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Paleomagnetic dating of prehistoric lava flows from the urban district of Catania (Etna volcano, Italy)

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ABSTRACT

Determining the ages of past eruptions of active volcanoes whose slopes were historically inhabited is vitally important for investigating the relationships between eruptive phenomena and human settlements. During its almost three-millennia-long history, Catania—the biggest city lying at the toe of Etna volcano—was directly impacted only once by the huge lava flow emplaced during the A.D. 1669 **[[Author: GSA places A.D. before the year. This was changed throughout. Periods after A.D., B.C., and B.P. were added, and commas were removed from 4-digit numbers in keeping with GSA style.]]** Etna flank eruption. However, other lava flows reached the present-day Catania urban district in prehistoric ages before the founding of the city in Greek times (729/728 B.C., i.e., 2679/2678 yr B.P.). In this work, the Holocene lava flows of Barriera del Bosco, Larmisi, and San Giovanni Galermo, which are exposed in the Catania urban district, were paleomagnetically investigated at 12 sites (120 oriented cores). Paleomagnetic dating was obtained by comparing flow-mean paleomagnetic directions to updated geomagnetic reference models for the Holocene. The Barriera del Bosco flow turns out to represent the oldest eruptive event and is paleomagnetically dated to the

11,234–10,941 yr B.P. and 8395–8236 yr B.P. age intervals. The mean paleomagnetic directions from the San Giovanni Galermo and Larmisi flows overlap when statistical uncertainties are considered **[[OK?]]**. This datum, along with geologic, geochemical, and petrologic evidence, implies that the two lava flows can be considered as parts of a single lava field that erupted in a narrow time window between 5494 yr B.P. and 5387 yr B.P. The emplacement of such a huge lava flow field may have buried several Neolithic settlements, which would thus explain the scarce occurrence of archaeological sites of that age found below the town of Catania.

INTRODUCTION

Mount Etna is the largest continental basaltic volcano in Europe and one of the most active in the world. It covers an area of ~1200 km^2 and has a maximum diameter of 45 km and a height of 3328 m above sea level (a.s.l.) (Fig. 1). During its eruptive history of the last 220 ka, Etna was characterized by magmas of predominantly basaltic composition and by volcanic events of variable intensity and magnitude that ranged from fissural to central activity, effusive to explosive phenomena, and strombolian to plinian eruptions (Branca et al., 2011a, 2011b; De Beni et al., 2011). The detailed knowledge of Etna's eruptive activity in the past 2700 years provided by historical accounts shows that the long-term behavior of the volcano, usually characterized by frequent and moderate summit eruptions, is accompanied by the occurrence of large flank eruptions such as that of A.D. 1669 (Branca and Del Carlo, 2005; Proietti et al., 2011; Branca and Abate, 2019). The SE Etna flank (Fig. 1), which is currently the most densely populated, is the volcano sector characterized by the highest number of flank eruptions in historical times. The town of Catania, which is located at the toe of the SE Etna flank and now hosts more than 330,000 inhabitants, was only directly impacted by the A.D. 1669 lava flow and was threatened in the twelfth century A.D. by the Mt. Arsi di Santa Maria lava flow (Branca et al., 2011b, 2016). As a consequence, Etna volcano hazard map (Del Negro et al., 2013) assigns a low-medium **[[low to medium?]]** probability of lava flow inundation to the present-day Catania urban area. The low frequency of lava flow invasions and favorable climatological, hydrological, and pedological conditions have allowed the development of human settlements at such peripheral areas of the volcano since the Neolithic epoch (Branca et al., 2017).

Less is known about the chronology of lava flows that reached the Catania area in prehistoric times. Although several studies were carried out on the Holocene Etna lavas exposed within the Catania urban district (Monaco et al., 2000; Tanguy et al., 2003, 2007, 2012; Speranza et al., 2006; Branca et al., 2011b, 2016), dating of volcanics from the town and its surroundings is limited. The aim of our work is to reconstruct the age of the prehistoric lavas on which the city of Catania is built by means of paleomagnetism using a dating/correlation tool for volcanic products of the last 14,000 years that has been used increasingly during the last 30 years to study volcanos in Italy and worldwide (Jurado-Chichay et al., 1996; Gonzalez et al., 1997; Zanella, 1998**[[Zanella, 1998 is not in the reference list.]]**; Tanguy et al., 2003, 2007; Speranza et al., 2006, 2008; Pavón-Carrasco and Villasante-Marcos, 2010; Di Chiara et al., 2014; Greve and Turner, 2017; Pinton et al., 2018; Branca et al., 2019; Risica et al., 2019, 2020, among many others). To corroborate our dating results, paleomagnetic results were compared with geological, geochemical, and archaeological evidence to properly define the Holocene eruptive history of the Catania urban area in relation to the human settlements that have developed since prehistoric times.

