Earth and Planetary Science Letters 273 (2008) 289–298

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Multi-stage evolution of a sub-aerial volcanic ridge over the last 1.3 Myr: S. Jorge Island, Azores Triple Junction

Anthony Hildenbrand [a,*], Pedro Madureira [b], Fernando Ornelas Marques [c], Inês Cruz [c], Bernard Henry [d], Pedro Silva [e]

[a] Interactions et Dynamique des Environnements de Surface, UMR 8148 IDES, Université Paris-Sud, Sciences de la Terre, Bâtiment 504, 91405 Orsay cedex, France
[b] Centro de Geofísica de Évora and Dep. de Geociências da Univ. de Évora, R. Romão Ramalho, 59, 7000-671 Évora, Portugal
[c] Univ. Lisboa, Fac. Ciências, Dep. Geologia and CGUL/IDL, Lisboa, Portugal
[d] Paleomagnetism, IPGP and CNRS, 4 Av. de Neptune, 94107 Saint-Maur cedex, France
[e] ISEL/DEC and IDL/CGUL, Lisboa, Portugal

ARTICLE INFO

Article history:
Received 22 December 2007
Received in revised form 18 June 2008
Accepted 18 June 2008
Available online 5 July 2008

Editor: R.W. Carlson

Keywords:
São Jorge
Azores triple junction
MAR
K/Ar
geochemistry
volcanic ridge evolution

ABSTRACT

New K/Ar dating and geochemical analyses have been carried out on the WNW–ESE elongated oceanic island of S. Jorge to reconstruct the volcanic evolution of a linear ridge developed close to the Azores triple junction. We show that S. Jorge sub-aerial construction encompasses the last 1.3 Myr, a time interval far much longer than previously reported. The early development of the ridge involved a sub-aerial building phase exposed in the southeast end of the island and now constrained between 1.32±0.02 and 1.21±0.02 Ma. Basic lavas from this older stage are alkaline and enriched in incompatible elements, reflecting partial melting of an enriched mantle source. At least three differentiation cycles from alkaline basalts to mugearites are documented within this stage. The successive episodes of magma rising, storage and evolution suggest an intermittent re-opening of the magma feeding system, possibly due to recurrent tensional or trans-tensional tectonic events. Present data show a gap in sub-aerial volcanism before a second main ongoing building phase starting at about 750 ka. Sub-aerial construction of the S. Jorge ridge migrated progressively towards the west, but involved several overlapping volcanic episodes constrained along the main WNW–ESE structural axis of the island. Mafic magmas erupted during the second phase have been also generated by partial melting of an enriched mantle source. Trace element data suggest, however, variable and lower degrees of partial melting of a shallower mantle domain, which is interpreted as an increasing control of lithospheric deformation on the genesis and extraction of primitive melts during the last 750 kyr. The multi-stage development of the S. Jorge volcanic ridge over the last 1.3 Myr has most likely been greatly influenced by regional tectonics, controlled by deformation along the diffuse boundary between the Nubian and the Eurasian plates, and the increasing effect of sea-floor spreading at the Mid-Atlantic Ridge.

1. Introduction

The study of volcanic elongated ridges (VERs) is of particular interest to constrain the interactions between magmatism and tectonics. A number of submarine VERs have been recognized in oceanic intra-plate settings, for instance the Walvis Ridge in the Atlantic (e.g., Wilson, 1965; Morgan, 1971), the Foundation Seamounts chain (Mammerickx, 1992) and the Pukapuka ridges (Sandwell et al., 1995) in the Pacific. Several mechanisms have been proposed to explain the formation of such elongated morphological structures, including: (1) the progressive construction of successive volcanic edifices as plates move above hotspots (e.g., Morgan, 1971; 1972; O'Connor et al., 1998); (2) the episodic extraction of plume-related magmas along preferential zones of weakness in the oceanic lithosphere (e.g., Maia et al., 2001; O'Connor et al., 2002; Clouard et al., 2003; Bonneville et al., 2006); (3) the development of linear or en-echelon volcanic structures controlled by cracking of the lithosphere during tensional/trans-tensional deformation (e.g., Winterer and Sandwell, 1987; Sandwell et al., 1995; Lynch, 1999). VERs developed close to major plate boundaries retain, more specifically, important information regarding the relationships between mantle dynamics, magma genesis, volcanic activity, and plate kinematics.

In the North Atlantic Ocean, the Azores archipelago extends on the eastern and western flanks of the Mid-Atlantic Ridge (MAR), near the present-day triple junction between the North American, Eurasian and Nubian lithospheric plates (Fig. 1). It is composed of nine active volcanic islands, which have developed over a thick oceanic plateau with a complex internal structure (e.g., Searle, 1980; Buforn et al., 1988; Luís et al., 1994; Miranda et al., 1998; Lourenço et al., 1998; Luís et al., 1998; Cannat et al., 1999; Gente et al., 2003). The genesis of the magmas building the Azores has been attributed to an enriched mantle source, probably sampled by a plume (e.g., Schilling, 1975; Flower et al.,

* Corresponding author. Tel.: +33 1 69156742; fax: +33 1 69154891.
E-mail address: anthony.hildenbrand@u-psud.fr (A. Hildenbrand).

0012-821X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2008.06.041

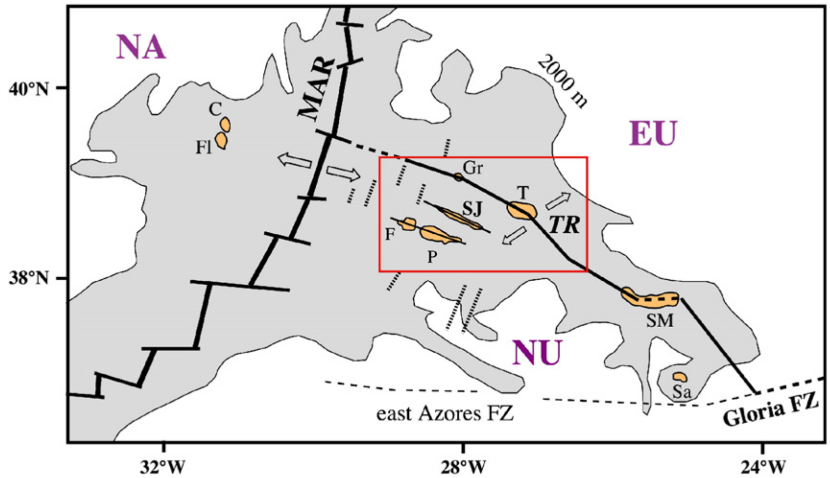

Fig. 1. Location of the Azores volcanic archipelago near the triple junction between the North American (NA), the Eurasian (EU) and the Nubian (NU) plates. The light grey area shows the extent of the Azores plateau. The rectangle localizes the central group of islands including S. Jorge. Bold lines show the Mid-Atlantic Ridge (MAR) and the Terceira rift (TR) and arrows indicate the present main direction of regional tectonic distension in the studied area. Dotted segments show sea-floor spreading magnetic lineations. SJ: S. Jorge; Gr: Graciosa; T: Terceira; F: Faial; P: Pico; Fl: Flores; C: Corvo; SM: S. Miguel; Sa: Santa Maria. After Vogt and Jung (2004), modified.

1976; White et al., 1976, 1979; Davies et al., 1989; Widom and Shirey, 1996; Turner et al., 1997; Moreira et al., 1999a; Bourdon et al., 2005; Madureira et al., 2005; Silveira et al., 2006; Yang et al., 2006). However, the geological evolution of the islands appears to have been greatly influenced by regional deformation (e.g., Haase and Beier, 2003), in particular sea-floor spreading along the MAR, and distension/transtension along the diffuse boundary between the Nubian and the Eurasian plates. The Azores plateau is affected by active faults responsible for recurrent high-magnitude earthquakes (Borges et al., 2007) and present-day deformation in the area also yields the preferential construction of the islands parallel to the WNW–ESE structural direction (Fig. 1).

S. Jorge, especially, has a very elongated shape and a steep topography (Fig. 2). Bathymetric analysis shows that S. Jorge corresponds to the emerged part of a submarine VER, a kind of morphology readily observed at the plateau scale (Lourenço et al., 1998).

Therefore, S. Jorge offers a unique opportunity to study, from direct field investigation, the geological evolution of a VER in an area where the interactions between tectonic deformation and magmatism over the Quaternary remain largely unresolved in the absence of sufficient reliable structural, temporal, petrologic and geochemical constraints. Regarding chronology, only four K/Ar ages on whole-rock samples have been previously published on S. Jorge (Féraud et al., 1980), three of which have been acquired on young volcanic units.

This paper aims to reconstruct the volcanic evolution of S. Jorge throughout its entire sub-aerial eruptive history. We wish to address fundamental questions such as: (i) Has the S. Jorge volcanic construction been continuous through time? (ii) What have been the processes governing the magma genesis and evolution? (iii) What are the possible relationships between volcanic evolution and regional tectonic regime(s)?

