Bull Volcanol (2016) 78: 22
DOI 10.1007/s00445-016-1015-6

RESEARCH ARTICLE

Stress-induced comenditic trachyte effusion triggered by trachybasalt intrusion: multidisciplinary study of the AD 1761 eruption at Terceira Island (Azores)

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Received: 15 September 2015 / Accepted: 21 February 2016 / Published online: 2 March 2016
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Abstract The AD 1761 eruption on Terceira was the only historical subaerial event on the island and one of the last recorded in the Azores. The eruption occurred along the fissure zone that crosses the island and produced a trachybasalt lava flow and scoria cones. Small comenditic trachyte lava domes (known as Mistérios Negros) were also thought by some to have formed simultaneously on the eastern flank of Santa Bárbara Volcano. Following a multidisciplinary approach, we combined geological mapping, paleomagnetic, petrographic, mineral and whole-rock geochemical and structural analyses to study this eruption. The paleomagnetic dating method compared geomagnetic vectors (directions and intensities) recorded by both the AD 1761 lava flow and Mistérios Negros domes and revealed that the two events were indeed coeval. Based on new data and interpretation of historical records, we have accordingly reconstructed the AD 1761 eruptive dynamics and distinguished three phases: (1) a precursory phase characterized by decreased degassing in the fumarolic field of Pico Alto Volcano and a gradual increase of seismic activity, which marked the intrusion of trachybasalt magma; (2) a first eruptive phase that started with phreatic explosions on the eastern flank of Santa Bárbara Volcano, followed by the inconspicuous effusion of comenditic trachyte (66 wt% SiO_2), forming a WNW-ESE-oriented chain of lava domes; and (3) a second eruptive phase on the central part of the fissure zone, where a Hawaiian to Strombolian-style eruption formed small scoria cones (E-W to ENE-WSW-oriented) and a trachybasalt lava flow (50 wt% SiO_2) which buried 27 houses in Biscoitos village. Petrological analyses show that the two batches of magma were emitted independently without evidence of interaction. We envisage that the dome-forming event was triggered by local stress changes induced by intrusion of the trachybasalt dyke along the fissure zone, which created tensile stress conditions that promoted ascent of comenditic trachyte magma stored beneath Santa Bárbara Volcano.

Keywords Bimodal volcanism · Paleomagnetic dating · Stress changes · Fissure zone · Dyke intrusion · Terceira (Azores)

Editorial responsibility: V. Acocella

Electronic supplementary material The online version of this article (doi:10.1007/s00445-016-1015-6) contains supplementary material, which is available to authorized users.

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Introduction

In extensional or transtensional tectonic settings, volcanic eruptions commonly occur through fissure zones (or rift zones) and involve the emission of mafic magmas. Eruptions may also occur from associated central volcanoes,

which erupt magmas with different degrees of evolution (e.g. Peccerillo et al. 2003; Lacasse et al. 2007; Civile et al. 2008; Eason and Sinton 2009; Klügel et al. 2009; Sigmundsson et al. 2010; Zanon et al. 2013; Acocella 2014). Tensile or transtensive stress conditions facilitate the ascent of magma into the lithosphere by dyke intrusion (Wadge and Burt 2011; Daniels and Menand 2015) and promote eruptions through eruptive fissures and/or marked alignments of cones (Walker 1999; Le Corvec et al. 2013).

The intrusion of a mafic magma may occasionally trigger an eruption. If the intrusion occurs near a central volcano, the ascending dyke can intrude into a more evolved magma reservoir and generate an explosive eruption, as reported for Icelandic volcanoes, such as Askja (Sparks et al. 1977; Sigurdsson and Sparks 1981), Katla (Larsen et al. 2001; Lacasse et al. 2007) and Eyjafjallajökull (Sigmundsson et al. 2010; Sigmarsson et al. 2011), and Gedemsa Volcano in the Ethiopian Rift (Peccerillo et al. 2003). Alternatively, if the dyke does not intrude a magma reservoir, it can change the stress regime of the surrounding rock (Bonafede and Danesi 1997; Maccaferri et al. 2010; Le Corvec et al. 2013; Daniels and Menand 2015) and create favourable conditions for the ascent of magma from the reservoir, which may also lead to an eruption, as reported for Mt. Etna (Currenti et al. 2008).

In the Azores archipelago, fissure zones and central volcanoes are also closely associated and characterized by coeval activity (e.g. Johnson et al. 1998; Calvert et al. 2006; Hildenbrand et al. 2008; Hildenbrand et al. 2012; Trippanera et al. 2014). Historical eruptions (since Portuguese settlement in the mid-15th century) occurred mostly along fissure zones and erupted mafic magmas (e.g. AD 1562–63 Planalto da Achada, Pico Island; Zbyszewski 1963; Weston 1964; AD 1998–2001 Serreta Ridge, offshore Terceira Island; Gaspar et al. 2003; Kueppers et al. 2012). Only a few have occurred at trachytic central volcanoes (e.g. AD 1630 Furnas Volcano, São Miguel Island; Cole et al. 1995).

Recent studies have shown that magma storage and plumbing systems of fissure zones and central volcanoes in the Azores are distinct and independently activated (e.g. Zanon et al. 2013; Zanon and Frezzotti 2013; Zanon and Pimentel 2015; Zanon 2015). Nevertheless, they are known to interact, as seen during the AD 1957–58 Capelinhos eruption (Faial Island), when a basaltic intrusion, at the western end of the Capelo Peninsula fissure zone, triggered a phreatic explosion in nearby Caldeira Volcano (Machado et al. 1962). It is therefore of paramount importance to obtain better understanding of the possible modes of interaction between fissure zone and central volcanism. The gained insights are of particular importance for the assessment of future eruptive behaviour and to explain the coeval activity and feeding of monogenic and central (polygenic) volcanoes in magmatic systems along extensional or transtensional settings.

We here report on the AD 1761 eruption on Terceira Island, which occurred along the WNW-ESE to NW-SE-oriented fissure zone that crosses the island. During this poorly known event, the only subaerial historical eruption on Terceira, a mafic lava flow reached the village of Biscoitos, in the north part of the island, where it buried 27 houses (Acrúcio das Neves 1826; Drummond 1856). Contemporaneously, a chain of small lava domes (known as Mistérios Negros) is thought to have formed on the eastern flank of Santa Bárbara Volcano (Zbyszewski et al. 1971; Calvert et al. 2006). However, the age of this dome-forming event is debated and not recognized by some previous studies (Weston 1964; Self 1976; Madeira 2005). These authors considered that the lava domes are recent but did not erupt in historical times, and that the activity on the flank of Santa Bárbara Volcano reported in AD 1761 was characterized only by phreatic explosions.

The main goals of this work are (1) to reconstruct the chronology of events and to interpret the eruptive dynamics following a multidisciplinary approach, aimed also at determining the age of the Mistérios Negros domes, and (2) to explore the possible interaction between the eruption of mafic magma along the fissure zone and the nearby effusion of felsic magma on the flank of Santa Bárbara Volcano.

Geological setting of Terceira Island

Terceira is one of the nine islands of the Azores archipelago, in the North Atlantic Ocean. The Azores region is characterized by a complex geodynamic setting dominated by the boundary between the Eurasian and Nubian lithospheric plates, east of the Mid-Atlantic Ridge. It is a diffuse plate boundary, where regional WNW-ESE to NW-SE-trending tectonic structures accommodate the differential motion between the two plates through a dextral-transtensive regime. The Terceira Rift corresponds to the northernmost structure (inset on Fig. 1), where linear volcanic ridges and central volcanoes form islands and seamounts, which alternate with tectonically controlled basins (e.g. Lourenço et al. 1998; Hipólito et al. 2013; Marques et al. 2013; Neves et al. 2013).

Terceira Island is composed of four overlapping central volcanoes: Serra do Cume-Ribeirinha (also called Cinco Picos, e.g. Self 1976), Guilherme Moniz, Pico Alto, Santa Bárbara, and a fissure zone (Fig. 1). Serra do Cume-Ribeirinha (>401 ka; Hildenbrand et al. 2014) and Guilherme Moniz (>270 ka; Calvert et al. 2006) are considered extinct and together constitute the eastern and south-central sectors of the island, respectively (Fig. 1). Santa Bárbara, Pico Alto and the fissure zone have erupted contemporaneously during the last 50 ka (e.g. Self 1976; Madeira 2005; Calvert et al. 2006).