GEOLOGICAL SETTING OF THE CATANIA AREA

The geological map of Etna volcano by Branca et al. (2011b), the third in the history of Etna's geological cartography (Branca and Abate, 2019), along with the volcanic evolution summarized by Branca et al. (2011a), documents an updated and accurate reconstruction of the stratigraphy of the volcano. The last 15 ka were characterized by the activity of the "Mongibello volcano," the most recent lithosomatic unit of Etna, which represents the currently active center of volcanic activity (Il Piano Synthem, stratovolcano phase of Branca et al., 2011a). The Mongibello volcano generated scoria cones, pyroclastic fallout deposits, and lava flows extending onto over 85% of the Etna surface. Two principal tephra layers, largely spread over the eastern and southeastern sectors of the volcanic edifice, were used to stratigraphically constrain the ages of the Mongibello lava flows. The older flow is correlated to a 3930 ± 60 ^{14}C yr B.P. sub-plinian eruption (FS **[[Provide words for FS rather than using acronym.]]** pyroclastic fall deposit in Coltelli et al., 2000), whereas the younger is associated with the 122 B.C. (2072 yr B.P.) basaltic plinian eruption (FG **[[Provide words for FG rather than using acronym.]]** tephra layer in Coltelli et al., 1998, 2000).

The stratigraphic sequence of the lower SE flank of Etna starts with marine marly clays evolving to littoral sands and continental polygenetic conglomerates; this succession represents the Pleistocene regressive phase (Fig. 1). The oldest Etna volcanics exposed at Catania are lava flows that belong to the Timpe phase (Branca et al., 2011a, 2011b) and lie on the early–middle Pleistocene marly clays and crop out discontinuously along the northern suburbs of the town. Radiometric (Ar/Ar) dating of such lavas yielded a result of ca. 130 ka (De Beni et al., 2011). However, the volcanics exposed over the lower SE Etna flank are predominantly represented by younger lava flows emplaced between 15 ka B.P. and 3.9 ka B.P. (lower member of the Pietracannone Formation of Branca et al., 2011b) and between 3.9 ka B.P. and the 122 B.C. (2072 yr B.P.) tephra layer (upper member of the Pietracannone Formation of Branca et al., 2011b). During the last 2 ka, several historical lava flows emplaced in the area between the towns of Nicolosi, Trecastagni, San Giovanni La Punta, and Mascalucia (Fig. 1). In particular, in the late Roman epoch, the Monpeloso, S.G. La Punta, and Piazza Sant'Alfio lava flows (mp, sq, and io in Fig. 1) erupted at around A.D. 300 and A.D. 450, respectively. Considering the A.D. 300 ± 100 paleomagnetic age by Tanguy et al. (2012), the Monpeloso lava flow could be associated with the A.D. 252 eruption quoted in the historical sources. Among all of the lava flows of the Middle Ages, only the Mt. Arsi di Santa Maria flow (sm in Fig. 1) reached the Ionian coast at the Ognina locality (~2.3 km NE of the Medieval town of Catania), and this occurred during the twelfth century A.D. During later centuries, the A.D. 1408 lava flow caused considerable damage to cultivated lands and to the village of Pedara, and the A.D. 1537 lava flow damaged the Nicolosi and Monpilieri villages. The best known eruptive event of the historical period occurred in A.D. 1669 and affected the lower SE flank of Etna. The 17-km-long A.D. 1669 lava flow covered ~40 km^2 of a highly urbanized and agriculturally productive area, destroying several towns and the SW part of Catania itself (Branca et al., 2013, 2015b).

STRATIGRAPHIC AND CHRONOLOGICAL CONSTRAINTS OF THE PREHISTORIC CATANIA LAVA FLOWS

Considered as a natural laboratory for volcanologists and geophysicists, Mt. Etna has been one of the most studied volcanoes in the world since the eighteenth century (Branca and Abate, 2019). Thanks to the presence of inhabited zones on its flanks for some 2700 yr B.P., the eruptive events of the volcano were occasionally reported by historical documents that date back to the Greek colonization (Tanguy, 1981; Guidoboni et al., 2014). Some of these documents described the effects of the eruptions on the city of Catania, which was begun as a Greek colony in 729/728 B.C. (2679/2678 yr B.P.) with the name of Katánē (Privitera, 2010). Thus, the availability of historical sources documenting numerous eruptive events and subsequent interpretations by different historians led to many errors and false ages (Guidoboni et al., 2014; Tanguy et al., 2012; Branca and Abate, 2019). It has been demonstrated that by integrating geological, historical, radiometric, and paleomagnetic analyses it is possible to adequately resolve doubts about the ages of debated volcanic products (Tanguy, 1969, 1980; Tanguy et al., 1985, 2003, 2007, 2012; Condomines and Tanguy, 1995; Condomines et al., 2005; Speranza et al., 2006; Branca and Vigliotti, 2015; Branca et al., 2015a, 2016).

Geological investigations performed by Sartorius von Waltershausen (1843–1861), author of the first geological map of Mt. Etna, helped to first link historical accounts to several lava flows produced by flank eruptions (Sartorius von Waltershausen, 1843). In particular, von Waltershausen deemed the information on the eruptive phenomena described in the Greek-Roman and early Middle Age sources too general and difficult to interpret; consequently, the oldest lava flow the author was able to robustly date was related to the year A.D. 1285 (Branca and Abate, 2019). Later authors devoted themselves to the study and interpretation of Etna lava flows of the Catania area. In the earliest geological map of the city, which was published at a scale of 1:21,276, Sciuto Patti (1872) erroneously attributed some lava flows that reached the town to a Roman age (122 B.C., i.e., 2072 yr B.P. and A.D. 253). Such incorrect age attributions conditioned later age interpretations that were made in the geological maps of the twentieth century even though just a few years after the publication of Patti's map archaeological investigations evidenced the presence of prehistoric settlements in the lava flows that Patti had attributed to the Roman age (for detail see Branca et al., 2016; Branca and Abate, 2019). As a consequence, in the second geological map of Etna at the 1:50,000 scale by Romano et al. (1979), several Greek-Roman ages (693 B.C., i.e., 2643 yr B.P.; 425 B.C., i.e., 2375 yr B.P.; 122 B.C., i.e., 2072 yr B.P.; and A.D. 252–253) were erroneously assigned to some lava fields mapped in the urban area of Catania due to the interpretation of both the historical catalogues of Etna's eruptions and the previous geological maps (Branca and Abate, 2019). Similarly, in the recent geological map of Catania published at the 1:10,000 scale by Monaco et al. (1999, 2000), the authors adopted Patti's incorrect A.D. 252 age attribution for an exposed lava flow.