In order to answer these questions, we carried out a geochronological and geochemical study on samples from the various accessible volcanic units. These new data provide insights on the processes that governed the sub-aerial development of the ridge and have important geodynamic implications.

2. Geology of S. Jorge

S. Jorge has a sub-aerial length of about 55 km and a maximal width of only 7 km. It has a maximal elevation of 1067 m above sea level, i.e. a total relief of about 3000 m above the Azores plateau. The western part of the island is characterized by a steep morphology overall dominated by an alignment of numerous young volcanic cones, while the eastern side is more eroded and delimited by large sub-vertical cliffs reaching up to 500 m in height (Fig. 2).

Three main volcanic systems have been distinguished on S. Jorge (Forjaz and Fernandes, 1975; Fig. 2): Serra do Topo, Rosais and Manadas. The Serra do Topo system is believed to include the whole eastern half of the island and has been considered as the oldest one. Previous K/Ar ages on whole-rock samples from Serra do Topo range between 0.11 ± 0.05 Ma and 0.55 ± 0.06 Ma (Féraud et al., 1980). These ages have been, however, mainly obtained on samples from the central part of S. Jorge, while the old volcanic lava piles from the eastern side have not been accurately examined until present (Fig. 2). Lava flow successions attributed to the Rosais volcanic system are partially exposed in the coastal cliffs from the western half of the island (Fig. 2). Yet, no isotopic age data are available for this eruptive system. The Manadas "volcanic system" is composed of numerous recent strombolian volcanic cones roughly constrained along the main WNW–ESE axis of the ridge. Most of the cones have developed on the older Rosais volcanic complex, especially during the historical period (Forjaz and Fernandes, 1975), but a few of them have also been built on Serra do Topo to the east (Fig. 2). Lava flows erupted from the young cones partly buried the older cliff successions in unconformity and form lava deltas at the shore level. The age of the Manadas unit is not well constrained, but radiocarbon data were interpreted as the result of volcanic activity during Holocene times (Madeira and Brum da Silveira, 2003).

The available geological map shows numerous faults and dykes cutting all the S. Jorge volcanic units (Fig. 2). They are mainly parallel to the main WNW–ESE elongation of the island, but some of them were mapped with an oblique direction, especially in the eastern part of the ridge. The "Ribeira Seca" fault, specifically, is drawn on the geological map as a main NNW–SSE tectonic structure cutting the central part of the ridge close to the contact between the Serra do Topo and Manadas volcanic systems (Forjaz and Fernandes, 1975, Fig. 2). Concentrations of dykes trending along the N150° direction (Moreira et al., 1999b) also intrude the base of the old volcanic successions at one of our sampling sites (S. João, Fig. 2).

In contrast with the other Azores islands, S. Jorge is characterized by strong erosion, which has been responsible for the development of large coastal cliffs. Coastal erosion and stream incision produced significant amounts of debris, which were partly remobilized and accumulated as sedimentary fans, locally termed "Fajãs" (also used to classify the lava deltas formed at the shore level).

3. New sampling

3.1. Sampling strategy

Particular attention was paid to the various volcanic successions exposed in the accessible cliffs over the whole width of the island.

Serra do Topo, the old volcanic succession, was extensively sampled in the southeast part of S. Jorge, at Fajã de S. João (S. João for short, Fig. 2). The volcanic lava pile is there incised by a well-developed canyon, which allows access to the oldest parts of the volcanic lava pile close to the shore-line (samples AZ05-O, AZ05-P and AZ05-Q). Subsequent lava flows from the same succession were sampled a few hundred meters farther east, along the road upward from S. João. This section offers a complete succession of reasonably fresh volcanic lava flows ranging in altitude between 100 m and about 400 m. Most of them (samples AZ05-R to AZ05-AB) were collected in order to constrain the timing of volcanic emplacement and the compositional variation of erupted lava through time. Numerous sub-vertical dykes intruding the base of the succession have been identified in the canyon and in the lower sections of the road. These dykes roughly trend along the N150 direction. Their concentration rapidly vanishes towards the top of the lava pile.

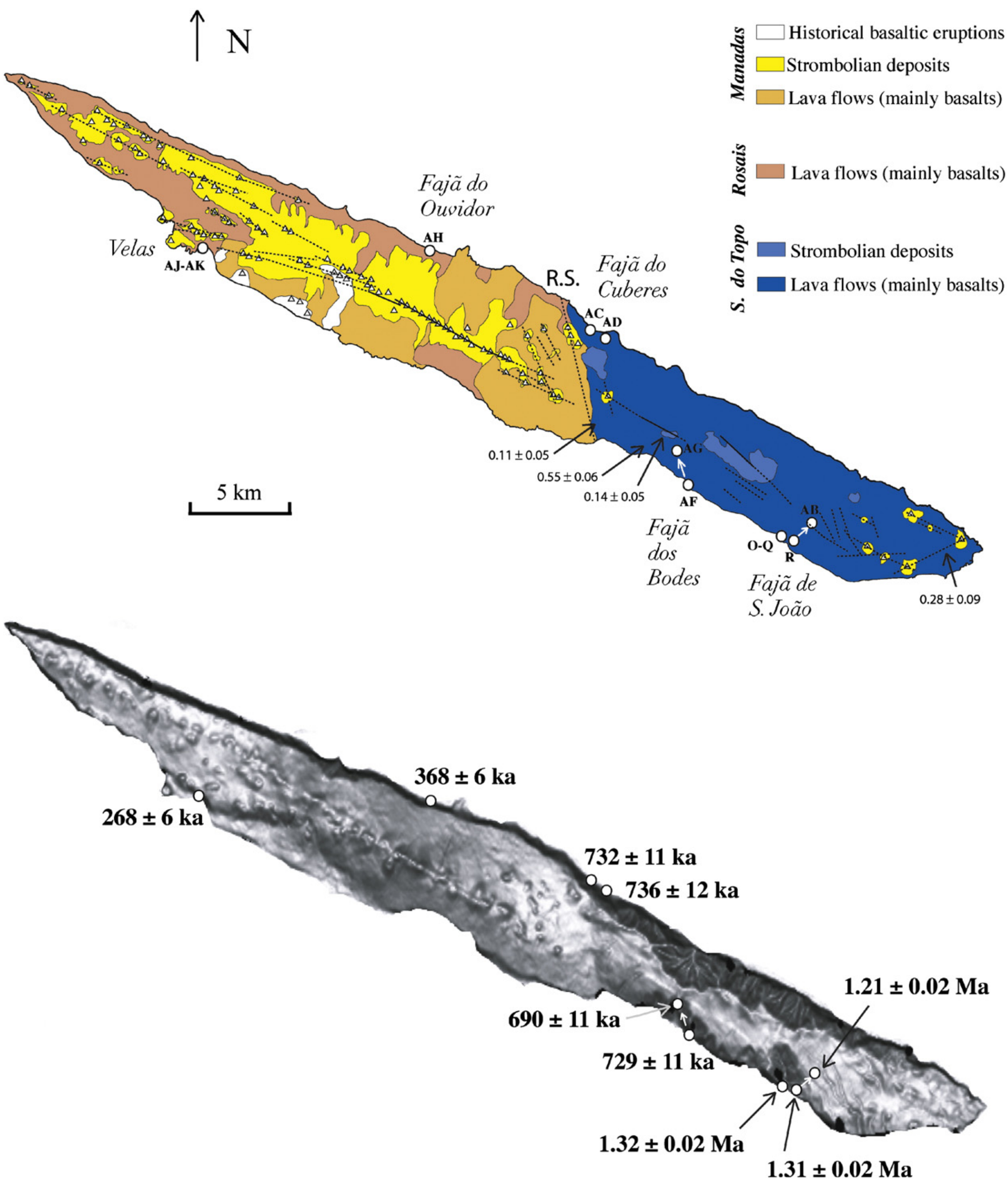

Fig. 2. Upper part: Geological sketch map of S. Jorge (modified after Forjaz and Fernandes, 1975). Previous K/Ar ages (in Ma) from Féraud et al. (1980) are indicated in black characters. White circles show the location of the samples from the present study. White arrows show the stratigraphic relations between lava flows sampled from the base towards the top of individual successions. Lower part: distribution of our new K/Ar ages in the different sectors of S. Jorge. The topography of the island is drawn as a shaded-relief map (STRM DEM data).

Lava flows related to the western end of Serra do Topo volcanic system on the geological map have been sampled on the northern and southern halves of the island, at Fajã dos Cuberes and Fajã dos Bodes, respectively (Fig. 2). To the south, the oldest and the youngest ones have been collected at the shore level and on the upper parts of the main road traversing the island from east to west, respectively (samples AZ05-AF and AZ05-AG). Note that these sample sites are located at the same elevation as the volcanic flows from the top of the S. João succession, while they are offset by only a few kilometres farther west.

