

## Recent eruptive history of Stromboli (Aeolian Islands, Italy) determined from high-accuracy archeomagnetic dating

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Received 26 May 2004; revised 21 July 2004; accepted 10 September 2004; published 7 October 2004.

[1] The “large sample method” of archeomagnetic dating was applied to Stromboli. 127 samples (10 sites) yielded paleofield directions with 95% confidence intervals less than 2°. Coupled with a reference curve for secular variation in western Europe, these allow accurate dating of volcanic events. A lava flow underlying San Bartolo village gave a minimum age of AD 100 ( $\pm 100$ ); a lava overflow predating the last sector collapse was dated from 1350 ( $\pm 60$ ), suggesting the recent occurrence of highly hazardous events. Lava spatters and a hot avalanche high on the northern flank were emplaced during the XXth century; lava spatters on the lower flanks could date the onset of the still-ongoing phase from AD 550 ( $\pm 50$ ). These results are different from those obtained in a recent study, probably because traditional paleomagnetic sampling cannot yield sufficient precision, considering the characteristics of the archeomagnetic secular variation curve. **INDEX TERMS:** 1503 Geomagnetism and Paleomagnetism: Archeomagnetism; 1522 Geomagnetism and Paleomagnetism: Paleomagnetic secular variation; 1560 Geomagnetism and Paleomagnetism: Time variations—secular and long term; 1594 Geomagnetism and Paleomagnetism: Instruments and techniques; 8419 Volcanology: Eruption monitoring (7280). **Citation:** Arrighi, S., M. Rosi, J.-C. Tanguy, and V. Courtillot (2004), Recent eruptive history of Stromboli (Aeolian Islands, Italy) determined from high-accuracy archeomagnetic dating, *Geophys. Res. Lett.*, 31, L19603, doi:10.1029/2004GL020627.

### 1. Introduction

[2] Archeomagnetism was founded in the 1930s by E. Thellier who showed that well-dated archeological materials could be used for retrieving the secular variation of the Earth’s Magnetic Field (EMF) and, reciprocally, that materials of unknown age could be dated by means of a reference geomagnetic curve. At the St. Maur Observatory (France), Thellier and his successors developed instrumentation for the high-precision sampling and measurements necessary to achieve reliable results [Thellier, 1966, 1981; Le Goff, 1975]. The so-called “large sample plaster method” (referred to as “large sample” in this paper) enables measurements on kg-sized samples and allows to obtain high precision on determinations of past directions of the EMF recorded by human artifacts (95% confidence

intervals less than 2°). The method has been applied to over 120 well-dated archeological sites, leading to a reference curve for Western Europe spanning the last 2100 years [Thellier, 1981; Bucur, 1994], being extended to the past three millennia [Gallet *et al.*, 2002].

[3] The method can also be used on volcanic rocks, and indeed has been applied to samples from Mount Etna (Sicily), involving also critical examination of written sources pertaining to the 2,700 year-long history of the volcano [Tanguy, 1970, 1981]. A “volcanic” reference curve for Sicily was published by Tanguy *et al.* [1985], and improved using additional studies based on samples from Vesuvius [Tanguy *et al.*, 1999]. Very good agreement between the French archeological and South Italian volcanic curves has allowed to show that archeomagnetic dating may be extended to the whole western Mediterranean [Tanguy *et al.*, 2003]. These results, however, revealed significant discrepancies with respect to data obtained on the same volcanoes using paleomagnetic techniques carried out through classical core-drilling methods [Rolph *et al.*, 1987; Carracedo *et al.*, 1993; Incoronato *et al.*, 2002]. It was concluded that paleomagnetic methods usually do not allow sufficient accuracy to reconstruct a reference directional curve that can be used for high-resolution archeomagnetic dating. Similar studies performed on Stromboli, located between Etna and Vesuvius, provide a further opportunity to compare results from the two methods, and to improve our understanding of the volcanic history of this volcano.

