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Distortion of the geomagnetic field in volcanic terrains: an experimental study of the Mount Etna stratovolcano

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Abstract

The inclination (*I*), declination (*D*) and total intensity (*F*) of the geomagnetic field were measured on Mount Etna in 1989–1991 at a dozen sites previously sampled for archeomagnetic studies. The purpose of the work was to determine the variations of these parameters at 30 cm above ground level, and how the distortion from the main field can affect the archeomagnetic record of volcanic rocks. Ten measurements were usually performed at each site with a three-component flux-gate magnetometer, whose estimated precision is $\pm 0.2^{\circ}$ on direction and ± 50 nT on intensity. This was considered sufficient on volcanic areas with highly magnetized rocks and where the geomagnetic gradient may be in excess of 1000 nT/m. Results averaged for each site generally show small variations in intensity ($\pm 3\%$ of the total field) and direction ($\pm 1.5^{\circ}$). The averaged values of the 12 sites ($I = 52.6^{\circ}$, $D = 0.3^{\circ}$, $F = 44010$ nT) are very close to those measured in sedimentary terrain away from the volcano ($I = 52.9^{\circ}$, $D = 0.35^{\circ}$, $F = 44110$ nT), themselves consistent with the interpolated IGRF in eastern Sicily. The largest deviations of the geomagnetic direction have been observed on four sites, three of them located on the South flank between 1900 and 700 m elevation. It is suggested that these anomalies are mainly related to dyke swarms which are common within the South Rift Zone of Mount Etna. Our findings show that reliable archeomagnetic results can be obtained from volcanic rocks, provided that lavas of the same eruption are sampled on several sites distributed over the largest possible area.

Keywords: Geomagnetic field; Secular variation; Magnetic anomaly; Rock magnetism; Etna

1. Introduction

A major problem for reconstructing the ancient geomagnetic field by means of volcanic rocks lies in the quality of archeomagnetic (or paleomagnetic) record. It is well known that samples collected from the same volcanic site show a dispersion of the results in direction that largely exceeds the admissible error made in sampling and measurements. If one excludes possible movements after magnetization of the lava, this dispersion is generally attributed to a distortion of the ambient geomagnetic field (1) by the high magnetization of the neighbouring cooled parts of the lava during its emplacement, and (2) by the cumulative magnetic effect of the flows which compose the volcanic pile. Although this distortion has often been considered from a theoretical standpoint (e.g. Chevallier, 1925; Coe, 1979), very few authors have tried to quantify its exact magnitude through measurements on the field. In his pioneering work on Mount Etna, Sicily, Chevallier carried out instrumental mea-

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surements involving only declination on the surface of rock samples he was collecting for archeomagnetic studies. He found that declination was on average close to that existing away from the volcano, although it should be increasing a few degrees westwards from the southern to the northern part of the volcano. Unfortunately, as his measurements were made directly on the samples before their collection, the acting geomagnetic field showed an unusually large distortion owing to the high magnetization of the nearest volcanic rocks (see above, 1) and, furthermore, to an undetermined "wall effect" of the quarry or trench of road used for sampling (Chevallier, 1925, pp. 83–99). Recently, Baag et al. (1995), and Valet and Soler (1999), published detailed experimental studies on the Hawaiian and Canary islands, respectively, and found large distortions from the true ambient field, so that determinations of the paleomagnetic field by means of volcanic rocks could be questioned. Other, numerous measures of the geomagnetic intensity through proton magnetometers were collected for the monitoring of some active volcanoes (e.g. Pozzi et al., 1979; Zlotnicki and Le Mouël, 1988), but they do not bring information on the magnetic direction. Here, we aim our study on the geomagnetic distortion in volcanic areas from archeomagnetic and paleomagnetic standpoints, including both intensity and direction measurements carried out in the same conditions where the rock samples are collected. This paper presents the results obtained at Mount Etna in 1989–1991, on a dozen of selected sites where extensive archeomagnetic investigations have been developing for over 30 years (Tanguy, 1970; Tanguy et al., 1985, 1999, 2003).

2. Geological setting

Mount Etna is a large composite volcano towering more than 3300 m above the East coast of Sicily. Its maximum diameter (47 km N–S × 38 km E–W) indicates elongation following two prominent "rift-zones" characterized by a high density of dykes, eruptive fissures and cinder cones (Kieffer, 1985). The volcanic edifice overlies a sedimentary basement gently inclined from the NW (1000 m elevation) to the SE, where in many localities volcanic products are presently found below sea level. The sedimentary rocks reach their highest point beneath the Central Crater at about 1200 m elevation, so that the whole mass of the volcano may barely exceed 350 km^3 (Tanguy, 1980). Although the general shape of the mountain is that of a large flattened cone, many exceptions are found, the most conspicuous of them being the "Valle del Bove", a caldera-shaped depression 7 km × 5 km wide located E of the summit and which opens towards the sea.