The Rosais Unit has been also sampled, in order to constrain whether the western part of the island was built as a single volcanic system or as the result of an eventual migration of the volcanic activity. One lava flow has been sampled at the base of the northern coastal cliffs at Fajã do Ouvidor (sample AZ05-AH). Farther west, two lava flows (samples AZ05-AJ and AZ05-AK) have been collected near the harbour of Velas village at the base of reduced cliffs, the upper part being inaccessible.

Recent flows related to the Manadas Unit have not been sampled here. Though they covered most of the western part of the island during sub-historical and historical periods, these thin lava flows cap the pre-existing main relief of the island. They thus represent a very small volume and do not provide significant information regarding the long-term construction of the dominant part of the ridge.

3.2. Petrographic description of the samples

A detailed petrographic observation of all samples allows the distinction between lavas sampled at S. João and those from the other sites. Lavas from S. João are mostly porphyritic. The major phenocryst phase corresponds to zoned plagioclase (often grouped in glomerocrysts), olivine and scarce clinopyroxene (augite). High amounts of plagioclase phenocrysts and/or glomerocrysts that can exceed 20–25% in volume occur in samples AZ05-AB, AZ05-S and, to a lesser extent, AZ05-T. Samples from the other sites are slightly porphyritic, with the exception of samples AZ05-AD (Fajã dos Cuberes) and AZ05-AH (Fajã do Ouvidor), for which the phenocrysts can reach 35 and 15% in volume, respectively. In contrast with the S. João lavas, the most abundant phenocryst phase is olivine, and clinopyroxene is significantly more abundant. For all samples, the micro-crystalline groundmass is essentially made up of plagioclase and oxides with minor olivine and clinopyroxene in the most mafic lavas.

4. K/Ar dating of the samples

K/Ar and $^{40}Ar/^{39}Ar$ both can be used to date basaltic samples and yield similar results when applied to fresh separated groundmass (e.g., Coulié et al., 2003; De Beni et al., 2005). However, the accurate dating of young basalts is critical since the amount of radiogenic argon accumulated in the samples is very low, generally two orders of magnitude lower than the ^{40}Ar from the atmospheric contamination. The use of the $^{40}Ar/^{39}Ar$ technique, especially, is delicate because irradiation of such high-Ca samples in a nuclear reactor yields isotopic interferences by the production of several argon isotopes, mainly ^{37}Ar and ^{36}Ar, which have to be accounted for, thereby increasing the age uncertainty. Taking into account those limitations, we decided to use a peculiar analytical approach of K/Ar, the unspiked Cassignol–Gillot technique (Cassignol and Gillot, 1982). With this technique, the level of atmospheric contamination is accurately determined by comparison of the $^{40}Ar/^{36}Ar$ ratio of the sample with the $^{40}Ar/^{36}Ar$ ratio of an air pipette measured in strictly similar pressure conditions. The Cassignol–Gillot technique allows the detection of minute amounts of radiogenic argon, as low as 0.1% (Gillot et al., 2006). It has been shown suitable to date low-K lavas of late Quaternary age with an uncertainty of only a few ka (e.g., Gillot et al., 1994; Lahitte et al., 2001; Hildenbrand et al., 2003, 2004; Samper et al., 2007), and for high-K lavas can be extended to very recent periods (Gillot and Cornette, 1986; Gillot et al., 2006), and even to the last millennium with an uncertainty of a few centuries (Quidelleur et al., 2001).

4.1. Samples preparation and analytical procedure

Nine samples out of the 23 collected in S. Jorge have been chosen for geochronological analyses on the basis of their freshness and geological significance (Supplementary data, Table S1). The microcrystalline groundmass was selected for the K–Ar analyses. It is composed of volcanic glass and microlites crystallized during the cooling of the lava flows at the Earth's surface. The rocks were first crushed and sieved at 125–250 μm. Phenocrysts greater than 125 μm in size (olivines, pyroxenes, oxides, and plagioclases) were removed with heavy liquids, because they may have crystallized earlier and deeper in the magma chamber. They are thus not representative of the age of eruption at the surface, and may carry significant inherited excess argon. They are additionally K-poor and may create heterogeneity in the samples. Narrow density spans, generally between 2.95 and 3.05 have been achieved to select the freshest part of the groundmass and eliminate the fraction with a lower density, which is potentially affected by alteration and secondary zeolitisation.

Potassium and argon were measured on two separate aliquots of the selected groundmass grains, the former by flame emission-spectrophotometry and the latter by mass spectrometry according to the Cassignol–Gillot unspiked technique (see Gillot et al., 2006 for a complete review of the analytical procedure). Both K and Ar were analyzed at least twice in order to obtain a reproducible value within the range of uncertainties. The decay constants used are from Steiger and Jäger (1977). The results are presented in Supplementary data, Table S1, where the uncertainties are quoted at the 1σ level.

4.2. Results

We have dated the S. João volcanic succession between 1.323 ± 0.021 Ma and 1.207 ± 0.017 Ma from the base to the top (Fig. 2). Sample AZ05-R, collected at an intermediate level of the volcanic pile yields an age of 1.310 ± 0.019 Ma, in agreement with its stratigraphic position.

Other samples related to Serra de Topo on the geological map and collected at the base of the northern coastal cliffs in the central part of the ridge (AZ05-AC and AZ05-AD) are now dated at 732 ± 11 ka and 736 ± 12 ka, respectively (Fig. 2). Lava flows sampled at the same structural level at the base of the southern cliffs (AZ05- AF) yield an undistinguishable value of 729 ± 11 ka, while the age obtained on AZ05-AG sample from the upper parts of the same succession is, as expected, younger (690 ± 11 ka). These new K/Ar determinations on fresh separated groundmass are older than a previous whole-rock K/Ar age of 0.55 ± 0.06 Ma (Féraud et al., 1980) measured on an "old" lava collected in a thalweg just to the west of our Fajã dos Bodes sampling site. The previous age has been most likely obtained on a lava sample related to a younger volcanic episode. New ages obtained here on volcanic flows sampled at the base of small cliffs cutting the Rosais volcanic system are of 368 ± 6 ka and 268 ± 6 ka (AZ05-AH and AZ05-AJ, respectively). These new data constitute the first geochronological constraints on the activity of the Rosais complex and show that a significant part of the western half of the S. Jorge volcanic ridge has been constructed prior to Holocene.

5. Geochemistry

Whole-rock major and trace elements analyses were performed at Activation Laboratories (Canada) using ICP-OES and ICP-MS, respectively, on 20 representative samples (Supplementary data, Table S2). The absence of significant supergenic alteration in the lavas analysed here is indicated by low values of LOI and K_2O/P_2O_5 ratios higher than 1 (e.g., Frey et al., 1994). In a TAS diagram, S. Jorge samples fall in the alkaline field defined by Irvine and Baragar (1971), ranging in composition between basalt/basanites (slightly nepheline normative) and mugearites. Lavas from the S. João section, especially, display the wider range of compositions.

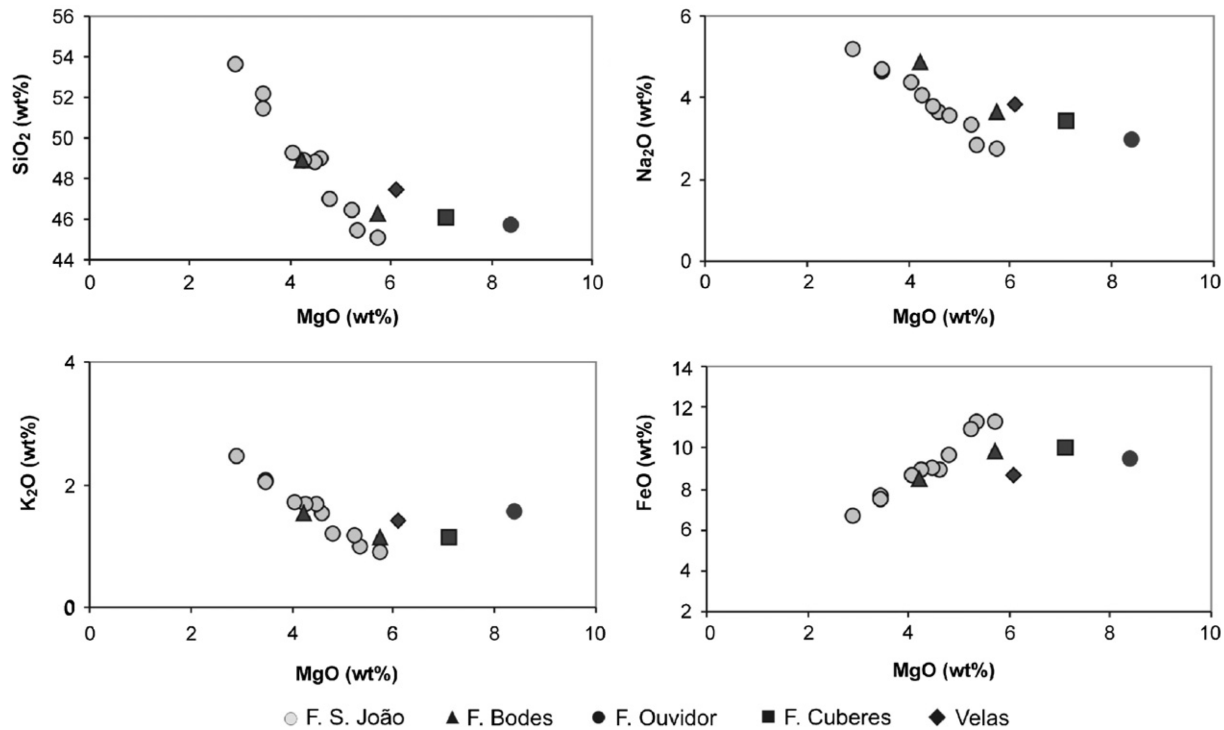

Fig. 3. Harker-like diagrams for S. Jorge samples. MgO concentration is used as an index of magmatic evolution.