In the most recent 1:50,000 scale geological map of Mt. Etna, Branca et al. (2011b), using an interdisciplinary approach including stratigraphy, revised historic analysis, and radiometric dating of the lavas, showed that 85% of lavas attributed to the Greek-Roman times until the sixteenth century A.D. are in fact either prehistoric or several centuries older. In particular, according to Branca et al. (2011b), the urban area of Catania is formed by two main lava flow fields of prehistoric age named Barriera del Bosco and Larmisi (bb and la in Fig. 1, respectively, Pietracannone Formation lower member, stratigraphic age between 15 ka B.P. and 3.9 ka B.P.) that are characterized by several archaeological artifacts from the Neolithic to the Greek and Roman ages lying above (Branca et al., 2016). A restricted portion of the coast at the Ognina locality is formed by a lava flow, named Ognina (og in Fig. 1), which was emplaced in the same stratigraphic age interval (15–3.9 ka BP) as the Barriera del Bosco and Larmisi flows. An additional prehistoric lava flow, named San Giovanni Galermo (le in Fig. 1), outcrops in the northwestern sector of Catania. Early Bronze age archaeological artifacts were found within its lava tubes, and the flow was dated by ^{226}Ra-^{230}Th technique at 2700 B.C. (+960/–750), i.e., 5610–3900 yr B.P. (Sample 090 of Tanguy et al., 2007).

In this work we focused on the Barriera del Bosco, Larmisi, and San Giovanni Galermo prehistoric lava flows (available age constraints are summarized in Table 1). The lower age boundary of the Barriera del Bosco flow is poorly known; however, the lava flow is considered to be part of the Pietracannone Formation, whose lower bound is dated at the AMS-constrained ages of 15,420 ± 60 yr B.P. and 15,050 ± 70 yr B.P. (D1a and D2a pumice layers, respectively, in Coltelli et al., 2000). The Middle Neolithic artifacts (6950–5950 yr B.P.; Privitera and La Rosa, 2007; Branciforti, 2010; Frasca, 2015; Nicoletti, 2015) found below the Benedettini Monastery, which lies above the Barriera del Bosco flow, provide the upper bound flow age.

The Larmisi flow frontal portion forms a 2-km-long and 10–15-km-high cliff (“Larmisi cliff”) that lies over a depositional marine platform located at 5 m below sea level (SG **[[Provide full term for SG rather than abbreviation.]]** layer in Monaco et al., 2000). Considering the relative sea level change curve of Lambeck et al. (2004), the sea was ~6 m below the present level in prehistoric times (8500–6500 yr B.P.). Modifying the Lambeck curve for a regional Holocene uplift rate of 1.2–1.4 mm/yr for eastern Sicily, the marine platform is inferred to have a 7500–7000 yr B.P. age (C. Monaco, 2020, personal commun.), which implies that the Larmisi flow is younger than 7500–7000 yr B.P. Several Late Copper Age artifacts (4550–4250 yr B.P.; Privitera and La Rosa, 2007) found inside some lava tubes distributed along this lava flow can be considered to represent the upper bound age of the Larmisi flow.

The San Giovanni Galermo flow had been previously dated at 5610–3900 yr B.P. by ^{226}Ra-^{230}Th dating (site 090 of Tanguy et al., 2007). In addition, the presence of pottery dating back to the Early Bronze Age (3950–3350 yr B.P.; Privitera and La Rosa, 2007) confirms the radiometric upper bound age.

To sum up, available geological, archaeological, and radiometric evidence constrains the Barriera del Bosco, Larmisi, and San Giovanni Galermo flows to the 13,950–6950 yr B.P., 7500–4550 yr B.P., and 5610–3950 yr B.P. age ranges, respectively.

PRINCIPLES OF PALEOMAGNETIC DATING

Paleomagnetic dating is based on the fundamental assumption that remanent magnetization, acquired by volcanic rocks at the time of their emplacement and cooling, is parallel to the Earth’s local magnetic field direction (e.g., Butler, 1992). Thus, comparing paleomagnetic directions recorded by volcanics and independently available reference curves showing the paleo-secular variation (PSV) swings of the geomagnetic field direction (some tens of degrees in declination and inclination at Sicily coordinates, Bucur, 1994; Gallet et al., 2002; Tanguy et al., 2003) during the last millennia can provide one or more emplacement age ranges within a given input time window. PSV reference curves were obtained by archeomagnetism, paleomagnetism of well-dated volcanics, and paleomagnetism of cores drilled within lacustrine successions deposited at a high sedimentation rate. Directional PSV data have regional validity and are abundant in Europe, where a wealth of reference data was gathered in past decades (e.g., Speranza et al., 2008). Thus, the accuracy of paleomagnetic dating is strictly dependent upon the availability of neighbor reference PSV data and reaches maximum reliability and potentiality for European volcanoes.