Volcanic activity in the Mount Etna area began more than 500,000 years ago (Gillot et al., 1994) and vigorously continues at the present time. A number of dark, recent lava flows, many of them emitted through fissures from the South and NNE rift zones, have covered most of the flanks and particularly the floor of the Valle del Bove. The predominant rock type is trachybasalt (or hawaiite), which namely composes almost all the recent and historic lavas (Chester et al., 1985; Tanguy et al., 1997), although an evolution towards alkali basalt is occurring since the last few years (La Delfa et al., 2001). Indeed trachybasalt can be derived from an alkali basalt parent magma by crystal fractionation at 20–30 km depth, and the degree of differentiation is thought inversely related to the eruption rate (Tanguy et al., 1997). Magma thus produced should be rising to the surface through a plexus of dykes and sills, without any significant shallow reservoir. In the geological past, however, temporary shallow chambers probably developed, thus explaining rare pulses of magma differentiation towards trachyandesites and trachytes, followed by caldera collapse (e.g. Elliptic Crater, 15,000 years ago). This view is supported by the presence of gravimetric and seismic anomalies found between 3 and 10 km depth and interpreted as due to a large volume of presently congealed magma (Neumann et al., 1985; Hirn et al., 1991).

The magnetic mineralogy of Etnean lavas is quite uniform, being dominated by more or less oxidized titanomagnetite with a Curie temperature close to 500 °C (Tanguy, 1980). As most volcanic materials, these lavas carry thermoremanent magnetization of high intensity, usually from 10^{-1} to 1 A m^{-1}.

3. Experimental procedure

The aim of this work was to determine the degree of uncertainty regarding precision and reliability of volcanic records in various regions of Mount Etna with respect to the true geomagnetic field acting in Sicily, previous studies made on the subject showing large discrepancies (e.g. Tanguy et al., 1985; Rolph et al., 1987). For this purpose, therefore, measurements of the ambient magnetic field were performed on a dozen of 'archeomagnetic sites' (Fig. 1) in the same manner as archeomagnetic work was carried out, that is ten or more measurements on each site over a distance of several tens of meters. Three additional sites located in sedimentary areas, respectively NW, NE and South of the volcano, were used to determine the mean geomagnetic field acting in Sicily out of the volcano, regardless a possible small lithospheric effect. The results were then averaged as in archeomagnetism (or paleomagnetism), by using Fisher statistics (Fisher, 1953) and bivariate statistics (Le Goff et al., 1992).

As in archeomagnetic work, we tried to avoid all effect that could lead to unusual distortion of the ambient field. Particularly, a considerable advantage of this method lies in the fact that regions of strong

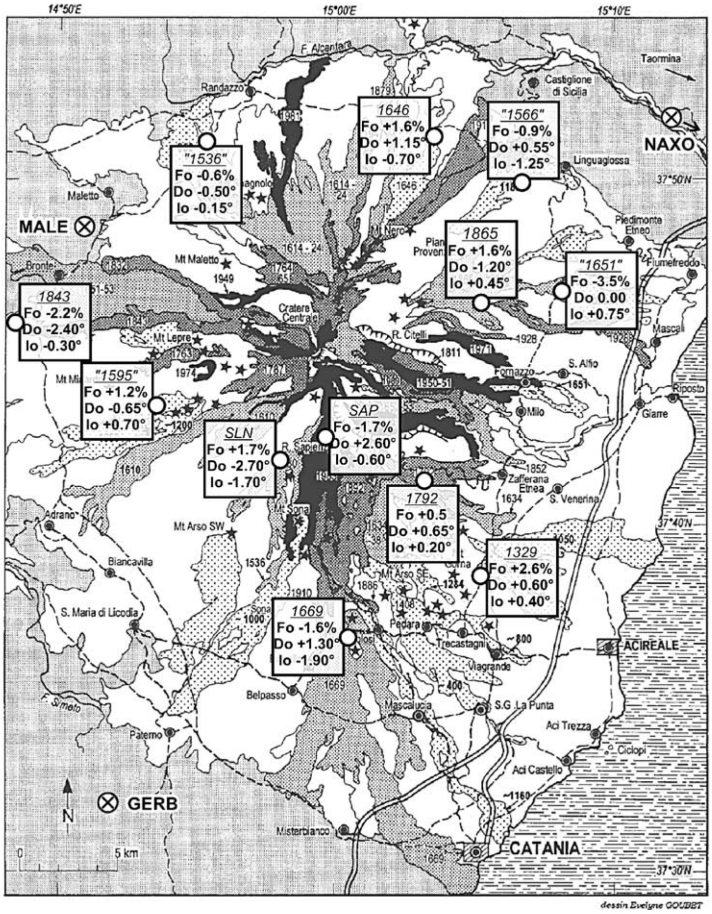

Fig. 1. Map of Mount Etna historical lavas on which magnetic measurements were done. *1669*, 1669 flow on the South flank; *1329*, foot of the 1329 cinder cone of Monte Rosso; *1792*, 1792 flow on SE flank; *"1651"*, presumed 1651 flow (actually c.1020, see Tanguy et al., 2003); *1865*, 1865 flow on NE flank; *"1566"*, presumed 1566 flow (c.1180) near Linguaglossa; *1646*, 1646 flow on Northern flank; *"1536"*, presumed 1536 flow (c.950) on NW flank; *1843*, 1843 flow on W flank; *"1595"*, presumed 1595 flow (c.1060) on SW flank; *SLN*, 1780 flow near Serra La Nave; *SAP*, 1763 flow near Sapienza hotel (this flow was buried by the 2001 and 2002 flows). NAXO, MALE, GERB, "sedimentary" sites of Naxos, Maletto, Gerbini. For each "volcanic" site is indicated deviation from average sedimentary field Fo, Do, Io. See text for further explanation.

