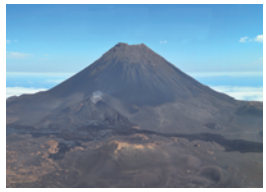
Feature



Volcanic and structural evolution of Pico do Fogo, Cape Verde

In recent months the media have drawn attention to the Cape Verde archipelago, with particular focus on the island of Fogo, the only island presently active and with an eruption that began on 23 November 2014, finally ceasing on 7 February 2015. The Monte Amarelo conical shield forms most of the 476 km^2 almost circular island of Fogo. After attaining a critical elevation of about 3500 m, the Monte Amarelo shield volcano was decapitated by a giant landslide that formed a caldera-like depression (Cha das Caldeiras), which was subsequently partially filled by basaltic nested volcanism. This younger eruptive activity culminated in the construction of the 2829 m-high Pico do Fogo stratocone, apparently entirely made of layers of basaltic lapilli. Continued growth of the Pico do Fogo summit eruptions was interrupted in 1750, most likely after the stratocone reached a critical height. Since then, at least eight eruptions have taken place inside the landslide depression at the periphery of the Pico do Fogo cone, including the 2014–2015 eruptive event. Strong geological similarities with the Canary Islands, 1400 km to the north, have been frequently noted, probably as a consequence of a common process of origin and evolution associated with a mantle hot-spot. These similarities are particularly evident when comparing Fogo with the Teide Volcanic Complex on Tenerife, where a lateral collapse of the Las Cañadas stratovolcano also formed a large depression (the Caldera de Las Cañadas), now partially filled with the 3718 m-high Teide stratocone. However, important geological differences also exist and probably relate to the contrasting evolutionary stages of both islands. The Las Cañadas volcano on Tenerife formed at a late post-erosional stage, with predominantly evolved (trachyte and phonolite) magmas, while at Fogo basaltic volcanism is still dominant.

Juan-Carlos Carracedo[1], Francisco J. Perez-Torrado[1], Alejandro Rodriguez-Gonzalez[1], Raphaël Paris[2], Valentin R. Troll[3] & Abigail K. Barker[3]

[1]University of Las Palmas de Gran Canaria, Dept. of Physics (GEOVOL), Las Palmas de Gran Canaria, Spain
jcarracedo@proyinves.ulpgc.es
[2]Université Blaise Pascal Clermont-Ferrand II, France
[3]Uppsala University, Department of Earth Sciences, Centre for Experimental Mineralogy, Petrology and Geochemistry (CEMPEG), Uppsala, Sweden.

East of the Mid-Atlantic Ridge, the Central Atlantic Ocean is host to several archipelagos of oceanic islands and seamounts, some of the latter developed over 143 Ma ago, in the early stages of the opening of the Atlantic Ocean. The Cape Verde Islands form, together with the Canaries, Madeira and the Azores, the Macaronesian archipelagos, a term derived from the Greek expression of the 'islands of the fortunate'. All of these islands are volcanic in origin and thought to be the product of several active hotspots (Fig. 1; see other articles in this special issue of *Geology Today*).

While all the Macaronesian archipelagos are considered to be the result of magmatism generated by ascending mantle plumes under a gradually moving Atlantic plate, they show contrasting features. For example, the Canaries and Madeira show a relatively linear alignment and a consistent age progression, which is not present in the Azores, where the hotspot coincides with regional fractures that obscure an age progression. The Cape Verde Islands show an

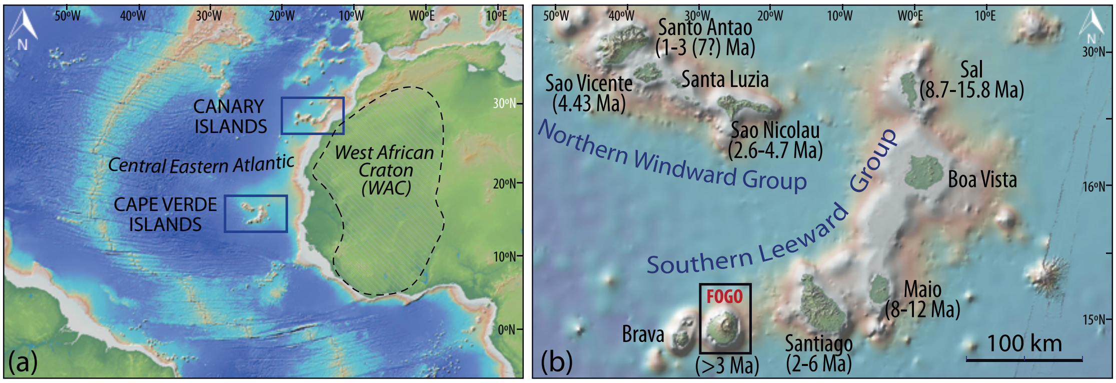


Fig. 1. Volcanic archipelagos and seamounts of the Central Eastern Atlantic. **a.** The Canaries and Cape Verde archipelagos lie close to the West African Craton (WAC), a plausible scenario for edge-driven convection. **b.** The Cape Verde Islands form two distinct lineations, the northern (Windward) and the southern (Leeward) islands. The ages are from the shield stage of each island (compiled in Holm *et al.*, 2008). The maps were created using GeoMapApp (http://www.geomapapp.org).

