
Volcanism in the Azores: A Marine Geophysical Perspective

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Abstract

In contrast to oceanic islands produced by mantle melting anomalies or “hotspots” lying in mid-plate settings, the central and eastern Azores islands are distributed on the Nubia-Eurasia tectonic plate boundary and experience frequent tectonic earthquakes. As they lie in an extensional to trans-tensional tectonic environment, volcanism is organised into submarine and subaerial ridges oriented perpendicular or oblique to the direction of plate separation. Much of the marine geophysical work undertaken to study these features and the submarine flanks of the islands has involved seabed mapping with sonars of various kinds, beginning with the GLORIA

long-range sidescan sonar deployed in the late 1970s and continuing more recently with the deeply towed sidescan sonar TOBI and multi-beam bathymetric sonars in dedicated expeditions and ship transits. These datasets give us a view of the topographic structure of the ridges and of the morphologies of the volcanic and tectonic features comprising them. Sonars also have been used to investigate the incidence of large- and small-scale landsliding around the islands, as well as the morphologies of lava flows originating from land and entering the sea. The overall picture emerging is one of landslides, cones, terraces and ridges analogous to those of Hawaii, Canaries and other oceanic island groups but with notable differences. For example, large-scale landslides appear to be rarer in the Azores and submarine cones tend to be steep-sided and pointed, not flat-topped or cratered as they are in some parts of the Hawaiian Islands. Faults are also more common in the Azores tectonic environment.

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1 Introduction

Whereas the islands of Corvo and Flores lie in a stable tectonic environment west of the Mid-Atlantic Ridge on the North America plate, the central and eastern Azores islands are distributed on and around the Nubia-Eurasia diffuse plate boundary (Fig. 1). Submarine volcanism

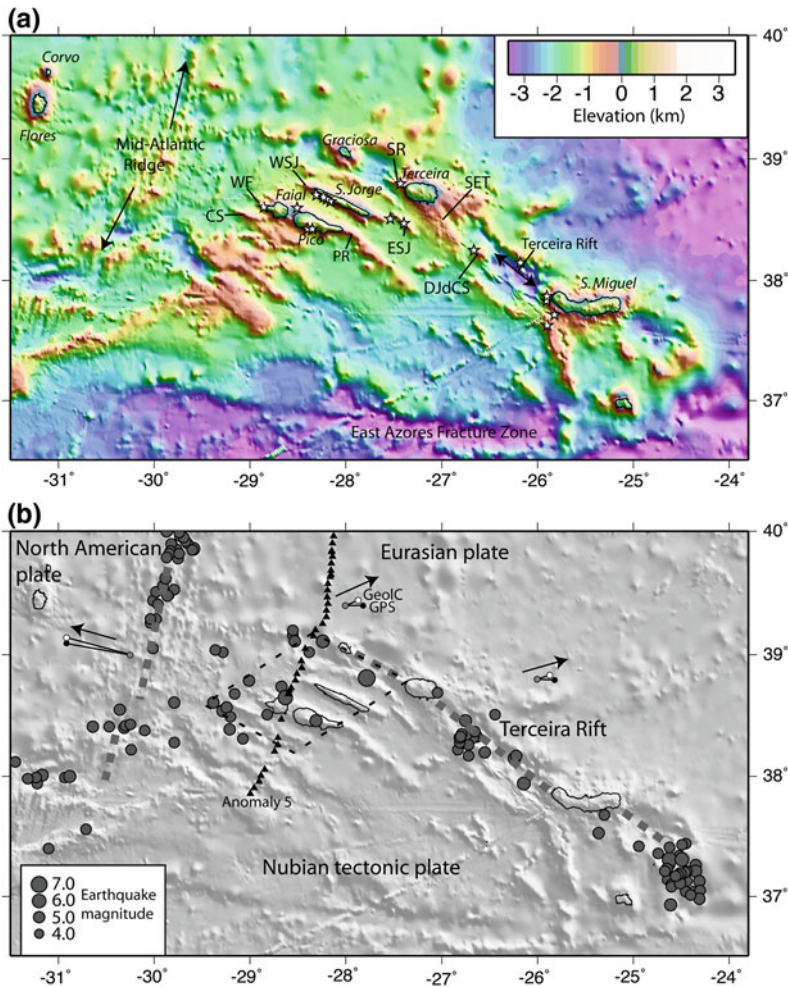


Fig. 1 Overview of the Azores archipelago. **a** Bathymetry and topography data from the Global Multi-Resolution Topography Synthesis (Ryan et al. 2009). Annotation DJdCS: Dom João de Castro Seamount, and submarine volcanic ridges: CS: Condor Seamount, PR: Pico Ridge, SR: Serreta Ridge, WF: West Faial, WSJ: West São Jorge, SET: Southeast Terceira and ESJ: East São Jorge. Island names are in italics. Open star symbols locate reported submarine eruptions prior to 1964 from Weston (1964). **b** Tectonics of the Azores. Grey shading is based on the elevation and bathymetry data in (a). Heavy dashed line east of 29°W is the Terceira Rift,

which is commonly regarded as the Nubia-Eurasia plate boundary. Grey circles are earthquake magnitudes from the US Geological Survey (scale in key, lower-left). Grey-filled triangles are identifications of magnetic anomaly 5 from Freire Luis et al. (1994). Small white and solid circles connected to grey-filled circles represent the effect of 3 m.y. of displacement of Eurasia and North America (Nubia fixed) based on the plate rotation poles GeolC and GPS of Calais et al. (2003), i.e., the displacement that would occur if these rates persisted for 3 m.y. into the future. Large arrows are drawn parallel to the long-term motion (GeolC pole prediction)

has not been much studied around Corvo and Flores, but areas around the central and eastern islands have now been extensively surveyed, providing an opportunity to study the products of submarine volcanism in an extensional to transtensional tectonic environment [an area

undergoing extension and transcurrent motion, i.e., where the displacement vector is oblique to the deforming zone (McCoss 1986)]. Volcanism arising from the Azores mantle melting anomaly has produced many submarine ridges (Ligi et al. 1999; Lourenço et al. 1998, Miranda et al.,

Chapter “[The Tectonic Evolution of the Azores Based on Magnetic Data](#)”) as well as elongated subaerial ridges on some islands, such as eastern Pico and São Jorge (Walker 1999; Hildenbrand et al. 2008; Fig. 1a). Earthquake seismic tomography has revealed a low-velocity anomaly at 112 km depth under Pico and São Jorge islands (Yang et al. 2006; O’Neill and Sigloch, Chapter “[Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics](#)”), which probably represents the mantle plume or other anomaly underlying the Azores that has caused the excess volcanism generating the islands (O’Neill and Sigloch, Chapter “[Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics](#)”; Beier et al., Chapter “[Melting and Mantle Sources in the Azores](#)”). These ridges can be considered distinct from those produced by “normal” mid-ocean ridge volcanism or from volcanism around oceanic islands without plate-tectonic extension. Most oceanic islands that have grown near to mid-ocean ridges are isolated from the influence of extension associated with the spreading processes (for example, Galapagos, Bouvet, Ascension, Tristan da Cunha, Easter, etc.). Examples of islands and seamounts that have apparently grown in extensional environments producing major elongated structures include Reykjanes Peninsula and Ridge in SW Iceland (Parson et al. 1993; Saemundsson 1986), Jan Mayen island (Fitch 1964), Spiess Ridge near Bouvet Island (Ligi et al. 1997; Mitchell and Livermore 1998), Guadalupe Island of Mexico (Batiza 1977), Marsili Seamount of Italy (Marani and Trua 2002), Axial Seamount on the Juan de Fuca Ridge (Embley et al. 1990), the region around St Paul and Amsterdam Islands in the Indian Ocean (Conder et al. 2000), volcanic ridges in the Gulf of California of Mexico (Fabriol et al. 1999) and in back-arc basins such as near the Antarctic Peninsula (Gracia et al. 1996). Elongated seamounts have also been found in the continental margin of California (Davis et al. 2002).

Ridges radiate from large oceanic guyots and seamounts probably because of processes related to volcanic rifting or spreading (Mitchell 2001; Vogt and Smoot 1984), such as the processes

actively generating the submarine Puna Ridge (Kilauea volcano) (Fiske and Jackson 1972; Dieterich 1988) and southerly ridges of La Palma and El Hierro in the Canaries (Gee et al. 2001a; Mitchell et al. 2002). The volcanic rift zones and the volcanic ridges that are commonly associated with them in the Azores lie perpendicular or oblique to the Nubia-Eurasia plate motion vectors (Fig. 1b) so they are more likely to have arisen from the plate tectonics than volcanic edifice spreading (Fiske and Jackson 1972), also because the short 1–3 km heights of the edifices may be insufficient to create much gravitational stress. The Azores provide an opportunity to study such submarine volcanic ridges in a shallow marine environment where high-resolution geophysical data can be acquired relatively easily using surface vessels. Resolution or acoustic “footprint” of a sonar is proportional to water depth, so swath systems with typically 1°–3° beam widths produce high quality data due to the proximity of the seabed to sensors on surface vessels.

Although many historical eruptions have been reported in the Azores, they are spread among the islands and building rates on individual islands tend to be modest. For example, the building rate on São Miguel was about 1 km³ per thousand years for the last 50,000 years (Booth et al. 1978) and was probably about an order of magnitude lower previously (Moore 1990). The rate of Booth et al. (1978) is an order of magnitude smaller than historical and geological rates for Kilauea (Clague and Dalrymple 1989, their Table 5) and the earlier rate (Moore 1990) is two orders of magnitude smaller. Volcanism in the Azores seems to be occurring at modest rates on individual islands, while the islands are subjected to frequent earthquakes (Fig. 1b), hence the islands are characterised by modest volcanism but frequent plate-tectonic seismicity.

The Azores region comprises an elevated plateau, roughly corresponding with areas shallower than 2000 m depth (Fig. 1a). From a grid of aeromagnetic data, seafloor spreading magnetic anomalies have been mapped across the plateau (Miranda et al., Chapter “[The Tectonic Evolution of the Azores Based on Magnetic Data](#)”).