In the last few years, paleomagnetic dating was routinely done using the SHA.DIF.14k global PSV reference model (Pavón-Carrasco et al., 2014) that extends back to the last 14 ka and discards reference sedimentary data, which is a possible source of bias. As the last 14 ka is virtually the same time range in which all three of the lava flows studied fall (Barriera del Bosco, Larmisi, and San Giovanni Galermo), the SHA.DIF.14k model was chosen for this work.

In the last three decades, paleomagnetic dating has been applied increasingly to date volcanic products worldwide in Iceland (Thompson and Turner, 1985; Pinton et al., 2018), the Canary Islands (Soler et al., 1984; Pavón-Carrasco and Villasante-Marcos, 2010; Risica et al., 2020), the Azores (Di Chiara et al., 2012, 2014), New Zealand (Cox, 1969; McClelland et al., 2004; Greve and Turner, 2017), Hawaii (Doell and Cox, 1963; Holcomb et al., 1986; Jurado-

Chichay et al., 1996), and Mexico (Gonzalez et al., 1997; Böhnel et al., 2016; Mahgoub et al., 2017). Eruptive products from famous Italian volcanoes were paleomagnetically investigated: Vesuvius (Hoye, 1981; Incoronato et al., 2002; Tanguy et al., 2003; Principe et al., 2004), Stromboli (Speranza et al., 2004, 2008; Arrighi et al., 2004**[[Arrighi et al., 2004 is not in the reference list. 2006 here?]]**; Risica et al., 2019), Vulcano (Zanella and Lanza, 1994; Arrighi et al., 2006), and Pantelleria (Speranza et al., 2010, 2012). On Etna, several flank eruptions of the past 2400 years were paleomagnetically dated (Chevallier, 1925; Rolph and Shaw, 1986; Incoronato et al., 2002; Speranza et al., 2006; Tanguy et al., 1985, 2003, 2007, 2012; Branca et al., 2011a, 2015a, 2019).

SAMPLING AND METHODS

In June 2019, we paleomagnetically sampled four sites from each of the three prehistoric Etna lava flows (Barriera del Bosco, San Giovanni Galermo, and Larmisi) exposed in the Catania urban district for a total of 12 sites (Fig. 1 and Table 1). We carefully selected the sampling outcrops to investigate several single flow units from the same lava field and focused on massive cores of lava flow units, where post-emplacement tilt, i.e., the main bias source of paleomagnetic dating (e.g., Pinton et al., 2018), is unlikely to occur.

Sites ETN23, 24, 25, and 26 were located at the Barriera del Bosco flow. Collection at site ETN23 was conducted in a single lava flow unit along Viale della Regione just north of the cemetery (Fig. 2A); at the same site, sandy sediments (likely the San Giorgio sands of Branca et al., 2011a) were burnt by the underlying hot lava flow through the degassing process and form the so-called "lithophysae" (Fig. 2B). Site ETN24 was sampled near San Severio Villa (Cibali neighborhood) at a small outcrop along the street floor; site ETN25 was sampled near Guglielmo Oberdan Street in a lava flow unit outcrop; site ETN26 was sampled along Santa Maria La Grande Street, where a massive core of basaltic lava characterized by joints is exposed.

Sites ETN27, 28, 29, and 33 are located in the San Giovanni Galermo flow. Site ETN27 was sampled at the crossroads of Santa Sofia Street and Fratelli Vivaldi Street from a single lava flow unit; collection at sites ETN28 and ETN29 was conducted along Sebastiano Catania Street and Via della Misericordia Street, respectively; site ETN33 was sampled at Egadi Street (San Nullo locality) from the massive basaltic lava core outcrops of three overlapping flow units (Fig. 2D) characterized by a ropy surface on their roofs (Fig. 2E).

Finally, four sites were sampled in the Larmisi lava flow: site ETN30 comprises several overlapping lava flow units along Don Luigi Sturzo Street (Fig. 2G–2H); site ETN31 was sampled along Via dei Miti Street, where three lobes with alternating massive cores and welded autobreccias crop out; site ETN32 in Gioeni Park lies in a wide lava field consisting of several flow units; and collection at site ETN34 sampled some lava lobes exposed near Justice Palace along Ramondetta Street.

Samples were collected by drilling 2.5-cm-diameter cores with a gas-powered portable drill cooled by water. At each site we systematically drilled 10 cores for a total number of 120 cores. All cores collected were spaced along the outcrop over a length of few meters to tens of meters and oriented in situ using both a magnetic compass and a sun compass. The comparison between sun and magnetic compass readings translates into local magnetic field declinations varying from 24° to –35° (4.8° on average), which compares to the regional geomagnetic field declination at Etna (D=3°) extrapolated for June 2019 from the International Geomagnetic Reference Field model (https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm; accessed April 2021).

Cores were cut into standard cylindrical specimens, and the natural remanent magnetization (NRM) of one specimen per core was measured in the shielded room of the Paleomagnetic Laboratory of Istituto Nazionale di Geofisica e Vulcanologia in Rome using a 2G Enterprises direct current superconducting quantum interference device cryogenic magnetometer. All specimens were demagnetized by alternating field (AF) cleaning with 10 steps until a maximum AF peak of 120 mT was reached.

