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Large-scale catastrophic flank collapses in a steep volcanic ridge: The Pico–Faial Ridge, Azores Triple Junction

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ABSTRACT

Large-scale flank collapses are common in the geological evolution of volcanic ocean islands in the Atlantic. To date, catastrophic lateral collapses in the Azores Islands have been difficult to identify, leading to suggestions that a lack of events may relate to the relatively small size of the islands. Here we show evidence for two major collapses on the northern flank of Pico Island (Pico–Faial volcanic ridge, central Azores), suggesting that this island had a collapse incidence similar to that of other Atlantic volcanic islands.

The study is based on the analysis of: (1) offshore and onshore high-resolution digital elevation models; (2) field data focused on the N flank; and (3) new K–Ar ages on selected lava flow samples.

Pico sub-aerial northern flank is marked by two conspicuous arcuate shaped depressions concave towards the sea, here interpreted as landslide scars. A main debris field is observed offshore the largest depression. This deposit has 20 km of maximum length, covers ca. 150 km^2, is composed of meter to hectometer blocks, and has an exposed volume here estimated between 4 and 10 km^3, though the actual volume probably exceeds 10 km^3. Debris flow towards the ESE was apparently determined by the slope of the narrow WNW–ESE S. Jorge channel.

Young lava flows cascade over the interpreted scars, thus concealing the older volcanic sequence(s) affected by the landslide(s). New K–Ar ages measured on these lava flows provide a minimum age of ca. 70 ka for the large-scale collapse(s) in Pico's northern flank.

1. Introduction

The destruction of volcanic islands occurs at small and large scales, gradually or suddenly on catastrophic events. Large-scale flank failure in volcanic islands can involve either gradual movement along deep listric faults (slump) or the generation of debris avalanche (Moore et al., 1989). These two mechanisms are not mutually exclusive, as a creeping slump may suddenly turn into a catastrophic debris avalanche. From on-land and offshore studies, catastrophic large-scale mass wasting has been identified on volcanic islands all over the world (e.g., Duffield et al., 1982; Moore et al., 1989; Gillot et al., 1994; Deplus et al., 2001; Krastel et al., 2001; Masson et al., 2002; Hildenbrand et al., 2006). In the Atlantic, more specifically, catastrophic failure episodes have been extensively documented, e.g. in the Canary (Navarro and Coello, 1989; Carracedo et al., 1999; Krastel et al., 2001; Masson et al., 2002; Boulesteix et al., 2012, 2013), in Cape Verde (e.g., Day et al., 1999; Masson et al., 2008), and along the Caribbean arc (Deplus et al., 2001; Le Friant et al., 2003; Samper et al., 2007; Germa et al., 2011).

To date, catastrophic flank collapses in the Azores Islands have been difficult to identify, leading to suggestions that a lack of collapses may relate to the relatively small volume of individual islands and volcanic ridges (e.g. Mitchell, 2003). Two topographic embayments on the southern flank of Pico Island have been related to lateral flank movement in the form of old catastrophic landslides or slumping processes (Woodhall, 1974; Madeira, 1998; Nunes, 1999, 2002; Madeira and Brum da Silveira, 2003; Hildenbrand et al., 2012b, 2013b; Mitchell et al., 2012, 2013), but none of these features is clearly and unambiguously associated with well-identified offshore deposits.

Here we put forward evidence of two major collapses, and respective submarine deposits, on Pico's northern flank, showing that the island has experienced episodes of flank instability like other Atlantic volcanic islands.

The identification of offshore debris deposits and the interpretation of onshore source zones in Pico's northern flank are here primarily based on morphological characterization, through combined analysis of a 10 m resolution sub-aerial digital elevation model (DEM) and the new 50 m resolution bathymetry of the narrow S. Jorge Channel (between Pico's northern flank and S. Jorge's southern flank). The analysis of the bathymetry also supports the discussion of the influence of channel morphology on the landslide submarine flow and deposition.

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In order to determine the age and recurrence of the failure events, we performed fieldwork focused on the establishment of volcanic stratigraphy/structure of the source zones, aiming at finding possible landslide scars/deposits and to sample the volcanic sequences affected by and covering the landslide related features. The sampled rocks were then processed according to the K–Ar Cassignol–Gillot unspiked technique.

2. Geologic setting

The Azores Islands are located about the triple junction between North-America, Eurasia and Nubia plates (Fig. 1). The study region is located on the locally diffuse Nubia/Eurasia plate boundary (Lourenço et al., 1998; Fernandes et al., 2006; Borges et al., 2007; Marques et al., 2013), where regional deformation has influenced the development of narrow and steep volcanic ridges (Fig. 1). The volcanic ridges of S. Jorge and Pico–Faial (Fig. 1) are characterized by slopes commonly around 25–35°, locally reaching higher values along coastal cliffs. These ridges are characterized by a multi-stage development during the last 1.3 Myr (Féraud et al., 1980; Demande et al., 1982; Hildenbrand et al., 2008, 2012a). This multi-stage development includes short periods of volcanic construction interrupted by long periods of island destruction. The island destruction processes are either gradual (e.g., erosion, graben development) or catastrophic like the events here reported. The growth of the sub-aerial Pico–Faial ridge started ca. 850 ka ago on the eastern part of Faial Island (Quartau et al., 2010, 2012; Hildenbrand et al., 2012a, 2013a; Quartau and Mitchell, 2013), with the growth of sub-aerial Pico during the last ca. 300 ka (Fig. 2, 250 ± 40 ka, in Demande et al., 1982). The oldest outcropping volcanic unit in Pico, the Topo Unit (TU), is located on its SE flank (Fig. 2), which is deeply affected by a currently active slump structure (Hildenbrand et al., 2012b) (Fig. 3, feature 1). A WNW–ESE fissural system (FS) developed N of Topo (Fig. 2), and a stratovolcano (Fig. 2, PS) constitutes the westernmost part of the island (Fig. 2, e.g., Forjaz 1966); both have been volcanically active through the Holocene and in historic times (Madeira, 1998; Nunes, 1999; Mitchell et al., 2008). Two topographic embayments on Pico's northern flank (Fig. 3) were considered by Mitchell (2003) as “ambiguous candidates for landslides”. Mitchell et al. (2008) identified a hummocky terrain area on the shallow bathymetry (depth up to of a few hundred meters) adjacent to a sub-aerial embayment (Fig. 2 in Mitchell et al., 2008, feature A), which was interpreted as a deposit resulting from debris avalanche or repeated lava delta failure. Despite these evidences, to date the published works (e.g., Mitchell, 2003; Mitchell et al., 2008) do not conclude unequivocally on the occurrence of major landslides in Azores islands.