"); the anomaly 5 locations in Fig. 1b are from Freire Luis et al. (1994). Their trend parallel with the Mid-Atlantic Ridge demonstrates that the plateau formed by excess volcanism at the Mid-Atlantic Ridge (similar to the modern Reykjanes Ridge and Peninsula), probably over a period beginning at 20 Ma (Gente et al. 2003). Dispersion of Rayleigh waves crossing the plateau and recorded at Ponta Delgada in São Miguel suggest an oceanic crustal structure approximately 60% thicker than normal (Searle 1976). Comparing with the Icelandic plateau, the differing rates of magma production in the two plateaux have led to contrasting gross morphologies and volcanic processes. Whereas the Icelandic plateau is mostly above sea level and includes central shield volcanoes, the Azorean plateau is largely below sea level and edifices are mostly stratovolcanoes (Saemundsson 1986), although there are also some shield volcanoes, e.g., on Faial and Terceira islands.

In this contribution, marine geophysical data are described to show how they can reveal aspects of the structure and morphology of the submarine volcanic features to suggest how they have developed by volcanism associated with the Azores mantle hotspot (O'Neill and Sigloch, Chapter "Crust and Mantle Structure Beneath the Azores Hotspot—Evidence from Geophysics"). Research by biologists characterising substrates and seabed morphology carried out as part of marine habitat mapping is also described where relevant to volcanology. The review concentrates on the seafloor around the central and eastern Azores Islands. Although not much marine geophysical work has been reported to date for the western islands, signs of volcanism within the last 2 m.y. on Flores and Corvo islands (Azevedo and Portugal Ferreira 2009; França et al. 2006; Larrea et al. 2013) suggest that interesting submarine volcanic structures may surround them also.

The main source of information on submarine volcanic structures has originated from seabed mapping sonars rather than data from other types of geophysical instruments. These data show the gross morphologies of ridges, the shapes of cones superimposed on them, how those cones

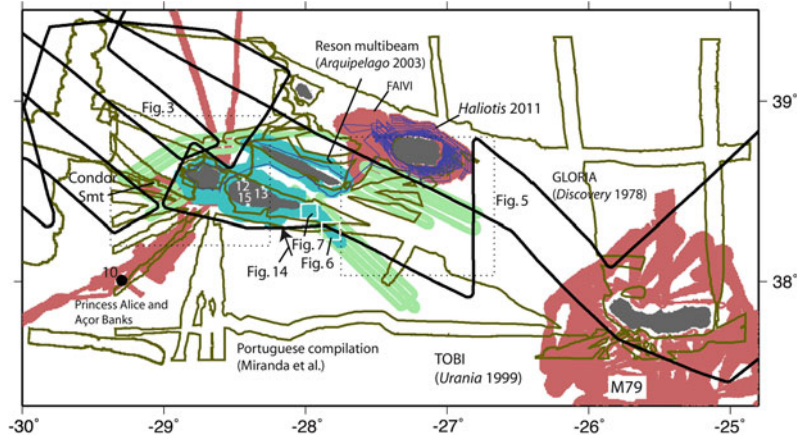
vary in shape with water depth suggesting influences of shallow marine eruptions, the structures of lava flows in shallow water originating from subaerial eruptions and landslides around the slopes of the islands. Each of these aspects is described in turn, after first outlining the main datasets that have been collected.

2 Marine Geophysical Datasets Collected Amongst the Azores Islands

The first systematic marine geophysical survey in the Azores was carried out on RRS *Discovery* using the Geological Long-Range Inclined Asdic (GLORIA) reconnaissance sidescan sonar (Searle 1980). The focus of that study was mainly the area west of the central Azores islands, in order to decipher its tectonic history, but two lines were run among the islands, also collecting single-channel seismic and other geophysical data (track marked by solid bold line in Fig. 2). With a lateral range set to 30 km, the system was capable of imaging the submarine slopes and ridges between the islands, outlining broad structures. The data have too low a resolution to reveal much detail; resolution is ~20–30 m cross-track from the effective pulse duration of the sonar but along-track resolution deteriorates considerably with acoustic spreading of the 2.7° beam (Mitchell 1991), e.g., 500 m at 10 km range.

The ports in the Azores have provided convenient locations for changing crews of research vessels working in the Atlantic and many lines of multibeam bathymetric sonar data have been collected opportunistically. Lourenço et al. (1998) compiled a bathymetric map from transits amongst the islands and some systematic surveys on the Azores plateau. More recently, Miranda et al. (2015) updated the compilation with data collected by the Task Group for the Extension of the Portuguese Continental Shelf, which includes the most extensive swath survey around the Azores so far. Although most of that survey work occurred 200 nautical miles beyond the island coastlines, sizeable areas within the Portuguese

Fig. 2 Locations of some of the marine geophysical datasets collected among the central and east Azores islands. Numbers 10–13, 15 locate Figs. 10, 11, 12, 13 and 15. See main text for explanation



Exclusive Economic Zone were covered including parts of the Mid-Atlantic Ridge, major seamounts and other areas around the islands (Dias Correia 2010). The extent of this combined dataset is outlined by the grey lines in Fig. 2 (marked “Portuguese compilation”).

In 1999, a survey was carried out on the Italian RV *Urania* with the Towed Ocean Bottom Instrument (TOBI) sidescan sonar (Ligi et al. 1999; Stretch et al. 2006). This system was towed nearer to the seabed along the tracks marked by wide dark grey lines marked “TOBI” in Fig. 2. It carried a 30 kHz sidescan sonar and a high-frequency sediment profiler, providing a higher resolution view (somewhat analogous to aerial photographs on land) than is typically obtained by either GLORIA or the many multibeam sonars.

A portable Reson Seabat 8160 multibeam sonar (50 kHz) was installed on the University of Azores RV *Arquipelago* in 2003 (Mitchell et al. 2008). The bathymetric coverage of that expedition is shown by the solid black areas in Fig. 2 around Faial, Pico and São Jorge islands (marked “Reson multibeam”). As the crew of the vessel were familiar with the local seas, surveying was allowed into shallow water, which as shown later was important for imaging fine lava structures. The 1.5° beam widths of the system provide an acoustic resolution of 0.26 and 2.6 m at 10 and 100 m depth, respectively. A subsequent deployment of a University of St Andrews phase-difference Submetrix bathymetric sonar

allowed some inshore areas to be surveyed (Tempera 2008). Inshore surveys with chirp and boomer seismic systems around the coasts of Faial, Pico, São Miguel and Flores (Bates 2005; Quartau et al. 2003, 2005) have also been useful for resolving shallow marine structures (Quartau et al. 2012, 2015a; Tempera et al. 2012a, b).

Some additional surveys have been carried out recently. Hübscher (2009) led a research cruise on the RV *Meteor*, collecting multibeam and seismic data around São Miguel island in 2009 (area of light grey marked M79 in Fig. 2). Those results are now appearing in the literature (Weiss et al. 2015a, b; Sibrant et al. 2015; Weiss et al. 2016). Results of two further cruises of RV *Meteor* in 2015 (Hübscher 2015) and RV *Meteor* in 2016 (Beier 2016) will extend that work. In 2010, a selection of seamounts to the SW of Faial were mapped by one of us (FT) for habitat mapping purposes including Condor Seamount and parts of Açor and Princess Alice banks (light grey areas emanating from Faial Island in Fig. 2). A shallow water multibeam survey of the Formigas Bank Marine Protected Area southeast of São Miguel Island in 2011 (also by FT) has imaged the headscarps of shallow landslides around the seamount and an intricate pattern of faults on the flat summit of the bank.

Two other surveys in 2011 (project FAIVI) covered a broad area around Terceira Island (Chiocci et al. 2013; Quartau et al. 2014; Casalbore et al. 2015). One of the surveys on RV *l’Atalante* mapped the submarine slopes and

ridges around the island (light grey area marked FAIVI in Fig. 2), while a survey with the inshore launch *Haliotis* (marked in Fig. 2 with continuous lines) acquired dense chirp and bathymetric data.

3 Plate-Tectonic Setting

The movements of the tectonic plates create the lithospheric stress conditions under which dykes are intruded and lava is erupted to build the submarine ridges in the Azores. The pattern of tectonic strain is therefore important for understanding the orientations of the ridges. McKenzie (1972) was one of the first researchers to speculate on the nature of the tectonics in the Azores region involving separation of the Eurasian and Nubian plates in the form of a “leaky” transform fault. Such a pattern of strain involving both shear and extension within a deforming zone has more recently been described as transtension (McCoss 1986; Madeira and Ribeiro 1990). The Terceira Rift, an elongate depression filled by São Miguel, Terceira and Graciosa islands (dashed line in Fig. 1b), is commonly considered the main Nubia-Eurasia plate boundary (e.g., Vogt and Jung 2004; Vogt and Jung, Chapter “The “Azores Geosyncline” and Plate Tectonics: Research History, Synthesis, and Unsolved Puzzles”). However, the seismicity shown in Fig. 1b becomes more widely distributed among the central islands (dashed parallelogram in Fig. 1b) and a variety of other geophysical and geodetic data now suggest that the deformation occurs broadly across the region encompassed by Faial, Graciosa, Terceira and Pico islands and not solely along the Terceira Rift (Madeira and Ribeiro 1990). For example, modelling of aeromagnetic anomalies suggests that the area between the islands and the Mid-Atlantic Ridge has moved independently of Nubia at times in the past (Freire Luis et al. 1994) rather than with Nubia as would be expected if the plate boundary followed the trend of the Terceira Rift to the ridge. This is confirmed by numerous faults and volcanic ridges cutting the older abyssal hill fabric of the Mid-Atlantic

Ridge in this area (Lourenço et al. 1998; Searle 1980) and by more recent studies of the magnetic anomalies (Luis and Miranda 2008; Miranda et al., Chapter “The Tectonic Evolution of the Azores Based on Magnetic Data”).

Fault-plane solutions of earthquakes among the central islands show both strike-slip and normal fault motions (Hirn et al. 1993) as expected within a transtensional deformation zone. A recent compilation including earthquakes to 1998 (Borges et al. 2007) shows that the T (extensional) axes of the solutions are mostly oriented NNE-SSW, perpendicular to the Terceira Rift, with the central islands dominated by strike-slip mechanisms (with conjugate NE-SW and NW-SE nodal planes) and the rift east of Terciera Island (including São Miguel Island) characterised by more nearly purely normal fault mechanisms. Generally, seismic strain appears to be oriented perpendicular to the direction of elongation of the central islands and submarine volcanic ridges.

