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Reconstructing the architectural evolution of volcanic islands from combined K/Ar, morphologic, tectonic, and magnetic data: The Faial Island example (Azores)

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ABSTRACT

The morpho-structural evolution of oceanic islands results from competition between volcano growth and partial destruction by mass-wasting processes. We present here a multi-disciplinary study of the successive stages of development of Faial (Azores) during the last 1 Myr. Using high-resolution digital elevation model (DEM), and new K/Ar, tectonic, and magnetic data, we reconstruct the rapidly evolving topography at successive stages, in response to complex interactions between volcanic construction and mass wasting, including the development of a graben. We show that: (1) sub-aerial evolution of the island first involved the rapid growth of a large elongated volcano at ca. 0.85 Ma, followed by its partial destruction over half a million years; (2) beginning about 360 ka a new small edifice grew on the NE of the island, and was subsequently cut by normal faults responsible for initiation of the graben; (3) after an apparent pause of ca. 250 kyr, the large Central Volcano (CV) developed on the western side of the island at ca 120 ka, accumulating a thick pile of lava flows in less than 20 kyr, which were partly channelized within the graben; (4) the period between 120 ka and 40 ka is marked by widespread deformation at the island scale, including westward propagation of faulting and associated erosion of the graben walls, which produced sedimentary deposits; subsequent growth of the CV at 40 ka was then constrained within the graben, with lava flowing onto the sediments up to the eastern shore; (5) the island evolution during the Holocene involves basaltic volcanic activity along the main southern faults and pyroclastic eruptions associated with the formation of a caldera volcano–tectonic depression. We conclude that the whole evolution of Faial Island has been characterized by successive short volcanic pulses probably controlled by brief episodes of regional deformation. Each pulse has been separated by considerable periods of volcanic inactivity during which the Faial graben gradually developed. We propose that the volume loss associated with sudden magma extraction from a shallow reservoir in different episodes triggered incremental downward graben movement, as observed historically, when immediate vertical collapse of up to 2 m was observed along the western segments of the graben at the end of the Capelinhos eruptive crises (1957–58).

1. Introduction

The geological evolution of oceanic islands is generally marked by rapid volcanic growth alternating with destruction by a variety of mass-wasting processes including giant sector collapses, vertical caldera subsidence, fault generation/propagation, shallow landslides and coastal erosion (e.g., Moore et al., 1989; Mitchell, 1998; Hildenbrand et al., 2004, 2006, 2008a, 2008b; Quartau et al., 2010; Boulesteix et al., 2012). The study of such destruction events is of particular societal relevance, since they can cause considerable damage. The Azores volcanic islands in the Atlantic are particularly sensitive to mass-wasting processes. The region is characterized by intense deformation responsible for high magnitude earthquakes (e.g., Borges et al., 2007). Like the neighbouring islands of Pico, S. Jorge, Terceira and Graciosa in the central Azores, Faial is still active and is characterized by the localization of volcanism along N110°-trending eruptive fissures and vents. Faial is additionally marked by a large graben-like structure elongated along the same azimuth (N110°). The island thus offers a great opportunity

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to study the interactions between volcanism and tectonics. We present here a new study aimed at reconstructing the architecture and the volcano–tectonic evolution of Faial during the last 1 Myr. Our approach combines new tectonic analysis, K/Ar dating and palaeomagnetic data on selected samples, which, together with high-resolution DEM data and analyses of magnetic anomalies carried out during an aerial survey (Miranda et al., 1991), provides valuable insight into the competition between volcanic construction and destruction by tectonic processes, mass-wasting, and erosion throughout the geological evolution of the island.

2. Geological background

The Central Azores islands (Fig. 1) were formed during the Quaternary on top of an oceanic plateau, the Azores Plateau, at the triple junction between the North American, Eurasian and Nubian lithospheric plates (e.g., Searle, 1980; Miranda et al., 1991; Luis et al., 1994; Lourenço et al., 1998; Vogt and Jung, 2004). The origin of the volcanism in the area is still controversial: some authors argue for an origin from volatile-enriched upper mantle domains (Schilling et al., 1980; Bonatti, 1990), whereas others, based on geochemical data (Schilling, 1975; White et al., 1979; Flower et al., 1976; Davies et al., 1989; Widom & Shirey, 1996; Turner et al., 1997; Moreira et al., 1999; Madureira et al., 2005; 2011) or seismic tomography (Silveira and Stutzmann, 2002; Montelli et al., 2004; Yang et al., 2006), consider the Azores volcanism to be related to a mantle plume. According to Silveira et al. (2006), the shallow S-wave negative anomaly (down to ~250 km) results from the presence of a dying and now untailed plume, the head of which was responsible for building of the Azores Plateau. Furthermore, regional deformation has largely controlled the distribution of volcanic vents, leading to the construction of submarine ridges with N150° and N110° main orientations (e.g., Lourenço et al., 1998; Stretch et al., 2006; Hildenbrand et al., 2008b; Silva et al., 2012). Most of the Azores islands have experienced historic volcanic activity. The most recent volcanic crisis on Faial, the Capelinhos eruption (1957–1958), was characterized by a surtseyan and strombolian activity, which increased the island area to the west (Machado et al., 1959; Zbyszewski and Veiga Ferreira, 1959; Machado et al., 1962).

Faial constitutes one of the emerged parts of a single main volcanic ridge, the Pico–Faial Ridge. This structure is roughly elongated along the N110° direction, but probably older N150° submarine ridges can be observed or are suspected offshore the eastern ends of both Faial and Pico (Fig. 1). The geology of Faial island has been divided by Chovelon (1982) into five main volcanic units (Fig. 2a): (i) the Galego volcano mapped in the east and northeast areas of the island, from north of Horta to the northern coast; (ii) a main volcanic edifice, the Central Volcano (CV), built on the western side of the Galego volcano, during at least two main phases of activity; (iii) recent volcanic units filling the graben, from 0.03 Ma to the present; (iv) basaltic units in the E (Horta) and W (Capelo). The Horta volcanism, located in the SE corner of the island, is characterized by a series of small scoria cones and associated basaltic lava flows. The Capelo volcanism corresponds to the most recent volcanic activity that formed a peninsula in the westernmost part of Faial. It was erupted during the last 10 kyr (Madeira et al., 1995), and is morphologically characterized by a series of volcanic cones aligned WNW-ESE that stretches the island towards the Capelinhos volcano, which emerged during the 1957–1958 eruption; (v) widespread trachytic pumice deposits generated by recent explosive activity of the Central Volcano over the last 10 kyr. Subsequently, other workers have conducted more detailed geological mapping, and have renamed the main units (e.g., Serralheiro et al., 1989; Madeira, 1998; Pacheco, 2001). These works were mostly based on the original geochronological framework established by Féraud et al. (1980) and Demande et al. (1982), which we therefore used as a basis for the present study.