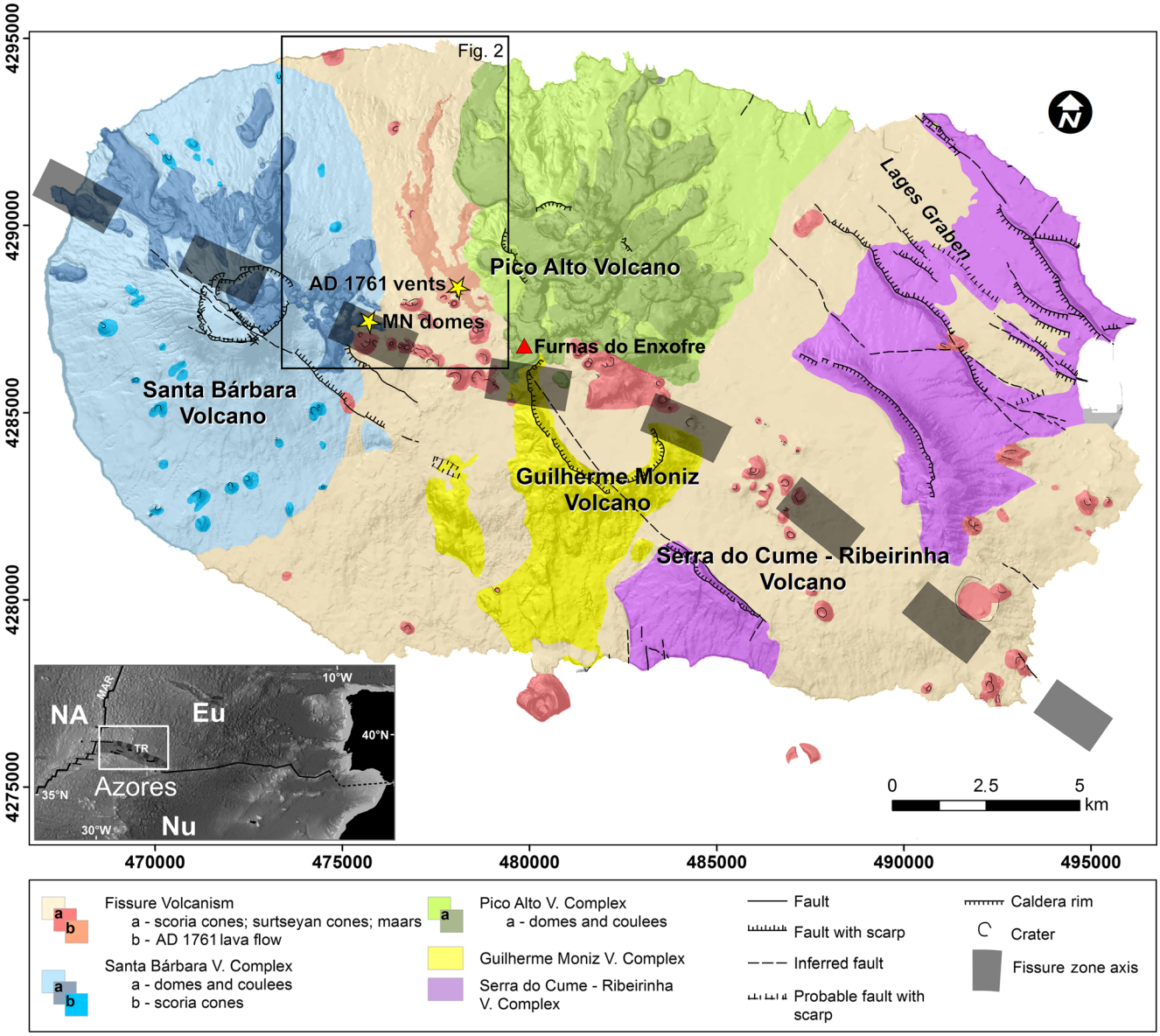

Fig. 1 Simplified geological map of Terceira Island (modified after Madeira 2005) showing locations of AD 1761 vents and lava flow and Mistérios Negros domes—MN; UTM projection, Zone 26S, Datum WGS1984. Inset shows sketch of Azores geodynamic setting. Eu Eurasian plate, Nu Nubian plate, NA North American plate, TR Terceira Rift, MAR Mid-Atlantic Ridge

Pico Alto Volcano (>141 ka; Gertisser et al. 2010), located north of Guilherme Moniz (Fig. 1), is characterized by a cluster of recent lava domes and coulees that concealed and overflowed an inconspicuous caldera. This volcanic complex is formed by trachytic to peralkaline rhyolitic products (Self 1976; Self and Gunn 1976; Mungall and Martin 1995), including major pyroclastic formations dominated by ignimbrites, erupted between 86 and 21 ka (Gertisser et al. 2010).

Santa Bárbara is the youngest volcano (>65 ka; Hildenbrand et al. 2014) and dominates the western third of Terceira (Fig. 1). It is a conical-shaped edifice topped by two small nested calderas, which are almost completely filled by lava domes. Numerous alignments of lava domes and coulees are found along its flanks. This volcanic complex includes a wide range of products, ranging from basaltic lavas to peralkaline rhyolitic lavas and pyroclastic deposits (Self 1976; Self and Gunn 1976; Mungall and Martin 1995).

The fissure zone (>43 ka; Calvert et al. 2006) crosses the island following a WNW-ESE to NW-SE orientation (Fig. 1) and extends offshore forming submarine ridges (e.g. Quartau et al. 2014; Casalbore et al. 2015). This volcanic system is defined by the alignments of scoria and spatter cones, which issued basaltic/trachybasaltic lavas (Self 1976; Self and Gunn 1976; Mungall and Martin 1995; Zanon and Pimentel 2015). Historical eruptions occurred in AD 1761 in the centre of the

island and offshore in AD 1867 and AD 1998–2001 along the Serreta Ridge (Weston 1964; Self 1976; Gaspar et al. 2003).

The tectonic structures of Terceira mainly trend WNW-SSE to NW-SE (e.g. Tzanis and Makropoulos 1999; Madeira 2005; Madeira et al. 2015). The latter fault system is well represented in the northeast sector of the island by the Lajes Graben (Fig. 1), with two major normal-dextral NW-SE-oriented faults, that extend offshore for several kilometres (Quartau et al. 2014; Casalbore et al. 2015). A second smaller graben, marked by WNW-ESE-trending faults, is located on the southeast flank of Santa Bárbara Volcano (Madeira 2005; Madeira et al. 2015).

Chronology of the AD 1761 eruption

The interpretation of historical records of the AD 1761 eruption (i.e. the church book of Vila Nova parish, written by the priest Caetano Antona, and the chronicles of Acrúcio das Neves 1826 and Drummond 1856) allowed reconstruction of the sequence of pre- and syn-eruptive events. However, these reports are sometimes exaggerated or incomplete and somewhat unclear. The description presented here required a careful analysis of the historical records in the light of present-day knowledge of volcanic phenomena (summarized in Table 1).

Precursory phase

About 1 year before the eruption (i.e. in the spring of AD 1760), the inhabitants of Terceira noticed a marked decrease in the degassing activity at Furnas do Enxofre fumarolic field, in the centre of the island (southwest flank of Pico Alto Volcano; Fig. 1). Later that year, on 22 November (approximately 5 months before the onset of the eruption), earthquakes started to be felt all around the island. Intermittent seismicity gradually grew in intensity during the following months. On 14 April AD 1761, a strong earthquake marked a significant increase in frequency and intensity of seismic activity.

First phase

On the morning of 17 April AD 1761, following 3 or 4 days of felt tremors, the first signs of volcanic activity were observed in an area located between Pico Gordo cone and the eastern flank of Santa Bárbara Volcano (Fig. 2). Historical records of the events in this area are scarce and do not specify the type of activity. Volcanic manifestations were described as 'strong underground explosions', 'bursts of fire' and 'underground fire', accompanied by the emission of minor amounts of ash and steam. Although not clear in the 19th century chronicles, the local priest described the rise of small hills in that area, which is thought to correspond to the inconspicuous effusion of a chain of small lava domes. These are consistent with the young (not covered with tephra) domes locally known as Mistérios Negros (Figs. 2 and 3a). It should be noted that the name of the domes itself contains the term 'Mistérios', meaning God's Mysteries, which is used in the Azores to designate historical lavas. This suggests that the eruption of the domes was witnessed by the local population. The duration of this phase is reported to have lasted for 10 to 12 days.

Second phase

On 21 April, 4 days after the initial manifestation, new signs of volcanic activity were observed 1.2 km east of Pico Gordo cone (Fig. 2), on the central part of the fissure zone. Differently from the earlier phase, historical records provide detailed descriptions on the type and duration of this phase of activity. The records clearly describe a Hawaiian to Strombolian eruption, with the effusion of lava, ash fallout over most of the island, ballistic projectiles and the formation of small scoria cones, the largest nowadays called Pico do Fogo (Figs. 2 and 3b). This name (translated as Fire Peak) is widely used in the Azores to describe scoria cones formed during historical eruptions.