GPS measurements at sites around the Azores show deformation occurring broadly throughout the central islands rather than in a narrow plate boundary zone (Fernandes et al., Chapter “The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction”). For example, data collected in six campaigns over an eight-year period show sites on Pico, São Jorge and western Terceira moving at intermediate rates between Eurasia and Nubia (Fernandes et al. 2006), rather than being clearly attached to either of the two plates (Fernandes et al., Chapter “The Contribution of Space-Geodetic Techniques to the Understanding of the Present-Day Geodynamics of the Azores Triple Junction”).

Calais et al. (2003) have characterized the motions of the major plates both from geologic (magnetic anomalies and transform faults) and GPS data. The rotation poles computed with these different data types are significantly different in terms of pole locations and rotation rates, implying a change in motion since 3 Ma. The open and solid circles in Fig. 1b show 3 m.y. of forward movement of the plates with respect to

fixed Nubia predicted by their GeolC and GPS poles. (Arrows highlight the trends in the reconstructions from the GeolC.) If the components of movement are resolved parallel to N025°E (perpendicular to São Jorge and Pico islands), the GPS results suggest 26% less movement than that in the GeolC reconstructions. This is interesting because the islands of São Jorge and Pico both have active strike-slip faults along their axial ridges revealed by sheared cinder cones (Madeira and da Silveira 2003). The Calais et al. (2003) results may provide an explanation for this observation, with a geologically recent change in motion (reduced extensional component) leaving a more important strike-slip motion.

4 General Morphologic Structure of the Azores Volcanic Ridges

Figure 3 shows an overview of the mosaicked TOBI data from west of Faial and São Jorge islands together with descriptions of samples collected by C. Beier and co-workers (Stretch 2007). Figure 4 shows two enlargements of those data. In Figs. 3 and 4, dark areas represent low acoustic backscattering (usually mud or acoustic shadows) and white areas represent high backscattering (usually fault scarps or exposed rocks such as lavas, rock talus or cold water corals). These data show a variety of irregular and smooth textures on submarine cones,

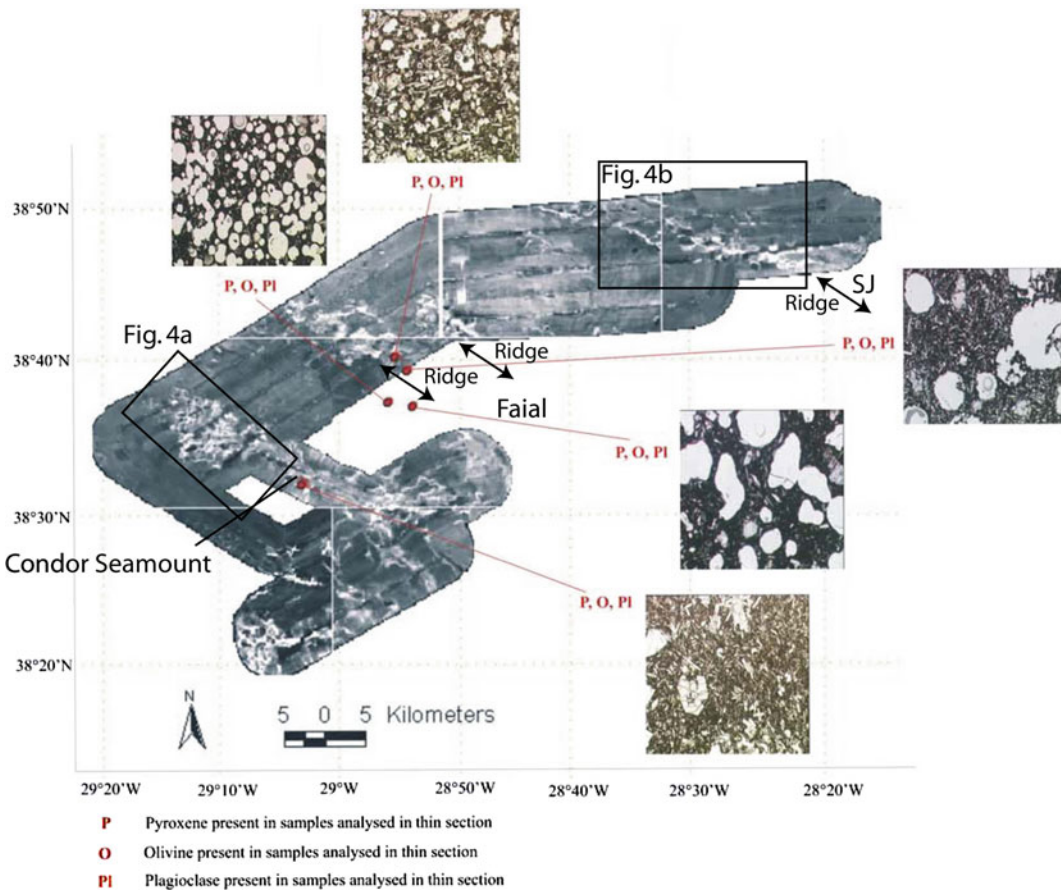


Fig. 3 TOBI deeply towed sidescan sonar data collected immediately west of Faial and São Jorge islands (white represents high acoustic backscattering), shown with some thin section images and minerals present in dredged

rock samples (Stretch 2007). Annotation P, O and PI represents the presence of pyroxene, olivine and plagioclase. “SJ” represents the western extension of São Jorge. (See Fig. 2 for location of tracks relative to the islands.)

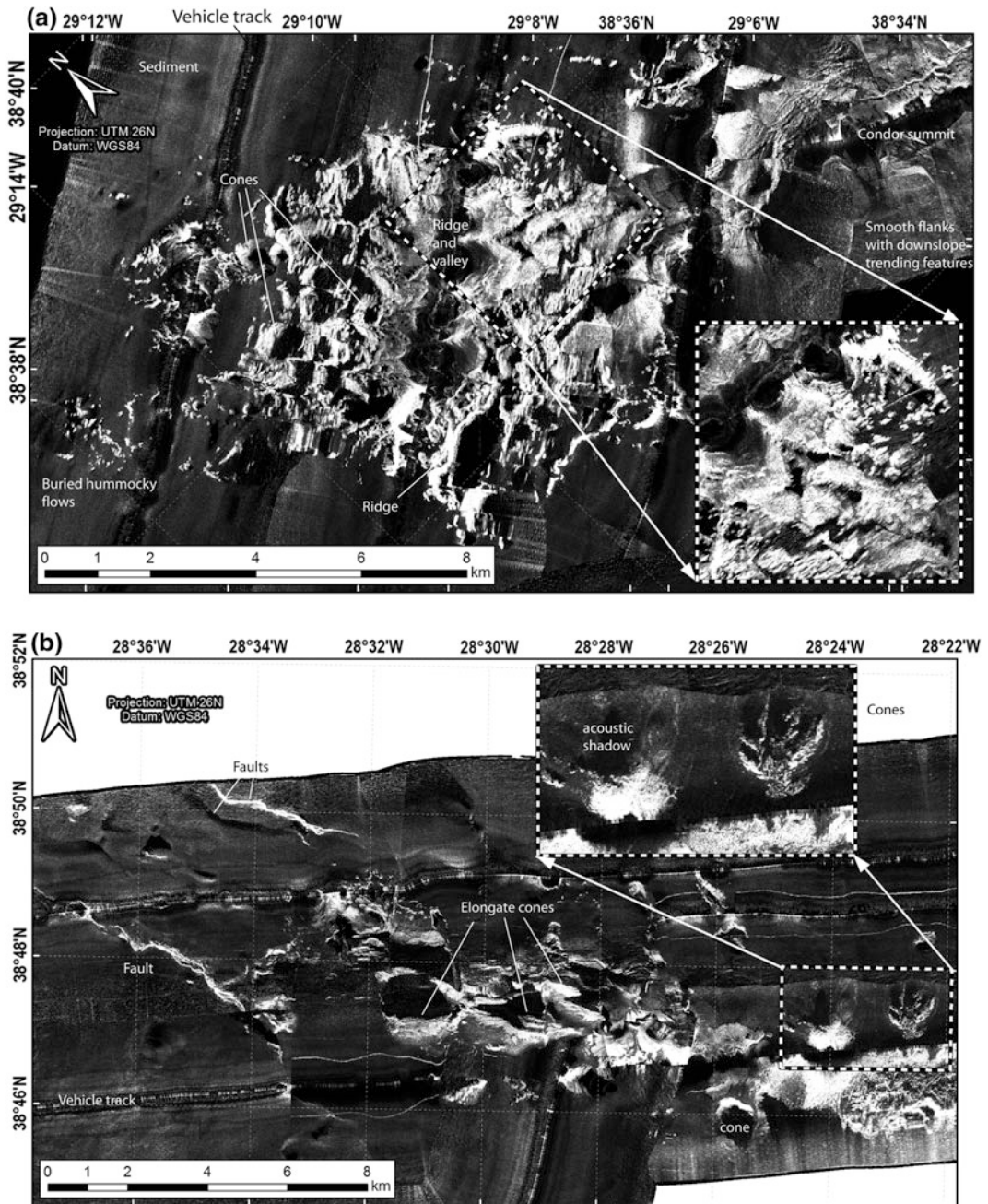
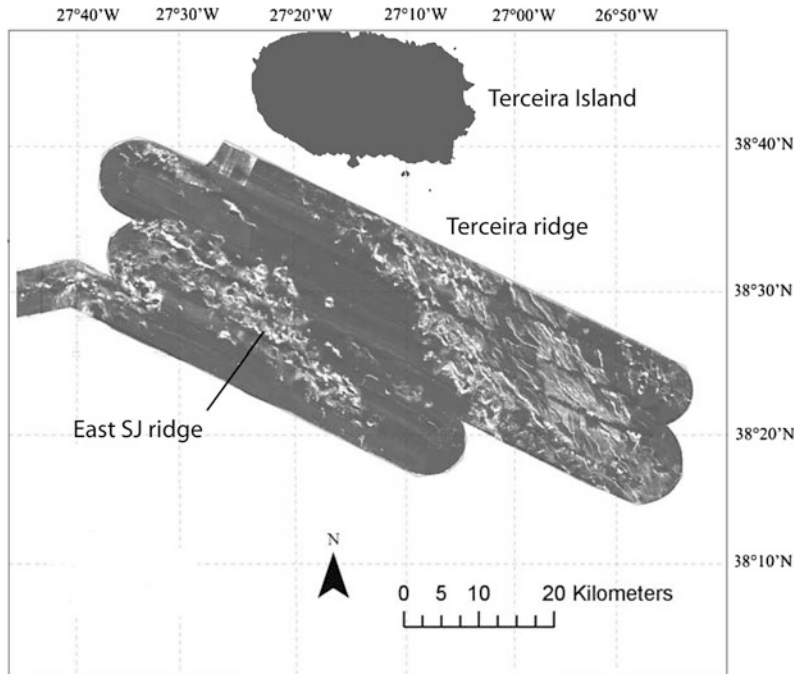


