Geochemistry, Geophysics, Geosystems®

RESEARCH ARTICLE
10.1029/2023GC011319

Key Points:

- Paleomagnetic data from Mt. Etna does often not reproduce the known geomagnetic field well
- Local magnetic anomalies explain bias in paleomagnetic data as function of topography
- Optimizing the paleomagnetic sampling strategy may suppress this bias in paleomagnetic data

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

R. Meyer,
r.meyer@uu.nl

Citation:

Meyer, R., & de Groot, L. V. (2024). Local magnetic anomalies explain bias in paleomagnetic data: Consequences for sampling. *Geochemistry, Geophysics, Geosystems*, *25*, e2023GC011319. https://doi.org/10.1029/2023GC011319

Received 31 OCT 2023
Accepted 9 APR 2024

Local Magnetic Anomalies Explain Bias in Paleomagnetic Data: Consequences for Sampling

Romy Meyer[1] and **Lennart V. de Groot**[1]

[1]Paleomagnetic Laboratory Fort Hoofddijk, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands

Abstract Volcanic rocks are considered reliable recorders of past changes in the Earth's magnetic field. Recent flows, however, sometimes fail to produce the known magnetic field at the time of cooling. Previous research on Mt. Etna suggests paleomagnetic data might not be accurately recorded. Here we test the accuracy of paleomagnetic data obtained from Mt. Etna lavas by comparing paleomagnetic data from historical flows to direct measurements of the magnetic field above the current topography. The inclinations and intensities in both data sets are biased toward lower values, while there is no such trend for the declination. Inclinations are on average 2.9° lower than expected; intensities are on average 8.8 μT lower. The deviations from the expected values depend on the height above the flow. Moreover, the inclinations and intensities vary as a function of topography. Both are higher above ridges and lower in gullies; the variations within a site are up to 14.1° in inclination and 12.9 μT for intensity. To suppress this paleomagnetic data bias it is important to take samples several meters apart and from different parts of the flow whenever possible. While this leads to a higher degree of scatter in paleodirections, the results better represent the Earth's magnetic field at the time of cooling. This emphasizes the importance of reporting paleomagnetic sampling strategies in detail.

Plain Language Summary Paleomagnetic data from lavas is routinely used in the Earth Sciences to for example, reconstruct the past behavior of the Earth's magnetic field, or make models of past plate motions. Very young flows for which the ambient magnetic field at the time of cooling is known, however, sometimes fail to produce the known reference values. Lava flows from Mt. Etna are extensively studied in the past and the paleomagnetic data obtained does often not agree with the known magnetic field value in which the lavas cooled. Here we show that the topography of volcanic terrain may influence the magnetic signal of new, overlying, flows, and we make recommendations for sampling strategies that suppress these terrain effects as much as possible.

1. Introduction

For decades magnetic signals from volcanic rocks have been used as a source to study the ancient behavior of the Earth's magnetic field. Volcanic rocks obtain a natural remanent magnetization which reflects the direction and intensity of the ambient geomagnetic field present during cooling. Paleomagnetic data from well-dated flows (e.g., historical observations, radiocarbon dating) are used to create regional paleosecular variation (PSV) curves, and models that describe the global behavior of the Earth's magnetic field through time. With PSV curves, lava flows from unknown ages may be dated to improve the knowledge of eruption frequency, which is vital for volcanic hazard assessment. An important prerequisite of the reliability of these models is the accuracy of the input data; volcanic rocks are often considered to be excellent recorders of the Earth's magnetic field. Of paleomagnetic data obtained from recent volcanic rocks, however, the inclination and intensity regularly fail to produce their known field values (see overview of 1960 Kilauea flow in Cromwell et al., 2015; Urrutia-Fucugauchi et al., 2004; Pavón-Carrasco et al., 2014) or their reference value from the International Geomagnetic Reference Field (IGRF (Alken et al., 2021)).

Recent lavas from Mt. Etna, Italy, have been extensively studied in terms of paleodirections and paleointensities. As a result there is a large paleomagnetic dataset, which is regularly inconsistent with the reference values. Moreover, the scatter in paleodirections from a single lava flow is often inexplicably large (Speranza et al., 2006), with inclinations around 2° too shallow (Calvo et al., 2002; Incoronato et al., 2002; Lanza et al., 2005; Rolph, 1997; Rolph & Shaw, 1986; Tanguy et al., 1985, 1999, 2003). Likewise, paleointensities are found to be generally too low (Biggin et al., 2007; L. V. de Groot et al., 2012, 2013; Rolph & Shaw, 1986; Sherwood, 1991). These deviations in both directions and intensities of Mt. Etna data have been attributed to arise from various explanations. Rolph and Shaw (1986) and Rolph et al. (1987) mention "magnetic refraction," that is, the deflection of directions are explained due to some parts of the material being already magnetized while the rest of the material is still cooling (Tarling et al., 1986; Tanguy, 1990; Schurr et al., 1985). This effect is commonly only described and extensively studied in archeomagnetic studies (Schurr et al., 1985). Hill and Shaw (1999) and Biggin et al. (2007) consider "multi-domain behavior" as possible cause of the observed inaccuracy in paleointensity results: "sagging" in Arai diagrams of Thellier-type experiments is explained by the presence of multi-domain (MD) grains, leading to inaccurate interpretations of these diagrams. Calvo et al. (2002) and L. V. de Groot et al. (2013) suggest "transdomain processes" to occur in paleointensity experiments, which means that during heating there is a reorganization of the magnetic domain structure in PSD grains which results in a loss of NRM. Lastly, Hill and Shaw (1999), Biggin et al. (2007), and L. V. de Groot et al. (2013) point to differences between the natural and the laboratory cooling rates for lower than expected paleointensities. In contrast to these rock-magnetic concepts pertaining to the behavior of the magnetic particles during remanence acquisition, the bias in paleomagnetic data might be explained by the presence of local magnetic anomalies, that is, a local disturbance of the magnetic field induced by the magnetic field from underlying lava flows.

Mt. Etna is characterized by irregular topography; virtually all lava flows are classified as a'a type and the terrain is rough with rubble up to boulder size on the surface (Calvari & Pinkerton, 1998; Kilburn & Lopes, 1988). The lava flow morphology is characterized by channels bounded by levees, which are topographically higher ridges (Hulme, 1974; Tarquini et al., 2012). Mt. Etna lavas are also strongly magnetized. The remanent magnetization of specimens at Mt. Etna sometimes exceeds 20 A/m and there is a large deviation between sun and magnetic compass readings (Speranza et al., 2006). The earliest volcanic products of Mt. Etna are dated around 500 ka ago (Branca et al., 2011), therefore all lava flows must be of normal polarity. Previously, measurements of the ambient geomagnetic field above the surface of lava flows were performed with a fluxgate magnetometer on Hawaii (Baag et al., 1995), La Palma and Tenerife (Valet & Soler, 1999) and on Mt. Etna (Tanguy & Le Goff, 2004). Baag et al. (1995) found a maximum declination deflection from the IGRF of $-10.7°$ and $-21.1°$ for inclination, Valet and Soler (1999) report deflections of up to 15° for directions and 20% for intensity. Both attribute these variations in the magnetic field to local magnetic anomalies arising from the highly magnetized underlying terrain. Baag et al. (1995) also developed two-dimensional models of the inclination above various topographic features. These predict different inclination deflections depending on the latitude of the site and the orientation and dip of the slope with respect to the ambient geomagnetic field. The models predict negative inclination anomalies in topographic lows in the Northern Hemisphere but positive anomalies in gullies the Southern Hemisphere. According to their theory, declination variations only depend on the location of the site with respect to the volcano: negative deviations are expected on the Eastern side of the volcano, and positive ones on the Western side. In contrast, variations in inclination also depend on the latitude and the exact shape of the gully or channel causing the local magnetic anomaly (Baag et al., 1995). They did not predict the influence of magnetic anomalies on the intensity signal. Valet and Soler (1999) suggest that sampling over a large distance would average out the anomalies, Baag et al. (1995) also suggests this to remove a possible declination bias but according to their models this will not always work for the inclination bias. On Mt. Etna, Tanguy and Le Goff (2004) followed an almost similar procedure and measured the geomagnetic field around 10 times above 12 different sites, while avoiding obvious terrain features. The average of their 124 measurements was close to the expected geomagnetic field. However, when comparing the results on site level there are differences and the averages for their sites show small deviations from the expected geomagnetic field (±3% in intensity and ±1.5° in direction). Tanguy and Le Goff (2004) conclude that there may be some local distortion of the geomagnetic field influencing archeomagnetic results, perhaps caused by dyke swarms in the South Rift Zone of Mt. Etna, but by sampling broadly (i.e., over several widely distributed lava flows of the same eruption) this effect may be minimized. However, it is often not possible to sample similarly aged lava flows on different flanks of a volcano. Furthermore, during measuring they avoided local terrain features, which a future lava flow will not, and this may have improved their results with respect to the studies of Baag et al. (1995), Valet and Soler (1999), and ours.