The recent eruptive history of Faial has been quite well documented from radiocarbon dating on charcoal fragments collected in pyroclastic deposits and/or palaeosoils (e.g. Madeira et al., 1995). The earlier volcano–tectonic evolution of the island, however, remains unclear in the absence of sufficient reliable temporal constraints. Five K/Ar ages have been published in the early 1980s for the whole island, two of which are being related to very young volcanic episodes (Féraud et al., 1980). The remaining three samples have been collected along the eastern end of the island, in an area attributed to the Galego volcano. The results on these samples vary from 0.73 ± 0.07 Ma to 0.21 ± 0.02 Ma, which means that the sub-aerial part of the old volcanic system would have developed over a period of about 0.5 Myr. A few additional unpublished K/Ar determinations

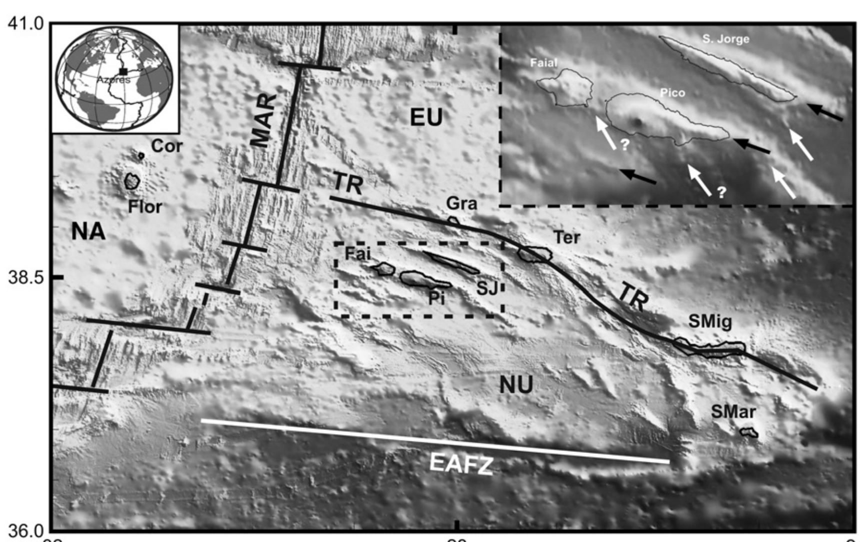

Fig. 1. Main figure: Location of the Azores volcanic archipelago near the triple junction between the North American (NA), the Eurasian (EU) and the Nubian (NU) plates. The dashed rectangle localizes the inset. Bold black lines show the Mid-Atlantic Ridge (MAR) and the Terceira Rift (TR), and the white line shows the East Azores Fracture Zone (EAFZ). SJ: S. Jorge; Gra: Graciosa; Ter: Terceira; Fai: Faial; Pi: Pico; Flor: Flores; Cor: Corvo; SMig: S. Miguel; SMar: Santa Maria. Background bathymetric data from Lourenço et al. (1998). Inset: Main submarine structures around Sao Jorge, Pico and Faial. Black and white arrows show linear submarine ridges with N110 and N150 directions, respectively. Modified from Hildenbrand et al. (2008b).

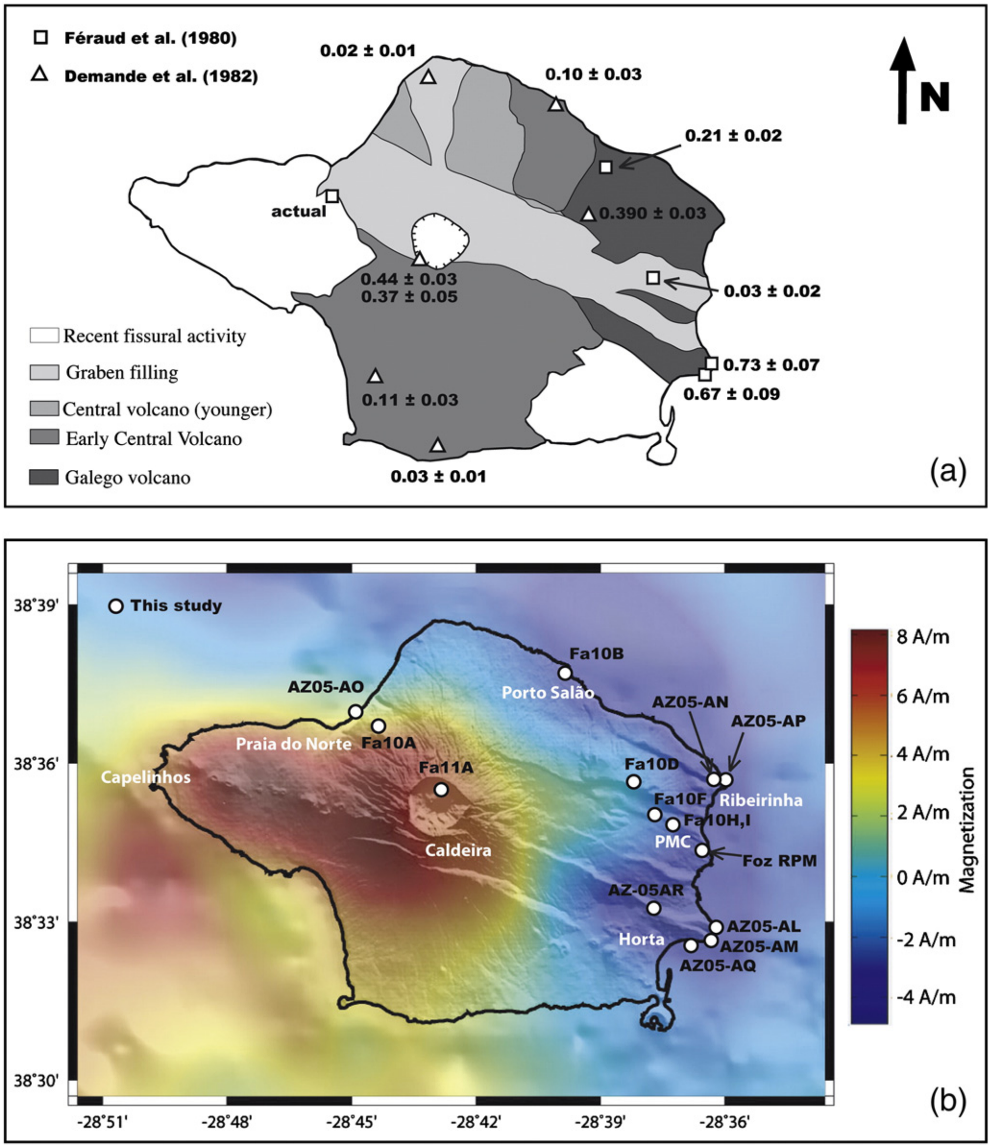

Fig. 2. (a) Geological map of Faial (modified after Chovelon, 1982). Previous K/Ar ages (in Ma) from Féraud et al. (1980) and Demande et al. (1982) are shown. (b) Magnetization map combined with a high-resolution digital elevation model (DEM) of the island. The colour scale shows the magnetization values. White dots with black circles show the location of our new samples collected for both K/Ar and magnetic analyses. Localities are shown in white. PMC: Pedro Miguel creek.