Fig. 4 Selection of the TOBI deeply towed sidescan sonar data from west of **a** Faial and **b** São Jorge. White represents high backscatter. Data are located in Fig. 3

probably representing different lava types, similar to features in the TOBI data collected over the submarine ridge extending SE of Pico island (Stretch et al. 2006). In Fig. 3, a generally rugged

seabed of cones and other outcrops forms three main volcanic ridges—Condor Seamount at 38° 30'N, the western extension of Faial Island (off the Capelo peninsula) at 38°40'N and, at the far

Fig. 5 TOBI sidescan sonar data collected east of São Jorge Island and south of Terceira Island adapted from Stretch (2007). The image reveals volcanic cones and other features on a ridge east of São Jorge and a tectonized ridge south-southeast of Terceira Island. White represents high backscatter



right at $38^{\circ}45'N$, the western extension of São Jorge island. Another small ridge runs parallel to these three immediately northwest of the “Faial” annotation in Fig. 3.

In Fig. 4a, a variety of image textures can be observed. For example, a “speckled” appearance can be seen in the far west of the data, most likely due to hummocky flows that are partly buried by sediment. Elsewhere, surfaces are smooth, as expected for volcanoclastic cones (Mitchell et al. 2012a; Stretch et al. 2006), which are a few hundred metres to 1–2 km across here. Where the sonar track runs up the page slightly left of centre in the figure, the beam pattern of the sonar projected onto the topography leads to a widening and narrowing of the near-nadir dark zone (Mitchell 1991). That pattern suggests a series of ridges and valleys running roughly parallel to the broader topography of Condor Seamount (“ridge and valley” in Fig. 4a, also see inset lower-right). A further highly elongate cone or ridge is highlighted in the lower part of the map. Little detail of the summit of Condor Seamount was obtained as it was obscured beneath the sonar track, but a series of downslope-trending bands in the backscatter are

most likely sedimentary features (channels) on the seamount flanks (upper-right in Fig. 4a).

Figure 4b from beyond the western end of São Jorge shows cones that are relatively circular in plan-view but also a series of elongate cones up to ~ 2 km long and oriented parallel to the main ridge trend. Furthermore, two systems of faults (revealed by highly backscattering bands and acoustic shadows in the west of the map) also run parallel with this trend. The elongate cone morphologies may indicate eruption over dykes (Mitchell et al. 2012a) oriented parallel with the island and these faults.

In further TOBI data shown in Fig. 5, a volcanic ridge east of São Jorge island is also associated with elongate and circular features, probably small ridges and cones, respectively. In contrast, the seabed south of Terceira island, which forms a broad ridge in the regional bathymetry (Fig. 1), is widely disrupted by faults and volcanic features are difficult to identify.

The Reson multibeam bathymetry collected in 2003 allows a closer look at the morphology of the ridge southeast of Pico Island (Mitchell et al. 2012a) and to a lesser extent ridges west of Faial and São Jorge islands near to

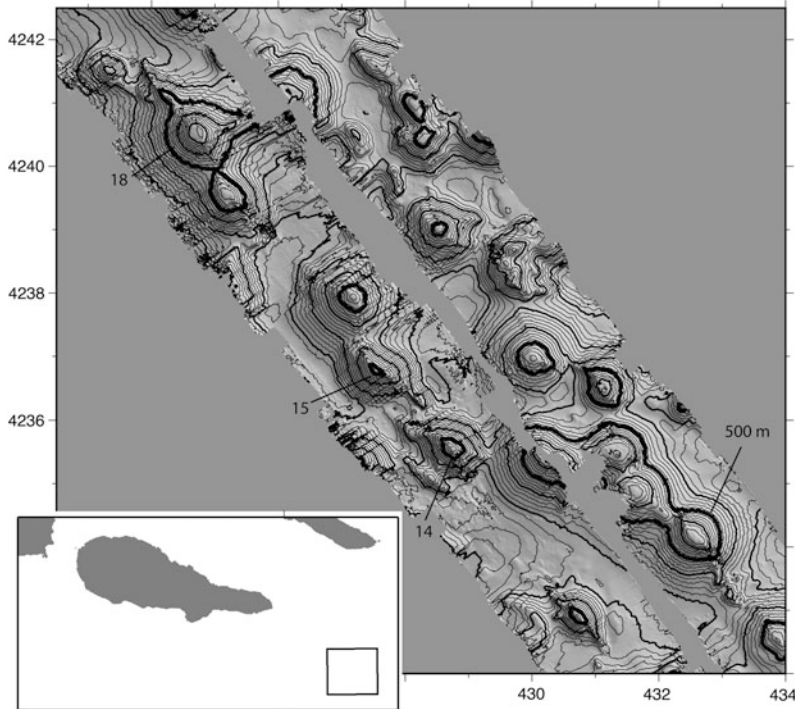


Fig. 6 Bathymetry of deeper section of the submarine ridge extending SSE from the eastern end of Pico Island. Coordinates are Universal Transverse Mercator (UTM) projection (zone 26) distances in km. Bathymetry data (from the Reson 8160 survey) have been gridded at 25 m and contoured at 50 m (500 m intervals are shown in bold). The bathymetry is shaded with an artificial sun to the upper-right. Lower-left inset shows location relative to

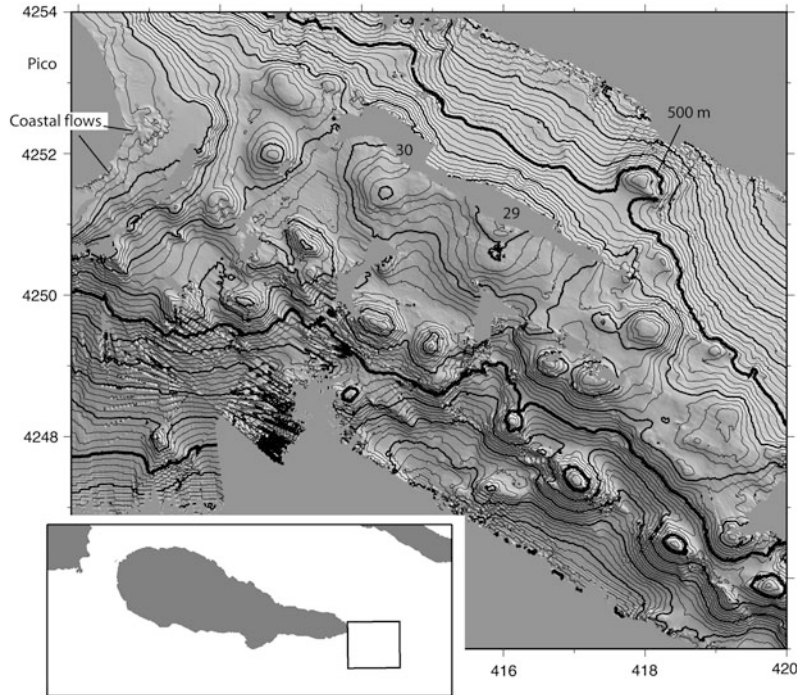
Pico Island. Values linked to cones refer to cone numbering scheme in Mitchell et al. (2012a). Note the relatively uniform spacing of contours on cone flanks consistent with volcanoclastic deposits at a uniform angle of repose. Small ridges oriented parallel to the main ridge trend are evidence for effusive eruptions over dykes intruded with this orientation

their coastlines. The crest of the SE Pico ridge comprises many small ridges and cones (Figs. 6 and 7), which are described in more detail in a separate section below. The morphology confirms the inference from TOBI images (Stretch et al. 2006) that the large-scale ridges are produced by eruption of many small cones and ridges over dykes. The greater apparent abundance of cones under water compared with scoria cones on the subaerial Pico Ridge probably arises because erosion of cones and their burial by lava flows are less effective underwater than on land (Stretch et al. 2006).

Condor Seamount was also surveyed with multibeam sonar as part of habitat mapping efforts and has been investigated with remotely

operated vehicles (ROVs) and “drop-down” cameras to provide “ground truth” (Tempera et al. 2012a). The multibeam data (Fig. 8) show smooth slopes on the flanks of the ridge in its central part (corresponding with the sedimentary features in the upper-right of Fig. 4a mentioned previously), whereas the distal ends are covered with many small cones. This contrast is similar to that observed at Kilauea volcano, Hawai’i, where the submarine slope of the island below the East Rift Zone has a smooth morphology of clastic material produced from fragmentation of lavas crossing the coastline, contrasting with the more rugged Puna Ridge where lavas have erupted underwater (Moore and Chadwick 1995). Over the smooth areas, the flanks of Condor seamount

Fig. 7 Bathymetry of shallower section of the submarine ridge extending SSE of Pico Island from Mitchell et al. (2012a), as Fig. 6 and also collected with the Reson 8160 multibeam sonar. Bathymetry shaded with an artificial sun to the upper-right. Lower-left inset shows location relative to Pico Island. Note the subdued relief of cones 29 and 30, speculated to have arisen from forced spreading of the eruption column by the air-sea density interface



observed in camera and ROV imagery are mostly covered with unconsolidated sediments that appear to overlie a volcanoclastic substrate. These smooth slopes are suspected to have been produced by a similar mechanism to that described for Kilauea, though perhaps with shallow marine eruptions creating the clastic material, rather than subaerial lavas reaching coastlines. The summit is highly backscattering acoustically and is covered with large rocky outcrops and some rounded boulders and gravels, characteristic of a paleo-beach. As the shallowest point of the summit at 184 m is deep for the Pleistocene sea level low stands, the seamount has probably subsided since it formed.