Here we test whether the strongly magnetized terrain of Mt. Etna influences the ambient magnetic field directly above it. First, we compile an overview of paleomagnetic literature data to characterize a potential bias in the data, while also paying attention to which sampling strategy is used. Second, we add new paleomagnetic directional data from 12 sites sampled from seven different historical flows. Third, we measure the magnetic field above four recent lava flows of Mt. Etna, three of which were also sampled for paleomagnetic measurements. Instead of several measurements spread out over a lava flow, the measurements are taken in high detail along the length of several paths with varying topography to observe the magnetic field a possible future overlying flow would record. Combining these datasets allows us to characterize the expression of local magnetic anomalies in paleomagnetic measurements, quantify the impact on paleomagnetic statistics, and provide recommendations for paleomagnetic sampling strategies in rough volcanic terrain.

2. Paleomagnetic Data

2.1. Data From Previous Studies

To characterize a possible bias in paleomagnetic data from Mt. Etna, we compiled an overview of all paleomagnetic results reported by previous studies of lava flows younger than 1850 CE. Older flows were not taken into account because the results will be compared with the expected values according to geomagnetic models; prior to 1850CE direct full vector measurements of the Earth's magnetic field are not available. The directional dataset (Table S1 in Supporting Information S1) consists of the declination, inclination and corresponding precision parameter (k) and α_{95} of 14 flows, which were deposited between 1853 and 1983. The other dataset (Table S2 in Supporting Information S1) consists of the paleointensities of 20 flows between 1853 and 2002, including their standard deviation and paleointensity method used.

How samples are generally obtained in the field, that is, the sampling strategy, differs between studies. Studies aiming to produce paleodirections often take samples spread out over a flow, and measurements are deemed reliable when there is a low scatter, a small α_{95}, and/or a high k (Fisher, 1953). For paleointensity studies samples are sometimes taken closer together to ensure homogeneity between the samples (L. V. de Groot et al., 2012, 2013), and results are found reliable when the standard deviation of the paleointensity results is low. These sampling strategies are, however, not universally defined and not all studies report their sampling strategy in detail. Previous studies on Mt. Etna that do report their sampling strategies or describe the sampled flow are: Tanguy et al. (1985, 1999, 2003), who use the "big sample method," taking samples spread out over a larger area. In contrast, Rolph (1997), Calvo et al. (2002), and Biggin et al. (2007) take their samples from top to bottom at one location of one single flow. The 1971 flow of Rolph (1997) was 2 m thick, flow thickness varied for Calvo et al. (2002) between 50 cm for the 1910 flow and up to 6 m for the 1928 flow. The samples of Biggin et al. (2007) were taken between 10 and 235 cm from the base of the flow. For intensity Calvo et al. (2002) sampled the 1928 flow at three different sites. Lastly, L. V. de Groot et al. (2012, 2013) used closely spaced drill cores, 8–12 samples taken less than 1 m of each other to ensure sampling homogeneity. L. V. de Groot et al. (2013) also sampled at different vertical levels within a lava flow, if known Table S2 in Supporting Information S1 includes the distance to the top and base of the sampled lava flow. Samples of L. V. de Groot et al. (2012)were obtained 0.5–1.5 m below the top of the flow.

2.2. Directional Data From Recent Flows

To complement the existing paleomagnetic data set, we sampled 12 new sites (Figure 1, named ET) from seven historical flows with ages between 1865 and 2002 during a fieldwork in April 2016. Flow 1923, 1971, and 2002 were sampled twice at different locations and flow 1983 was sampled at three different locations. Some sites were sampled at the same location as in L. V. de Groot et al. (2013) and most samples were taken along road cuts. For each site, standard paleomagnetic cores (2.5 cm in diameter, up to 10 cm in length) were taken using a petrol powered drill. Cores were drilled several meters apart, at different heights in the flow, and differed in borehole orientations. To orientate the cores the use of a sun compass is preferred to avoid the influence from the surrounding magnetized rock. Unfortunately, the weather did not permit the use of a sun compass during the fieldwork. Instead the samples were oriented using a magnetic compass and readings were corrected for the current declination of the IGRF.

Between four to 10 cores per site, depending on the amount of cores available, were selected for paleodirection experiments. Four samples per site were thermally demagnetized in 11 temperature steps: 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600°C and measured on a 2G cryogenic magnetometer. Some samples were magnetically so strong that they exceeded the measurement range of the magnetometer, and could not be interpreted. A further four to nine samples were subjected to alternating field demagnetization experiments. Because the samples were strongly magnetized they were sliced in half (A and B specimens), their NRM approximately at alternating field step 0 was in between 0.8 and 13.5 A/m and on average 4.1 A/m (Table S9 in Supporting Information S1). The A and B specimens should have the exact same paleomagnetic result, differences between them can be attributed to

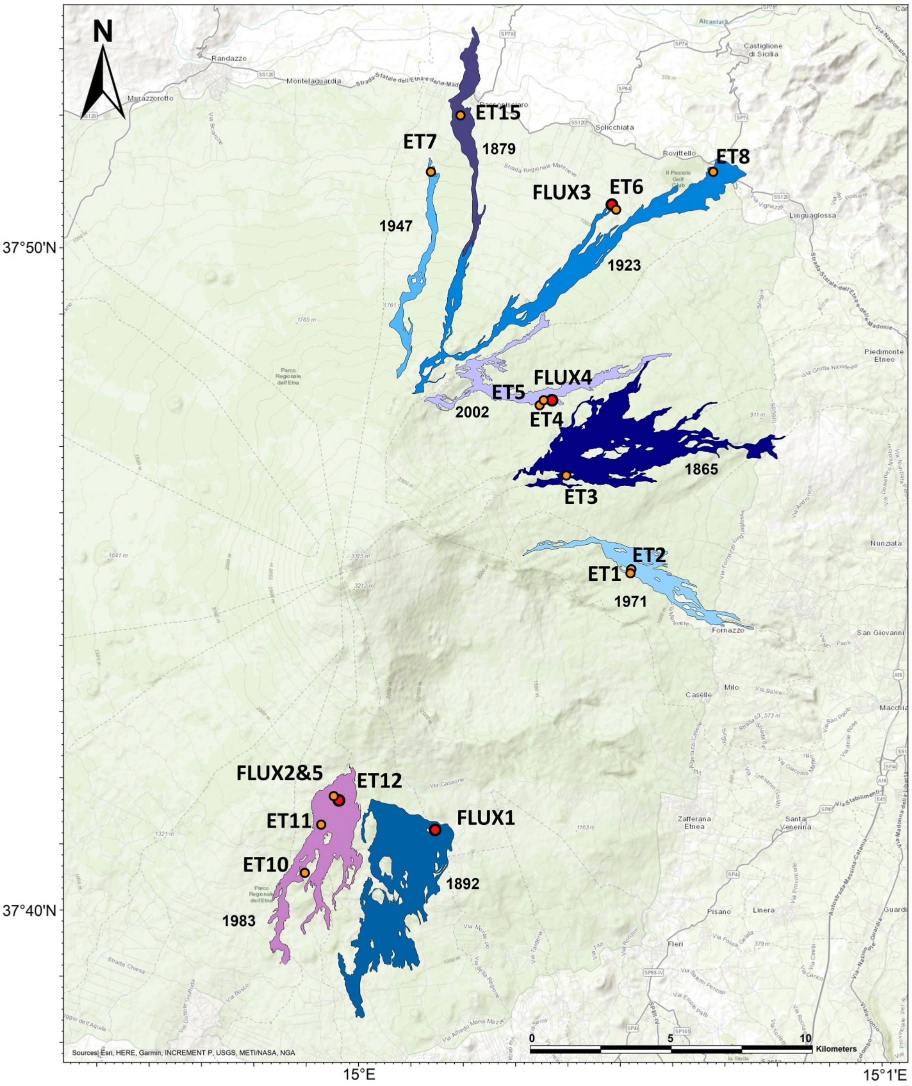

Figure 1. Sampling locations on Mt. Etna, Sicily, Italy. ET sites are where paleomagnetic samples were taken and FLUX are AnomalyMapper measurement sites. Outlines of lava flows from Branca et al. (2011).

measurement or sample orientation errors in the machine. The samples were demagnetized in a robotized 2G DC-SQUID magnetometer (Mullender et al., 2016) with stepwise increasing alternating fields of 2.5, 5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 100, 150, 225, and 270 mT. All demagnetization results were analyzed in paleomagnetism.org (Koymans et al., 2016). Afterward, site mean directions were calculated using Fisher statistics (Fisher, 1953) and the outliers are identified in the VGP distribution with the fixed 45° cut-off (Koymans et al., 2016). All other samples were retained for calculating site means (Figure 2; Table 1). The precision parameter k ranges from 23.3 to 207.8, resulting in α_{95} values between 3.2° and 7.3°. Our k-values are on average lower than those from previous studies, in existing data k-values as high as 1070 have been reported (e.g., Tanguy et al., 2003).