5.1. Major elements

Similarly to the other Azores Islands, the elementary compositions of S. Jorge lavas display different signatures from those erupted along the axis of the MAR. Regarding major elements, TiO_2 and P_2O_5 concentrations obtained for the most primitive lavas (MgO≥6 wt.%) range between 2.9 and 4 wt.%, and 0.46 and 0.67 wt.%, respectively, which is rather common in OIB and significantly higher than typical MORB values (TiO_2: 1.19–1.77 wt.%, P_2O_5: 0.10–0.16 wt.%; Sridhar and Ray, 2003 and references therein). Most of the samples have Na_2O/K_2O ratios ranging between 2.1 and 3.6, which is similar to values reported for the Azores (excluding S. Miguel) and other Atlantic Islands such as Madeira, Saint Helens, Cape Verde and Canary (e.g., Wilson, 1989; Davies et al., 1989; Mata, 1996; Holm et al., 2006; Gurenko et al., 2006).

Harker diagrams are presented in Fig. 3, considering the decrease in MgO concentration as an index for increasing magmatic evolution. Two different linear trends are observed on most diagrams: one formed by samples from S. João (older) and the other composed by lava flows sampled at Fajã dos Cuberes, Fajã dos Bodes, Fajã do Ouvidor and Velas (younger) (Fig. 2). The distinct trends point to different processes and degree of differentiation, i.e. distinct magmatic series. Moreover, the divergent pattern observed for most elements towards high MgO values suggests the existence of two distinct types of parental magmas.

The trend defined by S. João lavas is overall characterized by a significant increase in SiO_2, Na_2O, and K_2O, and a relative decrease in FeO during differentiation (Fig. 3). This evolution is accompanied by an increase in P_2O_5, and a decrease in TiO_2 and CaO/Al_2O_3. According to our petrographic observations, such variations can be related with fractional crystallisation of olivine, plagioclase, Fe–Ti oxides and clinopyroxene. The S. João magmatic series, however, does not reflect a single and continuous evolution, since several cyclic compositional changes, e.g. reflected by significant variations in K_2O, are observed from the base to the top of the succession over a period lasting less than 150 kyr (Fig. 4).

Samples from the younger lavas are characterized by relatively high MgO concentrations reflecting their dominant mafic character. In comparison with the S. João lavas, primary magmas from this magmatic series are enriched in SiO_2, Na_2O, and K_2O, and depleted in FeO (Fig. 3). They are also characterized by higher P_2O_5 and lower TiO_2 concentrations, and relatively low CaO/Al_2O_3 ratios. The magmatic evolution of the younger samples is interpreted as the result of fractional crystallisation of olivine and clinopyroxene, and to a minor extent Fe–Ti oxides, in accordance with petrographic observations.

5.2. Trace elements

Like most ocean island basalts, S. Jorge lavas here studied are characterized by an enrichment of incompatible elements and a fractionated REE profile (e.g. (La/Yb)*n*: 7.5–12.5). For all the lavas, we note a relative enrichment in Ta compared with light REE and LILE (Supplementary data, Fig. S1). Ratios between incompatible elements are quite similar for both magmatic series, but the S. João succession shows a wider range of values (e.g., Ba/Th: 75–135; Ba/Nb: 6.1–9.2; Rb/Ba: 0.07–0.11).

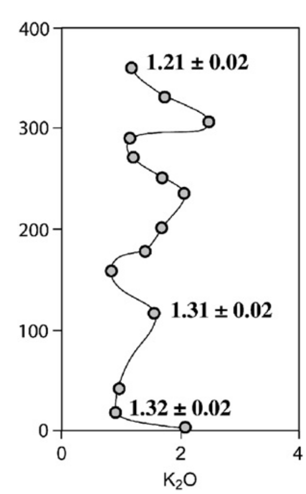

Fig. 4. Geochemical variations for K_2O over the S. João volcanic succession. Thin black lines enhance the main variations. The ages measured on samples AZ05-P, AZ05-R, and AZ05-AB are indicated.

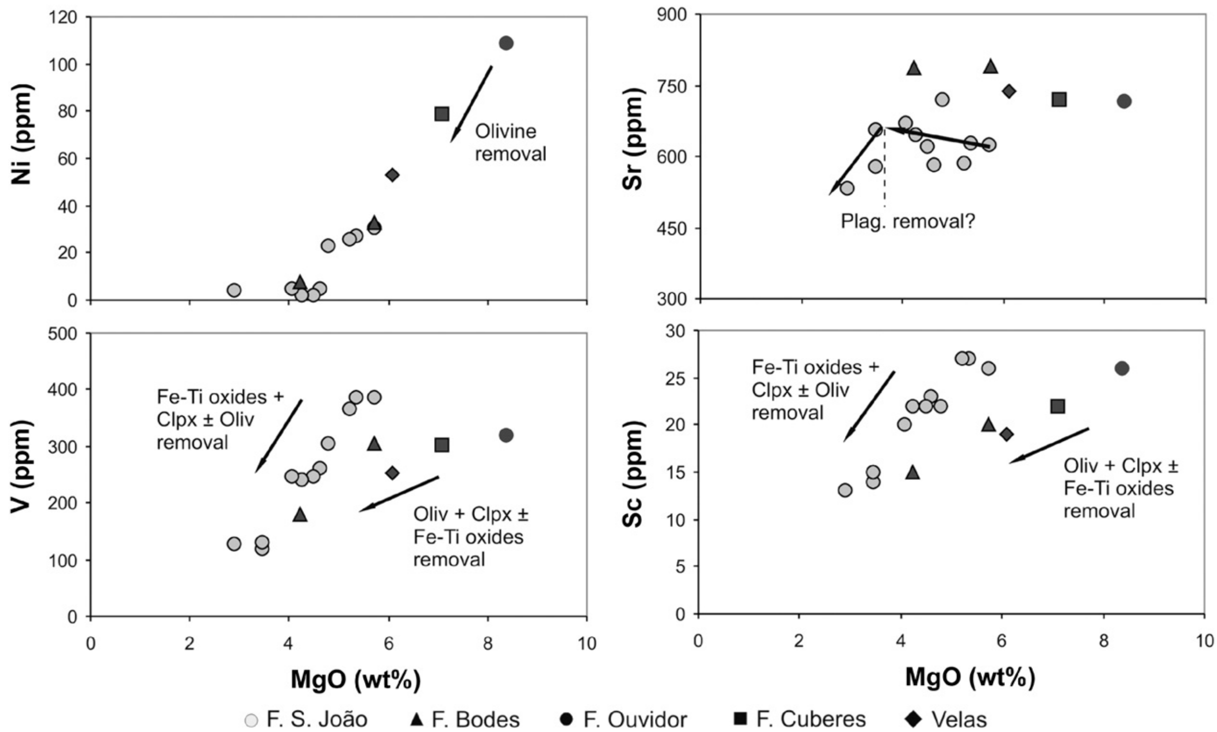

Fig. 5. MgO vs. Sr, Sc, V and Ni, considered to be compatible with plagioclase, clinopyroxene, (titano)magnetite and olivine crystallisation, respectively. The higher slope observed for Ni in the group of lavas sampled at Fajã dos Cuberes, Bodes, Ouvidor and Velas point to the higher importance of olivine fractionation when compared with samples from S. João.

Variations in compatible trace elements with respect to MgO (Fig. 5) confirm the existence of two main magmatic series. For both series, Ni, V and Sc decrease along with MgO, reflecting their fractionation by removal of olivine, Fe–Ti oxides and clinopyroxene. Lower concentrations in Sr observed for the S. João samples highlight the more significant role of plagioclase crystallization and removal. The Sr values show a significant scatter, which most probably indicates that the rising magma incorporated different amounts of plagioclase phenocrysts accumulated at the roof of the magma chamber, in accordance with the presence of glomerocrysts in S. João samples.