Two main cones were built during this phase: first Pico Vermelho and, shortly after, Pico do Fogo (Figs. 2 and 3b) with three minor lateral vents aligned ~N80°. The lava emitted formed three main branches that flowed in different directions. The first was small and flowed to the east and south, the

Table 1 Summary of main events of the AD 1761 eruption

Date	Description of event	Comment
Spring AD 1760	Decrease of fumarolic activity	Significant decrease of degassing noticed by the population
22 November AD 1760	Beginning of felt earthquakes	Seismic activity continued intermittently until the start of eruption
14 April AD 1761	Increase of frequency and intensity of seismic activity	Strong earthquake followed by felt tremors
17 April AD 1761	Onset of eruption (first phase—lava dome effusion?)	Historical records are vague about the type of activity
21 April AD 1761	Start of second phase (formation of scoria cones and emission of lava)	Formation of 3 lava flow branches in different directions
29 April AD 1761	End of eruption	Corresponds to the halt of the lava flow

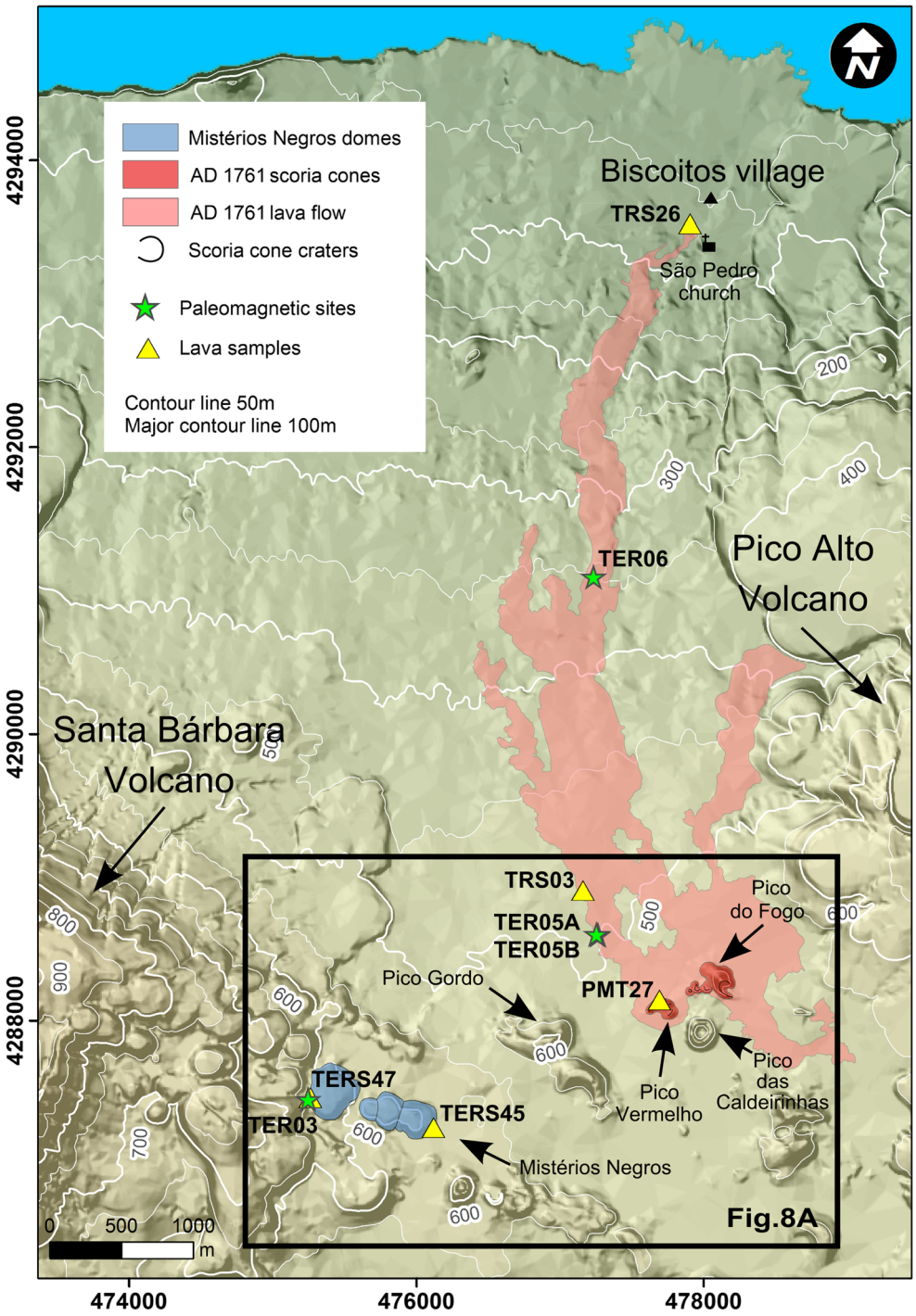

Fig. 2 Map showing extent of AD 1761 lava flow, associated scoria cones and Mistérios Negros lava domes. Locality names referenced in the text are indicated. Green stars and yellow triangles indicate locations of sampling sites; UTM projection, Zone 26S, Datum WGS1984

second flowed to the west and then breached to north and the third branch flowed down the northern steeper slope where it split in two. The longest of the latter branch reached the outskirts of Biscoitos village, approximately 6 km north of the vents, where it buried vineyards, croplands and 27 houses before stopping near São Pedro church (Fig. 2), about 1 km from the sea. There are no reports of causalities as the inhabitants of Biscoitos had time to abandon their houses and remove belongings. It should be noted that the areas covered by the lava flow are locally known as Mistério Novo (meaning New God's Mystery). This second phase of the eruption lasted for 8 days, ending around 29 April.

Paleomagnetic dating of Mistérios Negros domes

Volcanic products are commonly dated through isotopic methods. However, the half-life of many isotopes used for

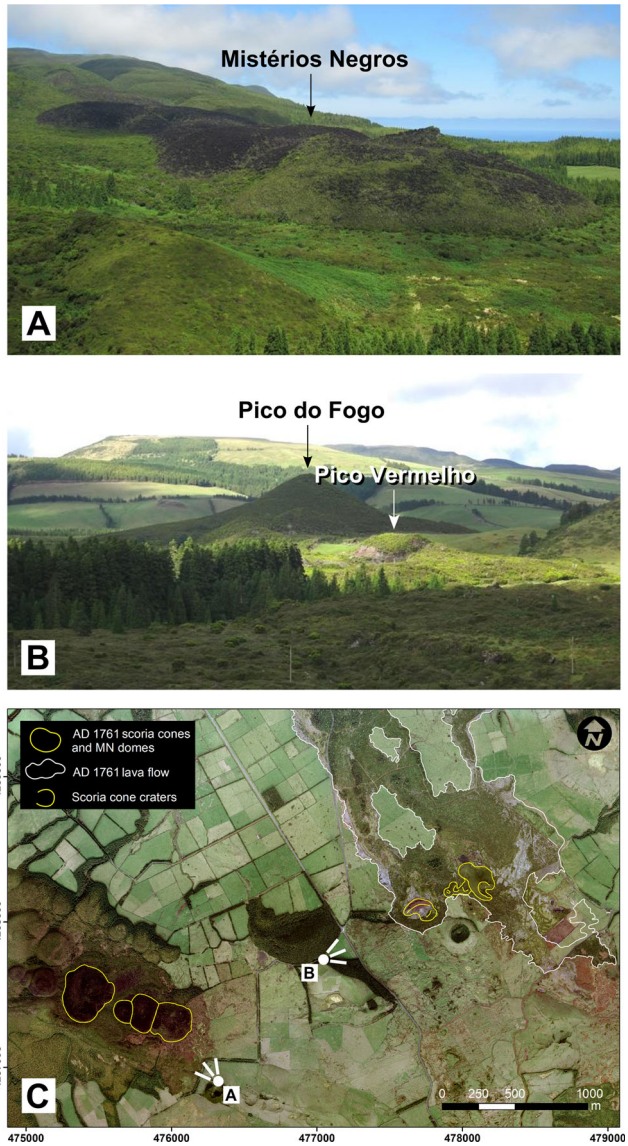

Fig. 3 **a** Photo of Mistérios Negros domes along flank of Santa Bárbara Volcano. **b** Photo of AD 1761 scoria cones, with Pico Vermelho (remains of the quarried cone) in front of Pico do Fogo cone. **c** Location of viewpoints of photos **a** and **b**, and limits of the AD 1761 lava flow and scoria cones, and Mistérios Negros domes draped over a high-resolution orthophotomap; UTM projection, Zone 26S, Datum WGS1984

radiometric dating (e.g. ^{234}U, ^{230}Th, ^{147}Sm, ^{40}K and ^{87}Sr) is too long to precisely date young historical eruptions and unambiguously constrain the potential contemporaneity of two very recent eruptive events. The only radio-isotope suitable to date such eruptions with sufficient temporal resolution is ^{14}C. Such radiocarbon determinations are not performed on the volcanic product itself but require carbon (from burned vegetation) associated with the emplacement of the volcanic product. However, depending on the climatic conditions and the eruption frequency, carbon is not always available.