Some flows (1923, 1971, 1983, and 2002) were sampled at multiple sites. The directions of these sites were grouped together to calculate "age means" (Table 1). The k-values for these age means are lower than the k-values for individual sites. As the number of samples increases for the age means, the α95-values are also lower than the α_{95}-values of the individual sites. The age means averages out the effect of sites with large deviations from the expected reference values. Therefore these age means might be considered better estimates of the paleomagnetic vector, although the data from some individual sites are closer to the expected field value.

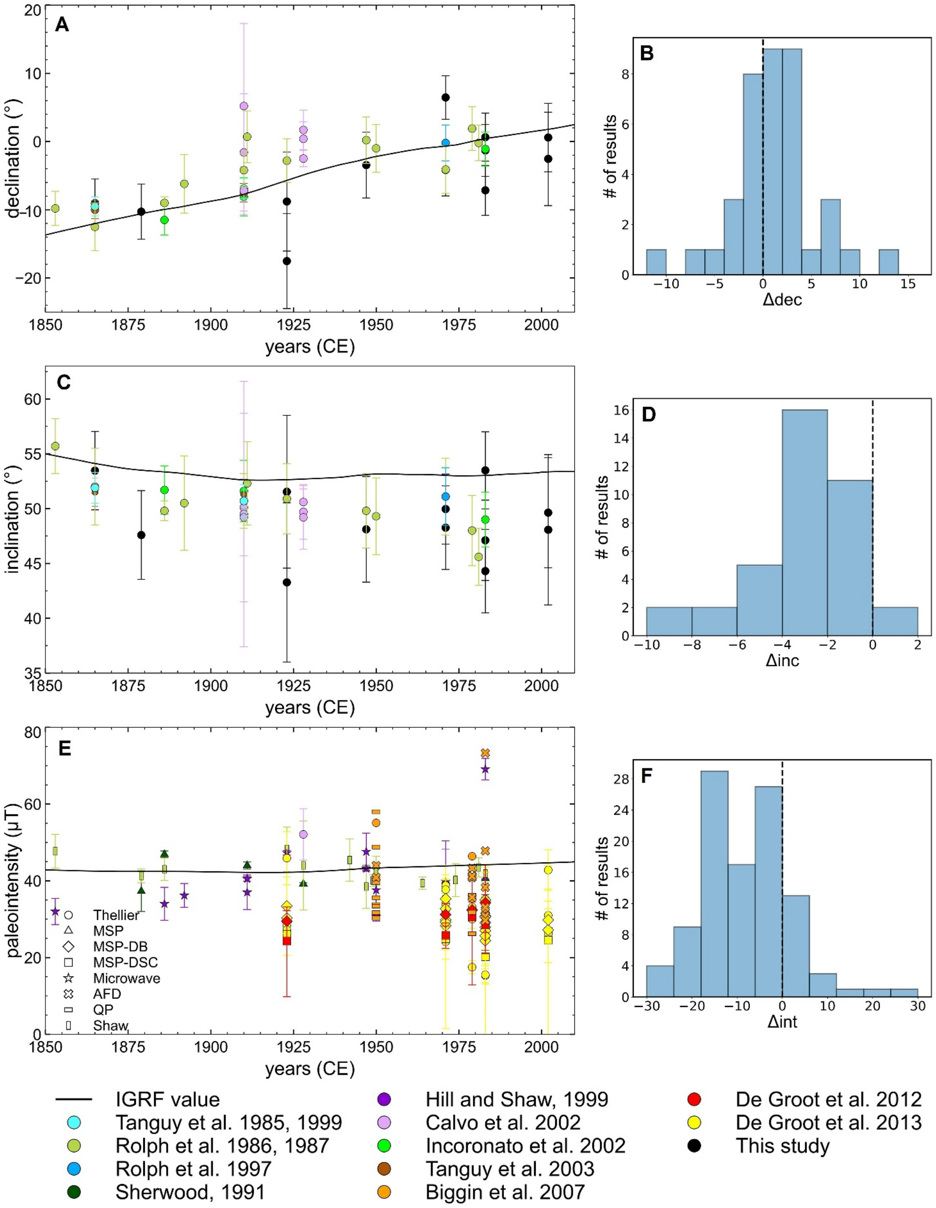

Figure 2. The (a) declination, (c) inclination and (e) intensity measurements of recent (>1850 CE) lava flows of Mt. Etna. In (a) and (c) the error bars are the corresponding α_{95} values and in (e) the error bars are the standard deviations. The histograms on the right-hand-side (b, d, f) show the paleomagnetic result—IGRF value. This is the difference (Δ) of the data points with respect to their expected field value.

2.3. Bias in Paleomagnetic Data

All above results are compared with their expected values according to the IGRF-13 model (Alken et al., 2021), or for flows prior to 1900CE with the gufm1 model (Jackson et al., 2000). The reference geomagnetic field is obtained for every lava flow at the corresponding sampling location and elevation. In older papers the GPS coordinates are not always given. In this case, the reference value was determined using a location from the same flow from another research paper, or the geological map of Branca et al. (2011). Rolph and Shaw (1986) do not provide the exact GPS coordinates but a map with sampling locations, from this map the approximate GPS coordinates and elevations were utilized. In Figure 2 the reference values are compared with the paleomagnetic data set of Mt. Etna, there is a systematic bias in the paleomagnetic data obtained. The declinations are generally in good agreement with the expected values according to the IGRF model: the median difference between the

Table 1

Sampling Sites and Directional Results This Study

Site	Year(CE)	Lat(N)	Long(E)	Elv(m)	c/n/N	Dec(°)	Inc(°)	k	α_{95}(°)
ET1	1971	37.752	15.087	1185	8/14/14	6.46	49.96	156.37	3.19
ET2	1971	37.753	15.087	1200	5/8/11	−4.16	48.26	212.62	3.81
ET3	1865	37.777	15.066	1606	10/18/20	−9.04	53.46	94.51	3.57
ET4	2002	37.796	15.062	1544	6/11/11	0.59	49.63	83.82	5.02
ET5	2002	37.795	15.057	1606	8/20/20	−2.54	48.07	23.69	6.85
ET6	1923	37.845	15.081	866	4/9/9	−17.52	51.54	55.58	6.97
ET7	1947	37.854	15.023	928	7/10/14	−3.45	48.11	101.59	4.82
ET8	1923	37.854	15.113	641	4/9/9	−8.79	43.27	51.22	7.26
ET10	1983	37.676	14.982	1423	8/20/20	0.64	53.49	86.84	3.52
ET11	1983	37.688	14.987	1671	7/12/12	−1.30	44.30	130.48	3.81
ET12	1983	37.695	14.991	1833	6/14/14	−7.15	47.11	118.88	3.66
ET15	1879	37.868	15.032	778	7/12/12	−10.28	47.59	115.65	4.05
1923_{mean}	1923	–	–	–	8/18/18	−12.81	47.49	46.01	5.15
1971_{mean}	1971	–	–	–	13/22/25	2.51	49.45	135.03	2.68
1983_{mean}	1983	–	–	–	21/46/46	−2.39	49.19	81.27	2.35
2002_{mean}	2002	–	–	–	14/31/31	−1.43	48.65	32.31	4.62
FLUX1	1892	37.687	15.019	1620	–	–	–	–	–
FLUX2	1983	37.695	14.992	1833	–	–	–	–	–
FLUX3	1923	37.845	15.081	865	–	–	–	–	–
FLUX4	2002	37.796	15.062	1539	–	–	–	–	–
FLUX5	1983	37.694	14.993	1826	–	–	–	–	–

Note. For each site the age of the flow, location and elevation (Elv) of sampling is given. The obtained directions per site are given by the parameters: (c/n/N) number of different cores/number of samples accepted/total amount of samples per site, the declination (Dec), inclination (Inc), precision parameter (k), 95% confidence interval α_{95}. Furthermore, the age means of four flows (1923,1971,1983 and 2002) are given. For the fluxgate measurement sites only the age of the flow above which was measured, the coordinates and elevation are given here.

declination of a site and the expected value ($\widetilde{\Delta}$dec) is just 0.8° too high (Figure 2b, declination—IGRF value), and the Δdec is approximately Gaussian distributed around this value. In contrast to the declination, the inclination values are skewed toward lower than expected values. Only two data points yield (slightly) higher than expected values, while the median difference ($\widetilde{\Delta}$inc) is −2.9° (Figure 2d, inclination—IGRF value). Of the flows sampled at multiple sites in this study (1923, 1971, 1983, and 2002) some results are closer to the reference value than others and there are large in between site discrepancies. For the 1923 flow, for example, there is almost a 9° declination difference between the two sites, and an 8° difference in inclination. The majority of the intensity data is also lower than the reference value: the median difference ($\widetilde{\Delta}$int) is −8.8 μT (Figure 2f, intensity—IGRF value).

