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Marine terrace development on reefless volcanic islands: New insights from high-resolution marine geophysical data offshore Santa Maria Island (Azores Archipelago)

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ABSTRACT

Submerged marine terraces are relict coastal erosional landforms now underwater due to rising sea level and/or land subsidence. Using as case study the shelf around Santa Maria Island (North Atlantic Ocean), we intend to advance our knowledge on the formation and preservation of these features on reefless volcanic islands. Santa Maria is an ideal place to study their combined generation, since it displays a sequence of subaerial and submerged marine terraces (the latter not studied before), distributed between 7/230 m in elevation, and −40/−140 m in depth, respectively. Based on some geological constraints, we investigated a possible correlation between the formation of the different terraces with known sea-level changes. Our results suggest that the spatial distribution of marine terraces at Santa Maria depends on the complex interplay between glacio-eustatic sea-level fluctuations, the island's vertical motion trends, the morphology of the shelf, and the intensity of marine erosion. Subaerial terraces probably developed from ~3.5 Ma to ~1 Ma following a fortuitous conjugation of optimal exposure to energetic waves and a suitable arrangement/lithology of the stratigraphic units promoting easier erosion. Their preservation was likely promoted by the uplift trend the island experienced in the last 3.5 Ma, which was rapid enough to prevent their destruction by subsequent highstands. The submerged terraces, presumably all younger than ~1 Ma, were largely influenced by shelf gradient, leading to more developed and preserved terraces in wider and low-gradient sectors. Displacement by active faults also conditioned the formation and further development of both subaerial and submerged terraces, with tectonic activity documented for the 0.693 Ma–2.7 Ma period.

1. Introduction

Relative sea-level changes have left unambiguous morphologies in the geological record, as attested by the presence of coastal notches (e.g. Ferranti et al., 2006; Trenhaile, 2015), marine terraces (e.g. Zazo et al., 2002; Pedoja et al., 2014) and beach rocks (e.g. Mauz et al., 2015). In submarine settings the effects of glacio-eustatic sea-level changes can be witnessed by markers such as the shelf breaks on insular shelves (Quartau et al., 2014) or depositional features formed below storm-wave base (e.g. submarine prograding wedges; Casalbore et al., 2017 and references therein). Marine terraces are frequently referred to as excellent tracers of palaeo sea-level (Pirazzoli et al., 1993) and they can be used to discern the vertical movements affecting the coastline (Campbell, 1986; Ferranti et al., 2006; Zazo et al., 2007). This approach has been successfully applied to study the history of uplifting volcanic islands (see Lucchi et al., 2007; Lucchi, 2009 and Ramalho et al., 2017) where vertical deformations usually operate at varied timescales (De Guidi and Monaco, 2009; Ramalho et al., 2013). Most studies so far did not integrate the offshore information (Quartau and Mitchell, 2013; Quartau et al., 2015), and when they did, mostly focused on oceanic

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islands surrounded by coral reefs (Coulbourn et al., 1974; Blanchon and Jones, 1995; Faichney et al., 2010). To date, only few studies have looked closely at submerged terraces on reefless volcanic islands or at seamounts (Passaro et al., 2011; Schwartz et al., 2018) and consequently little is known about the factors that control the generation and timing of submerged terraces in these settings.

Santa Maria is the southeastern-most and oldest island of the Azores Archipelago in the Atlantic Ocean, with a history of intermittent volcanism spanning between approximately 6 to 2.8 Ma (Sibrant et al., 2015; Ramalho et al., 2017). Its subaerial evolution is now well constrained (Serralheiro et al., 1987; Serralheiro, 2003; Ávila et al., 2008; Sibrant et al., 2015; Ramalho et al., 2017) and so is the history of vertical movements affecting the island edifice. Based on several volcanic, erosional, and sedimentary relative sea-level markers found onshore, Ramalho et al. (2017) inferred that Santa Maria was subjected to over 200 m of subsidence from emergence at 6 Ma until 3.5 Ma BP (at average ~100 m/m.yr), after which the island experienced an uplift trend at a slower pace (~60 m/m.yr on average) until recent times. Additionally, Ramalho et al. (2017) reported a sequence of subaerial marine terraces at elevations ranging between 7–11 m and 210–230 m, formed during the post-erosional stage of the island. In this paper, the analysis of newly acquired high-resolution multibeam bathymetry and seismic profiles reveal a sequence of submerged marine terraces extending to the shelf edge. This makes Santa Maria an ideal case study to employ a combined onshore/offshore approach to investigate the generation of subaerial and submerged marine terraces and their likely timing of formation in relation to the island's vertical motion history. Based on one dated subaerial terrace and a dated passage zone between subaerial and submarine lava flows (which were used as “anchor” points), we also present a possible correlation between each subaerial and submerged terrace identified on the island and their respective possible time of formation, as extracted from published eustatic curves. The case study of Santa Maria therefore will improve our understanding of the controlling mechanisms of marine terrace formation and preservation at reefless volcanic islands, and more generally in other settings.