### 2. The Large Sample Plaster Method Applied to Stromboli

[4] The island of Stromboli (Figure 1) represents the emerged part of a steep stratovolcano more than 200 ky old [Gillot and Keller, 1993]. During its growth, the volcanic edifice suffered repeated flank collapses, the most conspicuous being the Upper Vancori (circa 13 ky) and Neo-Stromboli ( $5.6 \pm 3.3$  ky). The Recent Stromboli developed within the scar left by the preceding collapses. It suffered two other less important destructive events (Pizzo Sopra la Fossa, and Sciara del Fuoco collapses) whose ages are unknown, but certainly younger than 5,000 years BP [Tibaldi, 2001]. Volcanic activity during the last 1,500 years [Rosi *et al.*, 2000] consisted of moderate incandescent jets occurring every few minutes, sometimes accompanied by lava outflows along the steep slope of Sciara del Fuoco. Such continuous mild activity could be interrupted by periods of quiescence lasting months or years, or by sudden outbursts showering the entire island with ballistic blocks and lava spatters [Barberi *et al.*, 1993]. These paroxysms represent one of the main volcanic risks, although greater

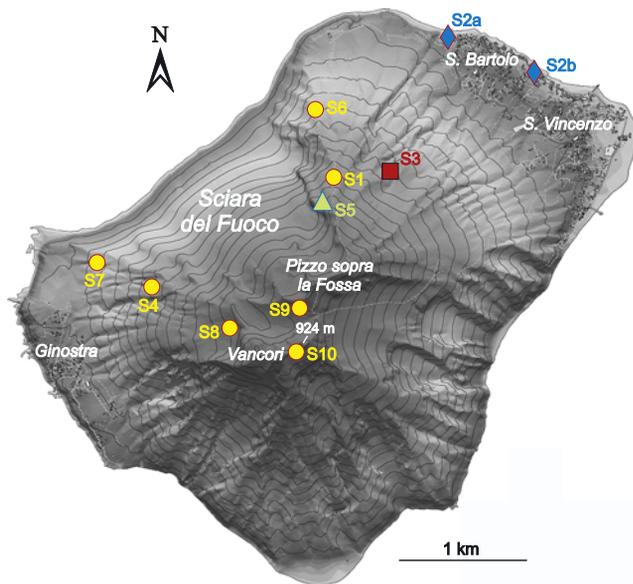
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**Figure 1.** Map of Stromboli [Pareschi et al., 2002] with indication of our sampled sites (lava flows in blue and green, 1930 hot avalanche in red, lava spatters in yellow). See Table 1 for explanation of individual sites.

hazard is linked to sector collapses triggering tsunamis (e.g., December 30, 2002 after a small collapse in Sciara del Fuoco [Global Volcanism Network, 2002]).

[5] Field work performed by SA and MR was focused on sampling hot avalanche deposits (site S3, Figure 1), belonging to the 1930 paroxysm [Rittmann, 1931], and lava spatters believed to have resulted from the same eruption (S1, S6), or whose ages are unknown, although probably no older than the past two millennia (S4, S7, S8, S10). A spatter-fed flow near the summit (S9) was attributed to the 1959 paroxysm (A. Bertagnini, personal communication, 2003). Two morphologically recent lava flows were also investigated, one below San Bartolo village on the northern coast (S2), and the other which overflowed the NW flank (S5), before being cut by the Sciara del Fuoco collapse. A total of 127 large samples distributed over 10 sites were collected (Figure 1). Regarding spatter material, great care was taken in plastering and orienting the samples before any attempt to detach them on unstable, sandy ground (see Arrighi [2004] for details).

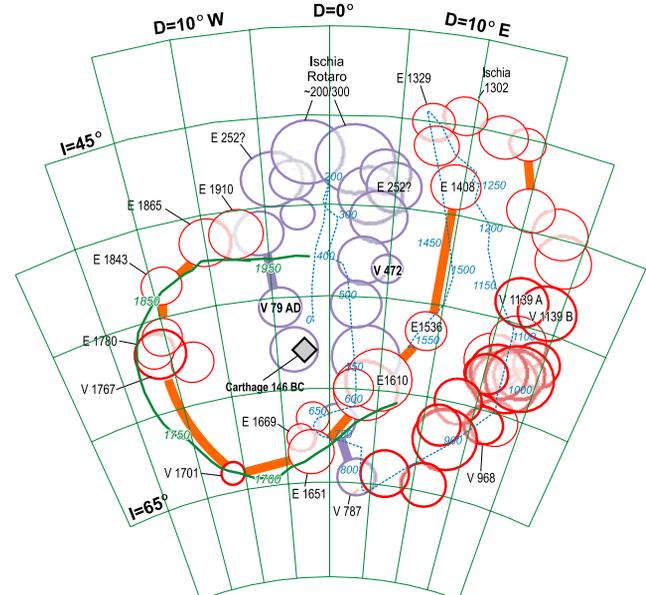
[6] The “large sample” procedure has been extensively described [Tanguy et al., 1985, 1999, 2003]. It involves samples detached with a hammer and plastered to support a 5–7 cm plate, set horizontally using a spirit level. The plate is removed and the sun shadow is marked for calculation of geographical North. In the laboratory, samples are replastered in square molds (12-cm) for measurements using a large rotating induction magnetometer and an alternating field demagnetization device. This allows to reach an accuracy of a few tenths of a degree on each sample paleodirection. Of course, a larger dispersion is observed among samples from the same site, mainly because of distortion of the ambient field induced by magnetization of previously cooled parts of the surrounding lava. However the half-angles of the 95% confidence cones ( $\alpha_{95}$ ) obtained are always less than  $2^\circ$  and often close to  $1^\circ$ . We insist on