apparent age progression, but split into two distinct island chains: the southern (Leeward) and northern (Windward) islands (Fig. 1B). These islands lie on a broad bathymetric anomaly, the Cape Verde Rise, in excess of 2000 m above the expected depth for the age of the local oceanic crust, and so forms the largest bathymetric anomaly in the world's oceans. The Cape Verde archipelago nevertheless shows significant gravimetric, geoid and thermal anomalies, which are characteristic of a mantle plume. Similar to the Canary Islands, finite-frequency tomographic images of low S-wave velocity confirm the existence of the Cape Verde Island's mantle plume, extending down to 2800 km (see Troll and others, this issue).

The Cape Verde Islands and the island of Fogo

The Cape Verde archipelago is a group of volcanic islands located 450–600 km off West Africa, approximately opposite the Cape Verde promontory in Senegal, from which they take their name (Fig. 1A). The Cape Verde Islands probably started to form in the Oligocene/Miocene and continued through the Holocene. The archipelago was discovered in 1460 AD by Portuguese sailors exploring the west coast of Africa. Since their discovery, historical eruptions in Cape Verde have been confined exclusively to the island of Fogo, the youngest and also the only volcanically active island of the Cape Verde archipelago, lying near the western end of the southern island chain (see Fig. 1B). Only the island of Brava is located further west, but the exposed volcanic rocks there are notably older than those on Fogo (see Figs 1B, 2A).

The island of Fogo rises nearly 6 km from the sea floor to 2829 m above sea level at Pico do Fogo, the highest elevation on the island (Fig. 2A). Fogo, 27 km in diameter, is a spectacular example of a single shield oceanic island, contrary to the majority of this type of volcano that generally forms from several coalescent shields (e.g. Tenerife, El Hierro, Fuerteventura, Hawaii). The reason is that the Fogo volcano is still in the main shield-building stage of growth, and erosive features remain rare or incipient.

Prior to volcanism at Pico do Fogo, the Monte Amarelo conical shield volcano formed most of the 476 km^2 almost circular island of Fogo. After attaining a critical elevation of about 3500 m, the Monte Amarelo shield volcano was decapitated by a giant landslide that formed a caldera-like depression (Cha das Caldeiras) and was subsequently re-filled by basaltic nested volcanism. A giant landslide producing the lateral collapse caldera and the subsequently nested Pico do Fogo stratovolcano (Fig. 2b), was found by multibeam bathymetry studies that showed landslide debris deposits to the east of the island (Fig. 2a). Eruptive activity inside the

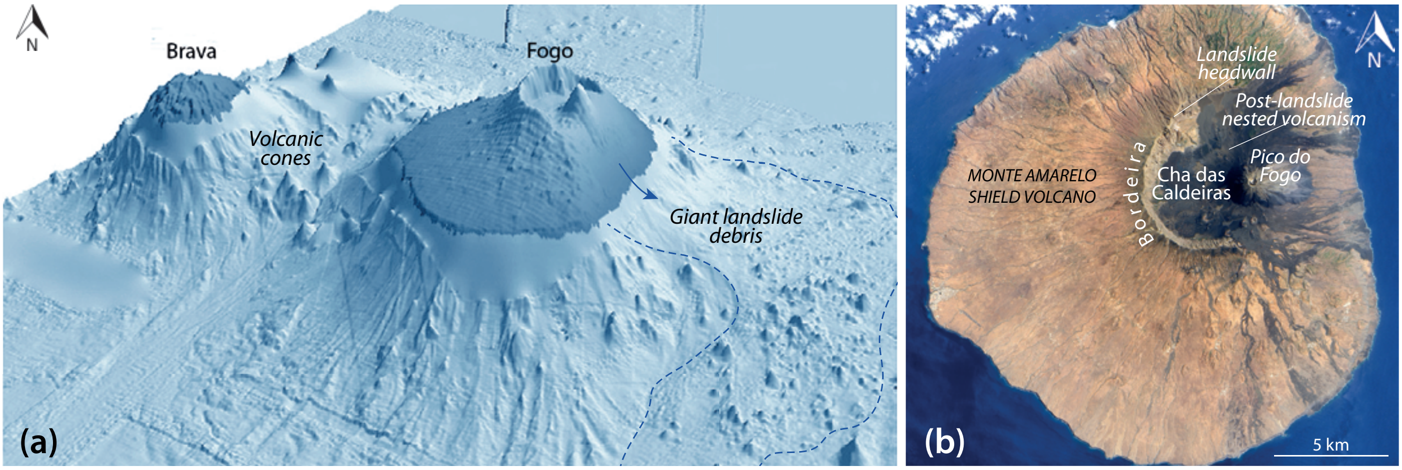


Fig. 2. **a.** Topographic and bathymetric three-dimensional model of Fogo and Brava islands. East of Fogo, the debris avalanche deposit of the prehistoric giant landslide is clearly visible (from Masson *et al.*, 2008). **b.** Satellite view of Fogo (NASA). The Cha das Caldeiras at the centre of the island represents the scar of the prehistoric, East directed giant lateral collapse of the Monte Amarelo shield, partly filled with nested volcanism that also constructed the Pico do Fogo stratocone.

