Geological Society of America Bulletin, published online on 18 April 2014 as doi:10.1130/B30933.1

Geological Society of America Bulletin

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THE GEOLOGICAL SOCIETY OF AMERICA

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Constraining chronology and time-space evolution of Holocene volcanic activity on the Capelo Peninsula (Faial Island, Azores): The paleomagnetic contribution

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ABSTRACT

Faial is one of the most volcanically active islands of the Azores Archipelago. Historical eruptions occurred on the Capelo Peninsula (westernmost sector of the island) during A.D. 1672–1673 and more recently in A.D. 1957–1958. The other exposed volcanic products of the peninsula are so far loosely dated within the Holocene. Here, we present a successful attempt to correlate scoria cones and lava flows yielded by the same eruption on the Capelo Peninsula using paleomagnetic data from 31 sites (10 basaltic scoriae, 21 basaltic lava flows). In the investigated products, we recognize at least six prehistoric clusters of volcanic activity, whereas 11 lava sites are correlated with four scoria cones. Dating was conducted by comparing our paleomagnetic directions with relocated Holocene reference curves of the paleosecular variation of the geomagnetic field from France and the UK. We find that the studied volcanic rocks exposed on the Capelo Peninsula are younger than previously believed, being entirely formed in the last 8 k.y., and that the activity intensified over the last 3 k.y. Our study confirms that paleomagnetism is a powerful tool for unraveling the chronology and characteristics of Holocene activity at volcanoes where geochronological age constraints are still lacking.

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INTRODUCTION

Dating and correlation of eruptive events are challenging aims in volcanic areas when no geochronological dating and reference stratigraphic levels are available. This may be further hampered by the lack of suitable rock chemistry of the investigated volcanic products, characterized by similar petrographic features, as occurs in basaltic-like intra-oceanic volcanic islands. In this paper, we show that analysis of the paleosecular variation (PSV) of the geomagnetic field recorded by volcanic rocks can be used as a valid correlating and dating tool, which may help to solve first-order geological problems. Our study is focused on the PSV of the geomagnetic field recorded in the Holocene volcanic rocks exposed in the western sector of Faial Island (Azores).

Faial is one of the most active volcanic islands of the Azores Archipelago (Fig. 1). Detailed studies of recent volcanic eruptions on the island have been mainly focused on the explosive eruptions of Caldeira volcano (e.g., Madeira, 1998; Pacheco, 2001) and the A.D. 1957–1958 Capelinhos Surtseyan eruption (Cole et al., 2001, and references therein), located on the Capelo Peninsula in the westernmost sector of the island. The Capelo Peninsula consists of a dextral en echelon alignment (WNW-ESE) of scoria cones, and minor tuff cones, with associated lava flows emplaced during the Holocene. The two historical witnessed eruptions of Faial occurred in this part of the island in A.D. 1672–1673 and 1957–1958. The bathymetric data offshore of the Capelo Peninsula provide a picture of the shelf morphology, which is characterized by well-preserved lava structures on the top of the insular shelf (30–50 m below the present-day sea level). The shelf formed during the warm Holocene period (11–9 ka; Dias, 1985; Dias et al., 2000), corresponding to the Bölling in northern Europe (e.g., Deschamps et al., 2012). The good preservation of these lava structures, corresponding to subaerial flows that crossed the cliff into the sea, suggests that their emplacement occurred after the Holocene transgression (11–9 ka) had submerged the insular shelf; otherwise, lava flows would not have survived surf erosion during sea-level rise (Quartau et al., 2010, 2012). The chronology of prehistoric volcanic activity on Capelo Peninsula is poorly constrained and exclusively based on stratigraphic correlations (Serralheiro et al., 1989) and geomorphological evidences (Madeira, 1998). Constraining the age of Holocene eruptions and understanding the stratigraphic relations among cones and between cones and lava flows are fundamental issues, both for the statistical assessment of spatial and temporal volcanic patterns and for hazard implications.

Pyroclasts generally pile up around circular or elongated vents, building up conical landforms (truncated at the top). Scoria cones are formed due to the accumulation of pyroclastic material around vents during Hawaiian, Strombolian, sub-Plinian, and/or phreatomagmatic eruptions. The majority of scoria cones are monogenetic, resulting from a single eruptive event (e.g., Wood, 1980a). Elongate monogenetic landforms can result from a single eruptive vent, occurring along a fissure (Breed, 1964; Wood, 1980a), or a number of vents aligned along a fissure (e.g., Riedel et al., 2003). Scoria cones

GSA Bulletin; doi: 10.1130/B30933.1; 6 figures; 3 tables; Data Repository item 2014182.

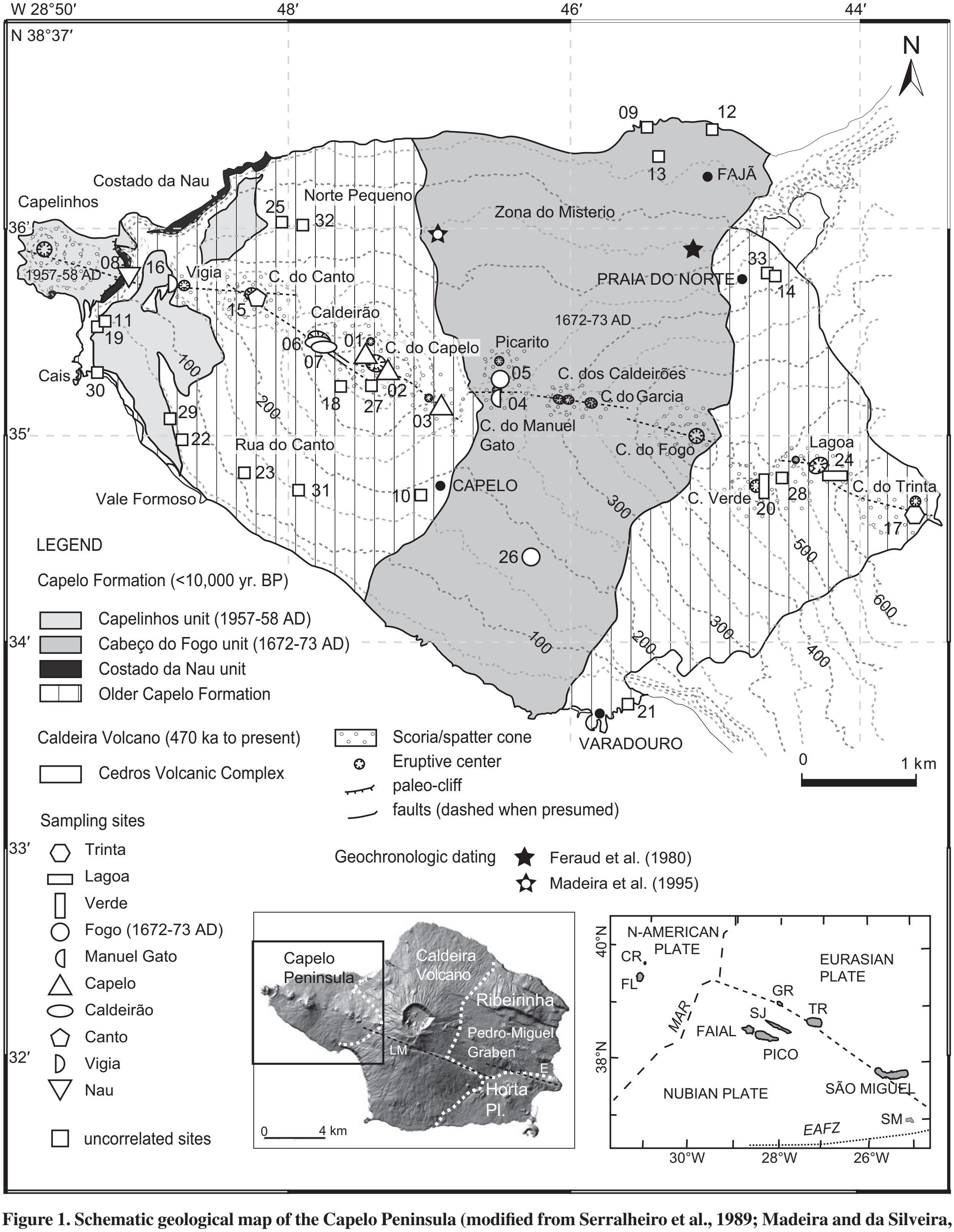

Figure 1. Schematic geological map of the Capelo Peninsula (modified from Serralheiro et al., 1989; Madeira and da Silveira, 2003) and location of paleomagnetic sampling sites (the "FAY" prefix is omitted). C—abbreviation for Cabeço (= local name for volcanic cone). Bottom middle inset: Digital elevation model (DEM) with geomorphological and volcanological subdivision of Faial Island is modified from Madeira (1998), where LM—Lomba do Meio fault and E—Espalamaca fault. Bottom right inset: Schematic map of the Azores Archipelago: CR—Corvo; FL—Flores; GR—Graciosa; TR—Terceira; SJ—Sao Jorge; SM—Santa Maria; MAR—Mid-Atlantic Ridge; EAFZ—East Azores fracture zone.

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are typically clustered in cone fields or distributed on plateaus (e.g., Michoacán–Guanajuato, Mexico—see Hasenaka and Carmichael, 1985; San Francisco volcanic field, Arizona—Priest et al., 2001), or they occur as parasitic cones along eruptive fractures on the flanks of stratovolcanoes (e.g., Etna—see Corazzato and Tibaldi, 2006).

In the case of the Capelo Peninsula, scoria cones dominate the axial part, while lavas are exposed at the peninsula toe and close to the sea. As a general rule, there are no clear field correlations between cones and lavas, mostly because of the lack of extensive outcrops and the thriving vegetation that is widespread in the Azores Islands. Wood (1980a) argued that scoria cone eruptions commonly produce lava flows, while cone eruptions without lava extrusion rarely occur. Traditionally, the petrography of volcanic products has been used to study the source characteristics of lavas and scoria and to correlate volcanic deposits whenever the stratigraphic approach is not conclusive. However, changes in petrographic characteristics can occur during eruptive events (e.g., Blake, 1981; Strong and Wolff, 2003), making correlation of syndepositional volcanic products questionable.

Elsewhere, scoria cones have also been dated and correlated through geomorphological studies based on morphometric and geometric characteristics using topographic maps (Wood, 1980b; Hooper, 1995), high-resolution digital terrain models (Parrot, 2007; Fornaciai et al., 2012), and satellite images (Wood, 1980b; Hasenaka and Carmichael, 1985; Hooper, 1995; Inbar and Risso, 2001; Parrot, 2007). The criterion applied is based on the time of exposure to erosional processes: the longer the period of erosion, the smaller is the aspect ratio of the cones. Surprisingly, the slope angle decreases rapidly in the first years after eruption (e.g., Wood [1980b] stated that recent cone slopes on Mount Etna decreased by 10° in only 450 yr). The alignment of cones generally suggests that they were formed by dike intrusion during a single eruptive event. However, in regions where tectonic processes control volcanic landform distribution over long periods of time, the repetition of similar elongation trends may complicate this straightforward interpretation.