Archeomagnetic dating has been used as a reliable alternative to radiocarbon dating for Holocene rocks (e.g. Doell and Cox 1965; Soler et al. 1984; Thompson and Turner 1985; Rolph et al. 1987; Hagstrum and Champion 1994; Carlut et al. 2000; Genevey et al. 2008, 2013; Di Chiara et al. 2014). However, its application is limited by the need for a high-resolution reference curve of the paleomagnetic secular variation (PSV) for the region (Casas and Incoronato 2007) and the time interval considered. The geomagnetic vector, stored in volcanic products upon cooling, can be measured in the laboratory and then compared to reference curves. The accuracy of this technique critically depends on (1) the quality and time resolution of the reference curves, (2) the reliability of the material as a magnetic recorder and (3) the uniqueness of the match with the records. Often, only the direction of the geomagnetic vector is considered but the accuracy of an archeomagnetic dating can be considerably enhanced if the paleointensity is also taken into account. For the Azores region, a new PSV reference curve of the last 3 ka was recently proposed (Di Chiara et al. 2012) and successfully applied to date volcanic products at Capelo Peninsula, Faial Island (Di Chiara et al. 2014).

We here test whether the Mistérios Negros lava domes are coeval with the AD 1761 lava flow. Therefore, we do not need to rely on PSV reference curves alone and can directly compare the geomagnetic vectors obtained from both the Mistérios Negros and the AD 1761 flow.

Methodology

Oriented drill cores were taken from the Mistérios Negros lava domes (10 samples from site 3, green star in Fig. 2) and AD 1761 lava flow (24 samples from sub-sites 5A and 5B and site 6, green stars in Fig. 2). Sampling was performed with a portable petrol-powered drill connected to a water-cooling unit. Cores measured approximately 2.5 cm in diameter and 4–10 cm in length; per (sub-)site, 7 to 16 samples were taken. These were oriented in the field with a magnetic compass and, whenever possible, a sun compass. Per sub-site, four samples were step-wise thermally demagnetized in an ASC-TD48 demagnetizer and measured on a 2G DC-SQUID cryogenic magnetometer. Furthermore, six samples per site were step-wise demagnetized by alternating fields (AF) on a robotized 2G DC-SQUID magnetometer. AF-demagnetized samples were also used to obtain paleointensity estimates by subjecting them to calibrated pseudo-Thellier experiments (de Groot et al. 2013), to complete the full geomagnetic vector as recorded by the Mistérios Negros and the AD 1761 flow.

Results

All 10 measured samples from Mistérios Negros domes (site 3) yielded univectorial Zijderveld diagrams (Zijderveld 1967) towards the origin (Fig. 4a), resulting in an mean paleodirection (Fisher 1953) with a declination of 335.1°, an inclination of 68.8° and an associated 95 confidence interval

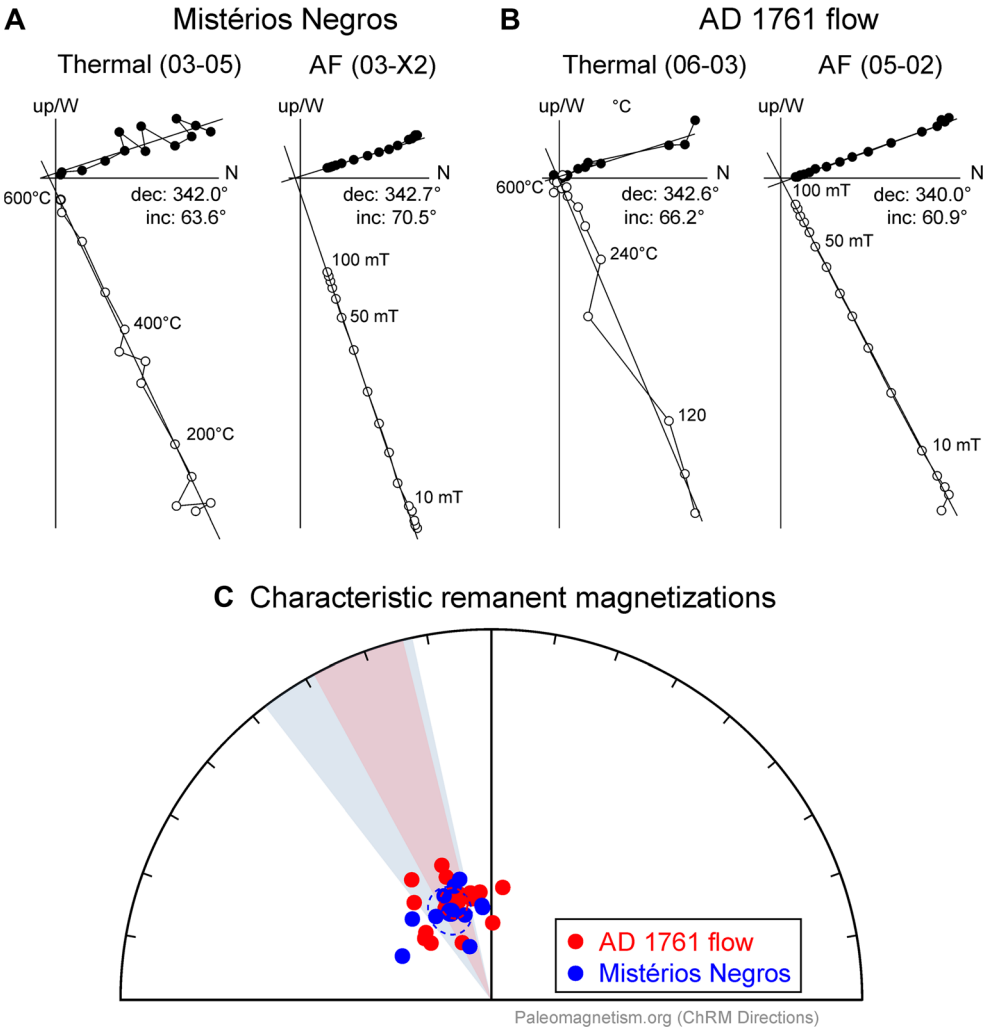

Fig. 4 Paleomagnetic results for Mistérios Negros domes and AD 1761 flow. **a** Typical Zijderveld demagnetization diagrams of Mistérios Negros domes and **b** AD 1761 flow: examples of thermal demagnetization experiment on the left, and alternating field (AF) on the right. Sample numbers are specified above diagrams; obtained directions are along North axis of Zijderveld diagrams. Typical temperature (thermal) and field strength (AF) values are indicated along projected inclination. **c** Paleomagnetic sample directions of Mistérios Negros and AD 1761 flow are compared in an equal area plot. Sample directions are indicated by small dots, the large dot is the obtained mean, together with associated (projected) 95 confidence interval (dashed ellipse). The 95 confidence interval of the declination is shaded in the appropriate colour

of 4.7° (Table 2). This direction is derived from the 10 independently oriented cores, and the precision parameter k is 104.5, which is in the expected range for a direction derived from a single cooling unit (k should be at least >50, but preferably >100 (e.g. Tauxe et al. 2014) (Fig. 4c). Four samples passed the selection criterion for pseudo-Thellier experiments (as specified in de Groot et al. 2013) and yielded an average pseudo-Thellier slope of 5.91 ± 1.13 (1). Following the relation of de Groot et al. (2015), this slope can be calibrated to an absolute paleointensity value of 61.0 ± 9.0 T.

Most of the 24 samples (sites 5 and 6) from the AD 1761 flow exhibit univectorial demagnetization behaviour towards the origin (Fig. 4b). Five samples showed deviating directions that can be explained by overprinting during drilling, transport or storage, weathering of the outcrop and/or orientation errors. The mean directions for sites 5 and 6 are (declination and inclination) 335.9°, 68.3° and 341.8°, 65.8°, respectively (Table 2). The Watson common true mean direction test (McFadden and Jones 1981; Watson 1983) applied to the distributions of the virtual geomagnetic poles derived for these

Table 2 Paleomagnetic results obtained from Mistérios Negros domes and AD 1761 flow. The number of samples measured (n), the obtained declination and inclination, the confidence interval 95 and the precision parameter k are reported

Site (description)	n (rejected)	Declination (°)	Inclination (°)	95 (°)	k
TER03 (Mistérios Negros)	10 (0)	335.1	68.8	4.7	104.5
TER05A and 5B (AD 1761 flow)	14 (4)	335.9	68.3	5.4	79.8
TER06 (AD 1761 flow)	10 (1)	341.8	65.8	3.0	291.7
TER05 and TER06 (average AD 1761 flow)	24 (5)	338.9	67.2	3.1	121.3

95 and k statistical parameters after Fisher (1953)

two sites is positive (class B); their results may therefore be joined and interpreted together to obtain one mean paleomagnetic direction for the AD 1761 lava flow sites. After a 45° cut-off, 19 out of 24 samples were used to calculate a mean direction for the AD 1761 flow resulting in a declination of 338.9° and an inclination of 67.2°, with a k of 121.3 and an 95 of 3.1° (Fig. 4b, c). Eight samples yielded interpretable pseudo-Thellier results and produced an average slope of 5.62 ± 1.0 that was converted into an absolute paleointensity of 58.7 ± 7.9 T.

