paleomagnetic declination ~10° greater than the declination of the reference curve of corresponding age, while there seems to be no significant inclination error. A similar declination deviation occurs for the paleomagnetic direction gathered from the same Linguaglossa flow by *Tanguy et al.* [2003], which is fully consistent with our data (Table 4 and Figure 5). We conclude that inclination shallowing is not an important factor producing deviations of the remanence direction frozen in the Etna flows.

[57] There can be other factors producing the misalignment of the remanence carried by volcanics with the magnetic field characterizing the eruption time, namely mechanical factors including tilting of blocks (due to volcanic or tectonic reasons), and differential subsidence of the various flow sectors during cooling. However, these factors should be statistically compensated if samples from three distant sites of the flows are considered (as we did). We conclude that the eastward deviation with respect to the PSV reference curve (though not significant adopting Bayesian statistics) of the paleomagnetic direction recorded at all sites sampled in the Linguaglossa flow (Etn13) is mainly due the to deflection of the magnetic field at the cooling time due to magnetic anomalies produced by the underlying terrain (i.e., local underlying flows and/or the whole volcanic edifice).

7. Conclusions: How Accurate Is Paleomagnetic Dating?

[58] The "paleomagnetic dating" method of recent (few centuries/millennia) volcanics has come to a point where experimental procedures and statistical treatment need codification, and a consensus should develop over the accuracy of dating that can be achieved.

[59] Our study may serve to try to establish which α_{95} values (and hence which age accuracy of dating) are to be expected by a paleomagnetic study carried out (with the classical drilling and systematic AF cleaning method) sampling twelve cores per flow spaced in three distinct (and distant) sites. We find 3.3° to 5.7° (4.5° on average) α_{95} values which, after comparison with the relocated French archeomagnetic curve (analysed using Bayesian statistics) translate into age determinations which can be established (at the 95% significance level) with an accuracy of 136–661 years (307 years on average). Such an estimate does not take into account several sources of error, which may affect both the fidelity of paleomagnetic recording and the PSV reference curve.

[60] The sources biasing a perfect recording of the geomagnetic field by the cooling lavas are synthesized by *Lanza and Zanella* [2006], and include factors internal to the lava flow (mineral magnetic variability, magnetic anisotropy, field gradient), local deflections of the paleofield, and mechanical factors.

[61] Conversely, the errors of the reference curve may consist of (1) possible flaws in the curve itself; (2) errors by 1°–3° due to data relocation from France to Etna [*Lanza et al.*, 2005a]; (3) a 0.38°/yr westward drift of the geomagnetic field for the last 2 millennia [*Merrill et al.*, 1996], implying a 30–40 year age error for similar trends in geomagnetic elements when the longitude differences between France and Etna are considered.

[62] It follows that the dating uncertainties of lavas suggested above should be considered as a lower bound, and might be significantly underestimated. We stress that it would be difficult to reach a similar dating accuracy using the same method in other volcanoes from other continents. In fact, it is only for Mediterranean volcanoes that both high-precision PSV reference curves, and well-constrained age windows of lava emplacement (from stratigraphy/historical accounts) are available.

[63] The paleomagnetic directions gathered from four "test" flows (with known age) are systematically consistent with the reference curve at the 95% significance level. Therefore the "paleomagnetic dating" method seems to yield sound results, at least if dating based on Bayesian statistics using a 95% confidence level is adopted [e.g., *Lanos et al.*, 2005].

[64] The scatter of paleomagnetic directions from a single flow we observe at Etna (~3°–6°) concur with evidence gathered (by using classical methodology) during many years and at several volcanoes such as Etna [*Rolph and Shaw*, 1986], Hawaii [*Doell and Cox*, 1963; *Hagstrum and Champion*, 1994], Stromboli [*Speranza et al.*, 2004; *Quidelleur et al.*, 2005], and Vulcano [*Lanza and Zanella*, 2003]. Such scatter is likely due to local magnetic field deflection related to the magnetization of the rugged terrain and the cooling flow itself, to other factors (variation in cooling rate through the flow, nonthermal components of magnetization) inducing within-flow mineral magnetic variations (as observed at Etna by *Rolph* [1997]), and to mechanical factors.

[65] Our work may represent a first step to try to codify the paleomagnetic dating technique, and hence establish a routine standard to be adopted, and consequent accuracy of dating to be expected. Further studies are needed to establish (1) whether the use of thermal cleaning is preferable (i.e., whether it yields smaller α_{95} values) and (2) how many samples and how many sites from a single flow have to be used to achieve both needed goals of a statistically representative sample and the smallest α_{95} values. Our data indicate that at least three sites from a single flow (selected as far as possible from each other) are needed to avoid statistical undersampling.

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