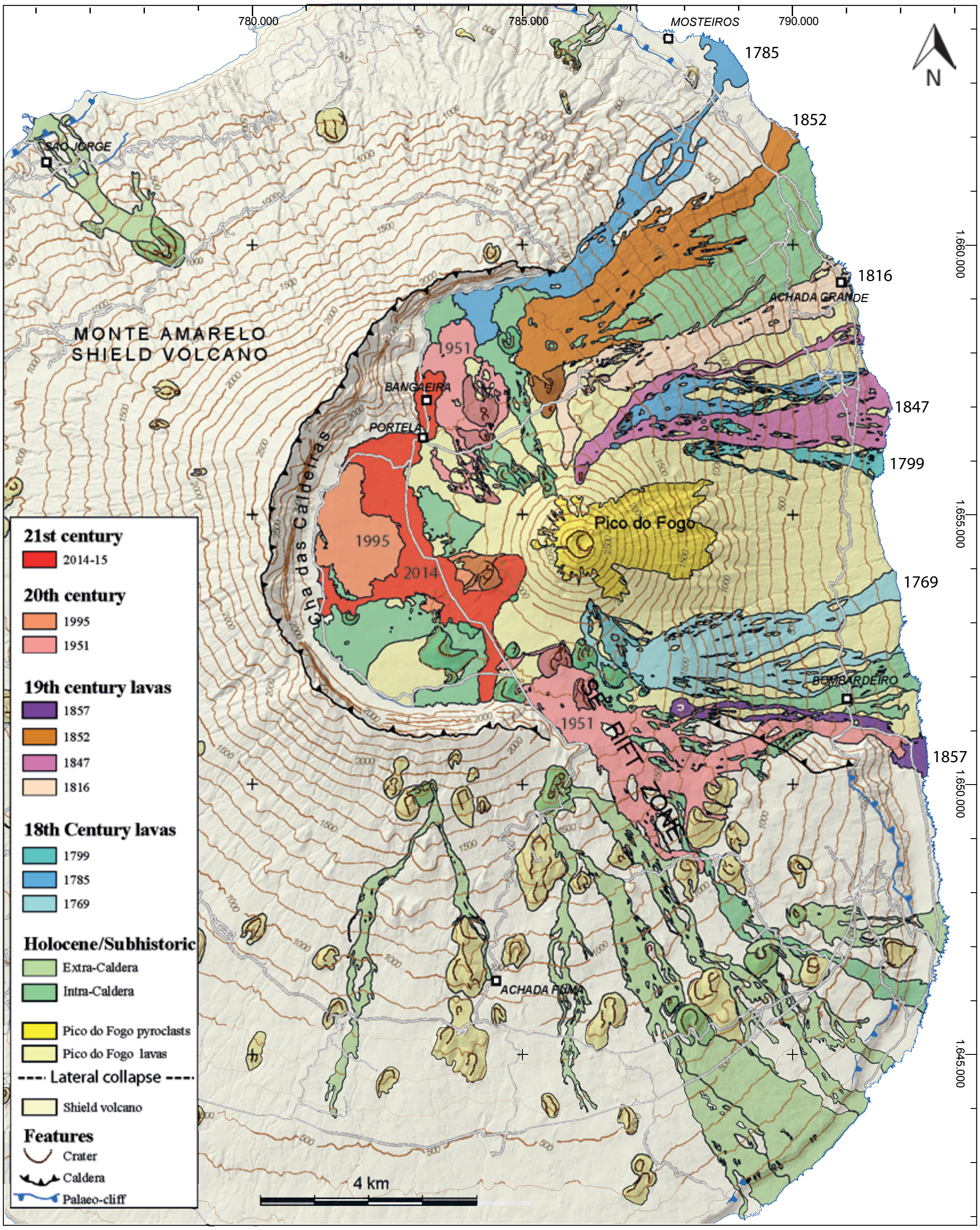
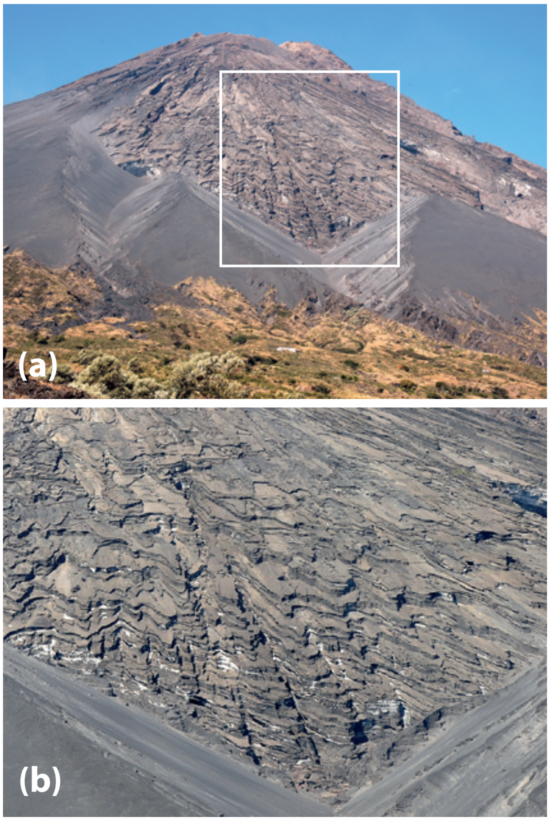