There is no general correlation between the difference with respect to the reference value and the paleointensity method used. There also seems to be no relation between the observed bias and the orientation of the flank of Mt. Etna where the sampling sites were located. Furthermore, because not all studies reported their sampling strategies it is hard to compare between studies with different sampling strategies. Some that sampled from top to bottom see a slightly larger deviation at the bottom, such as the 1971 flow of Rolph (1997) and the 1983 flow of L. V. de Groot et al. (2013), the latter attributes the deviation to cooling rate differences.

3. Mapping Magnetic Anomalies

The ambient geomagnetic field, that is, the magnetic field that would be recorded by a new lava flow, was measured at five sites above four lava flows in April 2018 (Figure 1, Table S3 in Supporting Information S1). Measurements were made with the AnomalyMapper, the same device as described in B. M. de Groot and de

Groot (2019). The AnomalyMapper is equipped with a three-axial fluxgate magnetometer, the Bartington Mag-03 (B. M. de Groot & de Groot, 2019) with a measuring range between 0 and 100 μT. According to specifications the orthogonality error between the three axes is <0.5°. The temperature offset coefficient of this type is 0.6 nT per degree Celsius, leading to a negligible bias of only a few nT compared to the ambient magnetic fields of 48,000 nT measured on Mt. Etna. The AnomalyMapper was used previously in B. M. de Groot and de Groot (2019) to test the variations in declination, inclination and intensity in a grid of 10 × 11 points in an area of 20 × 22 m, at different heights above the ground. They found visible variations depending on which height above the surface the measurements were done.

We extend the dataset in B. M. de Groot and de Groot (2019) to five more sites on Mt. Etna. At each site, three "paths" were measured perpendicular to ridges and gullies to obtain the largest topographic differences possible, with measurement locations being ∼1 m apart; the three paths were 20–80 m apart up/down the slope of the lava flow (Figure S1 in Supporting Information S1). At FLUX1 to FLUX4 the paths were measured twice, with the magnetometer positioned at 100 and 180 cm above the ground. The paths of FLUX5 were measured four times at 25, 75, 125, and 175 cm above the ground (Figures S3–S16 in Supporting Information S1). In total, we measured the ambient geomagnetic field above the lava flows of Mt. Etna 1,334 times. The exact topography was obtained from the GPS sensor mounted on the magnetometer.

The AnomalyMapper uses a scope to point the magnetometer toward a reference point with a known (GPS) location (B. M. de Groot & de Groot, 2019). Due to the irregular terrain it was not always possible to see the reference point, most often in topographic lows, therefore the declination record is discontinuous for some paths. This did not affect the inclination data, as this is only dependent on the leveling of the magnetometer which is done using a tilt sensor, or the intensity data, that is the length of the total vector measured irrespective of its orientation.

3.1. Local Magnetic Anomalies

For all paths we observe major variations in declination, inclination and intensity above the lava flows. The reference field according to the IGRF-model in April 2018 was calculated for each site at the corresponding GPS coordinates and average elevation (Table 1). Here we use the results of path 2 of site FLUX3 at 100 cm height and path 1 of site FLUX5 at 125 cm height as examples (Figure 3). Of FLUX3, the variation in declination is −6.5 to 5.4°; with a median difference of −3.2° with respect to the expected IGRF-value for measurements done at 100 cm above ground. The inclination is on average closer to the IGRF-value, with a median difference of −1.5°, and varies between 46.8 and 58.7°. The intensity varies between 42.1 and 47.9 μT, with a median offset of −0.9 μT. FLUX5 was measured with most detail, and has for the measurements done at 125 cm above the ground similar large fluctuations as FLUX3 has at 100 cm. Declination varies between −4.2 and 8.7°, with a median difference of −0.9°. Inclination measurements range from 49.7 to 54.2° and the median difference is −1.3°. Finally, the intensity varies between 40.9 and 47.2 μT with a median offset from the IGRF-value of −1.5 μT. The data for all paths and sites generally show similar behavior (Figures S3–S16 in Supporting Information S1; Tables S4–S7 in Supporting Information S1). The median deviations with respect to the expected IGRF values for all paths at 100 cm (or in the case of FLUX5 at 125 cm) above ground in the dataset ranges from −5.9 to −0.9° for $\widetilde{\Delta}$dec; −2.2 to 1.1° for $\widetilde{\Delta}$inc; and −2.2 to 0.1 μT for $\widetilde{\Delta}$int.

3.2. Variations With Height Above Surface

The deviations from the expected IGRF-values are largest close to the surface and become less pronounced higher above the flow (Figure S2 in Supporting Information S1). This is most prominent in the inclination and intensity data, and less in the declination data. For all three paths of FLUX3 the standard deviation decreases when measurement height above the flow increases (Figure S2 in Supporting Information S1). This is also reflected in the $\widetilde{\Delta}$ range of values. For path 2 of site FLUX3 the range of declination values is −9.8 to 2° at 100 cm above ground and −10.7 to 1° at 180 cm, inclination values are −6.6 to 5.1° at 100 cm above ground and −4.5 to 3.3° at 180 cm, and for the intensity the variation is −3.1 to 2.7 μT at 100 cm and only −2.4 to 1.3 at 180 cm (Figure 3). Site FLUX5 was measured at four different heights above the surface, with the lowest being at 25 cm above ground and the highest at 175 cm. The largest spikes in the measurement data are at 25 cm height, the level closest to the lava flow (Figure 3). For path one of FLUX5, the $\widetilde{\Delta}$dec range decreases from −12.5 to 8.0° at 25 cm to −7.1 to 2.8° at 175 cm. For the inclination the range at 25 cm above the flow is −7.1 to 1.8° and only −3.1 to 1.1° at

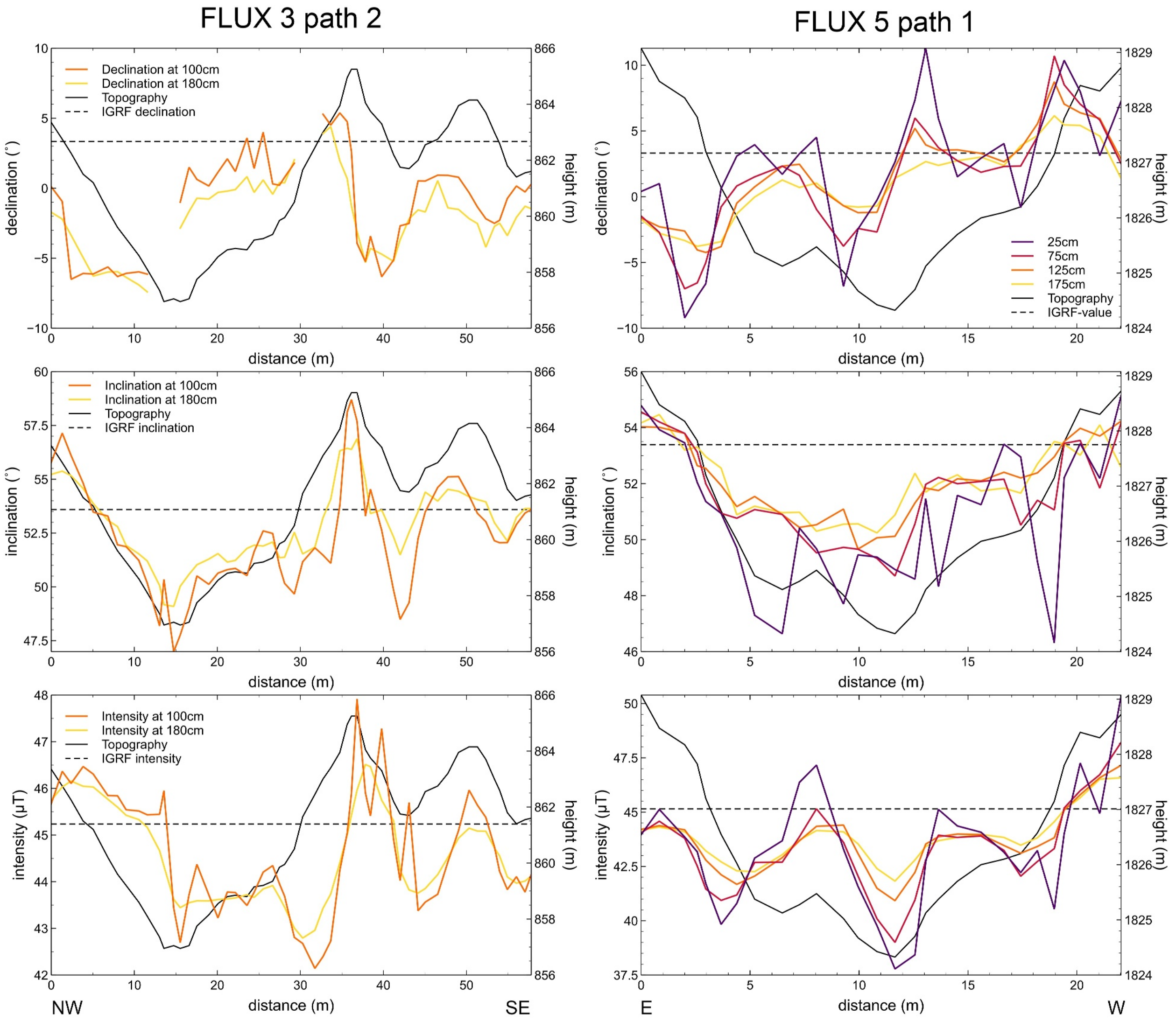

Figure 3. Fluxgate measurements of site FLUX3, path 2 (left) and FLUX5, path 1 (right). The variation in declination (top) does not show a clear correlation with topography (black line). The variations in inclination (middle) and intensity (bottom) correlate with the topography variations. Measurements closest to the ground surface (100 cm for FLUX3 and 25 cm for FLUX5) have the largest variation.