presented in a report (Demande et al., 1982) and a thesis (Chovelon, 1982) have been subsequently acquired on whole-rock samples from the central volcanism sampled in the northern and western parts of the island. They range in age between 0.44 ± 0.03 Ma and 0.03 ± 0.01 Ma. From the few previous K/Ar data available for Faial (Féraud et al., 1980; Chovelon, 1982; Demande et al., 1982), the two main volcanic systems would thus have experienced synchronous growth between 0.44 ± 0.03 Ma and 0.21 ± 0.02 Ma. This seems in apparent contradiction, since the main volume of the Central Volcano has apparently grown within the main graben cutting the Galego volcano (Fig. 2b). Therefore, the timing for graben initiation, and the relationships between volcanic construction and destruction, and tectonics remain insufficiently documented to allow the development of a coherent and comprehensive model.

3. Fieldwork and sampling strategy

The interactions between volcanic growth and partial destruction on volcanic islands such as Faial generally result in complex relationships of the different geological units, in response to a rapidly evolving topography. In such conditions, reconstructing the successive stages of construction and graben development requires strategic investigations on target areas. We first used available morphological and geophysical data to identify the zones of major interest for fieldwork and selective sampling. Such preliminary work includes the combination of a high-resolution DEM of Faial with a magnetization map built from magnetic data acquired during a previous aerial survey of the island (Miranda et al., 1991) merged with the aeromagnetic map of the Azores Platform (Luis et al., 1994) into a regular grid with a 0.005º step both in longitude and latitude (Fig. 2b). Magnetization was computed with the actual topography and using the 3D-inversion technique of Macdonald et al. (1980). This inversion procedure makes two main assumptions: (1) a constant thickness source layer (1.0 km), the upper surface of which is defined by the bathymetry, and (2) fixed values for the main field and the magnetization ($59.5\ A.m^{-1}$ and $-17\ A.m^{-1}$, respectively). A band pass filter (1.1–120 km) was applied to ensure convergence. The processing was made with the Mirone software suite (Luis, 2007).

The magnetization map evidences an area with high-magnitude negative values in the eastern side of the island. This zone coincides with a narrow morphological relief, the northern part of which is affected by the main graben. Such sector retains crucial information, because the predicted magnetization may reflect volcanic construction during a period with reversed polarity of the magnetic field, e.g., during the Matuyama chron prior to 0.789 ± 0.008 Ma (Quidelleur et al., 2003). The lowermost and uppermost parts of this apparently old volcanic succession thus have been extensively sampled for geochronological and magnetic measurements (samples AZ05-AL, AM, AQ, AR). The parts of the faults exposed along the eastern shore have also been investigated carefully.

The NE part of the island attributed to the Galego volcanism in earlier studies shows a zone of low-magnitude negative magnetization roughly elongated in the N110 direction. This sector is additionally characterized by a prominent topographic high with relatively steep slopes towards the North. It is composed of a moderately thick volcanic succession, including porphyritic lavas with dominant plagioclase phenocrysts. This succession is cut by the northern fault of the main graben, and by an additional scarp farther North, near the village of Ribeirinha. The lower and upper distal parts of this succession were sampled close to shore level in the NE tip of Faial (samples AZ05-AN and AZ05-AP, respectively). A sample was also collected at an elevation of ca 500 m on the upper rim of the main fault near Galego (Fa10D) to constrain a maximum age for initiation of the graben. The geometry and kinematics of the eastern end of the main fault were additionally examined at the shore level.

The Central Volcano in the western half of the island is marked by an overall positive magnetization highlighted by yellow to red colours on the magnetization map (Fig. 2b). The maximum is centred close to the present caldera depression, but rapidly vanishes towards the distal parts, where slightly negative values are observed. A lava flow at the base of the volcanic succession exposed in the caldera walls was sampled at an altitude of 575 m to constrain the earliest accessible stage of edification of the Central Volcano (sample Fa11A). The external parts of the volcano overall have smooth and gentle slopes extending up to the northern and southern shores of the island, where they are cut by large coastal cliffs. We took advantage of these natural sections to collect lava flows at the base of the succession at Praia do Norte and Porto Salão (samples AZ05-AO and Fa10B, respectively). A lava flow from the upper part of the CV succession was additionally sampled at an altitude of ca 300 m uphill Praia do Norte (sample Fa 10A).

The central part of the CV has relatively steep slopes incised by recent narrow canyons. The canyons have a relatively radial distribution close to the eruptive centre, but they bifurcate close to recent scars apparently truncating the (previous) external slopes of the volcano. Such bifurcation is quite obvious in the eastern sector, where individual lava flows and erosion have apparently been geometrically constrained within the graben. Consequently, detailed field investigations were carried out in the graben depression, along the Pedro Miguel creek. These investigations allowed us to identify old lava flows (sample Fa10H) overlain in unconformity by sedimentary deposits, which in turn have been buried by more recent lava flows. Some of the young lava flows were sampled throughout the longitudinal section of the creek (samples Fa10F, Fa10I, Foz RPM), where they define morphological steps. However, they exhibit complex local architecture with important internal flow patterns and complex lateral overlap (Fig. 3), suggesting their channelling into a low topography, down to sea level.

4. Methods and results

4.1. K/Ar geochronology

After careful petrographic examination of the samples in thin-section, the micro-crystalline groundmass was selected for potassium–argon (K–Ar) analyses. Some of the samples are characterized by high amounts of plagioclase phenocrysts/glomerocrysts, which can amount up to 40% in volume. They also contain pyroxene, minor olivine and various oxides. Such minerals partially crystallized at a deep level in the magma chamber and thus are not representative of the age of eruption at the surface. They are also K-poor and may carry significant amount of inherited excess Ar. After crushing and sieving the samples to 125–250 μm, all the phenocrysts have been so systematically removed with heavy liquids. Narrow density spans generally in the range 2.95–3.05 have been achieved to select the freshest part of the groundmass and eliminate the fraction with a lower density, that is potentially affected by alteration and secondary zeolitisation.