6. Discussion

6.1. Evidence for an old sub-aerial building phase in S. Jorge

The new ages obtained on the ca. 400 m-thick S. João succession show the existence of a previously undocumented old and apparently brief (<150 kyr) sub-aerial volcanic phase, constrained between 1.32 ± 0.02 Ma and 1.21 ± 0.02 Ma. Although the original volcanic system has experienced significant coastal and superficial erosion, its upper morphology is partly preserved as a gentle surface exposed on the southeast part of S. Jorge, near S. João (Fig. 2). The NW–SE to NNW–SSE main elongation of this surface suggests a structural control of volcanic outputs since the earliest stages of edification, but along a direction oblique to the present-day main WNW–ESE elongation of the island. Dyke concentrations intruding the base of the S. João lava pile are also dominantly oriented along the N150 direction. They most likely fed the late activity of the old volcanic system, since (1) no recent volcanic units have been recognized over the top of the S. João lava pile, and (2) the concentration of dykes vanishes toward the top of the succession. S. Jorge early sub-aerial evolution thus likely involved the development of a NW–SE ridge-like eruptive centre, which has been later encompassed to the west, and to a lesser extent to the east, by the more recent volcanic construction concentrated along the present main WNW–ESE axis of the island. Such a hypothesis is further supported by the existence of a small N150 linear submarine ridge in the direct prolongation of the S. João area (Fig. 6).

Old basic lavas in S. Jorge are alkaline and enriched in incompatible elements, reflecting partial melting of an enriched mantle beneath the island. The fractionated REE profile (Supplementary data, Fig. S1) suggests deep partial melting of a garnet peridotite mantle source (e.g., Wilson, 1989; Best and Christiansen, 2001). Though Harker-diagrams and compatible trace elements patterns suggest a common type of parental magma for the S. João lavas (Figs. 3 and 5), slight discrepancy between incompatible trace element ratios (Ba/Th, Ba/Nb, Rb/Ba) could reflect small variations in the composition of the source, which would require isotopic data to be examined in further detail. Our new data on the S. João succession additionally show successive differentiation cycles throughout the old building-stage (Fig. 4). Primitive melts generated in the upper mantle thus seem to have episodically transited through a shallow magma reservoir in which differentiation could have occurred. The successive cycles of basic magma ascent, storage and evolution have been most likely controlled by intermittent re-opening of the magma feeding system, probably during recurrent events of tectonic deformation.

6.2. Prolonged volcanic gap in S. Jorge

All the other volcanic units sampled in S. Jorge are younger than 750 ka, even the volcanic flows sampled at the base of accessible cliffs to the west of the S. João old volcanic succession (Fig. 2). S. Jorge sub-aerial evolution thus experienced an apparent period of volcanic quiescence of about 450 kyr between 1.2 and 0.75 Ma. This hiatus can reflect: (i) in part a sample bias due to the limited access to the eastern side of the island. A period of still unreported submarine construction prior to 750 ka can also be suspected to the west of the old volcanic system, which would be consistent with an overall westward migration of volcanic activity. (ii) a prolonged interruption of the magma production. Though two distinct main magmatic series are here recognized for the periods 1.32 Ma–1.21 Ma and 750 ka–230 ka, such a hypothesis is unlikely to explain the whole hiatus, since the geochemical characters of the lavas from the old volcano do no support evidence for a rapidly decreasing degree of partial melting of

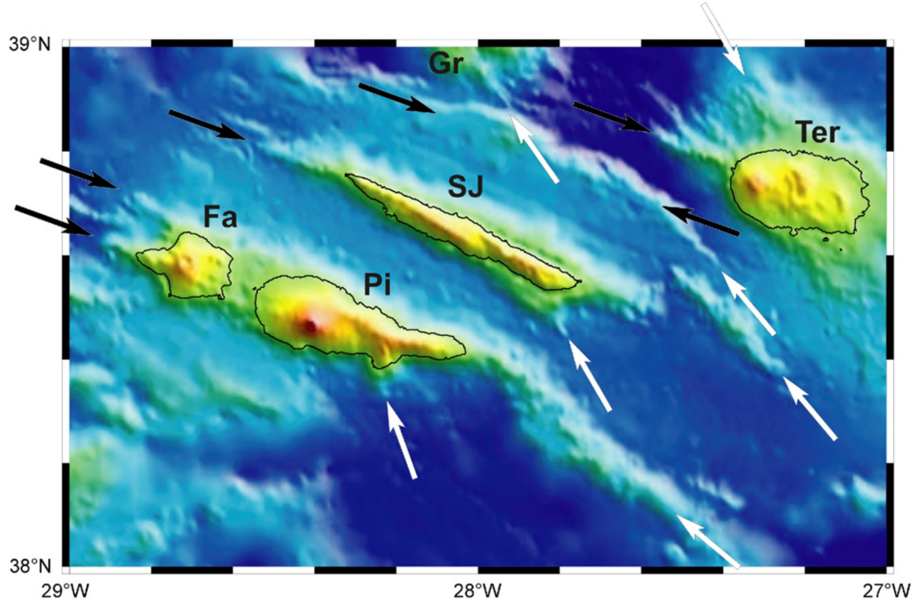

Fig. 6. Main submarine structures around the islands from the central Azores. White and black arrows evidence linear submarine ridges with N150 and N120 directions, respectively. SJ: S. Jorge; Gr: Graciosa; Ter: Terceira; Fa: Faial; Pi: Pico. After Lourenço et al. (1998), modified.

the mantle prior to 1.21 Ma. (iii) A significant re-organization of the regional stress regime, which would have precluded magma ascent beneath S. Jorge for a significant period of time. Such a change could partly explain the transition of the main volcanic construction from the N150 to the N120 direction. Note that this possibility, which we favour, is not incompatible with the first hypothesis, since renewed construction along the N120 direction has most probably involved a period of submarine volcanic construction.

6.3. Subsequent westward development of S. Jorge volcanic ridge

Geomorphological, geochronological and petrological evidence shows that the western and central parts of S. Jorge were built during a second main phase now dated between 736±12 and 236±6 ka. Since neither volcanic flows from the upper part of the young volcanic successions nor lava flows erupted during historical periods have been analysed in the present study, the duration of this late building period can reasonably be extended up to present day.

Renewed sub-aerial construction of the ridge is here constrained at about 730 ka at Fajã dos Cuberes and Fajã dos Bodes, in an area originally mapped as the oldest Serra do Topo volcanic complex (Fig. 2). The new age of 690±11 ka obtained on sample AZ05-AG from the upper part of the Fajã dos Bodes lava pile is very close to the ages of 736±12 ka and 729±11 ka obtained on the base of the same succession at Fajã dos Cuberes and Fajã dos Bodes, respectively. Taking into account the ranges of uncertainty on those ages, the dominant sub-aerial volume of the central part of the ridge has been edified in less than 70 kyr. The prolonged sub-aerial volcanic quiescence in S. Jorge was thus followed by a period of great volcanic activity to the west of the old volcanic system. The rather small distance between S. João and Fajã dos Bodes sample sites suggests a steep contact between the two main volcanic systems. In the absence of field evidence due to unfavourable ground conditions, this contact may be interpreted as: (1) lava flows from the younger volcanic system buttressed on a topographic relief, whose origin could be either the western flank of the older volcano, or erosional cliffs affecting the western side of the older volcano, or of tectonic origin (old fault scarp); (2) a later fault vertically displacing the two units. A morphologic step exists that could be the result of recent faulting, but shows the wrong sense of movement, since the lower topography is on the east, where the oldest rocks occur. Moreover, detailed bathymetry does not show evidence for a fault separating the two volcanic complexes (Fig. 6). Therefore, we favour the existence of a topographic relief older than ca. 730 ka.

Further westward migration of the main volcanic construction is confirmed by the ages of 336±6 ka and 236±6 ka now obtained on lava flows sampled at the base of the coastal cliffs to the west, at Fajã do Ouvidor and Velas, respectively. The lack of ages in our study between 690±11 ka and 336±6 ka likely reflects a sample bias, since (1) lava successions exposed on the cliffs could not be sampled over a large lateral distance between Fajã dos Cuberes and Fajã do Ouvidor (Fig. 2), and (2) the previous age of 0.55±0.06 Ma obtained by Féraud et al. (1980) may suggest that no significant volcanic interruption occurred during the time interval here considered.

Recent evolution of the ridge includes both volcanic construction and significant erosion. The development of large coastal cliffs in the central and eastern parts of the island suggests a prolonged exposition to coastal erosion, providing additional evidence for a shift of the main volcanic construction. In the central part of the ridge, the development of linear cliffs has been likely controlled by the existence of numerous WNW–ESE dykes, which compartmentalize the volcanic structure into large unstable blocks. Incision of the old volcanic system by linear NW–SE canyons, e.g. at S. João, additionally highlights a significant structural control of the N150-trending dykes on superficial erosion, as observed for other oceanic islands (Hildenbrand et al., 2008).