Fig. 3. Geological map of the island of Fogo, Cape Verde. The map shows a single, conical shield volcano, decapitated by an eastbound giant landslide that formed a caldera-like depression (Cha das Caldeiras). This depression was subsequently filled by mafic volcanism. Note that apart from some prehistoric eruptions that were mostly located on the southern flank of the shield volcano (Monte Amarelo), the recent volcanism is concentrated inside the collapse embayment, first as a nested central volcano (Pico do Fogo), and now producing satellite eruptions around the main stratocone (modified from Torres *et al.*, 1998).

landslide depression culminated in the construction of the 2829-m high Pico do Fogo stratocone, apparently entirely made of layers of basaltic lapilli. The growth of Pico do Fogo was, however, interrupted in 1750, after the stratocone reached a critical height. Since then, at least eight eruptions have taken place inside the landslide depression, i.e. at the periphery of Fogo volcano, including the 2014–2015 eruptive event.

The Cape Verde Archipelago, a former colony of Portugal from 1460 AD until the independence of the Cape Verde Republic in 1975, hosts a population of about 450 000 (Fig. 3). The latest eruption on Fogo, from November 2014 to February 2015 (see Worsley, in this issue), posed a significant risk for the island's population (55 000 inhabitants), particularly for the towns inside the Cha das Caldeiras, whereas previous eruptions have also threatened the eastern flank of the island.

Fig. 4. **a.** View of the eastern flank of Pico do Fogo stratocone. The entire ~1000-m-high cone seems to be made of layers of basaltic pyroclasts. **b.** Close-up view of Pico do Fogo's pyroclastic layers.



Volcanic history and structure of Fogo

The main volcanological and geomorphological elements of Fogo Island are outlined in Figs 2B and 3. A near circular basaltic shield volcano (Monte Amarelo), with the summit decapitated to form a 9-km-wide landslide caldera (Cha das Caldeiras), partially filled with nested volcanism forming a central basaltic stratocone that is encircled by peripheral basaltic eruptive vents. Recent (Holocene) extra-caldera eruptions are associated with three poorly defined vent alignments or rift zones in the NW, NE and SE (Fig. 3).

A lateral collapse origin for the Cha das Caldeiras caldera scar is supported by the absence of the expected eastern wall of the caldera, and by submarine landslide debris deposits east of the island (Fig. 2A), but also by the tsunami deposits observed on the island of Santiago, thought to relate to the Fogo giant landslide. In fact, pre-collapse lava flows have been dated by ^{3}He exposure chronology to 123.0 ± 5.2 ka, consistent with a U-Th age of 123.6 ± 3.9 ka from corals in the tsunami deposits on the island of Santiago. Post-collapse lava flows from the rim of the Cha das Caldeiras collapse scar ranged between 86 and 11 ka, which therefore constrains the Fogo lateral collapse to between 123 and 86 ka. Older carbonatite suites on Fogo island have been dated by K-Ar methods to 5.1 to 3.2 Ma.

Post-collapse nested volcanism

Following the lateral collapse, volcanism progressively increased inside the collapse scar. A stratocone, the Pico do Fogo, which is entirely constructed of layers of basaltic lapilli, arose in the centre of the caldera (Fig. 4). Prior to the landslide collapse, Fogo's magma plumbing system evolved towards shallower fractionation levels, but it seems this development was halted by the lateral collapse. Several eruptions from the summit crater of Pico do Fogo have been reported since the arrival of the first Portuguese settlers, up to 1785. From this time, eruptive activity ceased in the crater area and shifted to fissure-fed basaltic vents in the periphery of the stratocone (Fig. 3).

Although some pre-historic eruptions occurred outside the caldera, mainly on the south-east rift zones, lava flows from the majority of post-collapse eruptions are, however, confined to the collapse scar (Fig. 3). The historical eruptive vents, in turn, are consistently located inside the collapse scar, with only two of these eruptions (1785 and 1951) emitting lava flows that have run over the caldera rim. A notable

Fig. 5. **a.** Volcanic features forming the Teide Volcanic Complex (Tenerife): **1.** main stratocones (Teide and Pico Viejo); **2.** partially filled landslide depression; **3.** rift zones (NW and NE); **4.** pre-collapse Las Cañadas Volcano (LCV) (from Carracedo & Troll, 2013). **b.** Similar volcanic features on the island of Fogo, following a broadly similar geometrical arrangement.