K and Ar were measured on two separate aliquots of the selected grains, the former by flame absorption-spectrophotometry and the latter by mass spectrometry. K is determined with a 1% relative uncertainty from replicate analyses on standards (Gillot et al., 1992). The $^{40}Ar/^{36}Ar$ isotopic composition of Ar has been measured according to the Cassignol–Gillot unspiked technique (Gillot and Cornette, 1986; Gillot et al., 2006). With this particular technique, the ^{40}Ar and ^{36}Ar are simultaneously collected avoiding any potential drift associated with peak switching. The level of atmospheric contamination is then accurately determined by comparing

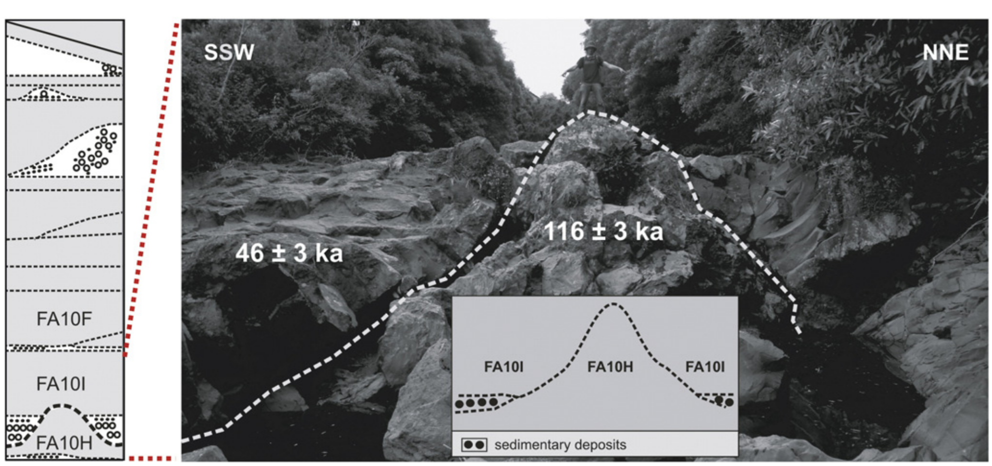

Fig. 3. Left: Schematic log showing the main geometrical relationships between the various units recognized in the Pedro Miguel creek. Light grey areas separated by thin dashed lines mark individual lava flows. White parts show sediments, with circles and dots representing coarse conglomerates and sandstones, respectively. The thick dashed line shows the main unconformity. Right: close up image on the main unconformity. The age of the lava flows below and above the unconformity reported here are shown.

the $^{40}Ar/^{36}Ar$ ratios of the sample and of an air pipette measured in strictly similar pressure conditions, allowing the detection of minute amounts of radiogenic Ar, as low as 0.1% (Gillot et al., 2006). The Cassignol–Gillot technique has been shown especially suitable to date low-K and high-Ca basalts and andesites of late Quaternary age with an uncertainty of only a few ka (e.g., Hildenbrand et al., 2003, 2008b; Quidelleur et al., 2008; Samper et al., 2009; Germa et al., 2010, 2011). For high-K lavas, it has been extended to the last millennium with an uncertainty of only a few centuries (Quidelleur et al., 2001). Both K and Ar were analysed 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 Table 1, where the uncertainties are quoted at the 1σ level.

The ages measured on our samples from Faial range between 848 ± 12 ka and 38 ± 1 ka. The results obtained on the different lava flows from the old volcanic succession are tightly clustered around 850 ka, and overlap within the range of uncertainties at the 1σ level. These results are significantly older than previous K/Ar determinations at 0.73 ± 0.07 Ma (Féraud et al., 1980). The new ages measured on lava flows from the distal part of the volcanic succession exposed on the NE corner of Faial (Ribeirinha) yield indistinguishable values of 358 ± 7 ka and 363 ± 8 ka (samples AZ05-AN and AZ05-AP, respectively). The lava flow sample collected on the same succession cut by the main graben is dated here at 389 ± 7 ka, which is similar to a previous age of 0.39 ± 0.03 Ma obtained by Demande et al. (1982) on an aphyric sample collected at a similar level to the West (Fig. 2).

The new ages measured on lava flows sampled at the base of the caldera wall and at the base of the coastal cliffs in the NE and N parts of the CV succession are very close to each other, ranging between 129 ± 2 ka and 118 ± 3 ka (samples Fa11 A and AZ05-AO, respectively). The age for the upper part of the same succession (sample Fa10A) yields a similar value of 118 ± 3 ka, showing that the CV has experienced a very rapid stage of sub-aerial growth at about 120 ka. The new age obtained on our sample Fa10H collected in the deepest parts of the Pedro Miguel creek is also dated at 116 ± 3 ka. The late phase of graben filling is finally constrained from dating successive young lava flows from Pedro Miguel creek between 46 ± 3 ka and 38 ± 1 ka. The oldest age is obtained on the lava flow (sample Fa10I) immediately covering sediments on top of the older lava flows here dated at 116 ± 3 ka (sample Fa10H), confirming therefore the existence of a major unconformity (Fig. 3).

Table 1
Results of the K–Ar dating on fresh groundmass separates. The ages are indicated in thousands of years (ka). The uncertainties are reported at the 1σ level.

Sample	Long.	Lat.	K%	$^{40}Ar^*$ (%)	$^{40}Ar^*$ (10^{12}at/g)	Age (ka)	Unc. (ka)	Mean (ka)
AZ05-AM	−28.609	38.552	1.430	29.9	1.2630	845	12	848 ± 12
				30.8	1.2704	850	12	
AZ05-AQ	−28.613	38.543	1.694	28.3	1.4948	845	12	847 ± 12
				35.4	1.5011	848	12	
AZ05-AL	−28.609	38.552	1.585	43.0	1.3976	844	12	846 ± 12
				40.1	1.4043	848	12	
AZ05-AR	−28.625	38.553	1.863	33.3	1.6399	843	12	843 ± 12
				39.5	1.6424	844	12	
FA10D	−28.631	38.591	1.060	9.7	0.4349	393	7	389 ± 7
				9.2	0.4262	385	7	
AZ05-AN	−28.612	38.599	1.222	14.8	0.4651	364	6	363 ± 6
				16.5	0.4618	362	6	
AZ05-AP	−28.608	38.599	1.264	7.7	0.4739	359	7	358 ± 7
				10.0	0.4727	358	6	
Fa11A	−28.713	38.592	3.173	9.2	0.4332	131	2	129 ± 2
				11.8	0.4217	127	2	
FA10B	−28.658	38.626	1.539	4.9	0.2023	126	3	127 ± 3
				5.0	0.2061	128	3	
AZ05-AO	−28.750	38.613	1.827	4.3	0.2203	115	3	118 ± 3
				3.7	0.2293	120	4	
FA10A	−28.750	38.608	1.419	3.8	0.1754	118	4	118 ± 3
				4.0	0.1750	118	3	
FA10H	−28.620	38.577	1.785	4.7	0.2195	118	3	116 ± 3
				5.2	0.2141	115	3	
FA10I	−28.620	38.577	1.503	1.8	0.0716	46	3	46 ± 3
				1.8	0.0735	47	3	
Foz RPM	−28.612	38.578	2.225	3.2	0.0960	41	1	40 ± 1
				3.6	0.0910	39	1	
FA10F	−28.622	38.577	1.919	2.9	0.0778	39	1	38 ± 1
				4.0	0.0757	38	1	