Volcanic activity over the last 250 kyr has been mostly concentrated in the western side of S. Jorge. Young volcanic episodes, though in minor amounts, have been also evidenced in the central and eastern sides of the island and dated between 0.11±0.06 Ma and 0.28±0.09 Ma (Féraud et al., 1980). Thus, S. Jorge late sub-aerial volcanic construction has been characterized by both a main westward progressive construction of the island and by repeated volcanic outputs along the main structural WNW–ESE axis of the ridge.

Magmas erupted during the second main building phase at S. Jorge are overall mafic in composition. Like the lavas from the old building stage, their genesis can be explained by partial melting of an enriched mantle source. Harker diagrams (Fig. 3), however, indicate a different type of parental magma characterized by higher concentrations in SiO_2, Na_2O, K_2O, and lower concentrations in FeO. The enrichment in SiO_2 and the relative depletion in FeO can be related with a lower mean depth of mantle melting (Klein and Langmuir, 1987). It supports the idea that magma genesis during the late evolution of the island has occurred at relatively shallow levels in the mantle beneath the western part of S. Jorge. Co-variations between La and (La/Yb)n additionally suggest relatively low and more variable degrees of partial melting during the last 750 kyr (Fig. 7). We note that such variations might reflect source heterogeneity, or chemical interactions between arising primitive melts and the surrounding mantle. Ratios between incompatible trace elements in the samples here analysed, however, suggest no significant variations in the source composition. The vertical scatter observed in Fig. 7 for lavas erupted during the second main building period thus most probably reflect the existence of several successive stages of melt production. Such episodes of magma genesis and their sporadic extraction over the length of the island could have been controlled, at least during the recent period, by successive stages of enhanced lithospheric deformation.

6.4. Implications of the study

6.4.1. S. Jorge geology

Previous geological work on S. Jorge distinguished three main volcanic systems, with ages globally decreasing from east to west (Forjaz and Fernandes, 1975). Our new data confirm an overall westward shift of the main volcanic construction (Fig. 8), but lead us to propose significant revisions of the existing geological information: (i) the eastern half of the island cannot be considered any more as a single main volcano ("Serra do Topo"), since its sub-aerial development involved two constructional periods separated by a great temporal gap. From geomorphological data and dykes measurements carried out at S. João area, we now propose that the southeast end of the island comprises the remnants of an old volcanic system with a main elongation fairly oblique with respect to the present-day WNW–ESE axis of the island. The N150-trending dykes from the S. João area are here interpreted as the primary feeding system of this old volcanic system. (ii) The new data suggest that the whole western half of the island has been constructed during a second main building-period, between 736±12 ka and present-day. Although the progressive development of the ridge likely involved several volcanic episodes, e.g. around 730 ka and 370–270 ka from our new age data, the dominant volume of the island was most probably built prior to Holocene. Sporadic eruptions from volcanic cones along the axis of the island during the sub-historical and historical periods covered a pre-existing relief. Hence, the "Rosais" and "Manadas" volcanic complexes (Forjaz and Fernandes, 1975) are now believed to be parts of a single main eruptive complex. (iii) The "Ribeira Seca" NW–SE fault as identified on the geological map (Forjaz and Fernandes, 1975) seems unrealistic. This inferred major tectonic structure would, indeed, cut the second main volcanic system over its whole width (Fig. 2), but no significant offset of the central part of the ridge along such a direction is really evident. A morphological step exists, but it more likely reflects the construction of young volcanic cones over the eroded older parts of the younger main volcanic system, as also observed in the western side of the island near Velas (Fig. 2). Immediately to the west of the S. João old succession, a hidden sub-vertical tectonic discontinuity, however, could be suspected to explain the lateral contact here inferred between the two main volcanic systems now recognized.

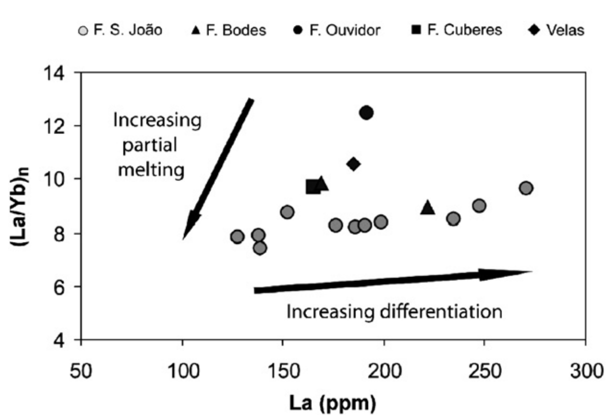

Fig. 7. Variations of (La/Yb)n *vs.* La for S. Jorge lavas. The ratio (La/Yb) for our samples is normalized with the values given by McDonough and Sun (1995) for CI chondrite.

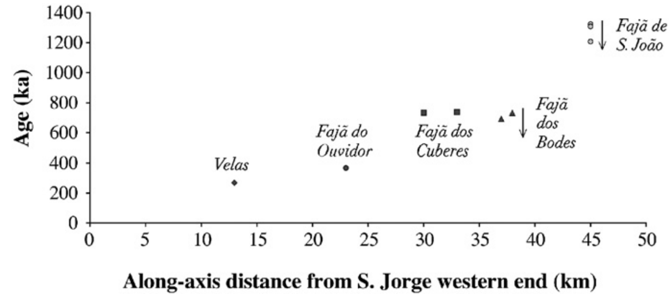

Fig. 8. Distribution of the new K/Ar ages as a function of the along-ridge axis distance of the sampling sites from the western end of S. Jorge Island. The uncertainty on the ages is included in the size of the symbols. Arrows show the age progression for the lavas sampled from the base towards the top of the individual successions.

6.4.2. Geodynamic implications

The sub-aerial eruptive history of S. Jorge volcanic ridge was till present ascribed to the last 0.61 Myr, based on four K/Ar ages (Féraud et al., 1980). Geochronological data published on the neighbouring islands of Pico, Faial, and Terceira (Féraud et al., 1980; Calvert et al., 2006) suggest that their sub-aerial volcanic construction has been restricted to the last 0.75 Myr. We now show that the construction of S. Jorge encompassed the last 1.3 Myr. Sub-aerial volcanism in the central Azores thus started much earlier than previously admitted, which has significant geodynamic implications.

Submarine ridges with a N150 elongation are readily observed all over the Azores plateau, in particular near S. Jorge (Lourenço et al., 1998, and this study), Pico (Stretch et al., 2006), and Terceira (Lourenço et al., 1998). A volcanic sample dredged on the submarine ridge SE of Pico has been recently dated with the $^{40}Ar/^{39}Ar$ technique at 1.49±0.12 Ma (Beier, 2006), in great coherence with our new ages measured in the S. João section in S. Jorge. Several (all?) of the N150 ridges exposed on the Azores plateau thus seem to have experienced an early and partly synchronous development. Their distribution does not seem to follow a well-individualized main linear or en-echelon system, such as recognized elsewhere, e.g. on the Pukapuka ridges (Sandwell et al., 1995). Hence, their formation most probably reflects diffuse deformation at the scale of the Azores plateau.

The later evolution of the Azores islands, however, highlights a recent reconfiguration of volcanic construction preferentially along the N120 direction. We here show a main westward migration of the volcanic construction in S. Jorge (Fig. 8), especially during the last 750 kyr. A similar westward migration of volcanic activity has been also reported for Terceira (Calvert et al., 2006) and can be suspected for the islands of Pico and Faial from available geochronological data (Féraud et al., 1980; Beier, 2006).

Although we do not have yet a full data set to explain the directional variations of volcanic ridges and the overall westward migration of volcanic activity over the last 1.5 Myr, some mechanisms can be proposed:

(1) The migration of volcanism could be interpreted as a consequence of the eastward displacement of the oceanic plate formed at the axis of the MAR above a stationary thermal anomaly, as observed in well-known oceanic volcanic chains like the Hawaii-Emperor. Our new geochemical data in S. Jorge (Supplementary data, Table S2) and previous geochemical works on the Azores

including radiogenic isotopes (e.g., White et al., 1979; Turner et al., 1997; Widom et al., 1997) attest the existence of an enriched mantle beneath most of the islands. However, the early construction of N150 ridges on the eastern sides of Pico and S. Jorge cannot merely be a simple consequence of sea-floor spreading at the MAR. Recent geodynamic reconstructions additionally suggest an absolute displacement of the Azores region towards the SW over the recent period (Gripp and Gordon, 2004; Vogt and Jung, 2004), which cannot explain the overall westward migration observed.

(2) The early construction of N150-ridges could have been controlled by far field kinematics linked with the relative movement between the Nubian and Eurasian plates. This generates a trans-tensional regime in the plateau (e.g., Vogt and Jung, 2004; Serpelloni et al., 2007) that could well be responsible for the generation of large-scale open gashes oriented N150. Such gashes would have worked as preferential conduits for magma ascent through the lithosphere. However, increasing ridge-push along the MAR tend to oppose opening in the N150 direction. The more recent construction of the central Azores islands, including S. Jorge, along the N120 could thus mean a change in the factor controlling regional deformation: from plate kinematics dominated to MAR dominated. The N120 volcanic ridges are approximately perpendicular to the MAR axis and parallel to fracture zones delimitating individual segments of the MAR. Hence they could have been formed by magma ascent through large-scale open gashes generated or reactivated mainly by MAR ridge-push, with a small contribution from Nubian/Eurasian plate kinematics.