3. Morphological analysis

3.1. Construction of the DEMs

The submarine grid of the deepest sector of the Pico–S. Jorge channel (50 m resolution, Fig. A.1a) was constructed using the multibeam data acquired with a 12 kHz Kongsberg EM120 multibeam echo sounder system (Lourenço, personal communication). The depth accuracy (RMS) for this system is estimated as 0.2–0.5% of the water depth (Kongsberg, 2007). Considering that the maximum water depth in the study area is ca. 1300 m, the maximum RMS expected for this data set lies in the range 2.6–6.5 m.

The multibeam data were processed using the CARIS software, clean of noise and converted to an ASCII file (Lourenço, personal communication). Next, the 50 m resolution ASCII data were converted to a raster structure of 50 m spatial resolution, using a simple gridding method.

The onshore data used in this study was produced from a digital topographic map of Pico Island (Portuguese Army Geographic Institute, IGeoE). Photogrammetric methods led to the production of this information at the 1:25,000 scale. The vertical accuracy of these data is approximately 5 m (Afonso et al., 2002). The nodes and lines with three-dimensional coordinates (x, y and z) of the contour lines were then used to generate a TIN (Triangulated Irregular Network) model, which is a vector-based representation of the relief based on a network of non-overlapping triangles (Burrough and McDonnell, 1998). The conversion of the TIN model to a raster structure was then performed interpolating the cell z-values from the input TIN at the spatial resolution of 10 m and 50 m to produce the final onshore DEMs for Pico Island (10 m spatial resolution), S. Jorge and Faial Islands (50 m spatial resolution). To this purpose, we used the ArcGIS 9.3 software from ESRI with the 3D Analyst extension. For the final grid, we introduced in the no-data zone on Pico's northern coast (between the sub-aerial and submarine grids described above) the 100 m spaced contours obtained from photogrammetry of Fig. 2 in Mitchell et al. (2008). The final 50 m resolution grid was built through combination of the sub-aerial and submarine DEMs described above (Fig. 4), filling the no-data zone with a 200 m resolution interpolation that included the depth contours

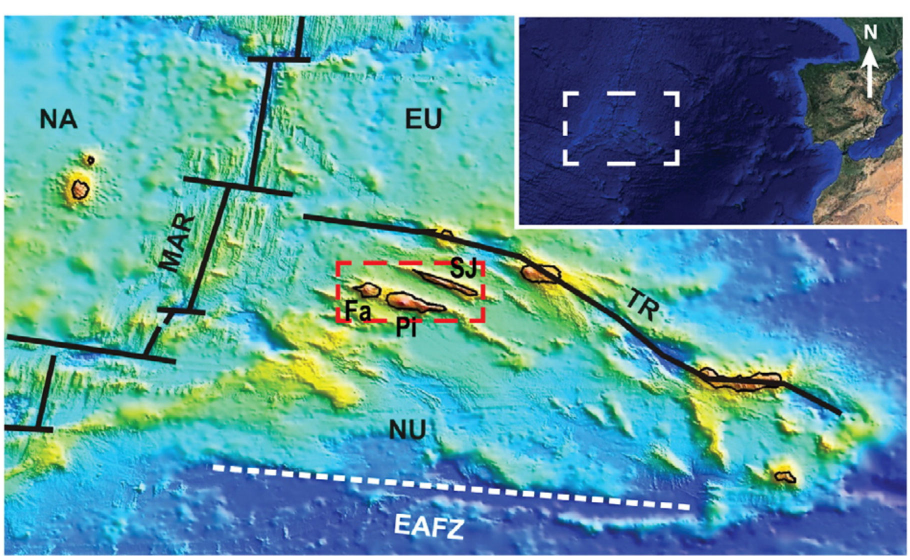

Fig. 1. Location of the Azores archipelago on the triple junction between the North America (NA), Eurasia (EU) and Nubia (NU) plates. Main active structures represented as thick black lines (Middle Atlantic Ridge — MAR, Terceira Rift — TR) and inactive structure as dashed white line (East Azores Fracture Zone — EAFZ). The white dashed rectangle encompassing the islands of Pico (Pi), S. Jorge (SJ) and Faial (Fa) limits the study area. Bathymetric data from Lourenço et al. (1998); Image available at http://w3.ualg.pt/~jluis/acores_plateau.htm. (right top rectangle) Inset for the location of the Azores Triple Junction (Google Earth image — 19-08-2013).