4.2. Paleomagnetic data

Silva et al. (2008, 2010, in preparation) performed a paleomagnetic study on Faial Island on 140 samples collected along 6 different sections that mostly correspond to the flows dated in this study. Rockmagnetic experiments identified magnetic carriers favourable for paleomagnetic study (presence of magnetite of Pseudo-Single Domain-Single Domain states). Demagnetizations have shown mostly the presence of a single stable magnetization component defining a characteristic remanent magnetization.

Virtual Geomagnetic Poles for 11 lava flows indicate a normal polarity of the Earth magnetic field and for 5 flows a reversed polarity. The reversed polarity is exclusively measured on the samples dated in this paper at about 0.85 Ma. This confirms that the phase of old volcano construction occurred at the final stages of the Matuyama reversed chron.

The other lava flows show a positive polarity, in accordance with their eruption during the Brunhes normal chron, i.e. during the last 0.789 ± 0.008 Myr (Quidelleur et al., 2003). When accessible, lava flows from the same lava pile generally exhibit very similar paleomagnetic directions, confirming the existence of massive pulses during volcano construction. We note, however, that data from 2 flows of the old volcanic sequence along the sea cliff show abnormal paleomagnetic direction with respect to the average values. This could be highlighting local tilting processes associated with differential movement along recent faults.

4.3. Tectonic analysis of fault geometry and kinematics

The most prominent tectonic feature in Faial is the central graben affecting the whole island. The graben fault scarps are clearly visible in successive topographic cross-sections (Fig. 4) but the actual fault surfaces are only visible locally along sea cliffs (Fig. 5). Faults and fault scarps strike N110° on average; some fault scarps dip 35–45º to the NNE or SSW, while others dip more steeply at the surface, at around 55–75º to the NNE or SSW. Tilting of the lavas in the hanging-wall block and steepness of faults at the Earth's surface indicate a listric geometry at depth. The observed fault striations are dip-slip, which means that they are normal faults. Fault displacement, as shown by the displacement of the topography, gradually increases away from the Central Volcano, especially to the E; this can mean that part of the older fault displacement has been gradually covered by CV eruptions. The few faults that presently show a significant displacement, even close to the south flank of the caldera, indicate that recent fault displacement has been greater in the south than elsewhere (Fig. 4). We dated the oldest rocks here at about 850 ka, so they are not associated with these southernmost faults bounding the graben. This implies that there was a south dipping topography of the old island, otherwise the southernmost fault would show the oldest rocks.

5. Discussion

5.1. Successive stages of volcano–tectonic evolution

5.1.1. Rapid construction of a first main volcano

The old volcanic succession cropping out in the eastern side of the island is dated here between 848 ± 12 ka (sample AZ05-AM) at the base

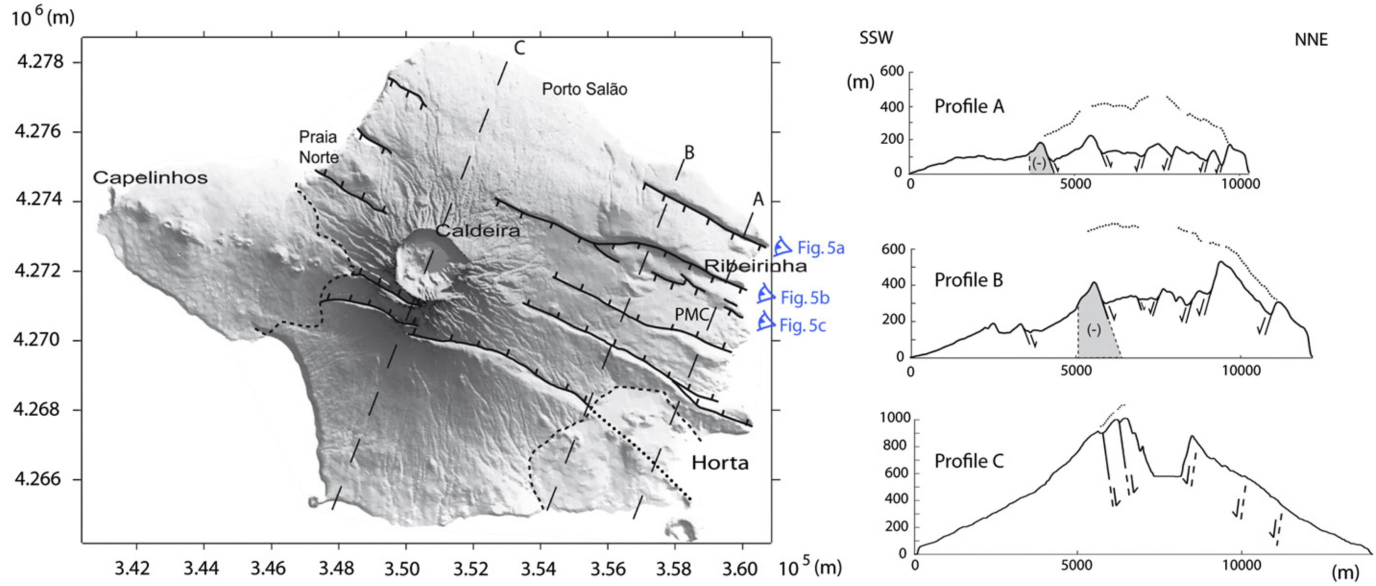

Fig. 4. Left: Shaded-relief map drawn from the high-resolution DEM (illumination from the North), showing the main topographical characteristics of the island. Thick black lines show the base of the various fault scarps, with ticks towards the footwall. The dotted line shows the inferred prolongation of the southern fault under recent basaltic volcanic cones in the Horta sector. Dashed lines localize the topographic profiles shown on the right. The eye symbols show the points of view from which the photographs in Fig. 5 have been taken. Right: Topographic cross-sections evidencing recent apparent fault displacements across the width of the Faial graben. Grey areas show the remnants of the volcanic system older than 850 ka (reversed magnetization). Thin dotted lines show the restored topography.

and 843 ± 12 ka (sample AZ05-AR) at the top, in full agreement with the reversed polarity recorded by the lava flows. These new ages overlap within the uncertainties, testifying to a rapid stage of growth prior to the end of the Matuyama period. Our new results are significantly older than previous K/Ar determinations of 0.73 ± 0.07 Ma and 0.67 ± 0.09 Ma acquired on whole-rock samples from the same area (Féraud et al., 1980). The latter value, despite its large uncertainty, is inconsistent with the reversed polarity here recorded for this sector. Such age under-estimation in earlier studies may result from the experimental procedure used previously. The samples dated by Féraud et al. (1980), were pre-degassed at ca 230 °C under vacuum for a period of up to 20 hours before analysis (Féraud, 1977). Such procedure, initially aimed at removing part of the atmospheric contamination adsorbed on the surface of the grains, is unsuitable because it can also result in partial diffusion and removal of radiogenic argon from the poorly retentive volcanic glass, which can in turn yield too young ages.