The Serreta Ridge west of Terceira Island (Fig. 1) was the site of a submarine eruption in 1999 (Freire Luis et al. 1999), which was observed from sea by some of us (NCM and ML) on RV *Urania*. During the eruption, porous balloon-like blocks of lava were observed reaching the sea surface, where they floated for ~15 min before sinking (Gaspar et al. 2003; Kueppers et al. 2012). The area has since been surveyed with multibeam sonars on RVs *Knorr*

(DK Smith chief scientist) and *l'Atalante* (Chiocci et al. 2013; Casalbore et al. 2015). The ridge morphology viewable online in Geomapp software (Ryan et al. 2009) is similar to that of Condor Seamount, with a smooth central section (where the eruption occurred) and rugged deeper section with superimposed cones.

5 Cone Morphologies

Mitchell et al. (2012a), Weiss et al. (2015b) and Casalbore et al. (2015) have described morphometric studies of Azorean submarine volcanic cones. Figure 6 shows a selection of the 2003 Reson multibeam bathymetry data from a deeper part of the ridge, revealing cones generally a few hundred metres to 2 km in basal width and up to 400 m in height. Their summits generally lack collapse pits or craters. The spacings of contours on the cone flanks are regular, indicating they are smooth with a common gradient, which is close to the 28°–30° angle of repose of submarine talus (Mitchell et al. 2000). Some indentations of the contours may indicate small superficial collapses,

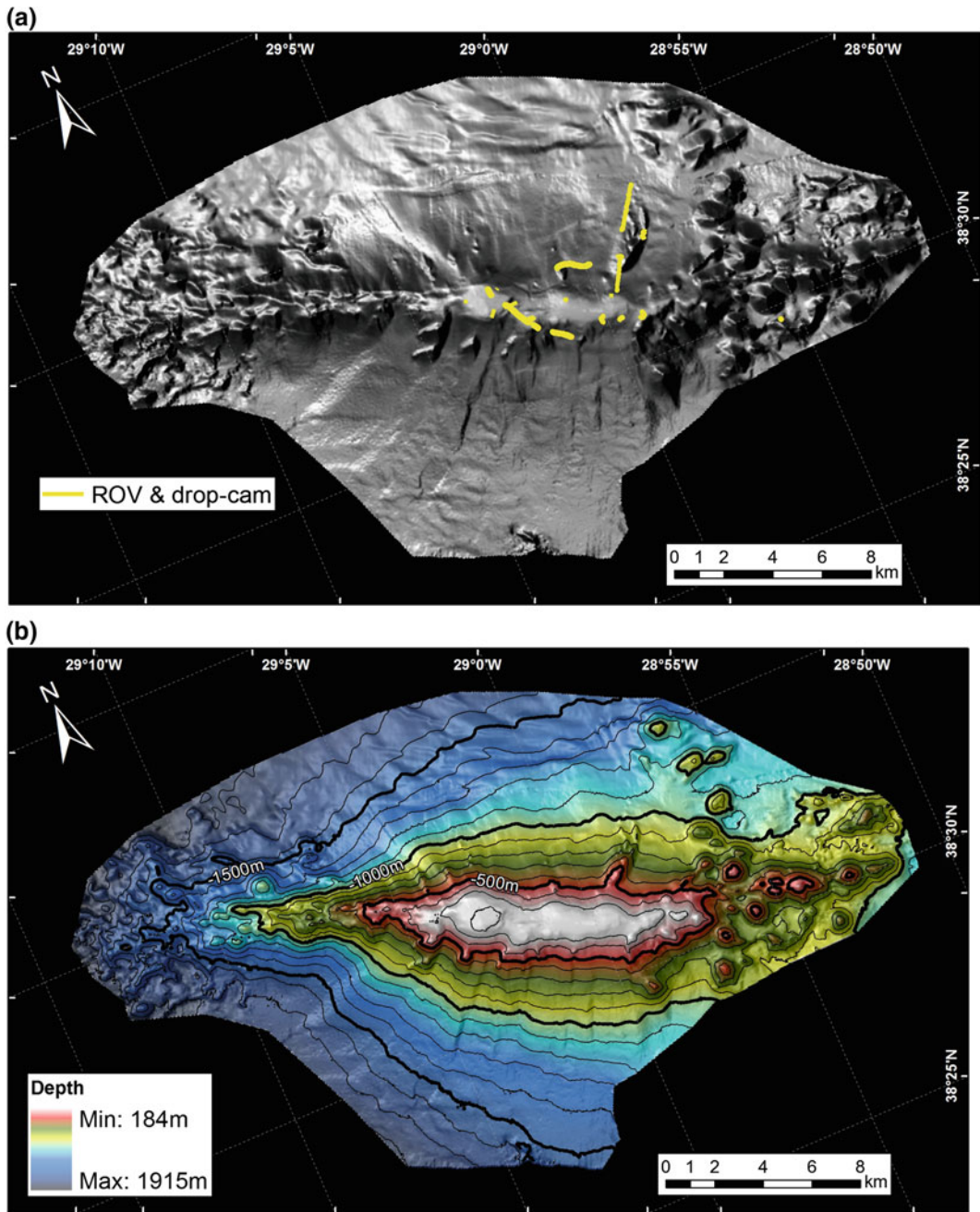


Fig. 8 **a** Shaded relief bathymetry (artificial sun from left of map) and **b** colour-coded bathymetry (10 m contours) of Condor Seamount. Figures adapted from Tempera et al. (2012a) based on data collected with a Kongsberg-Simrad EM120 multibeam sonar and gridded at 50 m. Note the

contrasting morphology of the flanks, which is smooth in the central section (probably slopes of volcanoclastic deposits) and rugged at both ends of the seamount (intact volcanic cones and lavas)

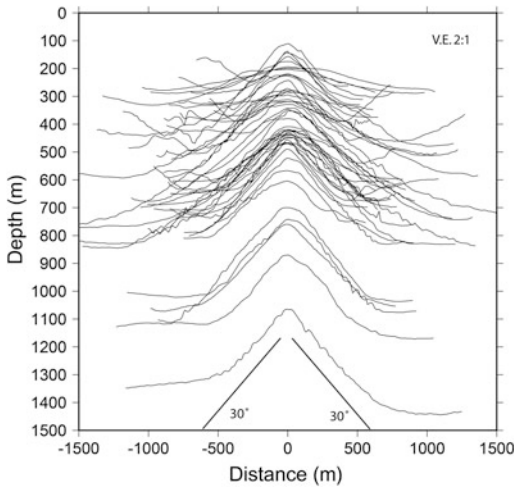


Fig. 9 Bathymetry profiles of the submarine cones from Mitchell et al. (2012a). Vertical exaggeration is 2:1. Whereas the gradients of cone flanks are typically $\sim 30^\circ$, the angle of repose of granular particles, some cones in shallow water have flatter profiles with shallower flank gradients. Two straight lines at base are at 30° to the horizontal

which serve to redistribute material from the summit to the flanks of the cones (Chadwick et al. 2008). Several of the cones in Fig. 6 are associated with small ridges oriented parallel with the submarine Pico Ridge. They have been interpreted as produced by effusive eruption over dykes intruded parallel to Pico Ridge. Clague et al. (2000) have described low-relief flat-topped (coin-like) cones below a depth of 650 m around Hawai'i, which they interpreted as caused by eruption of degassed lava forming submarine lava-lakes. Such features have not been observed in the Azores. The common pointed shapes of cones may indicate that gas-rich eruptions dominate in the Azores and have produced mostly fragmented material.

Figure 7, in contrast, shows some low-relief (mostly <200 m high), rounded cones in shallower water (e.g., cones 29 and 30) with summit depths of 200–300 m. These flatter cones are also evident in the stacked cone cross-sections in Fig. 9, where low-relief rounded profiles are more common for summits shallower than 400 m and steeper cones are more common in the deeper water. These flat cones have been interpreted as

comprising volcanoclastic particles because their acoustic backscattering suggests a smooth surface texture, unlike the rugged morphology of effusive lavas. Their flat profiles may have been produced by eruption into shallow water, which led to forced spreading of the eruption column by the air-sea density contrast (Mitchell et al. 2012a), as predicted by Cashman and Fiske (1991).

The multibeam datasets also reveal a number of possible shallow-water Surtseyan cones. Figure 10 shows an oblique 3D image of bathymetry data from the shallowest part of Princess Alice Bank to the southwest of Faial Island and Condor Seamount. Its summit (50–100 m depth) includes low-relief sub-concentric furrows and ridges. These features are suspected to have arisen from episodic eruption into shallow water (potentially intermittently subaerial) and subsequent wave erosion as observed at Surtla near Iceland (Kokelaar and Durant 1983). Erosion of separate volcanoclastic layers with varying cohesion have left the concentric furrows and ridges. The small mound in the shallowest part of the summit may represent intrusive rocks of the central conduit of the cone that remain after erosion. The small circular features around the margins may be littoral cones.