To test whether the distributions of the directions obtained from Mistérios Negros domes and AD 1761 flow have a common true mean direction and hence are statistically indistinguishable, we applied the Watson test (McFadden and Jones 1981; Watson 1983) to the distributions of the virtual geomagnetic poles derived from the paleomagnetic directions (Fig. 4c). The Watson test is positive (class B); therefore, we conclude that the paleomagnetic directions recorded by the Mistérios Negros domes and the AD 1761 flow are equal. The obtained paleointensity estimates for both units also agree within experimental error.

Furthermore, the reported geomagnetic vector does not occur at any other time in the PSV curve for the Azores (Di Chiara et al. 2012; Di Chiara et al. 2014), which clearly shows that the emplacement of the Mistérios Negros domes and the AD 1761 flow was coeval.

Petrography, mineral and whole-rock geochemistry

The coeval eruption of Mistérios Negros domes and AD 1761 mafic flow raises the possibility of magma interaction. Here, we combine petrographic observations with mineral and whole-rock geochemistry in order to identify possible evidence of magma mixing/mingling. The aim is to try to understand if the mafic magma intruded a more evolved felsic reservoir under Santa Bárbara Volcano and triggered its eruption, as commonly reported for other eruptions (e.g. Anderson 1976; Sparks et al. 1977; Sigurdsson and Sparks 1981; Larsen et al. 2001; Peccerillo et al. 2003; Sigmarsson et al. 2011), or whether some other process was involved.

Methodology

The petrographic features of four lava samples (yellow triangles in Fig. 2; TRS03 and TRS26 from the AD 1761 flow, and TERS45 and TERS47 from Mistérios Negros domes) were studied in detail and complemented with modal analyses by counting 2000 points on each thin section.

Electron microprobe analyses were performed on the same samples with a JEOL JXA 8200 Superprobe, at the Dipartimento di Scienze della Terra 'Ardito Desio' of the University of Milan (Italy). A spot size of 1 m with a current of 5 nA was used for all mineral phases, except alkali feldspar (5 m); groundmass glass was analysed with a spot size of 10 m. Counting times were 30 s on the peak and 10 s on each background. International standards were used to check the accuracy of the analyses, which on average is better than 5 % for all major elements except alkalis (11 %) and MnO (13 %). Full results are given in the Electronic Supplementary Material (ESM 1) together with detection limits for each element.

Whole-rock geochemical analyses of the AD 1761 lava flow are reported in Madureira et al. (2011) and Zanon and Pimentel (2015) (samples PMT27 and TRS03, respectively). The Mistérios Negros lava domes (samples TERS45 and TERS47) were analysed at Activation Laboratories Ltd., Ontario (Canada) (Table 3). Major and trace elements were measured through inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS), respectively. Alkaline dissolution with lithium metaborate/tetraborate followed by nitric acid was used for the analyses, except for Ni, Cu, Zn and Cd determination, for which multi-acid digestion was used (hydrofluoric followed by a mixture of nitric and perchloric acids). Further information on the analytical methods is available at the Activation Laboratories website (www.actlabs.com). Calculated error (1) is better than 5 % for all major elements, 8 % for all minor and trace elements, except La and Pr (15 %) and Pb (24 %).

Results

The AD 1761 mafic lava is porphyritic with 27–28 vol% total crystal content. Idiomorphic phenocrysts are plagioclase (19–21 vol%), olivine (~4 vol%) and clinopyroxene (~2 vol%). Ilmenite (~2 vol%) is present only as microphenocryst. The same mineral phases constitute the groundmass, which shows intergranular to intersertal textures. Glomeroporphyritic aggregates of mafic phases and plagioclase are also present.

Plagioclase crystals (up to 1.5 mm) can be grouped in two different morphological types: rare single tabular euhedral and twinned tabular subhedral crystals, with embayments and reaction rims. Some phenocrysts show sieve-textured cores (Fig. 5a). Despite this textural diversity, phenocrysts do not vary in composition ($An_{61–66}$, $Ab_{34–38}$, Or_1), except at the rim, where an increase of both CaO and Al_2O_3 is coupled with a decrease in alkalis (Fig. 6a). Microphenocrysts are not zoned and their composition is An_{70}, Ab_{29}, Or_1. In the groundmass, the composition is slightly variable, i.e. $An_{46–50}$, $Ab_{48–51}$, $Or_{2–3}$.

Olivine phenocrysts (up to 1.2 mm) are, in decreasing order of abundance, anhedral to subhedral and skeletal. Some phenocrysts show disequilibrium features such as embayments and reaction rims. Glomeroporphyritic aggregates are common, while the largest euhedral polygonal crystals constitute

Table 3 Whole-rock (WR) geochemical analyses of major and trace elements of AD 1761 flow and Mistérios Negros domes and average groundmass glass (gm) composition

Sample	TRS03[a]	PMT27[b]	TERS45	TERS47	TERS45 gm
Unit	AD 1761 flow	AD 1761 flow	Mistérios Negros domes	Mistérios Negros domes	Mistérios Negros domes
Type/number of analyses	WR	WR	WR	WR	11 spots (±1)
Major elements (wt%)					
SiO_2	49.13	50.00	65.53	66.10	67.82 (0.44)
TiO_2	3.12	3.18	0.52	0.39	0.66 (0.09)
Al_2O_3	15.00	15.26	14.76	14.23	13.28 (0.66)
Fe_2O_3	2.79	–	3.06	3.41	–
FeO	9.10	–	2.07	1.59	5.38 (0.54)[c]
Fe_2O_3t	–	12.19	–	–	–
MnO	0.25	0.21	0.22	0.22	0.26 (0.04)
MgO	4.50	4.67	0.31	0.18	0.22 (0.08)
CaO	8.41	8.31	0.99	0.75	0.32 (0.12)
Na_2O	4.25	4.23	6.86	6.95	4.67 (0.36)
K_2O	1.41	1.39	3.80	4.37	5.70 (0.18)
P_2O_5	1.34	1.30	0.08	0.04	0.08 (0.03)
LOI	0.59[d]	0.77[d]	0.39	0.36	–
Total	98.71	99.96	98.58	98.59	98.38
Trace elements (ppm)					
Sc	18	18	5	3	
Be	2	–	5	6	
V	240	210	bdl	bdl	
Cr	80	23	bdl	bdl	
Co	25	23	bdl	bdl	
Ni	bdl	16	bdl	bdl	
Cu	bdl	22	bdl	bdl	
Zn	230	119	160	190	
Ga	24	22	28	30	
Ge	1	1.5	2	2	
As	bdl	–	bdl	7	
Rb	31	28	75	97	
Sr	675	678	27	12	
Y	42	46.3	63	77	
Zr	253	253	689	897	
Nb	54	56.5	143	167	
Mo	3	–	7	9	
Ag	bdl	–	3.8	6.9	
In	bdl	–	bdl	bdl	
Sn	2	–	5	11	
Sb	bdl	–	bdl	bdl	
Cs	bdl	0.2	0.7	1	
Ba	766	883	1430	715	
La	50.4	71.7	82.7	103.7	
Ce	110	145	163	201	
Pr	15.2	18.1	18.2	22.2	
Nd	56.6	76.7	71.1	85.4	
Sm	12.7	16.6	14.6	17.7	
Eu	4.75	6.04	4.09	3.42	
Gd	12.3	14.8	13.5	15.9	

Table 3 (continued)

Sample	TRS03[a]	PMT27[b]	TERS45	TERS47	TERS45 gm
Unit	AD 1761 flow	AD 1761 flow	Mistérios Negros domes	Mistérios Negros domes	Mistérios Negros domes
Type/number of analyses	WR	WR	WR	WR	11 spots (±1)
Tb	1.9	2.23	2.3	2.8	
Dy	10.5	11.3	12.2	15.2	
Ho	1.8	2.05	2.3	2.9	
Er	4.6	5.01	7.1	8.9	
Tm	0.58	0.63	1.01	1.32	
Yb	3.3	3.68	6	7.8	
Lu	0.48	0.5	0.87	1.11	
Hf	6.5	6.9	17.4	22.7	
Ta	4	4.17	7.8	9.9	
W	1	–	5	2	
Tl	bdl	–	0.1	0.1	
Pb	bdl	2	bdl	9	
Bi	6.1	–	bdl	bdl	
Th	3.8	3.76	11.8	15.8	
U	1.4	1.27	4.3	5.5	

bdl below detection limit

[a] From Zanon and Pimentel (2015)

[b] From Madureira et al. (2011)

[c] FeO_{total}

[d] Gain on ignition

rare fragments of cumulates (Fig. 5b). Olivine show fairly constant forsterite content (Fo_{80}) across the crystals.