The initial geometry of the old volcanic system cannot be constrained precisely, because it was largely destroyed during a period of up to 500 kyr, and more recently was covered by volcanic activity and partly affected by tectonic activity and mass-wasting processes. However, the original dimensions can be estimated by combining all our data. Low magnitude negative magnetizations computed (light blue colour shades) for the eastern part of the island (Fig. 2) do not mean that the outcropping lavas have a reversed polarity, because the polarity measured on the samples collected in that area is normal. The inversion process we used computed a vertical average of the magnetization, interpreted to reflect a thin and young (<0.780 Ma) layer of rocks with normal polarity overlaying a deep and older layer of reversed polarity. Therefore, the thinner the layer of normal magnetic polarity lavas on top of the reversed polarity rocks is, the more the colour approaches deep blue. The persistence of the light blue area close to the island shore in the different sectors of Faial (except the SW) suggests that the original volcano is present underneath most of the recent lava units and therefore had a geographical extent encompassing most of the present island area (Fig. 2). The narrow sector presently cropping in the eastern sector (strong negative magnetizations evidenced by a deep blue colour, and measured ages of about 850 ka) must have been a persistent topographic high, which has not been covered by subsequent young lava flows. We can get a rough idea of the old topography (prior to present-day graben) by restoring surface displacements to their original position (Fig. 4). This shows that the topography prior to recent faulting was convex upward (topographic high), which is not favourable for blanketing by younger positive lava flows. Therefore, this area most likely coincides with a relatively high morphological crest in the eastern side of the original volcanic system. We note that the elongation of the inland negative magnetization is slightly oblique with respect to the present N110 axis of the island. High-magnitude negative values also extend offshore Faial to the northwest. This suggests that the old volcanic system possibly had a ridge-like morphology with a main axis closer to the northwest-southeast direction (Fig. 6a). Prolongation of such a volcanic edifice would thus extend into the Faial–S. Jorge channel as proposed by Miranda et al. (1991). An old volcanic edifice with such elongation is also compatible with the presence of northwest-southeast trending old ridges recognized at the scale of the Azores plateau, e.g., in the eastern part of S. Jorge (Hildenbrand et al., 2008b).

5.1.2. Prolonged volcanic gap and construction of a small edifice in the NE part of Faial

The oldest lava flows collected in the NE sector of the island are dated here at 387 ± 7 ka, revealing an apparent gap in volcanism of at least 450 kyr after the construction of the old volcano. Such a gap could reflect in part a sampling bias, i.e. un-investigated volcanic units could potentially be intercalated between the old volcanic succession and the lava pile here dated between 387 ± 7 ka and 358 ± 7 ka. However, this is not supported by the magnetization map, which shows low negative values in the NE sector reflecting a thin cover of lavas with normal polarity on top of the older units. The morphological surface in the NE tip of the island also supports lavas locally flowing from a small volcanic edifice towards the North and Northeast, on the partly preserved outer slopes of the Matuyama volcano (Fig. 6b).

Geomorphological data, however, do not support such lava flows on the southern and western sides of the island. Several authors have proposed that early sub-aerial construction of the CV could be

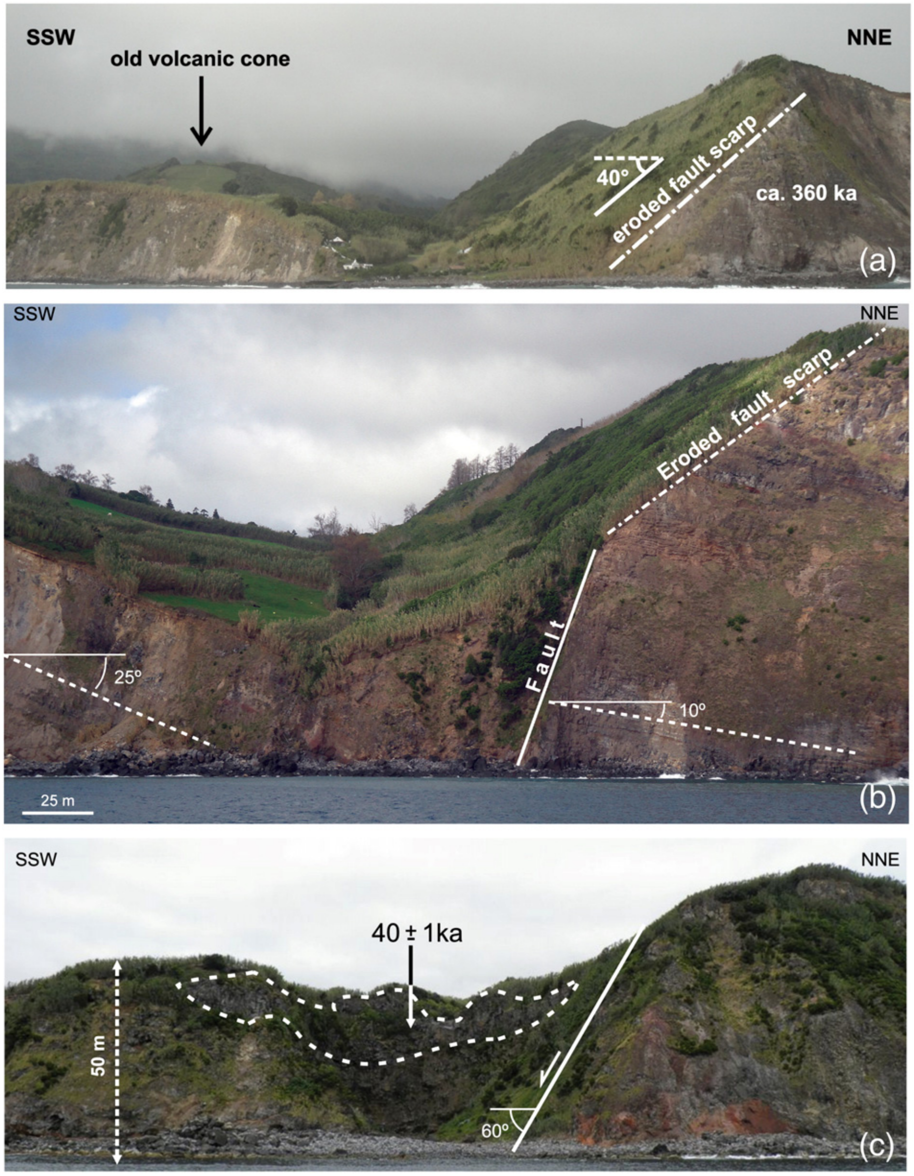

Fig. 5. Photographs taken from the sea showing the contrasted geometry of old and recent fault scarps. See Fig. 4 for localization.