(3) Other forces have to be taken into account in this discussion, in particular those generated by the topography of the islands. In most cases these forces must be significant, because the volcanic edifices are between 3 and 5 km high. Therefore, island load should locally contribute to the control of magma ascent and eruption localization (Pinel and Jaupart, 2000). The stress field induced by the island load can add to ridge-push in the space between the volcanic complexes and the MAR axis, thus facilitating volcanic ridge propagation to the west. From our new geochronological constraints (Fig. 8), the main westward migration of volcanic construction in S. Jorge occurred at an average rate of about 5 cm/yr during the last 750 kyr. This rate has to be considered as a maximum, since occasional volcanic episodes occurred at several locations along the axis of the island. The value calculated here is, however, significantly higher than the recent half-spreading rates at the MAR (Luís et al., 1994). Hence, the gradual load of the oceanic crust by the rapid construction of S. Jorge most probably contributed to increase the westward preferential extraction of the magma toward the surface.

7. Conclusions

The present study on S. Jorge provides new important constraints on the multi-stage development of a sub-aerial volcanic ridge over the last 1.3 Myr and has significant geodynamic implications. In addition, it highlights the lack of sufficient reliable temporal constraints presently available on most of the other islands of the Azores region. Multi-disciplinary investigations combining structural, morphological, geochronological, and geochemical data remain needed to document into further details the dynamic interactions between tectonics and magmatism in this key geodynamic area of the Azores Triple Junction.

Acknowledgements

Constructive remarks by two anonymous reviewers and Editor helped to significantly improve the manuscript. This study was in part supported financially by TEAMINT (POCTI/CTE/48137/2002) and EVOLV (PTDC/CTE-GIN/71838/2006) funded by FCT (Portugal). This is LGMT contribution 77.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.06.041.

References

Beier, C., 2006. The magmatic evolution of oceanic plateaus: a case study from the Azores. Ph.D. thesis, University of Kiel, Germany.
Best, M., Christiansen, E., 2001. Igneous Petrology. Blackwell Science, Inc. 458 pp.
Bonneville, A., Dosso, L., Hildenbrand, A., 2006. Temporal evolution of the south-Pacific superplume activity: new data from the Cook-Australes volcanic chain Earth Planet. Sci. Lett. 244 (1–2), 251–269.
Borges, J.F., Bezzeghoud, M., Bufon, E., Pro, C., Fitas, A., 2007. The 1980, 1997 and 1998 Azores earthquakes and some seismo-tectonic implications. Tectonophysics 435, 37–54.
Bourdon, B., Turner, S.P., Ribe, N.M., 2005. Partial melting and upwelling rates beneath the Azores from a U-series isotope perspective. Earth Planet. Sci. Lett. 239 (1–2), 42–56.
Buforn, E., Udías, A., Colombás, M.A., 1988. Seismicity, source mechanisms and tectonics of the Azores–Gibraltar plate boundary. Tectonophysics 152, 89–118.
Calvert, A.T., Moore, R.B., McGeehin, J.P., Rodrigues da Silva, A.M., 2006. Volcanic history and $^{40}Ar/^{39}Ar$ and ^{14}C geochronology of Terceira Island, Azores, Portugal. J. Volcanol. Geotherm. Res. 156 (1–2), 103–115.
Cannat, M., Briais, A., Deplus, C., Escartin, J., Georgen, J., Lin, J., Mercouriev, S., Meyzen, C., Muller, M., Pouliquen, G., Rabain, A., da Silva, P., 1999. Mid-Atlantic Ridge-Azores hotspot interactions: along-axis migration of a hotspot-derived event of enhanced magmatism 10 to 4 Ma ago. Earth Planet. Sc. Lett. 173 (3), 257–269.
Cassignol, C., Gillot, P.-Y., 1982. Range and effectiveness of unspiked potassium-argon dating: Experimental groundwork and applications. John Wiley, New York, pp. 159–179.
Clouard, V., Bonneville, A., Gillot, P.Y., 2003. The Tarava seamounts: a new but extinct hotspot chain on the South Pacific Superswell. Earth Planet. Sci. Lett. 207, 117–130.
Coulié, E., Quidelleur, X., Gillot, P.Y., Courtillot, V., Lefèvre, J.C., Chiesa, S., 2003. Comparative K–Ar and 40Ar/39Ar dating of Ethiopian and Yemenite Oligocene volcanism: implications for timing and duration of the Ethiopian traps. Earth Planet. Sci. Lett. 206 (3–4), 477–492.
Davies, G.R., Norry, M.J., Gerlach, D.C., Cliff, R.A., 1989. A combined chemical and Pb–Sr–Nd isotope study of the Azores and Cape Verde hot-spots: the geodynamic implications. In: Saunders, A.D.N., M.J. (Eds.), Magmatism in the ocean basins. Geol. Soc. Special Publication, vol. 42, pp. 231–235.
De Beni, E., Wijbrans, J.R., Branca, S., Coltelli, M., Groppelli, G., 2005. New results of $^{40}Ar/^{39}Ar$ dating constrain the timing of transition from fissure-type to central volcanism at Mount Etna (Italy). Terra Nova 17 (3), 292–298.
Féraud, G., Kaneoka, I., Allègre, C.J., 1980. K/Ar ages and stress pattern in the Azores: geodynamic implications. Earth Planet. Sci. Lett. 46, 275–286.
Flower, M.F.J., Schmincke, H.-U., Bowman, H., 1976. Rare earth and other trace elements in historic Azorean lavas. J. Volcanol. Geotherm. Res. 1, 127–147.
Forjaz, V.H., Fernandes, N.S.M., 1975. In: Portugal, S.G.d. (Ed.), Carta geologica de Portugal. Noticia explicativa das folhas A e B da ilha de San Jorge (Açores). Serv. Geol. Portugal.
Frey, F.A., Garcia, M.O., Roden, M.F., 1994. Geochemical characteristics of Koolau volcano: implications of intershield geochemical differenced among Hawaiian volcanoes. Geochim. Cosmochim. Acta 58, 1441–1462.
Gente, P., Dyment, J., Maia, M., Goslin, J., 2003. Interaction between the Mid-Atlantic Ridge and the Azores hotspot during the last 85 Myr: emplacement and rifting of the hotspot-derived plateaus. Geochem. Geophys. Geosyst. 4, 8514.
Gillot, P.Y., Cornette, Y., 1986. The Cassignol technique for potassium-argon dating, precision and accuracy: examples from late Pleistocene to recent volcanics from southern Italy. Chem. Geol. 59, 205–222.
Gillot, P.Y., Lefèvre, J.C., Nativel, P.E., 1994. Model for the structural evolution of the volcanoes of Réunion Island. Earth Planet. Sci. Lett. 122, 291–302.
Gillot, P.Y., Hildenbrand, A., Lefèvre, J.C., Albore-Livadie, C., 2006. The K/Ar dating method: principle, analytical techniques and application to Holocene volcanic eruptions in southern Italy. Acta Vulcanol. 18 (1–2), 55–66.
Gripp, A.E., Gordon, R.G., 2004. Young tracks of hotspots and current plate velocities. Geophys. J. Int. 150, 321–361.
Gurenko, A.A., Hoernle, K.A., Hauff, F., Schmincke, H.-U., Han, D., Miura, Y.N., Kaneoka, I., 2006. Major, trace element, and Nd–Sr–Pb,O–He–Ar isotope signatures of shield stage lavas from the central and western Canary Islands. Chem. Geol. 233, 75–112.
Haase, K.M., Beier, C., 2003. Tectonic control of ocean island basalt sources on São Miguel, Azores ? Geophys. Res. Lett. 30 (16), 1856.
Hildenbrand, A., Gillot, P.Y., Soler, V., Lahitte, P., 2003. Evidence for a persistent uplifting of La Palma (Canary Islands), inferred from morphological and radiometric data. Earth Planet. Sci. Lett. 210 (1–2), 277–289.
Hildenbrand, A., Gillot, P.-Y., Le Roy, I., 2004. Volcano-tectonic and geochemical evolution of an oceanic intra-plate volcano: Tahiti-Nui (French Polynesia). Earth Planet. Sci. Lett. 217 (3), 349–365.
Hildenbrand, A., Gillot, P.-Y., Marlin, C., 2008. Geomorphological study of long-term erosion on a tropical volcanic ocean island: Tahiti-Nui (French Polynesia). Geomorphology 93 (3–4), 460–481.

Holm, P.M., Wilson, J.R., Christensen, B.P., Hansen, L., Hansen, S.L., Hein, K.M., Mortensen, A.K., Pedersen, R., Plesner, S., Runge, M.K., 2006. Sampling the Cape Verde mantle plume: evolution of melt compositions on Santo Antao, Cape Verde Islands. J. Petrol. 47 (1), 145–189.