To sum up, petrographic and geomorphologic studies may not be conclusive for correlation among scoria cones and correlation with lava flows exposures. Conversely, in this paper, we demonstrate how paleomagnetic directions from scoria (or spatter) cones and underlying lava flows can be used as an accurate correlative and dating tool, thus providing significant constraints for the interpretation of the Holocene volcanic history of the Capelo Peninsula.

Use of the Paleosecular Variation of the Geomagnetic Field as a Dating and Correlation Tool for Volcanic Rocks

Absolute ages of volcanic products are best determined through isotopic dating. However, both Ar/Ar and K/Ar methods lose accuracy when applied to young (Holocene) products, and they can hardly be used in K-poor volcanic rocks (e.g., basalts erupted in most intra-oceanic volcanoes). The ^{14}C isotope is a powerful dating tool for the last few millennia, but it needs carbon-rich soils, which can be uncommon under some climatic conditions and in regions with high eruption frequencies.

As a consequence, during recent years, there has been an increasing use of the paleosecular variation (PSV) of the geomagnetic field recorded in volcanic rocks as an accurate dating and correlation tool for eruptions (Rutten and Wensink, 1960; Doell and Cox, 1965; Soler et al., 1984; Thompson and Turner, 1985; Rolph et al., 1987; Hagstrum and Champion, 1994; Carlut et al., 2000; Incoronato et al., 2002; Lanza and Zanella, 2003; Tanguy et al., 2003; Lanza et al., 2005; Speranza et al., 2008, 2010; Vezzoli et al., 2009; among many others). During cooling, volcanic rocks record an instantaneous snapshot of the local geomagnetic field direction, which undergoes large swings through time (at least 40° in declination and 30° in inclination, at the latitude of the Azores). The advantage of the paleomagnetic dating method is that it can be used on whole-rock samples, and it does not require particular petrographic or geochemical characteristics (magnetic remanence is generally carried by titanomagnetite, which is ubiquitous in volcanic rocks).

Paleomagnetic dating is achieved by comparing the paleomagnetic directions "frozen" in lava flows and scoria cones to a PSV reference curve gathered in nearby regions by geomagnetic observations, archeomagnetism, and paleomagnetism of sedimentary successions deposited at high rates, and relocated to the sampling site by the conversion via pole method (Noel and Batt, 1990). A recent compilation of all European geomagnetic–archeomagnetic data sets (Speranza et al., 2008) revealed that during the Holocene, the field reached a maximum rate of change of ~7° per 100 yr in the central Mediterranean region. Therefore, a paleomagnetic direction defined with an accuracy of 2°–4° can translate (after comparison with a PSV reference curve) into dates defined with an accuracy of ~100 yr in the most favorable cases (see discussions in Speranza et al., 2006; Lanza and Zanella, 2006). However, we stress that volcanic products of different ages may share the same paleomagnetic direction by chance, because the geomagnetic field may reoccupy the same direction after a few centuries or millennia. Thus, the paleomagnetic dating method is effective only when an input age window (preferably small) is provided by independent methods (e.g., isotopic dating). Moreover, although the geomagnetic field is predominantly dipolar, the non-dipole component imparts a significant regional component to the geomagnetic field, such that PSV reference curves do not have a global validity (Merrill et al., 1996) and cannot be safely relocated by the conversion via pole method at distances greater than ~3000 km.

Noel and Batt (1990) evaluated the angular differences with respect to the International Geomagnetic Reference Field (IGRF) of the year 1985 to be expected at different locations on Earth when the relocation via pole method is used. They found maximum errors of 2° for 40–60°N latitudes and a circular relocation area of 1200 km of radius. Lanza et al. (2005) showed that the relocation of data by pole method from Chambon La Forêt (France) to L'Aquila (Italy), a distance of ~1100 km, introduces an error of less than 2°. Conversely, Casas and Incoronato (2007) argued that the relocation error for the present geomagnetic field increases linearly with the relocation distance (with a maximum of 7° for a 1700 km radius). Pavòn-Carrasco and Villasante-Marcos (2010) investigated the error induced by the relocation from Madrid to the Canary Islands, concluding that the error was generally smaller than the statistical errors affecting the paleomagnetic directions themselves. On the other hand, available global models (e.g., CALS10k by Korte et al., 2011), which overcome the pole relocation problem, can barely be used for dating purposes because their trend is typically smoothed, tending to average out the secular variations or swings (see discussion in Snowball et al., 2007; Zananiri et al., 2007; Speranza et al., 2008).

In this study on the Faial Island, we used the pole method to relocate the French archeomagnetic curve (gathered 2300–2800 km away; Bucur, 1994; Gallet et al., 2002) and UK master curve (2500–2600 km away; Turner and Thompson, 1981, 1982), which have been widely used for paleomagnetic dating on Italian volcanoes and Holocene marine cores from the Mediterranean Sea (Sagnotti et al., 2011). For testing the effective applicability of the two curves as a dating tool, we compared their angular deviation with CALS10k calculated at Faial coordinates. We suggest that the UK-French curves can be safely used for dating purposes at Faial, as the angular deviation we found (from 1° to 5°) is equal to or smaller than the mean error of our data set. Besides yielding absolute dating (if appropriate PSV reference curves are available), paleomagnetism is always a powerful correlative tool for volcanic products lacking field correlation evidence. Hagstrum and Champion (1994) used paleomagnetism as a correlative tool for scattered outcrops of late Quaternary lava flows in the lowest east rift zone of Kilauea volcano (Hawaii). Jurado-Chichay et al. (1996) paleomagnetically studied the Pohue Bay flow (Mauna Loa volcano, Hawaii) and used the associated cones to determine the cone origin (primary or secondary processes). Recently, Speranza et al. (2012) correlated several dispersed Pleistocene ignimbrite deposits on Pantelleria Island (Italy), relying on their paleomagnetic directions.

Faial Island

The island of Faial belongs to the central group of the Azores Archipelago (Fig. 1). The nine volcanic islands of the archipelago straddle the Mid-Atlantic Ridge, where the Eurasian, Nubian, and North American plates meet. Tectonically, the Azores correspond to a transtensional regime as described by global positioning system (GPS) kinematic models, with ENE-WSW–trending extension of 3–4 mm/yr (e.g., Sella et al., 2002; Vogt and Jung, 2004; Fernandes et al., 2006; Marques et al., 2013).

The pentagonal shape of Faial (21 km long and 14 km wide) arises from a general WNW-ESE regional tectonic trend, the Pico-Faial Ridge alignment, and subordinate NW-SE and NE-SW fault systems (Agostinho, 1937; Machado, 1955, 1982; Tazieff, 1959; Zbyszewski et al., 1959; Zbyszewski and Ferreira, 1959; Chovelon, 1982; Serralheiro et al., 1989; Madeira and Ribeiro, 1990; Madeira, 1998; Camacho et al., 2007; Trippanera et al., 2014).

Pacheco (2001) provided an updated volcanostratigraphic framework of Faial previously described by Zbyszewski et al. (1959), Machado and Forjaz (1968, 1978), Forjaz (1977), Chovelon (1982), Serralheiro et al. (1989), and Madeira (1998). Four geomorphologic regions, corresponding roughly to four main volcanostratigraphic units, are recognized (inset of Fig. 1): (1) The Pedro Miguel graben region includes the products from the Ribeirinha volcanic complex, located in the NE part of the island, which was emplaced from ca. 730 to 580 ka (Feraud et al., 1980; Serralheiro et al., 1989). The Ribeirinha complex is formed by an extinct shield-volcano mainly constituted of hawaiitic lavas and later dislocated by the faults of Pedro Miguel graben. Paleomagnetic results from Silva et al. (2010) and isotopic dating of Hildenbrand et al. (2012) demonstrated that the onshore volcanic activity started during the Matuyama chron at ca. 0.85 Ma, ~0.1 m.y. older than the age reported in previous works. (2) The Caldeira volcano, located in the central part of the island, is a stratovolcano truncated by a 2-km-wide caldera and comprises the Cedros volcanic complex, which was emplaced from >440 ka (Feraud, 1977; Feraud et al., 1980; Demande et al., 1982; Serralheiro et al., 1989; Madeira and da Silveira, 2003) to present day. (3) The Horta Platform, located in the SE part of the island, is a plateau of basaltic lavas and scoria cones, named the Almoxarife Formation, poorly dated between 30 ± 20 ka (K/Ar method by Feraud et al., 1980) and ~10 ka (Madeira, 1998). (4) The Capelo Peninsula, located in the westernmost part of the island, was built by the products of the Capelo Formation. The Capelo Peninsula is thought to have developed entirely during the Holocene (Madeira et al., 1995; Quartau et al., 2012), and it is related to the position of scoria and tuff cones aligned along a WNW-ESE ridge. Two historical eruptions have been recorded: the A.D. 1672–1673 Cabeço do Fogo eruption (Zbyszewski, 1960; Machado, 1958a, 1959c, 1967; Machado et al., 1962), and the A.D. 1957–1958 Capelinhos eruption (Machado, 1958a, 1958b, 1959a, 1959b; Castello-Branco et al., 1959; Zbyszewski and Ferreira, 1959; Machado et al., 1962; Cole et al., 2001). A reconstruction of the temporal and spatial evolution of the volcanism and erupted volumes of the prehistorical (i.e., pre–A.D. 1672) activity at Capelo Peninsula has not been attempted so far.

Recently, Hildenbrand et al. (2012) provided 15 new K/Ar dates, further constraining the ages of Faial rocks, which, when integrated with digital elevation model (DEM) and magnetic anomaly and tectonic analyses, lead to a different evolution scheme of timing and distribution of volcano-stratigraphic units. However, the work of Hildenbrand et al. (2012) has been criticized by Quartau and Mitchell (2013).

The present study focuses on revealing the volcanic chronostratigraphy of the Capelo Peninsula, the most recent and least age-constrained products of the volcanic history of Faial Island.

Capelo Peninsula: Main Features of Studied Scoria Cones and Lava Flows

The Capelo Peninsula is a triangle-shaped, 27 km^2 basaltic ridge forming the western part of Faial (Fig. 1), and it is thought to have developed entirely during the Holocene (Serralheiro et al., 1989), according to analysis of its submerged insular shelf (Quartau et al., 2012). Predominantly subaerial low-explosivity (Hawaiian to Strombolian) basaltic eruptions yielded 15 well-preserved scoria cones (locally called Cabeços; we refer to Pacheco [2001] for cone nomenclature and characteristics). Some of the cones (probably from Trinta to Manuel Gato; Fig. 1) developed above the western mountainside of the Caldeira volcano (Fig. 1). Evidence of submarine/hydromagmatic phases can be observed on the westernmost part of the peninsula, at paleo–sea cliffs at Costado da Nau (Fig. 2), and was witnessed during the historical eruption of Capelinhos in A.D. 1957–1958.

The 15 major cones of the Capelo Peninsula are aligned along WNW-ESE– to NW-SE–trending, en echelon, offset-to-the-right tectonic structures. Madeira (1998) suggested that the Capelo fracture zone may constitute the western extension of the Lomba do Meio fault (LM; Fig. 1), corresponding, along with the Pedro Miguel graben faults (Fig. 1), to the same tectonic structure as the Faial-Pico lineament. This represents a very high concentration of eruptive vents (Trippanera et al., 2014), which could correspond to a high volcanic activity frequency in recent times (i.e., during the Holocene). Madeira (1998) found that the vent clusters in Capelo are arranged in an overall left-stepping, en echelon configuration, implying a dextral component of shear, in good agreement with kinematic data obtained by geodesy and seismology (e.g., Madeira and da Silveira, 2003; Borges et al., 2007).