as old as 0.47 Ma (Demande et al., 1982; Madeira and da Silveira, 2003; Quartau et al., 2010). Such an inference relies on a K/Ar whole-rock age of 0.44 ± 0.03 Ma obtained on a highly porphyric sample containing high amounts of olivine and pyroxene phenocrysts, which was sampled in the western wall of the caldera (Demande et al., 1982). Whole-rock dating on such porphyric and/or weathered samples in the Azores and elsewhere has clearly shown to yield abnormaly old ages by incorporation of inherited excess argon and/or potassium removal by alteration processes (e.g., Johnson et al., 1998; Quidelleur et al., 1999; Hildenbrand et al., 2004). In contrast, the new age of 129 ± 2 ka obtained on the fresh-separated groundmass of our sample Fa11A from the base of the caldera succession shows that most of the CV has been built much later (see next section). Therefore, prior to such recent volcanic growth, the western side of the old volcano has most probably experienced a prolonged period of volcanic inactivity exceeding 500 kyr. Partial destruction of the original morphology by mass wasting processes, including coastal and stream erosion and tectonics, and subsequent blanketing by the CV on the western side of the island can thus explain the absence of the negative anomaly such as observed in the eastern sector.

5.1.3. Initiation of the Faial graben and early development of the Central Volcano

Early sub-aerial growth of the CV within a very short period is supported by our new age constraints obtained for samples from the base and uppermost parts of the thick succession exposed both in the caldera walls and at the northern part of the island near Praia do Norte. We note that two similar, though less precise ages, have been previously measured at 0.10 ± 0.03 Ma and 0.11 ± 0.03 Ma on sub-aphyric samples from the northern and southern coasts, near Porto Salão and Lombega, respectively (Demande et al., 1982). The positive anomalies observable on the magnetization map in the sector of Praia do Norte are consistent with emplacement of a thick lava cover immediately to the North of the main Caldera eruptive centre. A similar pattern, though less pronounced, is also visible as far as the southern coast of the island. In contrast, the persistence of negative anomalies in the sector of Porto de Salão indicates a more reduced thickness. There, the northern gentle slope of the CV also exhibits a clear morphological lateral contrast with the prominent unit here dated between 389 ± 7 ka and 358 ± 7 ka, which confirms that the latter had a restricted geographical extension.

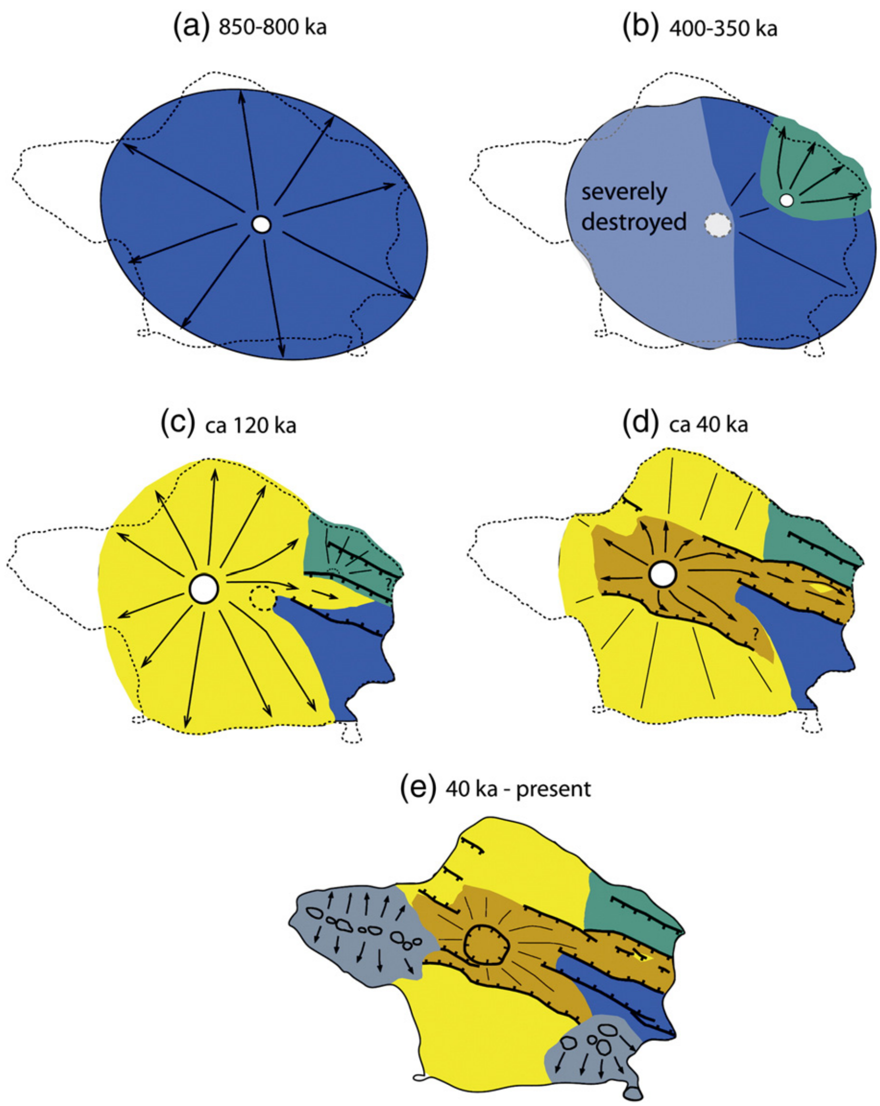

Fig. 6. Schematic model of evolution showing the main stages of volcanic construction separated by incremental fault migration and graben development.

Our new sample collected in the deeper parts of the graben is dated at 116 ± 3 ka, very much in agreement with the age we obtained for the upper northern flank of the CV (sample Fa10A, 118 ± 3 ka). This clearly shows that (1) the graben was already partly formed at that time, and (2) lava flows from the upper part of the CV were channelized in this prominent topographic low (Fig. 6c). Therefore, the eastern part of the graben experienced a significant phase of development between 390 ka and 120 ka, which is much older than previously thought. We note that the fault near Ribeirinha could have formed during this period, which could explain the eroded aspect of the scarp recognized in the field (Fig. 5a).