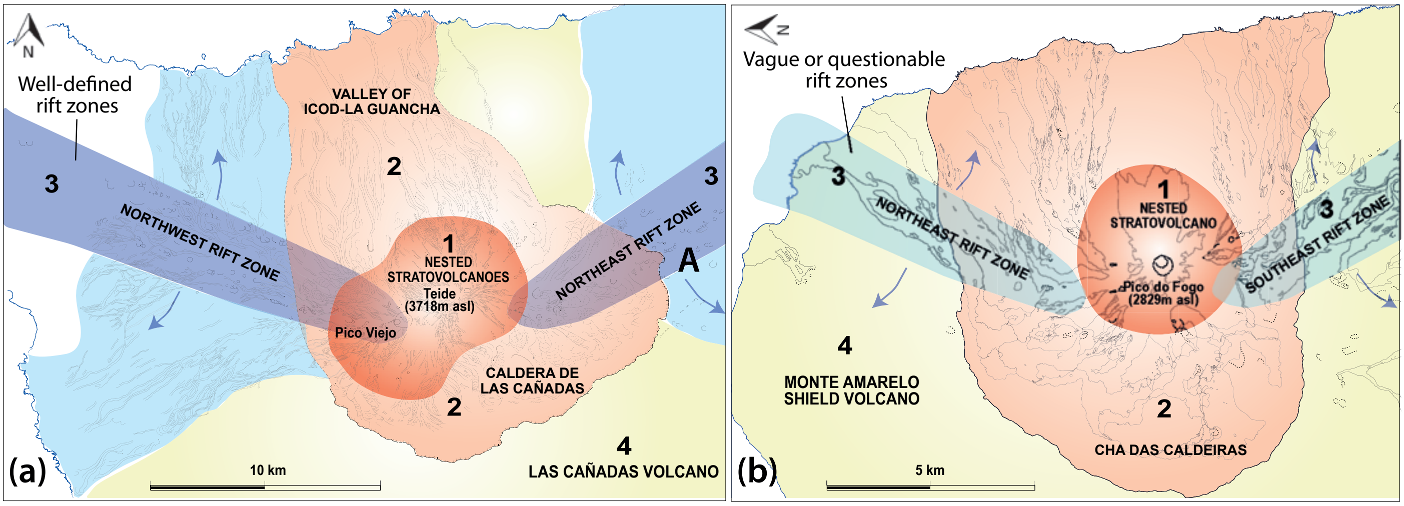


Fig. 6. **a.** View of the Cha das Caldeiras that formed by the giant landslide from the top of Monte Amarelo volcano. The depression is partly filled with nested volcanism that also constructed the 2829-m-high Pico do Fogo cone. Eight intra-caldera eruptions, the latest in 2014 (the vent is indicated with an arrow) are recorded since the colonisation in 1460. **b.** View of the Caldera de Las Cañadas landslide depression, also in part filled with lava flows and towered over by Teide volcano. However, lavas in Fogo are basaltic, whereas in the central Teide complex predominantly phonolitic material is erupted.

feature inside the landslide caldera are the horizontal lava flows confined between Pico do Fogo and the ~1000 m high vertical caldera wall (the Bordeira), forming a ~1500 m-thick pile of dominantly semi-horizontal lava flows.

Pico do Fogo, Cape Verde and Pico del Teide, Tenerife, Canary Islands

The island of Fogo is architecturally remarkably similar to the Teide Volcanic Complex on Tenerife, where a lateral collapse scar, the Caldera de Las Cañadas, hosts the Teide stratovolcano. Further