From east to west, 15 volcanic cones are observed and well exposed (Figs. 1 and 2): Cabeço dos Trinta, Lagoa, Cabeço Verde, Cabeço do Fogo, Cabeço do Garcia, the twin cones of Cabeços dos Caldeirões, Cabeço do Manuel Gato, Cabeço do Picarito, Cabeço Verde W or do Capelo, Caldeirão, Cabeço do Canto, Vigia, Costado da Nau (or Cabeço dos Concheiros), and Capelinhos.

Among them, the Cabeço do Fogo cone (Fig. 2B) was emplaced during the historical eruption of A.D. 1672–1673 (Zbyszewski, 1960; Machado, 1967; Machado et al., 1962; Camus et al., 1981), which began on 24 April 1672 and ended in February 1673. It was characterized by Strombolian phases, building the Cabeço do Fogo (Zbyszewski and Ferreira, 1959; Zbyszewski et al., 1959; Castello-Branco et al., 1959), and later, the Picarito cones (different from the "Picarito" referred by Castello-Branco et al. [1959], which is now recognized as Cabeço do Fogo; Zbyszewski et al., 1959), and by a profuse outpouring of lava from the two scoria cones along a N75°W trending fissure. Lava flows covered the northern Capelo slope among Norte Pequeno, Fajã, and Praia do Norte, and to the south reached the coast, covering the area west of Varadouro village (Fig. 1).

Costado da Nau (Waters and Fisher, 1971; Camus et al., 1981) is the product of a prehistoric eruption, located on the westernmost tip of Capelo Peninsula; the remnant of the vol-

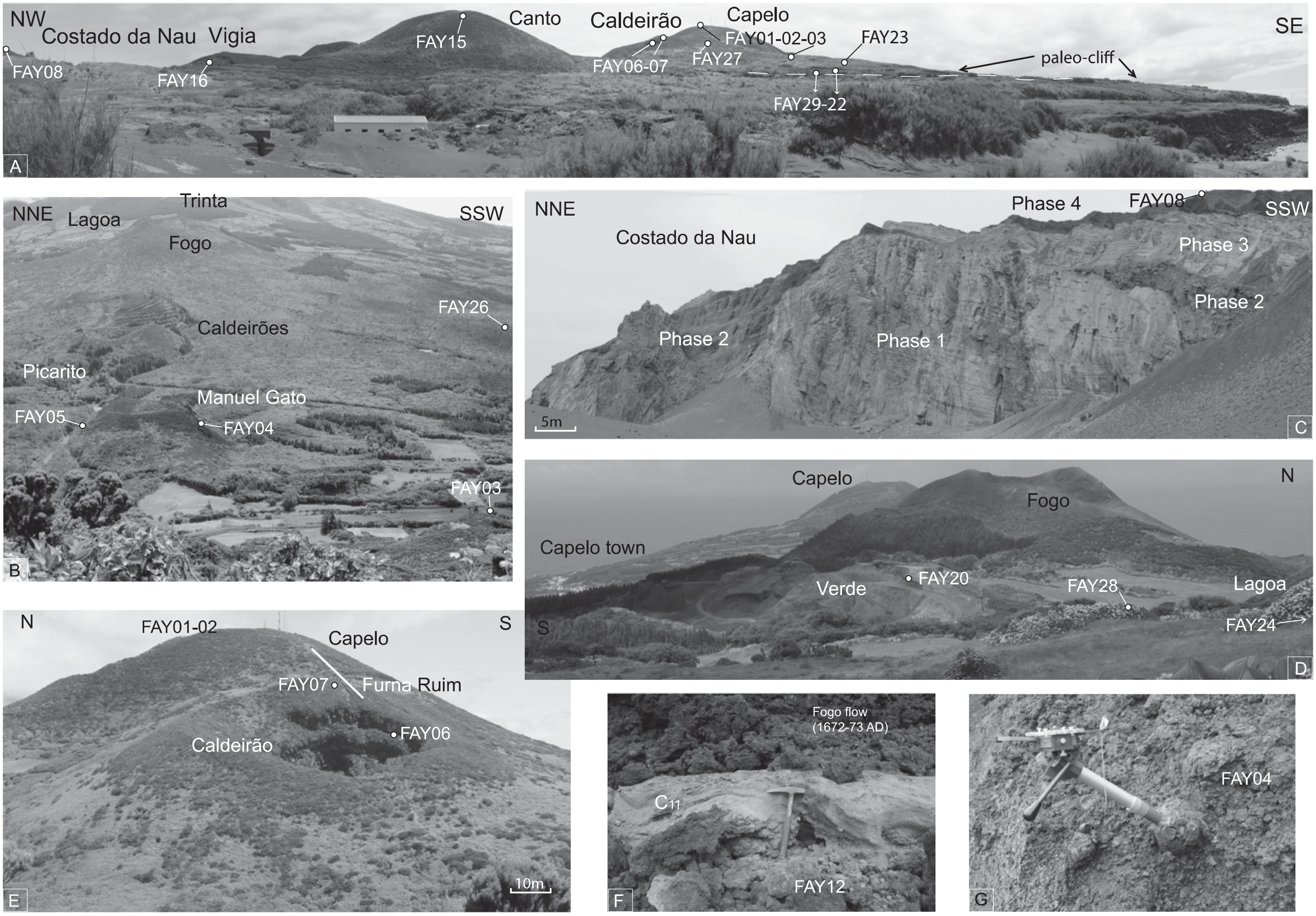

Figure 2. Photos from Capelo Peninsula. (A) Overview from Cais harbor of WNW-ESE–aligned scoria cones of Capelo (sampling sites FAY01, FAY02, FAY03, FAY27, and FAY29), Caldeirão (FAY06 and FAY07), Canto (FAY15), Vigia (FAY16), and Costado da Nau (FAY08), as well as an older paleocliff (FAY22 and FAY29). (B) Overview (from the top of the Capelo cone) of the aligned scoria cones: from Picarito (site FAY05), Manuel Gato (FAY04), the twin Caldeirões cones, Fogo (FAY26; A.D. 1672–1673 historical eruption), and of the Lagoa and Trinta cones in the rear. (C) Costado da Nau cone section cut by marine erosion, showing the four magmatic/hydromagmatic phases. (D) Landscape from the Trinta cone looking westward, and cones of Lagoa (site FAY24), Verde (FAY20), Fogo, and Capelo. (E) Capelo (FAY01 and FAY02) and Caldeirão (FAY06 and FAY07) cones seen from Canto cone; the Furna Ruim fracture between the two cones is marked with a line. (F) Key outcrop of the C11 pyroclastic deposit between the A.D. 1672–1673 lava flow and site FAY12, at Fajã beach. (G) Close-up of paleomagnetic core on a rounded bomb during in situ orientation by solar and magnetic compass, at site FAY04 on Manuel Gato scoria cone.

cano is exposed along a paleo–shore cliff (Fig. 2C), active before the A.D. 1957–1958 Capelinhos eruption. The volcanic appearance has similarities with Capelinhos, since it resulted from a sequence of two hydromagmatic phases (phase 1 and 3, with layered welded and nonwelded tuffs), alternated with two magmatic events; the lower magmatic phase (phase 2) is characterized by ~100-m-thick lava flows, and the upper phase is characterized by spatter scoriae and bombs (phase 4; Fig. 2C). A network of dikes, exposed in the northern coast, feeds these lava flows. In the geological map of Serralheiro et al. (1989), Costado da Nau is reported as an independent unit without any age indication.

The latest A.D. 1957–1958 eruption took place on the westernmost tip of the island. The Capelinhos eruption was described by several authors (e.g., Machado, 1958a, 1959a, 1960; Machado et al., 1962; Tazieff, 1959; Castello-Branco et al., 1959; Zbyszewski and Ferreira, 1959; Zbyszewski, 1960, 1963; Forjaz, 1965; Machado and Forjaz, 1968; Waters and Fisher, 1971; Camus et al., 1981; Cole et al., 1996, 2001), and an extensive photographic record is available.

Geochronological data available for the Capelo Peninsula are scarce, as they likely all refer to the A.D. 1672–1673 historical event. In the area of Praia do Norte, Feraud et al. (1980) sampled a hawaiite lava (FA71 site) and obtained a seventeenth-century age by K/Ar dating. Madeira et al. (1995) reported a ^{14}C age of 320 ± 50 yr B.P. on charred wood (site FA2, Norte Pequeno locality) sampled from a mudflow deposit. By using the program CALIB6.0 Online (Stuiver et al., 2005; http://calib.qub.ac.uk/calib/calib.html), we get an A.D. 1455–1654 (1σ) calibrated age, again suggesting that the overlying flow is from the Cabeço do Fogo event.

A key stratigraphic marker used to assess the age of Capelo volcanic rocks is the so-called

TABLE 1. LOCATIONS OF SAMPLING SITES AT CAPELO PENINSULA, FAIAL

Site	Locality	Latitude (°N)	Longitude (°W)	Altitude (masl)	d (°)
Fay01	Sc. from C. do Capelo cone	38.59226	28.79894	482	–11.1 ± 1.7
Fay02	Sc. from C. do Capelo cone	38.5919	28.79649	473	–13.9 ± 1.7
Fay03	Sc. from C. do Capelo cone	38.58923	28.79155	282	–4.1 ± 1.3
Fay04	Sc. from C do Manuel Gato cone	38.59007	28.78573	242	–6.9 ± 4.0
Fay05	Sc. from historical Picarito cone (A.D. 1672–1673)	38.59143	28.785	251	1.7 ± 3.0
Fay06	Lava from Caldeirão, rim	38.59401	28.80385	341	–17.5 ± 1.9
Fay07a	Sc. from Caldeirão cone rim	38.59396	28.80327	380	–0.9 ± 4.3
Fay07b	Sc. from Caldeirão cone rim	38.59404	28.80299	391	–0.9 ± 4.3
Fay08	Sc. from Costado da Nau, phase 4	38.59848	28.82321	117	–9.3 ± 0.9
Fay09	Xenolith-rich lava from Fajã quarry	38.61238	28.76964	14	–7.8 ± 6.8
Fay10	Lava from Capelo town	38.58278	28.79357	203	–13.9 ± 2.0
Fay11	Cais lava from Capelinhos, lighthouse	38.59546	28.82701	39	–9.3 ± 3.6
Fay12	Xenolith-rich lava from Fajã beach	38.61209	28.76286	7	–8.0 ± 3.1
Fay13	Fogo lava (?) from Zona do Misterio quarry	38.60933	28.76859	46	–8.0 ± 1.9
Fay14	Lava from Casa do Povo, in Praia do Norte town	38.60002	28.75914	315	–14.0 ± 2.2
Fay15	Sc. from Canto cone	38.59812	28.81012	331	–6.9 ± 3.1
Fay16	Sc. from Vigia cone	38.59846	28.81906	147	–5.0 ± 1.7
Fay17	Sc. from Trinta cone	38.58173	28.74157	720	–17.7 ± 2.5
Fay18	Lava from Capelo cone S flank	38.59099	28.80136	343	–12.8 ± 3.7
Fay19	Cais lava from Capelinhos, lighthouse	38.59523	28.82735	18	–7.6 ± 2.2
Fay20	Sc. from Verde cone	38.58417	28.75782	520	–14.2 ± 2.9
Fay21	Lava from Varadouro hydrothermal bath	38.56623	28.77079	4	–13.3 ± 7.0
Fay22	Lava from Vale Formoso lighthouse	38.58517	28.81746	54	–4.3 ± 3.7
Fay23	Lava from Vale Formoso locality	38.58443	28.81128	54	–3.8 ± 2.9
Fay24	Lava from C. do Lagoa	38.5863	28.75132	566	–8.9 ± 2.8
Fay25	Lava from Norte Pequeno	38.60331	28. 80622	223	–20.0 ± 1.9
Fay26	Historical lava from C. do Fogo (A.D. 1672–1673)	38.57798	28.78052	183	–6.3 ± 8.1
Fay27	Lava from C. di Capelo, S flank	38.59106	28.79789	446	–5.5 ± 2.7
Fay28	Lava from Levada-Praia do Norte crossroad	38.58443	28.75619	511	–14.4 ± 1.1
Fay29	Lava from Vale Formoso cliff	38.58686	28.81833	38	–5.8 ± 1.8
Fay30	Lava from Cais, harbor	38.59167	28.82629	2	–6.8 ± 1.7
Fay31	Lava from Rua do Canto	38.58309	28.80425	150	–3.3 ± 2.7
Fay32	Lava from Norte Pequeno	38.60347	28.8053	132	–9.3 ± 5.6
Fay33	Lava from Praia do Norte	38.60022	28.7595	312	