parasitic magnetization owing to lightning (high intensity IRM) may be detected through the rock samples study during archeomagnetic work. In fact, it has long been noticed (Chevallier, 1925) that places struck by lightning ("punti distinti") present an ambient magnetic field anomalously strong and largely distorted, the magnetic compass showing in some cases a difference of 180° within a few meters. However, in most of our archeomagnetic samples, the lightning IRM was either absent or very weak, being eliminated by AF cleaning to 15–20 mT rms.

Instrumental measurements of the ambient magnetic field were performed in July 1989 by means of a three component flux-gate magnetometer lying on a tripod about 30 cm above ground level. Great care was taken to keep the tripod away from prominent outcropping of rocks that could have produced anomalously distorted field because of their geometry. Before the magnetic measure itself, the tripod covered with a sheet of paper had been set horizontal through a spirit level and the sun shadow was drawn at a precisely known time in order to determine the azimuth of the geographic North. Then, the sun shadow device was substituted by the magnetometer for tracing the direction of the magnetic North. The magnetometer had been enclosed inside a 8 cm cubic box in order to determine both declination and inclination of the ambient magnetic field, together with its intensity after calibration in a magnetic observatory. Practically, one of the horizontal components (Y) was made equal to zero, the other (X) being therefore equal to the horizontal magnetic component H and indicating the direction of the magnetic north. By reading the value of the vertical component Z, it was easy to calculate both magnetic inclination and field intensity.

The calibration of the magnetometer was made at the Chambon la Forêt Observatory (France) by operating in the same manner as at Mount Etna. Ten measurements were carried out around the observatory house where *D*, *H* and *Z* are recorded (Table 1). *D* was determined as indicated above and compared to the true value of *D* at the observatory, the difference (0.04°) being within the instrumental error. Similarly, the horizontal (Xa) and vertical (Za) components were read on the fluxgate magnetometer and compared to the values of the observatory (*H* and *Z*, nT). Coefficients × 25.2 and × 25.08, respectively, were then used to convert the values of Xa and Za into *H* (nT) and *Z* (nT). These values were subsequently used for calculations of the magnetic inclination (*I*) and total field intensity (*F*).

The precision of the method was estimated through the dispersion of measurements made at Chambon la Forêt (Table 1). It was found to be around 0.2° on direction (alpha 95 equal to 0.1°) and 50 nT on intensity. This precision is considered sufficient for measurements on a volcanic area where the geomagnetic gradient may be in excess of 1000 nT/m (see also Table 3). A source of error difficult to estimate lies in the stability of the tripod during sun shadow and magnetic

Table 1
Calibration of the three component flux gate magnetometer at the Chambon La Forêt observatory (France)

SITE	Za	*Z* (nT)	Xa	*H* (nT)	*F* (nT)	*I* (°)	*D* (°)	*k*	α 95 (°)
CHAM 1	1680	42134	832	20966	47063	63.54	−2.76		
CHAM 2	1687	42310	829	20891	47186	63.72	−3.36		
CHAM 3	1688	42335	830	20916	47220	63.71	−3.80		
CHAM 4	1685	42260	835	21042	47209	63.53	−3.18		
CHAM 5	1686	42285	833	20992	47209	63.60	−3.31		
CHAM 6	1686	42285	835	21042	47231	63.54	−3.48		
CHAM 7	1687	42310	828	20866	47175	63.75	−3.01		
CHAM 8	1685	42260	837	21092	47231	63.48	−2.99		
CHAM 9	1688	42335	825	20790	47164	63.85	−3.65		
CHAM 10	1684	42235	827	20840	47097	63.74	−3.02		
Mean (10)		42275		20944	47178	63.65	−3.26	183950	0.10

Za, Xa: values of vertical and horizontal components read on the magnetometer. *Z* (nT), *H* (nT), *F* (nT): values converted in nT (see text, Section 3).

measurements. However, the difference between several measurements made at the same point is usually of a few tenths of a degree on direction and lower than a few tens of nT on intensity. Diurne variations of the Geomagnetic field were considered as negligible, nevertheless, it was checked from observatory records that no magnetic storm occurred during measurements.

4. Results and discussion

Before discussing the results, it must be pointed out that the dispersion of declination (D) and inclination (I) is not comparable, and is dependent upon the local inclination as $\cos(I)$. For instance, to an inclination value of around 55°, a cylindrical dispersion of 1° corresponds to 1° on inclination and about 2° on declination. This is the reason for which the scales on D and I are different in Fig. 3.