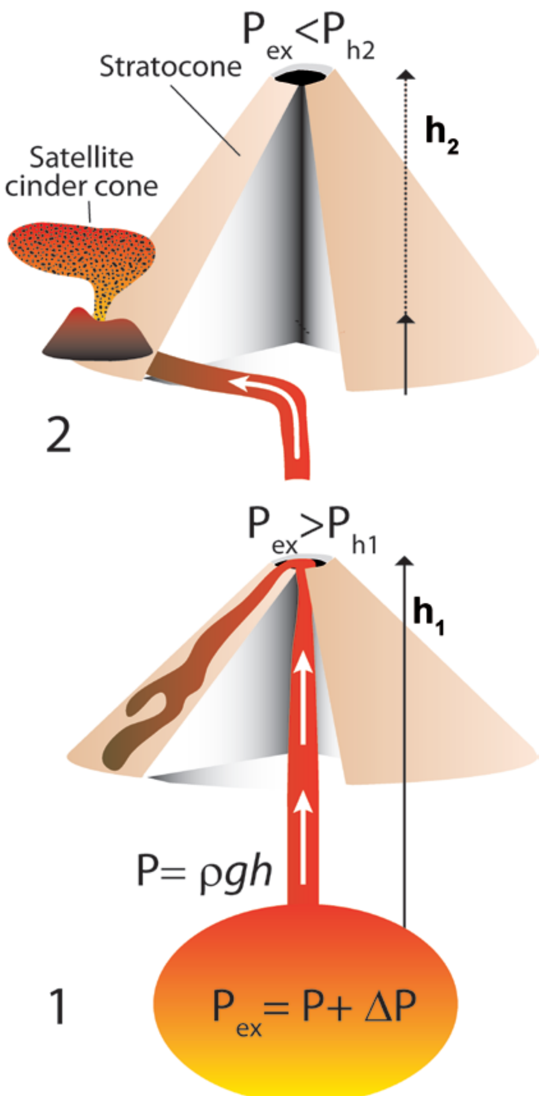


Fig. 7. Schematic diagram showing the relationship between lithostatic pressure *P* and eruption driving overpressure P_{ex}. **1.** While Pex remains greater than *P*, lava can ascend to the summit crater. As the stratocone grows to the critical height (h_2), lithostatic pressure may become greater than the eruption driving overpressure and summit eruptions are then no longer viable. However, if more evolved and less dense magmas are available, summit eruptions can continue, since *P* is depending on the density of the magma (ρ). If, eventually, summit eruptions are no longer feasible, eruptions will shift to around the basal perimeter of a stratovolcano to form satellite or peripheral vents and lava domes (modified from Davidson & De Silva, 2000).

geological similarities are found in the rift zone, although the rift zones are less prominent on Fogo Island (Fig. 5).

Rift zones constitute the most pronounced and persistent structures in the development of mature oceanic volcanic islands, as known from, for example, Tenerife. Rift zones control the construction of the volcanic edifices, form the main relief, concentrate eruptive activity, and frequently play a key role in the generation of flank collapses. Rifts form by magma supplied through fissures (dykes). As rifts evolve by intrusive and eruptive growth, the system progressively develops a well-established plumbing system. In contrast, collapse unloading (i.e. decompression, gas expansion, and possibly isostatic rebound) facilitate the ascent and eruption of mafic, high density, and crystal-rich fractions of magma that resided in the lower part of the magma supply column prior to a collapse and likely explains why volcanism concentrated inside the collapse scars on Fogo and at the Teide volcanic complex.

Along with these similarities, there are also some notable differences. For instance, the lavas filling the Cha das Caldeiras depression are dark, relatively thin (1–3 m) and of a mafic composition (Fig. 6a). In contrast, lava flows inside the Las Cañadas caldera are much thicker (up to 80 m thick), light-coloured and frequently of phonolitic composition (Fig. 6b). These differences may be explained by the contrasting stages of development of both volcanoes. The collapse scar in Fogo (the Bordeira), exposed 1000 m of mafic Quaternary lavas associated with the early (Monte Amarelo) shield volcano. In contrast, the Las Cañadas caldera scar shows a sequence of lava flows, ignimbrites and pumice deposits from a central felsic volcano, the Las Cañadas Volcano, that formed on top of the Miocene Central Shield of Tenerife after a prolonged period of eruptive quiescence. The extended volcanic history of the Las Cañadas Volcano likely favoured magma differentiation processes and the evolution of volcanism towards more explosive (Plinian) eruptions. This type of magma composition and its associated explosive eruptions are as yet absent from the volcanic record of Fogo where activity is thus far restricted to mafic volcanic products.

Another important difference is the way both stratocones were constructed. The exposure at Pico do Fogo is made entirely of basaltic cinder (Fig. 4), whereas the Teide stratocone is made of basaltic lava flows in its lower part that progressively changed to