Note: Site coordinates and altitude were gathered with a Garmin global positioning system (GPS) using WGS84 datum. Sc.—scoriae or spatter deposit; C—Cabeço (= local name for volcanic cone); L.—lava flow deposit. masl—meters above sea level; d—site-mean magnetic declination (and standard deviation) calculated by comparison between magnetic and sun compass readings of the paleomagnetic core orientations.

C11 pyroclastic deposit of the Upper Group of the Cedros volcanic complex (Pacheco, 2001). The C11 is a trachytic pyroclastic layer, well constrained from ^{14}C dates (Pacheco, 2001) to 980 ± 50 yr B.P., which, calibrated using the online program CALIB6.0, yields an age of A.D. 1076 ± 103 (2σ, A.D. 973–1179). On the NE side of the Capelo Peninsula, unequivocal stratigraphic relations between the C11 deposit and lavas flows were observed (Fig. 2F).

SAMPLING AND METHODS

During July 2011, we paleomagnetically sampled 33 sites in the Capelo Peninsula, 11 from scoria/spatter deposits from 9 different cones and 22 from basaltic-like lava flows (Figs. 1 and 2; Table 1). Five of the sampled lava sites showed clear field correlations with four cones, as they were sampled on lava flows unquestionably coming from given vents: FAY24 with Lagoa scoria cone, FAY06 with Caldeirão, FAY18 and FAY27 with the Capelo cone, and FAY26 with Cabeço do Fogo. At each site, we drilled 15 (on average) 2.5-cm-diameter cores using a water-cooled, gasoline-powered portable drill. We spaced the cores as much as possible in the studied outcrops to gather a well-averaged, representative paleomagnetic direction for each site. All cores were oriented using a magnetic and a sun compass, except site FAY33, for which we could only get orientation by the magnetic compass. The local field declination values (i.e., the differences between the magnetic and sun compass readings) are between –20° and 1° (average –9.1°; Table 1), which compare well with the declination yielded by the IGRF-11 model (International Association of Geomagnetism and Aeronomy, Working Group V-MOD, 2010) for Faial at 38.59°N, 28.80°W (D = –10°33′). Some of the sites show clear stratigraphic relations with the well-dated (A.D. 1076 ± 103) C11 pyroclastic layer: Lava sites FAY14 and underlying FAY33 are both older than C11; at Fajã beach, a lava characterized by large xenoliths (up to 30 cm in diameter) of olivine and clinopyroxene, sampled at sites FAY09 and FAY12, is mantled by C11, in turn lying below the A.D. 1672–1673 lava (Fig. 2F).

The sampled cores were cut into standard cylindrical specimens. The natural remanent magnetization (NRM) of all specimens was first measured using a 2G Enterprises DC-SQUID cryogenic magnetometer hosted in the shielded room of the paleomagnetic laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (Roma). In total, 187 specimens from 13 sites, characterized by a NRM lower than 10 A/m, were further measured in the cryogenic magnetometer and demagnetized by online alternating field (AF), using 16 demagnetization steps, from 5 mT up to a maximum peak field of 120 mT. The strong (>10 A/m) NRM of the remaining 242 specimens (20 sites) was measured using an AGICO JR6 spinner magnetometer, and thermal demagnetization (TH) was carried out in seven demagnetization steps up to maximum temperatures of 580 °C, using a Pyrox shielded oven.

AF and TH demagnetization data were plotted on orthogonal vector component diagrams (Zijderveld, 1967), and the magnetization components were isolated by principal component analysis (Kirschvink, 1980). Site-mean paleomagnetic directions were computed using Fisher (1953) statistics (Table 2).

In addition, to clarify the magnetic properties of Capelo samples, the following rock magnetic experiments were conducted for 33 samples: (1) thermo-magnetic curves (see supplementary Figs. S2A–S2C[1]), (2) hysteresis

[1]GSA Data Repository item 2014182, Supplementary Figure S1–Thin sections microphotomicrographs under crossed-polarized light; Supplementary Figure S2—Representative results of magnetic mineralogy analyses from sample FAY01, 09, and 11, is available at http://www.geosociety.org/pubs/ft2014.htm or by request to editing@geosociety.org.

TABLE 2. MEAN PALEOMAGNETIC DIRECTIONS FROM CAPELO PENINSULA, FAIAL, AND PALEOMAGNETIC DATING

Site	Unit	*n*/*N*	D (°)	I (°)	k	α_{95} (°)	UK master curve[§] (95%) (7890 B.C.–A.D. 1950)	France[§] (95%) (950 B.C.–A.D. 1800)	SML[§] (95 %) (1000 B.C.–A.D. 1650)	Inferred emplacement age[#]	Inferred volcanic phase
Fay01	Capelo, sc.	09/13	17.3	63.5	437	2.5	1358–982 B.C., 491–458 B.C., 264–217 B.C.	676–398 B.C., 766–870 A.D.		1400–200 B.C.	Capelo ss.
Fay02*	Capelo, sc.	10/10	13.1	58.7	177	3.6	1381–1002 B.C., 482–203 B.C., 622–771 A.D.	734–282 B.C., 619–943 A.D., 672–943 A.D.		1300–200 B.C.	Capelo ss.
Fay03*	Capelo, sc.	11/12	12.2	56.9	254	2.9	1398–1121 B.C., 470–225 B.C., 604–765 A.D.	950–898 B.C., 739–274 B.C., 803–964 A.D.		1300–300 B.C.	Capelo ss.
Fay04	Manuel Gato, sc.	06/09	352.7	57.0	326	3.7	6225–5736 B.C., 5352–5319 B.C., 3551–3407 B.C., 1988–723 B.C., 406 B.C.–76 A.D., 319–382 A.D., 404–516 A.D., 1541–1612 A.D.	145–514 A.D.			?
Fay05	Picarito, sc.	12/12	358.7	65.5	171	3.3	400–100 B.C., **1650–1800 A.D.**	384–122 B.C., 626–754 A.D., 1637–1800 A.D.	852–716 B.C., 230–576 A.D.	1672–73 A.D.	Fogo
Fay06	Caldeirão, l.	10/11	8.0	69.5	167	3.7	**304–147 B.C.,** 1625–1742 A.D.	**508–232 B.C.,** 681–846 A.D.	816–738 B.C., **373–588 A.D.**	300–150 B.C. or 350–550 A.D.?	Caldeirão
Fay07	Caldeirão, sc.	0/10	–	–	–	–	–				–
Fay08[†]	C. da Nau, sc.	0/06 [18/…]	– [8.0]	– [59.4]	– [164.3]	– [2.7]	[5393–5367 B.C., 429–177 B.C., 625–814 A.D., 1622–1634 A.D.]	[589–204 B.C., 545–901 A.D., 1585–1670 A.D.]	*991–194 B.C.,* ***393–652 A.D.***	5400–5350 B.C., or 500–800 A.D.	Nau
Fay09	Xenolith-rich l	13/14	11.7	56.1	415	2.0	1040–1159 B.C., 457–248 B.C., 606–753 A.D.	950–895 B.C., 690–303 B.C., 844–961 A.D., 1571–1645 A.D.	1000–824 B.C., **712–154 B.C., 537–693 A.D.,** 1604–1650 A.D.	450–200 B.C. or 500–800 A.D.	9 = 12
Fay10	Capelo town, l.	10/12	1.6	50.5	416	2.4	6395–6325 B.C., 5414–5258, 3696–3509 B.C., 3481–3306 B.C., 2084–1432 B.C., 150–900 A.D.	950–936 B.C., 392–486 A.D., 1144–1214 A.D., 1424–1568 A.D.		Older than 1400 B.C. or 150–900 A.D.	?
Fay11*	Cais, l.	12/14	26.6	59.7	177	3.3	1357–1330 B.C., **1134–857 B.C., 748–670 B.C., 653–464 B.C.**	740–549 B.C.	628–265 B.C.	1300–450 B.C.	Capelo ss.
Fay12	Xenolith-rich l.	13/15	8.1	57.2	154	3.3	5405–5354 B.C., 1323–1274 B.C., **449–183 B.C., 535–831 A.D.,** 1608–1629 A.D.	950–929 B.C., 611–137 B.C., 493–738 A.D., 803–950 A.D., 1563–1665 A.D.	1000–104 B.C., 455–679 A.D., 1551–1645 A.D.	450–200 B.C. or 500–800 A.D.	9 = 12
Fay13*	Fogo l.	14/14	2.2	72.0	166	3.1	Ca. 170 B.C., **1673–1745 A.D.,** 1756–1811 A.D.	313–292 B.C., **1680–1800 A.D.**	388–358 A.D.	1672–1673 A.D.	Fogo
Fay14*	Praia do Norte, l.	14/15	339.2	50.5	155	3.2	7848–7658 B.C., **3065–2816 B.C.,** 1442–1496 A.D.	950–935 B.C.		3050–2800 B.C. or 1450–1470 A.D.	Lagoa
Fay15*	Canto, sc.	0/15	–	–	–	–	–				–
Fay16	Vigia, sc.	14/15	1.2	58.8	526	1.7	**5405–5358 B.C., 291–289 B.C., 767–847 A.D.**	342 B.C.–23 A.D., 489–648 A.D., 1592–1654 A.D.	927–697 B.C., **304–590 A.D.,** 1531–1592 A.D.	5400–5350 B.C. or 300–600 A.D.	Vigia

(*continued*)