AF demagnetization data were plotted on orthogonal demagnetization diagrams (Zijderveld, 1967) and equal area projections, and magnetization components were isolated through principal component analysis (Kirschvink, 1980). Site-mean and lava flow-mean paleomagnetic directions (calculated by averaging all individual characteristic remanent magnetization [ChRM] direction components from the same flow) were computed using Fisher's (1953) statistics.

Paleomagnetic dating was performed using the Matlab tool developed by Pavón-Carrasco et al. (2011). The SHA.DIF.14k global model used in this work (Pavón-Carrasco et al., 2014) spans the 12,000 B.C.–A.D. 1900 (13,950–50 yr B.P.) period and relies on archaeomagnetic and well-dated volcanic paleomagnetic data from the GEOMAGIA50v2 data set (Donadini et al., 2006; Korhonen et al., 2008).

For two specimens from each lava flow (a total of six specimens), we also measured the variation of the low-field magnetic susceptibility during a heating and cooling cycle performed in air at a room temperature of up to 700 °C using an AGICO MK1-FA Kappabridge coupled with a CS-3 furnace. The Curie temperature (T_c) of the magnetic minerals present in the samples was determined from the thermomagnetic curves (Fig. S1[1]) as the temperature, or range of temperatures, at which paramagnetic behavior starts to dominate, following the approach outlined by Petrovský and Kapička (2006).

For one specimen per site, hysteresis loops were also measured (Fig. S2; see footnote 1) using a Princeton Measurement Corporation MicroMag alternating gradient magnetometer (Model 2900) with a maximum applied field of 1 T. The acquired hysteresis parameters are saturation magnetization (M_s), saturation remanent magnetization (M_{rs}), and coercive force (B_c). Coercitivity remanence parameter B_{cr} was measured by aquiring an isothermal remanent magnetization (IRM) and subsequent back-field DC remagnetization (both in a succession of fields up to 1 T).

Rock blocks at some paleomagnetic sites were also gathered for petrographic analyses: 11 samples from Barriera del Bosco flow (sites ETN23, ETN24, ETN25, and ETN26), one from San Giovanni Galermo flow (site ETN27), and three from Larmisi flow (sites ETN30 and ETN31). Thirty-µm-thick rock sections were obtained from each block at the Thin Section Laboratory of the Roma Tre University.

RESULTS

Petrographic Analyses

For all three lava flows studied, petrographic analyses show porphyritic and phaneritic texture with large phenocrysts (2–7 mm) inside a hypocrystalline groundmass (Figs. 2C–2F and 2I **[[OK?]]** and Fig. S3; see footnote 1). The predominant phenocrysts are plagioclases (Pl) with minor clinopyroxenes (Cpx), olivines (Ol), and opaque oxides (Ox), which comprise the common mineralogical assemblage of Etna products (Corsaro and Pompilio, 2004). The Barriera del Bosco lava flow (Fig. 2C and Fig. S3) presents a porphyricity index (P.I. = total phenocryst abundance expressed in volume %) of around 30% with elongated plagioclases (labradorite, 3–6 mm) constituting 80%–90% and euhedral clinopyroxenes/olivines representing 10%–20% (2–4 mm). The Pl/Cpx+Ol ratio ranges from 9 to 4. The groundmass, which forms 70% of the rock volume, is characterized by an intersertal texture in which plagioclase microlites form a network whose intergranular spaces are filled with mafic minerals and/or volcanic glass. Groundmass microlites have the same paragenesis of phenocrysts.

In the San Giovanni Galermo lava flow (Fig. 2F), mafic minerals are more abundant, with a Pl/Cpx+Ol+Ox ratio of 1.5–1.9. The P.I. is 40%–45%, which is greater than that of the Barriera del Bosco flow, with plagioclase being the most abundant phenocrysts (60%–65%, andesine, 3–5 mm) followed by euhedral clinopyroxenes (20%–22%, augite to aegirine-augite, 3–4 mm), and sub-rounded olivines (15%–18%, 1–3 mm). Pyroxenes are often arranged as glomeroporphyritic aggregates with phenocrysts bracketed in groups. The groundmass (55%–60% of the total volume) presents an intersertal structure with paragenesis of microlites (<0.5 mm) similar to that of phenocrysts (60% plagioclase; 30% clinopyroxene; 10% olivine).

The Larmisi lava flow (Fig. 2I) has Pl/Cpx+Ol+Ox ratios of between 1 and 1.9 and a P.I. of 40–45%, which fully overlap those of San Giovanni Galermo. Elongated plagioclases are always the predominant phenocrysts (60%–65%, andesine, 2–6 mm), followed by euhedral clinopyroxenes (30%–20%, augite to aegirine-augite, 1–5 mm, sometimes in glomeroporphyritic aggregates) and sub-rounded olivines (10%–20%, 0.5–3 mm). The groundmass forms 55–60% of the rock and shows an intersertal texture with paragenesis of microlites (<0.5 mm) similar to that of phenocrysts (50%–60% plagioclase; 30% clinopyroxene; 10%–20% olivine).

