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RESEARCH ARTICLE

Mount Etna eruptions of the last 2,750 years: revised chronology and location through archeomagnetic and ^{226}Ra-^{230}Th dating

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Abstract A careful re-examination of the well-known written documents pertaining to the 2,750-year-long historical period of Mount Etna was carried out and their interpretation checked through the high-accuracy archeomagnetic method (>1,200 large samples), combined with the ^{226}Ra-^{230}Th radiochronology. The magnetic dating is based upon secular variation of the direction of the geomagnetic field (DGF) and estimated to reach a precision of ±40 years for the last 1,200 years, and ±100 to 200 years up to circa 150 B.C. Although less precise, the ^{226}Ra-^{230}Th method provides a unique tool for distinguishing between historic and prehistoric lavas, which in some cases might have similar DGFs. We show that despite the abundance of details on ancient historical eruptions, the primary sources of information are often too imprecise to identify their lava flows and eruptive systems. Most of the ages of these lavas, which are today accepted on the geological maps and catalogues, were attributed in the 1800s on the basis of their morphology and without any stratigraphical control. In fact, we found that 80% of the "historically dated" flows and cones prior to the 1700s are usually several hundreds of years older than recorded, the discrepancies sometimes exceeding a millennium. This is proper the case for volcanics presumed of the "1651 east" (actually ~1020), "1595" (actually two distinct flows, respectively, ~1200 and ~1060), "1566" (~1180), "1536" (two branches dated ~1250 and ~950), "1444" (a branch dated ~1270), "1408" (lower branches dated ~450 and ~350), "1381" (~1160), "1329" (~1030), "1284" (~1450 and ~700), "1169 or 812" (~1000) eruptions. Conversely, well-preserved cones and flows that are undated on the maps were produced by recent eruptions that went unnoticed in historical accounts, especially during the Middle Ages. For the few eruptions that are recorded between A.D. 252 and 750 B.C., none of their presumed lava flows shows a DGF in agreement with that existing at their respective dates of occurrence, most of these flows being in fact prehistoric. The cinder cones of Monpeloso (presumed "A.D. 252") and Mt. Gorna ("394 B.C."), although roughly consistent magnetically and radiochronologically with their respective epochs, remain of unspecified age because of a lack of precision of the DGF reference curve at the time. It is concluded that at the time scale of the last millennia, Mount Etna does not provide evidence of a steady-state behavior. Periods of voluminous eruptions lasting 50 to 150 years (e.g., A.D. 300–450, 950–1060, 1607–1669) are followed by centuries of less productive activity, although at any time a violent outburst may occur. Such a revised history should be taken into account for eruptive models, magma output, internal

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plumbing of the volcano, petrological evolution, volcano mapping and civil protection.

Keywords Etna · Archeomagnetism · Radium dating · Chronology of eruptions · Volcano mapping · Magmatic evolution · Volcanic hazards

Introduction

Mount Etna is unique volcano for which historical documents go back as early as about 2,750 years B.P., that is, when the first Greek settlements were founded on the eastern coast of Sicily (Thucydides, in Huré 1957). Yet this period could be extended further into the past when considering some myths and legends that may be regarded as resulting from volcanic phenomena. Diodorus Siculus wrote (V, 5, 1) that terrific eruptions circa 1400 B.C. forced the Sicanians, a people living in the Etna region, to emigrate towards the western part of Sicily. These events were possibly the cause of a crop failure symbolized through the kidnapping of Demeter's daughter, goddess of agriculture, by Hades, god of the lower world (note that Demeter and Hades correspond to Ceres and Pluto in Roman mythology). On the other hand, the well-known myth of Hephaestos (Vulcan) and his Cyclopean collaborators, reported by Homer, has long been attributed to Etna's activity. However, Homer did not cite the name of Etna, and the landscape he described better describes some parts of the gulf of Naples (Bérard 1924). Similarly, it is quite unlikely that Hesiod, who lived in the 8th century B.C., alluded to Mount Etna in a verse of his Theogony, this part of the poem being altered later and, therefore, probably not written by Hesiod himself (Mazon 1928).

These examples show the many difficulties which arise when one tries to use old written documents for a scientific purpose. During the Greek and Roman periods, there are enormous gaps in the report of eruptions, and no precise activity can be ascertained between A.D. 252 and 1062. In addition to the reliability of the documents themselves, problems are still greater regarding the localization of lava flows and eruptive centers. Local names, when indicated, are no longer used or have been altered. Confusion often results from various homonyms dispersed on different parts of the mountain such as Mt. Arso, Mt. Nero, Mt. Frumento, Mt. Rosso (or Rossi, or Grosso), etc. Moreover, for a volcano which was strongly active during the last millennia, many lava flows and cinder cones have subsequently been buried by the products of further activity, and others were produced by eruptions that went unnoticed in written documents. Although reliable dates are available for some of the eruptions during antiquity, it is virtually impossible to identify, in the entanglement of innumerable flows, those which genuinely correspond to eruptions mentioned by the historians. Finally, the primary sources of information have constantly been distorted and reinterpreted through modern authors, so that many "historically dated" volcanic units that are displayed on maps and catalogues (Sartorius 1848–1859, 1879; Chaix 1892–1902; CNR 1979; Romano and Sturiale 1982; Chester et al. 1985) are in fact of spurious ages, as was demonstrated using archeomagnetism (Tanguy 1969, 1980; Tanguy et al. 1985, 2003), whose results were confirmed by ^{226}Ra-^{230}Th radiometric dating (Condomines et al. 1995, 2005).

Here we propose a full reexamination of Mount Etna's history during the past 2,750 years (Fig. 1), checking the interpretation of written documents by means of the high-accuracy (large-sample) archeomagnetic dating, combined with the ^{226}Ra-^{230}Th radioactive disequilibria. These two methods are complementary. Archeomagnetism gives very precise results, especially during the last 1,200 years, but when going further back in age, similar geomagnetic directions at different times could lead to several possible dates. The ^{226}Ra-^{230}Th method enables these ambiguities to be overcome, though it is less precise and requires a careful geochemical consideration. Before giving our results, it is of crucial importance to present a summary of the primary sources of information, which often drastically differ from reinterpretations made by "modern" authors (i.e., post-1700s authors).

Eruptions of Mount Etna recorded in ancient historical documents (see also Appendix 1)

In addition to classical Greek and Latin writings, many old printed books contain more or less detailed information about the eruptions of Mt. Etna. We have personally checked, mainly at the Bibliothèque Nationale in Paris and the Biblioteca Nazionale di San Marco in Venice, the original editions of Pietro Bembo (1495); Silvaggio (1542); Fazello 1558; Filoteo (1590); Amico (1740–1746). Among books entirely devoted to the history of Mt. Etna, we have to cite those of the Jesuit Carrera (1636), the canon Recupero (1815), the abbot Ferrara (1818), the canon Alessi (1832–1835), the baron Wolfgang Sartorius of Waltershausen (1880). In this section, we will refer to these authors without necessarily quoting the date of publication. Since a discussion of the volcanological information that can be extracted from these documents has already been published (Tanguy 1981; Tanguy and Patanè 1996; Patanè et al. 2004), only the most useful data for our purpose will be presented here and these are summarized in Tables 1 and 2, and a detailed discussion can be found in Appendix 1.

In addition to our new interpretation of the "Sicanian eruptions" (Appendix 1), we have to point out that many authors from antiquity (e.g., Plato, Aristotle, Ovid, Lucretius),

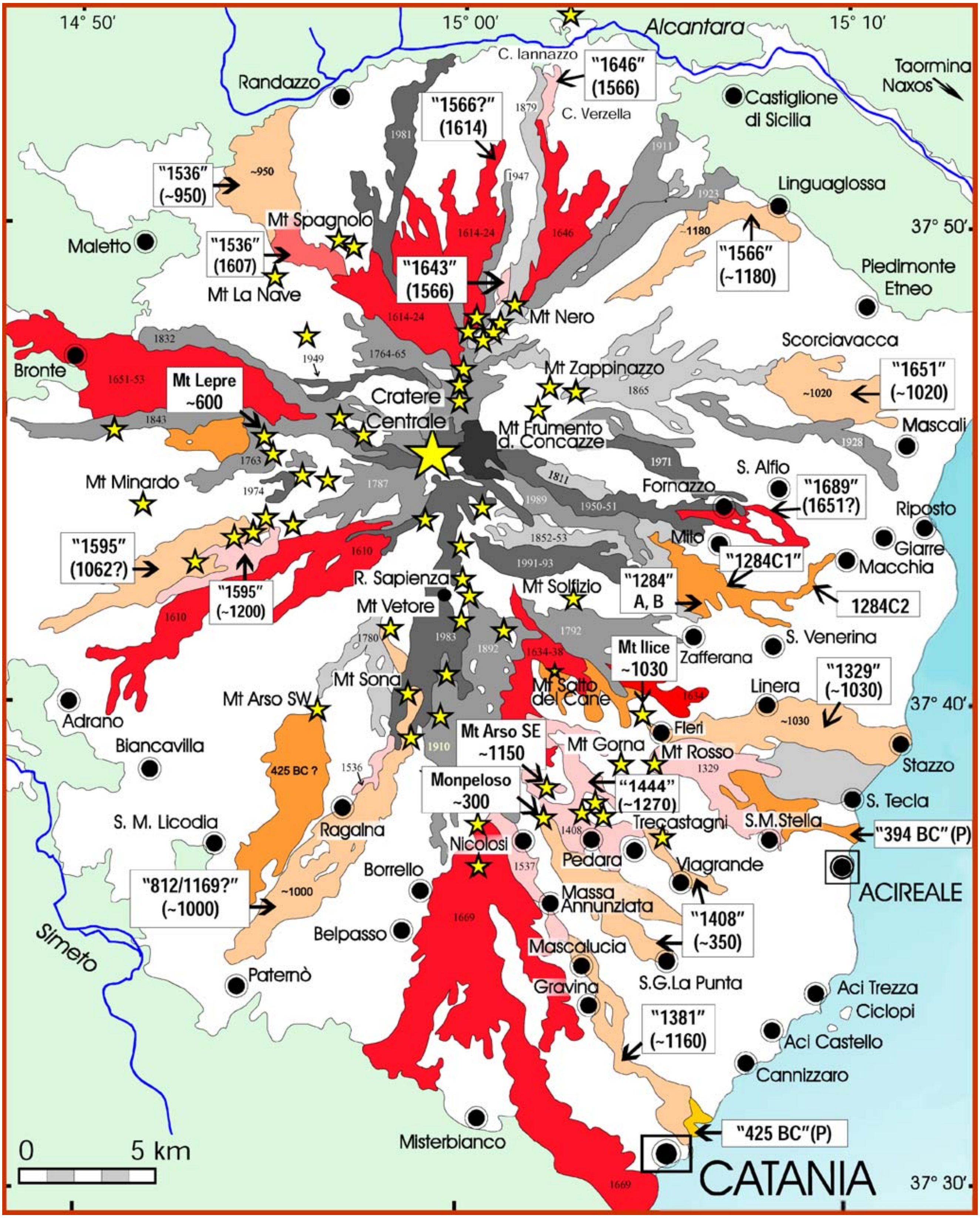

Fig. 1 Geological map of Mount Etna (simplified after CNR 1979) showing the various localities quoted in the text. Major volcanics of presumed age are indicated *between quotation marks*, with their proposed archeomagnetic ages *between parentheses* (see section Discussion in the text, *P* Prehistoric). *Stars* indicate the main pyroclastic cones

Table 1 Ancient historical eruptions of Mount Etna

Date	Type of activity and location	References
1400 B.C. circa	Cataclysmic eruptions	Diodorus Siculus, V, 6
(?) 695 B.C.	Southern flank, lava flow near Catania (?)	Stobaeus quoting Aelian (Bergk 1873)
479 B.C., August	East or SE flank, lava flow at sea	Arundel's Table (Parian Marble), Pindar, Aeschylus, and possibly Thucydides (see text)
475 B.C. (?)	Unlocated lava flow	Thucydides, possible confusion with 479
425 B.C., March–April	Lava flow in the neighboring of Catania	Thucydides, III, 116
396 B.C., spring	E or SE flank, lava flow at sea cutting terrestrial links between Naxos and Catania	Diodorus, XIV, 59
140 B.C.	"fires" larger than usual	Obsequens *De prodigiis*
135 B.C.	Lava flows, cinders, vapors, ash fall	Obsequens, Orosius V, 6, 2
126 B.C.	Earthquakes, summit and flank eruptions (submarine eruption near Lipari Island, Tyrrhenian Sea)	Obsequens, Orosius V, 10, 11 St. Augustine *City of God* III, 31
122 B.C. (?)	Large ash clouds darkening the sky for 3 days, lightnings in the plume	Cicero *De natura deorum*, Seneca *Quaest. Naturales* (no date indicated)
122 B.C.	Hot ash fall causes roof collapse in Catania, possibly lava flows	St. Augustine, *City of God* III, 31, Orosius V, 13, 1
49 B.C.	Large ash plume with lightnings, flank eruption westward	Petronius *Satyricon* 119, Lucan *Pharsalus*
44 B.C.	Fires, ash fall to Reggio Calabria	Virgilius *Georg.* I, 471, Livy
36–35 B.C.	Summit and/or flank (?) eruption, possibly N or NW	Appianus *Bell. Civ.* V, 114
32 B.C.	Lava flow?	Dion Cassius
A.D. 10–20 circa	Permanent activity within caldera	Strabo VI, 2, 3–8
38–40	Large eruption with rumblings heard to Messina	Suetonius
252, 1–9 February	Flank eruption and lava flow towards Catania	Bollandus and Henschenius 1643
1062–1064	Large lava flow westwards that could be seen from Troina city	Gaufredo Malaterra (in Alessi)
...?...	Lava flow at sea to Ognina, north of Catania	Bembo 1495, Fazello 1558 p. 59 (no precise date indicated)
1169, 4 February	Tectonic earthquake, doubtful eruption	Silvaggio 1542, Fazello 1558, Amico 1740–1746, etc.
1284–1285...	Earthquakes, flank eruption towards E	Nicolo Speciale (in Recupero)
1329, 28 June–August	Earthquakes, flank eruptions in Valle del Bove and near the Fleri village	Speciale, Silvaggio, Recupero, etc.
1381(?), 5 or 6 August	Lava flow in the vicinity of Catania	Simone da Lentini manuscript (Muratori 1738), doubtful account according to Ferrara (1818)
1408, 8–25 November	Earthquakes, fire fountaining at the summit crater, flank lava flows partly destroying Pedara to the SE	Silvaggio 1542
1444 ...?...	Lava flow towards Catania	Ranzano manuscript, Fazello 1558
1446, 25 Sept.	Flank eruption in Valle del Bove	Silvaggio 1542
1447, 21 Sept.	Summit eruption with lava flow	id.
1493–1500	Summit mild activity	Bembo 1495, Tornambeni 1537
1536, 22 March to April	Earthquakes, summit overflows towards NW and NE, and south flank eruption at ≈2200–1500 m elevation	Silvaggio, Fazello, etc.
1537, 10 May to June–July...	Summit and south flank eruption between 1,900 and 1,700 m in elevation, 15-km-long lava flow beyond Nicolosi	id.
1566, November or December	North flank eruption, lava flow close to the Alcantara River	Conti 1581, Recupero 1815
1579, September	Flank eruption towards SE (?)	id.

Information is extracted from the primary written sources before they became distorted by further interpretation (see text). Note that there are enormous gaps, especially during the Middle Ages. Code: (?) 695, doubtful eruption; 475 (?), an eruption that actually occurred but where the date is uncertain

though alluding to Etna, actually do not cite any precise year. Their accounts therefore cannot be used to reconstruct a valid chronology (see also Introduction). This fact is contrary to what was stated by Stothers and Rampino (1983), who described from the same imprecise accounts many features of eruptions during the Greek and Roman epoch. For example, their Table 1 begins with a long list of references that they believe to quote the "696–693" B.C. eruption, although none of these references can confidently be attributed to this date, including Thucydides and Aelian as we show in Appendix 1. These references were attributed to "693 B.C." through *further interpretation* by modern writers, following Bergk (1873) and Sartorius (1880). This led us to propose alternative interpretations not only for the "693" eruption, which in our sense appears highly questionable, but also for those of 479 and/or 475 B.C. (Appendix 1). In a similar way, the famous Latin poem "*Aetna*", which consists of 643 hexameters, is so poorly constrained in time that its author himself remains anonymous (Vessereau 1961), and none of the descriptions it contains can confidently be attributed to one of the dated eruptions. More generally, it results from this discussion that the eruptive events of this epoch which are truly recorded remain very few.