Tables 2 and 3 summarize the results obtained at Mount Etna in 1989. As expected, measurements made on sedimentary area away from the volcano (Table 2) show a very little dispersion, so that only five points per site were necessary. The average of 15 measurements (three sites) is $D = 0.35°$, $I = 52.96°$, $F = 44106$ nT. These values are in excellent agreement with those interpolated from the International Geomagnetic Reference Field (IGRF) and believed to be representative of the mean geomagnetic field in Sicily in July 1989.

The average of the 12 'volcanic' sites on Mount Etna is very close to that of the three 'sedimentary' sites, with a mean 'volcanic field' of $D = 0.3°$, $I = 52.6°$, $F = 44{,}006$ nT (Table 3 and Fig. 2). It may be concluded, therefore, that the volcanic pile has no global effect on the average direction and intensity of the geomagnetic field.

Within each site reported on Table 3, the average direction and intensity show, in general, relatively small deviations with respect to the mean geomagnetic field (less than 2° on direction and less than 3% on intensity, see Figs. 1 and 2). Most of the sites show greater dispersion on inclination than on declination. The dispersion of the results is comparable to that observed when using an equivalent number of archeomagnetic samples (Tanguy et al., 2003), and could explain most of the differences in direction from one sample to

Table 2
Measurements of the geomagnetic field in Sicily on sedimentary terrain around Mount Etna (see Fig. 1)

Site	Za	Z (nT)	Xa	H (nT)	F (nT)	I (°)	D (°)	k	α 95 (°)
NAXO 1	1398	35062	1056	26611	44017	52.80	0.36		
NAXO 2	1400	35112	1056	26611	44057	52.84	0.37		
NAXO 3	1405	35237	1056	26611	44157	52.94	0.45		
NAXO 4	1397	35037	1057	26636	44012	52.76	0.67		
NAXO 5	1399	35087	1057	26636	44052	52.80	0.91		
Mean (5)		35107		26621	44059	52.83	0.55	260530	0.12
MALE 1	1402	35162	1052	26510	44036	52.99	0.42		
MALE 2	1400	35112	1053	26536	44011	52.92	−0.09		
MALE 3	1405	35237	1050	26460	44066	53.10	−0.22		
MALE 4	1401	35137	1052	26510	44016	52.97	−0.12		
MALE 5	1405	35237	1049	26435	44051	53.12	0.16		
Mean (5)	35177			26490	44036	53.02	0.03	205620	0.14
GERB 1	1402	35162	1049	26435	43991	53.06	0.94		
GERB 2	1413	35438	1051	26485	44242	53.23	0.43		
GERB 3	1406	35262	1058	26662	44207	52.91	0.38		
GERB 4	1413	35438	1057	26636	44332	53.07	0.40		
GERB 5	1411	35388	1060	26712	44338	52.95	0.13		
Mean (5)		35338		26586	44222	53.04	0.46	139700	0.17
General mean (15)					44106	52.96	0.35	109780	0.11

Table 3
Measurements of the geomagnetic field on 12 selected sites within Mt. Etna volcano (see Fig. 1)

Site	*Z* (nT)	*H* (nT)	*F* (nT)	σF (nT)	*I* (°)	*D* (°)	*k*	α 95 (°)
1792 1	35990	27115	45061		53.01	−0.18		
1792 2	35087	24620	42863		54.94	−0.88		
1792 3	36817	27166	45755		53.58	−0.12		
1792 4	34886	26410	43755		52.87	2.06		
1792 5	36466	26611	45144		53.88	−0.90		
1792 6	35112	26460	43966		53.00	1.63		
1792 7	35739	26636	44573		53.30	2.32		
1792 8	35112	26989	44286		52.45	2.31		
1792 9	34836	26863	43991		52.36	3.46		
1792 10	34610	27065	43936		51.98	0.25		
Mean (10)	35466	26594	44329	786	53.15	1.01	4153	0.69
“1651” 1	36366	24394	43790		56.15	1.01		
“1651” 2	35739	26183	44304		53.77	1.82		
“1651” 3	30873	26107	40432		49.78	0.42		
“1651” 4	31475	24872	40117		51.68	2.03		
“1651” 5	34209	24948	42340		53.90	−1.63		
“1651” 6	35187	24091	42644		55.60	−2.08		
“1651” 7	38071	24620	45339		57.11	−0.05		
“1651” 8	35087	23638	42306		56.03	0.89		
“1651” 9	34435	27090	43814		51.81	−1.42		
“1651” 10	31827	25704	40910		51.07	2.29		
Mean (10)	34327	25165	42563	1648	53.70	0.35	915	1.46
1865 1	36592	26838	45379		53.74	−1.36		
1865 2	36466	27770	45837		52.71	−2.67		
1865 3	37545	26636	46034		54.65	−3.90		
1865 4	37043	26788	45714		54.13	3.54		
1865 5	36642	28400	46360		52.22	1.95		
1865 6	36868	25855	45030		54.96	−1.53		
1865 7	36291	26132	44720		54.24	−0.81		
1865 8	35388	26687	44323		52.98	−2.82		
1865 9	32729	25553	41523		52.02	−0.18		
1865 10	34134	26636	43297		52.03	−1.02		
Mean (10)	35970	26730	44814	1396	53.39	−0.87	2191	0.95
“1566” 1	35915	25956	44312		54.14	2.04		
“1566” 2	34335	28224	44446		50.58	0.29		
“1566” 3	33883	28904	44537		49.53	0.78		
“1566” 4	35388	26510	44217		53.16	0.21		
“1566” 5	33808	27065	43307		51.32	−0.53		
“1566” 6	34585	28426	44768		50.58	2.14		
“1566” 7	32754	27644	42861		49.84	1.25		
“1566” 8	37194	26662	45763		54.37	0.35		
“1566” 9	31902	25729	40984		51.11	0.09		
“1566” 10	33306	25704	42071		52.34	2.33		
Mean(10)	34307	27082	43708	1348	51.70	0.89	1959	1.00
1646 1	37219	26964	45960		54.08	2.64		
1646 2	34385	27594	44088		51.25	3.41		
1646 3	33758	28652	44278		49.68	−2.79		
1646 4	36592	28375	46304		52.21	−1.45		
1646 5	35664	27292	44908		52.58	0.33		