175 cm. The intensities vary from −7.4 to 5.2 at 25 cm, and from 3.3 to 1.4 μT at 175 cm above the flow. As the intensity of the magnetic field decays with the power of three as function of distance to its source, the observed gradients as function of height above the flow imply that the source of the local magnetic anomalies must be close to the surface. This means that the magnetic signal of the flow(s) closest to the surface have the most impact on the ambient magnetic field above the flow.

3.3. Correlation With Topography

Beyond the influence of the height above the flow, both the inclination and intensity variations seem to correlate with changes in topography. All paths are characterized by an irregular topography with at least one distinct gully (Figures S3–S16 in Supporting Information S1). Path 2 of site FLUX3 is a good example of such a distinct gully which is approximately 35 m wide and 8 m deep (Figure 3). The gully in FLUX5 path 1 is around 20 m wide and 4 m deep. Both the inclination and intensity are higher above ridges and lower in gullies. For path 2 of FLUX3 the differences compared to the IGRF are +4.1° in inclination and +2.7 μT in intensity with respect to the IGRF-value at 100 cm above the highest peak in the profile. At 100 cm above the lowest point, that is, in the gully, the inclination is −5.6° and the intensity −2.4 μT with respect to the IGRF-value. For FLUX5 path 2 most

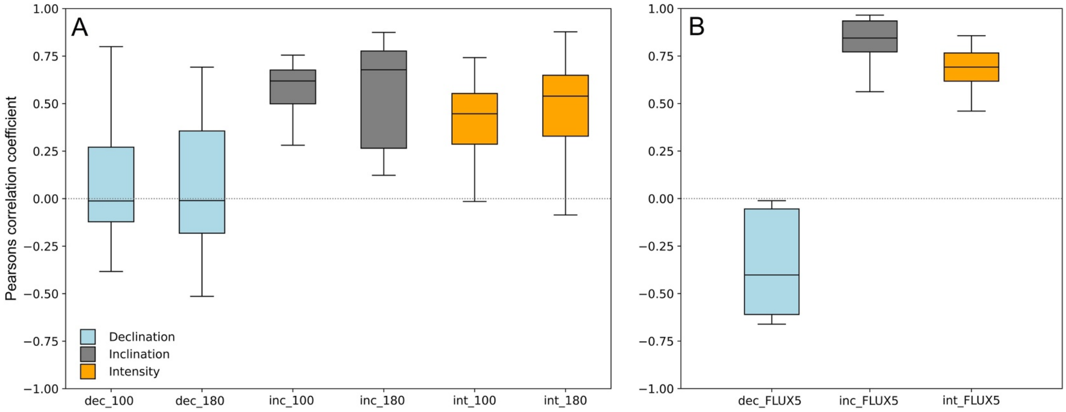

Figure 4. Box-plots for Pearson's correlation coefficient of (a) FLUX1 to 4 and (b) FLUX5. For each path a Pearson's correlation coefficient was calculated between the topography and the declination, inclination or intensity. For FLUX1-4 the coefficients are grouped for inclination, declination and intensity at 100 or 180 cm height. For FLUX5 all four different measurement levels (25, 75, 125, and 175 cm) are together. See Table S8 in Supporting Information S1 for the individual correlation coefficients.

measurements are done in the gully, there is not a clear ridge in the profile but the peaks are located at the edges. At 125 cm height above the highest peak the difference with the IGRF-value is +0.6° in inclination and −0.9 μT for intensity. Above the lowest peak they are −3.3° and −4.2 μT, respectively. To statistically assess the correlation between the fluxgate measurements and the topography, the Pearson's correlation coefficient and its corresponding *p*-value were calculated for each path and at each height. A Pearson's coefficient of +1 is a positive correlation, 0 is no correlation and with −1 there is a negative correlation. In terms of our fluxgate measurements, for a positive correlation the measurement value increases with increasing topography. Table S8 in Supporting Information S1 includes all Pearson correlation coefficients for each site and path. In Figure 4 the correlation coefficients are grouped for FLUX1-4 (Figure 4a) based on measurement height above the surface of the lava flows (100 and 180 cm). Because FLUX5 was measured at four different levels we consider that site independently in Figure 4b. The median correlation coefficient of declination is around 0 for FLUX1-4, which statistically suggests there is no trend between the declination and the topography. Inclination and intensity have a medium to strong positive correlation, these appear to have a positive trend with topography. Finally, for some paths the intensity signal seems to be slightly offset with respect to the topography, as illustrated at distance 30–35 m in path 2 of site FLUX3 (Figure 3). This offset, however, is small, not always present and does not correlate with the orientation of the gully or with the orientation with respect to the summit of Mt. Etna.

4. Discussion

4.1. Systematic Bias Due To Local Magnetic Anomalies

Paleomagnetic data produced by this and previous studies were compared with the reference value predicted by the IGRF-13 or gufm1 model, both are estimations of the Earth's magnetic field at that time and might not be fully accurate. We, however, expect minor errors in the prediction of these models. Measured values at three different Italian magnetic observatories show a good correlation with the IGRF-model during the period of 1960–2020 (Di Mauro et al., 2021). This confirms that we can reliably compare our paleomagnetic measurements from historical lava flows with the predicted reference values, at least the flows younger than 1960. The gufm1 model is based on full-vector measurements of the Earth's magnetic field between 1850 and 1899. Especially in Europe the data coverage is good (Jackson et al., 2000), therefore we assume that the errors prior to 1960 might slightly increase but overall to be negligible. The paleomagnetic data set of Mt. Etna shows a systematic bias in both the inclination and intensity, but not for the declination.

The paleomagnetic directions and intensities vary for sites sampled at different locations from a single flow, and sometimes by different studies. The inclinations reported for the 1983 flow, for example, differ 9.1°, and declination for the 1923 flow differs by 8.7° between sites (Figure 2). The sites from a single flow may be hundreds of meters to a few kilometers apart. Our fluxgate measurements cannot explain these between-sites differences, because our fluxgate measurements were taken over short distances. They therefore reveal changes in the ambient field on a scale of tens of meters. The differences between sites from a single flow may reflect a bias in the ambient magnetic field with a longer wavelength. Another explanation may be that the influence of local topography differs between sites: for example, if a larger portion of a flow is deposited in a gully, a more prominent bias in the resulting paleomagnetic direction could be expected. It is interesting to note that a large deviation from the IGRF value in inclination does not correlate to a large deviation in declination, and vice versa.

4.1.1. No Bias in Declination

The declinations of the paleomagnetic data show variation around the expected IGRF-values (Figures 2a and 2b), but there is no systematic offset. The median declinations in our direct measurements, however, are up to 6.5° lower than the expected IGRF-values. Due to the design of the AnomalyMapper, the declination is prone to errors and potentially a bias (B. M. de Groot & de Groot, 2019). It relies on aiming the AnomalyMapper to a fixed reference point using a scope, while the inclination is determined using a tilt-sensor, and the intensity is independent of the orientation of the device. If the scope is slightly offset in its mount this would lead to a systematic bias in the declinations and limit their interpretation to describing relative variations. The requirement of having a line of sight to a reference point also sometimes prevents determining a declination. Especially in deeper gullies the reference point is sometimes not visible. If the bias in declinations would be strongly positive deep in the gullies, a lack of declination measurements there may also explain the bias toward negative values for the median declinations. For the sites that do have continuous declination data in the gullies, such a trend may be suggested (e.g., site FLUX5 paths 2 and 3 which have Pearson correlation coefficients at 125 cm of −0.4 and −0.6, respectively), but it is not present for all sites, and it is certainly not strong enough to explain the deviations in median declinations fully. Lastly, (Baag et al., 1995) predicts positive declination deflections on the western side of a volcano, and negative ones on the eastern side. The fluxgate sites and most paleomagnetic sampling sites in this study are only on the northern and southern slopes. Except ET1 and ET2 which were on the eastern flank, but the largest positive declination deflection is of ET1 so this does not correlate.