The end of the Roman Empire and the Middle Ages are entirely lacking of precise accounts regarding Mt. Etna. A strong outburst recorded by Olympiodorus probably occurred in A.D. 417 (Uchrin 1990; Chester et al. 2000), but its characteristics are unknown. Possible dates of eruptions within intervals 590–604, 638–644, 768–814, etc., are highly doubtful. Some of these events appear even fantastic, such as that presumed of "812", which was thought to have occurred during a most improbable journey of Charlemagne in the Middle East. This eruption was put on the scene by Chevallier (1925) who extrapolated his "periodic" hypothesis of the geomagnetic secular variation. Although this hypothesis was later recognized as entirely unfounded (Thellier 1966, 1971), an "812?" lava flow still appears on the 1979 CNR map (Fig. 1, the other proposed date of "1169?" for the same flow lacks of any historical support, see Appendix 1).

Possible periods of activity are quoted by Alessi in 836, 859, 911, 970, 1004 and 1044. According to the monk Odilon de Cluny, volcanic fires were expanding in this epoch in all directions. Other probable eruptions are reported from various sources between 1000 and 1050 (Boschi and Guidoboni 2001), but it is after the Normans had invaded Sicily (1061) that precise dates and some reliable accounts become available (Appendix 1 and Table 1). A true chronology of eruptions, however, can be reconstructed only from 1603 onwards (Table 2).

In addition, many more recent lava flows (e.g., 1689, 1702, 1755..., see asterisks in Table 2) were largely buried beneath products from further activity, so that their actual extent and volume are today quite difficult to assess. This is even the case for flows as recent as 1999 (SE crater) or 2001 (upper south flank), and for virtually all the lavas of the sustained summit activity between 1955 and 1971, calculated to 370×10^6 m^3 at their time of emplacement (Table 2). This could explain why the volume data compiled from the literature are often uncertain, even for those resulting from true calculations based on examination of maps before and after eruption, which can show discrepancies reaching 50% or more, despite a claimed accuracy of 10–20% (Murray 1990; Behncke et al. 2005).

On the whole, eruptions posterior to the 1600s on the southern half of Etna and close to Catania are well located, whereas many misconceptions have arisen for those of the northern part, even in very recent times, because craters and flows were not precisely mapped at the time they were produced. A reconstruction of the 1879 eruptive system from a detailed contemporaneous account (Silvestri 1879) shows that the "true" Mt. Umberto-Margherita, which was built by this eruption, lies more than a kilometer away from its present presumed place (Tanguy 1980). Furthermore, mistakes are made at the occasion of each new edition of topographical maps (e.g., "1776" for the 1766 flow, "1848" for the 1843 vents, or "Mt. Frumento netto" for Mt. Frumento sett.=settentrionale, i.e., northern, etc.). Some of these misconceptions were corrected by recent authors (e.g., Romano and Sturiale 1982; Chester et al. 1985), and there is a present tendency to re-examine the history of Etna through more impartial scientific observations such as archeology and ^{14}C radiochronology (Boschi and Guidoboni 2001; Branca and Del Carlo 2004). These works however remain hampered by the rarity of carbonized wood available and the lack of a dating method on lava itself that should be precise enough for distinguishing between volcanics that differ by centuries or even decades.

Archeomagnetic dating

The fact that lavas during cooling record the ambient magnetic field, and that the direction of the geomagnetic field (***DGF***) changes substantially in a matter of centuries (secular variation, or ***SV***), provides a powerful tool for both reconstructing the SV curve and, conversely, for checking the ages of lava flows and hot-emplaced pyroclasts. Archeomagnetism, however, was primarily defined as the magnetic study of human artefacts whose ages are known through archeological means (Thellier 1966, 1971). At the St. Maur laboratory we benefited from the high-accuracy archeomagnetic method which involves large samples weighing 0.5 to 1 kg and their measurements using adequate devices, constantly improved through time. Compared to the classical core-drilling method used by paleomagnetists (e.g., Rolph et al. 1987; Lanza et al. 2005), our "large-sample" method applied to volcanic materials was proven better in precision and accuracy and particularly suitable for retrieving the SV of the DGF (Tanguy et al. 1985, 2003; see also discussion in Tanguy et al. 2005). These results, added to those obtained from archeological materials (Thellier 1981; Bucur 1994; Gallet et al. 2002), allowed the precise construction of SV curves for the two or three last millennia that will be used here for archeo-

Table 2 Eruptions of Mount Etna from A.D. 1603 to 2003, compiled from Tanguy 1980, 1981; Tanguy and Patanè 1996; Patanè et al. 2004, and references therein (also Behncke et al. 2005; Branca and Del Carlo 2005)

Date (beginning-end)	**Location**, elevation (m)	**Lava flows** (10^6 m^3)	**Pyroclasts** (10^6 m^3)	**Notes**
1603–1610**	CC (≈3,300)	n.d.	n.d.	Continuous summit activity, frequent overflows from 1607 to 1610
1607 (28 June–...?...)*	NW 2,500–1,500 (?)	n.d.	n.d.	Fissure above Mt. Spagnolo cinder cone, lava flow “3 miles in length”
1610 (6 Feb–3 May)	SSW 2,800–2,200	30	3	Grotta degli Archi craters
“(3 May–15 Aug)	SW 2,300–1,700	90	<1	Large flows nearly reach Adrano
1614 (1 July)–**1624** (...?...)*	N≈2,500–2,000	≥1.000	2	Due Pizzi super-hornitos, lava flows “10 miles in length, 6 miles in width”
1619 (...?...)**	CC	n.d.	n.d.	Lava overflow
1634 (18 Dec)–**1636** (June)*	SSE 2,100–1,950	180	1	Minor activity at vents until 1638
1646 (20 Nov)–**1647** (17 Jan)*	NNE 1,900	160	7	Northern Mt. Nero cinder cone
1651 (17 Jan)–**1653** (...?...)*	WNW≈2,000	500	n.d.	Village of Bronte partly destroyed
“(...?...)*	ENE≈1,500 (?)	25	n.d.	Flow toward Macchia di Giarre
1669 (11 March–11 July)	S 3,000–800	600	250	Strong seismic and explosive activity, large cinder cone of Mt. Rossi above Nicolosi, 15 villages and part of Catania destroyed (volume calculations are our own estimate)
“(25 March)	CC	0	n.d.	CC explosion and summit collapse
1682 (September...), 1688**	E≈2,900	n.d.	n.d.	Subterminal (?) lava flows
1689 (14 March–...?...)**	E≈1,800–1,700	≈20 (?)	n.d.	Vents in Valle del Bove (above R. Musarra), flow identification possibly confused with 1651 east (see text)
1693, 9 and 11 January	Eastern Sicily			Tectonic earthquakes, about 60,000 deaths
1702 (8 March–8 May)**	SE≈2,500–2,000 (?)	≈30–40 (?)	n.d.	Flows reaching Valle di Calanna, today completely buried by further lavas
1723–1724, 1732–1765**	CC	≈90 (?)	n.d.	Continuous explosive and effusive activity at Central Crater, flows largely buried
1755 (10–15 March)**	E≈2,500–2,000 (?)	≈5 (?)	n.d.	Lava and debris flows in Valle del Bove
1763 (6 Feb.–15 March)	W 1,600	15	2	Monte Nuovo cinder cone
1763 (19 June–10 Sept)*	S 2,500	65 (?)	35	Violent explosive activity, large cinder cone of “La Montagnola”, flows largely buried
1766 (28 April–7 Nov)*	S 2,100–1,900	125	2	Mt. Calcarazzi cinder cones
1780 (18–31 May)	SSW 2,300–1,850	25	<1	Possible weak activity until July
1787 (17, 18, 19 July...)**	CC	7	n.d.	Fire fountaining 3 km high, lava overflows towards S and W flanks
1792 (12 June)–**1793** (... May)	SSE 2,600–1,900	90	<1	Cisternazza pit-crater, lava flows nearly reach Zafferana
1798–1809...	CC	n.d.	n.d.	Nearly continuous summit activity
1802 (15–16 Nov)**	E≈1,800	≈5 (?)	<1	Small flow in Valle del Bove, today buried
1809 (27 March–9 April)*	NNE 3,000–1,500	35	2	Chain of craters along NNE rift
1811 (27 Oct)–**1812** (24 April)**	E 3,000–2,000	45	4	Mt. Simone cinder cone, flows in Valle del Bove
1819 (27 May–1 Aug)**	SE 2,800–2,100	50	4	Vents on the upper W wall of Valle del Bove
1827–1833...**	CC	n.d.	n.d.	Continuous summit activity
1832 (1–22 Nov)	W 2,900–1,750	50	3	Mts Ognissanti (or Nunziata)
1838–1839, 1842**	CC	20	n.d.	Flows in Valle del Bove
1843 (17–28 Nov)	W 2,500–1,900	55	3	Flow 15 km long, 59 deaths due to secondary phreatic explosion at lava front
1852 (20 Aug)–**1853** (27 May)*	ESE 2,500–1,800	125	12	Mt. Centenari cinder cones, lava flow nearly reaches Zafferana
1863 (July), 1864 (Aug.–Sept)	CC	<1	<1	Explosive eruptions, small overflows
1865 (30 Jan–28 June)	NE 2,200–1,650	90	4	Mt. Sartorius
1868 (27 Nov, 8 Dec)	CC	0	n.d.	Fire fountaining 2 km high

1869 (26 Sept)**	E 3,000	**3**	<1	N–S oriented fissure at eastern base of central cone
1874 (29 Aug)*	N 2,800–2,030	**2**	1	Strong seismic activity
1879 (26–27 May)*	SSW 2,650–2,300	**2**	<1	10-km-long N–S fractures cutting CC, violent explosive activity on the northern flank (Mt. Umberto-Margherita)
“(26 May–6 June)	NNE 2,450–1,690	**23**	20	
1883 (22–24 March)**	S 1,200–1,025	<1	<1	Strong seismic activity, fissures on the upper south flank
1886 (18 May–7 June)*	S 1,500–1,300	**50**	10	Mt. Gemmellaro, lava flows nearly reach Nicolosi
1892 (9 July–29 Dec)*	S 2,025–1,800	**135**	8	Mt. Silvestri
1893–1907	CC	<1	n.d.	Nearly continuous weak activity, lava within the CC. Paroxysmal explosions in 1899 (19 and 25 July, 4 Aug)
1908 (29–30 April)** “(May–June...)	SE 2,500–2,200 CC	**2**	<1	Seismicity, eruption followed by explosive activity at CC
1908, 28 December	Messina, Reggio-di-Calabria			Tectonic earthquake, about 80,000 deaths
1910 (23 March–18 April)*	S 2,300–1,930	**51**	<1	Fissure from the CC, rapid lava flow nearly reaches Belpasso
“(27 Dec–17 Feb 1911)	CC	<1	n.d.	Small eruption within CC
1911, 27 May	CNE 3,100			Formation of the NE crater by collapse of the lower slope of central cone
1911 (10–21 Sept)*	NNE 2,550–1,700	**41**	1	Rapid lava flows to the NE base of the mountain, fissure from the CC extending on the upper south flank
1912–1923**	CC, CNE	n.d.	n.d.	Continuous activity: explosions, lava fountains, small flows
1918 (29 Nov?)*?	NW 3,000–1,900	5 (?)	n.d.	Small unobserved eruption (bad weather), flow location uncertain
1923 (17 June–18 July)	NNE 2,500–2,000	**63**	<1	Flank eruption heralded by small outflow from CNE in May. Fissure from the summit, lava flow travels 7 km in 10 h
1928 (2 Nov)	CNE, CC	n.d.	n.d.	Flank eruption begins with explosions from CNE and CC, Mascali village reached within 36 h by rapid lava flows and entirely destroyed
1928 (2–20 Nov)	ENE 2,900–1,200	**33**	1	
1929–1942	CC, CNE	n.d.	n.d.	A CNE explosion kills two people on 2 Aug, 1929. Large fire fountaining at CC on 16 March 1940
1942 (30 June)**	SSW 2,780–2,240	**3**	<1	Brief flank eruption followed by fire fountaining at CC
1947 (24 Feb–10 March)	N 3,050–2,200	**10**	<1	Flank eruption preceded by fire fountains at CC and CNE
1949 (1–4 Dec)*	S 3,100-N 3,200–3,000	5 (?)	n.d.	Large fissure cutting the CC, strong degassing at CNE after eruption
	NNW 2,470–1,990	**4**	<1	
1950 (25 Nov)–**1951** (2 Dec)*	E 2,820–2,250	**137**	1	Large lava flows to Fornazzo and Milo, weak explosive activity along the fissure
1955 (29 June)–1964 (Feb) 1966 (10 Jan)–1971 (March)**	CNE	**250 (+120?)**	n.d.	Nearly continuous lava outflow accompanied by moderate explosions. Lava volume measured from 1955 to 1967 (average output 1 m^3/s), ≈120 million m^3 must be added until 1971 by assuming 1 m^3/s (Guest 1973)
1955 (Sept), 1956 (28 Feb–2 March, 2–7 April), 1960 (17 July–5 Aug), 1961 (12–13 May), 1964 (1 Feb–5 July)**	CC	10 (?)	20 (?)	Violent explosions or lava fountaining, often accompanied by overflows
1971 (5 April–12 June)	S, SE, ENE 3,000–1,800	**43**	2	Complex flank eruption, lava flows nearly reach Sapienza and Fornazzo. Pit-crater at SE base of the central cone as an ancestor of CSE
1974 (30 Jan–17 Feb, and 11–29 March)	W 1,680–1,650	4	2	Mt. De Fiore
1974 (28 Sept)–1977 (8 Jan)*	CNE, N 3,000–2,600	70 (?)	<1	Volume estimated by assuming 1 m^3/s (see 1955–1971)

Table 2 (continued)

Date (beginning-end)	**Location**, elevation (m)	**Lava flows** (10^6 m^3)	**Pyroclasts** (10^6 m^3)	**Notes**
1977, 1978 (16 July to 28 March)**	CNE	n.d.	n.d.	Series of 20 short and violent outbursts with fire fountains and rapid lava flows
1978 (29 Apr–5 June, 23–29 Aug 23–29 Nov)**	CSE, SE, ENE 3,000–1,650	30	n.d.	Succession of three flank eruptions accompanied by violent fire fountaining at CSE
1979 (3–9 Aug)*	CC, CSE SE, E, ENE 2,900–1,600	10	n.d.	Violent explosive activity, complex flank eruption. A phreatic explosion from Bocca Nuova (CC) kills nine people on 12 September
1980–1981 (1, 6 Sep, 5–7 Feb)**	CNE	**13**	n.d.	Violent outbursts
1981 (17–22 March)	NNW 2600–1120	**18**	1	Rapid lava flow to the Alcantara River
1983 (28 March–6 Aug)*	S 2,700–2,280	**79**	<1	Moderate, but sustained output
1984 (29 Apr–16 Oct)**	CSE	**15**	n.d.	Seismic crisis at the end of the eruption
1985 (10 March–13 July)*	S 2,600–2,450	**25**	<1	Same area as 1983
1985 (25–31 Dec)**	E 2,800–2,600	<2	n.d.	Small eruption, but violent seismicity: one death
1986 (14–24 Sept)**	CNE	<1	1	Strombolian activity ending by violent paroxysm
1986 (30 Oct)–**1987** (25 Feb)*	CSE, ENE 2,900–2,190	**71**	2	Mt. Rittmann. Phreatic explosion at CSE causes two deaths on 17 April 1987
1989 (27 Sept–9 Oct)	CSE, NE 3,000–2,600	**43**	<1	Series of lava fountains at CC and CSE herald flank eruption, “dry” fissure to the SSE
	SSE 3,000–1,500	0	0	
1990 (4, 11, 14 Jan, 1 Feb)	CSE	2	2	Violent outburst on 4 January
1991 (14 Dec)–**1993** (31 Mar)	SSE 3,000–2,200	**231**	<1	Sustained flank eruption, with low output after 30 June 1992
1995–1999	CNE, CC, CSE	7	10	Increasing summit activity ending with a series of violent outbursts at CSE. Large lava fountain at CC on 22 July 1998
1999 (4 Feb–5 Nov)*	CSE, SE 3,000–2,800	**32**	<1	Fissure downslope CSE
1999 (4 Sept)	CC (Voragine)	<1	3	Fire fountain exceeding 1,500 m in height
1999 (17–31 Oct)	CC (Bocca Nuova)	**17**	n.d.	Strong explosions, rapid lava overflows westward exceed 5 km in length
2000–2001	CSE	**46**	12	Series of about 80 violent fire fountains with lava overflows, sustained degassing at CC
2001 (17 July–9 August)*	S 3,100–2,100 NE 2,600	**25**	5	Large seismic swarm heralds complex flank eruption fed by both τβ and β magmas, strong explosive activity builds a 100-m-high cinder cone, degassing at CSE, CC and CNE
2002 (27 Oct–3 Nov)	NNE 2,500–1,890	**10**	**1**	Diametrical fracture from the south (β magma) to NNE (τβ magma), strong explosive activity to the south builds two large cinder cones, occasional strong degassing at CC and CNE
“(27 Oct)–**2003** (28 Jan.)	S 2,700–2,800	**30**	20–30 (?)	