Magnetic Properties

Almost all thermomagnetic curves show an irreversible variation trend during heating-cooling cycles, which indicates magnetic mineralogy changes during heating (Fig. S1). Samples ETN2301 and ETN3007 show similar heating-cooling cycles and T_c of 580 °C, which is characteristic of magnetite. In the remaining samples, multiple T_cs are apparent in the 150–500 °C temperature range likely due to the occurrence of minerals belonging to the titano-magnetite series. Moreover, noticeable magnetization above the magnetite T_c in samples ETN2301, ETN3007, ETN3203, and ETN3310 may be associated with the occurrence of hematite, contributing to magnetic susceptibility to a lesser degree. To sum up, thermomagnetic analyses show that magnetite and Ti-magnetites are the predominant magnetic minerals of the lava flows investigated.

All samples analyzed show low coercive force values (B_c) ranging between 4.6 mT and 26 mT. The great variation in magnetization and coercivity parameters suggests a wide range of magnetic behaviors. Some specimens (ETN2304, ETN2504, ETN3007, and ETN3107) show hysteresis cycles with a noticeably wide shape related to single-domain (SD) grains (Fig. S2A), while other samples (ETN2604 and ETN2810) have narrower hysteresis loops that are typical of multi-domain (MD) grains (Fig. S2B). Remaining specimens display intermediate magnetic behaviors between these two end members (Figs. S2C–S2D). Hysteresis parameters were plotted in a Day plot (Day et al., 1977; Dunlop, 2002a, 2002b; Fig. S2E) of saturation remanence to saturation magnetization (M_{rs} / M_s) against the ratio of remanent coercive force to coercive force (B_{cr} / B_c). All of the samples follow the theoretical mixing curves for SD and MD magnetite (Fe_3O_4), with the exception of a single specimen (ETN3405) lying on a TM60 titanomagnetite (i.e., $Fe_{3-x}Ti_xO_4$, with x = 0.6) mixing curve.

Paleomagnetic Directions

In all AF-cleaned specimens, a well-defined ChRM was isolated in the 20–120 mT field interval (Fig. 3). More than 90% of magnetic remanence was removed at 100 mT, thus pointing to low-coercivity minerals as main magnetic carriers. However, for ~10% of the samples (mostly from sites ETN25, ETN30, and ETN31), only 75%–80% of NRM is removed at the maximum available 120 mT alternating field (see ETN3102 specimen in Fig. 3), which suggests the occurrence of both low- and high-coercivity minerals. Given the not negligible amount of hematite documented by some thermomagnetic curves (Fig. S1), the high-coercivity fraction is possibly represented by both hematite and SD and/or deuterically oxidized titanomagnetite (e.g., Dunlop and Özdemir, 2001).

Site-mean declinations (except at site ETN26) vary from −9.1° (site ETN31) to 15.0° (ETN25), and inclinations range from 40.4° (ETN23) to 60.8° (ETN34; Fig. 4A and Table 2). Site ETN26 at the Barriera del Bosco flow shows a scattered direction that lies 26°–27° apart from the directions of the remaining three sites from the same flow. This site was sampled in an isolated, 8-m-long outcrop left along the urban Via Santa Maria La Grande Road and thus was most likely tilted after emplacement. Site ETN26 was thus considered an outlier and discarded from further consideration. The α_{95} values relative to the mean paleomagnetic directions evaluated for each site range between 2.7° and 7.1° (5.0° on average, Fig. 4A and Table 2), whereas they vary from 2.6° to 3.2° depending on the **[[OK?]]** lava flow (average 2.9°, Fig. 4B and Table 2).

DISCUSSION

Age Determinations

Our paleomagnetic data reveal that the Larmisi and San Giovanni Galermo lava flows share overlapping paleomagnetic directions (Figs. 4A–4B); thus, the question arises of whether the two lava flows in fact belong to the same lava field. Indeed, while two significantly different paleomagnetic directions from two volcanic units are definitive proof of distinct emplacement age (with a 100–200 year time resolution, e.g., Speranza et al., 2012), similar paleomagnetic directions may either indicate coeval emplacement or be related to the characteristics of the geomagnetic field that may reoccupy the same directions a few centuries or millennia later (Butler, 1992).

Some statistical tests are used to verify whether two data sets share a common mean direction. The most widely used is the F-test (Watson, 1956), recently adopted by Larrea et al. (2019), which compares a statistic parameter, F, with tabulated values for the chosen significance level. Another test, considered to be more statistically reliable (Tauxe et al., 2018) and used here, is the Watson test or V_w test (Watson, 1983). In the simplest terms, if two data sets share a common mean direction, then the statistic parameter V_w (that increases with growing difference between the mean directions of the two data sets) will be lower than a critical value (V_{crit}) determined through the Monte Carlo simulation (see Supplemental Material S4 for the detailed theory and calculation process; see footnote 1). We applied the Watson test, using the PmagPy function of Tauxe et al. (2016), to the Larmisi and San Giovanni Galermo directions to examine if these two data sets share a common mean direction. The obtained V_w value (5.5) is smaller than the V_{crit} (6.2) (see Supplemental Material S4 for the results); consequently, the two data sets share a common mean direction.

We also note that petrographic analyses indeed suggest similar characteristics of the two flows, although this is not a conclusive criterion given the similarity of most Etna lava flows (Corsaro and Pompilio, 2004). Both lavas have a porphyricity index of 40%–45%, plagioclase phenocryst content ranging from 60% (Larmisi flow) to 65% (San Galermo Galermo flow), high amounts of mafic minerals (Pl/Cpx+Ol+Ox ratio of ~1–1.9), and clinopyroxenes in places arranged as glomeroporphyritic aggregates. Moreover, it must be recalled that there is no field evidence of stratigraphic boundaries between the two lava flows.