5.1.4. Incremental evolution of the graben and further construction of the Central Volcano

The several lava flows sampled on top of the unconformity in Pedro Miguel Creek range in age between 46 ± 3 ka and 38 ± 1 ka. These new ages do not overlap each other but attest to very rapid burying of the graben. Although a few scoria cones have developed recently within the graben, such massive filling was most probably fed by renewed activity at the Caldera eruptive centre, as revealed by the present prominent morphology of the volcano (Fig. 6d). The unconformity in Pedro Miguel creek shows an apparent volcanic gap of ca. 80 kyr, which can explain the deep erosion of the older lava flows and the local accumulation of sedimentary deposits on their remnants. The presence of large boulders (up to 1 m in size) most probably highlights morphological rejuvenation upstream, which can therefore be associated with significant vertical deepening of the graben between 120 ka and 40 ka. Furthermore, the younger succession shows that the pilling of lava flows was interrupted from time to time by smaller erosion surfaces and smaller grain-size conglomeratic deposits (see Fig. 3). We interpret these interruptions in the lava piling as times of movement along the adjacent normal faults, which could thus be linked with repeated eruptions at the CV. The scars developed on the southern side of the volcano have a very prominent surface expression, featuring high slopes and a significant vertical offset. This suggests recent reconfiguration of the deformation, with increasing displacement along the southern edge of the graben. The more prominent positive magnetization along these scars supports partial buttressing of the lava flows erupted from the CV against the southern faults.

5.1.5. Late evolution during the last 40 kyr

The young units of Faial Island previously dated by radiocarbon (<10 ka) are mainly related to the very recent explosive volcanic activity at the CV (Madeira et al., 1995). Several basaltic volcanic cones are additionally distributed along the southernmost fault of the graben, suggesting that magma ascent was constrained along this mechanical discontinuity, but they do not give precise information as to whether the latter was active at that period, because a pre-existing fault could also have focussed magma ascent. The southern faults in the western sector do, however, affect the recent part of the CV, showing downward movement very recently, i.e., additional westward propagation of the graben during the last 40 kyr, and most probably during the last 10 kyr. Several recent basaltic cones and vents on the western tip of the island, including the historical eruptions, also occurred during the last 10 kyr (Madeira et al., 1995). The caldera could thus have experienced partial development in response to magma withdrawal associated with emptying of a shallow reservoir during the several differentiated pyroclastic eruptions and/or an additional phase of graben development (Fig. 6e), two processes which might be intimately linked, as discussed in the next section.

5.2. Links between regional deformation, volcano growth and graben development

Our new data show that volcanic activity on Faial has occurred through short periods of robust volcanic construction, each lasting less than 30 kyr and being separated from the others by prolonged hiatuses, up to 500 kyr in duration. This is similar to the case of the neighbouring island of S. Jorge, where multi-stage volcanic growth alternating with prolonged gaps have been recently shown by geochronological analyses on samples prepared according to the same procedure and analysed with the same technique (Hildenbrand et al., 2008b). Furthermore, comparison of these data with recent stepwise $^{40}Ar/^{39}Ar$ analyses on separated volcanic groundmass on Terceira (Calvert et al., 2006) shows synchronous short phases of volcanic construction on the three islands, e.g. between 400 ka and 350 ka, and probably throughout most of the last 300kyr. Recent magma outputs in the area thus have been concentrated along the N110 direction to develop simultaneously S. Jorge, Faial and Terceira, which most probably reflects significant episodes of intense regional deformation. Similarly, volcanic construction has been constrained by $^{40}Ar/^{39}Ar$ at about 850 ka in S. Miguel (Johnson et al., 1998), i.e., synchronous with the construction of the old volcano on Faial.

MacDonald (1972) concluded that the exact origin of the Faial graben was not known but proposed three mechanisms: (1) removal of magma from an underlying chamber, or (2) stretching of the surface of the volcano, or (3) stretching of the entire underlying crust due to spreading of the Atlantic Ocean basin. Our new data support the first hypothesis, and provide additional insight on the iterative development of the Faial graben in relation with the several volcanic pulses. The most conspicuous arguments for our interpretation are:

(1) The inward listric geometry of the faults responsible for local tilting of the island surface suggests their flattening at shallow depth, strongly indicative of the existence of (an) underlying magma chamber(s) developed within the volcanic edifice.
(2) Each of the short volcanic episodes here evidenced included the eruption of either highly porphyric lavas featuring plagioclase phenocrysts/glomerocrysts, or evolved lavas like mugearites, benmoreites and trachytes. Such characteristics support intermittent storage of the magma in a reservoir prior to their extraction to the surface.
(3) Each volcanic stage, at least during the last 400 kyr, has been followed by a period of graben development. Westward migration of volcanic construction has also been followed by systematic westward propagation of the graben faults, supporting dominant deflation above the main zone of magma withdrawal.
(4) The presence of sediments intercalated within the lava flows here dated at 120 ka and 40 ka suggests the morphologic rejuvenation of the scarps during the interval separating the two main periods of eruption, supporting incremental displacement along the main faults of the graben.
(5) Such a mechanism occurred in recent time during the Capelinhos eruption, where 1.5 m of vertical displacement were measured in 1958, late in the eruptive crisis that started in 1957 (Machado et al., 1959; Zbyszewski and Veiga Ferreira, 1959; Machado et al., 1962; Catalão et al., 2006).

6. Conclusions

This study shows the suitability of using complementary approaches for retrieving the architecture and understanding the evolution and development of oceanic islands in response to complex interactions between volcanic growth and partial destruction by a variety of mass-wasting processes. The combined use of precise K/Ar geochronology on separated groundmass, morpho-tectonic analyses, and magnetic data allow us to depict a step by step model emphasizing short stages of volcanic growth separated by long periods of inactivity during which the volcanic units were subjected to significant mass wasting, including coastal and stream erosion, possibly lateral collapse, and incremental normal faulting. Therefore, the present architecture of the island does not result from simply the coeval development of two main volcanic edifices that were synchronously active over long periods of time.

The successive phases of rapid volcano growth shown in this study have apparently been controlled by short volcanic pulses confined along the main lithospheric structures, triggered by brief episodes of regional deformation. In contrast, the gradual development of the Faial graben appears to be closely linked to the dynamics of magma extraction from ESE-WNW elongated magma chamber(s) at depth, which episodically loses volume and triggers passive gravitational collapse. Such a model is applicable to other oceanic islands, in the Azores and elsewhere.

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