In 1720 AD, a volcanic eruption between Terceira and São Miguel islands within the Terceira Rift created an island reaching 150 m above sea level, which was subsequently eroded by waves to below sea level, forming Dom João de Castro Seamount (DJdCS, see Fig. 1 for location) (Cardigos et al. 2005; Santos et al. 2010). Bathymetric mapping has revealed that the summit now comprises a 300 by 600 m elongate crater (Cardigos et al. 2005). The shallowest part of the edifice was last reported at 13 m below sea level. In contrast, the summit of volcanoclastic materials on Surtla (Iceland) was eroded down to 45 m depth in the 18 years following its eruption (Kokelaar and Durant 1983). This difference may either reflect different degrees of cementation of the substrate or that bed shear stresses are larger during storms at Surtla associated with longer periods and larger wave heights [100-year significant wave heights are estimated to be 30% higher at Surtla (Sterl and Caires 2005)]. The DJdCS edifice has active

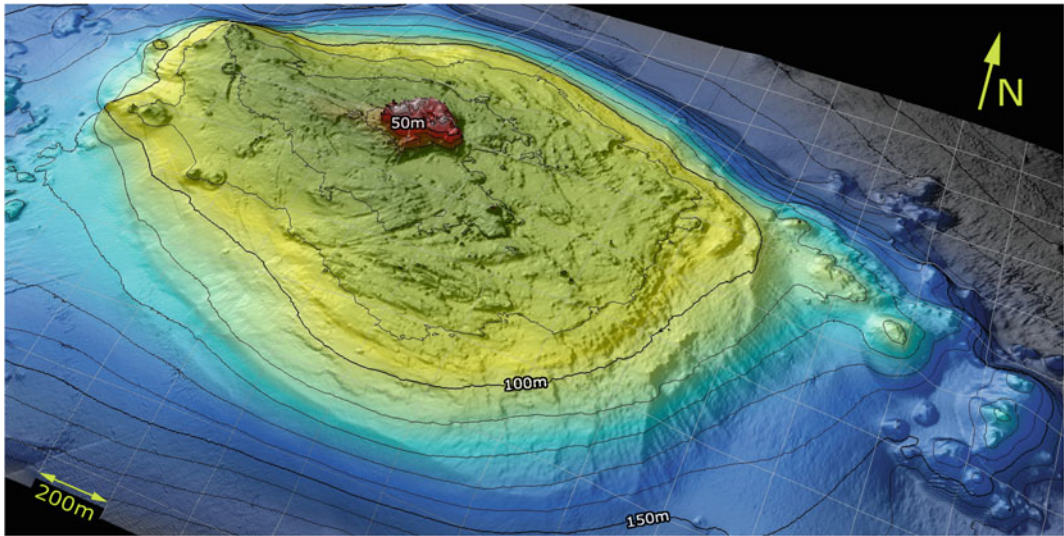


Fig. 10 Possible Surtseyan cone surveyed on the Princess Alice Bank to the southwest of Faial Island and Condor Seamount (oblique view of multibeam sonar data collected with a Kongsberg-Simrad EM120 multibeam

sonar and gridded at 2 m). Note the concentric-like pattern of ridges and troughs on the summit, which are possible evidence for different layers of volcanoclastic particles left after wave erosion. Located by “10” in Fig. 2

hydrothermal vents as shallow as 20 m depth, which emit primarily CO₂ but also other volcanic gases (Cardigos et al. 2005).

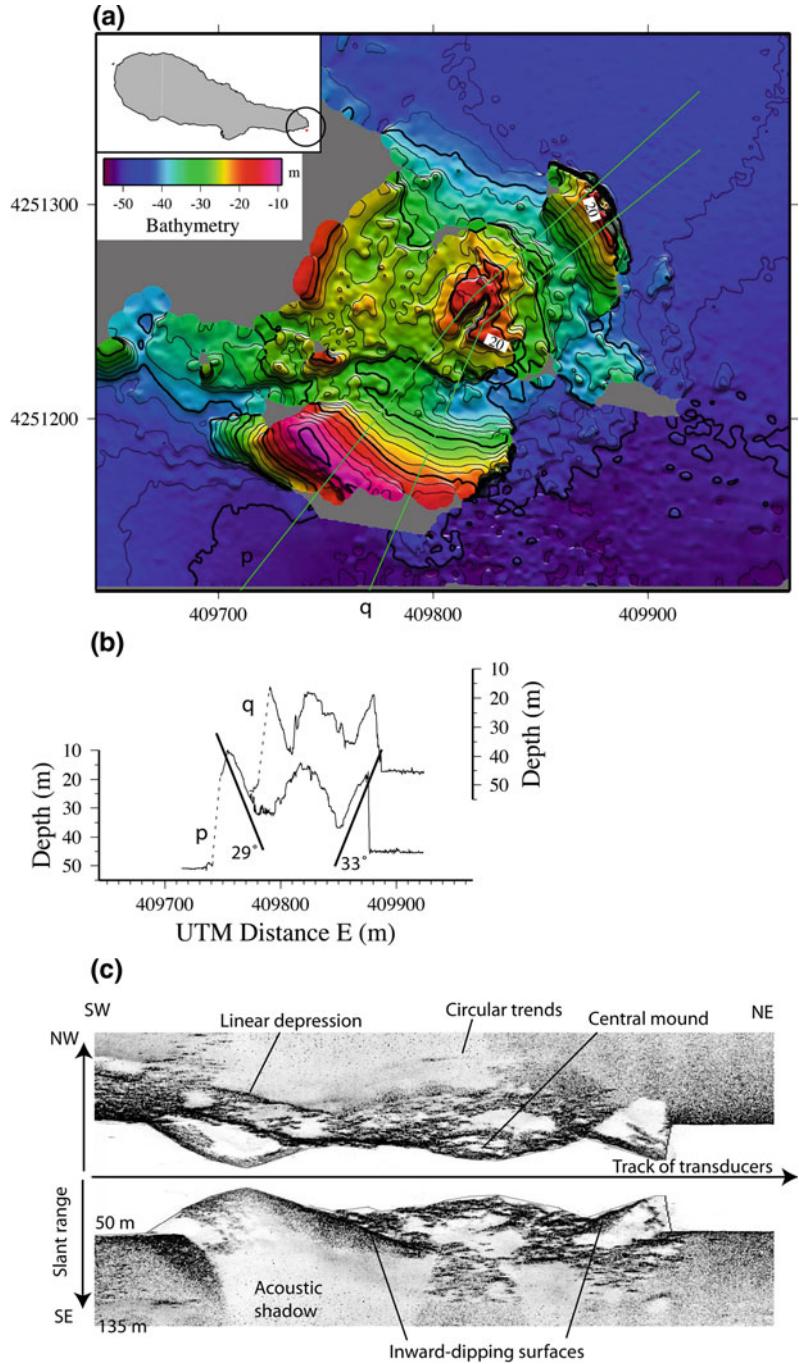
Figure 11a shows an unusual near-shore cone that was previously published in electronic supplementary material to Mitchell et al. (2008). It shows two smooth surfaces dipping towards a central 20–30 m central high mound (best seen in the cross-sections in Fig. 11b). This inward-dipping morphology was also confirmed by the sidescan sonar display of the corresponding backscatter data shown in Fig. 11c collected roughly along line ‘p’. Those data are shown without slant-range correction so that the shape of the seabed can be observed (i.e., the water column has not been removed). Various features can be correlated with the bathymetry map in Fig. 11a, including a linear depression (apparently filled with a highly backscattering, rugged material casting small acoustic shadows), the central mound and the inward-dipping surfaces. In the grey-shaded image in Fig. 11a and where marked “Circular trends” in the sidescan data in Fig. 11c, the inward-dipping surfaces contain concentric furrows and ridges as in Fig. 10. The central mound is highly

backscattering and rugged, casting acoustic shadows. The presence of acoustic shadows close to the track implies very steep outward-facing surfaces (Mitchell 1991). This feature is suggested to have formed by eruption of a littoral cone. The inward-dipping surfaces forming a roughly inverted cone shape probably were created by excavation of central material by hydromagmatic explosions (Mattox and Mangan 1997; Moore 1985), a similar though much smaller structure to that originally produced by the 1957–1958 Capelinhos eruption (Cole et al. 2001). Varied cohesion of clastic materials has left the concentric trends.

6 Submarine Lava Flows

Subaerial lava flows have been observed entering water directly only rarely, for example, around Hawai’i by SCUBA divers (Moore et al. 1973). Other observations have been on already emplaced lavas, for example, deeper lavas mapped with sonar data and submersible dives and sampled for geochemistry around Hawai’i (e.g., Wanless et al. 2006) and with sonar data in a lake

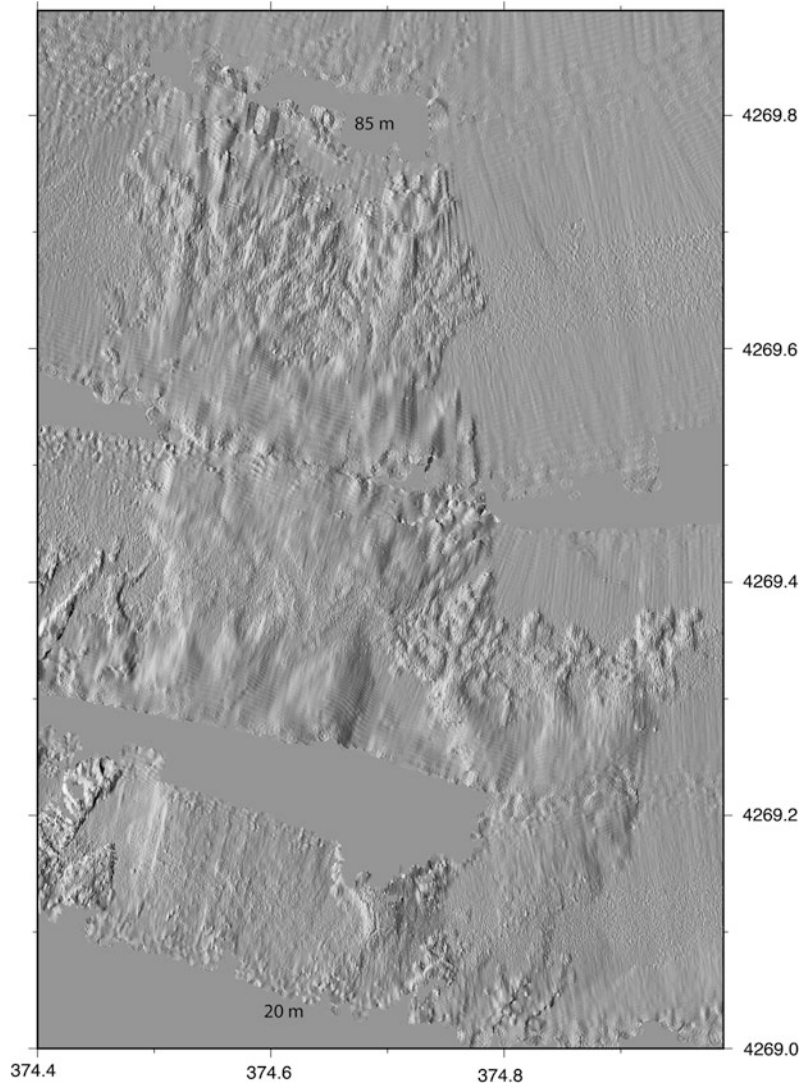
Fig. 11 a Multibeam bathymetry data showing an unusual littoral cone off the east coast of Pico Island (from the 2003 Reson 8160 survey). Coordinates are UTM metres and artificial sun is from the northeast. The data are gridded at 0.25 m and contoured at 2 m intervals with every 10 m in bold. **b** Depth profiles along two separate lines located in (a). Straight lines against profiles and associated numbers are representative gradients (corrected for directions of the lines). Profile q has been offset vertically for clarity. Map is located by “11” annotation in Fig. 2. **c** Sidescan sonar display collected with the Reson 8160 multibeam approximately along line p in (a). Black represents high backscattering and white represents low backscattering or acoustic shadows cast by seabed features. In order to show the shape of the seabed profile, the image data have not been corrected for slant-range distortions. Distances from the central track are acoustic slant ranges from the transducers (values in the lower-left; seabed echo for example is at 50 m depth)