Table 3 (*Continued*)

Site	Z (nT)	H (nT)	F (nT)	σF (nT)	I (°)	D (°)	k	α 95 (°)
1646 6	37419	28778	47206		52.44	0.44		
1646 7	35262	27896	44963		51.65	1.30		
1646 8	34661	26788	43806		52.30	5.92		
1646 9	33958	24847	42078		53.81	4.10		
Mean (9)	35435	27465	44833	1437	52.25	1.51	1420	1.24
1329 1	35363	27493	44793		52.14	0.53		
1329 2	35764	27317	45003		52.63	1.38		
1329 3	35814	27014	44860		52.97	1.48		
1329 4	35839	27216	45002		52.79	1.53		
1329 5	37018	27014	45827		53.88	2.27		
1329 6	37068	26788	45734		54.15	−1.04		
1329 7	35413	27166	44632		52.51	2.19		
1329 8	36968	26687	45594		54.17	0.52		
1329 9	37369	28022	46709		53.13	1.19		
1329 10	36918	25452	44841		55.42	−0.45		
Mean (10)	36353	27017	45293	618	53.38	0.97	4645	0.65
1669 1	33708	28904	44403		49.39	0.23		
1669 2	32203	26939	41985		50.09	3.04		
1669 3	34084	27518	43806		51.08	2.10		
1669 4	34936	26611	43917		52.70	1.16		
1669 5	33055	26989	42674		50.77	1.37		
1669 6	33407	27770	43442		50.26	1.11		
1669 7	34510	26611	43579		52.36	3.44		
1669 8	34962	28476	45091		50.84	1.42		
1669 9	34635	27065	43956		52.00	0.39		
1669 10	31952	25805	41071		51.08	2.37		
Mean (10)	33745	27269	43386	1122	51.06	1.66	4287	0.68
"1595" 1	34234	25704	42810		53.10	−2.19		
"1595" 2	37068	27922	46408		53.01	0.85		
"1595" 3	33231	26107	42260		51.85	−1.91		
"1595" 4	34886	26359	43725		52.93	−0.46		
"1595" 5	35664	26712	44558		53.17	0.27		
"1595" 6	35839	25704	44104		54.35	1.47		
"1595" 7	36366	26561	45033		53.86	−0.06		
"1595" 8	39677	26813	47887		55.95	0.89		
"1595" 9	35538	26384	44262		53.41	−1.66		
"1595" 10	37118	26032	45337		54.96	−0.18		
Mean (10)	35962	26430	44630	1568	53.66	−0.32	3404	0.76
"1536" 1	36416	24242	43747		56.35	0.24		
"1536" 2	33858	27040	43330		51.39	−3.92		
"1536" 3	34008	27166	43526		51.38	−1.17		
"1536" 4	35538	27014	44640		52.76	1.58		
"1536" 5	34209	26662	43372		52.07	0.14		
"1536" 6	35889	26359	44529		53.70	−0.21		
"1536" 7	35614	27140	44776		52.69	1.42		
"1536" 8	33933	25780	42615		52.78	−0.02		
"1536" 9	32955	26334	42184		51.37	1.36		
"1536" 10	36943	27166	45856		53.67	−0.65		
Mean (10)	34936	26490	43844	1043	52.83	−0.13	2001	0.99

Table 3 (*Continued*)