Irvine, T.N., Baragar, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Can. J. Earth Sci. 8, 523–548.

Klein, E.M., Langmuir, C.H., 1987. Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness. J. Geophys. Res. 92 (B8), 8089–8115.

Lahitte, P., Coulié, E., Mercier, N., Tesfaye, K., Gillot, P.-Y., 2001. Chronologie K–Ar et TL du volcanisme aux extrémités sud du propagateur Mer Rouge en Afar depuis 300 ka. C.R. Acad. Sci. Paris 332, 13–20.

Lourenço, N., Miranda, J.M., Luis, J.F., Ribeiro, A., Victor, L.A.M., Madeira, J., Needham, H.D., 1998. Morpho-tectonic analysis of the Azores Volcanic Plateau from a new bathymetric compilation of the area. Mar. Geophys. Res. 20 (3), 141–156.

Luís, J.F., Miranda, J.M., Galdeano, A., Patriat, P., Rossignol, J.C., Mendes Victor, L.A., 1994. The Azores triple junction evolution since 10 Ma from an aeromagnetic survey of the Mid-Atlantic Ridge. Earth Planet. Sci. Lett. 125, 439–459.

Luís, J.F., Miranda, J.M., Galdeano, A., Patriat, P., 1998. Constraints on the structure of the Azores spreading center from gravity data. Mar. Geophys. Res. 20, 157–170.

Lynch, M.A., 1999. Linear ridge groups: evidence for tensional cracking in the Pacific plate. J. Geophys. Res. 104, 29,321–29,333.

Madeira, J., Brum da Silveira, A., 2003. Active tectonics and first paleosismological results in Faial, Pico, and Sao Jorge islands (Azores, Portugal). Ann. Geophys. 46 (5), 733–761.

Madureira, P., Moreira, M., Mata, J., Allègre, C.J., 2005. Primitive neon isotopes in Terceira Island (Azores archipelago). Earth Planet. Sci. Lett. 233 (3–4), 429–440.

Maia, M., Hémond, C., Gente, P., 2001. Contrasted interactions between plume, upper mantle, and lithosphere: foundation chain case. Geochem. Geophys. Geosyst. 2 2000GC000117.

Mammerickx, J., 1992. The foundation seamounts: tectonic setting of a newly discovered seamount chain in the South Pacific. Earth Planet. Sci. Lett. 113 (3), 293–306.

Mata, J.M., 1996. Petrologia e geoquímica das lavas da Ilha da Madeira: implicações para os modelos de evolução mantélica. Ph.D thesis, Univeristy of Lisboa, Portugal.

McDonough, W.F., Sun, S.-S., 1995. The composition of the Earth. Chem. Geol. 120, 223–253.

Middlemost, E.A.K., 1989. Iron oxidation ratios, norms and the classification of volcanic rocks. Chem. Geol. 77, 19–26.

Miranda, J.M., Mendes Victor, L.A., Simões, J.Z., Luis, J.F., Matias, L., Shimamura, H., Shiobara, H., Nemoto, H., Mochizuki, H., Hirn, A., Lépine, J.C., 1998. Tectonic setting of the Azores Plateau deduced from a OBS survey. Mar. Geophys. Res. 20, 171–182.

Moreira, M., Doucelance, R., Dupré, B., Kurz, M., Allègre, C.J., 1999a. Helium and lead isotope geochemistry in the Azores archipelago. Earth Planet. Sci. Lett. 169, 189–205.

Moreira, M., Geoffroy, L., Pozzi, J.P., 1999b. Ecoulement magmatique dans les dykes du point chaud des Açores: étude préliminaire par anisotropie de susceptibilité magnétique (ASM) dans l'île de San Jorge. C. R. Acad. Sci. 329, 15–22 Paris, Sciences de la terre et des planètes.

Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 43–44.

Morgan, W.J., 1972. Deep mantle convection: plumes and plate motion, 1972. Am. Assoc. Pet. Geol. Bull. 56, 203–213.

O'Connor, J.M., Stoffers, P., Wijbrans, J.R., 1998. Migration rate of volcanism along the Foundation Chain, SE Pacific. Earth Planet. Sci. Lett. 164, 41–59.

O'Connor, J.M., Stoffers, P., Wijbrans, J.R., 2002. Pulsing of a focused mantle plume: evidence from the distribution of foundation chain hotspot volcanism. Geophys. Res. Lett. 29 (9). doi:10.1029/2002GL014681.

Pinel, V., Jaupart, C., 2000. The effect of edifice load on magma ascent beneath a volcano. Phil. Trans. R. Soc. Lond. 358, 1515–1532.

Quidelleur, X., Gillot, P.-Y., Soler, V., Lefèvre, J.C., 2001. K/Ar dating extended into the last millennium: application to the youngest effusive episode of the Teide volcano (Canary Islands, Spain). Geophys. Res. Lett. 28, 3067–3070.

Samper, A., X, Q., Lahitte, P., Mollex, D., 2007. Timing of effusive volcanism whithin the whole Basse Terre Island (Guadeloupe, F.W.I.) from new K–Ar Cassignol–Gillot Ages. Earth Planet. Sci. Lett. 258 (1–2), 175–191.

Sandwell, D.T., Winterer, E.L., Mammerickx, J., Duncan, R.A., Lynch, M.A., Levitt, D.A., Jonhnson, C.L., 1995. Evidence for diffuse extension of the Pacific plate from Puka-Puka ridges and cross-grain gravity anomalies. J. Geophys. Res. 100, 15,087–15,099.

Schilling, J.G., 1975. Azores mantle blob: rare earth evidence. Earth Planet. Sci. Lett. 25, 103–115.

Searle, R., 1980. Tectonic pattern of the Azores spreading centre and triple junction. Earth Planet. Sci. Lett. 51, 415–434.

Serpelloni, E., Vannucci, G., Pondrelli, S., Argnani, A., Casula, G., Anzidei, M., Baldi, P., Gasperini, P., 2007. Kinematics of the Wester eastern Africa–Eurasia plate boundary from focal mechanisms and GPS data. Geophys. J. Int. 169, 1180–1200.

Sridhar, D.I., Ray, D., 2003. Structure, tectonic and petrology of mid-oceanic ridges and the Indian scenario. Curr. Sci. 85 (3), 277–289.

Silveira, G., Stutzmann, E., Davaille, A., Montagner, J.-P., Mendes-Victor, L., Sebai, A., 2006. Azores hotspot signature in the upper mantle. J. Volcanol. Geotherm. Res. 156, 23–34.

Steiger, R.H., Jäger, E., 1977. Subcommission on geochronology: convention on the use of decay constants in geo and cosmochronology. Earth Planet. Sci. Lett. 36, 359–362.

Stretch, R.C., Mitchell, N.C., Portaro, R.A., 2006. A morphometric analysis of the submarine volcanic ridge southeast of Pico island (Azores). J. Volcanol. Geotherm. Res. 156, 35–54.

Turner, S., Hawkesworth, C., Rogers, N., King, P., 1997. U–Th isotope disequilibria and ocean island basalt generation in the Azores. Chem. Geol. 139 (1–4), 145–164.

Vogt, P.R., Jung, W.Y., 2004. The Terceira Rift as hyper-slow, hotspot-dominated oblique spreading axis: a comparison with other slow-spreading plate boundaries. Earth Planet. Sci. Lett. 218, 77–90.

White, W.M., Schilling, J.-G., Hart, S.R., 1976. Evidence for the Azores mantle plume from strontium isotope geochemistry of the Central North Atlantic. Nature 263, 659–663.

White, W.M., Tapia, M.D.M., Schilling, J.-G., 1979. The petrology and geochemistry of the Azores Islands. Contrib. Mineral. Petrol. 69, 201–213.

Widom, E., Shirey, S.B., 1996. Os isotope systematics in the Azores: implications for mantle plume sources. Earth Planet. Sci. Lett. 142, 451–465.

Widom, E., Carlson, R.W., Gill, J.B., Schmincke, H.-U., 1997. Th–Sr–Nd–Pb isotope and trace element evidence for the origin of the São Miguel, Azores, enriched mantle source. Chem. Geol. 140, 49–68.

Wilson, J.T., 1965. Evidence from ocean islands suggesting movement in the Earth. Phil. Trans. Roy. Soc., A 258, 145–167.

Wilson, M., 1989. Igneous petrogenesis. A global tectonic approach. Chapman and Hall, London. 466 pp.

Winterer, E.L., Sandwell, D.T., 1987. Evidence from en-echelon cross-grain ridges for tensional cracks in the Pacific Plate. Nature 329.

Yang, T., Shen, Y., van der Lee, S., Solomon, C., S.-H., H., 2006. Upper mantle structure beneath the Azores hotspot from finite-frequency seismic tomography. Earth Planet. Sci. Lett. 250 (1–2), 11–26.