this level of accuracy which is almost never reached in more traditional applications of paleomagnetism. Our reference “volcanomagnetic” curve for Southern Italy (SIVC), obtained from 836 large samples distributed at 63 volcanic sites, is shown in Figure 2: the uncertainty is no more than  $2^\circ$ . This curve provides the best available tool for archeomagnetic dating at Etna, and can be used at Stromboli (120 km northward), provided a small change of coordinates is operated through calculation of virtual geomagnetic poles (VGP). For more clarity for dating purposes, the SIVC has been redrawn in Figure 3 as a shaded band whose width is roughly equal to the global uncertainty given by individual data points in Figure 2.

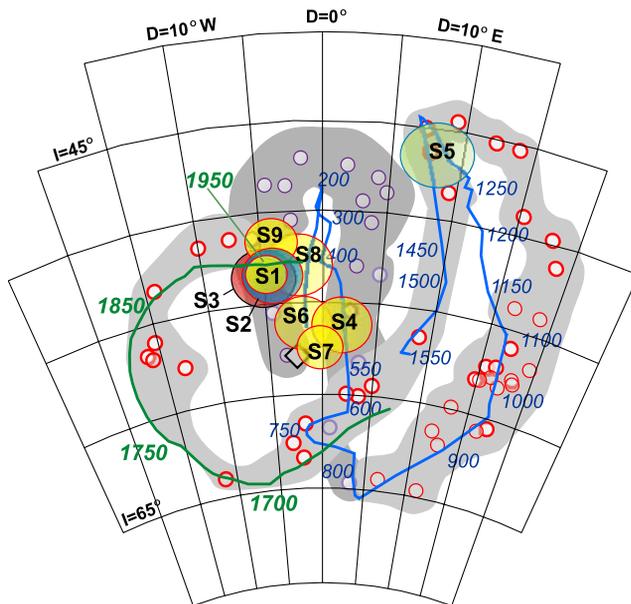
[7] The geomagnetic field shows variable behavior with time, sometimes leading to limitations in archeomagnetic dating. Thus, its variation is larger during the last millennium, but much more restricted during the early Middle Ages and the Roman periods. Moreover, there are several epochs when field directions were identical, because the field was stationary or the path crossed on itself (e.g., 1950–2000 and  $\sim 100$ –200, or 1600–1650 and 600–700), preventing accurate dating through archeomagnetic means. The numbers of such ambiguities increases when going further back into the historical (and pre-historical) past.

### 3. Results From Recent Lava Flows and Lava Spatters at Stromboli

[8] Results obtained on our sites are presented in Table 1 [Arrighi, 2004].  $\alpha_{95}$  values range from  $1.0$  to  $1.8^\circ$  (average  $1.4^\circ$ ), either for lava flows or lava spatters. The



**Figure 2.** A summary of data compiled to construct a South Italian volcanic reference curve, then used as a dating tool based on secular changes in geomagnetic field directions [after Tanguy et al., 2003] (E = Etna, V = Vesuvius). The dashed blue line indicates the path of the French archeological curve [Gallet et al., 2002]. The solid green curve refers to instrumental measurements from the last centuries [Alexandrescu et al., 1996]. All data reduced to Etna coordinates.