Clinopyroxene (up to 1.5 mm) is rare and occurs as euhedral or subhedral crystals in association with ilmenite. Some crystals exhibit oscillatory zoning; however, the composition is slightly variable $Wo_{34–38}$, $En_{38–39}$, $Fs_{8–12}$. Occasional phenocrysts show evidence of disequilibrium features and include poikilitic plagioclase.

Ilmenite (~0.1 mm) is present as single or twinned microphenocrysts.

The Mistérios Negros felsic lava is porphyritic (34–43 vol%) with a mineral assemblage constituted by alkali feldspar (31–40 vol%), clinopyroxene (~1 vol%), oxides (1–2 vol%) and olivine (<1 vol%). Groundmass exhibits trachytic texture and is constituted by the same mineral phases, plus occasional aenigmatite, apatite and eudyalite in decreasing order of abundance, and interstitial glass.

Alkali feldspar (up to 4.7 mm) is found either as isolated tabular and euhedral or subhedral crystals, sometimes in association with clinopyroxene, or in polycrystalline association showing disequilibrium features (Fig. 5c). The latter are smaller (~2.5 mm) than isolated phenocrysts, subhedral and twinned, with embayments and resorbed cores. Although optical microscopy, backscattered electron and cathodoluminescence emission imaging revealed some zoning of these crystals, chemical profiles obtained by electron microprobe indicated a limited compositional variability (=1.1–2.2), confined within the analytical error (Fig. 6b). Only at the rim of some crystals do CaO, Al_2O_3, BaO and alkalis show variations. The overall composition is anorthoclase ($An_{3–7}$, $Ab_{78–82}$, $Or_{12–19}$). Microphenocrysts (0.3–0.4 mm) are very common and are euhedral and twinned, without disequilibrium features (Fig. 5d). These crystals are also of anorthoclase composition ($An_{6–9}$, $Ab_{79–83}$, $Or_{9–15}$) with limited variation confined within the analytical error.

Other mineral phases are rarer and include clinopyroxene (up to 0.6 mm) as subhedral to anhedral crystals (augite $Wo_{38–40}$, $En_{18–29}$, $Fs_{26–33}$), olivine (up to 0.5 mm) also as subhedral to anhedral crystals (Fo_{27}), and partially resorbed Ti-magnetites. These can occur either as isolated crystals or in association with other phases.

The two samples of the AD 1761 mafic lava flow are trachybasalts with SiO_2 contents between 49.1 and 50 wt% and total alkali content (Na_2O+K_2O) of about 5.6 wt% (Fig. 7a). When compared with other lavas emitted from the fissure zone, the AD 1761 lava is slightly more evolved due to an increased amount of fractionating olivine and clinopyroxene (low value of compatible elements, e.g. Cr, Sc, Ni Co, Cu, and moderately low value of Fe and Mg; Self and Gunn 1976; Mungall and Martin 1995; Beier et al. 2008; Zanon and Pimentel 2015).

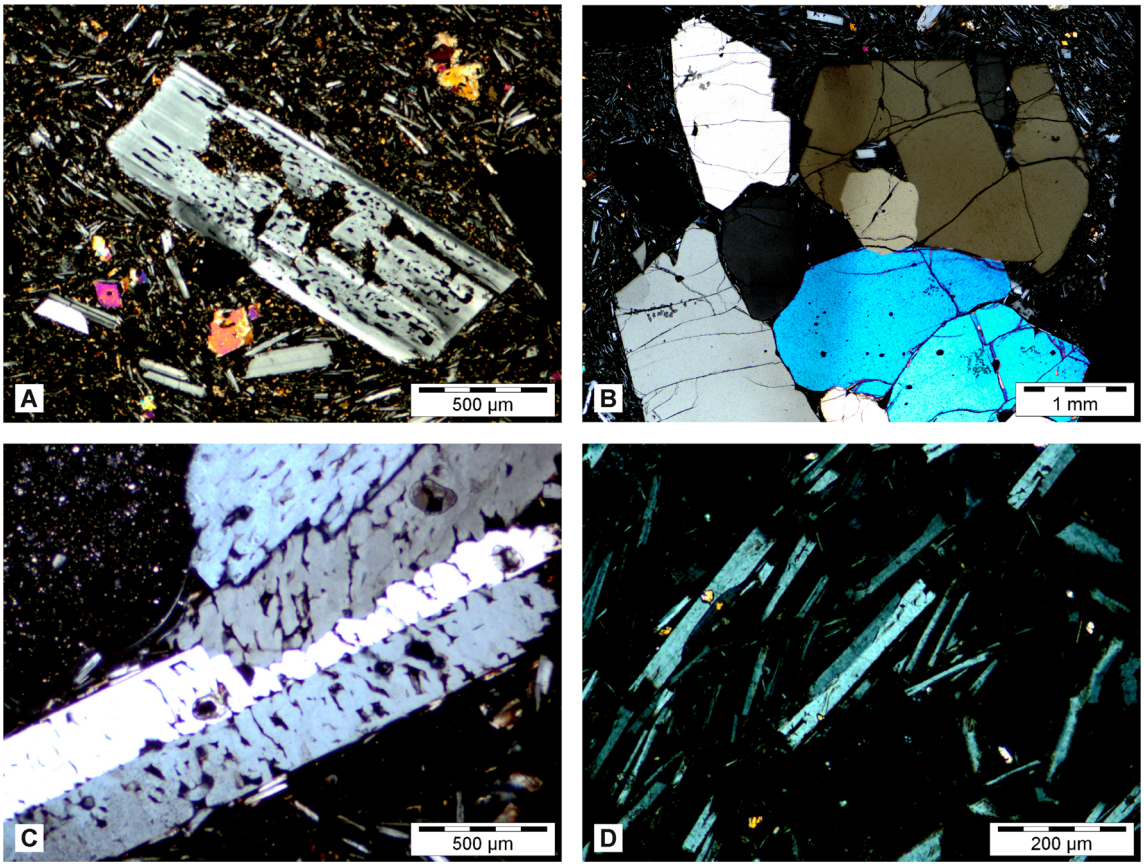

Fig. 5 Photomicrographs showing representative petrographic features of AD 1761 mafic lava: **a** plagioclase phenocryst with sieve-textured core and **b** glomeroporphyritic aggregate of olivine; and of Mistérios Negros felsic lava: **c** association of alkali feldspar phenocrysts with disequilibrium features and **d** euhedral alkali feldspar microphenocrysts

The samples of Mistérios Negros domes are slightly peralkaline comenditic trachytes (according to the classification of Macdonald 1974) characterized by SiO_2 contents of 65.5 and 66 wt%, total alkalis of 10.7–11.3 wt% (Fig. 7a) and peralkaline index (molar $[Na_2O+K_2O]/Al_2O_3$) of 1.04–1.14. The Mistérios Negros lava has similar composition to that of the other evolved lavas (domes and coulees) erupted from Santa Bárbara Volcano (Self and Gunn 1976; Mungall and Martin 1995; Pimentel 2006; Beier et al. 2008).

The groundmass glasses of lava dome samples are somewhat variable and more evolved than the whole-rock compositions, straddling the limit between comenditic trachytes and comendites, with SiO_2 contents in the range 67.2–68.6 wt%, total alkalis of 9.4–10.9 wt% (Fig. 7a) and peralkaline index 1. We were unable to obtain reliable glass compositions of the trachybasalt lava due to the high amount of microliths in the groundmass.

In the primordial mantle-normalized multi-element diagram (Fig. 7b), the comenditic trachytes of Mistérios Negros are accordingly more enriched in incompatible elements than the trachybasalt lava, when compared to the primordial mantle (McDonough and Sun 1995). The diagram also shows marked negative anomalies of Sr and Ti and Zr positive anomaly in the comenditic trachyte lava. By contrast, the AD 1761 trachybasalt lava shows Th, K, Pb, Hf and Zr negative anomalies and a slight enrichment in Eu.

Overall, petrographic, mineral and whole-rock geochemical data did not reveal evidence of interaction between the co-erupted trachybasalt and comenditic trachyte magmas.