Site	Z (nT)	H (nT)	F (nT)	σF (nT)	I (°)	D (°)	k	α 95 (°)
1843 1	33356	27065	42955		50.94	−0.97		
1843 2	32554	26737	42126		50.60	−3.05		
1843 3	32629	27443	42635		49.93	−1.57		
1843 4	35288	26611	44197		52.98	−2.14		
1843 5	34911	25956	43503		53.37	−2.82		
1843 6	33708	26636	42962		51.68	−0.27		
1843 7	35589	25124	43563		54.78	−3.42		
1843 8	36190	25301	44157		55.04	−4.20		
1843 9	34360	24847	42402		54.13	−1.01		
1843 10	34360	25855	43001		53.04	−1.39		
Mean (10)	34294	26158	43131	661	52.66	−2.06	1750	1.06
SLN 1	35689	28753	45831		51.14	−2.11		
SLN 2	36291	28854	46363		51.51	−3.04		
SLN 3	35288	29333	45887		50.26	−3.06		
SLN 4	34686	27922	44528		51.17	−2.18		
SLN 5	34535	27821	44347		51.15	−2.72		
SLN 6	33682	27670	43590		50.60	−1.51		
SLN 7	34711	27317	44171		51.80	−1.91		
SLN 8	34560	27670	44272		51.32	−2.77		
SLN 9	34911	27443	44406		51.83	−1.86		
SLN 10	35463	27770	45043		51.94	−2.12		
Mean (10)	34982	28055	44842	854	51.27	−2.33	16357	0.35
SAP 1	35062	26964	44231		52.44	−0.07		
SAP 2	33106	26284	42271		51.55	3.45		
SAP 3	35313	26107	43915		53.52	−0.14		
SAP 4	36491	23537	43424		57.18	1.31		
SAP 5	35814	25326	43864		54.73	6.46		
SAP 6	32805	27292	42673		50.24	0.19		
SAP 7	31225	27443	41570		48.69	1.42		
SAP 8	33306	25654	42041		52.40	2.39		
SAP 9	32228	27216	42182		49.82	4.15		
SAP 10	35614	27493	44991		52.33	3.40		
SAP 11	34510	26939	43779		52.02	2.79		
SAP 12	35212	26460	44046		53.08	2.34		
SAP 13	35162	26712	44158		52.78	1.51		
SAP 14	33983	25880	42716		52.71	4.47		
SAP 15	34962	27392	44415		51.92	5.18		
Mean (15)	34319	26447	43327	993	52.37	2.59	1207	1.04

another. As these differences are randomly distributed, it is likely that they result from very localized distortions of the field owing to the closest parts of the neighbouring lavas, rather than a global effect of the whole mass of the mountain.

Regarding the particular effect commonly mentioned as 'magnetic refraction' resulting in 'shallow' inclinations within the cooling flow because of its demagnetizing field (already considered by Chevallier, 1925), it was found that archeomagnetic rock samples commonly present inclinations shallower by 1 or 2° with respect to the Geomagnetic Secular Variation curve retraced through instrumental measurements (Alexandrescu et al., 1997). In the present work, however, the magnetic mean inclination value obtained from our 12 'volcanic' sites is shallower by only 0.36° with respect to that from the 3 'sedimentary' sites away from the volcano (see above, also Fig. 2).

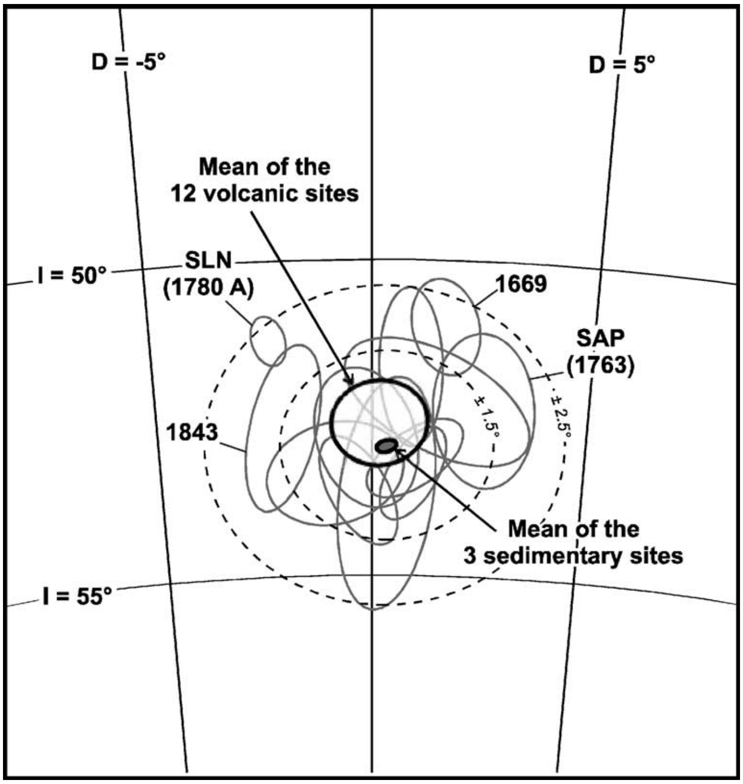

Fig. 2. Confidence ovals (bivariate statistics, Le Goff et al., 1992) of the 12 volcanic sites and their mean as compared to the mean of the three sedimentary sites.