Years in *bold* are those of flank eruptions. *Asterisks* indicate eruptions whose lava flows are partly (*) or almost totally buried (**) by products of further activity. Volumes are average values from the literature (probably no better than ±50%) expressed as dense rock equivalents (by using 2.6 g/cm^3 for lava flows, 1.5 g/cm^3 for pyroclasts), however, values shown in *bold* result from proper topographic measurements (±10%, Murray 1990, and pers. comm.). *CC* Summit central crater, *CNE* Summit crater of north-east, *CSE* Summit crater of south-east magnetic dating of Etna lavas (Fig. 2). More details on laboratory processing are provided in our methodological papers listed above, and we insist now on the difficulties encountered for valuable dating.

Although the DGF may present variations of more than 40° in declination (D) and 20° in inclination (I), the path of its change often traces segments going parallel and very close each other, so that the highest accuracy is needed for discriminating between paleodirections of lavas that may only be a few degrees apart for hundreds of years (e.g., A.D. 800–1300 and 1300–1700, Fig. 2). Our method of sampling and measurement thus allows precision of a few tenths of a degree on each individual sample. A larger dispersion is in fact observed between samples from a given site because of properties inherent to volcanic materials. These include small displacements of the lava during and after cooling or magnetization being acquired in a region where the DGF is disturbed by the volcanic pile and the already magnetized parts of the cooling flow. However, experience gained in comparing results from hundreds of sites shows that the half-angles of the 95% confidence cones from Fisher's statistics (1953) are usually less than 2° and often close to 1°. This is in the same range as what was observed from instrumental measurements of the present geomagnetic field made on 12 archeomagnetic sites distributed in the whole area of Mount Etna (Tanguy and Le Goff 2004). Therefore, magnetic disturbances in volcanic terrains are usually not large enough to prevent a reasonable retrieval of the DGF, provided that sampling is carried out on a relatively large area in order that those disturbances will cancel each other. The low level of uncertainty of 1–2° for each volcanic unit reported on the reference SV curve leads to an average error on archeomagnetic dating of no more than ±40 years for the last 1,200 years, and ±100 to 200 years for the older period. In this latter case, the lesser precision mainly comes from the reduced amplitude of SV (Fig. 2), but also from an increasing uncertainty on the SV reference curve. According to Gallet et al. (2002), the DGF shows very little variation between 0 and 400 B.C, so that materials from this period can hardly be distinguished. Where the SV mostly affects inclination (e.g., 1875–1750 A.D., or 1600–1300, Fig. 2), an additional error on dating may be due to the fact that thick lava flows tend to record the DGF with inclination lower by 1–2° than real (e.g., Chevallier 1925). This is obvious for lavas between 1843 and 1763, which appear 30–40 years too young. However, this deviation is

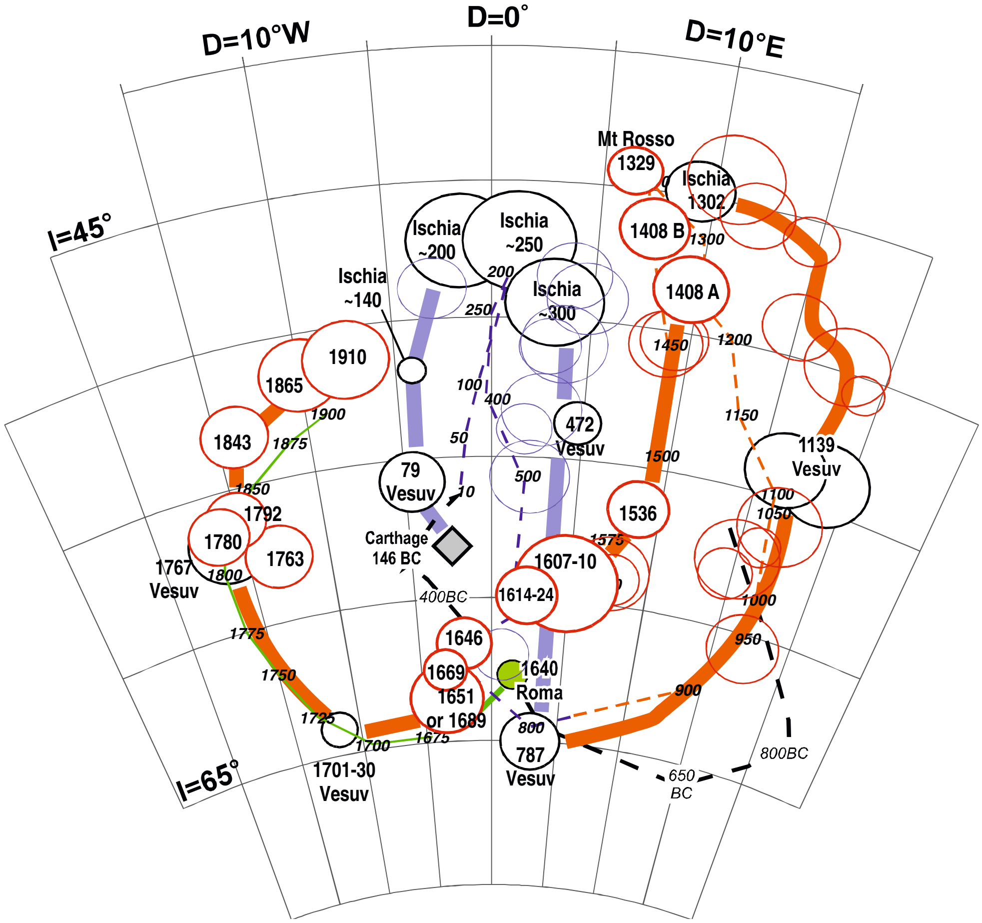

Fig. 2 Directional curve of the Geomagnetic Secular Variation (*heavy orange and blue lines*, *I* Inclination, *D* Declination), reconstructed from well-dated Italian lavas with their 95% confidence circles (*undated circles* represent lavas of doubtful ages, see Fig. 3a). The *green line* indicates a synthesis of instrumental measurements backward in time until A.D. 1640 (Jackson et al. 2000, except for the 1640 point which comes from Cafarella et al. 1992). The *dashed orange and blue line* is the French archeomagnetic curve relocated to Sicily (from Gallet et al. 2002). The 146 B.C. point corresponds to Carthage (Thellier 1981). All results recalculated to Etna coordinates (37.75°N, 15°E)

Table 3 Magnetic directions and revised ages of previously dated historical lavas

Volcanic units (lava flows or pyroclastic cones)	N/n	α95 (°)	k	I(°)	D(°)	Magnetic age	Given eruption
1) 1669 flows on the southern flank (4 sites)	30/30	0.71	1310	62.5	−3.3		1669**
2) Presumed 1689 flow to the east at Fornazzo and Sciara S. Giovanni villages (4 sites)	36/36	0.93	633	64.1	−3.1	1670±20	1689** or 1651**
3) 1646 flows on the northern flank (2 sites)	17/19	0.94	1302	61.6	−1.9		1646**
4) Presumed 1566 A flow on the northern flank (Sciara Nuova, 2 sites)	13/14	1.02	1458	59.9	2.3	1610±20	1614–24**
5) 1610 flow above Adrano town on the SW flank* [1610-140]	10/10	1.61	750	60	3.5		1610**
6) Presumed 1536 A flow on the upper NW flank	6/6	1.67	1172	59.4	4.8	1600±40	1607**
7) Presumed 1646 flow on the lower northern flank, contrada Iannazzo (3 sites)	14/25	0.86	1900	59.1	7.7	1580±20	1566**
8) Presumed 1643 spatter ramparts NW of Mt. Nero, middle northern flank (2 sites)	13/18	1.34	906	58.9	7.5	1570±30	1566**
9) 1536 flow on the middle southern flank (2 sites)* [1536-23]	21/21	1.04	855	56.5	8.7		1536**
10) Presumed 1284 A flow on the eastern flank (after Sartorius, 1879), Ballo village, north of Zafferana (2 sites)* [814]	13/14	1.07	1309	50.3	9.2	1450±30	1446**
11a) Presumed 1284 C1 upper flow at Monacella*, north of Santa Venerina (2 sites)* [2249, 4110]	21/22	1.13	732	50.6	9.0	1450±30	1446 (?)**see text
11b) Presumed 1284 C2 lower flow near Dagala (2 sites)	14/18	1.60	545	44.2	10.2	1290±40	1284**
12) Presumed 1408 A flow on the SE flank, above Pedara (2 sites)* [1408-1]	17/20	1.22	783	48.4	9.6	1430±30	1408** or 1444
13) Presumed 1408 B flow between Pedara and Nicolosi, contrada Ràgala (3 sites)* [027]	26/27	1.1	621	46.4	7.5	1400±30	1381 (?) or 1408**
14) Monte Rosso 1329 cinder cone near Fleri village (E flank), and flow 2 km downslope (2 sites)	20/20	0.86	1333	44.6	6.3		1329**
15) Presumed 1444 flow east of Tre Monti on the lower SE flank (2 sites)* [2601, 4144]	16/16	1.2	850	45.3	12	1270±20	
16) Presumed 1535 and 1536 B flows downslope Mt. Nero degli Zappini on the southern flank, sampled at Botanic garden and west of Mt. Vetore (2 sites)	18/18	0.82	1613	45.6	14.6	1250±20	1250 (?)
17) Presumed 1595 A flow on the SW flank (upper Gallo Bianco flow)* [2042]	10/10	1.2	1351	48.9	15.1	1200±30	1194, 1197 or 1222 (?)
18) Presumed 1566 B flow above and below Linguaglossa on the lower NE flank (2 sites)* [2149]	19/19	1.37	549	49.8	17.9	1180±30	1194 or 1197 (?)
19) Presumed 1381 A flow, eastern branch near Gravina on the lower south flank* [1132]	12/12	1.41	815	51.1	18.6	1150±30	
Presumed 1381 B flow, western branch near Gravina	13/14	1.33	853	49.8	19.2	1170±30	
Presumed 1381 C flow at Catania, via Gasperi	6/7	1.2	2258	50.6	20.1	1160±30	
Presumed 1381 D flow, Catania seashore (Guardia)	9/13	1.85	717	50.7	18.9	1160±40	
Presumed 1381 flow from vents to the sea, average of the 4 sites	40/46	0.75	901	50.6	19.1	1160±20	1169 (?)
20) Presumed 1595 B flow on the SW flank (lower Gallo Bianco flow)* [2027]	16/16	1.44	591	56	17	1060±50	1062**
21) Mt. Ilice cinder cone* [4323] and adjacent craters on ESE flank, presumed 1329 A	9/13	1.46	1016	57.5	17	1020±30	
Presumed 1329 B flow at SE base of Mt. Ilice* [5915]	9/11	1.78	690	56.9	16.7	1030±40	
Presumed 1329 C flow at Linera* [471]	9/10	1.11	1455	56.5	16.2	1030±20	
Presumed 1329 D flow at seashore (Stazzo)	15/17	1.59	553	57.1	16.1	1030±30	
Presumed 1329 Mt. Ilice cinder cone and large flow at sea, average of the 4 sites	42/51	0.74	841	56.8	16.2	1030±20	
22) Presumed 1651 east flow at Scorciavacca, lower eastern flank (2 sites)	15/17	1.44	627	57.5	15.1	1020±40	
23) Mt. Sona cinder cone on the southern flank, presumed 812 or 1169	10/11	1.6	768	57.5	14.8	1020±40	
Sona flow near Ragalna village (Sciara Galifi)* [050]	8/8	2	600	58.2	14	1000±50	
Sona flow at its front near Paterno town* [1193]	7/8	1.04	2578	58	14.8	1000±20	
Presumed 812 or 1169 cinder cone of Mt. Sona and large flow towards Paterno,	25/27	0.9	883	58.1	14.6	1000±30	

average of the 3 sites							
24) Presumed 1536 C lower flow on the NW flank near Randazzo (Sciara del Pomiciaro, 2 sites)* [2052]	16/18	1.23	809	60.5	17	950±30	
25) Presumed 1284 B flow north of Zafferana (after Sartorius, 1879), 2 sites* [3672]	12/17	0.87	2158	62	0.7	700±50	
26) Presumed 12th century flow downslope Mt. Ciacca near 1,500 m elevation on southern flank* [2154]	9/9	1.3	1358	55.7	2.2	500±50	
27) Presumed 1408 C flow on the SE flank above St. Alfio church, Trecastagni	10/11	0.9	2440	54	1.8	450±40	
28) Presumed 17th-century flow on west flank near Bronte	8/11	1.3	1504	53.3	2.7	450±50	
29) Presumed 1408 D flow downslope Trecastagni (SE of 1408 C)* [4074]	14/17	1.05	1274	51	3	350±50	
30) Presumed 1408 E flow on SE flank near St. Giovanni La Punta (sciara Pulea, 2 sites)* [3871]	14/14	1.42	697	50.9	3.7	350±60	
31) Presumed 252 A flow at the base of Monpeloso cinder cone, lower southern flank* [4102]	13/13	1.3	833	49.2	4.7	300±100	See text
32) Presumed 1408 F flow on southern flank near Massannunziata, about 3 km downslope Monpeloso	8/8	1.22	1633	48.4	4	300±100	Probably the Monpeloso flow (31)
33) Presumed 1537 flow on southern flank below Sapienza refuge	9/10	1.09	1835	48.9	−2.9	200±100	
34) Presumed 252 B flow at Cibali, NW part of the circonvallazione, Catania* [090]	11/11	1.5	780	48.8	−4.4	200±100 or P	See text, ≈2700 B.C. from Ra-Th (Table 6)
35) Presumed 122a B.C. flow of Carvana (Sciuto-Patti 1872), Piazza Gioeni, northern Catania* [6122]	7/7	1.2	1952	51.7	−5.7	100±100 or P	See text, ≈2440 B.C. from Ra
36) Presumed 122b B.C. Mt. Serra cinder cone on the lower SE slope (Romano and Sturiale 1982)	4/5	1.5	2180	41.7	−1.2	P	
37) Presumed 394a B.C. flow on the lower SE flank at Santa Maria la Stella, west of Acireale (2 sites)* [4048]	15/17	1.21	891	57.2	−4.3	150 B.C.±200	122–140 B.C.? cf. Ra (Table 6)
38) Presumed 394b B.C. flow on SE flank, base of Mt. Gorna cinder cone (2 sites)	14/16	1.19	985	58.1	−3.5	150 B.C.±200	122–140 B.C.?
39) Presumed 394c B.C. cinder cone of Mt. Gorna on the SE flank* [3843]	17/25	1.36	619	60.1	8	≈500 B.C. (?)	≈680 B.C. from Ra (see text)
40) Presumed 394d B.C. flow NW of Acireale	10/10	1.71	672	50.1	−10.1	P	
41) Presumed 394e B.C. flow NE of Acireale just above the sea (old railway trench)	5/8	1.9	1085	40.9	−11.8	P	
42) Presumed 425 B.C. flow near Catania seashore (2 sites: Lungomare and via Rotolo)* [3790]	12/15	1.06	1453	51.2	−2.6	150±100 or P	≈2000 B.C. from Ra
43) Presumed 693a B.C. flow at Catania (Fortino Vecchio, viale della Regione)* [1906]	6/7	1.92	883	44.1	10.3	P	≈3600 B.C. from Ra
44) Presumed 693b B.C. flow at southern base of Etna, east of Misterbianco town	8/8	1.7	842	48.4	11.9	P	Overlain by Roman aqueduct

Presumed ages are from the 1979 geological map (CNR 1979), unless otherwise indicated. Results are reported in order of increasing corrected ages (penultimate column). *N/n* Samples used for calculations/Total number of samples; *I* magnetic Inclination, *D* Declination; α95 and *k* statistical parameters; * volcanics also studied by ^{226}Ra-Th with their sample number, e.g., [1610–140], see Tables 5 and 6; ** eruptions for which topographic information is available in written accounts, see text. *P* Prehistoric (older than 750 B.C. circa, given the uncertainty of dating methods for this period). Volcanics of undoubted age (e.g., 1669) are included for comparison not systematic, and as dating is mainly made by reference to well-dated lavas (see results below), no correction was made.