Structural analysis

In volcanic areas characterized by extensional/transtensional settings, the presence of faults and fractures, acting as crustal discontinuities, may play a significant role in providing preferential pathways for magma ascent. Tensile or transtensive stress conditions favour the propagation of magma towards the surface and thus eruptions (e.g. Walker 1999; Wadge and Burt 2011; Le Corvec et al. 2013; Daniels and Menand 2015). During ascent, magma can move either vertically through dykes, linking deep-seated reservoirs to the surface (Gudmundsson 1995, 2000), or laterally from shallow reservoirs to different sites of intrusion/eruption (Einarsson 1991; Einarssom et al. 1997) or by a combination of both (Wright

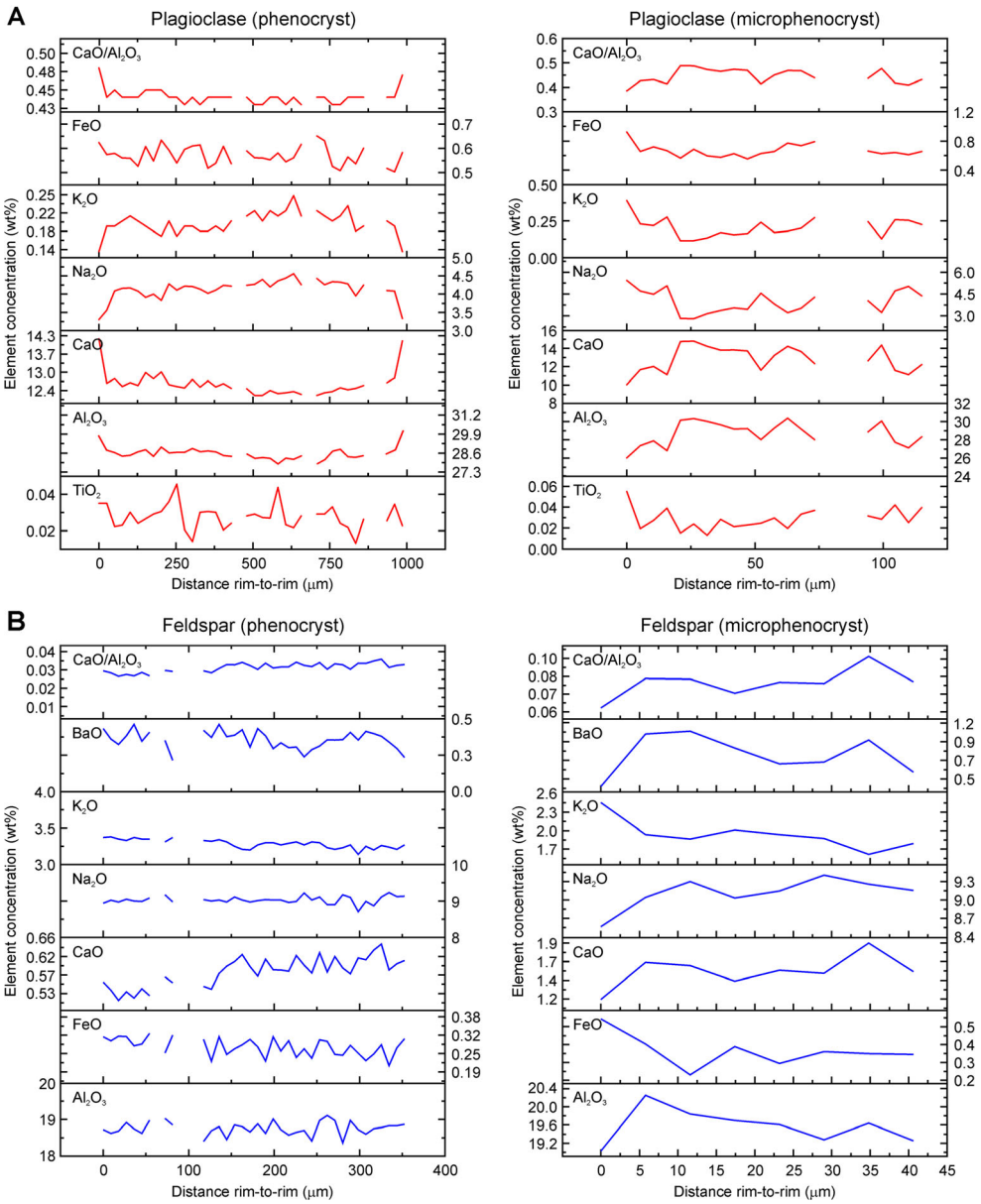

Fig. 6 Compositional rim-to-rim profiles across representative **a** plagioclase crystals from AD 1761 mafic lava and **b** alkali feldspar crystals from Mistérios Negros felsic lava

et al. 2012). The regional stress field strongly influences the paths of feeder dykes in the shallow crust. However, the final pathways of the magma towards the surface can deviate according to the influence of local stress fields (e.g. McGuire and Pullen 1989; Acocella and Funiciello 1999; Perry et al. 2006).

It is also well known that rising magma can create its own magma-filled fractures, overcoming the stress exerted by the surrounding rocks as the fracture expands (magma overpressure; Le Corvec et al. 2013). Hence, the pattern of fissures through which magma reaches the surface is controlled by a combination of regional tectonic stress, local stress induced by the magma overpressure and topographic effects (e.g. Pinel and Jaupart 2000; Acocella et al. 2006; Gudmundsson 2006; Acocella and Neri 2009; Wadge and Burt 2011; Le Corvec et al. 2013).

In the Azores region, the main structural trend (WNW-ESE to NW-SE) is expressed by major tectonic structures and also seems to control the spatial distribution of eruptive centres (e.g. Madeira and Brum da Silveira 2003; Hipólito et al. 2013; Carmo et al. 2015; and references therein).

Methodology

Fieldwork was combined with remote-sensing analyses using vertical aerial photographs (1:15,000 scale; from 1986, Instituto Português de Cartografia e Cadastro), a high-resolution orthophotograph (1:10,000 scale; Direção de Serviços de Cartografia e Informação Geográfica), a topographic map (1:25,000 scale; Instituto Geográfico do Exército—IGeoE) and a digital elevation model (DEM, cell

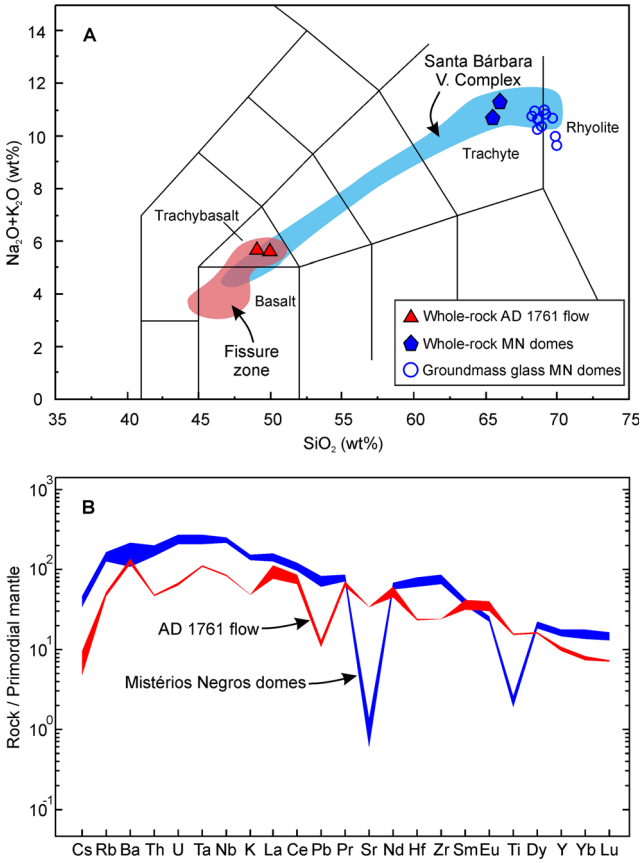

Fig. 7 **a** Total alkalis vs. silica (TAS) diagram (Le Bas et al. 1986) for classifying whole-rocks and groundmass glasses. Shaded areas represent geochemical datasets of the fissure zone (in red) and Santa Bárbara Volcano (in blue) (from Pimentel 2006; Beier et al. 2008; Zanon and Pimentel 2015). **b** Primordial mantle-normalized multi-element diagram (McDonough and Sun 1995) for AD 1761 trachybasalt flow and Mistérios Negros comenditic trachyte domes

size of 10 m, produced from topographic map) to map the limits of the lava flow, scoria cones and lava domes, and morphologic features related to possible tectonic origin (fault scarps) or tectonically controlled (i.e. cones, craters or domes alignments, eruptive fissures and elongated volcanic features). The information was combined in a GIS environment in order to determine morphometric parameters and structural trends.