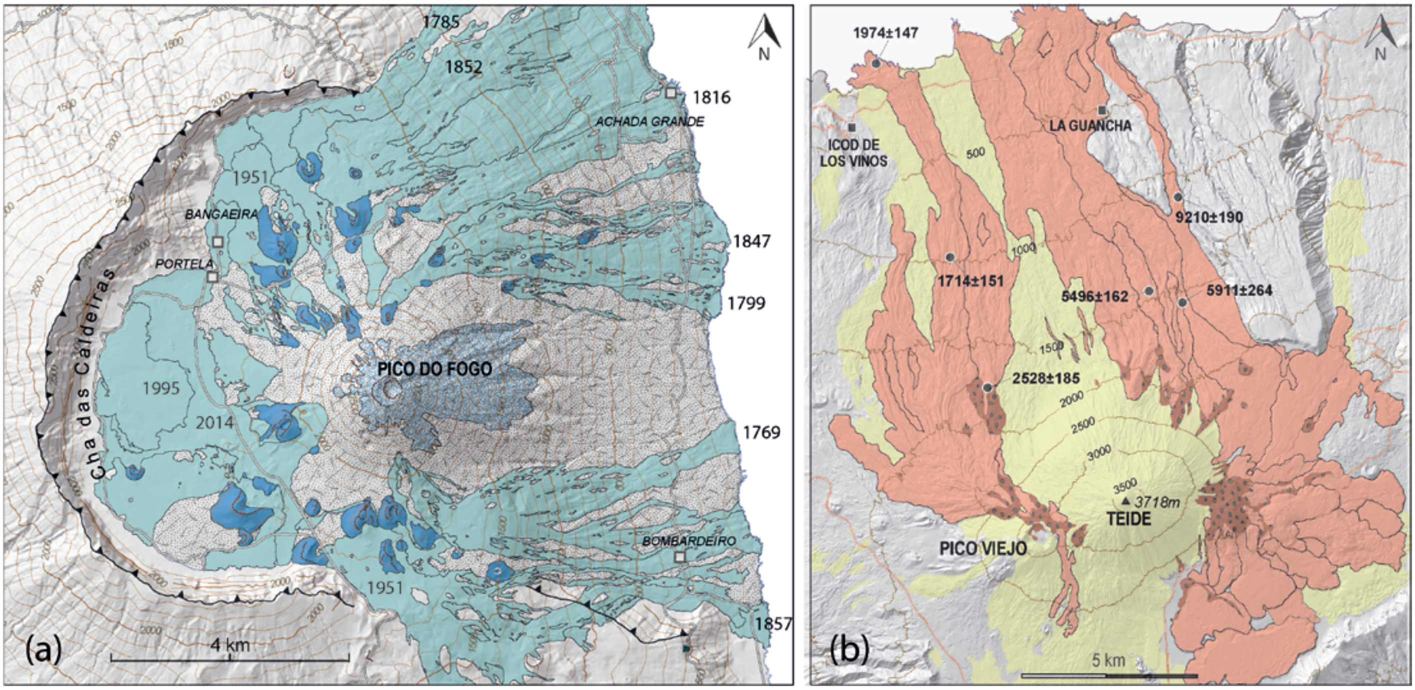


Fig. 8. a. The 'density filter', established by the progressive increase in height of Pico do Fogo and Pico de Teide stratovolcanoes, finally put an end to summit eruptions which in both cases changed to satellite vents at the basal perimeter of the volcanic edifices in recent geological history. Only dense (mafic) magmas were available at Pico do Fogo, and consistently, the satellite eruptions were also mafic. **b.** In the Teide volcanic complex, evolved and less dense phonolite magmas (pale red in map) reside in shallow reservoirs and replaced the basaltic summit eruptions already several tens of kyr ago. The latest phonolitic phase of Teide's growth forced the formation of basal satellite vents and lava domes around Teide stratovolcano.

evolved lavas (phonolites) with time. These differences probably affect the 'density filter' imposed by gravity. As a volcano grows, the distance the magma has to ascend to the surface increases. As illustrated in the sketch in Fig. 7, if h increases, there will be a limit above which it will be physically unlikely that further lava can be erupted from the summit (the density filter). The magma needs an overpressure (P_{ex}) that exceeds the lithospheric pressure (P) to drive an eruption (Fig. 7, Stage 1). Since P is dependent on the density of the magma and the distance from the magma chamber to the summit crater, there will be a limit for a given magma density as to how high it can rise and so prevent ascent to the summit of the volcano once a volcanic edifice rises beyond a certain point. On the other hand, if a volcano has attained this critical height, it can still erupt from the summit crater if the density of the lava decreases, e.g. if the magma composition changes from mafic (dense) to felsic (light), as occurred during the later stages of the activity at Teide.

The density filter probably plays a major role in the construction of the Pico do Fogo stratocone and may even explain why it is constructed entirely of basaltic pyroclasts. Volcanism at Fogo is fed from magma previously stored in the uppermost mantle between 17 and 22 km depth and through syn-eruptive short-term magma stalling within the lower crust at 8–13 km depth. Teide's magma chamber depth is estimated to be 3–4 km and the Pico do Fogo has consequently a much lower critical cone height than Teide because of its longer transport distance and higher magma density. This view is in agreement with the near perfect conical shape of the 2829-m-high Pico do Fogo, implying a steady vent location over considerable time that shifted only recently.

In comparison, Teide Volcano (3718 m) is fed by a stratified magma source, with evolved magma forming the late stage of activity that allowed Teide to surpass the critical density limit for dense mafic magmas erupting from the summit crater. For Teide, the latest summit eruption of obsidian phonolite (Lavas Negras) took place in the 8th Century. Both volcanic complexes continued erupting after summit activity ceased, opening satellite vents around the basal perimeter of the volcanic edifices (Fig. 7, Stage 2, and Fig. 8), implying that Teide and Fogo have now arrived at their specific maximal critical heights.

Acknowledgements

We would like to thank Alexandre Nesky Rodrigues and Herculano Dinis of the Fogo Natural Park for logistic help during field work on the island. We also thank the Centre for Natural Disaster Science (CNDS) at Uppsala University for financial support.

Suggestions for further reading

Amelung, F. & Da, S. 2002. InSAR observations of the 1995 Fogo, Cape Verde, eruption: implications for the effects of collapse events upon island volcanoes. *Geophysical Research Letters*, v.29, pp.47-1–47-4.

Carracedo, J.C. 1994. The Canary Islands: an example of structural control on the growth of large oceanic-island volcanoes. *Journal of Volcanology and Geothermal Research*, v.60, pp.225–242.

Carracedo, J.C., Rodriguez-Badiola, E., Guillou, H., Paterne, M., Scaillet, S., Pérez-Torrado, F.J., Paris, R., Fra-Paleo, U. & Hansen, A. 200. Eruptive and structural history of Teide volcano and rift zones of Tenerife, Canary Islands. *Geological Society of America Bulletin*, v.19, pp.1027–1051.

Carracedo, J.C. 1999. Growth, structure, instability and collapse of Canarian volcanoes and comparisons with Hawaiian volcanoes. *Journal of Volcanology and Geothermal Research*, v.94, pp.1–19.