Finally, geochemical data from the literature for the two flows show nearly identical chemical compositions (Corsaro and Cristofolini, 1993; Table S1; see footnote 1), which further confirms that the two lava flows can reliably be considered products of the same eruption.

We conclude that the San Giovanni Galermo and Larmisi flows belong to the same volcanic unit emplaced during a single eruptive event. Thus, we calculated a single mean paleomagnetic direction for the San Giovanni Galermo-Larmisi lava flows (Fig. 4C) by averaging the 76 reliable ChRMs obtained from the two flows.

Eruption ages were obtained by comparing mean paleomagnetic directions from the Barriera del Bosco and San Giovanni Galermo-Larmisi flows to field direction values expected at Etna considering the SHA.DIF.14k global model (Fig. 5; Pavón-Carrasco et al., 2014) by using the "archaeo_dating" Matlab tool.

Three age intervals were obtained for the Barriera del Bosco flow: 11,234–10,941 yr B.P., 8395–8236 yr B.P., and 7309–6950 yr B.P. (Table 2 and Fig. 5). Conversely, two possible age windows between 5610 yr B.P. and 4550 yr B.P. (i.e., the input time window overlapping both individual time windows from the two flows) were obtained for the San Giovanni Galermo-Larmisi lava flow (Table 2 and Fig. 5).

In Figure 6, the paleomagnetic ages are compared with input time windows arising from archaeological/radiometric ages reported in the literature from the Barriera del Bosco and San Giovanni Galermo-Larmisi lava flows. Although all of the paleomagnetically inferred ages are equally probable, the presence of Middle Neolithic finds (6950–5950 yr B.P.) on the Barriera del Bosco lava flow allows us to rule out its youngest age interval (7309–6950 yr B.P.), which is temporally too close to enable the communities of that period to settle there. The most likely paleomagnetic ages of the Barriera del Bosco flow are then 11,234–10,941 yr B.P. and 8395–8236 yr B.P. (bold contour boxes in Fig. 6). Both age determinations are in agreement with the oldest human presences recognized in the Catania area and suggest that the Barriera del Bosco lava flow was emplaced during the early stage of the Holocene epoch and was afterwards widely covered by lacustrine and alluvial deposits (Fig. 1).

Concerning the San Giovanni Galermo-Larmisi lava flow, the ^{226}Ra/^{230}Th age (5610–3900 yr B.P.) of Tanguy et al. (2007) overlaps with both paleomagnetic age intervals. Furthermore, following the same criterion previously adopted for the Barriera del Bosco flow, the youngest age span (5125–4550 yr B.P.) of the San Giovanni Galermo-Larmisi lava flow is very close to the Late Copper Age artifacts (4550–4250 yr B.P.) discovered on the lava flow itself and consequently should be discarded. Accordingly, the only paleomagnetic age for the San Giovanni Galermo-Larmisi flow that is consistent with both geologic and archaeologic evidence is the narrow 5494–5387 yr B.P. age window (Fig. 6).

Archeological Implications

The new paleomagnetic datings, cross-correlated with both archaeological and geological evidence, allow constraints on the age of the prehistoric lava flow that was emplaced where the urban district of Catania later developed. Undistinguishable paleomagnetic directions, along with petrographic and geochemical evidence, show that the San Giovanni Galermo and Larmisi lava flows, which had been considered to be related to distinct eruptions (Branca et al., 2011b), form in fact a unique wide lava field generated by a flank eruption in Etna's SE lower slope between 5494 yr B.P. and 5387 yr B.P. (Fig. 7). This wide lava field almost entirely covered the Barriera del Bosco flow, whose paleomagnetic age ranges from 11,234–8236 yr B.P.

In addition, the new datings of the lavas lying below the metropolitan district of the town of Catania explain the scarce distribution of Neolithic archaeological sites found in this area of the volcano. Archaeological sites here are limited to the Mt. Vergine hill, where the Benedettini Monastery is located (Fig. 7). At this site, the human colonization of the Barriera del Bosco lava flow started in the Middle Neolithic (Branciforti, 2010; Nicoletti, 2015). The emplacement of the wide San Giovanni Galermo-Larmisi lava flow radically modified the morphological setting of the Late Neolithic landscape and probably masked further evidence of the human presence in this sector of the Etnean coast during the Neolithic period. In fact, the oldest traces of human colonization on the San Giovanni Galermo-Larmisi lava flow date back to the Upper Copper and Early Bronze periods (Fig. 7). This new morphological and geological setting represented the substratum of the following human settlements until the foundation of the Greek colony of Katánē in 729/728 B.C. (2679/2678 yr B.P.). Since the founding of the town 2700 years ago, the interaction between volcanic events and urban development has been very limited **[[OK?]]** (Branca et al., 2016). In fact, during the Greek-Roman domination (from the eighth century B.C. to the fifth century A.D.), only the 122 B.C. (2072 yr B.P.) Plinian eruption produced significant pyroclastic fallout that severely damaged the town (Coltelli et al., 1998; Guidoboni et al., 2014). After a millennium passed without any eruptive event, in the twelfth century A.D. the Mt. Arsi di Santa Maria lava flow reached the Ionian coast ~3.5 km north of the Medieval town (Fig. 7). Finally, in A.D. 1669, a lower flank eruption generated a 17-km-long lava flow that impacted Catania (Branca et al., 2015b, 2016).