Again, this suggests that magnetic refraction mainly results from an effect of the early magnetized parts of the cooling flow closest to the future sample, and not from the underlying older flows within the volcanic pile.

When comparing the averaged results from one site to another (Table 3 and Fig. 2), it is clear that the directions (*D*, *I*) show small, but significant differences. They have tendency to cancel one to another, so that the general mean is fairly representative of the true direction away from the volcano (see above).

Fig. 2 shows four sites whose confidence ovals do not intersect the 95% mean confidence oval, with the deviations reaching more than 1.5° of the angular difference (up to -2.7° and 2.6° on declination). The reason for these relatively high deviations is unclear, particularly for the 1843 site. The three other sites (SLN, SAP and 1669, Fig. 1) are located on the South Rift Zone (SRZ) of Mount Etna. It is possible that the dyke swarms characterizing the SRZ at shallow depth cause a larger deviation of the geomagnetic field. This view is supported by additional measurements made in 1991 along two traverses West of SLN and East of SAP. Meanwhile the SLN profile shows a rapid decrease of the anomaly westwards out of the SRZ, the SAP profile (Fig. 3), which has crossed recent and conspicuous eruptive fissures (dykes) formed during historical eruptions, shows erratic deflections of *D* peaking to 4.5°, accompanied by strong variations of *I* and *F*, although anomalies of *D*, *I*, *F*, are not necessarily correlated. One may suspect in some cases the effect of anomalous regions struck by lightning (see Section 3), however, among the 50 measurements performed along the 1 km long SAP traverse, only one clearly revealed such a para-

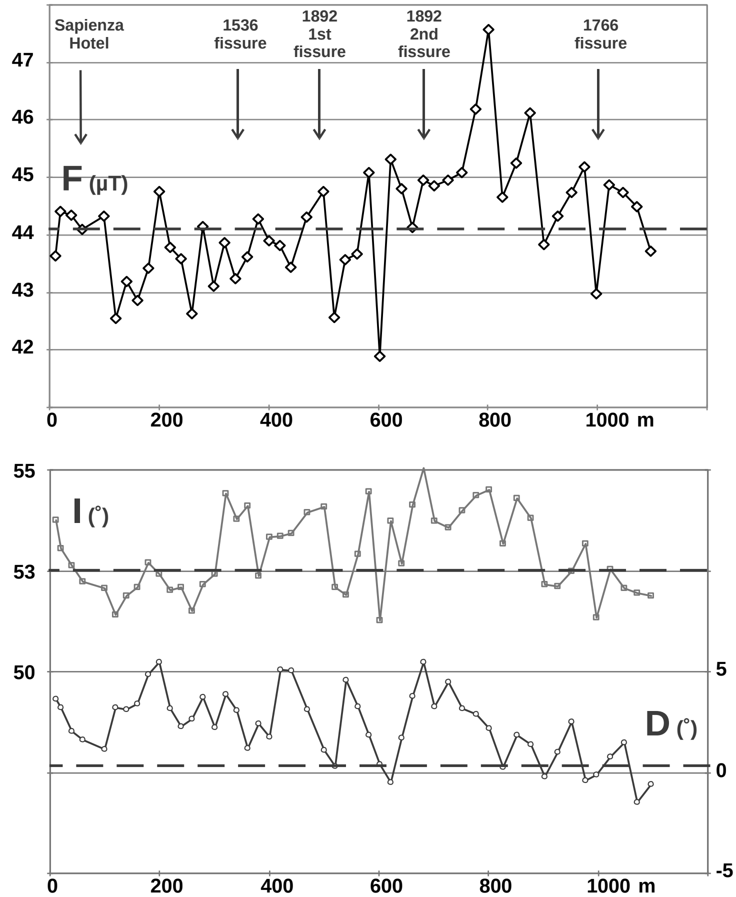

Fig. 3. Magnetic profile carried out from the Sapienza hotel eastwards (see text). The dashed lines represent values of *F*, *I*, *D* on the sedimentary sites away from the volcano.

sitic magnetization and had to be excluded from the figure.

It should be emphasized that declination *D* in the SAP profile remains almost constantly East of the true value (average 2.32°). Additional archeomagnetic sampling later performed (1999) on the 1763 flow, close to the SAP site within the anomalous zone, showed declination results about 3° East of the expected value. On the other hand, the SLN samples (1780 A site in Tanguy, 1980) give $D = -18.2°$, as compared to −16.2° obtained by averaging all the 1780 samples which include three other sites several kilometers away. On the present Fig. 4 it may be seen that the discrepancies disappear when making a correction of +2.7° (1780 A site) and −2.6° (1763 site), accordingly to the difference observed in the present work. The 1669 site is also improved by making a correction in the same manner, particularly on inclination. For the other sites there is no significant difference and the shape of the secular variation curve remains unaltered at the archeomagnetic precision level.