TABLE 2. MEAN PALEOMAGNETIC DIRECTIONS FROM CAPELO PENINSULA, FAIAL, AND PALEOMAGNETIC DATING (*continued*)

Site	Unit	n/N	D (°)	I (°)	k	α_{95} (°)	UK master curve[§] (95%) (7890 B.C.–A.D. 1950)	France[§] (95%) (950 B.C.–A.D. 1800)	SML[§] (95 %) (1000 B.C.–A.D. 1650)	Inferred emplacement age[#]	Inferred volcanic phase
Fay17	Trinta, sc.	07/09	348.5	59.9	277	3.6	**6157–5458 B.C.,** 149–154 A.D., 1721–1763 A.D.	322 B.C.–146 A.D., 277–486 A.D., 1741–1800 A.D.		6150–5450 B.C.	Trinta
Fay18*	Capelo, l.	10/16	13.2	60.4	844	1.7	1336–1251 B.C., 1181–1177 B.C., 451–216 B.C., 276–213 B.C.	661–368 B.C., 777–897 A.D.		1350–200 B.C.	Capelo ss.
Fay19	Cais, l.	11/12	26.1	56.7	244	2.9	**1114–1064 B.C., 1005–836 B.C., 794–450 B.C.**	768–602 B.C.	574–281 B.C.	1100–450 B.C.	Capelo ss.
Fay20	Verde E, sc.	13/14	359.2	50.5	144	3.9	6454–6200 B.C., 5706–5648 B.C., 5491–5142 B.C., 4020–3902 B.C., 3725–3288 B.C., 2281–1493 B.C., 155–899 A.D., 1188–1189 A.D., 1536–1608 A.D.	68–508 A.D., 1166–1275 A.D., 1384–1561 A.D.		Older than 1100 A.D.	?
Fay21	Varadouro, l.	14/14	351.0	59.9	334	2.2	**6104–5704 B.C.,** 5564–5496 B.C., 148 B.C.–150 A.D.	327B.C.–80 A.D., 1780–1800 A.D.		6150–5450 B.C.	Trinta
Fay22*	Vale Formoso, l.	15/15	5.5	50.2	117	3.5	**5407–5348 B.C., 3672–3530 B.C.,** 3363–3317 B.C., 1741–1673 B.C., **1610–1385 B.C.,** 427–383 B.C., 174–212 A.D., 383–414 A.D., 510–765 A.D., 863–865 A.D., 870–1010 A.D.	950–897 B.C., 992–1223 A.D., 1443–1590 A.D.		5400–5350 B.C. or 2000–1300 B.C.	22 = 29
Fay23*	Vale Formoso, l.	15/15	20.1	63.7	126	3.4	1360– 967 B.C., 575–455 B.C., 252–244 B.C.	696–405 B.C., 769–874 A.D.		1350–250 B.C.	Capelo ss.
Fay24*	Lagoa, l.	15/16	345.3	54.8	136	3.3	6235–5732 B.C., 5662–5467 B.C., **3186–2822 B.C.**, 2787–2697 B.C., 2526–2458 B.C., 2359–2283 B.C., 1283–2128 B.C., 82–127 A.D., 1355–1553 A.D.	114–366 A.D.		3150–3000 B.C. or 1350–1470 A.D.?	Lagoa
Fay25*	Norte Pequeno, l.	14/16	349.6	59.8	215	2.7	**6130–5482 B.C.,** 3480 B.C. **147 B.C.–150 A.D.**, 1730–1756 A.D.	328 B.C.–110 A.D., 348–448 A.D., 1759–1800 A.D.	32 B.C.–395 A.D.	150 B.C.–150 A.D.	?
Fay26	Fogo l.	12/13	2.9	64.1	204	3.0	309–137 B.C., 67 B.C.–43 A.D., 774–829 A.D., **1614–1718 A.D.**	440–133 B.C., 585–815 A.D., **1624–1764 A.D.**	1547–1650 A.D.	1672–1673 A.D.	Fogo
Fay27	Capelo, l.	12/13	0.5	62.8	382	2.2	**202 B.C.–54 A.D., 782–833 A.D.,** 1611–1703 A.D.	391–45 B.C., 576–736 A.D., 1624–1750 A.D.	884–684 B.C., 183–593 A.D.	200 B.C.–50 A.D.	Capelo ss.
Fay28*	Lagoa, l.	15/16	354.9	60.4	327	2.1	**6008–5671 B.C., 5530–5490 B.C.,** 3490–3475 B.C., 1908–1861 B.C., 821–837 A.D., 1640–1701 A.D.	331 B.C.–55 A.D.		6150–5450 B.C.	Trinta
Fay29*	Vale Formoso, l.	12/13	0.5	56.1	250	2.7	5924–5917 B.C., 5734–5658 B.C., 5485–5317 B.C., 3616–3459 B.C., **2011–1523 B.C.,** 306–282 B.C., 105–50 B.C., 127–287 A.D., 342–585 A.D., 649–885 A.D., 1565–1644 A.D.	293 B.C.–92 A.D., 369–605 A.D., 1539–1627 A.D.		5400–5350 B.C. or 2000–1300 B.C.	22 = 29

(*continued*)

Geological Society of America Bulletin, published online on 18 April 2014 as doi:10.1130/B30933.1

TABLE 2. MEAN PALEOMAGNETIC DIRECTIONS FROM CAPELO PENINSULA, FAIAL, AND PALEOMAGNETIC DATING (*continued*)

Site	Unit	*n*/*N*	D (°)	I (°)	k	α_{95} (°)	UK master curve[§] (95%) (7890 B.C.–A.D. 1950)	France[§] (95%) (950 B.C.–A.D. 1800)	SML[§] (95 %) (1000 B.C.–A.D. 1650)	Inferred emplacement age[#]	Inferred volcanic phase
Fay30*	Cais down, l.	14/16	14.1	55.7	241	2.6	**1399–1101 B.C., 1057–1045 B.C., 476–332 B.C.,** 628–632 A.D.	950–861 B.C., 786–392 B.C., 844–971 A.D.	1000–873 B.C., **681–167 B.C.,** 551–700 A.D., 1618–1650 A.D.	1400–300 B.C.	Capelo ss.
Fay31	Rua do Canto, l.	10/13	7.5	58.8	228	3.2	5417–5343 B.C., 3585–3543 B.C., 1908–1840 B.C., 1723–1712 B.C., 1576–1530 B.C., 1406–1143 B.C.	584–146 B.C., 517–913 A.D., 1565–1673 A.D.		1400–1350 B.C.	Capelo ss.
Fay32	Norte Pequeno, l.	09/12	3.8	52.5	549	2.2	5412–5347 B.C., 3645–3535 B.C., 3350–3336 B.C., 1737–1427 B.C., 413–405 B.C., 172–212 A.D., 386–414 A.D., 511–771 A.D., 873–904 A.D.	950–931 B.C., 449–536 A.D., 1470–1599 A.D.			?
Fay33	Praia do Norte, l.	09/09	2.5	54.1	511	2.3	**5420–5337 B.C., 3663–3504 B.C.,** 2029–1931 B.C., 1750–1477 B.C., 160–224 A.D., 372–467 A.D., 473–785 A.D., 813–896 A.D., 1579–1615 A.D.	950–939 B.C., 287–213 B.C., 377–588 A.D., 1481–1620 A.D.		5400–5300 B.C. or 3650–3500 B.C.	?

Note: Site names and locations are defined as in Table 1. *n*/*N*—the number of paleomagnetic directions used to calculate the mean direction/total number of samples; D—paleomagnetic declination; I—paleomagnetic inclination; k and α_{95}—statistical parameters after Fisher (1953). Sc.—scoriae or spatter deposit; C—Cabeço (= local name for volcanic cone); l.—lava flow deposit; ss—sensu stricto.

*Sites were alternating field (AF) demagnetized and measured with the 2G cryogenic magnetometer; other sites were thermally (TH) demagnetized and measured with the Agico JR6 Spinner magnetometer. Our results from site FAY08 are scattered, so we considered for Costado da Nau the paleomagnetic directions obtained by Porreca (2013, personal commun.).

†Site FAY08 has a different label since it is from Porreca (2013, personal commun.).

§Ages calculated using archeo_dating program (Pavòn-Carrasco et al., 2011) with 95% confidence, using the UK master curve (Turner and Thompson, 1981, 1982), French (Bucur, 1994; Gallet et al., 2002), and São Miguel (SML) curve (Di Chiara et al., 2012). Preferred ages are in bold.

#Emplacement ages are inferred after this study.

loops (Figs. S2D–S2F [see footnote 1]), and (3) Saturation isothermal remanent magnetization (SIRM) curves (Figs. S2G–S2I [see footnote 1]). We measured hysteresis properties using a Princeton Measurements Corporation MicroMag alternating gradient magnetometer (AGM, model 2900). The low-field magnetic susceptibility during a heating and cooling cycle performed in air, from room temperature up to 700 °C, was measured using an AGICO KLY-3 kappabridge coupled with a CS-3 furnace. In addition, petrographic observations were carried out on four thin sections (see supplementary Figs. S1A-S1D) from lavas and scoriae from Caldeirão cone (FAY06), from Fajã xenolithic lava (FAY09), and from the Fogo historical flow (FAY13 and FAY26). In all of the studied samples phenocrysts and microphenocrysts of olivine, plagioclase and clinopyroxene occur in different proportions. The same mineral phases are found to be part of the groundmass (Fig. S1). Occasionally, Fe-Ti oxides are also present as microphenocrysts and in the groundmass.

RESULTS

Paleomagnetic Results

A well-defined characteristic remanent magnetization (ChRM) was isolated for nearly all lava and scoria samples in the 30–120 mT and 300–580 °C intervals (Fig. 3A). Predominantly low magnetic coercivities and complete demagnetization occurring between 550 °C and 580 °C suggest that ChRMs are carried by Ti-poor titanomagnetites. The α_{95} values relative to the mean paleomagnetic directions for 30 sites vary from 1.7° to 3.9° (2.9° and 2.8° on average for the AF- and TH-demagnetized sites, respectively). Three sites, FAY07, FAY08, and FAY15, yielded scattered directions, which did not improve with the demagnetization, and so they are discarded from further consideration. These three sites were sampled on spatter scoria blocks cropping out on the edges of Caldeirão, Costado da Nau, and Canto cones, respectively, and were probably tilted after deposition. Since our site FAY08 failed, for Costado da Nau we consider the paleomagnetic directions obtained here by Porreca (2013, personal commun.) (Table 2). Site-mean paleomagnetic declinations are mostly positive and vary from ~30° to –20° values (Fig. 3B; Table 2), while inclinations vary between ~50° and 70° (for comparison, the geocentric axial dipole field inclination expected at Capelo Peninsula is 57.9°).