Perhaps the most severe limitation of archeomagnetism applied to volcanoes lies in the increasing number of ambiguous ages when the SV curve crosses itself by going back further into the past. For example (Fig. 2), the DGF was practically the same during A.D. 1600–1650 and A.D. 600–700, and again around 500 B.C. Whereas lavas only 400 years old may be distinguished morphologically, the problem remains for the historically more ancient flows and eruptive systems. In these cases other criteria must be used, such as stratigraphy, archaeology (lava over or underlying human artefacts of known age), or radiochronology. Radioactive methods are usually less precise than the archeomagnetic one just described. However, if the ambiguity to be solved is a matter of centuries or millennia, then a clear response can be given. In the Etna case, such a response is provided by a new method based on ^{226}Ra-^{230}Th disequilibria (Condomines et al. 1995, 2005), which is suitable for volcanic rocks younger than the last 8,000 years (see Ra-Th dating below).

Archeomagnetic sampling and results

This work includes a number of newly studied volcanic units with a total of more than 1,200 large samples. Most of the lavas sampled during previous work were revisited and sampled again so that the final results were substantially improved, which was also due to better performance of laboratory measurements and treatment of the data. For instance, it was stated that the viscous component of the natural remanent magnetization did not exceed 5% (Tanguy 1980). We are presently able to ascertain that it never exceed 2% and is most generally lower than 1%. The alpha 95 of the Fisher's statistics, which are critical for discussion of archeomagnetic ages, are here comprised between 0.6° and 1.9°, except for the pyroclastic cone of Mt. Lepre where it reaches 2.3°.

Archeomagnetic results on "historically dated" lavas whose ages were found incorrect are shown in Table 3 and Figs. 3a and 4, by going back further into the past (i.e., towards increasing uncertainty). As no lava flow younger than A.D. 1700 was found incorrectly dated, the results begin for the 1600s including those flows for which no age

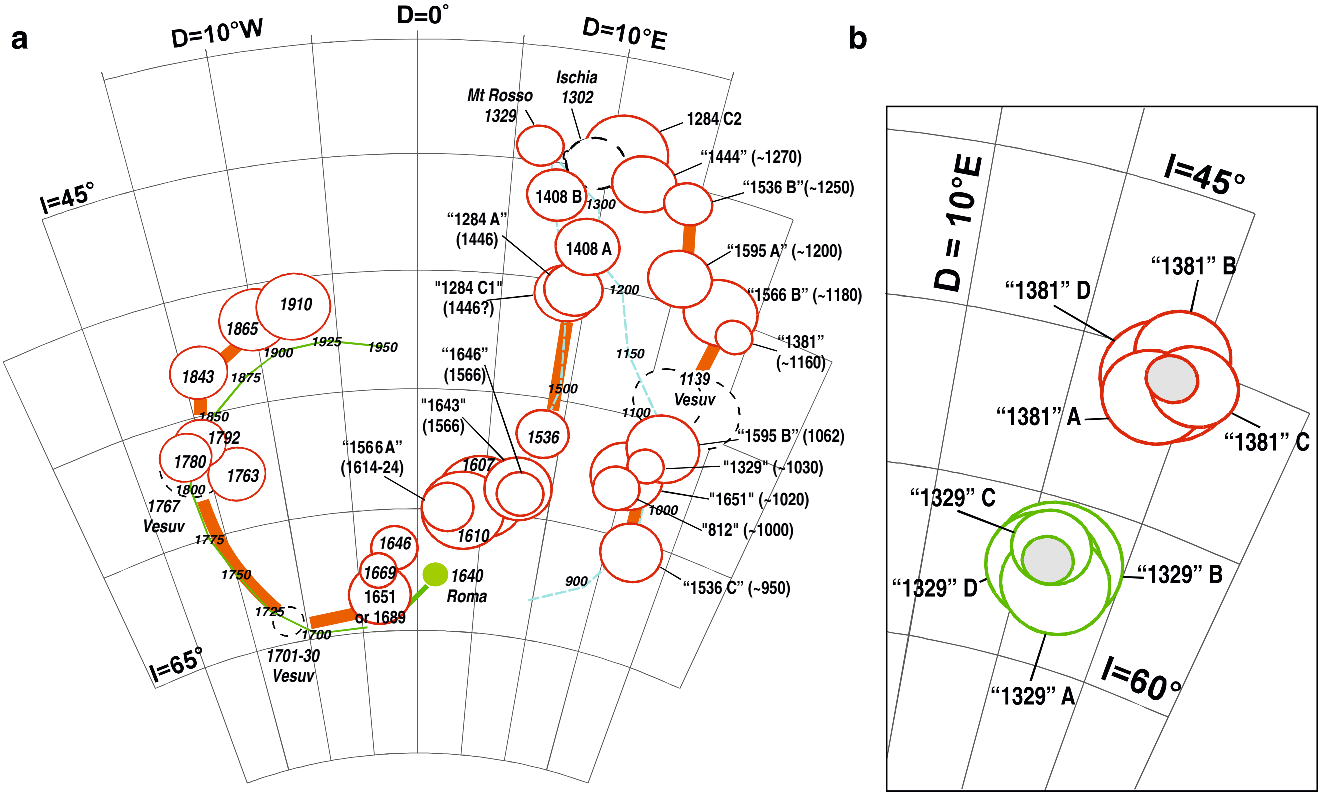

Fig. 3 **a** Archeomagnetic diagram (same representation as in Fig. 2) showing Etnean lavas of known or presumed ages for the last 1,200 years (see Table 3). *Dates between quotation marks* indicate lavas for which age attribution is doubtful, with their corrected ages between parentheses. **b** Detail of **a** for two lavas extensively sampled from their source to the front (Table 3). The *shaded circle* indicates the mean

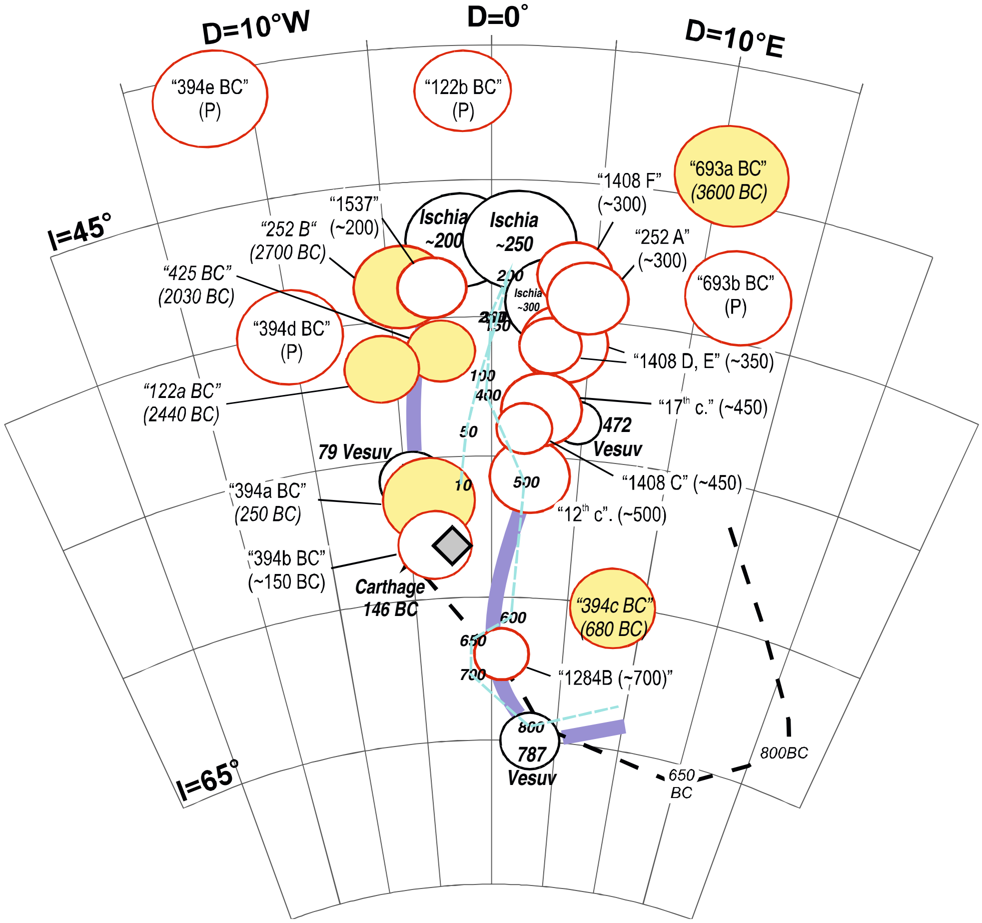

Fig. 4 Archeomagnetic diagram of lavas of presumed ages older than 1,200 years (A.D. 800 backward, penultimate column of Table 3), with the same representation as in Figs. 2 and 3. *Yellow circles* indicate lavas which were studied through Radisequilibria, with their resulting ages in *italics* (Table 6)

attribution problem has arisen because of destruction in inhabited areas (e.g., 1669). In addition, Table 4 and Fig. 5 present the results obtained on undated, although geologically recent flows or cinder cones (CNR map, CNR 1979).

We prospected more than 130 sites distributed on about 75 volcanic units (col. 1 of Tables 3 and 4, see also Appendix 2 for location). Usually 5–10 samples or more were collected on each site. In some cases, one or several samples had to be rejected (col. 2 of Tables 3 and 4) for the two reasons indicated above (displacement after cooling or locally greater magnetic distortion), a third cause of rejection concerns samples too strongly struck by lightning for their primary thermoremanence to be recovered. Slightly displaced samples were of constant concern for lava spatters from the pyroclastic cones and this probably explains, for instance, the relatively low precision of the Mt. Lepre result (Table 4). However, when hot-emplaced pyroclasts were not disturbed afterwards, the results are in the same range, or even better than for lava flows (e.g., Mt. Rosso, Mt. Ilice in Table 3; Mt. Arso SE, Mt. Ronzini in Table 4). A particular case was encountered on the Monpilieri cone (below Nicolosi), where various attempts were unsuccessful, probably because most of the pyroclasts were low temperature phreatic material (Chillemi 1998).

For the most controversial eruption ages, because they seemed until now not prone to error (particularly the so-called "1381" and "1329" flows), the detail of the various sites is given in order to show the consistency of results along the whole length of the flow (Fig. 3b). According to our methodological papers (e.g., Tanguy et al. 2003), the various samples of a given site were at least several meters and often tens of meters apart. The various sites were separated by more than 100 m, and sometimes by kilometers. This is absolutely necessary, in our sense, for avoiding the effects of possible strong local magnetic disturbances (Tanguy and Le Goff 2004).

In the penultimate column of Tables 3 and 4 are listed the magnetic ages derived from the reference SV curve of Fig. 2. The error bars are obtained by projection of the limits of the 95% confidence intervals on the SV curve and do not take into account uncertainty on the reference curve itself (Tanguy et al. 2003). This curve is calibrated in time thanks to volcanics of undoubted age in southern Italy, but also by comparison with ages from the French archeolog-

Table 4 Magnetic directions and possible ages of undated, geologically recent lavas

Volcanic units (lava flows or pyroclastic cones)	N/n	α95 (°)	k	I(°)	D(°)	Possible magnetic age(s)	Notes
Mt. Arso SE cinder cone on the SSE flank above Pedara village* [3516]	11/12	0.82	2650	51.7	18.3	c. 1150 A.D.	Roman amphorae within the cone, recent age from Ra
Mt. Pizzillo cinder cone on the northern flank	6/6	0.91	3896	60.2	17.7	c. 980 A.D.	Fresh morphology
Flow from Mt. Zappinazzo on the NE flank	8/8	1.53	1044	59.9	2.5	c. 600 A.D.	id.
Mt. Lepre cinder cone on the west flank* [232]	9/10	2.3	406	59	1.5	c. 600 A.D.	Recent age from Ra
Mt. Solfizio cinder cone and flow on the SE flank (2 sites)* [5912]	10/12	1.67	700	56.7	0.2	c. 550 A.D.	Recent age from Ra
Flow above Emmaus hotel, W of Zafferana	7/7	1.7	971	58.5	3.3	c. 550 A.D.	Fresh morphology
Flow from Cavolo fissure, east of Mascalucia on the southern flank (3 sites)	15/19	1.02	1297	45.0	2.2	c. 250 A.D.	Fresh morphology, possible 252 flow
Mt. Ronzini spatter rampart, north of Trecastagni	5/6	0.6	10826	60.8	−1	c. 650 A.D., or 450 B.C., or P	
Flow from Mt. Arso SW towards Santa Maria di Licodia (2 sites)* [1199]	11/11	1.9	488	59.9	6.9	c. 500 B.C. (?)	See text (“open questions”) for uncertain magnetic age, 920 B.C. (±550) from Ra (Table 6)
Flow upslope Zafferana on the eastern flank, sampled 300 m N of hotel Airone	7/8	1.04	2572	59.6	9	c. 550 B.C. (?) or P	Uncertain age
Flow at Chiesa Vecchia on lower eastern slope	7/8	1.57	1136	59.4	9	c. 550 B.C. (?) or P	Probably the same as the preceding
Santa Tecla flow at sea (2 sites)	13/15	1.12	1208	59.1	11.6	c. 600 B.C. (?)	Fresh morphology, possible 396 B.C. flow (see “open questions”)
Castello del Greco flow at sea, NE of Santa Tecla (3 sites)* [3966]	20/24	1.24	642	61.6	12.1	c. 650 B.C. (?)	Fresh morphology, c. 530 B.C. from Ra
Flow in contrada Verzella, northern lower slope (2 sites)* [3985]	8/11	1.39	1265	51.9	−2.4	c. 150 A.D. or P	c. 2070 B.C. from Ra
Lava spatters near the NW base of Mt. Nero, middle NE rift	6/8	1.09	2745	54.2	−7	c. 100 A.D. or P	
Flow east of the pseudo 1381 C flow, eastern circonvallazione of Catania (5 sites)* [3894]	27/31	0.76	1252	53.7	0.3	c. 450 A.D. or P	c. 2600 B.C. from Ra
Large flow at sea in the Cannizzaro area, north of Catania (3 sites)* [3861]	14/15	0.98	1443	56.6	1.5	c. 550 A.D. or P	c. 1680 B.C. from Ra
Flow at Trecastagni on southern border of the pseudo 1408 C flow* [535]	11/12	1.23	1176	66.6	3.8	c. 800 A.D. or P	c. 3600 B.C. from Ra
Flow overlain by the pseudo 1381 B flow near Gravina village (lower south flank)* [4120]	9/10	1.37	1163	57.3	17.8	c. 1050 A.D. or P	c. 5000 B.C. from Ra
Large flow at sea south of Aci Castello village	11/11	1.2	1165	57.3	8.2	P	
Mt. Serra Pizzuta cinder cone at 1700 m elevation on the SSE flank (2 sites)* [2197]	11/12	1.07	1565	54.8	−2.5	P	c. 2670 B.C. from Ra
Mt. Frumento delle Concazze cinder cone and flow on the NE flank (2 sites)	11/17	1.53	761	51.6	−14.9	P	c. 1540 B.C. from ^{14}C (Del Carlo et al. 2004)