4.1.2. Bias in Inclination

The median difference in inclination (−2.9°) is very close to the inclination shallowing of 3° that Pavón-Carrasco et al. (2014) reported for paleomagnetic data from volcanic products on the Northern Hemisphere for the past 400 years. Our AnomalyMapper measurements indicate that the inclination varies as a function of topography and is lower in the gullies. The correlation between the variations in inclination and topography are strong: the Pearson's correlation coefficient is positive for all sites, and the median coefficient is well above 0.5 for all heights above the surface (Figure 4). We expect the largest volume of a new flow to be deposited in the gullies, where it would record inclinations that are biased to lower values. Therefore our direct field observations with the AnomalyMapper may explain the overall bias in the paleomagnetic inclination data (Figure 2d).

Our observed inclination anomalies agree with the theoretical models of Baag et al. (1995). Their models predict that on the Northern Hemisphere negative inclination anomalies occur in gullies, or channels. Especially their V-shaped valley models closely resemble some of our inclination anomalies in the gullies, for example, as in site FLUX2 path 2. In the models of Baag et al. (1995) these channels are E-W oriented; in our AnomalyMapper measurements the orientation of channels does not seem to correlate with the amount of inclination shallowing. Baag et al. (1995) predicts the inclination anomalies to be negative in gullies on the Northern Hemisphere and positive in the gullies in the Southern Hemisphere, and therefore to be latitudinally dependent. This would imply that our inclination bias on Mt. Etna is specific to this latitude.

4.1.3. Bias in Intensity

For the intensities we observe a bias similar as the one for the inclinations: the intensities are biased to somewhat lower values in the gullies. This correlation is supported by the Pearson's coefficients, although somewhat less strong compared to the correlations for the inclinations (Figure 4). The big caveat here is that the we only find deviations up to a few (2–3) μT in our AnomalyMapper observations, while the paleomagnetic data generally shows much larger deviations from the expected IGRF field, sometimes up to 20 μT (Figures 2e and 2f). Our direct field observations therefore only explain a (small) part of the bias observed in our paleomagnetic data.

Table 2
Random Sampling of Fluxgate Measurements

	All measurements						Gully +3m					
Site	N	$\tilde{\Delta}$dec	$\tilde{\Delta}$inc	$\tilde{\Delta}$int	k med	σ	N	$\tilde{\Delta}$dec	$\tilde{\Delta}$inc	$\tilde{\Delta}$int	k med	σ
FLUX2	187	−2.76	−0.81	−0.82	1226	1.26	134	−2.67	−0.96	−1.20	1522	1.12
FLUX3	257	−4.87	−0.38	−0.79	953	1.12	96	−5.12	−1.78	−1.25	1372	1.05
FLUX5	344	−2.27	−0.94	−1.49	461	2.24	188	−0.84	−2.23	−2.69	667	1.89
Average	788	−3.30	−0.71	−1.03	880	1.54	418	−2.88	−1.66	−1.72	1187	1.35
	Gully +2m						Gully +1m					
Site	N	$\tilde{\Delta}$dec	$\tilde{\Delta}$inc	$\tilde{\Delta}$int	k med	σ	N	$\tilde{\Delta}$dec	$\tilde{\Delta}$inc	$\tilde{\Delta}$int	k med	σ
FLUX2	71	−3.03	−1.16	−1.33	1504	1.19	53	−2.82	−1.41	−1.61	1457	1.21
FLUX3	60	−4.89	−2.18	−1.16	1857	1.02	28	−5.15	−2.50	−1.25	2026	1.16
FLUX5	148	−0.55	−2.64	−2.94	908	1.85	88	0.04	−2.94	−3.41	980	1.87
Average	279	−2.82	−1.99	−1.81	1423	1.35	169	−2.64	−2.28	−2.09	1488	1.41

Note. Simulated paleomagnetic data based on AnomalyMapper measurements. N is the amount of measurements available to take random samples from, $\tilde{\Delta}$dec,inc,int is the difference of the median with the IGRF-value, k med is the median of the precision parameter and σ is the standard deviation of the intensity measurements.

It is important to emphasize that obtaining a paleointensity is difficult, and that all paleointensity methods have low success rates. The low paleointensities for Mt. Etna have been attributed to "magnetic refraction" by Rolph and Shaw (1986) and Rolph et al. (1987); "multi-domain behavior" by Hill and Shaw (1999) and Biggin et al. (2007); "transdomain processes" by Calvo et al. (2002) and L. V. de Groot et al. (2013); and differences between natural and laboratory cooling rates by Hill and Shaw (1999), Biggin et al. (2007) and L. V. de Groot et al. (2013). The common ground for these rock-magnetic processes is that they violate the central assumptions underpinning paleointensity experiments, for example, the laws of additivity and reciprocity (Tauxe, 2010), and therefore hamper a reliable reconstruction of the paleointensity. The study of obtaining a reliable paleointensity is entire research field on its own. Why these aforementioned rock-magnetic processes seem to systematically lead to even lower paleointensities than predicted by our direct field observations is therefore beyond the scope of this study.

4.2. The Impact on Paleomagnetic Statistics

If a hypothetical new flow on Mt. Etna would record the ambient magnetic field that we measured directly with the AnomalyMapper, we can simulate what the effect of local magnetic anomalies would be on a paleomagnetic study. More than 20% of the data points in sites FLUX1 and FLUX4 lack declinations, we therefore exclude these sites from this simulation. For the other sites we randomly drew 10 AnomalyMapper measurements for each site and calculated what the resulting declination, inclination, intensity, k and intensity error (σ) would be. This was repeated a 1000 times and we report the median values for each site in Table 2. We expect the largest volume of a new flow to be deposited in the gullies of the underlying flow, we therefore repeated this analysis by selecting only AnomalyMapper measurements from the gullies. We defined a gully as the lowest point in the topography, the local minimum, and selected the measurements around it up to +1, +2 m or +3 m height.

The k-value is an expression of how well measurements from individual samples agree. The median k-values are 1226 for FLUX2, 953 for FLUX3, and 461 for FLUX5, when all measurements per site are considered. If a new flow would be deposited deep in the gullies (+1 m from the lowest point), the k-values increase to 1457, 2026, and 980, respectively. This illustrates that high k-values in rough volcanic terrain may indicate that a local magnetic anomaly is not averaged out sufficiently. Moreover, it should be emphasized that the AnomalyMapper measurements do not suffer from orientation errors that occur during paleomagnetic sampling and measurements that would certainly lower our simulated k's. k's associated with real paleomagnetic data are therefore expected to be lower than these theoretical upper limits for these flows from our simulation. The standard deviation of paleointensity measurements, σ, is a measure of how well paleointensity results from different samples agree. For this parameter we see for some sites the same trend as for the k-value, but the σ's reported here are negligible compared to the uncertainties arising from paleointensity experiments (e.g., Biggin et al., 2007; L. V. de Groot et al., 2012, 2013).

It is important to emphasize that these theoretical "maximum" k-values from our simulations only pertain to these specific flows and cannot be generalized to other flows and/or locations. Local circumstances such as the morphology of the underlying terrain and the magnetization of the flows will impact the actual bias at each new location. Our observations do suggest that very high k-values do not necessarily imply that the paleodirection reproduces the expected geomagnetic field at that location within error; while low k-values do not necessarily mean that the paleodirection is unreliable.

4.3. Optimal Sampling Strategies

Our observations have consequences for paleomagnetic sampling strategies. To suppress the influence of local magnetic anomalies arising from the underlying terrain, it is important to take samples for both paleodirectional and paleointensity studies far apart on the outcrop, in an area of several tens of meters wide. If possible, take samples not far from the top of a flow or throughout a flow. If there are substantial differences between samples taken from the top and bottom this could indicate that the bottom of the flow was influenced by the magnetized terrain below.

The question of how many samples (N) are enough for a reliable paleomagnetic result has been addressed previously, although this differs for paleodirectional and paleointensity data. For paleodirections, it was previously shown that the α_{95} uncertainty interval decreases with each additional sample up to $N = 10$ (Tauxe, 2010). Beyond 10 samples, the effect of adding more samples on α_{95} is small. Even though we show that a small α_{95} does not imply that the resulting direction is close to the true paleomagnetic direction, an average based on $N = 10$ seems a good target. By bootstrapping a published dataset Cromwell et al. (2018) showed that the resulting paleomagnetic direction already came close to the published value for only four samples. They therefore suggest a minimum of four samples and a precision parameter $k \geq 50$. Here we show that a higher k-value does not necessarily correspond to a more accurate measurement of the expected paleomagnetic direction. A sampling strategy based on only four samples therefore seems less ideal for volcanic terrains with a topography like Mt Etna's. For paleointensities, the variations between samples from a single site can be quite large and the optimum number of samples may be as large as 24 (Paterson et al., 2010) although such a high number is likely not achievable because of the time consuming paleointensity techniques. The CCRIT paleointensity selection criteria demands a minimum of three specimens per site (Cromwell et al., 2015). This is however the absolute minimum, as Paterson et al. (2010) considers studies with $N < 10$ less reliable. Given the low success rates of paleointensity studies it is advisable to measure at least 10 samples per site, and only accept a result for a site if it is based on a minimum of three samples.