Geological Society of America Bulletin, published online on 18 April 2014 as doi:10.1130/B30933.1

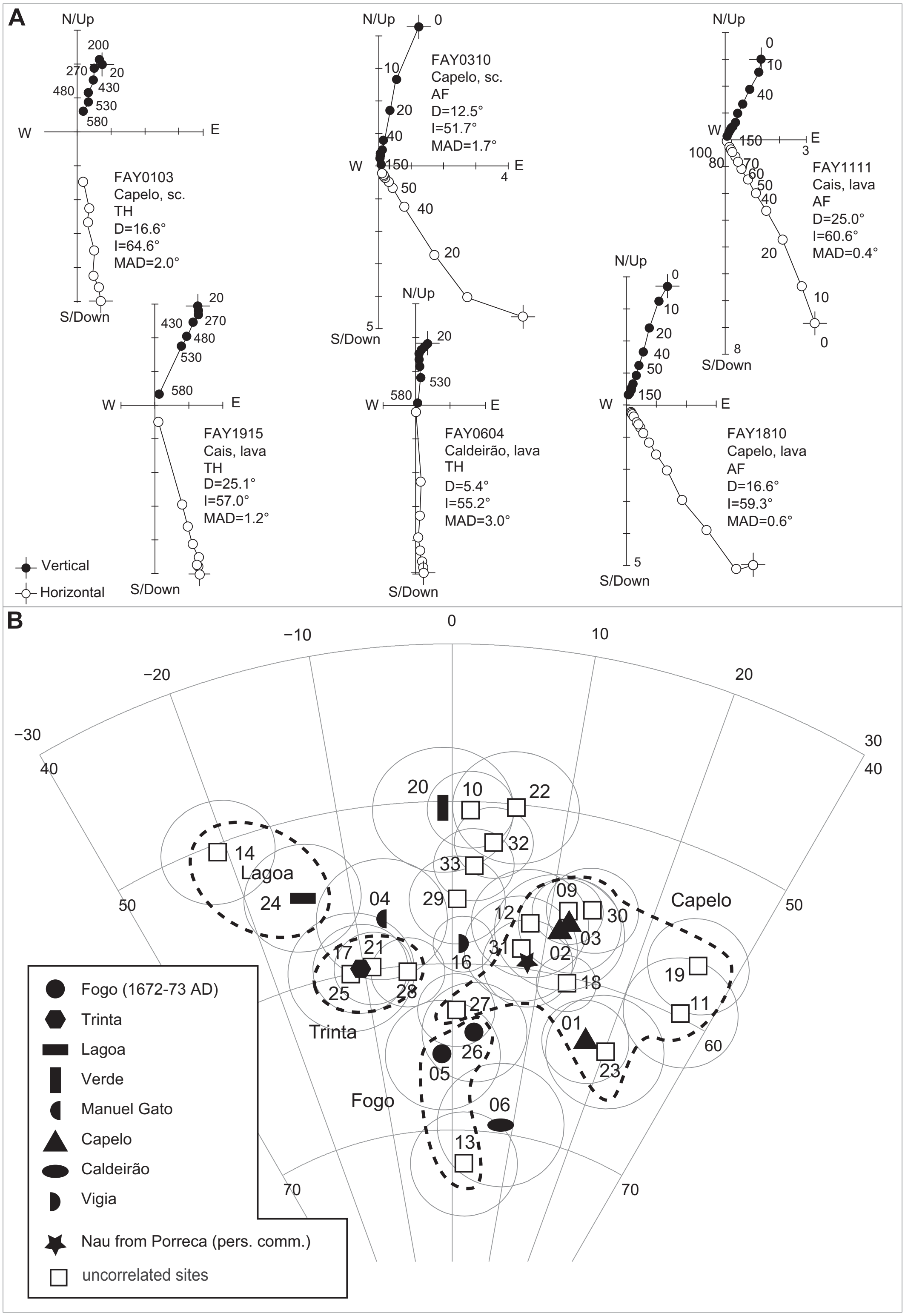

Figure 3. (A) Six representative orthogonal vector diagrams of typical thermal demagnetization data, in situ coordinates. Demagnetization step values of the thermally demagnetized (TH) samples are in °C; demagnetization step values of the alternating field (AF)–demagnetized samples are in mT. MAD—Maximum angle of deviation (Kirschvink, 1980). (B) Equal-area projection (lower hemisphere) of site-mean paleomagnetic directions from scoria cones and lavas of the Capelo Formation (the “FAY” prefix of each site is omitted). The ellipses around the paleomagnetic directions are the projections of the relative α_{95} cones. All paleomagnetic directions are listed in Table 2. Black-filled symbols indicate scoria cones and clearly correlated lava flows; empty symbols mark uncorrelated lavas. Four data clusters, associated with different eruption phases, are evidenced. Since results from site FAY08 failed, we consider for Costado da Nau directions obtained by Porreca (2013, personal commun.)

The susceptibility-T curves reveal three main behaviors: an almost reversible variation trend in the heating-cooling cycle, with a distinct Curie temperature (Tc) at ~580 °C and a reduction in Tc on cooling at 575 °C; an almost reversible variation trend and multiple Curie temperatures in the 250–600 °C range (four different Tc values), indicating a complex and variable composition in the titanomagnetite series; and an irreversible trend with three Tc values at ~200°C, 550 °C, and 600 °C, and the formation of new magnetic phases during heating, which resulted in markedly increased susceptibility values during cooling. These results, along with the hysteresis analyses (hysteresis loops and SIRM curves), confirm that the main magnetic carrier of Capelo's basalts is represented by Ti-poor titanomagnetite.

DISCUSSION

Correlation of Scoria Cones and Lava Flows Produced by the Same Eruption

Sites sampled in the same cone or in correlative cones (as for the three sites from Capelo cone, FAY02, FAY03, and FAY18), or in a correlated cone and lava flow (as for sites FAY05 and FAY26 from the A.D. 1672–1673 eruption), yield similar paleomagnetic directions within a maximum angular distance of 8.8°. This is consistent with evidence gathered in other volcanoes, where paleomagnetic directions from the same eruptive unit (lava or ignimbrite) cluster within an ~10° spread (e.g., Hagstrum and Champion, 1994; Speranza et al., 2010, 2012).

The paleomagnetic directions from the Capelo Peninsula can be used first to correlate lava flows with given scoria cones and then to date volcanic activity after comparing paleomagnetic directions with geomagnetic directions expected from appropriate PSV reference curves. In the past, the similarity of paleomagnetic directions has been used to correlate lava and ignimbrite outcrops (e.g., Rolph and Shaw, 1986; Hagstrum and Champion, 1994; Jurado-Chichay et al., 1996; Tanguy et al., 2003; Riisager et al., 2003; Speranza et al., 2008, 2012; Vezzoli et al., 2009), but never (to the best of our knowledge) to correlate scoria cones with lava flows produced during the same eruption.

Site FAY26 from the A.D. 1672–1673 lava flow yields a direction close to site FAY05 from Picarito cone and the lava site FAY13 sampled at Fajã quarry, within an angular range of 7.9°. Site FAY04 from Cabeço do Manuel Gato was considered by Machado et al. (1962) as one of the vents of the A.D. 1672–1673 eruption but was described by Serralheiro et al. (1989) as not being associated with this eruption. Although its direction appears scattered, the angular distances with sites FAY26 and FAY05 are 7.9° and 6.6°, respectively, and thus it could belong to the same eruptive phase.

In the northern coast of the Capelo Peninsula, sites FAY09 and FAY12, collected from the thick xenolith-rich lava, share a common paleomagnetic direction with sites from the Capelo cone, although they are located far northwest of it. Moreover, their directions do not overlap with the A.D. 1672–1673 flow directions (sites FAY05 and FAY26), consistent with stratigraphic evidences that indicate that they are below (and thus older) than the C11 deposit of A.D. 1076 ± 103.

A cluster of paleomagnetic directions is concentrated between 0° and 20° of declination and 56° and 64° of inclination from sites sampled on the Capelo cone sensu stricto and along the peninsula nearby (Fig. 3B). In particular, directions from the two sites sampled on top of the Capelo cone (FAY02 and FAY18) and from a site sampled on the small satellite scoria cone on the cone flank (FAY03) are similar. Lava flows sampled on the southern flank of Capelo cone sensu stricto at sites FAY18, FAY27, and FAY31 correlate well with the Capelo cone mean direction, as does FAY30 sampled in the Cais harbor locality. Site FAY01, sampled on the top of the Capelo cone, correlates well with the lava flow (FAY23) sampled on the cone southern flank, in the Rua do Canto locality. Sites FAY11–FAY19 have similarly high declinations. Common petrographic features and no paleosols are observed between the two lava flows, thus suggesting that they were emplaced contemporaneously. Field evidence indicates that sites FAY11–FAY19 overlie FAY30 and therefore are coeval or younger (neither erosion surfaces nor paleosols were observed). Thereby, we assign sites FAY11–FAY19 to the Capelo cone group, although their mean paleomagnetic directions do not overlap with directions gathered from the Capelo sensu stricto sites.

Lavas from the Lagoa cone (FAY24) and site FAY14 sampled in Praia do Norte show similar peculiarly western declinations (between –21° and –15°) and inclinations from 50° to 55°, and can thus be safely correlated. Site FAY14 stratigraphically overlies the FAY33 lava, and both are below the C11 pyroclastic deposit.

At a first glance, seven sites have similar paleomagnetic directions: sites FAY22 and FAY29, two lavas cut by the NNW-SSE scarp south to the Vigia cone (Fig. 2A), site FAY16 from the Vigia cone, site FAY10, close to the Capelo village, site FAY20 from Cabeço Verde, and FAY33 from Praia do Norte (Fig. 3B). Sites FAY22, FAY29, and FAY32 are located below the Canto cone, and may thus be related to it (unfortunately, site FAY15 from the Canto cone failed). Site FAY06 from the Caldeirão cone is characterized by a particularly high inclination (~70°) and a declination of 8°. While sites FAY22 and FAY29 can be safely correlated in the field, it is difficult to define a straightforward stratigraphic correlation for the other five sites (FAY06, FAY10, FAY16, FAY20, FAY32), except with paleomagnetism.

The other cluster of paleomagnetic data, characterized by ~–10° declinations and 60° inclinations, includes FAY17 from Cabeço dos Trinta, the lava flow sampled at site FAY28 between Lagoa and Cabeço Verde, the lava flow of the Varadouro village (FAY21), and the far site FAY25, from Norte Pequeno (Fig. 3B).

Recently, Porreca (2013, personal commun.) documented the paleomagnetic direction (D = 8.0°; I = 59.4°) of a feeder dike site from Costado da Nau, which we will consider in our study. It is noteworthy that Costado da Nau scoriae (from phase 4) crop out (Fig. 2G) on the top of Vigia cone (site FAY16), proving that the Costado da Nau volcanic apparatus is younger than Vigia.

Dating Using Reference Curves of the Paleosecular Variation of the Geomagnetic Field

Paleomagnetic dating of Holocene volcanic rocks from Italy has been done routinely using the French archeomagnetic curve (Bucur, 1994; Gallet et al., 2002) for the last 3 k.y., and the UK master curve (Turner and Thompson, 1981, 1982) for older Holocene times (see Tanguy et al., 2003; Speranza et al., 2004, 2008, 2010). Reference data were relocated to the Faial coordinates by the pole method (Noel and Batt, 1990). For ages older than 2500 yr B.P., we recalibrated the original ages of the UK master curve according to the new calibration points proposed by Snowball et al. (2007), relying on the comparison with the FENNOSTACK curve from Fennoscandia. Following Speranza et al. (2008), declinations of the UK master curve were lowered by 10° (before relocation), as a similar systematic error is apparent in the original data set when compared to other European archeomagnetic curves (the UK curve is constructed from sedimentary cores that were not oriented azimuthally). We preferred the French archeomagnetic curve and the UK master curve to the last available CALS10k.b1 global model of Korte et al. (2011), because the latter yields smoothed directional trends with respect to both curves. The validity of directions relocated from the French archeomagnetic curve and UK master curve for paleomagnetic dating in Europe has

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been clearly demonstrated by several studies of Italian volcanoes, where global models clearly yielded overly smoothed trends (see discussion in Zananiri et al., 2007; Speranza et al., 2008). However, we used the CALS10k model (at Faial coordinates) to evaluate the importance of the non-dipolar component while relocating the UK and French curves. Since the mean error of our data set is from 2.0° to 3.9° and the angular deviation (between UK, French, and CALS10k curves) is from 1° to 5°, we conclude that we can safely use these curves for dating.