CONCLUSION

The urban area of Catania, with its 330,000 citizens, is the main inhabited zone around the Etna volcano. Our new paleomagnetic data, coupled with geological and petrographic evidence from the Holocene lava flows emplaced within the present metropolitan district of Catania, define their ages and highlight the eruption timing in relation to the human presence in the prehistoric epoch. Moreover, the new paleomagnetic datings have significantly improved knowledge of the geochronology of Holocene lava flows exposed within the Catania urban district.

The oldest archaeological evidence of human presence in this area dates back to the Middle Neolithic ages (6950–5950 yr B.P.) and lies on the lava field known as Barriera del Bosco, which yields a paleomagnetic age range of between 11,234 and 8236 yr B.P. Above this lava flow we have correlated to the same eruptive event two lava flows that are interpreted so far as distinct, which are known as the San Giovanni Galermo and Larmisi flows. When considered together, the two flows are paleomagnetically dated to a narrow age range between 5494 yr B.P. and 5387 yr B.P. The emplacement of such a wide lava field almost covered the Barriera del Bosco flow and highly impacted the Catania area; the flow reached the Ionian Sea. Even though the San Giovanni Galermo-Larmisi lava flow caused significant changes in the morphological setting of this sector of Etna's SE coast during the late Neolithic age, continuous development of the human presence is evidenced by the Early Bronze age (3950–3350 yr B.P.) archaeological artifacts discovered in the lava tubes of this flow. A few centuries later, the Chalcidian (Greek) settlers founded the town of Katánē on the Barriera del Bosco lava flow in 729/728 B.C./2679 yr B.P.

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Figure 1. Geological map shows the lower southeastern flank of Mt. Etna volcano (modified from Branca et al., 2011b, 2016). The locations of the paleomagnetic sampling sites are also shown: Barriera del Bosco (circles), Larmisi (triangles), and San Giovanni Galermo (asterisks).

Figure 2. Representative photographs show the outcrops, lithologic details, and thin sections (cross-polarized light) of each lava flow. (A–C) Barriera del Bosco flow images show: (A) a flow unit with its massive core and upper autoclastic breccias; (B) particular of sedimentary

deposit (contoured by a white line) burned by underlying unit through “lithophysae” degassing process; (C) thin section with a detail of the porphyritic texture (note the abundance of plagioclase phenocrysts). (D–F) San Giovanni Galermo flow photographs show: (D) view of a flow outcrop; (E) particular of lava flow roof characterized by ropy surface; (F) thin section with a porphyritic texture and plagioclase (Pl), clinopyroxenes (Cpx), and olivine (Ol) phenocrysts. (G–I) Larmisi flow photographs represent: (G) a 3-m-high outcrop characterized by several stacked flow units with alternating massive cores and autobreccias; (H) detail showing the high vesicularity of the lava flow (a 2.5-cm-diameter paleomagnetic drill hole is visible); (I) thin section showing a porphyritic texture with plagioclase, clinopyroxene, and olivine phenocrysts.

Figure 3. Orthogonal vector diagrams show representative alternating field demagnetization data and in situ coordinates. Black and white dots indicate projections of paleomagnetic directions onto the horizontal and vertical planes, respectively. NRM—natural remanent magnetization.

Figure 4. (A) Equal-area projections (lower hemisphere) of site-mean paleomagnetic directions from the three lava flows are shown. Ellipses around the paleomagnetic directions are the projections of the relative α_{95} cones. (B–C) Projection of flow-mean paleomagnetic directions obtained by averaging (B) all characteristic remanent magnetizations (ChRMs) from each lava flow and then (C) considering the San Giovanni Galermo and Larmisi flows together. Ellipses around the paleomagnetic directions are the projections of the relative α_{95} cones. All paleomagnetic directions are listed in Table 2.

Figure 5. Paleomagnetic dating results of the Barriera del Bosco and San Giovanni Galermo-Larmisi flows are shown according to the Pavón-Carrasco et al. (2011) method and software and the Pavón-Carrasco et al. (2014) paleo-secular variation (PSV) reference model. In each panel, PSV curves for the declination (left-hand panel) and the inclination (right-hand panel) are shown as thick light gray lines (thin light gray lines indicate associated errors at the 95% confidence level) with the probability density curves (in gray-shade below each PSV). Paleomagnetic declination and inclination values are shown in the PSV graphs as dark gray straight lines; the light gray straight lines above and below are the 95% associated errors. In the probability density graphs the 95% confidence level is shown as a light gray straight line. Ages are in yr B.P. (present is A.D. 1950).

Figure 6. Overall framework of the paleomagnetically inferred ages for the Barriera del Bosco, Larmisi, San Giovanni Galermo, and San Giovanni Galermo-Larmisi flows (more likely age intervals are shown with bold countour boxes; see text for details). Dashed boxes indicate the lava flows’ input time windows. Arrows represent the archaeologically constrained ages. The two dark gray straight lines are the lower and upper age constraints shared by the San Giovanni Galermo and Larmisi flows, respectively, which were used to date the new unified San Giovanni Galermo-Larmisi lava flow. Ages are in yr B.P. (present is A.D. 1950).

Figure 7. Updated geological map of the Catania urban district (modified from Branca et al., 2011b) considers the new paleomagnetic data and includes the locations of archaeological sites recognized within the lava flows (modified from Branca et al., 2016).