Pozzillo flow at sea to the north of Stazzo village	5/5	1.54	1650	51.3	−7.2	P	
Flow overlain by the pseudo 1329 D flow near Stazzo village (via Trionfo, Grotticelle)	4/5	1.88	1382	47.5	−9.9	P	
Flow at Acireale center (IRMA institute)	6/7	1.43	1592	49.1	−12.3	P	
Capo Mulini flow at sea and south of Acireale (2 sites)	9/10	1.11	1773	48.2	−8.5	P	
Flow from La Nave crater on the lower NW slope, contrada Santa Venera (2 sites)* [1146]	12/12	1.8	482	41	−16.6	P	>8000 B.C. from Ra

Same presentation as in Table 3, however volcanics found prehistorical from Ra dating are listed at the end of the Table (see Table 6)

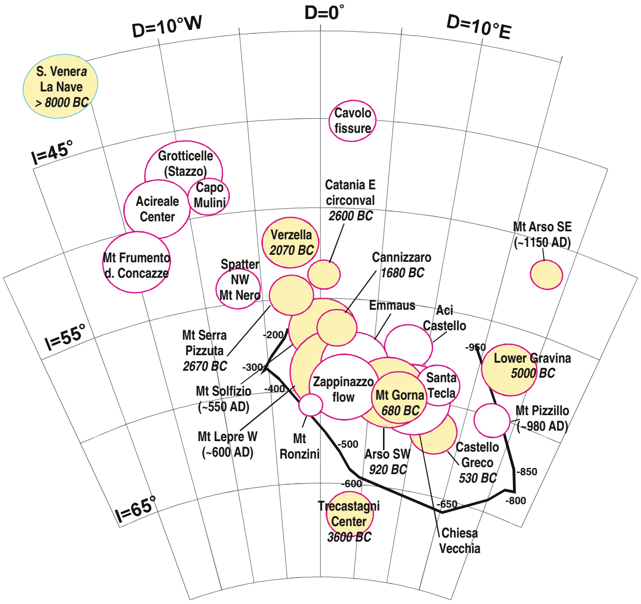

Fig. 5 Diagram of undated, geologically recent lavas (Table 4). *Yellow circles* indicate lavas which were studied through Ra-disequilibria, with their resulting ages in *italics*. Magnetic ages are *between parentheses* as in Fig. 3a

ical curve relocated to Sicily. Although this latter operation may introduce an additional error in the order of 2°, this uncertainty in the present case is actually very small as attested by excellent agreement with the points coming from unequivocal eruptions in the Ischia Island (1302), and at Vesuvius in 1139, 787, 472 and 79 (Principe et al. 2004). The same conclusion is reached by comparison with the exceptionally well-dated 146 B.C. archeological site of Carthage, close to Sicily (Thellier 1981).

The ultimate column of Table 3 indicates the most probable eruptions to whom the studied volcanics may be attributed. Strictly speaking, we cannot exclude the possibility of some unnoticed eruption having occurred within the same time range as reported in the penultimate column. However, when the event to which it is referred is reasonably well-constrained in place by historical accounts, there is little room for doubt that the given eruption is correct. The major individual cases are discussed in greater detail below.

^{226}Ra-^{230}Th dating

The principle of this method, first proposed by Condomines et al. (1995) and later detailed and applied to date several recent lava flows from Mt. Etna (Condomines et al. 2005), is only briefly described here. The method is based on the existence of ^{226}Ra excesses compared to its parent ^{230}Th, in the ^{238}U decay series (i.e., (^{226}Ra/^{230}Th) ratios higher than

Table 5 ^{226}Ra and Th data on Mt. Etna samples from the last two millennia (see Appendix 2)

Sample number	Magnetic or historic age	Th (ppm)	K_2O/Th ($*10^{-3}$)	(^{226}Ra) (dpm/g)	$(^{226}Ra)_0$ (dpm/g)
1610-140*	1610	13.92	1.47	4.78±6	5.05±14
1536-23*	1536	18.67	1.39	5.94±8	6.28±19
814*	1450±30	16.35	1.34	5.24±5	5.61±7
2249	1450±30	22.79	1.32	7.16±6	7.65±10
4110	1450±30	22.83	n.a.	7.16±7	7.65±11
4314	1450±30	22.66	n.a.	7.10±7	7.58±10
1408-1*	1430±30	14.73	1.38	4.76±6	5.14±16
027*	1400±30	14.55	1.40	4.68±8	5.05±10
2601*	1270±20	14.65	1.37	4.75±8	5.23±12
4144	1270±20	14.69	1.36	4.75±5	5.23±7
2042	1200±30	16.21	1.34	5.28±5	5.90±8
1132*	1160±30	12.04	1.41	4.01±4	4.53±7
2149*	1180±30	12.57	1.40	4.14±5	4.63±15
3516	1150±20	14.51	1.35	4.78±4	5.40±8
2027*	1060±50	10.94	1.38	3.73±4	4.32±7
5915	1030±40	11.65	1.42	4.00±4	4.65±7
471	1030±40	11.70	1.40	4.00±4	4.64±7
4323	1030±30	11.76	n.a.	3.93±4	4.53±8
1193*	1000±20	12.25	1.42	4.29±5	4.98±16
050	1000±50	12.40	n.a.	4.34±7	5.11±13
2052*	950±30	11.98	1.32	3.94±5	4.51±16
3672	700±50	12.82	1.36	4.16±4	5.04±10
232*	600±50	9.03	1.38	3.04±5	3.82±11
5912	550±30	13.01	1.35	4.08±4	4.98±10
2154*	500±50	9.65	1.36	3.16±3	3.96±9
4074	350±50	11.25	1.45	3.66±3	4.73±11
3871	350±60	11.98	1.43	3.82±4	4.88±12
4102	300±100	11.93	1.41	3.82±4	4.92±14

The historic or archaeomagnetic ages are used to calculate the $(^{226}Ra)_0$ activities (at the time of eruption), which are reported in Fig. 5 (quoted uncertainties on Ra data are 2 σ. Relative 2 σ errors on Th contents are around 1%). Successive sample numbers written in bold characters (normal or italic type) indicate several samples belonging to the same lava flow. *=Ra and Th data from Condomines et al. (1995, 2005)

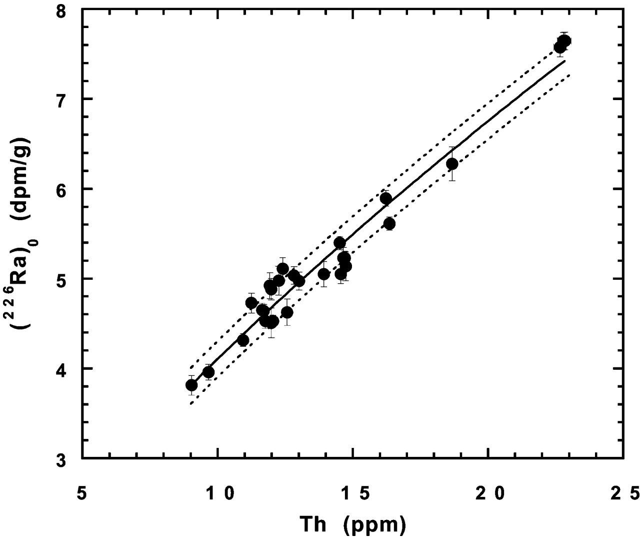

Fig. 6 $(^{226}Ra)_0$-Th correlation obtained from the data reported in Table 5. *Errors bars* represent 2 σ errors. The *dashed lines* correspond to the best fit curve ±0.2 dpm/g for $(^{226}Ra)_0$

1). This Ra excess is present in Mt. Etna magma and lavas upon eruption. After eruption, the Ra excess in the volcanic rock will decrease with time, according to the ^{226}Ra half-life of 1,600 years, until the $(^{226}Ra/^{230}Th)$ ratio ultimately attains its equilibrium value of 1, after about 8,000 years. If the initial ^{226}Ra excess (at the time of eruption) is known, then the time needed to reach the presently measured ^{226}Ra excess (i.e., the age of the volcanic rock) can be calculated from a classical radioactive decay equation. ^{226}Ra initial activities cannot be a priori inferred, without a preliminary study of ^{226}Ra-^{230}Th disequilibria in a suite of well-dated samples for a given volcano. In the case of Mt. Etna, such a study has revealed a good correlation between the $(^{226}Ra)_0$ initial activity and the Th content (i.e., the degree of differentiation) of historical or well-dated lavas from the last millennium (Condomines et al. 1995). This correlation was then used to infer the Ra initial activity of a sample of unknown age (Condomines et al. 1995, 2005).

In the present work, we report additional Ra and Th analyses on several historic or prehistoric samples, and

Table 6 Ra ages of some geologically recent lavas (see appendix 1), and 2 σ uncertainties

Sample number	Th (ppm)	K_2O/Th (*10^{-3})	$(^{226}\mathrm{Ra})$ (dpm/g)	$(^{226}\mathrm{Ra}/^{230}\mathrm{Th})$	Ra age	Magnetic age
4048[a]	13.69	1.50	3.94±4	1.227±34	250 B.C.+320 −310	c. 150 B.C., or P
3966	13.55	1.50	3.82±2	1.201±34	530 B.C.+350 −330	c. 900 A.D., or 650 B.C. (?)
3843[a]	14.79	1.31	4.09±10	1.178±42	680 B.C.+530 −470	c. 500 B.C. (?), or P
1199[a]	13.75	1.50	3.77±5	1.169±44	920 B.C.+590 −510	c. 500 B.C. (?)
3861	15.06	1.36	3.93±2	1.114±32	1680 B.C. +570 −500	c. 550 A.D., or P
333	14.72	1.39	3.85±3	1.114±36	1710 B.C.+690 −570	c. 400 A.D., or P
3790	12.24	1.41	3.20±2	1.114±32	2030+590 −520	c. 150 A.D., or P
3985	14.20		3.66±4	1.100±32	2070 B.C.+680 −570	c. 150 A.D., or P
6122[b]	13.37	1 .14	3.42±2	1.089±30	2440 B.C.	c. 200 A.D., or P
3894	14.58	1.39	3.69±2	1.078±30	2600 B.C.+860 −690	c. 450 A.D., or P
2197[b]	12.85	1.12	3.27±2	1.083±30	2670 B.C.	c. 150 A.D. or P
090[a]	11.95	1.43	3.05±3	1.087±36	2700 B.C.+960 −750	c. 200 A.D., or P
1906[a]	15.66	1.33	3.85±5	1.048±40	3580 B.C.+2280 −1260	P
535	12.30	1.44	3.05±8	1.058±60	3600 B.C.+3150 −1470	c.800 A.D., or P
4120	13.71	1.40	3.31±2	1.029±30	5000 B.C. +2910 −1470	1050 A.D. or P
1146[b]	14.09	1.26	3.32±2	1.005±28	>8000 B.C.	P

Reported errors on Ra data are 2 σ errors (for Th, 2 σ relative uncertainties are always close to 1%)

[a] Th and Ra results from Condomines et al. (1995, 2005)

[b] Ra ages for these samples are maximum ages because of a probable K and Ra loss (see text)

refine the $(^{226}\mathrm{Ra})_0$-Th correlation, and the age equation. In fact, the previous correlation included samples erupted between 950 and 1970 A.D. The samples erupted after 1970 cannot be included in this correlation because they are characterized by large enrichments in Ra, alkaline elements (K, Rb, and Cs), and radiogenic Sr (Clocchiatti et al. 1988, 2004). However, enrichments in alkaline elements and radiogenic Sr are also present, to a lower degree, in relatively basic samples erupted in the 1624–1970 period, compared to the more differentiated lavas of the pre-1624 period (see for example the K_2O/Th ratios reported in Fig. 8 of Clocchiatti et al. 2004). Although there is no clear evidence for a significant Ra enrichment during the 1624–1970 period, we decided to define the $(^{226}\mathrm{Ra})_0$-Th correlation only with well-dated samples erupted before 1624 A.D. and having the K_2O/Th ratio characteristic of Etnean lavas older than this date (1.4±0.1*10^3) (Joron and Treuil 1984; Clocchiatti et al. 2004). This approach is further justified by the fact that most lava flows of unknown ages subjected to Ra dating are older than the XVIIth century. The samples selected to establish the $(^{226}\mathrm{Ra})_0$-Th correlation come mostly from lava flows well identified through historical accounts or lava flows (or more rarely cinder cones) whose ages have been inferred from archeomagnetic measurements (see Tables 3 and 4). Ra, Th and K_2O/Th data are reported in Table 5. A total of 28 samples, representing 22 different eruptions between 300 A.D. and 1610 A.D., have been analyzed in this work and previous ones (Condomines et al. 1995, 2005). The calculated $(^{226}\mathrm{Ra})_0$ activities are reported versus Th contents in Fig. 6. As previously explained (Condomines et al. 2005), the $(^{226}\mathrm{Ra})_0$-Th correlation is fitted through a power law equation, corresponding to the fractional crystallization process considered to be producing both the Ra and Th variations. The best fit (with a correlation coefficient R=0.982) is obtained with the following equation:

$$\left({}^{226}Ra\right)_0 = 0.7863 * [Th]^{0.7178} \tag{1}$$

Taking into account the average (^{230}Th/^{232}Th) ratio of recent Etnean lavas (0.960), the age of an unknown sample can be determined through the following age equation (see detailed development and Eq. (4) in Condomines et al. 2005):

$$\begin{aligned} t(yr) =& 2308 * \ln\{(0.7863[Th]^{0.7178} - 0.2343[Th])/ \\ & (({}^{226}Ra) - 0.2343[Th])(({}^{226}Ra) - 0.2343[Th])\} \end{aligned} \tag{2}$$

It should be noted that the (^{226}Ra)$_0$-Th correlation has been extended towards higher Th contents, thanks to new analyses of the differentiated "1284 C" flow at Monacella to the north of Santa Venerina (lower eastern flank, Fig. 1). Its large Ra excess (34%) unambiguously shows that this lava was emitted during the historic period, although its particular petrochemistry previously suggested it was prehistorical (Tanguy et al. 1985). The possibility that it was anomalously enriched in Ra has been considered, but discarded in view of its normal K_2O/Th ratio of 1.32*10^3. Such a lava displays the highest Th content (22.8 ppm) of the whole suite of historic or prehistoric volcanic rocks analyzed so far, so that it could be classified as a benmoreite. It also contains small amphibole phenocrysts, a very rare feature in historic lavas (Tanguy 1980). Assuming that the hawaiitic magma in the deep reservoir has 8.5 ppm Th (Condomines et al. 1995), the production of the differentiated magma would require about 63% of crystal fractionation. Although this high degree of differentiation could appear rather exceptional, it is clear that the 1200–1610 period is characterized by the emission of differentiated lavas (mugearites), compared to the preceding and following periods (see for example the Th contents in Table 1). During 1200–1610, the effusion rate was low and magma batches were probably stored at relatively shallow depth, where they underwent extensive crystal fractionation. Since these differentiated samples do not deviate significantly from the (^{226}Ra)$_0$-Th correlation (Fig. 6), differentiation episodes took place on a rather short timescale (<200 years).

Equation (2) was used to infer the ages of several other lavas, whose magnetic ages were uncertain. The results are reported in Table 6. Most of these samples are prehistoric, in spite of the fact that their magnetic directions would also be compatible with dates within the last two millennia. Although the age uncertainties can become rather large beyond 4 or 5 ka B.P. due to moderate Ra excesses in Mt. Etna lavas, Ra data are still very useful to clearly distinguish between historic and prehistoric samples. Examination of the K_2O/Th ratios reveals that while most of the samples have ratios in the usual range between 1.3*10^3 and 1.5*10^3, three samples have lower ratios. This might indicate K (and possibly Ra) loss during post-eruptive alteration, and thus their calculated ages can only be considered as upper limits.

Discussion

As for the general presentation of the results in the section archeomagnetic dating, we will discuss thereafter the major cases by going backward in time, but in order of the presumed ages because in many cases, different lavas having erupted at different times were attributed to the same eruption. Although most of these lavas overlie all the other products, it was checked whenever possible that the following statements agree with stratigraphical data. This was made thanks to various fieldtrips led by S. Branca and M. Coltelli who are responsible for the new geological map in preparation. As in our Table 3, the lavas are listed in order of their corrected ages (penultimate and last columns), the various volcanic units are numbered for clarity. Reference to every unit will be indicated in this manner: Table 3-22 (Table 3, plus the unit no. 22 in this example).