on Iceland (Stevenson et al. 2012). One remarkable LiDAR dataset has been collected by Japanese scientists of a lava flow that entered a lake near Mount Fuji and is now exposed following draining of the lake (Obata and Umino

1999). Systematic mapping of such features around the nearshore parts of volcanic islands has been rare, however. The 2003 multibeam survey in the Azores was effective because the small draft of the RV *Arquipelago* permitted

Fig. 12 Lava flow on the shelf immediately north of where the historical flow produced by the 1718 AD eruption on Pico entered the ocean revealed in multibeam bathymetry data collected during the 2003 Reson 8160 survey (located by small box above “12” in Fig. 2). The depth data have been gridded at 0.25 m and are shown in shaded-relief form with an artificial sun from the NW. Coordinates are UTM distance in km. Depth variation is indicated by “20 m” and “85 m” annotation [colour depth-coded version was shown in Mitchell et al. (2008)]



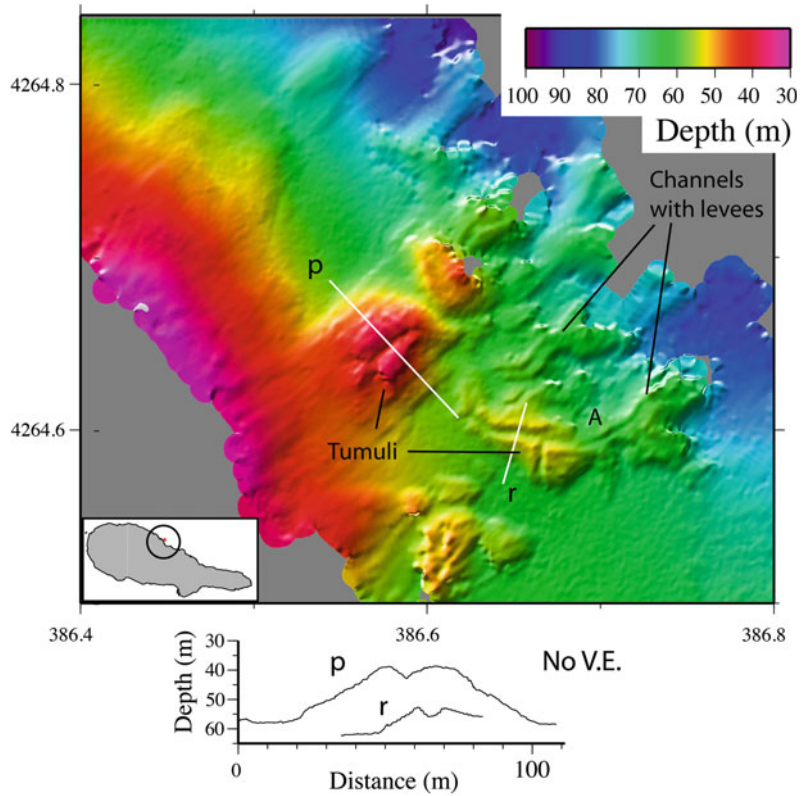
surveying close to coasts and the crew were familiar with the working environment.

Mitchell et al. (2008) described many off-shore lava structures revealed in the 2003 Reson 8160 multibeam bathymetric data, which they argued were mostly Holocene in age. Figure 12 shows a shaded relief image of data collected immediately seaward of where an ‘a’ lava flow entered the sea in 1718 AD. The lava on land immediately adjacent to this image (underlying the airport of Pico Island) has the blocky morphology of ‘a’ lava. However, the underwater flows in Fig. 12 show a remarkable series

of branching flow lobes, forming a dendritic pattern, quite unlike the rounded fronts of ‘a’ lava typically found on land. Individual flow lobes in Fig. 12 are 5–10 m in vertical relief, while the central body of the flow is about 20 m in relief. The flow front was shown to be a statistical fractal within the limits of the data resolution, with a fractal dimension more similar to those of pahoehoe than ‘a’ flow fronts.

Many examples of these dendritic flow morphologies were found around Pico Island and some examples have also been mapped around Faial (Quartau et al. 2012). Pahoehoe lavas on

Fig. 13 Shallow-water bathymetry (2003 Reson 8160 survey) showing two tumuli and flows with levées on the central north shelf of Pico Island. The depth data have been gridded at 0.25 m and are shown with shading from the NW. Coordinates are UTM kilometres



land typically develop a viscoelastic layer as they cool, forming the strongest part of the lava surface (Hon et al. 1994). Pahoehoe lava fields evolve by successively inflating lobes under this viscoelastic layer like oblate balloons until the visco-elastic layer ruptures allowing a new lobe to form at a breakout. Given the similar branching patterns of these submarine lavas to pahoehoe, in Mitchell et al. (2008) the branching behaviour was speculated to have arisen from a similar development. Enhanced cooling by sea-water entering cracks on the lava surface was suggested to thin the visco-elastic layer of the lava locally, reducing its strength and rendering it susceptible to breakouts. Thus, whereas cooling might be expected to toughen lava (and solidification will clearly reduce mobility ultimately), initial irregular cooling may actually promote mobility. The fractal-like branched patterns of the lava then occur because of episodicity in lava pressure arising from flow discharge variations and from the distribution of open cracks in the

lava surface controlling the locations of breakouts. Measurements of heat loss on actively flowing lava along with its evolving morphology are needed to test whether this occurs in practice.

Figure 13 shows further examples of lava flows, in this case revealing the typical clefts of 10–20-m-high tumuli and flow channels with levées in front of a coastal lava delta. The former is evidence that pressure varied within the flow beneath the crust during emplacement, as typically occurs during emplacement of subaerial lavas (Hon et al. 1994).

7 Gross Morphology and Structure of Island Flanks

The submarine slopes of volcanic ocean islands can be broadly classified into two types on the basis of gross morphology in profile—smooth and concave, or rugged and steep. Debris avalanches (produced by catastrophic collapses

(Moore et al. 1989) or smaller downslope movements of volcanoclastic sediments) leave smooth, low-gradient slopes with exponential-like profiles, whereas slopes constructed of lava or affected by deep-seated slumps tend to be more rugged (varied gradient) and steeper (Gee et al. 2001b). In submarine slopes offshore from lava deltas, gradients are also typically steep, reaching 28° – 30° , the angle of repose of rock talus in tectonically active marine environments (Mitchell et al. 2000). Unlike in the Canary Islands where submarine channels commonly lie immediately below onshore valleys (Krastel et al. 2001; Mitchell et al. 2003), the submarine slopes of the Azores islands contain few deep submarine channels or canyons.

Graphs of the statistical characteristics of seabed gradients for sectors of island slopes plotted versus elevation can be useful to characterise the slope profiles semi-objectively. For example, the median average of gradient magnitudes and their inter-quartile range (a measure of variability somewhat similar to standard deviation but less affected by outliers) can be computed in given depth intervals. Plotting those gradient statistics versus elevation for Pico and Faial Islands (Mitchell et al. 2008; Quartau and Mitchell 2013) reveal that they are most like those of constructional flanks or those containing debris below lava deltas (Quartau et al. 2015b) and unlike those of debris avalanches, supporting the contention below that the islands have experienced few major catastrophic landslides. In both cases, the median gradient increases from around 5° or less around the deep base of the islands to 23° – 28° just below the shelf break.

Low sulphur contents of lava emplaced on the deep submarine flanks of Hawai'i were speculated by Garcia and Davis (2001) to be due to the lava having originally degassed on land and then emplaced in the submarine environment, potentially via lava tubes. The submarine parts of islands may thus not necessarily be formed by direct eruption of lavas. Unfortunately, the smooth morphology of Kilauea down-slope from where lava enters the sea suggests that the lava usually breaks up to form a steep ramp of clastic material (Moore and Chadwick 1995) so details

are commonly obscured. The submarine parts of volcanic islands are much larger by volume than their subaerial parts, so resolving which of these alternatives (direct eruption or material provided from land) is more common in the Azores is important to understanding the growth of islands. Most of the lava flows mapped in 2003 in the Azores (Mitchell et al. 2008) terminated on the relatively flat shelf, though some, such as those in Figs. 12 and 13 reached the outer shelf. One example was traced to nearly 400 m depth on the southwest side of the island. Unfortunately, these observations still cannot resolve which alternative applies best to the Azores because the lack of lava flow structures on the steeper submarine slopes may either represent a problem of sonar resolution at those depths or that lava may simply disintegrate to a breccia quickly after emplacement on steep slopes (which reach the $\sim 30^{\circ}$ angle of repose immediately below the shelf break) as has been observed around Kilauea (Sansone and Smith 2006).