**Figure 3.** South Italian mean reference curve of Figure 2 shown as data points within an approximate band of uncertainty (shading), used for archeomagnetic dating of Stromboli lavas. Our mean archeomagnetic directions for sites S1 to S9 are shown with their  $\alpha_{95}$  confidence circles (using the same color code as in Figure 1).

error bars on magnetic ages are estimated considering the  $\alpha_{95}$  values of each site with respect to the nearest dated sites of Figure 2, including also reference to the French archeomagnetic curve (dashed blue line).

[9] For the lava flow which underlies San Bartolo (S2, Figures 1 and 3), all 22 samples were retained for the paleodirection. When discarding the date of AD 1950, simply because San Bartolo is much older, this paleodirection is consistent with two solutions: an age of AD  $100 \pm 100$  (Figure 2), or an even more ancient epoch of about 1500–2000 BC, by extrapolating to Sicily the results from *Le Goff et al.* [1998]. This second hypothesis, however, is difficult to reconcile with the absence on the San Bartolo flow of archeological artifacts from the 17th to the 1st century BC, whereas these are widespread in the surrounding area.

[10] The Sciara del Fuoco overflow (S5) predates the last conspicuous flank collapse. The age obtained (11/11 samples, Table 1) is AD 1350 ( $\pm 60$ ), although there is a much lower probability (<5%) for a date around AD 300

(Figure 3). As far as we know, no other comparable field direction existed during the past 4,000 years. This would mean that the last large sector collapse at Stromboli took place during historical times, but further investigations are needed to clarify this important point (both for scientific and public-safety reasons).

[11] The lava spatters gave concentrated results, near the center of Figure 3. Some (S1, S8, S9) are consistent with the age of the 1930 hot avalanche deposit (S3), or any paroxysm having occurred near the middle of the XXth century. But others (S4, S7, and to a lesser degree S6) significantly differ from the former group. These latter spatters are all distributed on the lower sandy slopes of the volcano (Figure 1). Unless they were tilted after cooling, they could be ascribed to a violent paroxysm occurring around 550 AD, that marked the onset of spatter activity [*Rosi et al.*, 2000]. This suggestion needs further support from 14C dating and geochemical studies. Finally, samples from site S10, located near a summit, were struck by lightning and their primary magnetization could not be recovered.

#### 4. Comparison Between Archeomagnetic and Paleomagnetic Studies

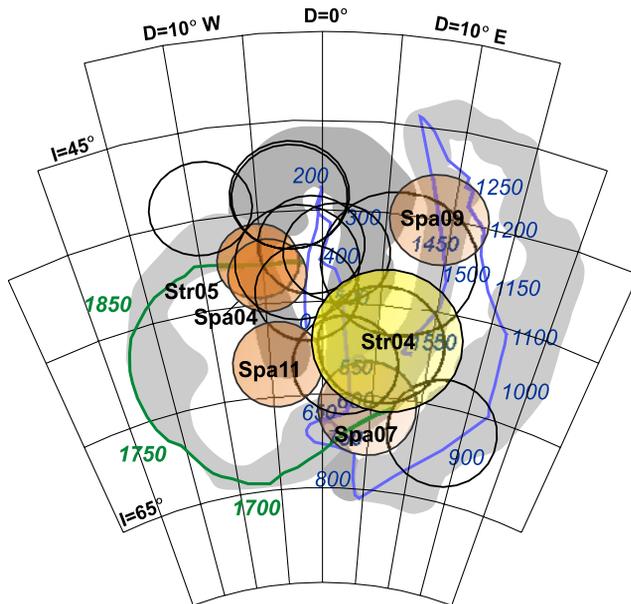
[12] Our results are significantly different from those of a study carried out by *Speranza et al.* [2004] using classical core-drilling paleomagnetic techniques. These authors reported paleodirections of spatter deposits given by 18 sites located in the same areas we sampled. However, their results (Figure 4) include 8 sites with an  $\alpha_{95}$  of  $3^\circ$  or larger, and none with  $\alpha_{95}$  below  $2^\circ$ , which is the upper limit we accept in our rather stringent data selection procedure (the overall average is  $3.2^\circ$ , to be compared to our  $1.4^\circ$ ). The reference curve used by these authors is not clearly defined, does not show any reference point and does not have the low level of uncertainty that is required for accurate dating. The two studies share one common site, which allows comparison: their site Str04 (yellow circle in Figure 4), corresponding to our site S1 (samples taken next to their core holes), points to a significantly different paleodirection, despite a much larger uncertainty ( $\alpha_{95} = 4.3^\circ$  against  $1.0^\circ$ ). When taking into account their five results with  $\alpha_{95} \leq 2.6^\circ$  (orange circles), only one site gives a result consistent with ours (Str05, located at the summit, agrees with S9). Spa04, close to AD 550 S4, appears instead to date from the XXth century. Spa07 and Spa09, close to S6 and S8, respectively, give significantly different paleodirections.