The so-called ***"1651" eastern flow*** (Scorciavacca, Fig. 1) cannot have been produced at this time, as its DGF differs by more than 15° from that expected in the 1600s (Fig. 3a), and is only consistent with an epoch around A.D. 1020 (see also Table 3-22). This finding is further supported by the fact that the Scorciavacca flow lies more than 5 km distant from the Macchia Valley, where the 1651 east flow is located by a written account (see end of Appendix 1). On the other hand, the presumed "1689" flow below Fornazzo might represent the true 1651 east flow, although we are in this case at the limit of the resolution power of archeomagnetic dating for volcanics whose ages differ by less than 40 years. The representative circle of the 95% confidence cone of the "1689" flow DGF falls just between the two dates, so that there is an equal chance for 1651 or 1689.

As already suspected (Appendix 1), the presumed ***"1595" flow*** on the west flank is unlikely to have been erupted that year when no activity is reported. In fact the lava field can be subdivided into two flows which are magnetically and chemically different (Table 3-17 and -20, samples 2042 and 2027 in Appendix 2). The younger one ("1595 A", Fig. 3a) was emitted in c. 1200, the older ("1595 B") very probably corresponds to the 1062 eruption, that could be seen from Troina town, west of Mount Etna.

For the presumed ***"1566 A" flow*** to the north (Sciara Nuova), its DGF on the diagram virtually joins that of

1610, and differs by more than 5° from the true 1566 points (Fig. 3a). There is little doubt, therefore, that the Sciara Nuova flow belongs to the 1614-24 eruption, which involved a large part of the northern flank.

A second presumed ***"1566 B" flow***, petrologically quite different from the first (compare samples 2149 and 1614-1 in Appendix 2), underlies the small town of Linguaglossa to the NE of the mountain. However, its DGF entirely differs from that in 1566 and is consistent with c. 1180 (Table 3-18). This is in accordance with the historical accounts that do not mention destruction of the town in 1566, and also with the popular belief that at the time Linguaglossa was protected by its patron, St. Egidio. Even if a lava flow was directed towards Linguaglossa, it did not reach the town and was later overlain by those of 1646, 1911, and 1923.

The ***true 1566 flow*** lies in contrada Iannazzo, close to the Alcantara River (Fig. 1 and Table 3-7), and is largely buried upslope by the 1646 flows (Table 3-3). Indeed, the 1566 Iannazzo lava was considered by Sartorius as a part of the 1646 flow itself, although it is petrologically different, without pyroxene phenocrysts. The Iannazzo flow was erupted by a fissure forming spatter ramparts west of Mt. Nero (and on the NE slope of Mt. Timpa Rossa), at about 2,000 m a.s.l. (Table 3-8). This fissure is dated "1643" on the CNR geological map, however the DGFs obtained from both the spatter rampart and the Iannazzo flow are practically identical and consistent with 1,570±30 years, differing by about 10° from the expected DGF in 1643. Although the two outcrops are of poor quality (lack of deep incision in the flow and spatters often displaced after cooling), a majority of samples (14/25 and 13/18, respectively) gave consistent results with excellent 95% confidence circles.

The presumed ***"1536" flow on the NW*** side cannot date from this epoch, in agreement with the historical accounts which do not mention a NW flank eruption that year. It differs entirely from the true 1536 flow on the middle southern flank (Table 3-9), and its two DGFs show that it must actually be divided into two magnetically different units. The upper one ("1536 A", Table 3-6) was emitted around 1600 and could correspond to the 1607 flow (Carrera 1636). The lower unit ("1536 C", Table 3-24), which reached the foot of the mountain near Randazzo, is a large, highly composite flow that results from an unrecorded long-lived eruption in c. A.D. 950 (Fig. 3a).

A third presumed ***"1536 B" flow***, which outcrops on the upper southern flank to the west of Mt. Vetore (Table 3-16), actually erupted around 1250, when activity has been reported (Alessi). This lava seems macroscopically similar to, but is chemically different from, that of the true 1536 flow lying a few hundred meters downward (analyses in Tanguy 1980). Another branch of the same ≈1250 lava was mistakenly dated "1535" within the botanic garden, about 1.5 km westward.

Two flows are good candidates for the 1408 eruption (***1408 A and B flows***, Table 3-12 and -13), although they are magnetically distinct through their 95% confidence circles (Fig. 3a). By interpolating linearly the SV curve between 1536 and 1329, the unit 1408 A was initially considered as being the true 1408 flow (Tanguy et al. 1985, 2003), and 1408 B was attributed to a slightly older eruption, possibly 1381 which is unlocated. However, it has been shown (Gallet et al. 2003) that sudden changes in the speed of the SV can occur, especially in the vicinity of a sharp cusp of the curve such as around A.D. 1400. For this reason, we alternatively envisage that 1408 B could have been produced by the 1408 eruption, and then 1408 A should be the 1444 flow, although this latter is not precisely located by historical accounts. Clearly, we are here at the limit of the resolution power of archeomagnetic dating, and the question can definitely be solved only when a much more detailed reference curve will be available, e.g., by using very well-dated archeological materials.

As indicated in Appendix 1, many other presumed ***"1408" flows at lower elevation*** ("1408 C and D" at and below Trecastagni, "1408 E" above San Giovanni la Punta, "1408 F" near Massannunziata) are in fact considerably older, sometimes more than a millennium (Fig. 4).

The presumed ***"1381" flow*** just north of Catania could actually be dated 1169 (Table 3-19 and Fig. 3a), if Mount Etna really erupted this year. The four sites prospected for this lava, from its source to the seashore (Fig. 3b), have a DGF consistent with the end of the 1100s, and no other epoch can be realistic for the preceding 4,000 years (Turner and Thompson 1982; Le Goff et al. 1998). It should be noticed that this flow is not reported by Monaco and Tortorici (1999) at the place where we sampled "1381 D" (southern part of the Guardia Bay).

The ***Mt. Ilice*** cinder cone, its adjacent vents upslope ***and its large flow***, which extends from its SE base to the sea (Stazzo), traditionally dated at ***"1329"***, have a magnetic age no younger than c. A.D. 1030 (Table 3-21 and Fig. 3b). This result is also supported by a closer examination of the historical accounts which do not mention that the 1329 flows reached the sea (Appendix 1). There is no doubt, therefore, that the Mt. Ilice cone and flow are actually 300 years older than believed, until now.

The presumed ***"1284" flows*** are different following Sartorius ("1284 A, B, C", Table 3-10 and -25) and the CNR Geological map ("1284 C" alone, Table 3-11). Only the lower part of this latter flow is magnetically consistent with 1284 (Table 3-11b, 1284 C2), the remainder being rather ascribed to c. 1450 (1284 C1, see also Fig. 3a). Although the 1284 C flows have a petrochemistry close to that of some prehistoric lavas (s. 2249 in Appendix 2), both their stratigraphical relationships (S. Branca, pers. comm.) and Ra data (see above) definitely indicate a recent epoch, so that the magnetic historical ages are accepted here (last columns of Table 3-11). The problem is further complicated by the presence in the same area of a petrologically "normal" flow showing exactly the same DGF as "1284 C1". This is the Ballo flow, north of Zafferana ("1284 A", Table 3-10 and s. 814), which corresponds to the location indicated for the 1446 eruption by Silvaggio.

For the ***Mt. Sona lava*** directed to the SSW towards Paterno, we show in the historical section that the presumed dates of ***"1169? or 812?"*** are unlikely, a statement substantiated by the archeomagnetic age close to A.D. 1000 (Table 3-23 and Fig. 3a).

The ***"St. Agatha eruption" (A.D. 252)*** is not precisely located by historical accounts, which nevertheless indicates its relatively short duration of 9 days (Appendix 1). Both the Monpeloso cinder cone (252 A, Table 3-31) and the Cibali flow (252 B, Table 3-34), presumed to have been produced by this eruption, are magnetically roughly consistent with 252, given the relatively low precision of archeomagnetic dating for this epoch. However, the two units cannot have resulted from the same eruption because their respective paleo DGFs differ by more than 8° (Fig. 4), despite a similar chemistry (s. 090 and 4102, Appendix 2). On the other hand, Ra dating shows the Cibali flow to be much older (about 2700 B.C., Table 6), a result in accordance with the fact that such a large, composite flow could have hardly been emplaced within the short time of 9 days. Furthermore, this flow reached the very downtown of Catania, and this is contradictory with the miracle emphasized by the Bollandists. Another possible candidate for 252 should be a flow east of Mascalucia (Cavolo fissure, Table 4 and Fig. 5), which is largely overlain by the pseudo 1381 flow.

The presumed ***"122a B.C."*** flow of Carvana at Piazza Gioeni, Catania (Table 3-35), as well as the presumed ***"425 B.C."*** flow forming the seashore (via Rotolo and Lungomare, Table 3-42), cannot have erupted at this time, as they have DGFs consistent with either A.D. 150, or a prehistorical epoch (Fig. 4). These ambiguities are solved through the Ra dating method, which indicates ages around 2400 and 2000 B.C., respectively (Table 6). On the Carvana flow, furthermore, neolithic artefacts were found (C. Monaco, pers. comm.).

Among other lavas much older than previously believed, we have to cite the presumed ***"394 B.C."*** flows near Acireale (two different outcrops, Table 3-40 and 41, see also Fig. 4), the presumed ***"693 B.C."*** flows at Fortino Vecchio (Catania) and east of Misterbianco (Table 3-43 and 44), and the Monte Serra cinder cone (Table 3-36) on the SE lower flank of the mountain (which is different from Mt. Serra Pizzuta on the middle southern flank). All these lavas are necessarily more than 4,000 years old as their DGFs are not reproduced as identical since this epoch (Turner and Thompson 1982; Le Goff et al. 1998).

Conversely, Table 4 and Fig. 5 show that some undated, although geologically recent eruptive systems and flows are in fact historical. Mt. Arso SE, above the Pedara Village, is dated c. A.D. 1150 from archeomagnetism, an age consistent with its large Ra excess (41%). It could represent the explosive crater of the pseudo 1381 flow, although chemically the two lavas are slightly different (s. 1132 and 3516 in Appendix 2). Several other well-preserved cones and flows are found to have erupted in the last 2,000 years (western Mt. Lepre, Mt. Solfizio, flows from Mt. Zappinazzo and above Emmaus Hotel, Table 4). The morphologically fresh flow coming from Mt. Arso on the SW slope (not to be confused with its SE homonymous) could represent the 425 B.C. flow mentioned by Thucydides, all the more so since at the time this area was densely inhabited. But other recent flows within or around Catania (eastern circonvallazione and Cannizzaro areas), whose DGFs are consistent with either the beginning of the Middle Ages or prehistorical times, are shown from Ra-Th to date between 1600 and 2600 B.C. (Table 6).

Questions remaining open

It follows from the preceding statements that no ancient historical lava flow was found to have reached the area of the pre-1669 city of Catania. This is quite surprising and contrary to popular belief, but in agreement with archeological research (Boschi and Guidoboni 2001) and stratigraphical investigations in progress (S. Branca, pers. comm.).

We have seen that during a part of the Roman and Greek epochs, the DGF varies very slowly, and this makes it difficult to distinguish between 0 and 400 B.C. (Gallet et al. 2002). With this problem we enter the subject of poorly constrained questions that are likely to remain open until more accurate results are available. Thus the Mt. Gorna cinder cone on the SE flank, thought by Sartorius to be the 396 ("394") B.C. vent, presents both magnetic and Ra-Th ages roughly consistent with this date (Tables 4 and 6). However, the flow at its NE foot is magnetically different, with an age around 150 B.C., practically joining the 146 B.C. point of Carthage relocated to Sicily (Fig. 4). It might be that this flow overlies the Mt. Gorna flow, which could be retrieved at some distance, but none of the other presumed 394 B.C. outcrops presents a DGF consistent with that of the Mt. Gorna cone, all the flows prospected being undoubtedly prehistorical (western declination and low inclination, Table 3-40 and 41), even if they were produced by different eruptions. Conversely, the undated Santa Tecla flow at sea, whose DGF (Table 4) and chemical composition are very close to those of Mt. Gorna (s. 3645 and 3843,

Appendix 2), could be an excellent candidate for 396 B.C. However, the two DGFs present a slight difference of 3.6° in declination, although they are not statistically distinguishable (Fig. 5). A possible explanation might be that a relatively large magnetic anomaly exists beneath Mt. Gorna, or that the part of the crater rim available to sampling was twisted by slumping at the end of the eruption.

From a more general standpoint, no paleo DGF from Etna was found to fit the Gallet et al.'s curve (relocated to Sicily) for the period 500–1000 B.C. Conversely, several lavas from the same epoch, including Mt. Gorna and the S. Tecla flow, present inclinations which are 4–5° lower than expected, so that their archeomagnetic dating is quite uncertain. However, it is unlikely that these lavas could belong to another period for at least three reasons: (1) their magnetic ages are confirmed by Ra dating, (2) their DGFs are consistent with those of archeological artefacts from southern Italy for the similar 300–800 B.C. period (Evans and Hoye 2005), and (3) if one excepts improbable medieval ages for these lavas, no comparable DGF in Western Europe is known for the last five millennia. This discrepancy could be solved by hypothesizing that the geomagnetic field no longer presents a dipolar character for this period because of the vicinity at the time of an archeomagnetic jerk (Gallet et al. 2003), and this would prevent a possible relocation of its direction from France to Sicily. If so, then the Castello Greco flow (Table 4 and Fig. 5) could belong to the 479 B.C. eruption, and the Santa Tecla flow to the 396 B.C. one, or vice versa, the two flows having very close DGFs and chemical compositions. But it must be recognized that the available reference curves of the DGF for this period are rather imprecise, and it is necessary to await further information for elucidating the problem.

Conclusion

Despite the abundance of details on the 2,750-year-long historical period of Mount Etna, the primary sources of information are too imprecise for localizing most of the eruptions and, therefore, their lava flows and eruptive systems. Practically, all the "historically dated" lavas prior to the 1600s result from age attributions made in the 1800s by workers who were unaware of any dating method other than the morphological aspect of the flows and cones. It is shown here that the directional variation of the geomagnetic field (DGF) recorded in Etna lavas, which remains in close agreement with that from archeological artefacts in France for the last 2,100 years (Tanguy et al. 2003), provides a powerful tool for checking the ages of volcanics from the same period. The high accuracy, "large-sample" archeomagnetic method (±40 years backward from the present to A.D. 800, and ±100 or 200 years for the older period), combined with ^{226}Ra-^{230}Th disequilibria dating, allows a full reexamination of the chronology and location of the eruptions.

We conclude here that more than 80% of the lava flows and cinder cones attributed by modern authors to eruptions occurring prior to the A.D. 1700s were wrongly dated. They are usually several hundreds of years older, the discrepancies sometimes exceeding a millennium. This is the case for volcanics presumed of "1651 east" (actually ~1020), "1595" (actually two distinct flows, respectively ~1200 and ~1060), "1566" (two branches dated 1614 and ~1180), "1536" (two branches dated ~1250 and ~950), "1444" (a branch dated ~1270), "1408" (lower branches dated ~450 and ~350), "1381" (~1160), "1329" (~1030), "1284" (only one of the various flows being consistent with this date, the other being ~1450 and ~700), "1169 or 812" (~1000), etc. Conversely, well-preserved cones and flows, which are undated on the maps, were produced by eruptions that went unnoticed in historical accounts, especially during the Middle Ages (Mt. Arso SE ~1150, Mt. Pizzillo ~980, Mt. Lepre W ~600, Mt. Solfizio cone and flow ~550). For the few eruptions that are recorded between A.D. 252 and 750 B.C., none of their presumed lava flows shows a DGF in agreement with that existing at their respective dates of occurrence, most of these flows being in fact prehistoric. The presumed 394 B.C. Mt. Gorna and A.D. 252 Monpeloso, although roughly consistent magnetically and radiochronologically with their respective epochs, remain of unspecified age because of lack of precision of the DGF reference curve at the time.