It is clear that local distortion of the Geomagnetic Field over volcanic terrains may affect the archeomagnetic results. However, the resulting bias can be minimized by sampling several widely distributed sites on the various lava flows of the same eruption, or at least by sampling sites over several tens of meters on the same volcanic unit.

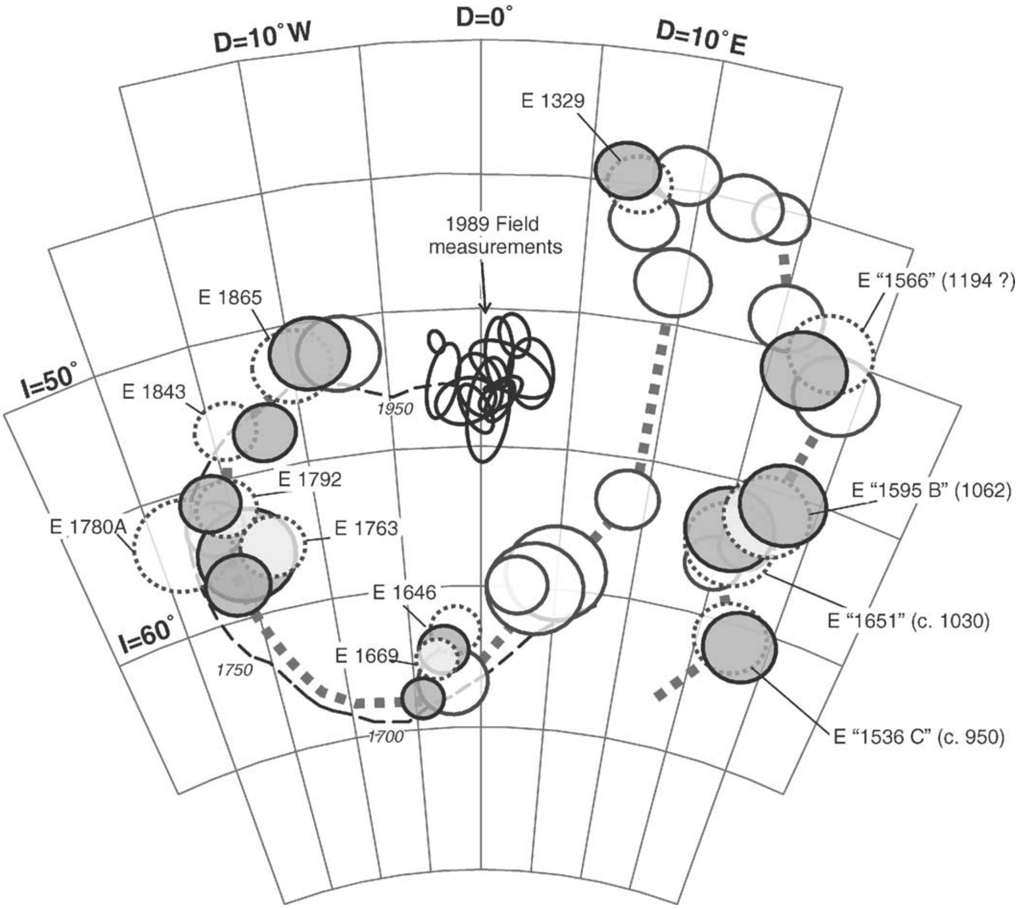

Fig. 4. Archeomagnetic curve from Etna historical lavas (modified from Tanguy et al., 2003). For the various sites studied in the present work are reported the Alpha 95 confidence circles of the paleomagnetic directions before (dashed circles) and after correction (shadowed circles) of the deviations indicated in Fig. 1. Note that for the 1780 flow, only the 1780 A site is indicated.

5. Conclusions

Our main conclusions may be summarized as follows:

(1) The volcanic edifice of Mount Etna has no global effect on either direction or intensity of the geomagnetic field, the results averaged over a dozen of sites within the volcanic edifice being almost identical to those of measurements made away from the volcano.
(2) From site to site, however, significant small distortions may be noticed. Such distortions usually do not exceed $\pm 1.5^\circ$ on direction and ± 1500 nT on intensity. This is less than 3% of the total field intensity (44,000 nT circa).
(3) At four sites, three of them located within the South Rift Zone of the volcano, a larger deflection of the direction is observed, although still remaining within less than 3° of the general mean. Such a deflection may be related to the shallow swarms of dykes characterizing the rift zone.

These conclusions are somewhat different from those of Baag et al. (1995) in Hawaii and Valet and Soler (1999) in Canaries, who found considerably larger variations. However, these authors seem to have emphasized the role played by topographic effects and did not take into account possible disturbances due to lightning. Instead we made our measurements in the same manner as rock sampling carried out for careful archeomagnetic work, i.e. avoiding any prominent feature or outcrop suspected to present unusual magnetic anomaly or to have been struck by lightning. This particular approach could very well explain the differences observed. It shows that accurate results can be obtained when using volcanic rocks, provided that sampling is extended over at least several tens of meters. The best guarantee is offered by using several sites distributed along the same volcanic unit.

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