[13] High-resolution archeomagnetic curves display swings in magnetic field directions with amplitudes of a

**Table 1.** Archeomagnetic Results From Stromboli<sup>a</sup>

Site	N	$\alpha_{95}$ ( $^\circ$ )	k	I ( $^\circ$ )	D ( $^\circ$ )	Magnetic Age (years A.D.)
S1, North flank spatter, $\sim 550$ m a.s.l.	12/17	1.0	1507	53.4	-4.7	1950 $\pm$ 30
S2, S. Bartolo lava flow	22/22	1.5	386	53.4	-4.2	100 $\pm$ 100 or prehistoric
S3, hot 1930 avalanche	8/9	1.6	973	53.5	-5.0	1950 $\pm$ 40
S4, West flank spatter, $\sim 450$ m a.s.l.	11/16	1.5	776	56.2	1.8	530 $\pm$ 40 (see text)
S5, Sciara del Fuoco lava overflow	11/11	1.8	546	46.5	8.2	1350 $\pm$ 60
S6, N flank spatter, $\sim 250$ m a.s.l.	7/8	1.4	1335	56.2	-1.7	Tilted samples? See text
S7, W flank spatter, $\sim 150$ m a.s.l.	7/8	1.2	2054	57.5	-0.2	550 $\pm$ 30 (see text)
S8, W flank spatter, $\sim 650$ m a.s.l.	9/15	1.7	755	53.0	-2.0	1970 $\pm$ 40
S9, Pizzo sopra la Fossa spatter flow	6/6	1.3	1929	51.6	-4.1	1950 $\pm$ 30

<sup>a</sup>See *Arrighi* [2004]. N, number of samples giving consistent results/total number sampled.  $\alpha_{95}$ , k = statistical parameters. I = inclination, D = declination. Age uncertainties are determined following *Le Goff et al.* [2002]. All data are reduced to the coordinates of Etna ( $37.75^\circ$ N,  $15.00^\circ$ E).



**Figure 4.** Same as Figure 3, with paleomagnetic results from Speranza *et al.* [2004]. Their site Str04 in yellow corresponds to our site S1. Other sites with  $\alpha_{95} \leq 2.6^\circ$  are shown in orange (see discussion in the text, section 4).

few degrees to tens of degrees over decades to centuries. The drift velocity of the magnetic vector along its path varies significantly with time [e.g., Gallet *et al.*, 2003], and so do the amplitudes and curvatures of secular variation loops, leading to uncertainties, and possibly ambiguities in dating at some times. The paleomagnetic techniques which are normally used to determine paleomagnetic poles from lavas involve smaller numbers of smaller-size samples and result in larger confidence intervals, acceptable for such applications but not for archeomagnetic dating. Uncertainties not much larger than  $1^\circ$  are required for sufficient time resolution.

[14] Thus, the conclusions of Speranza *et al.* [2004] are different from ours regarding the volcanic history of Stromboli. These authors suggest that “high-energy eruptions occurred between ca. 1400 and 1600 AD”, whereas we find no evidence for these. They propose “that the powerful XXth century eruptions spread spatter over most of the western flank”. Instead, from both our results and contemporaneous witness reports, we found that these pyroclasts are mostly distributed on the northern flank. Finally they add that “no paroxysms are inferred to have occurred before 1400 AD”, whereas we argue for a large explosive eruption in AD 550, and a (possibly major) flank collapse after 1350. These dates are important not only for understanding the workings of the Stromboli volcano as a scientific goal, but also to properly decipher its detailed volcanic history in order to improve evaluation of future risks.

[15] **Acknowledgments.** We acknowledge Maxime Le Goff for technical assistance, and L. Francalanci and an anonymous reviewer. This is IGGP contribution no. 2914.

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