A sun compass is preferable for sample orientation to avoid the influence of local magnetic anomalies on drill core orientations. Other techniques to suppress this influence are backsighting using distinct landmarks (Tauxe, 2010) or a differential GPS technique (Lawrence et al., 2009), originally developed for high-latitude sampling sites but also useful when due to weather conditions a sun compass cannot be used. Sometimes, however, non of these orientation methods are available, and one has to revert to using a magnetic compass for orienting the samples. This was also the case for the paleomagnetic data in this study, as weather conditions only allowed using a magnetic compass. This is not the ideal scenario because Speranza et al. (2006) already demonstrated that there might be significant differences between Sun and magnetic compass declination readings on Mt. Etna. The use of a magnetic compass, however, would only influence the declination of the sample orientation. When determining a magnetic direction for a site/flow the results of several samples are averaged. We do not find a systematic trend between the magnetic declination and topography (Figure 4); and the declination of paleomagnetic data from Mt. Etna does not show a systematic deviation from their expected values (Figure 2b). This implies that the error made by using a magnetic compass can be reduced when samples are taken well spread out over the flow, with different bore hole orientations, and on different sides of an outcrop.

If a paleomagnetic protocol prescribes the use of sister specimens it is necessary to take multiple groups of samples to average out local magnetic anomalies. Then, it is important to avoid using samples from the same group to determine the paleodirection or paleointensity of the entire cooling unit. Finally, if a certain cooling unit is accessible at different locations, for example, on both sides of a lava flow, higher or lower on a mountain, or even at different flanks of the volcano, taking multiple sites from a cooling unit several hundreds of meters apart and calculating "age means" greatly increases the chance of being closer to the "true" paleomagnetic vector at the time of cooling. In practice it is often difficult to find multiple lava flows of the same eruption on different flanks of the mountain, in this case sampling as widely as possible on one site is the only option. As shown in Table 2 it is possible that when the samples are taken spread out over an outcrop and the area is affected by magnetic anomalies, a low *k*-value is obtained - but this does not necessarily indicate a poor paleomagnetic result. It is worth noting that taking samples well spread out over the flow and from different parts also averages out possible variations in the properties of the magnetic minerals present in the sample (e.g., Thellier, 1977; L. V. de Groot et al., 2014).

To follow all optimal sampling strategy recommendations is of course often difficult during paleomagnetic fieldwork because of limitations in availability and/or accessibility of outcrops. This emphasizes the need to report the sampling strategy in high detail in forthcoming publications and as metadata in data repositories.

5. Conclusion

Paleomagnetic data from recent flows of Mt. Etna often yield lower inclinations and intensities than expected from the IGRF. Inclinations are on average 2.9° lower than expected, the intensities are on average 8.8 μT lower. The declination of paleomagnetic data does not show a systematic bias from the expected IGRF fields. The bias in inclination can be explained by local magnetic anomalies due to the underlying irregular terrain of Mt. Etna. Our direct measurements of the current geomagnetic field made with a three-axial fluxgate magnetometer above the strongly magnetized lava flows show that inclination varies as function of topography: the inclination is biased to lower values in the gullies and higher values above ridges. The site level variations in inclinations are up to 14.1°. The largest deviations are found closest to the surface, which emphasizes the influence of the underlying terrain on the ambient magnetic field. For the intensities we find similar behavior as for the inclinations: a systematic bias that correlates with topography, with a maximum within site variation of 12.9 μT. The bias found, however, only explains a small portion of the bias in intensities reported in paleomagnetic data for Mt. Etna.

Our observations have implications for optimal paleomagnetic sampling strategies. The variation of the geomagnetic field on Mt. Etna with topography emphasizes the need to take samples spread out over a larger area. This may lower the *k*-value but averages out local magnetic anomalies best. Because local morphology of the volcanic terrain and magnetic properties of the rocks will influence local magnetic anomalies elsewhere, it is difficult to generalize our findings for Mt. Etna any further. Nevertheless, our findings illustrate that the sampling strategy should always be reported alongside paleomagnetic data and preferably also in metadata of paleomagnetic data in repositories.

Data Availability Statement

All paleomagnetic data measured in this study can be found in MagIC (https://doi.org/10.7288/V4/MAGIC/20068) (Meyer & de Groot, 2024b). The AnomalyMapper data is available at Yoda (https://doi.org/10.24416/UU01-NQXN82) (Meyer & de Groot, 2024a).

Acknowledgments

Esmee Waardenburg, Meeke van Ede, Maartje van de Biggelaar, Lynn Vogel, and Wout Krijgsman are kindly acknowledged for their help in the field and with (the processing of) the measurements. Bertwin de Groot developed the AnomalyMapper. This project has received funding from the Dutch Research Council (NWO) under its Talent program (VENI Grant 863.15.003 and VIDI Grant VI.Vidi.192.047 to LVdG).

References

Alken, P., Thébault, E., Beggan, C. D., Amit, H., Aubert, J., Baerenzung, J., et al. (2021). International geomagnetic reference field: The thirteenth generation. *Earth Planets and Space*, *73*(1), 49. https://doi.org/10.1186/s40623-020-01288-x

Baag, C., Helsley, C., Xu, S.-Z., & Lienert, B. (1995). Deflection of paleomagnetic directions due to magnetization of the underlying terrain. *Journal of Geophysical Research*, *100*(B6), 10013–10027. https://doi.org/10.1029/95jb00148

Biggin, A. J., Perrin, M., & Dekkers, M. J. (2007). A reliable absolute palaeointensity determination obtained from a non-ideal recorder. *Earth and Planetary Science Letters*, *257*(3–4), 545–563. https://doi.org/10.1016/j.epsl.2007.03.017

Branca, S., Coltelli, M., Groppelli, G., & Lentini, F. (2011). Geological map of Etna volcano, 1: 50,000 scale. *Italian Journal of Geosciences*, *130*(3), 265–291. https://doi.org/10.3301/ijg.2011.15

Calvari, S., & Pinkerton, H. (1998). Formation of lava tubes and extensive flow field during the 1991–1993 eruption of Mount Etna. *Journal of Geophysical Research*, *103*(B11), 27291–27301. https://doi.org/10.1029/97jb03388

Calvo, M., Prévot, M., Perrin, M., & Riisager, J. (2002). Investigating the reasons for the failure of palaeointensity experiments: A study on historical lava flows from Mt. Etna (Italy). *Geophysical Journal International*, *149*(1), 44–63. https://doi.org/10.1046/j.1365-246x.2002.01619.x

Cromwell, G., Johnson, C., Tauxe, L., Constable, C., & Jarboe, N. (2018). Psv10: A global data set for 0–10 ma time-averaged field and paleosecular variation studies. *Geochemistry, Geophysics, Geosystems*, *19*(5), 1533–1558. https://doi.org/10.1002/2017gc007318

Cromwell, G., Tauxe, L., Staudigel, H., & Ron, H. (2015). Paleointensity estimates from historic and modern Hawaiian lava flows using glassy basalt as a primary source material. *Physics of the Earth and Planetary Interiors*, *241*, 44–56. https://doi.org/10.1016/j.pepi.2014.12.007

de Groot, B. M., & de Groot, L. V. (2019). A low-cost device for measuring local magnetic anomalies in volcanic terrain. *Geoscientific Instrumentation, Methods and Data Systems*, *8*(2), 217–225. https://doi.org/10.5194/gi-8-217-2019

de Groot, L. V., Dekkers, M. J., & Mullender, T. A. (2012). Exploring the potential of acquisition curves of the anhysteretic remanent magnetization as a tool to detect subtle magnetic alteration induced by heating. *Physics of the Earth and Planetary Interiors*, *194*, 71–84. https://doi.org/10.1016/j.pepi.2012.01.006

de Groot, L. V., Dekkers, M. J., Visscher, M., & ter Maat, G. W. (2014). Magnetic properties and paleointensities as function of depth in a Hawaiian lava flow. *Geochemistry, Geophysics, Geosystems*, *15*(4), 1096–1112. https://doi.org/10.1002/2013gc005094

de Groot, L. V., Mullender, T. A., & Dekkers, M. J. (2013). An evaluation of the influence of the experimental cooling rate along with other thermomagnetic effects to explain anomalously low palaeointensities obtained for historic lavas of Mt Etna (Italy). *Geophysical Journal International*, *193*(3), 1198–1215. https://doi.org/10.1093/gji/ggt065