It should be emphasized that archeomagnetism is also helpful in the volcano mapping carried out for the new geological map (Branca et al. 2004, and work in progress). In fact, the various outcrops of eruptive products from a given eruption must have the same DGF. Conversely, outcrops showing DGFs that differ by more than 3–4° must be attributed to different eruptions. This can be of considerable help for chronology in the absence of any stratigraphical succession, particularly for many pyroclastic cones, all the more so since petrochemistry cannot be considered as a definite argument for distinguishing different eruptions. Although lavas from the same eruption usually show a nearly constant chemical composition, small (and sometimes large) variations can occur within a given eruptive period and, conversely, lavas of very different age can display similar characters.

A good temporal record is necessary to enable proper analysis of changes in magma output and detailed variations in petrology required in developing and understanding of the way in which the internal plumbing of Mount Etna has operated over the last millennia. By examination of the new chronology presented here, it appears that the volcano does not show a steady-state behavior, periods of voluminous eruptions building large pyroclastic cones and lasting 50 to 150 years (e.g., c. A.D. 300–450, 950–1060, 1607–1669) being followed by centuries of less productive activity. Each of the high activity periods ended with large eruptions at low elevation, however, low-sited eruptions also occurred as isolated outbursts outside of the high output periods (A.D. 252, ≈1160, 1329, 1928). Such a revised history should be taken into account for eruptive models and statistics, magmatic evolution, volcano mapping, and civil protection.

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Appendix

Appendix 1: Critical review of historically dated eruptions of Etna

Very little can be said about the reference by Diodorus to eruptions that led to the Sicanians fleeing from the Etna region (see Introduction), in c. 1400 B.C. Although he refers unambiguously to lava streams (ρν́ακος in the text), it is likely that he alludes to activity of his time (Roman epoch), as only strong explosive outbursts were capable to force an entire people to emigrate (Tanguy 1980, 1981). Such cataclysmic eruptions could have produced one or several of the pyroclastic levels dated around 3400 years B.P. by Del Carlo et al. (2004).

Eruptions of 693, 479, 475, 425 B.C. The oldest work quoting the name of Etna is represented by Pindar's first Pythian ode, that a substantial amount of evidence shows to have been composed around 475 B.C. (Puech 1922). The poet describes the arrival of a lava flow at sea: "*He* [the giant Typhon] *is fast bound by the pillar of the sky, even by snowy Etna, nursing the whole year's length her dazzling snow. Where out pure springs of unapproachable fire are vomited from the inmost depths: in the daytime the lava streams pour forth a lurid rush of smoke ; but in the darkness a red rolling flame sweeps rocks with uproar to the wide deep sea*" (translation in Rodwell 1878). This is probably the same eruption which is quoted in Arundel's Table, or Parian Marble, as contemporaneous of the Plataea battle in ***479 B.C***. The date appears further confirmed by the historian Thucydides (III, 116) when alluding to another eruption that occurred in the spring of ***425 B.C.***: "*A stream of fire flowed from Etna, as on former occasions, and destroyed some land of the Catanians ... It is said that fifty years had elapsed since the last flow, there having been three flows in all since the Greeks have inhabited Sicily*". The interval of 50 years might be understood here as approximate, or perhaps the 479 eruption had a rather long duration of 4 years. Alternatively, it remains the possibility that Thucydides was precise enough in writing 50 years (and not 54). In this case, two distinct eruptions should have taken place in 479 *and* 475 B.C.

In fact, if one accepts the 479–475 B.C. event as a unique phase of activity, then the third and chronologically the first eruption becomes problematic. It is today believed to have occurred in ***693 B.C.*** (Sartorius 1880, and practically all the following authors), on the basis of a very old legend of two pious brothers (the *Fratelli Pii*) who rescued their aged parents from being overwhelmed by the lava. This act is quoted as an example of filial devotion by many writers from antiquity, the earliest of these being the Athenian Lycurgos in 330 B.C. However, no date is indicated for the eruption, except by Stobaeus (quoting Aelian) who wrote that the event happened during the Olympiad 81, that is about 455 B.C. But this date obviously disagrees with Thucydides' history, so that Bergk (1873) suspected an error in the manuscript study and corrected it as "Olympiad 21", actually ***695 B.C.*** because the year of the Olympiad is not specified. Such an interpretation appears highly speculative, all the more so since Aelian and Stobaeus lived in the 3rd and 5th century of the Christian era, which is about a millennium after the event they described.

There is some additional evidence that the 479 B.C. eruption was unusually large and, therefore, the first reported by the Greek writers. This event is linked by the Greek poets Pindar and Aeschylus to the myth of Hephaestos. However, Hephaestos was previously located not in Sicily, but in the Greek island of Lemnos (Guirand 1935; Johnston 2005), where he was then the god of heaven's fire (lightning). It seems therefore that both his migration to Sicily and his volcanic attribution resulted from Etna's activity emphasized through the Greek poets of the 4th century B.C.

396 B.C. Diodorus Siculus reports (XIV, 59) that during the war between the Carthaginians and the tyrant of Syracuse (first year of Olympiad 96 and therefore 396 B.C., not 394 as various modern authors indicate) "*Imilcar and his army quickly reached Naxos by land* [coming from Messina and going southward], *but he was then aware that a lava flow from Etna had recently expanded to the sea, so that the terrestrial troops could not follow the seashore together with the vessels because a large part of land had been devastated by what is called lava. For this reason the troops had to walk round Mount Etna*".

140 B.C. According to Julius Obsequens (De prodigiis, quoted by Alessi), "*Mount Etna was plentiful of fires, a marvel that went expiated by the sacrifice of forty major victims*". It must be pointed out that victims offered to the gods were sheep, not human beings!

135 B.C. "*Etna burned more than usual*" (Obsequens), "*Mt. Etna belched large fires that flooded as torrents the area located below the place from where flames burst forth, whereas distant regions were devastated through heavy vapours and hot ashfall*" (Orosius, V, 6, 2).

126 B.C. "*Mt. Etna suffered earthquake and spread fires from its summit over a large area, meantime the sea boiled near the island of Lipari*" (Obsequens). These events are also reported by St. Augustine and Orosius, probably using the same source.

122 B.C. "*During this summer it is said that Sicily was invaded by such an amount of ash that roofs of the city of Catania were oppressed and overburden, and finally collapsed*" (St. Augustine, III, 31). "*At this time Mt. Etna burned more than usual and threatened the city of Catania and its outskirts by fiery torrents, so that the roofs of buildings collapsed, being overload and burned by hot ashes*" (Orosius, V, 13, 1). The more ancient authors Cicero and Seneca probably allude to the same event when they report that darkness lasted three days and lightning occurred in the volcanic plume. Let us point out that lava flows are indicated by Orosius alone, who wrote more than five centuries after the eruption. Such information, therefore, is of little value (see above a similar discussion regarding Diodorus and the Sicanians).

Most current scientists, following Kieffer (1985), consider the 122 B.C. eruption as a large Plinian outburst (e.g., Coltelli et al. 1998). According to Kieffer, this event created the small caldera of the *Cratere del Piano* which is today almost entirely buried by the central cone. This view is supported by Strabo's Geography describing, about a century later, a summit depression 3.8 km in circumference, or 1.2 km in diameter. Seneca said also that at his time (c. A.D. 60), Mt. Etna had a lower elevation than before (*letter to Lucilius*, n. 51). Moreover, it seems that a long repose period followed the 122 B.C. eruption, as usually occurs after a caldera forming event.

49 B.C. Petronius confirms that an eruption in this year followed a long repose, by saying that "*Mt. Etna displayed unusual fires*", and Lucan adds that "*the fire split open the slope towards Hesperia*" [i.e., westwards], thus indicating a western flank eruption.

44 B.C. Shortly before Julius Caesar was murdered, Etna produced a large eruption (Virgil, *Georg*.) and heavy ashfall reached as far as Reggio Calabria, 75 km away (Livy). It is worth noting that Virgil, in his poem "Aeneid", alludes to an "immense harbour" close to Etna. His description, however, was inspired from the Mythology of his time (see Introduction), and does not refer to personal observation.

36 B.C. As indicated in Appianus (*Bell. Civ*., V, 114), Mt. Etna was shaked by earthquakes and fire was seen from its NW side, very probably linked to a flank eruption.

32 B.C. According to Dion Cassius, an eruption took place this year, but it is not even sure that a lava flow occurred.

At the beginning of the Christian Era, a continuous mild activity within a summit caldera is reported by Strabo (VI, 2, 3–8), although he took his information from Posidinios and this description could be dated some decades earlier. Violent eruptions did occur, however, as attested by Suetonius who wrote (51) that Imperator Caligula was put to flight in Messina because of Etna rumblings, in c. A.D. 38–40.

A.D. 252. This is a famous eruption because it broke out a year after St. Agatha had been martyred in Catania (251): "*a year later, almost at her birthday, Mt. Etna suffered a conflagration so that a violent fire which seemed to melt the land and rocks arrived above the city of Catania. Then the crowd of the countrymen fled away and went down to the city. They went to the tomb* [of Agatha], *took the veil of which it was covered and put this veil against the forthcoming fire: at the same time, the fire was diverted. It began the first day of February calends and stopped on the ninth of them*" (Bollandus and Henschenius 1643). This flow was believed to be the "Cibali" flow which invaded the western part of the present Catania (Sciuto Patti 1872), and Sartorius adds that it could have originated from the Monpeloso cinder cone, above the village of Nicolosi (Fig. 1).

1062 (or 1064?). According to Gaufredo Malaterra (*in* Alessi), a large eruption on the western part of Etna was observed from Troina, at a distance of about 40 km.

1169. On 4 February 1169, a tremendous earthquake struck eastern Sicily, killing some 15,000 people in Catania, but it is unclear whether or not this tectonic event was accompanied by an eruption of Etna. Various reports (see Amico, vol. 2, p. 49–53) make Etna responsible for the catastrophe without definitely quoting an eruption. However, some authors indicate volcanic "fires" and ashfall having caused damage in the country, and Falcando adds that a summit collapse occurred towards Taormina, but there is no allusion to a lava flow directed towards Paterno, as suggested by the CNR map.

At the same time, Pierre de Blois (*Petrus Blesensis*), the French preceptor of Guglielmo II (king of Sicily from 1167 to 1189), alluded to Etna as a window of the Hell. Dates of possible eruptions, or at less activity, are found in Alessi for the years 1157, 1164, 1194, 1197, 1222, and 1250.

1284–85. A few days before the death of Charles d'Anjou (i.e.,, December 1284 or January 1285), *"Mount Etna was violently shaked and from its part regarding towards orient it vomited a terrific fire ... which descended as a torrent on the slope of the mountain and surrounded St. Stephen's hermitage without damaging it, so that this is today considered as a miracle"* (Nicolo Speciale, in Recupero 1815). Such information led Sartorius (1859, 1879) and Romano and Sturiale (1982) to attribute to this event different flows NE of the present Zafferana village.

1329. A violent eruption this year was eye-witnessed by the historian Nicolo Speciale. "*On 28 June Mount Etna was violently shaked ... On the eastern flank above the Musarra Rock ... the earth was split open and a violent fire burst forth, together with heavy black fumes and rumbling noises ... this fire cascaded on the slope like a fiery torrent ... On the eastern and southern parts of the mountain the shocks were felt with major violence, near Mascali seashore boats were pulled out by the sea waves ... On 15 July, meanwhile the Musarra fires were still going on, in the lower part regarding the South East, the earth opened near San Giovanni Paparumetta church...*" The author then describes the opening of new vents amid forests and "*three torrents of fire, two of which advanced for many days towards the region of Aci* [presently Acireale] *and localities close to the sea ... and the third pointed to the limits of the Catanian territory, where it stopped*". It must be emphasized that no flow is reported to have *reached* the sea, so that the presumed date of "1329" for the large flow forming the coast at Stazzo (Sartorius 1859, CNR 1979) appears highly questionable (see archeomagnetic results). The eruption ended with strong explosions at the summit Central Crater, making darkness with thunder and causing crop failures, especially around Catania, so that "*many men and women died from terror*". Ashfall was noticed as far as the Malta Island.

Similar descriptions are sometimes reported in 1321, 1323, 1328 or 1334, which are obviously misprints (for instance MCCCXXXIIII instead of MCCCXXVIIII). According to Fazello (1558), the 1329 eruption occurred after the mountain was "*for many years without burning nor even emitting fume*". Interesting precision is provided by Recupero (p. 28) who found two manuscripts (in Sicilian) that refer to the lower vent of this eruption by the name of "*Mt. Russu di San Giovanni Paparometto a lu Fireri*". This can undoubtedly be identified, therefore, as Mt. Rosso near San Giovannello, a church of the Fleri village (Fig. 1).

1333. According to Silvaggio (1542), "*similarly it* [the volcano] *belched with noise fired and burned stones*". This account, added to the misprint quoted above (1334), suggested to Sartorius that a second eruption from Mt. Rosso occurred in these years, an indeed unlikely event because flank cinder cones almost never erupt several times. As the place of the 1333 eruption is unspecified, it could have occurred at the summit Central Crater.

1381. In a manuscript attributed to the monk Simone da Lentini (or his anonymous successor, Muratori 1738), it is reported that "*on 6 August 1381 came a fire from Mongibello which burned many olive-trees around the city of Catania*". This led Amico (1741) and most of the subsequent authors to the belief that was then produced the lava flow coming to the sea in the present northern part of Catania, between Ognina and Guardia (Fig. 1). However, Ferrara (1818, p. 80–81) did not agree with this view, rightly observing that such a dreadful fiery stream, so close to the town, could not be alluded to briefly and without apparent emotion. Furthermore, in Fazello's chronology (1558), this flow is mentioned *before* the description of the 1169 earthquake.

Whatever the date, the event led to lengthy discussion among the modern authors for determining how and when the "immense harbor" which sheltered Ulysses vessels could have been buried by the lava. This harbor, however, probably never existed when admitting that Homer did not allude to Sicily in his poem (see Introduction).

1408. A flank eruption that year is accurately described by Silvaggio (1542): "*On Friday 9 November, towards the 3rd hour of the night* [i.e., 3 hours after sunset], *Mt. Etna belched a fire, firstly from its main crater, and then from various vents that opened on its lower flank, three miles above the monastery of St. Nicola* [near Nicolosi]". The eruption "*caused considerable damage as it devasted many vineyards and houses of the Pedara village. It lasted twelve days, until the 20th of the month*". In another account from Simone da Lentini, "*the fire buried the church of Santa Maria del Bosco Inchiuso and lasted 16* days and more". An anonymous manuscript found by Recupero adds that eruptive activity was preceded by strong earthquakes, and that heavy ashfall occurred as far as Messina and Calabria.

Three large flows between Viagrande and S. Giovanni la Punta (Fig. 1) were attributed to this eruption by Sartorius and all the following authors. However, there is no indication that Viagrande, which already existed at the time, was reached nor even threatened.

1444. In this year, a lava flow was produced towards Catania and, according to Fazello (1558) and Filoteo (1590), the summit Central Crater (thereafter CC) collapsed. We point out that these authors do not allude to the 1408 eruption and, conversely, nothing is reported in 1444 by Silvaggio, who nevertheless indicates two minor events in 1446 and

1447. It may be questioned, therefore, whether or not the 1444 eruption was confused with the 1408 one, so that we checked the existence in Palermo of a manuscript quoted by Fazello, and which is attributed to the bishop Ranzano (S. Scalia, pers. comm.). It is written here: "*in the year XLIIII plus MCCCC, when I was 16 years old*", the lava was diverted by St. Agatha's veil, and then continued for another 20 days. The flow itself, however, is not precisely located.

In the years 1470, 1533, and 1535, eruptions were sometimes reported that were obviously coming from misinterpretations (see Tanguy 1981, p. 596). Instead, it seems that the volcano was rather calm for almost a century, except for the usual mild activity at the summit.

1536. After Mt. Etna had been "*for many years without smoke or fire*" (Fazello), a large eruption took place on 22 March 1536, which may be summarized as follows: 1) violent fire fountaining at the CC, with lava overflows to the NW and the NE, leading to destructive lahars; 2) opening of three new vents "*in the middle of the Schiena dell'Asino close to the Castellacci, one towards Catania, another above the monastery of San Lio del Bosco, and another towards Adrano, above Mt. Minardo, and this later was buried by the 1763 flow*" (Recupero, p. 41); 3) opening of a lower fissure SE of Mt. Vetore. This lower flow is the only one accurately located because it overwhelmed the monastery of San Leo. The flank eruption probably ended on 8 April with strong explosions from the CC, which subsequently remained in magmatic activity: "*for all the year round flames were seen at the summit, and from time to time extended beyond the crater terrace*" (Silvaggio).