8 Landslides

With systematic mapping with sonars around many oceanic islands, the early observations of widespread landslides (Holcomb and Searle 1991; Moore et al. 1989) have been generally confirmed (Keating and McGuire 2000). However, the Azores islands are unusual in that only two large landslides are revealed by the subaerial geomorphology (Mitchell 2003). One lies in the southeast side of Pico Island [Topo volcano, Fig. 14, Costa et al. (2015)]. A smaller embayment on the south subaerial flank of Pico volcano was dismissed as unlikely in Mitchell (2003) but probably also is a landslide based on the presence of an embayment of the volcano topography on land typical of a landslide headwall. More recently, Costa et al. (2014) have interpreted two further landslides using multibeam data from the Pico-São Jorge channel. Such landslides, if they were to occur today, could produce unusually large tsunami impacts on the adjacent island coasts because the channel may effectively form a reflecting waveguide (Omira et al. 2016).

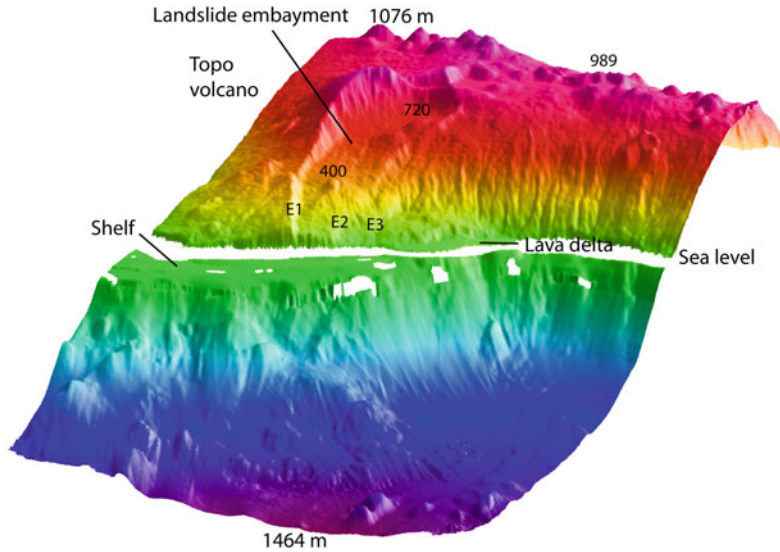


Fig. 14 3D oblique view of topography and bathymetry data from the south coast of Pico Island showing slump structure on land (Mitchell et al. 2012b) (view location shown by the arrow in Fig. 2). Numbers 400–989 are altitudes (m) of volcanic cones identified as potential

sources of lava forming the Holocene lava delta marked on the figure. Geophysical data collected on the shelf just below sea level here show little evidence of relief on faults, suggesting little movement of the slump has occurred during the Holocene

The conditions at the time of failure are unknown for major pre-historic landslides, hence many reasons for failure have been suggested (Keating and McGuire 2000). However, the lack of major landsliding in the Azores is consistent with the observation that landslides or sector collapses are common in volcanic ocean islands and seamounts taller than 2500 m but rare in those shorter than 2500 m (Mitchell 2003) as the Azores Islands lie on an elevated plateau (Fig. 1a). In oceanic seamounts and guyots, this transition also coincides with a transition in the shapes of seamounts, whereby the taller edifices are more star-like in plan-view, with radiating volcanic ridges (Mitchell 2001). Landslides commonly form embayments between the ridges, thus contributing to the star-like morphology. The fact that volcanic rift zones occur in the Azores (where they appear in shorter edifices than in the global pattern) thus reflects their plate-tectonic rather than volcano-tectonic origin.

Some of the explanations for deep-seated slumping that have been suggested for the Hawaiian islands probably do not apply here. For example, the Hawaiian islands are built on a

layer of impermeable hemipelagic sediment which forms a basal décollement (Moore et al. 1994), a ductile layer of thick olivine cumulates may induce movement (Clague and Denlinger 1994) and over-pressuring of pore fluids during intrusions may temporarily elevate fluid pressures (Elsworth and Voight 1995). The presence of an igneous basement in the Azores may imply higher permeability than beneath the Hawaiian islands and there is likely to have been less compaction of volcanic materials leading to permeability reduction given the shorter elevations of the islands, so pore fluids are potentially less pressurized. The lower volcanic building rate suggests that major bodies of hot olivine cumulate are less likely, although a density anomaly suggesting a possible intrusion has been identified in the SE of Pico Island (Nunes et al. 2006) beneath the slump described below.

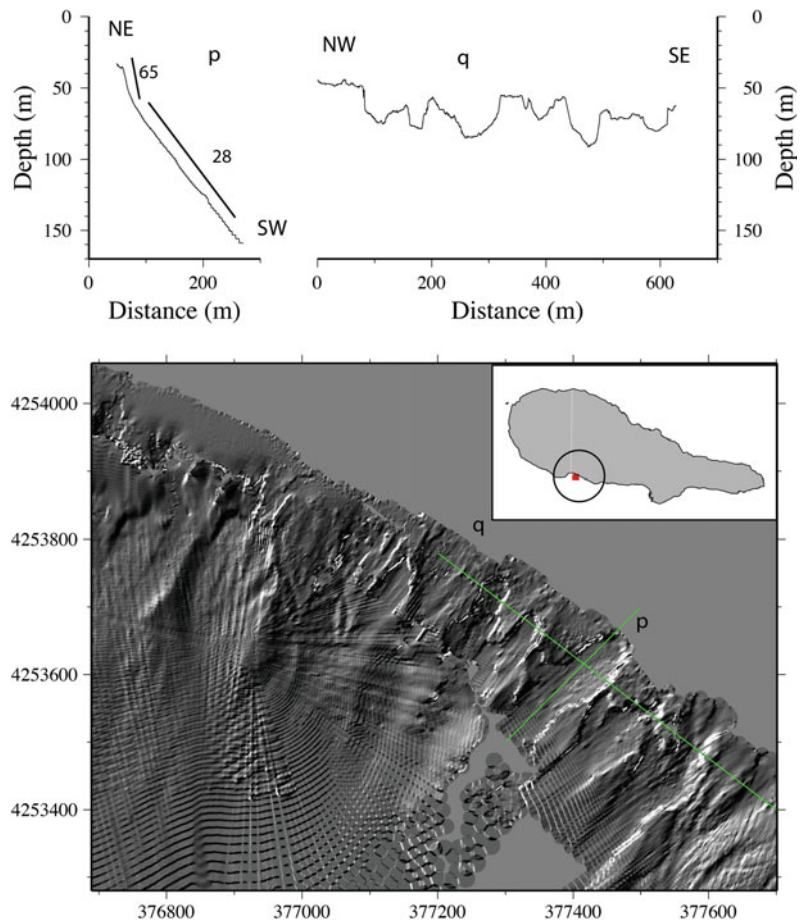
Despite the general absence of major slumping, there is potential evidence that one of the slumps is active, a rare feature of volcanic ocean islands and so worthy of further study. Mitchell et al. (2012b) studied the Topo landslide using boomer seismic and chirp sediment profiler data collected on the

shelf as well as coincident multibeam data. The island shelves were last modified by surf erosion during sea level transgression after the last glacial maximum (Quartau et al. 2010) so the presence or absence of relief on faults can help reveal whether they have been active in the Holocene after they became isolated from surf. Where the three onshore escarpments E1-E3 observed in Fig. 14 continue offshore, little evidence was found of fault relief on the shelf. Furthermore, no offsets are observed in the lavas on land within the east and north sides of the landslide embayment (Madeira 1998). In contrast, Hildenbrand et al. (2012) have published GPS and InSAR data, which suggest that parts of the coast here within the landslide embayment are presently mobile and some evidence from a separate GPS campaign (Madeira, personal communication, 2012) also suggest the

feature is mobile at the coast. The apparent discrepancy between these results might indicate that the landslide has only recently begun moving (Mitchell et al. 2012c).

In the uppermost submarine slopes of the islands, smaller, superficial landslides are common (Mitchell et al. 2008; Quartau et al. 2012). For example, the multibeam data in Fig. 15, from the south coast of Pico Island show a number of embayments of the uppermost slope forming discrete depressions of the seabed. The depressions, which are several 10 s of metres deep, probably represent failure of material that is cohesive, because steep head- and side-walls remain (steeper than the $\sim 30^\circ$ angle of repose of granular material). Whereas the hazards from major landslides have received attention as potentially causing ocean-traversing tsunamis

Fig. 15 Examples of surficial landslides in the uppermost slope of south Pico Island in shaded relief imagery of the 2003 *Arquipelago Reson* 8160 multibeam sonar data (shaded from the upper-left). The data have been gridded at 0.25 m. Fan-shaped pattern on left is an artifact from where the vessel was turning. Lines locate the cross-sections shown in upper panels. Values above cross-sections are gradients in degrees (the steep headwall gradients above the typical angle of repose of clastic material $\sim 30^\circ$ suggest that the failed material has finite cohesion). Coordinates are UTM metres



(Ward and Day 2001), these smaller landslides may present a threat to local populations by creating smaller but nevertheless locally significant water surges. Such a surge was caused by a landslide entering the sea at Stromboli island, Italy (Tinti et al. 2005). Similar upper submarine slope landslides may explain some of the local tsunamis in the Azores that have not been associated with specific earthquakes (Andrade et al. 2006). Although much smaller than the large trans-ocean tsunamis, such small landslide events are probably more frequent.

9 Future Submarine Research in the Azores

Further work on the morphology of volcanic structures can be expected to be published over the coming years, based on the new datasets. The islands of Flores and Corvo remain to be surveyed but evidently will likely reveal interesting features if surveyed also. The potentially active slump in south Pico should be subject to detailed monitoring. Given the number of lava flows and cones now well characterised in the various kinds of sonar data, there is ample scope for more detailed work based on samples, photographic observations and relating their structures to lavas on land (requiring perhaps scientific diving). However, although there is certainly much to be learned though “forensic” earth science, a remaining challenge will be to observe active processes with the level of detail that is common in subaerial volcanology (Mitchell 2012d). For example, the branching behaviours of these submarine lava flows may reflect an interesting effect of cooling by seawater on their visco-elastic layers, an inference that is difficult to test with further observations of already emplaced flows. In the ocean, we are unable to measure temperatures with infra-red emissions as is possible on land but heat flow might instead be measurable from heat advection above actively developing submarine lavas and could be combined with morphologic and other data from autonomous vehicles.

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