Di Mauro, D., Regi, M., Lepidi, S., Del Corpo, A., Dominici, G., Bagiacchi, P., et al. (2021). Geomagnetic activity at lampedusa island: Characterization and comparison with the other Italian observatories, also in response to space weather events. *Remote Sensing*, *13*(16), 3111. https://doi.org/10.3390/rs13163111

Fisher, R. A. (1953). Dispersion on a sphere. *Proceedings of the Royal Society of London - Series A: Mathematical and Physical Sciences*, *217*(1130), 295–305. https://doi.org/10.1098/rspa.1953.0064

Hill, M. J., & Shaw, J. (1999). Palaeointensity results for historic lavas from Mt. Etna using microwave demagnetization/remagnetization in a modified thellier-type experiment. *Geophysical Journal International*, *139*(2), 583–590. https://doi.org/10.1046/j.1365-246x.1999.00980.x

Hulme, G. (1974). The interpretation of lava flow morphology. *Geophysical Journal International*, *39*(2), 361–383. https://doi.org/10.1111/j.1365-246x.1974.tb05460.x

Incoronato, A., Angelino, A., Romano, R., Romano, A., Sauna, R., Vanacore, G., & Vecchione, C. (2002). Retrieving geomagnetic secular variations from lava flows: Evidence from mounts Arso, Etna and Vesuvius (southern Italy). *Geophysical Journal International*, *149*(3), 724–730. https://doi.org/10.1046/j.1365-246x.2002.01672.x

Jackson, A., Jonkers, A. R., & Walker, M. R. (2000). Four centuries of geomagnetic secular variation from historical records. *Philosophical Transactions of the Royal Society of London,Series A: Mathematical, Physical and Engineering Sciences*, *358*(1768), 957–990. https://doi.org/10.1098/rsta.2000.0569

Kilburn, C. R., & Lopes, R. M. (1988). The growth of AA lava flow fields on Mount Etna, Sicily. *Journal of Geophysical Research*, *93*(B12), 14759–14772. https://doi.org/10.1029/jb093ib12p14759

Koymans, M. R., Langereis, C. G., Pastor-Galán, D., & van Hinsbergen, D. J. (2016). *Paleomagnetism. org: An online multi-platform open source environment for paleomagnetic data analysis*. Elsevier.

Lanza, R., Meloni, A., & Tema, E. (2005). Historical measurements of the Earth's magnetic field compared with remanence directions from lava flows in Italy over the last four centuries. *Physics of the Earth and Planetary Interiors*, *148*(1), 97–107. https://doi.org/10.1016/j.pepi.2004.08.005

Lawrence, K., Tauxe, L., Staudigel, H., Constable, C., Koppers, A., McIntosh, W., & Johnson, C. (2009). Paleomagnetic field properties at high southern latitude. *Geochemistry, Geophysics, Geosystems*, *10*(1). https://doi.org/10.1029/2008gc002072

Meyer, R., & de Groot, L. V. (2024a). Data supplement to: Local magnetic anomalies in rugged volcanic terrain explain bias in paleomagnetic data: Consequences for sampling [Dataset]. *YODA*. https://doi.org/10.24416/UU01-NQXN82

Meyer, R., & de Groot, L. V. (2024b). MagIC data supplement to: Local magnetic anomalies in rugged volcanic terrain explain bias in paleomagnetic data: Consequences for sampling [Dataset]. *Magic*. https://doi.org/10.7288/V4/MAGIC/20068

Mullender, T. A., Frederichs, T., Hilgenfeldt, C., de Groot, L. V., Fabian, K., & Dekkers, M. J. (2016). Automated paleomagnetic and rock magnetic data acquisition with an in-line horizontal "2 g" system. *Geochemistry, Geophysics, Geosystems*, *17*(9), 3546–3559. https://doi.org/10.1002/2016gc006436

Paterson, G. A., Heslop, D., & Muxworthy, A. R. (2010). Deriving confidence in paleointensity estimates. *Geochemistry, Geophysics, Geosystems*, *11*(7). https://doi.org/10.1029/2010gc003071

Pavón-Carrasco, F. J., Tema, E., Osete, M. L., & Lanza, R. (2014). Statistical analysis of palaeomagnetic data from the last four centuries: Evidence of systematic inclination shallowing in lava flow records. *Pure and Applied Geophysics*, *173*(3), 839–848. https://doi.org/10.1007/s00024-014-0946-0

Rolph, T. (1997). An investigation of the magnetic variation within two recent lava flows. *Geophysical Journal International*, *130*(1), 125–136. https://doi.org/10.1111/j.1365-246x.1997.tb00992.x

Rolph, T., & Shaw, J. (1986). Variations of the geomagnetic field in sicily. *Journal of Geomagnetism and Geoelectricity*, *38*(12), 1269–1277. https://doi.org/10.5636/jgg.38.1269

Rolph, T., Shaw, J., & Guest, J. (1987). Geomagnetic field variations as a dating tool: Application to Sicilian lavas. *Journal of Archaeological Science*, *14*(2), 215–225. https://doi.org/10.1016/0305-4403(87)90008-2

Schurr, K., Soffel, H., & Becker, H. (1985). Archaeomagnetic study of medieval fireplaces at mannheim-wallstadt and ovens from herrenchiemsee (southern Germany) and the problem of magnetic refraction. *Journal of Geophysics*, *56*(1), 1–8.

Sherwood, G. J. (1991). Evaluation of a multi-specimen approach to palaeointensity determination. *Journal of Geomagnetism and Geoelectricity*, *43*(5), 341–349. https://doi.org/10.5636/jgg.43.341

Speranza, F., Branca, S., Coltelli, M., D'Ajello Caracciolo, F., & Vigliotti, L. (2006). How accurate is "paleomagnetic dating"? New evidence from historical lavas from Mount Etna. *Journal of Geophysical Research*, *111*(B12). https://doi.org/10.1029/2006jb004496

Tanguy, J. (1990). Abnormal shallow palaeomagnetic inclinations from the 1950 and 1972 lava flows, hawaii. *Geophysical Journal International*, *103*(1), 281–701.

Tanguy, J.-C., Bucur, I., & Thompson, J. (1985). Geomagnetic secular variation in Sicily and revised ages of historic lavas from Mount Etna. *Nature*, *318*(6045), 453–455. https://doi.org/10.1038/318453a0

Tanguy, J.-C., & Le Goff, M. (2004). Distortion of the geomagnetic field in volcanic terrains: An experimental study of the Mount Etna stratovolcano. *Physics of the Earth and Planetary Interiors*, *141*(1), 59–70. https://doi.org/10.1016/j.pepi.2003.10.003

Tanguy, J.-C., Le Goff, M., Chillemi, V., Paiotti, A., Principe, C., La Delfa, S., & Patane, G. (1999). Secular variation of the geomagnetic field direction recorded in lavas from etna and vesuvius during the last two millennia. In *Comptes rendus de l Academie des Sciences Serie II Fascicule A-Sciences de la Terre et des Planetes* (Vol. 329, pp. 557–564). https://doi.org/10.1016/s1251-8050(00)87211-0

Tanguy, J.-C., Le Goff, M., Principe, C., Arrighi, S., Chillemi, V., Paiotti, A., et al. (2003). Archeomagnetic dating of Mediterranean volcanics of the last 2100 years: Validity and limits. *Earth and Planetary Science Letters*, *211*(1–2), 111–124. https://doi.org/10.1016/s0012-821x(03)00186-9

Tarling, D., Hammo, N., & Downey, W. (1986). The scatter of magnetic directions in archaeomagnetic studies. *Geophysics*, *51*(3), 634–639. https://doi.org/10.1190/1.1442117

Tarquini, S., Favalli, M., Mazzarini, F., Isola, I., & Fornaciai, A. (2012). Morphometric analysis of lava flow units: Case study over lidar-derived topography at Mount Etna, Italy. *Journal of Volcanology and Geothermal Research*, *235*, 11–22. https://doi.org/10.1016/j.jvolgeores.2012.04.026

Tauxe, L. (2010). *Essentials of paleomagnetism*. University of California Press.

Thellier, E. (1977). Early research on the intensity of the ancient geomagnetic field. *Physics of the Earth and Planetary Interiors*, *13*(4), 241–244. https://doi.org/10.1016/0031-9201(77)90106-6

Urrutia-Fucugauchi, J., Alva-Valdivia, L., Goguitchaichvili, A., Rivas, M., & Morales, J. (2004). Palaeomagnetic, rock-magnetic and microscopy studies of historic lava flows from the Paricutin Volcano, Mexico: Implications for the deflection of palaeomagnetic directions. *Geophysical Journal International*, *156*(3), 431–442. https://doi.org/10.1111/j.1365-246x.2004.02166.x

Valet, J.-P., & Soler, V. (1999). Magnetic anomalies of lava fields in the Canary Islands. Possible consequences for paleomagnetic records. *Physics of the Earth and Planetary Interiors*, *115*(2), 109–118. https://doi.org/10.1016/s0031-9201(99)00071-0