2. Geological background

The Azores Archipelago consists of a group of nine volcanic islands in the mid-North Atlantic, located around the triple junction between the North American, Eurasian and Nubian lithospheric plates (Fig. 1). The Eastern (São Miguel and Santa Maria) and Central group of islands (Terceira, Graciosa, São Jorge, Pico, and Faial Islands) are located on a roughly triangular-shaped area between the Terceira Rift (TR in Fig. 1) and the inactive East Azores Fracture Zone (EAFZ in Fig. 1) on the eastern side of the Mid-Atlantic Ridge (MAR in Fig. 1; Lourenço et al., 1998; Gente et al., 2003; Miranda et al., 2018). This complex volcano-tectonic structure is the result of a right-transtensional shear zone that links the MAR with the Gloria Fault (GF) (Hipólito et al., 2013; Lourenço et al., 1998; Marques et al., 2013). Santa Maria Island is considered now outside the influence of such wide structure after a ridge-jump, occurred at ~4 Ma, from the incipient Princess Alice Rift (PAR in Fig. 1) to the present-day Terceira Rift (Miranda et al., 2018).

Santa Maria was the first island in the Azores Archipelago to emerge above sea level, at approximately 6 Ma (Ramalho et al., 2017). The present-day edifice rises from the −2500 m isobath to a summit at 587 m (Pico Alto, Fig. 2). The emergent stage of island building corresponds to the Cabrestantes and Porto Formations, which crop out on the western side of the island (age ~ 6 Ma, Fig. 2a). Then, a subaerial shield volcano was formed about 5.8–5.3 Ma, which consolidated the island edifice (Anjos Volcanic Complex, Fig. 2a). During the following ~1 Ma, volcanic activity waned, leading to a partial or complete dismantling of the shield volcano and to marine deposition synchronous with occasional, low-volume submarine volcanism (Touril Volcano-sedimentary Complex, Fig. 2a). This stage is considered as mainly erosional and occurred alongside a significant subsidence trend, which further contributed to the planation and possibly complete submergence of the island edifice (Ramalho et al., 2017). At ~4.1 Ma, however, renewed volcanic activity, which culminated in the creation of the Pico Alto Volcanic Complex (Fig. 2a), caused the edifice to re-emerge, as attested by the vertical succession of submarine and subaerial volcanic products. At ~3.5 Ma subsidence reversed into uplift, as attested by the presence of raised submarine volcanic sequences and a succession of subaerial marine terraces on the western (windward) side (Ramalho et al., 2017), arranged in a typical staircase morphology. Conversely, the eastern (leeward) side is characterized by a rugged morphology, featuring high plunging cliffs (up to 250–300 m in elevation) with occasional wave-cut notches at varying elevations. A last stage of volcanism (3.2–2.8 Ma) created the Feteiras Formation (Fig. 2a), but this activity did not reverse the dominantly erosional trend the island has experienced in the last 3.5 Ma (Ramalho et al., 2017).

In terms of tectonics, Santa Maria is mainly dominated by NW–SE-, N-S and NE–SW-trending extensional faults (Madeira et al., 2015), as attested by the existence of main morphological lineaments in the subaerial topography that displace some of the subaerial terraces (Fig. 2a; Madeira et al., 2015). Numerous dikes, contemporaneous with the two main shield building stages, striking N 045° and N 150° have also been reported (Zbyszewski and Ferreira, 1960; Serralheiro et al., 1987) (Fig. 2a).

In the Azores Archipelago the wave regime is dominated by waves impacting the coastline from the NW (29%), W (24%) and N (16%), with average significant heights (H_s) ranging between 2.5 m and 3 m (Quartau et al., 2012). Storminess in the Azores is high, and the archipelago is struck by severe storms, at least once every seven years (Andrade et al., 2008) that are able to produce maximum wave heights up to 20 m (Rusu and Guedes Soares, 2012). The Azores is subjected to semidiurnal regular tides and the annual mean tidal range in Santa Maria Island is about 1,44 m (Instituto Hidrográfico, 2000).

3. Data and methods

3.1. Marine geophysical data acquisition

High-resolution multibeam bathymetric and seismic reflection data were collected around Santa Maria between −20 m and −250 m onboard the R/V *Arquipélago* from 24th August to 15th September 2016. High-resolution multibeam bathymetry was collected mostly parallel to the isobaths along overlapping track lines, relying on DGPS with OMNISTAR corrections for positioning and using a pole-mounted Kongsberg EM2040C™ system (operating frequency range of 200–400 kHz and angular coverage of 130°). Sound velocity profiles (SVP, yellow dots, Fig. 3) were regularly collected during the survey. Data were processed using Caris Hips & