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Construction and destruction of a volcanic island developed inside an oceanic rift: Graciosa Island, Terceira Rift, Azores

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ABSTRACT

There is a great lack of knowledge regarding the evolution of islands inside active oceanic rifts, in particular the meaning of the different evolutionary steps. Therefore, we conducted an investigation in Graciosa Island, which lies at the northwestern end of the Terceira Rift in the Azores Triple Junction, with the objective of constraining the evolution of the island in terms of volcanic growth and mass wasting, in particular the meaning and age of the destruction events.

From digital elevation model (DEM) analysis, stratigraphic and tectonic observations, K/Ar dating on key samples, and available bathymetry and gravity data, we propose that Graciosa comprises five main volcanic complexes separated by major unconformities related to large scale mass wasting: (1) The older volcanic edifice (Serra das Fontes Complex) grew until ca. 700 ka, and was affected by a major flank collapse towards the southwest, which removed the whole SW flank, the summit and a part of the NE flank. (2) The Baía do Filipe Complex developed between at least 472 ka and 433 ka in two different ways: in the SW (presently offshore) as a main volcano, and in the NE unconformably over the sub-aerial remnants of the Serra das Fontes Complex, as secondary volcanic edifices. (3) The Baía do Filipe Complex was affected by a major flank collapse towards the SW, again removing most of the edifice. (4) The remnants of the Baía do Filipe Complex were covered in unconformity by the Serra Dormida Complex between ca. 330 and 300 ka, which in turn was unconformably covered by the younger Basaltic Cover Complex between ca. 300 ka and 214 ka. These two units were affected by a third major sector collapse that removed the whole western flank, the summit and part of the eastern flank of the Serra Dormida and Basaltic Cover complexes. (5) Despite the relatively young age of Graciosa, the collapse scars are not well preserved, and not active anymore. (6) A central-type volcano has been growing since at least 60 ka at the southeastern end of the island, inside the scar left by a fourth sector collapse towards the SE, which affected most previous complexes. Contemporaneously, parasitic strombolian cones formed all over the island. Despite the location of Graciosa inside the active Terceira Rift, the new data indicate that the evolution of the island has been driven by a competition between volcano growth and repeated destruction by catastrophic sector collapses, rather than by slow incremental faulting associated with the tectonics of the rift.

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1. Introduction

The evolution of oceanic islands results from the interplay between volcanic construction and destruction by a variety of processes. Large-scale landslides, especially, are known to be one of the most efficient processes in the catastrophic destruction of oceanic volcanic islands. From onshore and offshore studies, lateral flank collapses have been recognized all over the world, either on large islands like Hawaii (e.g. Lipman et al., 1988; Moore et al., 1994), medium-size like the Canaries (e.g. Watts and Masson, 1995; Carracedo et al., 1999a,b; Hildenbrand et al., 2003; Boulesteix et al., 2012, 2013), Reunion Island (Lénat et al., 1989; Gillot et al., 1994) or French Polynesia (Clouard et al., 2001; Hildenbrand et al., 2004, 2006), and smaller islands like Pico Island in the Azores (Hildenbrand et al., 2012a, 2013; Costa et al., 2014).

In regions affected by active tectonics, in particular close to plate boundaries, large-scale gravitational instabilities occur typically associated with major faults. These instabilities can involve the development of slow and gradual rotational landslides along a deep detachment (usually termed slumps, e.g. Hildenbrand et al., 2012a, 2013), slides along major faults, or in turn may proceed as sudden catastrophic sector collapses of variable magnitude (e.g. Deplus et al., 2001; Le Friant et al., 2003; Samper et al., 2008). In seismically active areas, however, the contribution of slow-rate destruction by faulting and sudden lateral flank failure needs to be carefully assessed, since both gravitational and

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tectonic processes can produce scarps on the volcanic edifices, and thus can be confused.

The Graciosa Island in the central Azores (Atlantic) is a target of particular interest to address such problems. The island lies close to the present Triple Junction between North America (NA), Eurasia (EU) and Nubia (NU) lithospheric plates (Fig. 1), and has developed more specifically inside the western end of an active oceanic rift, known as the Terceira Rift (TR, Fig. 1), which presently materializes the northern limit of the Eurasia–Nubia plate boundary. Therefore, Graciosa offers a unique opportunity to study large-scale mass wasting in an environment of active tectonics. Here we examine the successive phases of volcanic construction and partial destruction of Graciosa. From stratigraphic relationships, the analysis of a high-resolution digital elevation model (DEM) (10 m), new K/Ar dating, and available gravity and bathymetry data, we reconstruct the multi-stage evolution of Graciosa and discuss the relative contribution of faulting processes and large-scale flank instabilities in the repeated destruction of the island over its lifetime.

2. Geological setting

The geology, stratigraphy, geochemistry and geochronology of Graciosa have been the subject of previous studies (e.g. Zbyszewski et al., 1972; Féraud et al., 1980; Gaspar and Queiroz, 1995; Gaspar, 1996; Hipólito, 2009; Hipólito et al., 2011; Larrea et al., 2014). According to Gaspar and Queiroz (1995), Graciosa comprises 3 main volcanic complexes (Fig. 2): (1) the older volcanic complex is partly preserved as a succession of hawaiitic lava flows. One of them was collected on a road-cut and dated at 620 ± 120 ka by K/Ar (Féraud et al., 1980), whilst a similar (same?) flow from this succession yielded a $^{40}Ar/^{39}Ar$ age of 1057 ± 28 ka on separated groundmass (Larrea et al., 2014, isochrone ages). (2) The intermediate volcanic complex is mostly composed of trachyte lava flows and pyroclastic deposits, with reported ages ranging between 350 ± 40 ka (Féraud et al., 1980) and 434 ± 13 ka (Larrea et al., 2014). (3) The younger volcanic complex comprises two sub-units: a NW platform (basaltic cover) composed of many scattered small volcanic cones dated between 96 ± 32 ka and 46 ± 22 ka (Larrea et al., 2014), with associated basaltic lava flows blanketing most of the earlier volcanism; and the SE central-type volcano, composed of basaltic to trachytic lava flows, and pyroclastic deposits dated between 59 ± 19 ka and 4 ± 1 ka (Larrea et al., 2014).

According to Gaspar (1996) and Larrea et al. (2014), the evolution of Graciosa (Fig. 2) consists of a succession of volcanic edifices built one over the other, which have been affected and dismantled in a symmetric way by the active faulting of the Terceira Rift. This would mean that the current morphology of the edifice is tectonically induced, and due to the position of the island inside the rift. Many lineaments can be interpreted from the DEM, but their tectonic meaning has not been confirmed on the outcrop (e.g. Gaspar and Queiroz, 1995; Hipólito, 2009; Hipólito et al., 2011). Several of the lineaments are drawn using the alignment of young scoria cones, but the interpreted faults have not been observed inland or even on the coast. The measured fault directions are NW-SE and NNE-SSW, and the dip is to SW or NE, and WNW or ESE, respectively. These main fault orientations and the NW-SE elongated shape of the island have been interpreted as a consequence of the regional tectonics (Gaspar, 1996; Hipólito et al., 2011).

At present, no published work has, to our best knowledge, described or considered possible large-scale gravitational flank collapses in Graciosa.

3. Bathymetry, gravity, DEM analysis, fieldwork data and sampling strategy

3.1. Bathymetry and gravity

Despite the low resolution of the available bathymetry (Lourenço et al., 1998) and free-air gravity data (Catalão and Bos, 2008) near Graciosa, some relevant information can be extracted (Figs. 3 and 4). Graciosa has developed inside the TR, but not in the middle of the rift (Figs. 3 and 4); the northernmost part of the island sits on the TR's

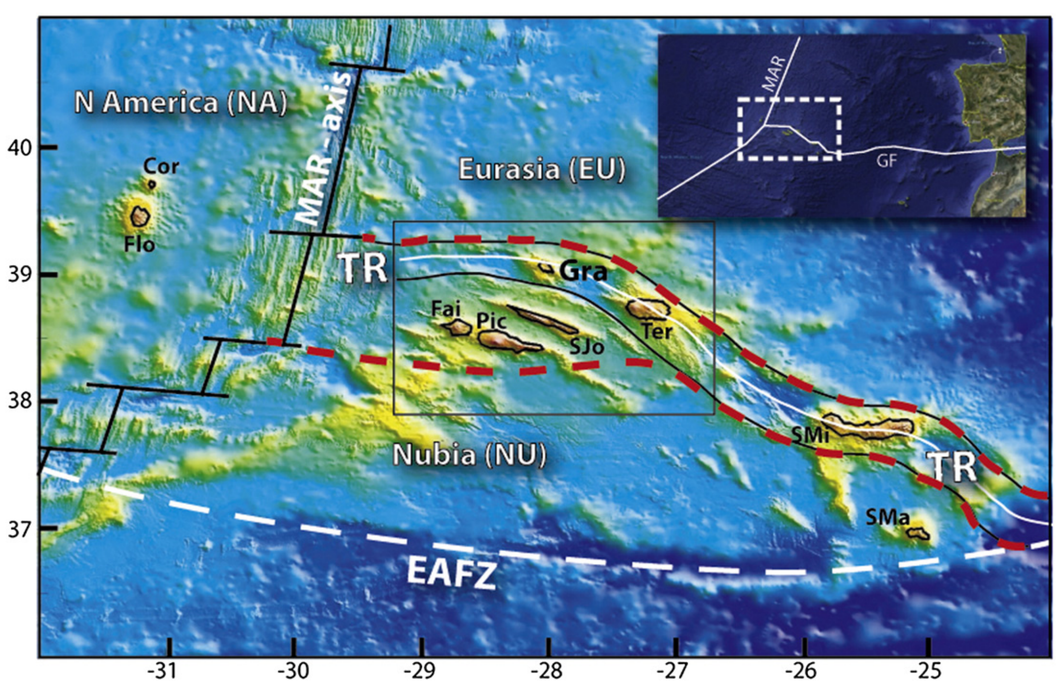

Fig. 1. Bathymetric map of the Azores region, after Lourenço et al. (1998). The black lines indicate the location of the Mid-Atlantic ridge (MAR) axis and associated fracture zones. The thin white and black lines indicate the wall and the centre of the Terceira Rift (TR), respectively. The white dashed line marks the East Azores fracture Zone (EAFZ). The black rectangle indicates the location of Fig. 3. The red dashed lines mark the diffuse boundary between the Eurasia and Nubia plates from Marques et al. (2013a, 2014a). The islands are referenced as Cor—Corvo; Flo—Flores; Fai—Faial; Pic—Pico; SJo—S. Jorge; Gra—Graciosa; Ter—Terceira; SMi—S. Miguel; SMa—Santa Maria. Inset on the right top for location.

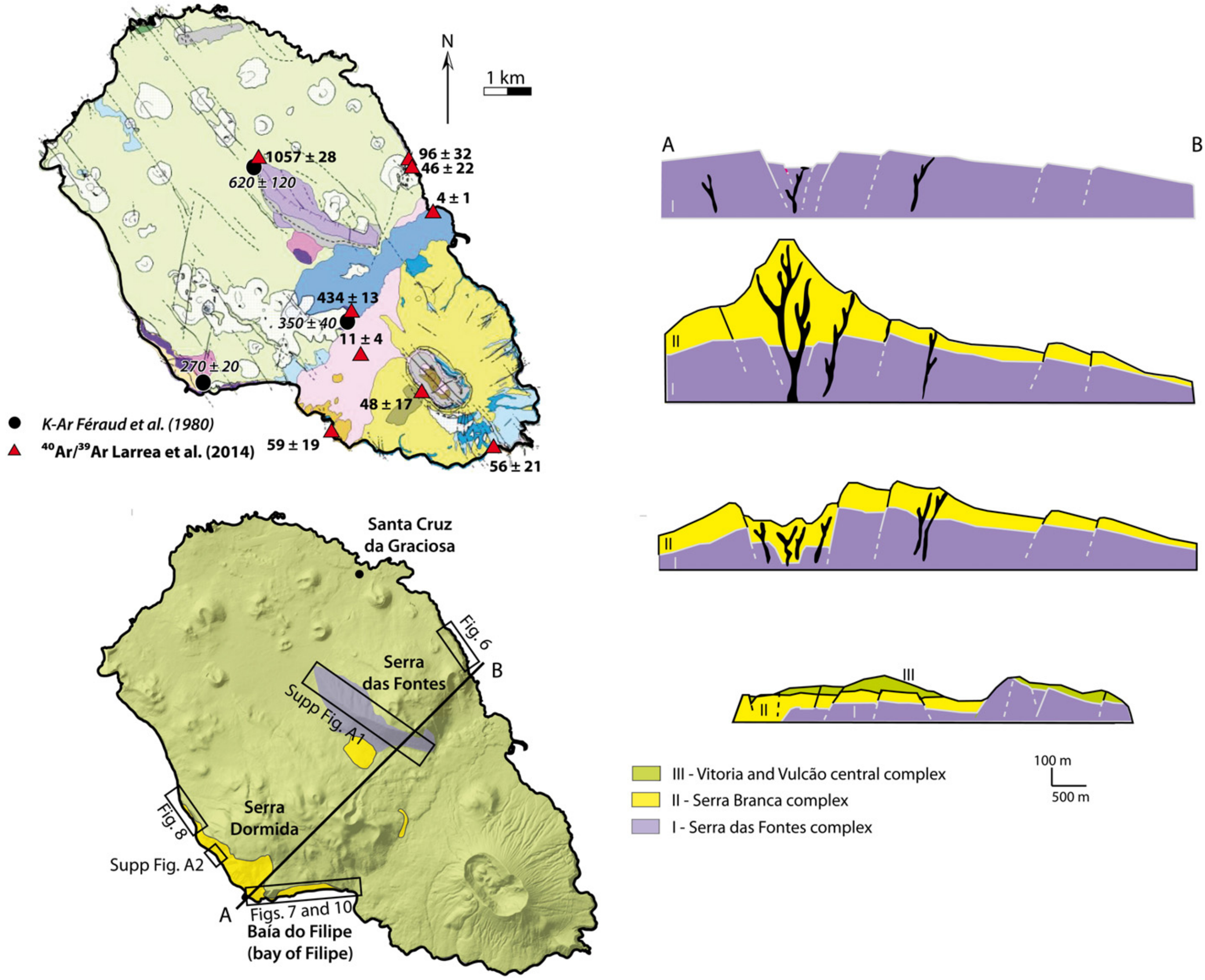

Fig. 2. (A) Geological map from Gaspar and Queiroz (1995), and previous ages in ka from Féraud et al. (1980) and Larrea et al. (2014). The light and dashed lines indicate the faults measured and presumed by Gaspar and Queiroz (1995), respectively. (B) Shaded relief map of Graciosa with the simplified geological map. The rectangles mark the location of Figs. 6, 7, 8 and 10, and Supplementary Figs. A1 and A2. (C) The panel on the right shows the evolution of the Graciosa Island after Gaspar (1996).

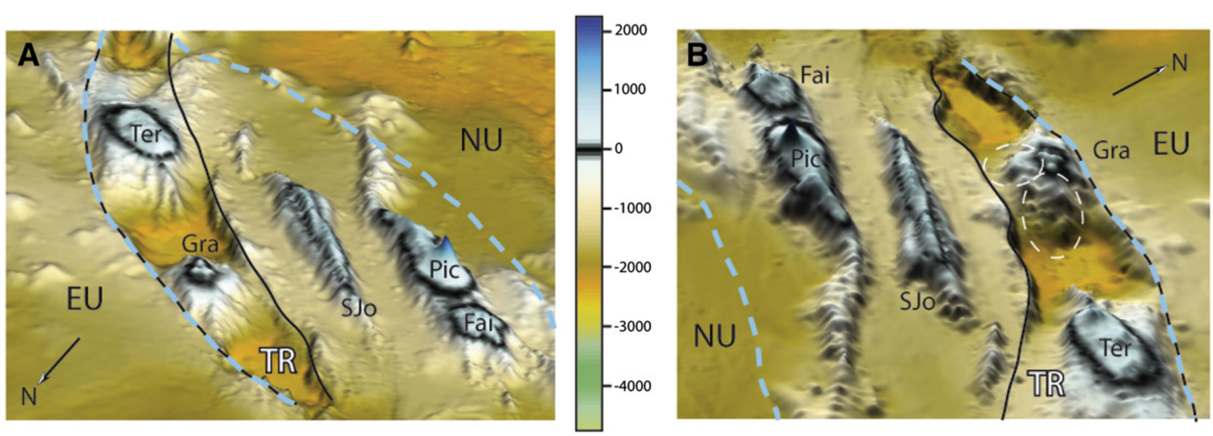

Fig. 3. 3D bathymetric map viewed from the west (left panel—A) and from the east (right panel—B). Depth in metres. The black lines indicate the northern and the southern walls of the Terceira Rift (TR), and the blue dashed lines indicate the diffuse plate boundary between the Eurasia (EU) and the Nubia (NU) plates. The white dashed circles indicate possible debris deposits. The islands are referenced as Ter—Terceira; Gra—Graciosa; SJo—S. Jorge; Pic—Pico; Fai—Faial. The raw figure without our interpretation is shown in the Supplementary Fig. A4.

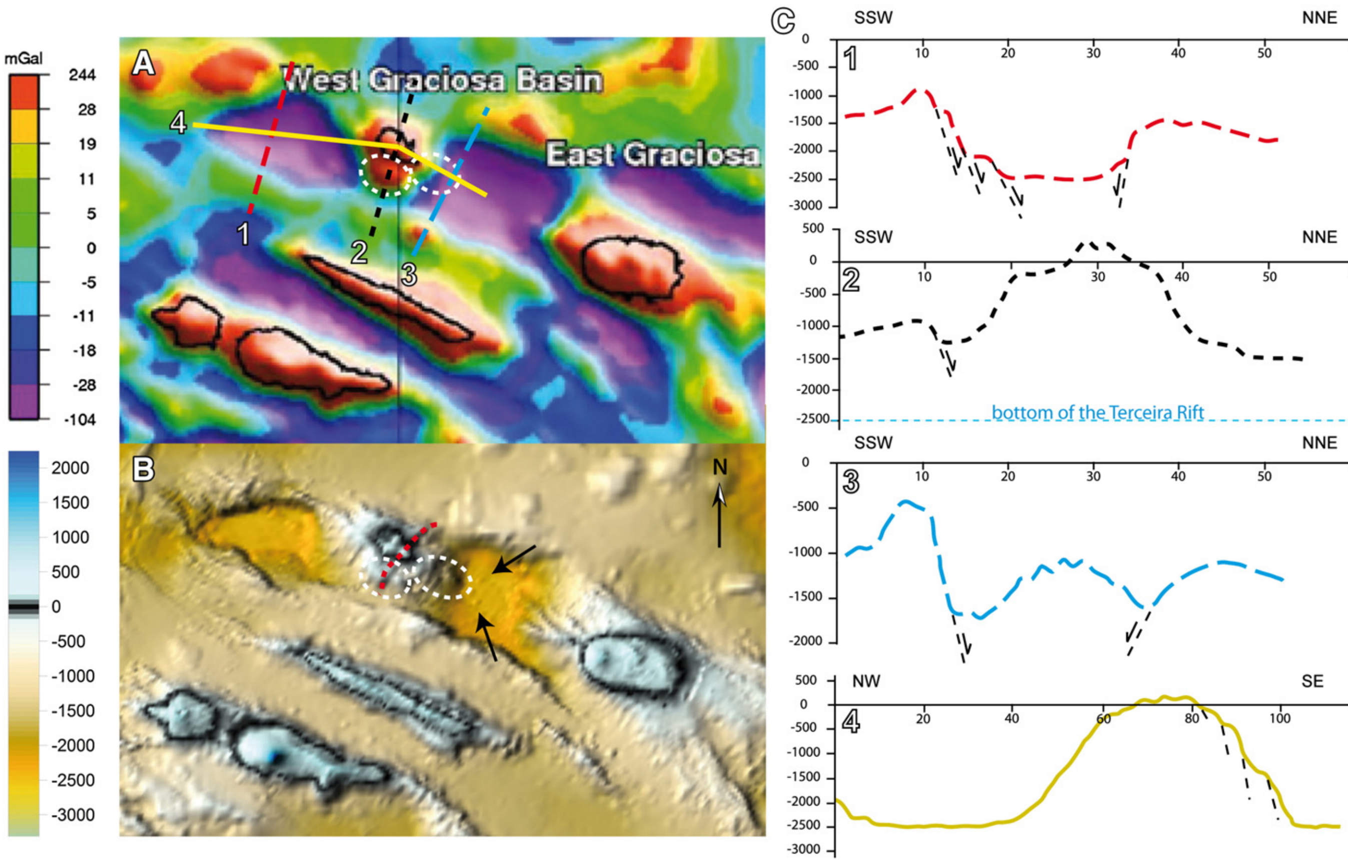

Fig. 4. (A) Gravity around Graciosa showing a flat platform in the south. Dotted circles highlight possible debris deposits that can be related to the landslides towards the SW and the SE. The coloured lines mark the location of the cross-sections shown in (C). (B) Bathymetry around Graciosa showing a flat morphology in the south. The white dashed circles show possible debris deposits. The arrows show possible few large debris blocks. The red line shows a possible collapse scar. The raw figure without interpretations is shown in the Supplementary Fig. A5.

northern wall (Fig. 4), thus concealing it, and leaving room between the submarine base of the edifice and the southern wall as seen on the topographic profile perpendicular to the rift and across the island (Fig. 4). Graciosa is flanked in the WNW and ESE by two deep basins (Western and Eastern Graciosa Basins, respectively). The Western Graciosa Basin shows a long flat bottom, whereas the bottom of the SE basin appears more irregular with a hummocky morphology suggesting the presence of large isolated blocks within a debris deposit. Graciosa's eastern flank is additionally characterized by a step-like topography, with a major NE-SW scarp at the top (Fig. 4b, c). On Graciosa's southwestern flank, there is a prominent flat platform bounded in the NE by a major curved scarp concave to the SW. Debris deposits and associated collapse scars can be interpreted from the bathymetry, as marked on Fig. 4.

Unfortunately, the resolution of the bathymetry available to us does not allow undisputable localization of the debris deposits resulting from the inferred large sector collapses discussed below. On the gravimetric map, Graciosa shows high gravity values (red and yellow, Fig. 4) like the other islands and seamounts in the central Azores (white and blue, Figs. 3 and 4). In contrast, the topographic lows, e.g. bottom of the adjacent basins (yellow and green, Fig. 3 and 4) correspond to low gravity (deep blue to purple, Fig. 4). However, it is important to notice that the gravity signature of the basins on both sides of Graciosa (deep blue to purple) is different than the signature of the rift bottom on the S part of Graciosa (light blue and green) and than the SW platform making up the southern submarine flank of the island (red colour).

3.2. Inland DEM analysis

Regarding topography, Graciosa is elongated NW-SE and may be divided into three main regions (Fig. 5), which are from NW to SE: (1) a low altitude and flat platform comprising the northwesternmost third of the island. It dips gently to the NW and is dotted by several well-preserved scoria cones (highlighted in yellow in the colour slope legend) attesting to their young age. (2) A central region dominated by two asymmetric topographic highs striking NW-SE, with a steep slope facing SW and a gentle slope facing NE (Fig. 5): (1) a prominent asymmetric topographic high, peaking at 375 m of altitude and named “Serra das Fontes” (Serra means hill in Portuguese), bounded by two steep scarps, with similar slope of ca. 45°, one facing SW and the other facing SE. The NE slope is gentle, in contrast to the steep SW and SE scarps. Along strike, the NW-SE scarp is curved and convex towards the SW. This prominent scarp is mostly made of the older volcanic complex. The scarps around Serra das Fontes comprise the older volcanic complex, and the NE facing gentle slope shows younger volcanic cones and lava flows lying unconformably over the lavas of the older volcanic complex. (2) A topographic high, known as “Serra Dormida”, bounded by a prominent sea cliff peaking at 372 m of altitude in the SW, and by an E-W linear sea cliff in the South. Both Serra das Fontes and Serra Dormida die out to the NW and the SE. Serra Dormida is where the intermediate complex was recognized in the previous works (Gaspar and Queiroz, 1995; Gaspar, 1996). (3) A well-preserved central-type volcano peaks at 405 m and occupies the southeasternmost third of the island. The summit shows an elliptical collapse caldera elongated NW-SE. The volcano external slopes are gentle in all directions.

3.3. Field data and sampling strategy

Fieldwork was carried out to investigate the various volcano-stratigraphic units making up the island. As field criterion, we used major unconformities to establish a preliminary stratigraphy and

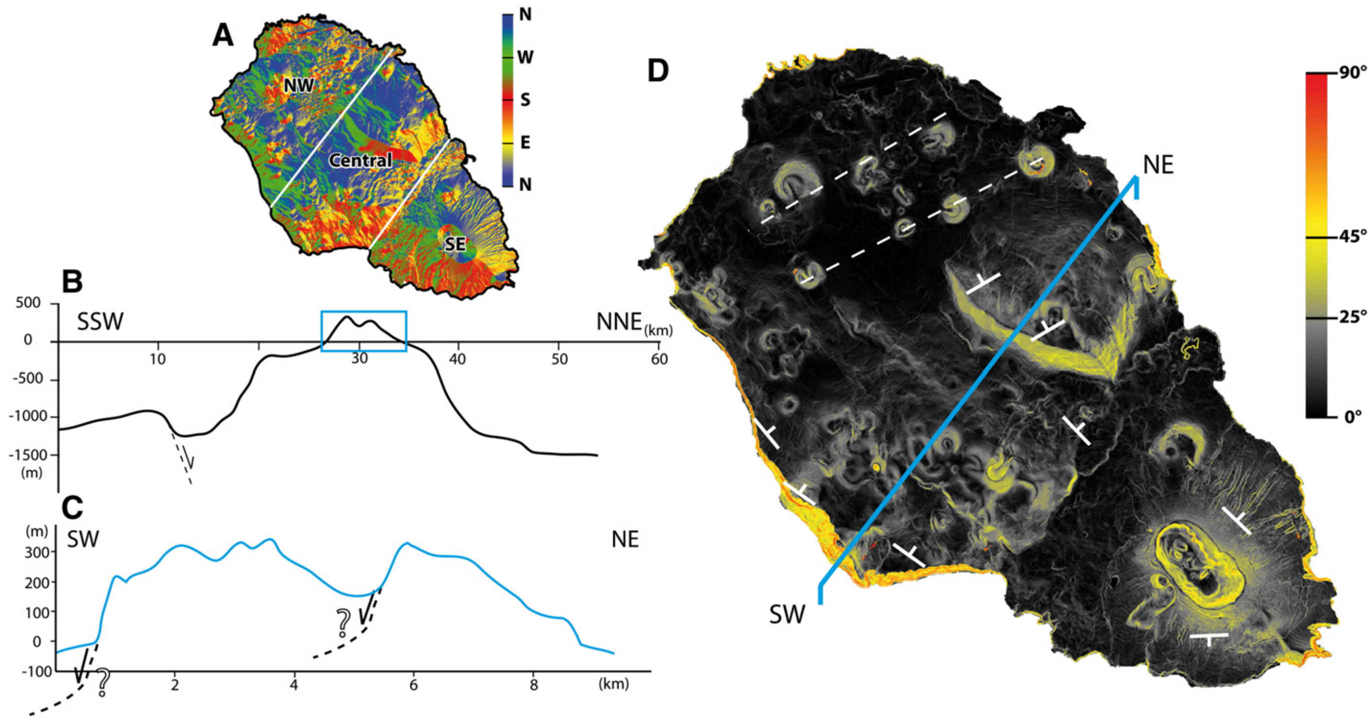

Fig. 5. (A) Direction slope map of Graciosa Island. (B) Cross-section perpendicular to the TR across the Graciosa Island. The blue rectangle indicates the cross-section zoom in (C). The location of the cross section is the blue line in (D). (D) Slope map of Graciosa in degrees. The white symbols indicate the attitude of lava flows. The white dashed lines indicate probable strombolian cones alignments.

guide us on sample collection for subsequent dating. The main outcrops occur mostly along the coast; therefore, we walked down the cliffs where possible, or took a boat to observe the cliffs from the sea and swim ashore to collect samples. Our sampling strategy was devised to constrain the main volcanic complexes of Graciosa, and ultimately the evolution of the island. We took advantage of the high coastal cliffs to observe the stratigraphic relationships between the different volcanic complexes and to sample the base and the top of the accessible units.

The top of Serra das Fontes is composed of basic lava flows dipping gently to the NNW (<10°). We did not observe lava flows dipping to the SW or the SE. Instead, there are two scarps steeply dipping to the SW and the SE, and bounding Serra das Fontes (Supplementary Fig. A1). This is where the older volcanic complex can be found (Fig. 2). On the ground, the SW scarp is made of rounded boulders of basalt comprising a slope deposit that covers the basement lavas, which we could thus not sample. This suggests that the SW facing scarp is the remnant of an earlier fault scarp associated with a fault dipping to the SW, which could be responsible for the displacement or removal of the missing volcanic edifice. Depending on the nature of the destructive event (tectonic normal fault or major flank collapse), a part of the older complex could be preserved at Serra Dormida, on the prominent southern SW sea cliff; therefore we paid special attention to the stratigraphy and sampling on this sea cliff. The SE termination of Serra das Fontes, striking NNE-SSW, is composed of lava flows pouring out of overlying young volcanic cones and cascading over a scarp on the older lavas. To constrain the age of Serra das Fontes, where the oldest part of the island has been defined, we sampled a lava flow at the top of Serra das Fontes (GR13G). We also sampled another lava flow further NW (GR13B), which corresponds to the sample previously collected and dated at 620 ± 120 ka by Féraud et al. (1980), and at 1057 ± 28 ka by Larrea et al. (2014). Due to the general NNW dip of the succession exposed in the Serra dos Fontes scarp (see Supplementary Fig. A1), our samples GR13G and GR13B correspond to very similar lava flows from the uppermost part of the volcanic pile.

A boat trip along the coastal cliff of the island revealed the presence of major unconformities. In the northern sector, the base of the coastal cliff close to Serra das Fontes comprises a reduced succession of thick basaltic lava flows, with an apparent dip towards the N (Fig. 6). We collected one of them (sample GR13Q). This succession appears to be overlain in unconformity by a suite of thinner lava flows inter-bedded with red strombolian deposits. The latter succession is itself intruded by a few dikes oriented mostly N70-N80E. The dykes apparently served as the feeders of very young strombolian cones (e.g. Quitadouro cone, Fig. 6), the products of which cascaded in unconformity over the older units.

On the geological map, differentiated lava flows (identified as the intermediate complex) can be found in a few places on the island. They crop out especially on the southern and western coastal sectors of Serra Dormida. The deep erosional surfaces cutting Serra Dormida comprise two steep and high sea cliffs, one E-W, in the south (Fig. 7), and another NW-SE, in the west (Fig. 8), which together allow a three dimensional view of the geometry and stratigraphy in the area. On the southern E-W sea cliff (Baía do Filipe, Figs. 2 and 7), we distinguished four main volcanic units (and one plug) separated by major unconformities:

1. The base of the cliff shows east dipping basaltic lava flows cut by faults and dykes. We collected samples from both sides of the main fault, GR13F in the SW and GR13O in the NE, in order to estimate possible fault displacement and determine whether the basaltic flows can be linked to the intermediate volcanic complex or come from an older volcanic complex. From the morphology, the dykes and the nature of the rocks, this unit looks similar to the one found at the base of the Quitadouro cliff on the NE coast (Fig. 6). The basal volcanic complex, here coined Baía do Filipe Complex, is capped by a prominent unconformity, on top of which lies thick and more differentiated rocks, mainly trachytic in character (sample GR13N). The Baía do Filipe Complex is interrupted to the west by a conspicuous and steep scarp, which can be due to a major tectonic fault or the lateral rim of a flank collapse. The lava succession cut by this major

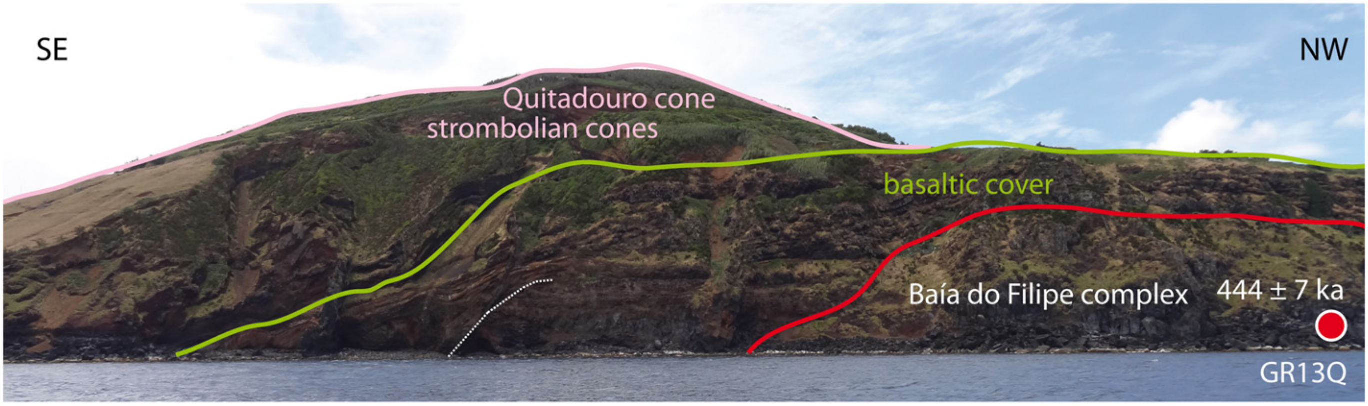

Fig. 6. NW-SE sea cliff on the NE coast of the island, below the Quitadouro cone, with interpreted volcanic stratigraphy. The number gives the age obtained by K/Ar dating in this study. The white dotted line indicates a scarp. The raw picture without our interpretations is shown in Supplementary Fig. A6.

discontinuity has a general dip towards the ENE. No similar lava flows are exposed further west over the whole cliff section, which indicates that most of the Baía do Filipe Complex is missing.

2. The volcanic succession lying unconformably on the Baía do Filipe Complex is mostly trachytic in nature. It includes pyroclastic deposits and thick lava flows, which dip to the ENE. This unit is here coined Serra Dormida Complex, which is also topped by a major unconformity. The Serra Dormida pyroclastic deposits hang steeply to, and cover, the scarp bounding the Baía do Filipe Complex in the west, which means that the steep palaeoscarp, and inferred fault (either tectonic or gravitational), predates the Serra Dormida Complex. This is relevant to the interpretation of the nature of the scarp, as discussed below. The Serra Dormida and the Baía do Filipe complexes are intruded by a few dikes trending N50-N70E.
3. The Serra Dormida Complex is unconformably overlain by basaltic lava flows dipping towards the NE (Figs. 7 and 8). We here coin this unit the Basaltic Cover Complex. The Serra Dormida Complex is intruded in the western half of the E-W cliff by a basaltic neck that seems to be one of the main feeders of the Basaltic Cover. We collected the most suitable and lowermost basaltic lava flows above the basal unconformity (samples GR13K—Fig. 8, and GR13M—Fig. 7).
4. The Basaltic Cover is unconformably overlain by the youngest basaltic lavas, related to the young cones developed over the island surface.

On the western sea cliff we could distinguish two units (Fig. 8): a lower unit composed of differentiated lava flows, which is unconformably covered by basaltic lava flows. Only the nature of the top of the differentiated rocks varies, passing upwards from trachytic lava flows and pyroclastic deposits into a massive ignimbrite flow (Fig. 8). Once we could not observe major faults displacing the lower unit between the southern and western sea cliffs, we infer that the differentiated rocks comprise the same unit, i.e. the Serra Dormida Complex. We collected one sample at the top of this unit (sample GR13E), and a sample at the base (sample GR13J). We also collected the base of the basaltic lava flows (sample GR13K) of the Basaltic Cover.

Relevant to the understanding of the evolution of Graciosa is the ca. 10° general northeastward dip of the lava flows of the Baía do Filipe and Serra Dormida complexes (Supplementary Fig. A2), and the remarkable absence of flows dipping to the SW over the whole width of the cliffs.

Finally, to better constrain the age of the SE central-type Volcano, we collected a lava flow within the caldera (sample GR13A), which probably corresponds to a lava lake stage, and a lava flow pouring out of the volcano (sample GR13P).

4. New K/Ar dating

Amongst the 17 samples collected, 12 were selected to constrain the key steps of evolution of Graciosa throughout its entire sub-aerial eruptive history (Table 1 and Fig. 9). Examination of thin sections (see photography in Supplementary Fig. A3) allowed ensuring the freshness of the samples, which is crucial to get meaningful geochronological data (see Hildenbrand et al., 2012b for a review). All the samples were prepared and dated at Lab. GEOPS in Orsay (France).

Fig. 7. E-W sea cliff at Baía do Filipe, with interpreted volcanic stratigraphy. The circles show the location of our samples and the new K/Ar ages (in ka).

Fig. 8. NW-SE sea cliff of Serra Dormida, with interpreted volcanic stratigraphy. The circles show the location of our samples and the new K/Ar ages (in ka).

The K/Ar Cassignol–Gillot technique used in the present study is particularly well adapted to date Pleistocene material (Gillot and Cornette, 1986; Gillot et al., 2006) and especially suitable to date low-K young volcanic rocks such as young basalts and andesites with an uncertainty of only a few ka (e.g. Hildenbrand et al., 2008, 2012b; Quidelleur et al., 2008; Samper et al., 2009; Boulesteix et al., 2012). Samples were crushed and sieved to the adequate size (typically 125–250 μm), deduced from thin-section examination. For most of our samples, especially basic rocks (basalts and hawaiites), the microlitic groundmass was extracted, whilst K-feldspar phenocrysts were separated for the differentiated lava GR13E. After a 10 mn ultrasonic cleaning in a 10% nitric acid solution followed by complete rinsing in distilled water and drying, heavy liquids were used to eliminate early crystallizing phenocrysts (olivine, pyroxene or plagioclase phenocrysts), and thus avoid any potential incorporation of inherited excess-argon. K was measured by flame emission spectroscopy, and compared with standards MDO-G and ISH-G (Gillot et al., 1992). Ar was measured with a mass spectrometer identical to the one described by Gillot and Cornette (1986). Owing to the stability of the analytical conditions, the mass spectrometer can perform highly reproducible ^{40}Ar measurements, thereby avoiding the need to deal only with ratios with the use a ^{38}Ar spike. For each analysis, the ^{40}Ar signal calibration is obtained from air-pipette measurements calibrated against the interlaboratory standard GL-O with the recommended value of 6.679×10^{14} at/g of ^{40}Ar* (Odin et al., 1982) and regularly checked with HD-B1 standard (see Germa et al., 2011 for a review). The correction of atmospheric contamination, also carried out after each sample analysis, is done by comparison of the ^{40}Ar/^{36}Ar ratio of the sample with an air-pipette measured in the same analytical conditions at strictly similar ^{40}Ar pressure. For a given ^{40}Ar signal, a reproducibility of better than 0.1% is observed for successive atmospheric ^{40}Ar/^{36}Ar measurements. Typical uncertainties of 1% are achieved for the ^{40}Ar signal calibration and for the K determination. The uncertainty on the ^{40}Ar* determination is a function of the radiogenic content of the sample, the detection limit of our system being presently of 0.1% of ^{40}Ar* (Quidelleur et al., 2001), corresponding to around 1 ka for a 1% K basaltic lava. Decay constants of Steiger and Jager (1977) were used. The K/Ar ages obtained in this study are reported in Table 1. Uncertainties are quoted at the 1σ confidence level.

The new ages range between 702 $\pm$ 10 ka and 23 $\pm$ 3 ka, with a K content between 1.063 and 4.128%, and a radiogenic argon content (^{40}Ar*) between 0.6 and 43.9%. These new ages are consistent but more precise than previous whole-rock K/Ar determinations (Féraud et al., 1980), and generally are comparable with the recent ^{40}Ar/^{39}Ar ages obtained by Larrea et al. (2014) on groundmass and mineral separates, except for one sample (see below). Our two samples on the west dipping upper lava flow of Serra dos Fontes yield strictly similar ages of 702 $\pm$ 10 ka (GR13G) and 700 $\pm$ 10 ka (GR13B). These are comparable with the age of 620 $\pm$ 120 ka obtained by Féraud et al. (1980) when uncertainties are accounted for, but significantly younger than the age of 1057 $\pm$ 28 ka obtained by Larrea et al. (2014) on the same succession.

Table 1
New K/Ar ages obtained with the unspiked Cassignol-Gillot technique on fresh separated groundmass and alkali feldspars (sample GR13E). For each sample, the mean age is obtained by weighing by the amount of radiogenic argon. The uncertainties are quoted at the 1σ level.

Sample material	UTM 26 E	UTM N	K%	40Ar* (%)	40Ar* (10^{11}at/g)	Age (ka)	Unc. (ka)
GR13G	412977	4323701	1.226	20.52%	8.951	699	10
Gdm				22.06%	9.040	706	10
						702	**10**
GR13B	411904	4324748	1.286	28.31%	9.311	693	10
Gdm				35.03%	9.477	705	10
						700	**10**
GR13F	411881	4319884	1.794	11.00%	8.918	476	8
Gdm				11.31%	8.765	468	8
						472	**8**
GR13N	412565	4320006	4.128	43.90%	19.654	456	7
Gdm				35.55%	19.555	454	7
						455	**7**
GR13O	412565	4320006	2.061	25.15%	9.829	457	7
Gdm				28.65%	9.926	461	7
						459	**7**
GR13Q	415117	4325069	1.063	14.82%	4.938	445	7
Gdm				16.76%	4.929	444	7
						444	**7**
GR13J	409146	4321678	1.776	10.75%	6.011	324	5
Gdm				4.05%	6.326	341	10
						329	**7**
GR13E	410339	4320458	3.603	40.11%	12.136	322	5
Feld				27.75%	12.160	323	5
						323	**5**
GR13K	409084	4321771	1.258	11.95%	3.884	296	5
Gdm				11.87%	3.982	303	5
						299	**5**
GR13M	412565	4320006	1.347	4.43%	3.023	215	6
Gdm				3.81%	3.002	213	6
						214	**6**
GR13A	416082	4320103	1.153	0.72%	0.492	41	6
Gdm				0.91%	0.569	47	5
						44	**5**
GR13P	412809	4319896	1.148	0.78%	0.273	23	3
Gdm				0.60%	0.277	23	4
						23	**3**

The bold data indicates the mean age for each sample.

The new ages measured on lava flows from the Baía do Filipe Complex range between 472 ± 8 ka and 455 ± 7 ka (samples GR13F and GR13N). The base of the Quitadouro cliff is dated at 444 ± 7 ka (sample GR13Q). These new results are comparable with the age of 434 ± 13 ka obtained by Larrea et al. (2014) on a lava collected between the two highest peaks of the island, in a small outcrop previously attributed to the intermediate complex (Fig. 2). The lavas from the Serra Dormida Complex are here dated between 329 ± 7 ka and 323 ± 5 ka. The samples collected at the base and top of the Basaltic Cover Complex are here dated between 299 ± 5 ka and 214 ± 6 ka (samples GR13K and GR13M, respectively), in agreement with an age of 270 ± 20 ka obtained by Féraud et al. (1980) on the same unit. Finally, the new ages measured on lava flows sampled at the SE elliptical volcano at the base of the caldera wall and the most recent lava flow range between 44 ± 5 ka and 23 ± 3 ka (samples GR13A and GR13P).

5. Discussion

5.1. Proposal of a new stratigraphy for the Graciosa Island

Based on the observed relationships between volcanic complexes and the new K/Ar data, we propose a new volcanic stratigraphy for the Graciosa Island (Fig. 9).

The late activity of the old volcanic stage is here constrained at around 700 ka from our two samples collected on the upper part of the succession exposed at Serra das Fontes. Therefore, we here coin it Serra das Fontes Complex. The older age obtained by Larrea et al. (2014) on their sample GRZF8 from the same succession may indicate that the earlier activity of this complex has not been sampled in the present study. However, the proximity between our sampling sites and the fact that no lava flow crops out in the lower parts of the SW Serra das Fontes scarp, renders this assumption improbable. In such circumstances, we cannot exclude that the age obtained by Larrea et al. (2014) on their sample GRZF8 is slightly over-estimated. On this sample, Larrea et al. (2014) obtained a very low K/Ca content of 0.0433, which is almost three times lower than for all their other samples (on groundmass). For such very low K/Ca, ^{36}Ar production from Ca during irradiation is significant, which renders the correction of atmospheric contamination delicate, and can bias the age.

The Serra das Fontes Complex is topographically truncated by two scarps oriented NNE-SSW and NW-SE, and no lavas dipping other than NNW were observed; therefore the original geometry of the older volcanic edifice is difficult to constrain. However, given the gentle slope of the still remaining lavas, we infer that it was a shield volcano.

Along the Baía do Filipe coastal cliff we observed three major unconformities that separate four complexes, instead of the two identified in the previous geological map (Gaspar and Queiroz, 1995):

1. At the base, we identified the new Baía do Filipe Complex. The age of the Baía do Filipe Complex is here bracketed between, at least 472 ± 8 ka and 434 ± 13 ka (this work and Larrea et al., 2014, respectively). Given that the lavas generally dip to the E, and Larrea et al.'s (2014) sample was collected to the E of our sample, it is stratigraphically logical that the age reported here is older. This temporal and spatial relationship between the two samples also means that no major faulting (tectonic or gravitational) occurred between the two outcrops since ca. 434 ka ± 13 ka. Therefore, it suggests that there is no major recent graben in the middle of the island, between Serra das Fontes and Serra Dormida, as proposed by Gaspar and Queiroz (1995) and Gaspar (1996). Our sample GR13Q collected at the base of the Quitadouro cliff and here dated at 444 ± 7 ka is topographically below the rock here dated at ca. 700 ka (Fig. 9). It is also located to the east of the NNW-dipping 700 ka flows, and therefore corresponds to lava flows unconformably overlying the Serra das Fontes Complex. The similar ages between GR13Q and the Baía do Filipe Complex allow linking one to the other. Considering together the location of the outcrops and the age obtained at Quitadouro sea cliff (ca. 444 ka), we infer that the Baía do Filipe Complex was built in two different ways: in the SW, as a main volcano (formerly offshore and currently destroyed), and in the NE unconformably over the subaerial eastern flank of the Serra das Fontes unit, as a secondary volcanic edifice. The eruptions were initially effusive and produced basaltic lava flows, and later more evolved trachytic lavas. The new ages here reported thus suggest that the differentiation in the magma chamber of the Baía do Filipe Complex, from basalt (GR13F) to trachyte rocks (GR13N), occurred over a maximal period of 30 kyr (between 472 ± 8 ka and 458 ± 7 ka), in the hypothesis of a single magma chamber.
2. The Serra Dormida Complex unconformably covers the Baía do Filipe Complex (Fig. 7), and is separated from the uppermost trachyte lava by ca. 100 ka. Indeed, we constrain the Serra Dormida Complex activity around 325 ka (329 ± 7 ka at the base and 323 ± 5 ka at the top). The ages are very similar, which indicates that either the edification of the Serra Dormida Complex was very fast, or there is a great deal of rocks missing. This complex comprises differentiated trachytic flows, pyroclasts and massive ignimbrites. The latter eruptions were thus mostly explosive, probably of sub-plinian type. This unit is the equivalent of the Serra Branca Complex of Gaspar and Queiroz (1995).
3. Previous studies proposed that the younger phases of volcanic activity in Graciosa could be separated into two distinct geographic areas, but they are stratigraphically not distinguished in the geological map: (1) a Basaltic Cover (Unidade de Vitória) constructed from

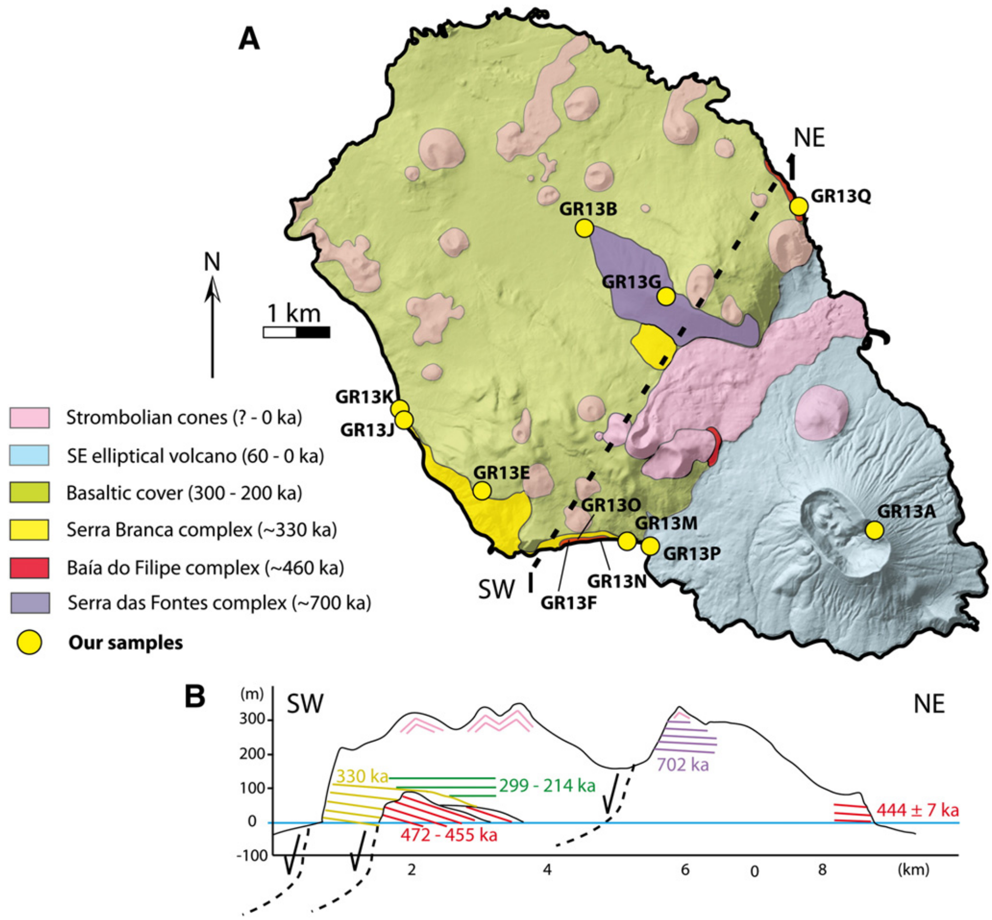

Fig. 9. (A) Main stratigraphic units distinguished in this work, with the location of our samples. Notice that we attributed the lenticular outcrop in the middle of the island as the Baía do Filipe complex, based on the ages of Larrea et al. (2014). (B) Schematic cross section summarizing our field observations and our new K/Ar ages.

monogenetic cones covering both Serra das Fontes and Serra Dormida, and making up the NW platform; and (2) a central-type volcano located in the SE end of the island. From our new dating, we propose that this separation is not only geographic but also chronologic. Here we constrain the Basaltic Cover on the southwestern part of the island between 299 ± 5 ka and 214 ± 6 ka (samples GR13K and GR13M, respectively). The new ages of 44 ± 5 ka and 23 ± 3 ka obtained on our samples GR13A and GR13P provide temporal constraints on the effusive volcanic activity of the SE central-type volcano. Further South, similar young flows are unconformably overlying the Basaltic cover at Baía do Filipe. Therefore, the activity of the SE central-type volcano cannot be related to the activity of the Basaltic Cover Complex (gap > 150 ka). Accordingly, we separated the former Vitória and Vulcão Central complexes into two distinct complexes, the Basaltic Cover and the SE Central-type Volcano complexes. Moreover, the younger eruptions from the young strombolian cones marked on our new stratigraphic map (Fig. 9) have yielded similar ages, or are even younger than the SE Central-type Volcano (Larrea et al., 2014). Therefore, we also separated them from the Basaltic Cover.

To conclude, based on major observed unconformities and new isotopic dating, we propose that the Graciosa Island comprises 6 well-individualized volcano-stratigraphic units (Fig. 9).

5.2. Repeated destruction of Graciosa: tectonic faulting or gravitational collapse?

The field observations and stratigraphic relationships are summarized in Fig. 9. They reveal that the remnants of the Serra das Fontes, Baía do Filipe and Serra Dormida are mostly composed of lava flows dipping to the NNW, E and NE, respectively. This means that the western flank, the summit and part of the eastern flank of these volcanic edifices are missing. The analysis of the DEM reveals that the lavas are truncated by a scarp and by a sea cliff in the SW, in Serra das Fontes and Serra Dormida, respectively, and a NNE-SSW scarp in Serra das Fontes. Moreover, field observation reveals that the Baía do Filipe Complex is truncated by a major scarp in the west, and topped by a major unconformity. We infer that these discontinuities comprise the scars of destruction affecting the Serra das Fontes Complex, the Baía do Filipe Complex, and then the Serra Dormida Complex and the Basaltic Cover. Therefore, the questions are: (1) what is the nature of dismantling? Is it tectonics via faults, or gravitational via major flank collapses? (2) What are the ages of the destruction processes?

5.2.1. The NNE-SSW scarp in Serra das Fontes

From the gentle NNW dip of the lava flows of the Serra das Fontes Complex, we infer that they are part of a shield volcano, whose summit and southern flank do not exist anymore. Instead of the SE dipping lava flows expected south of the scarp, the missing old volcano is presently occupied by the young SE central-type volcano. In between the two volcanoes, a clear NNE-SSW scarp is visible (Fig. 5). Although the difference in age between the lavas of the older and the younger volcanoes (ca. 640 kyr) is possibly enough for normal erosion (rain and wave erosion) to remove the large amounts of lava flows missing in the older complex, such a linear scarp is unlikely to result solely from protracted erosion. An alternative is that most of the older volcano has been removed by a large-scale catastrophic event, in the form of a giant sector collapse. Indeed, the NNE-SSW scar is also visible on the available bathymetry (red dashed lines in Fig. 4), which indicates that this structure is bigger than the scale of the present island. Moreover, the irregular topography in steps on the SE submarine flank of Graciosa (white dashed circle in Figs. 3 and 4) and the abnormal high bottom of the basin further east (cross sections Fig. 4) can be interpreted as a large debris deposit.

The current NNE-SSW strike of the scarp is almost perpendicular to the main orientation of the TR; therefore, the flank collapse suggested here cannot be directly linked to the tectonic activity of the normal faults of the rift. It can, however, be linked to faults along the transform direction associated with the TR (Marques et al., 2014b), which is close to NE-SW in Graciosa (DeMets et al., 2010). The flank collapse created a scar that was later filled by the SE Central-type Volcano. From our K/Ar dating, previous ages, and our new field observations, the Quitadouro lavas cascade over the scarp. Some of them have been dated at 96 ± 32 ka (Larrea et al., 2014), which gives a minimum age to the flank collapse. Taking into consideration the location of the Baía do Filipe Complex outcrops on both the northern and southern coastal cliffs and inside the island (Fig. 9a), we infer that the eastern part of this complex was removed, which gives a maximum age of ca. 450 ka to the major SE-directed flank collapse here proposed.

5.2.2. The NW-SE scarp in Serra das Fontes

According to previous studies (Fig. 2), Graciosa comprises a central graben that affects all volcanic complexes (Gaspar and Queiroz, 1995; Gaspar, 1996). A topographic section across this proposed graben (Figs. 4, 5 and 9) shows two asymmetric topographic highs, with a steep slope facing SW and a gentle slope facing NE. This morphology is not consistent with what would be expected for a graben. Furthermore, the new ages and spatial distribution of the Baía do Filipe Complex indicate that there is no major graben developed in central Graciosa after ca. 434 ± 13 ka. We thus conclude that there is no graben, but we do not exclude, at this stage of the discussion, the existence of an older half-graben.

From the bathymetry and the topographic section across the rift, it is clear that Graciosa is asymmetrically located inside the TR, because the northwesternmost part of the island sits on top of the northern shoulder of the active TR. This means that: (1) possible flank collapses towards the SW (along NW-SE failures) may be arrested by the southern wall of the TR (Figs. 1, 3, 4 and 5); (2) the dismantling of the successive volcanoes towards the SW may have been triggered by normal fault displacement at the TR's northern wall.

Given that the TR is active, we need to determine if displacement along the faults inferred from scarps is compatible with the ages and known plate kinematics, in order to ascribe the scarps to a tectonic or gravitational origin. The major scarps show two main orientations, NE-SW and NW-SE, which we will discuss separately:

1. Regarding the NE-SW scarp, the tectonic vertical displacement is negligible because the transform faults with this direction are pure strike-slip (Marques et al., 2014b). Relevant to this discussion is the existence of conspicuous NE-SW alignments of strombolian cones in NW Graciosa (cf. Fig. 5), and the measured trend of dykes, which is also close to NE-SW on average. Therefore, if such a fault exists, it may have triggered a large-scale, earthquake-driven, landslide, but it cannot by itself be responsible for the displacement necessary to remove the summit and the SE flank of the Serra das Fontes volcano.
2. Regarding the NW-SE scarp, it could be a normal fault of tectonic or gravitational origin; therefore, we have to discuss displacement rates and ages. Graciosa sits in the western half of the TR, where the Nubia/Eurasia plate boundary is diffuse (Marques et al., 2013a, 2014a). Therefore, the ca. 4 mm/yr rifting is not all taken up by the TR, and Marques et al. (2013a, 2014a) estimated that the TR is most likely opening only ca. 2.4 mm/yr in the diffuse region. Once we are discussing the TR's northern wall only, the half opening is 1.2 mm/yr. However, at the longitude of Graciosa, the TR is ca. N110° in azimuth, i.e. it is significantly oblique to maximum extension (ca. N60°, DeMets et al., 2010), which implies that the orthogonal opening is $1.2\cos30° = 1$ mm/yr, using conservative values (not the actual 40°). If the whole half opening were taken up by only pure normal faulting (northern TR bounding fault), it would imply that the pure normal fault had an average vertical displacement ($1.0 \times \tan60°$) of ca. 1.7 mm/yr. If the 1.2 mm/yr half opening were taken up by two pure normal faults with similar displacement, then the average rate of vertical displacement on each pure normal fault would be ca. 0.85 mm/yr. However, the ca. N110° wall of the TR is significantly oblique to maximum extension, which means that the vertical component has to be shared with a horizontal component, and therefore the ca. 0.85 mm/yr is overestimated. Given such low tectonic rates of vertical displacement, it is most unlikely that the observed scarps and displacements of the main volcanic complexes can be due to tectonics alone. Finally, but most importantly, the possible normal faults we are discussing are located to the S of the actual TR's northern wall, actually closer to the centre of the TR. The topographic profile (Fig. 4c top panel) shows evidence of only one master fault bounding the TR in the north, and no evidence of major faults in the flat bottom. Therefore, it is not likely that the possible normal faults dismantling the three main volcanic edifices are directly related to the TR's northern wall.

The contact between the Serra das Fontes Complex and the younger Baía do Filipe Complex was not directly observed (Fig. 9). Nevertheless, most of the Baía do Filipe Complex grew to the SW of the Serra das Fontes Complex, and the new ages indicate an inverted stratigraphy, if no major erosion or displacement (tectonic or collapse) is considered: the Baía do Filipe rocks (~470 ka, close to sea level) are at much lower altitude than the Serra das Fontes rocks (~700 ka, 350 m altitude) (Fig. 9). Moreover, the lava flows of both complexes dip to the N, which, in the absence of faults or major erosion, puts the younger rocks in the SW below the older rocks in the NE. From the gentle NNW dip of the lava flows of the Serra das Fontes Complex, we infer that the Serra das Fontes main edifice could not exist, as a whole, when the Baía do Filipe Complex was active. If the vertical displacement were due to a normal fault, it would have to be significantly greater than 350 m, because we do not know the top of the older Serra das Fontes Complex, and the base of the younger Baía do Filipe Complex. A simple calculation (400 m divided by 200 000 years) gives an average 2 mm/yr of downward displacement, which is much greater than the tectonic vertical displacement estimated above.

Typically, fault scarps are straight along strike, and flank collapse scarps show a horseshoe shape (e.g. Ownby et al., 2007; Tibaldi et al., 2008; Karaoglu and Helvaci, 2012). Therefore we have to discuss the observed shapes. The current NW-SE scarp does not show a straight linear shape or a curved shape concave towards the SW. From field observation, it is clear that the scarp is almost exclusively composed of rounded debris blocks, which are covered by a dense forest where the trees show vertical trunks, i.e. there is no evidence for current movement rotating the trees. This indicates that the scarp is old, significantly retreated, and currently inactive; therefore if any active fault existed, it should crop out to the SW, where it has not been observed and is not expected from the new ages and volcanic unit spatial distribution. On the geological map of Gaspar and Queiroz (1995), some faults are inferred from the NW-SE alignment of a few strombolian cones. However, neither these cones nor their volcanic basement (even the oldest) show evidence for significant recent vertical movement, which would be expected if the present topography was the result of still active major normal faults. Instead, we propose that the NW-SE scarp making up Serra das Fontes is most probably an old scar of a main flank collapse that occurred between 700 and 472 ka (youngest age of the Serra das Fontes Complex, and oldest age of the Baía do Filipe Complex, respectively). The Baía do Filipe Complex filled the SW depression created by the flank collapse of the Serra das Fontes volcano, like in most flank collapses in volcanic islands (Hildenbrand et al., 2006; Quidelleur et al., 2008; Samper et al., 2008; Boulesteix et al., 2012; Jicha et al., 2012).

5.2.3. The scarp bounding the Baía do Filipe Complex in the west

The lavas making up the Baía do Filipe Complex, here dated between 472 ± 8 ka and 455 ± 7 ka, dip to the ENE and are truncated in the west by a steep scarp. Therefore, most of the initial volcano is missing: the whole southwest flank, the summit, and part of the northeast flank (Figs. 7 and 10). The younger Serra Dormida Complex, here dated around 330 ka, sits unconformably on the Baía do Filipe Complex, which means that major dismantling of the Baía do Filipe Complex occurred after ca. 450 ka and prior to ca. 330 ka. Such major destruction may have occurred either by normal faulting or gravitational collapse, Given that the TR is active, we would expect to see a normal fault propagating upwards into the Serra Dormida Complex, if dismantling were due to vertical tectonic displacement associated with the activity of the TR. However, no major fault has been observed upward in the more recent units (cf. Figs. 7 and 10), which means that the fault (tectonic or gravitational) has been inactive during at least the last 330 kyr. The steep scarp at Baía do Filipe lies in the southwesternmost part of the island. This is close to the centre of the TR, where no tectonic faults are observed on the flat bottom, and already far from the TR's northern wall. In the context of an active rift like the TR, it is therefore difficult to attribute the missing part of the Baía do Filipe Complex to a tectonic normal fault. Instead we infer that the observed scarp is the result of an instantaneous event like a flank collapse. Therefore, the differentiated pyroclastic eruptions from the Serra Dormida Complex could have been triggered by the sector collapse through depressurization of an underlying differentiated magmatic chamber (e.g. Manconi et al., 2009; Boulesteix et al., 2012).

To conclude, we propose that the steep western scarp in Baía do Filipe Complex is an old scarp of a flank collapse, which occurred between ca. 450 ka and 330 ka, the youngest age of the Baía do Filipe Complex and the oldest age of the Serra Dormida Complex, respectively.

5.2.4. The NW-SE sea cliff of Serra Dormida

The Serra Dormida Complex and the Basaltic Cover Complexes are abruptly truncated by the coastal cliff, and both show lava flows generally dipping towards the NE (Figs. 8, 10 and A2). If we assume that the Serra Dormida volcano had a former typical conical shape, then the whole southwest flank, the summit and part of the northeast flank are missing. We note that both the Serra Dormida Complex and most of the Basaltic Cover developed in a previous flank collapse depression (dismantling of the Baía do Filipe and Serra das Fontes edifices). They thus settled in a weakened and probably unstable sector, which may have served as a main structure for subsequent gravitational destabilization. In such circumstances, the younger Serra Dormida and Basaltic Cover complexes may have also been affected by a lateral flank collapse towards the SW.

Bathymetric and geophysical data, even at low-resolution, are important to detect and better constrain the first-order characteristics of debris fields generated by large flank instabilities (e.g. Deplus et al., 2001; Masson et al., 2008; Costa et al., 2014). Directly southwest of Graciosa, the voluminous bathymetric platform (Figs. 3 and 4, and cross section Fig. 5) is associated with a positive gravity anomaly (Fig. 4). This could be interpreted as (1) a remnant volcanic basement of the island, apparently much more developed in the SW than in the NE, (2) a relief created by downward displacement of Graciosa's southern flank by normal faulting associated with the tectonics of the TR, or (3) the presence of material (either debris or recent volcanism) accumulated in the southwest in response to major sector collapses. In the first hypothesis, the flat submarine relief in the SW would represent an old volcanic edifice, which would have experienced significant subsidence and marine abrasion. However, the new age data do not support such a hypothesis, as the main volcanic complexes here dated are globally younger in the S and SW than in the N and NW. Hypothesis 2 would imply the existence of several faults successively developed towards the S. Each would affect/dismantle a given volcanic complex and then become inactive, whilst a new volcanic complex built to the south, and a new set of faults would appear southward and affect/dismantle it without affecting the previous volcanic complex(es). This seems improbable, because each fault would then have been active over a limited period of time, down to only a few tens of kyr, which appears rather short in the context of an active rift. Last but not least, successive jumps of faulting preferentially to the south are inconsistent with the overall morphology of the TR, which typically shows a flat bottom bounded by one or two master faults. Therefore, the hypothesis of several major flank collapses is the most likely in the light of the new data and the tectonic setting. The southern shoulder of the TR is close to the island, which may have reduced the dispersion of potential debris and led to buttressing of the deposits at the base of the TR's southern wall. The depth of the rift in this area is 300 m less than in the neighbouring SE basin. From this

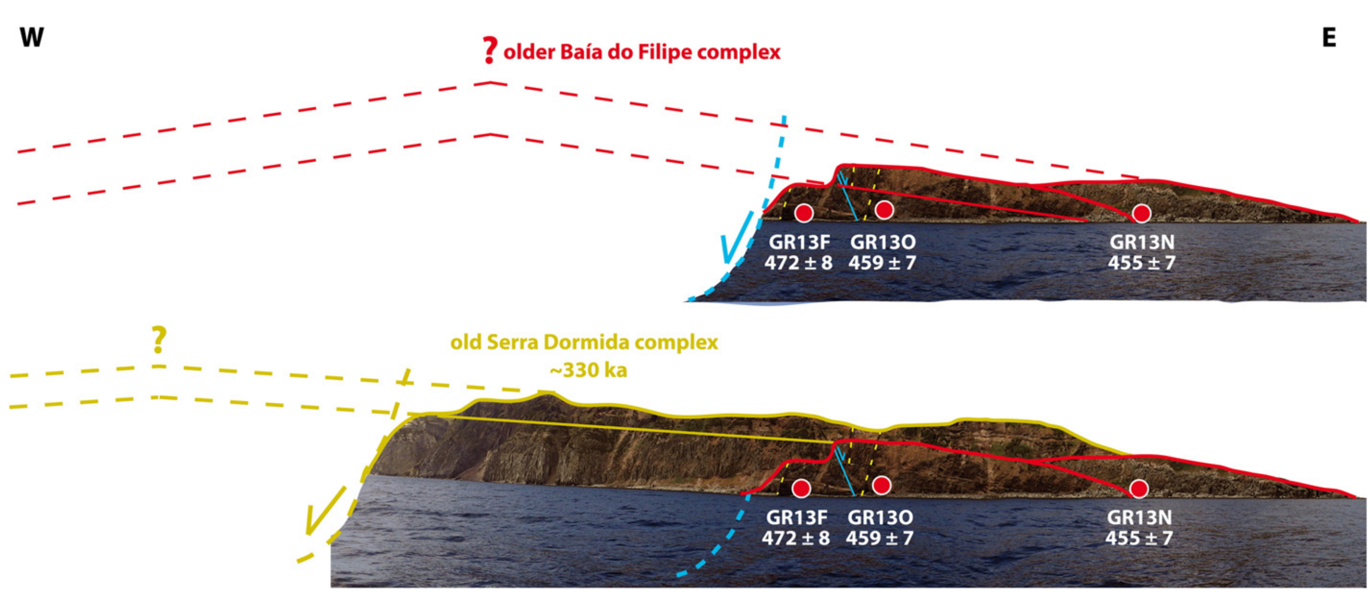

Fig. 10. Proposed evolution of the Baía do Filipe and Serra Dormida complexes along the E-W sea cliff at Baía do Filipe. The circles show the location of our samples and the new K/Ar ages (in ka). The location of the coastal cliff is show in Fig. 2.

observation, it seems reasonable to infer that the Serra Dormida Complex and a part of the Basaltic Cover have probably been affected by a flank collapse since 214 ± 6 ka, the youngest age of the Basaltic Cover in the Serra Dormida area.

The evidence presented here of major landsliding in Graciosa is consistent with previous work in the Azores by Hildenbrand et al. (2012a) and Costa et al. (2014), and work in progress (Marques et al., 2013b) and (Sibrant et al., 2013), who have found onshore and offshore evidence of major landslides in Pico, Santa Maria and S. Miguel islands.

6. Conclusions

Based on morphological analyses, stratigraphic and tectonic observations, and new geochronological data, we propose a new view of the geological evolution of the Graciosa Island. The island emerged and grew thanks to short and repeated volcanic construction punctuated by major flank collapses. The evidence encompasses the establishment of a volcanic stratigraphy (with special attention to the nature and geometry of the contacts between main volcanic complexes), the recognition of the geometry of the main volcanic successions, and the identification of landslide scars. Despite the position of the Graciosa Island partly along the northern shoulder of the TR, we conclude that the several destruction stages did not involve slow and gradual faulting linked to the tectonic activity of the rift, but in contrasts occurred through sudden and most probably catastrophic lateral flank collapses. However, we cannot exclude that such repeated destabilization episodes may have been triggered by major earthquakes.

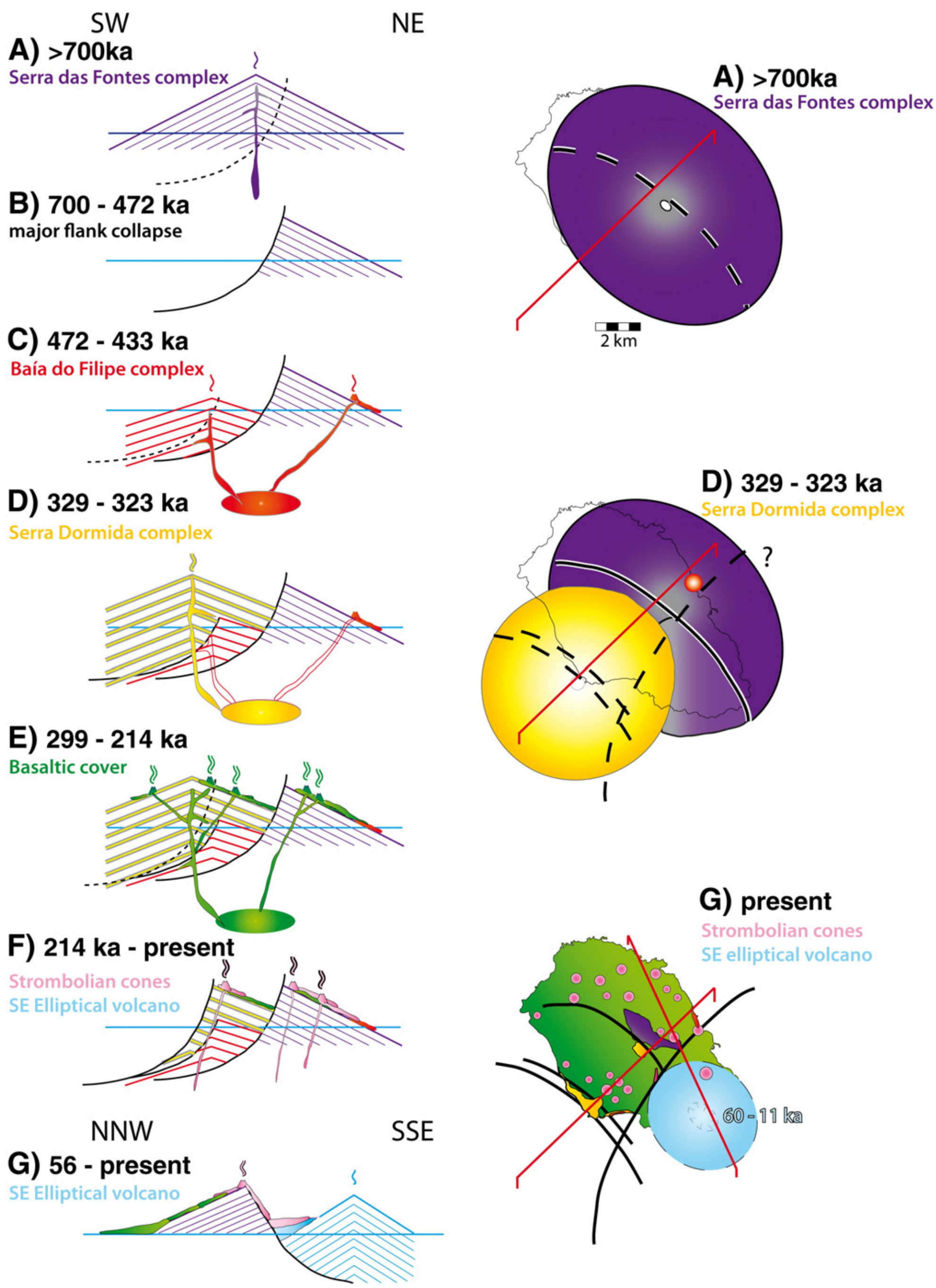

Fig. 11. New schematic morphostructural evolution of the Graciosa Island.

Before 700 ka, a volcano emerged to form the Graciosa Island (Fig. 11). A sudden catastrophic event towards the SW removed the SW flank, the summit and part of the NE flank of this older volcanic edifice (Serra das Fontes), between 700 ka and at least 472 ka. Then, a new basaltic edifice here called the Baía do Filipe Complex grew rapidly in the depression left by the flank collapse, until ca. 433 ka. This edifice was subsequently affected by a flank collapse towards the SW that only spared the eastern flank of the edifice. At ca. 330 ka, a new, differentiated, volcano (Serra Dormida Complex) was growing very rapidly in the depression left by the second flank collapse. The Serra Dormida Complex was then unconformably covered by the Basaltic Cover Complex between ca. 300 ka and 200 ka. Both were most probably affected by a flank collapse, which removed the western flank, the summit and part of the eastern flank of these complexes, and controlled the current shape of the island in the SW. More recently, the island was affected by a new flank collapse towards the SE, and the resulting depression was filled by the SE Central-type Volcano. The present day topography of Graciosa shows several very well preserved strombolian cones, recently built unconformably on top of the older volcanic units (probably during the last 30 ka).

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