1537. The CC activity increased in early May with rumblings. On the 10th (or 11–12?) began a new flank eruption just above the lower 1536 fissure ("*Grotte di Paterno*" and "*Montenegro*", today Mt. Nero del Bosco, at 1700 m elevation below the Sapienza refuge). The 1537 flow was "*much longer than that of the preceding year*" and traveled for about 15 km, reaching the village of Torre del Grifo near Mascalucia (Fig. 1).

No flank eruption is reported on the NW side in the years 1536–1537, so that the date of ***"1536"*** for the large and composite flow reaching the foot of the mountain to the west of Randazzo (CNR 1979) is highly questionable. Possibly there is a confusion with the summit overflows mentioned at the beginning of the eruption, which were unable, however, to reach the lower region.

1566. In November–December of this year, various vents opened on the northern flank "*above Mt. Collabasso*", and "*a lava flow ran to the chesnuts of Iannazzo*" close to the Alcantara River (Recupero, p. 46). A detailed contemporaneous account (Conti 1581) describes five explosive vents above Randazzo and three lava flows, one of which was directed towards Linguaglossa. However, contrary to what is said by Sartorius and the following authors, there is no indication that this small town was reached by the lava.

1578–1580. One or several eruptions occurred these years, apparently towards the SE flank, but no precise location is given. Two different flows dated ***"1595"*** on the SW flank in Sartorius'atlas of Etna (1848–1859) do not correspond to any mentioned eruption, not even by Sartorius himself in his 1880 compilation (see discussion in Tanguy 1981; Tanguy et al. 2003).

From 1603 onwards, the eruptions are better described and their location generally do not pose problems (Table 2), however with several exceptions. Thus, the 1610 flows on the SW flank (Carrera 1636) are today reported as 1607 on the geological maps, because they are confused with another eruption taking place that year, but on the northwest side. The long-lived 1614–24 lava effusion on the northern flank produced many advanced flows that were poorly located, and some of them were confused with the 1566 flow (see Fig. 1 and section "Discussion"). Similar misconceptions occurred for the 1643 vents and the 1646–47 flows. In addition to the large 1651 eruption that devastated Bronte on the western foot of the mountain, another flow to the east was mistakenly identified as the "Scorciavacca" flow by Chaix (1892), and unfortunately by all the following authors. In fact, it is specified that the 1651 east flow "*took the way between Mascali and Fondo Macchia, descending into the valley of Macchia*" (Recupero, p. 60), this being today the "*Cavagrande*" above the Macchia village, more than 5 km distant from Scorciavacca.

Appendix 2: Location and chemical analyses of samples used for petrochemistry and Ra-Th studies (XRF analyses by CRPG, Nancy, France; Th values taken from Tables 5 and 6)

027, presumed 1408 flow in contrada Ràgala, upslope Nicolosi and Pedara villages on the SSE flank of Mount Etna (SSE, ≈750 m elevation, 37°37′30″N–15°02′30″E)

050, presumed 812 or 1169 flow of Mt. Sona at Sciara Galifi, east of Ragalna (SSW, 800 m, 37°38′–14°57′)

090, presumed 252 flow at Cibali, NW circonvallazione of Catania (SSE, 100 m, 37°31′30″–15°04′15″)

232, large bomb from Mt. Lepre cinder cone on the western flank (W, 1500 m, 37°45′30″–14°55′10″)

333, flow overlain by the presumed 1408 flow, north of S. Giovanni La Punta (SE, 350 m, 37°35′–15°05′)

471, presumed 1329 flow at Linera village (SE, 300 m, 37°40′–15°08′)

535, flow about 400 m north of Trecastagni center (SE, 550 m, 37°37′30″–15°05′)

814, presumed 1284 flow in contrada Ballo, northern Zafferana (E, 600 m, 37°42′–15°06′30″)

1132, presumed 1381 flow east of Gravina village (SSE, 350 m, 37°34′–15°04′)

1146, large lava field of La Nave in contrada Santa Venera (NW, 800 m, 37°51′–14°50′)

1193, presumed 812 or 1169 flow from Mt. Sona at its front near Paterno (SSW, 300 m, 37°35′–14°54′)

1199, recent lava flow from Mt. Arso SW near its front S of S.M. Licodia (SSW, 400 m, 37°36′–14°54′)

1408-1, presumed 1408 flow just above Pedara (SSE, 680 m, 37°37′30″–15°03′30″)

1536-23, 1536 flow west of Mt. San Leo (SSW, 1,075 m, 37°39′30″–14°58′30″)

1610-140, 1610 flow upslope Adrano (SW, 1,000 m, 37°42′–14°53′)

1614-1, 1614-24 flow east of Mt. Spagnolo, northern flank (N, 1200 m, 37°50′–14°58′)

1906, presumed 693 B.C. flow in southern Catania, viale della Regione (SSE, 30 m, 37°30′–15°04′15″)

2027, presumed 1595 lower flow west of Mt. Gallo (WSW, 1,430 m, 37°43′30″–14°54′30″)

Sample number	SiO2 (wt%)	Al2O3	Fe$_2$O$_3$ (total)	MnO	MgO	CaO	Na$_2$O	K$_2$O	TiO2	P$_2$O$_5$	L.O.I.	Total	Th (ppm)
027	50.58	19.30	8.15	0.16	3.08	8.49	4.53	2.03	1.51	0.76	0.46	99.05	14.55
090	49.08	16.63	10.69	0.18	5.49	9.65	3.61	1.71	1.67	0.59	0.14	99.44	11.95
232	46.70	16.52	11.32	0.17	6.11	10.25	2.46	1.25	1.59	0.51	2.54	99.42	9.03
333	49.40	17.33	9.99	0.17	4.81	8.95	4.25	2.05	1.63	0.76	0.30	99.64	14.72
471	47.91	18.18	9.92	0.17	4.86	9.90	3.69	1.64	1.55	0.58	0.05	98.45	11.70
535	50.26	18.90	9.41	0.17	4.14	9.33	4.32	1.77	1.39	0.62	−0.31	100.00	12.30
814	51.13	19.34	8.37	0.16	2.98	7.99	5.33	2.19	1.50	0.77	0.05	99.81	16.35
1132	49.67	18.24	9.79	0.16	4.77	9.62	4.28	1.76	1.59	0.64	−0.19	100.33	12.04
1146	50.51	16.61	10.52	0.17	6.49	8.72	4.17	1.77	1.54	0.58	0.17	101.25	14.09
1193	49.63	19.34	9.29	0.14	3.75	9.92	4.37	1.74	1.53	0.50	0.16	100.37	12.25
1199	51.21	19.28	8.57	0.13	4.07	8.13	5.06	2.06	1.39	0.65	0.06	100.61	13.75
1408$_{-1}$	51.03	19.15	8.70	0.14	3.18	8.66	5.04	2.04	1.49	0.76	0.16	100.35	14.73
1536$_{-23}$	51.89	19.16	8.62	0.17	2.92	7.33	5.39	2.59	1.55	0.74	0.10	100.46	18.67
1610$_{140}$	49.95	19.85	8.53	0.15	3.14	8.96	4.90	2.05	1.44	0.68	0.30	99.95	13.92
1614$_{-1}$	50.33	18.99	8.76	0.17	3.86	9.24	4.66	1.99	1.45	0.73	0.16	100.34	n.d.
1906	51.02	18.63	9.90	0.14	2.98	8.51	4.69	2.08	1.66	0.71	0.21	100.53	15.66
2027	49.32	18.47	9.77	0.16	5.00	10.12	3.98	1.51	1.50	0.54	n.d.	100.37	10.94
2042	51.38	18.35	9.11	0.17	3.28	8.08	5.13	2.18	1.60	0.74	n.d.	100.02	16.21
2052	47.81	18.85	9.84	0.16	4.93	10.18	4.11	1.58	1.47	0.71	0.13	99.77	11.98
2149	49.91	20.34	8.47	0.14	3.26	9.28	4.58	1.76	1.51	0.62	0.47	100.34	12.57
2154	48.05	17.46	10.39	0.16	6.39	10.43	3.68	1.31	1.42	0.66	0.20	100.15	9.65
2155	47.97	16.84	10.88	0.17	5.29	10.10	3.87	1.67	1.57	0.62	0.27	99.25	12.25
2197	47.20	16.32	11.14	0.18	6.40	10.06	3.26	1.44	1.59	0.67	1.40	99.66	12.85
2249	54.61	18.02	7.74	0.18	2.51	5.42	6.32	3.00	1.53	0.64	n.d.	99.97	22.79
2257	49.44	19.14	9.38	0.16	3.82	9.72	4.55	1.73	1.47	0.59	n.d.	100.00	n.d.
2601	50.39	19.54	8.43	0.16	3.12	8.55	4.66	2.01	1.54	0.79	0.13	99.32	14.65
3516	50.04	18.65	8.99	0.16	3.57	8.70	4.45	1.96	1.53	0.69	0.76	99.50	14.51
3645	51.49	18.78	8.66	0.16	2.94	7.62	5.06	2.22	1.51	0.79	0.09	99.32	14.50
3672	49.21	19.35	8.90	0.15	3.68	9.63	4.23	1.74	1.41	0.64	0.02	98.96	12.82
3790	48.65	16.91	10.90	0.17	5.24	9.75	3.96	1.72	1.64	0.62	0.20	99.76	12.24
3843	50.75	18.98	8.72	0.17	2.98	8.04	4.48	1.94	1.55	0.79	0.99	99.39	14.79
3861	49.30	17.35	10.07	0.16	4.67	8.82	4.17	2.05	1.66	0.78	0.03	99.06	15.06
3871	49.07	17.63	10.71	0.17	5.46	10.07	3.95	1.71	1.62	0.61	−0.26	100.74	11.98
3894	49.83	17.42	10.37	0.17	5.05	9.28	4.18	2.03	1.69	0.77	−0.29	100.50	14.58
3966	50.94	19.02	8.75	0.16	2.96	7.88	4.75	2.03	1.50	0.77	0.10	98.86	13.55
4048	50.54	18.90	9.01	0.17	3.19	8.28	4.90	2.05	1.53	0.80	0.06	99.43	13.69
4074	48.35	18.01	10.31	0.16	5.06	9.80	3.77	1.63	1.59	0.59	0.14	99.41	11.25
4102	48.72	17.66	10.59	0.17	5.40	9.91	3.76	1.68	1.57	0.62	−0.11	99.97	11.93
4120	51.86	18.85	9.05	0.16	2.72	8.23	4.35	1.92	1.51	0.67	0.32	99.64	13.71
4144	50.06	19.78	8.56	0.16	3.12	8.72	4.95	2.00	1.50	0.80	−0.12	99.53	14.69
5912	50.13	19.75	9.07	0.16	3.44	9.53	4.28	1.76	1.46	0.68	−0.01	100.25	13.01
5915	48.54	18.17	10.10	0.16	4.83	9.89	3.85	1.65	1.54	0.60	0.13	99.46	11.65
6122	48.78	17.23	10.60	0.17	5.63	10.14	3.64	1.53	1.53	0.51	0.19	99.95	13.37

2042, presumed 1595 upper flow from the east of Mt. Gallo (WSW, 1,360 m, 37°43′–14°54′30″)

2052, presumed 1536 flow west of Randazzo (NW, 900 m, 37°51′–14°55′)

2149, presumed 1566 flow above Linguaglossa (NE, 750 m, 37°50′–15°06′30″)

2154, small lava flow downslope Mt. Ciacca, presumed 12th century (S, 1,450 m, 37°41′–14°59′)

2155, presumed 1537 flow below Sapienza refuge and "Funivia" cable-car station (S, 1,900 m, 37°42′–15°00′)

2197, lava spatters from Mt. Serra Pizzuta Calvarina (SSE, 1,700 m, 37°41′30″–15°01′30″)

2249, 4110, presumed 1284 flow above Monacella, north of S. Venerina (E, 500 m, 37°42′–15°08′)

2257, presumed 1651 Scorciavacca flow on the lower east flank (E, 840 m, 37°47′–15°08′)

2601, presumed 1408 flow overlain by 027 in contrada Ràgala (SSE, 800 m, 37°37′45″–15°02′45″)

3516, lava spatter from Mt. Arso SE above Pedara (SSE, 950 m, 37°38′45″–15°02′30″)

3645, geologically recent flow at sea below Santa Tecla village (SE, 5 m, 37°38′–15°10′30″)

3672, presumed 1284 flow, 1 km north of Zafferana church (E, 600 m, 37°42′15″–15°06′45″)

3790, presumed 425 B.C. flow at sea, via Rotolo, Catania (SSE, 10 m, 37°31′30″–15°07′)

3843, lava spatter from Mt. Gorna cinder cone on SE flank, presumed 394 B.C. (SE, 780 m, 37°39′–15°04′30″)

3861, geologically recent flow at sea near Cannizzaro (SSE, 10 m, 37°32′–15°07′30″)

3871, presumed 1408 flow north of S. Giovanni La Punta, sciara Pulea (SE, 350 m, 37°35′–15°05′)

3894, geologically recent flow, eastern circonvallazione of Catania (SSE, 50 m, 37°32′–15°06′)

3966, geologically recent flow of Castello del Greco, NE of Santa Tecla (SE, 5 m, 37°38′30″–15°11′)

3985, geologically recent flow in Contrada Verzella, lower north flank (N, 600 m, 37°53′–15°03′)

4048, presumed 394 B.C. flow south of Santa Maria la Stella, lower SE flank (SE, 300 m, 37°36′30″–15°08′)

4074, presumed 1408 flow between Trecastagni and Monte Serra (SE, 490 m, 37°37′–15°05′30″)

4102, presumed 252 flow at southern base of Monte Peloso (or Monpeloso, SSE, 800 m, 37°38′–15°02′)

4120, geologically recent flow overlain by the pseudo 1381 flow SE of Gravina (SSE, 300 m, 37°30′–15°04′)

4144, presumed 1444 flow east of Tre Monti above Trecastagni, lower SE flank (SE, 680 m, 37°38′–15°04′)

4314, presumed 1284 flow west of Dagala village (E, 350 m, 37°42′–15°08′15″)

4323, pyroclastic deposit on SE border of Mt. Ilice (SE, 830 m, 37°39′45–15°05′)

5912, geologically recent flow from Mt. Solfizio (SE, 1700 m, 37°42′–15°02′)

5915, presumed 1329 flow at vent, SE base of Mt. Ilice (SE, 700 m, 37°39′30″–15°05′)

6122, presumed 122 B.C. flow at Piazza Gioeni, northern Catania (SSE, 90 m 37°31′30″–15°05′30″)

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Addendum

While our paper was in review, Speranza et al. (2006) published a discussion on the respective merits of our "large-sample method" (LSM) opposed to the core drilling results from Mount Etna. This makes necessary a brief additional explanation here. Speranza et al. attempt to show that our LSM "may yield a fictitious improvement in statistical uncertainty" thanks to "unjustified rejection of scattered samples". They add that we "did not consider factors causing the misalignment between the paleomagnetic direction frozen in lavas and the regional geomagnetic field", and conclude that their larger alpha 95 values (4.5° in average, in great contrast with our 1.2°, Tables 3 and 4) might paradoxically "yield sound results, at least if dating based on Bayesian statistics is adopted". In the present work, we rejected ~10% of the samples, a treatment which is common in usual paleomagnetic studies and cannot affect significantly our results (see the excellent alpha 95 in our many sites where no sample is discarded, Tables 3 and 4). We demonstrated through instrumental measurements on the field (Tanguy and Le Goff 2004, see main text) that the problem of magnetic anomalies may be overcome when taking the average of results over a large area, as in our LSM. And while the Bayesian statistics may be of some help for setting up the reference curve, as any statistical method it cannot improve the primary results, which necessarily need low alpha 95 (less than 2°) for discriminating between various trends of geomagnetic variation often differing by no more than a few degrees. These questions, as other very technical ones (methods of demagnetization, drilling induced remanence, westward drift of the geomagnetic field, etc.) were already discussed in Arrighi et al. (2005), and the readers should therefore refer to this reply.

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