Recently, Pavón-Carrasco et al. (2011) developed the "archeo_dating" program, a new tool for dating following the Bayesian approach described by Lanos (2004). The program relocates the adopted secular variation curve to the coordinates of Faial (38.59°N, 28.80°W) and then compares it to the mean declination, inclination, and α_{95} of the sites with unknown age. The probable age range is computed by combining the probability density function of declination and inclination of the studied data. The archeo_dating tool had been extensively used, for instance, by Donadini et al. (2012) for dating medieval fireplaces at the Mühlegasse (Zürich). In the present study, dating was attempted using three paleosecular variation curves: the UK master curve recalibrated by us as described above (from 7890 B.C. to A.D. 1950), the French archeomagnetic curve by Bucur (1994) and Gallet et al. (2002) (from 975 B.C. to A.D. 1830), and the curve for the last 3 k.y. recently gathered by historic and ^{14}C-dated lavas from São Miguel, Azores (Di Chiara et al., 2012).

Dating Volcanic Activity at Capelo Peninsula

The paleomagnetic directions of sites FAY26 (D = 2.9°; I = 64.1°) and FAY13 (D = 2.2°; I = 72.0°) sampled in the A.D. 1672–1673 historical flow, as well as FAY05 sampled in Picarito cone (D = –1.3°; I = 65.5°) are consistent with field directions predicted by the gufm1 global model (Jackson et al., 2000) for A.D. 1673 (D = –0.5°; I = 64.1°; Fig. 4). Hence, we confirm that Picarito cone was built during the Cabeço do Fogo historical eruption. We propose the same origin for Manuel Gato cone (FAY04), which yields a lower inclination (D = –7.3°; I = 57.0°), and an angular distance with respect to FAY05–FAY26 within 10°. Our paleomagnetic data thus confirm the validity of the gufm1 model

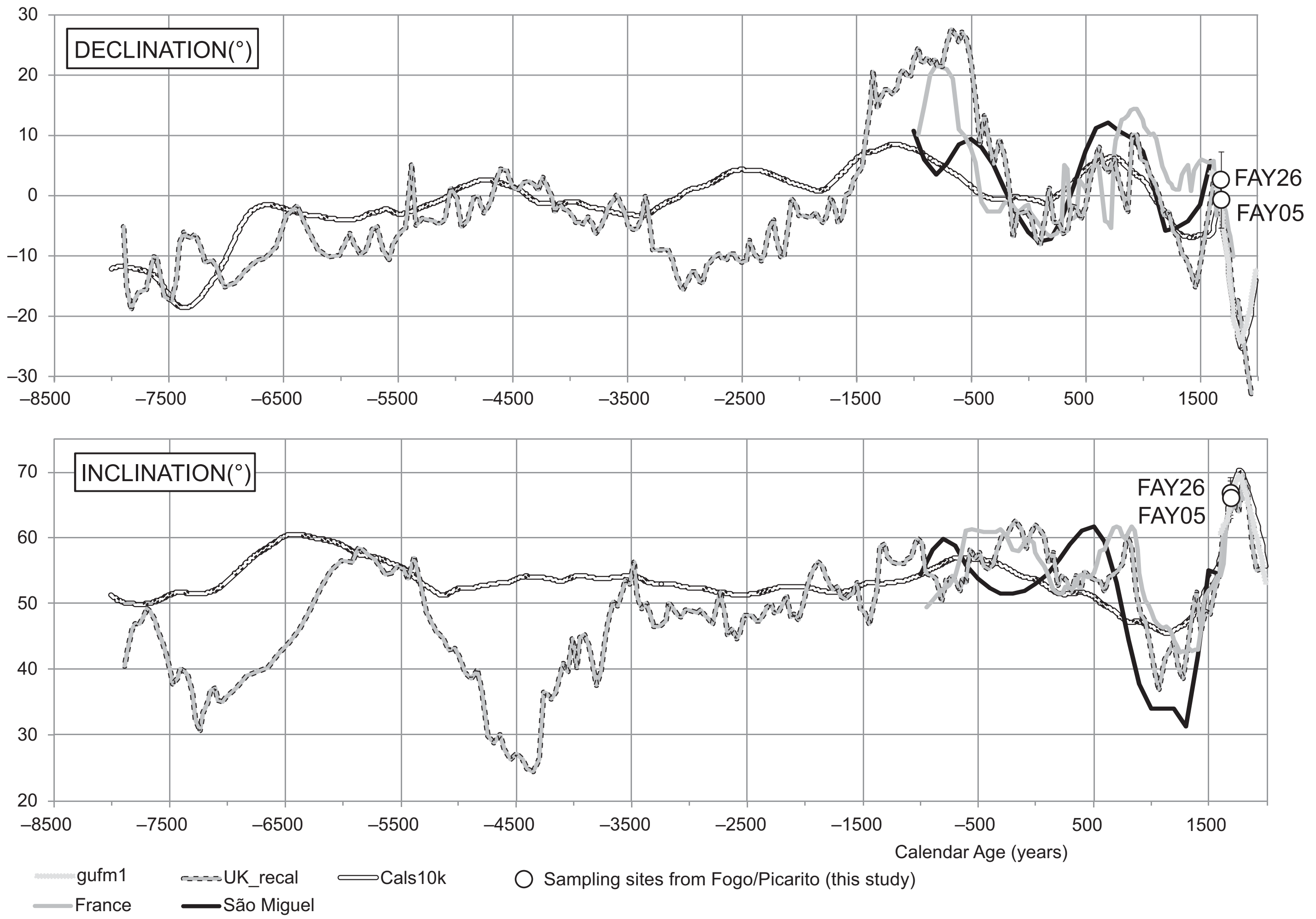

Figure 4. Declination and inclination vs. calendar age plot of global field model predictions at Faial coordinates from gufm1 (Jackson et al., 2000), CALS10k (Korte et al., 2011), as well as French archeomagnetic curve (Bucur, 1994; Gallet et al., 2002), UK master curve (Turner and Thompson, 1981, 1982), and São Miguel (Azores) curve (Di Chiara et al., 2012) relocated at Faial by pole method (Noel and Batt, 1990). Age model of the UK master curve is from Snowball et al. (2007); original declination values of the UK master curve were lowered by 10° (see discussion in Speranza et al., 2008).

Geological Society of America Bulletin, published online on 18 April 2014 as doi:10.1130/B30933.1

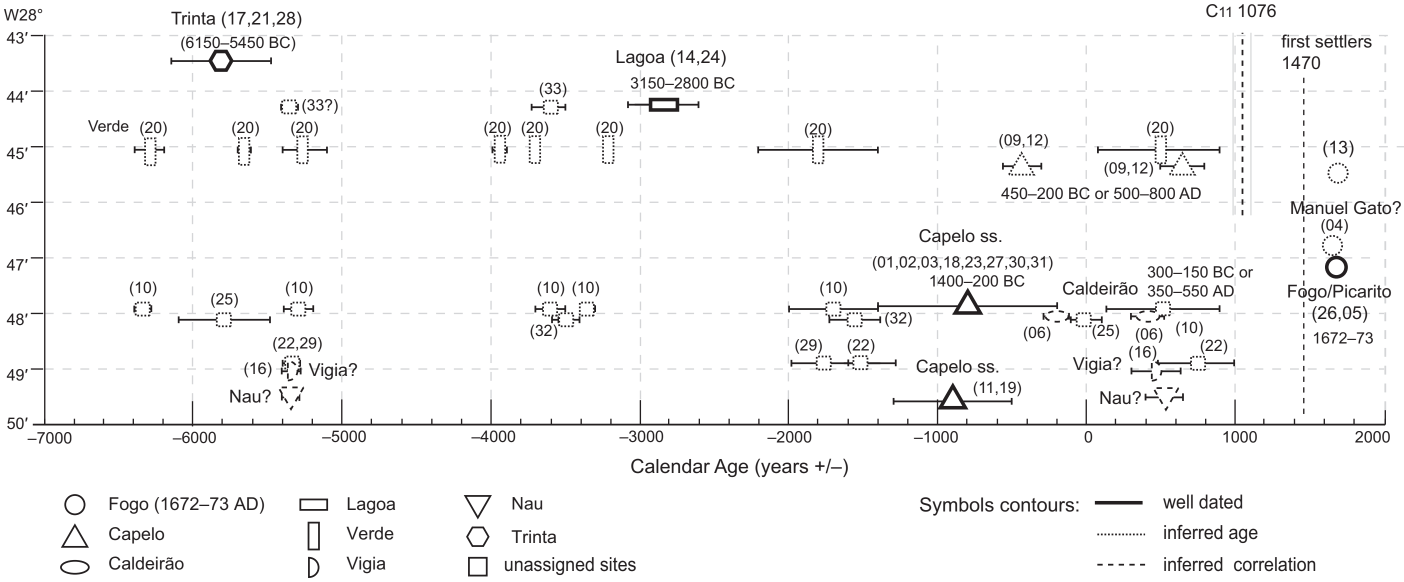

Figure 5. Schematic plot of the clusters of mean paleomagnetic results and their age error bars, with calendar ages and longitude (°W). Dating was obtained using the archeo_dating program from Pavón-Carrasco et al. (2011). Dashed symbols indicate multiple solutions for dating of the given paleomagnetic site; ss—sensu stricto.

for the Azores in the late seventeenth century, while data from the A.D. 1652 lava flow at São Miguel yielded an inclination ~15° lower than gufm1 predictions (Di Chiara et al., 2012). We put forward two hypotheses for this mismatch: (1) The A.D. 1652 flow at São Miguel did not faithfully record the local field direction (as has been observed for the A.D. 1943–1952 eruption of Paricutin volcano [Mexico] by Urrutia-Fucugauchi et al., 2004), or (2) the flow assigned to the A.D. 1652 event in the geological map of Moore (1991) in fact has a different age (a 150 yr older age would fit the expected inclination). This last hypothesis is the most plausible because it is also supported by Ferreira (2000), who reinterpreted the historical description and delimited the areal distribution of the A.D. 1652 lava.