Results

The morphotectonic structures identified in the study area, which includes the central part of the fissure zone and eastern flank of Santa Bárbara Volcano, are mainly expressed by alignments of volcanic features (lava domes, cones, craters/vents), eruptive fissures, elongated forms (cones, craters, vents) and breached craters. The direct observation of eventual tectonic structures was hindered by the dense vegetation, characteristic of the Azores islands and anthropogenic modification of the terrain, particularly persistent quarrying of the historical and other recent scoria cones. In fact, no syn-eruptive cracks or lava-filled fissures related to the AD 1761 eruption were found (even in older vertical aerial photographs, prior to the establishment of the quarries), limiting the determination of the strain pattern prevailing during the eruption. Likewise, no post-eruptive tectonic structures affecting the volcanic features formed during this event were recognized.

Overall, two main structural directions dominate the study area, mostly WNW-ESE (N110–120°) and minor ENE-WSW (N70–78°) to E-W (N82–98°) (Fig. 8). The Mistérios Negros eruption area (Fig. 8 inset II) is marked by the WNW-ESE (N110–118°) trend, defined by the alignments of these lava domes and other neighbouring domes. The same trend is also represented south and southeast of this area by alignments of several scoria cones, a spatter cone and eruptive fissures. By contrast, the Pico do Fogo eruption area (Fig. 8 inset III) is characterized by E-W to ENE-WSW trends, expressed by the N87° (average strike) alignment of Pico do Fogo cone and the three small adjacent vents to the west, the ~N75° alignment defined by the elongation and breached crater of Pico Vermelho, and the ~N90° alignment crossing Pico das Caldeirinhas (ESE of Pico do Vermelho), marked by an eruptive fissure on its eastern flank and a small lateral vent on the opposite flank. Less represented are the NW-SE and NNW-SSE directions which seem to control the elongation of the scoria cone WSW of Pico Vermelho and the geometric distribution of the craters of Pico Gordo cone, where a curved alignment trending N72° to N128° may indicate the influence of both tectonic directions. Additionally, the alignment of two older vents (NNE of Pico das Caldeirinhas) and the presence of a crater breached to the north, in the small vents adjacent to Pico do Fogo, suggest a NNW-SSE (N166°) control.

Physical parameters of the eruption

The physical parameters were obtained from analyses of the mapped volcanic products (lava flow, scoria cones and lava domes; Fig. 2) and interpretation of the historical records. It should be noted that the values presented here are considered minima, as the pre-eruptive topography is unknown and the amount of dispersed ash cannot be estimated.

The trachybasalt lava flow reached a maximum length of 5.8 km (from the vents to the Biscoitos flow front) and covered an area of 3.5×10^6 m^2. The average thickness of the lava is 3 ± 1 m, which, multiplied by the covered area, yields a volume of $11 \pm 4 \times 10^6$ m^3 (dense rock equivalent, DRE). An average flow velocity of 30 m/h is estimated considering the maximum length of the flow divided by 8 days of activity. The mean effusion rate (total volume divided by duration) is estimated at 15 ± 5 m^3/s.

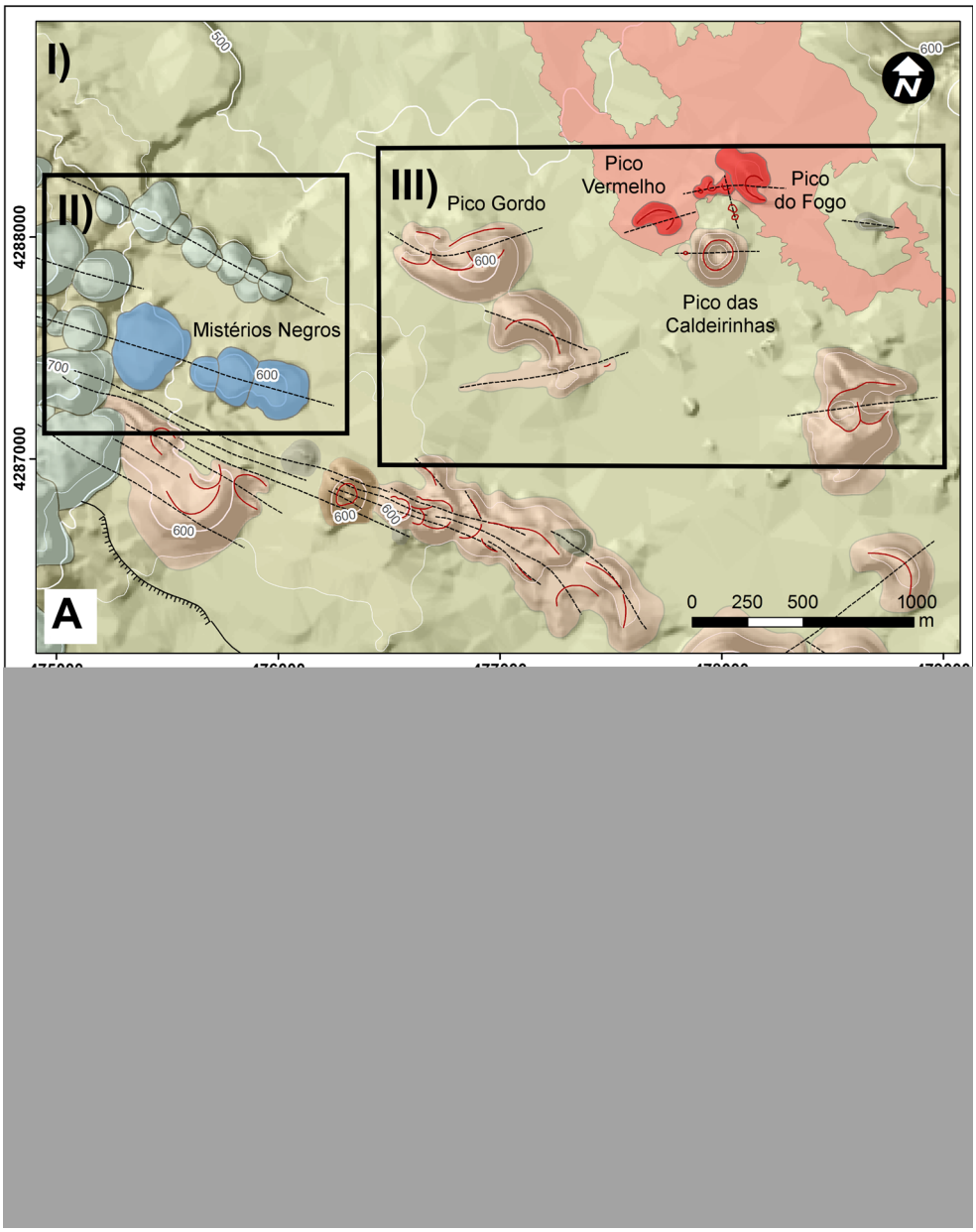

Fig. 8 **a** Morphotectonic sketch of the study area (central part of the fissure zone and eastern flank of Santa Bárbara Volcano); UTM projection, Zone 26S, Datum WGS1984. **b** Geometry of tectonic structures (circular histograms of unweighted azimuth frequency distribution, lower hemisphere, Schmidt net)

The two main scoria cones (Pico do Fogo and Pico Vermelho) have average basal radii of 122 and 96 m and heights of 53 and 52 m, respectively. Their volumes are calculated assuming a truncated cone shape, which yields 1.2×10^6 m^3 for Pico do Fogo and 9.4×10^5 m^3 for Pico Vermelho. It must be considered that the morphology of Pico Vermelho is altered by intense quarrying. The three smaller lateral vents formed west of Pico do Fogo account for 2×10^5 m^3. Together with the main cones it gives a total bulk volume of 2.4×10^6 m^3 of explosively erupted material. This value can be converted to DRE volume of 2.2×10^6 m^3, using a bulk scoria deposit density of 2600 kg/m^3 and a magma density of 2800 kg/m^3 (obtained from the whole-rock composition).

Overall, the total DRE volume of trachybasalt magma emitted during the second phase is conservatively estimated at $13 \pm 4 \times 10^6$ m^3. When compared with other mafic historical eruptions in the Azores, the AD 1761 event is a medium size eruption; the most voluminous was the AD 1562–63 Planalto da Achada eruption (Pico Island) with an estimated lava volume of 100×10^6 m^3 (Cappello et al. 2015).

The Mistérios Negros lava domes occupy a small area of only 2.1×10^5 m^2 on the eastern flank of Santa Bárbara Volcano. Four individual domes are recognized, with average basal radii ranging from 73 to 190 m and heights from 20 to 68 m. The volume of each dome is calculated assuming a paraboloid shape (Blake 1990; Lyman et al. 2004), with individual DRE volumes