Carracedo, J.C. & Troll, V.R. 2013. *Teide volcano – Geology and Eruptions of a Highly Differentiated Oceanic Stratovolcano*. Springer-Verlag, Berlin/Heidelberg.

Carracedo, J.C. & Troll, V.R. 2015. *Geology of the Canary Islands*. Dunedin Academic Press.

Courtney, R.C. & White, R.S. 1986. Anomalous heat flow and geoid across the Cape Verde Rise: evidence for dynamic support from a thermal plume in the mantle. *Geophysical Journal of the Royal Astrophysical Society* v.87, pp.815–867.

Crough, S. 1978. Thermal origin of mid-plate hot-spot swells. *Geophysical Journal International*, v.55, pp.451–469.

Davidson, J.P. & de Silva, S. 1999. Composite volcanoes. In Sigurdsson, H. (ed.) *Encyclopedia of Volcanoes*, pp.663–681. Academic Press, San Diego, CA, USA.

Day, S.J., Heleno Da Silva, S.I.N. & Fonseca, J.F.B.D. 1999. A past giant lateral collapse and present-day flank instability of Fogo, Cape Verde Islands. *Journal of Volcanology and Geothermal Research*, v.94, pp.191–218.

Delcamp, A., Petronis, M., Troll, V.R., van Wyk de Vries, B., Carracedo, J.C. & Pérez-Torrado F.J. 2010. Paleomagnetic evidence for rotation of the NE-rift on Tenerife, Canary Islands. *Tectonophysics*, v.492, pp.40–59.

Foeken, J.P.T., Day, S. & Stuart, F.M. 2009. Cosmogenic ^{3}He exposure dating of the Quaternary basalts from Fogo, Cape Verdes: implications for rift zone and magmatic reorganisation. *Quaternary Geochronology* v.4.1, pp.37–49.

Gerlach, D.C., Cliff, R.A., Davies, G.R., Norry, M. & Hodgson, N. 1988. Magma sources of the Cape Verdes archipelago: isotopic and trace element constraints. *Geochimicia et Cosmochimica Acta*, v.52, pp.2979–2992.

Hildner, E., Klügel, A. & Hansteen, T.H. 2012. Barometry of lavas from the 1951 eruption of Fogo, Cape Verde Islands: implications for historic and prehistoric magma plumbing systems. *Journal of Volcanology and Geothermal Research*, v.217–218, pp.73–90.

Hoernle, K.A., Tilton, G., Le Bas, M.J., Duggen, S. & Garbe-Schönberg, D. 2002. Geochemistry of oceanic carbonatites compared with continental carbonatites: mantle recycling of oceanic crustal carbonate. *Contributions to Mineralogy and Petrology*, v.142, pp.520–542.

Lodge, A. & Helffrich, G. 2006. Depleted swell root beneath the Cape Verde Islands. *Geology*, v.34, pp.449–452.

Longpré, M.-A., Troll, V.R., Walter, T.R. & Hansteen, T.H. 2009. Volcanic and geochemical evolution of the Teno massif, Tenerife, Canary Islands: some repercussions of giant landslides on ocean island magmatism. *Geochemistry, Geophysics. Geosystems*, v.10, pp.Q12017.

McNutt, M. 1988. Thermal and mechanical properties of the Cape Verde Rise. *Journal of Geophysical Research (Solid Earth)*, v.93, pp.2784–2794.

Manconi, A., Longpré, M.-A., Walter, T.R., Troll, V.R. & Hansteen, T.H. 2009. The effects of flank collapses on volcano plumbing systems. *Geology*, v.37, pp.1099–1102.

Montelli, R., Nolet, G., Dahlen, F. & Masters, G. 2006. A catalogue of deep mantle plumes: new results from finite-frequency tomography. *Geochemistry, Geophysics, Geosystems*, v.7, pp.1–69.

Paris, R., Giachetti, T., Chevalier, J., Guillou, H. & Frank, N. 2011. Tsunami deposits in Santiago Island (Cape Verde archipelago) as possible evidence of a massive flank failure of Fogos volcano. *Sedimentary Geology*, v.239, pp.129–145.

Pim, J., Peirce, C., Watts, A.B., Grevemeyer, L. & Krabbenhoeft, A. 2008. Crustal structure and origin of the Cape Verde Rise. *Earth and Planetary Science Letters*, v.272, pp.422–428.

Torres, P.C., Madeira, J., Silva, L.C., Brum Da Silveira, A., Serralheiro, A. & Mota Gomes, A. 1997. Carta geológica das erupções históricas da Ilha do Fogo: revisão e actualização. In: *A erupção vulcânica de 1995 na ilha do Fogo, Cabo Verde*. Edição do Instituto de Investigação Científica Tropical e Ministério da Ciência e Tecnologia, Portugal, pp.119–132.

Walter, T.R., Troll, V.R., Caileau, B., Schmincke, H.-U., Amelung, F. and van den Bogaard, P. 2005. Rift zone reorganization through flank instability on ocean islands – an example from Tenerife, Canary Islands. *Bulletin of Volcanology*, v.65, pp.281–291.