The eight sites from the Capelo sensu stricto cone activity (FAY01, FAY02, FAY03, FAY18, FAY23, FAY27, FAY30, and FAY31) were dated using archeo_dating to the 1400–200 B.C. age interval (Fig. 5; Table 3). Lavas sampled near Cais harbor at sites FAY11 and FAY19 correlate rather well with the declination maxima observed in the French curve between 650 and 850 B.C., and a 1300–450 B.C. interval is obtained by archeo_dating (Fig. 5; Table 3). Hence, they were emplaced during the Capelo cone formation. FAY09 and FAY12 lavas are slightly younger than Capelo cone, dated to 450–200 B.C. or A.D. 500–800, and were probably fed from another eruptive cone now buried below the Cabeço do Fogo products (Fig. 6).

TABLE 3. PALEOMAGNETIC DATING OF THE VOLCANIC ACTIVITY OF THE CAPELO PENINSULA, FAIAL

Inferred volcanic unit	Site(s)	Inferred emplacement ages
Fogo	05, **04, 13, 26**	1672–73 A.D.
Caldeirão	06	300–150 B.C. or 350–550 A.D.
?	**9–12**	450–200 B.C. or 500–800 A.D.
Capelo ss.	**11–19**	1300–450 B.C.
Capelo ss.	01, 02, 03, **18, 23, 27, 30, 31**	1400–200 B.C.
Lagoa	14, **24**	3150–2800 B.C.
?	**22–29**	5400–5350 B.C. or 1700–1400 B.C.
?	33	5400–5350 B.C. or 3650–3500 B.C.
Vigia	16	5400–5350 B.C. or 300–600 A.D.
Nau	[08]	5400–5350 B.C. or 500–800 A.D.
?	25	6100–5400 B.C. or 1350–1470 A.D.
Trinta	17, **21, 28**	6150–5450 B.C.

Note: Volcanic units discussed in this study are grouped using volcanological and paleomagnetic criteria; ss—sensu stricto. Bold sites are those correlated in this study. Inferred emplacement ages were obtained using archeo_dating tool by Pavòn-Carrasco et al. (2011). Age of Costado da Nau was obtained using the paleomagnetic data from Porreca et al. (2013, personal commun.). For sites FAY10, FAY20, FAY25, and FAY32, no definite ages were obtained because the paleomagnetic directions were too close to the mean values of the Holocene geomagnetic field.

The Caldeirão cone (site FAY06) has two equally probable age intervals, 300–150 B.C. or A.D. 350–550, which, however, constrain its formation to be younger than the Capelo sensu stricto cone.

The declination minimum recorded by the sites from Lagoa cone (FAY14 and FAY24) can be necessarily dated to 3150–2800 B.C., as the FAY14 lava lies above the FAY33 lava flow, which is dated to 5400–5300 B.C. or 3650–3500 B.C.

The two sites sampled in the scarp NW of the Vale Formoso lighthouse, FAY22 and FAY29, can be dated to either 5400–5350 B.C. or 1700–1400 B.C.

The Vigia cone has two equally probable ages assigned: 5400–5350 B.C. or A.D. 300–600. The Costado da Nau dating also yielded two solutions, 5400–5350 B.C. or A.D. 500–800. We consider the second solution as more probable than the first, since no paleosols or evidences of erosive breaks are apparent between the Vigia and Costado da Nau cones and the younger products.

For four sites (FAY10, FAY20, FAY25, and FAY32), no definite ages were obtained, since the paleomagnetic directions were too close to the mean values of the Holocene geomagnetic field. Site FAY25 was not correlated with any cone, but the archeo_dating output indicates two equally probable ages: 6100–5400 B.C. and A.D. 1350–1470. Despite the proximity to the previous site, the FAY32 lava output age is different: 5400–5350 B.C. or 3650–3500 B.C. The two sites are exposed near the Canto cone, but unfortunately our site from Canto failed, and the correlation cannot be assessed.

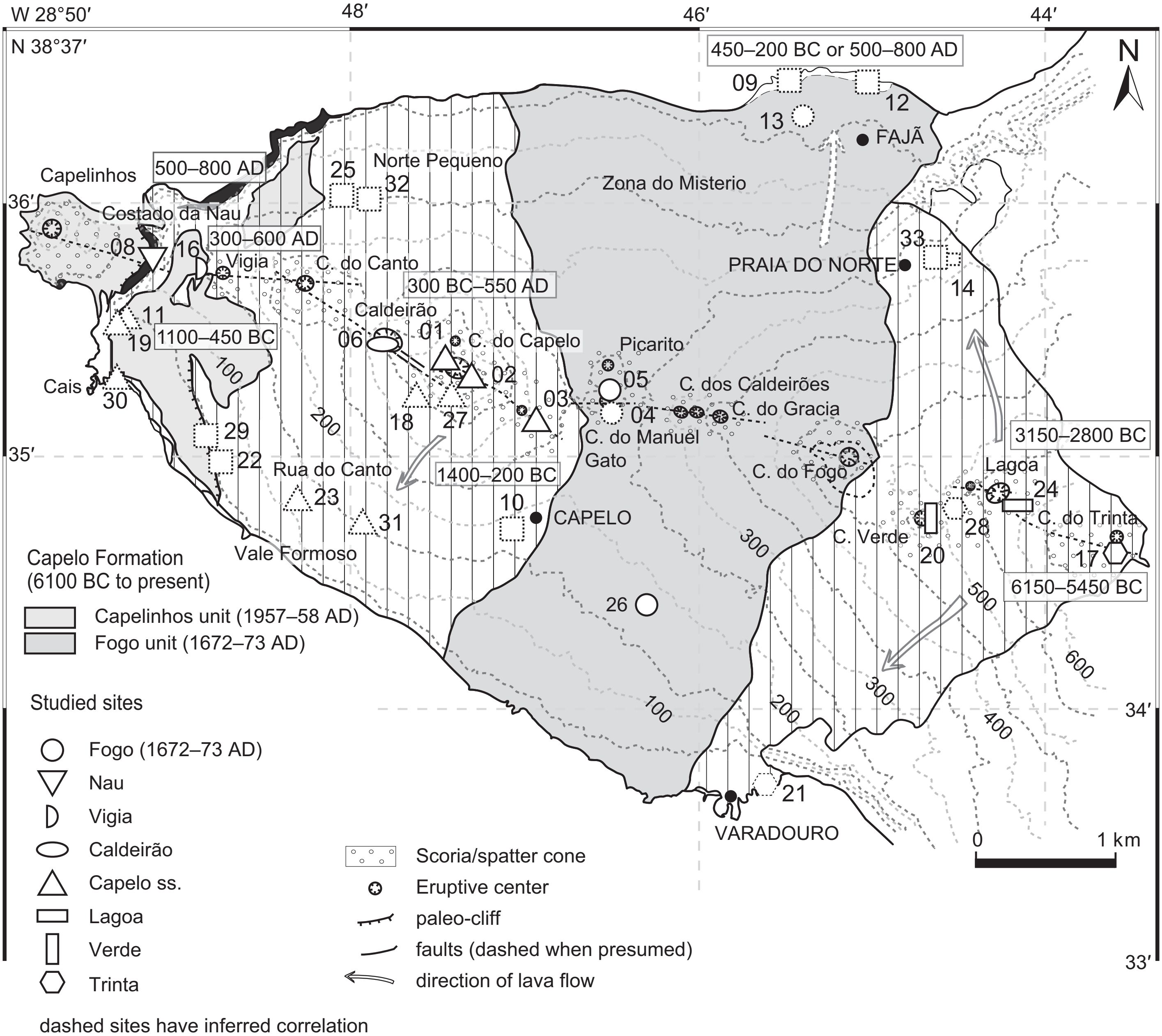

Figure 6. Reinterpreted geological map of the Capelo Peninsula; ss—sensu stricto.

Finally, the Trinta cone (FAY17), emplaced on the easternmost part of the Capelo Peninsula, was dated to 6150–5450 B.C. and correlates with the dates of lavas from sites FAY28 and FAY21 (Figs. 5 and 6; Table 3), representing the oldest products sampled in this study.

CONCLUSION

By paleomagnetically studying the volcanic rocks exposed on the Capelo Peninsula of Faial Island (Azores), we documented a successful attempt to use paleomagnetism as a correlative tool between scoria cones and syneruptive lava flows. Correlations are inferred from the similarity of paleomagnetic directions and supported by stratigraphic evidence where available. Our data support the correlation of 11 lava flow sites with four scoria cones.

Furthermore, paleomagnetic dating of volcanic events was attempted, relying on the comparison of our paleomagnetic directions and expected paleofield directions derived from relocated PSV reference curves from São Miguel, France, and UK, using the archeo_dating tool (Pavón-Carrasco et al., 2011). We find that the volcanic products of the Capelo Peninsula, previously loosely constrained to the last 11 k.y. (Holocene), were in fact formed in the last 8 k.y. The oldest volcanic activity detected on the Capelo Formation corresponds to the Trinta cone (6150–5450 B.C.) and associated lava flows spreading west and southward, on the western mountainside of the Caldeira volcano (Fig. 6).

After a break of ~2300–3350 yr (although we cannot exclude the possibility that some eruptive products are now buried or eroded), Lagoa cone formed. Between 1400 B.C. and present day, the subaerial volcanic activity migrated westward and intensified, yielding the formation of the prominent Capelo (1400–200 B.C.), Caldeirão (300 B.C.–A.D. 550), Vigia (A.D. 300–600), Costado da Nau (A.D. 500–800), Fogo-Picarito (A.D. 1672–1673), and Capelinhos (A.D. 1957–1958) cones and related lava flows. At least the Capelo, and possibly the Caldeirão, eruption occurred along at least two different vents, or along multiple cones spread along the WNW-ESE eruptive fissure (as was observed during the A.D. 1672–1673 eruption).

Our data demonstrate that paleomagnetism is a powerful tool for both correlating volcanic cones and lava flows, and dating Holocene volcanic products, if reliable PSV reference curves can be used for the studied area (the best reference curves are available for Europe and neighboring regions). We confirm that paleomagnetism, coupled with field evidences and geochronology (if available), can allow the spatial and temporal behavior of Holocene volcanic activity to be unraveled. This method provides an accuracy that can hardly be attained by other tools, and this has important implications for a proper determination of recent volcanic activity and correct volcanic hazard assessment.

ACKNOWLEDGMENTS

F. Mariani, D. D'Elia, and A. Pintòn helped with sampling. We thank J. Madeira for interesting discussion on Costado da Nau stratigraphy, as well as C. Onheiser and P. Lurcock for correcting the English. We also thank J. Pavón-Carrasco for his competent advice on the paleosecular variation reference curves and dating tools. We are grateful to the Associate Editor M. Ort, D. Champion and A. Gogichaishvili for providing very thorough and constructive comments on our manuscript. Di Chiara and Speranza were funded by INGV (Istituto Nazionale di Geofisica e Vulcanologia) and FIRB MIUR C2 funds (responsible L. Sagnotti), while Porreca, Pimentel, and Pacheco were financially supported by CVARG (Centro de Vulcanologia e Avaliação de Riscos Geológicos). Di Chiara thanks the FAPESP support (2013/08938-8). The Italian authors wish to dedicate this work to the memory of the friend and colleague Roberto Lanza, pioneer among Italian scientists in the applications of paleomagnetism to volcanology.

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Science Editor: Nancy Riggs
Associate Editor: Michael Ort

Manuscript Received 16 May 2013
Revised Manuscript Received 28 February 2014
Manuscript Accepted 25 March 2014

Printed in the USA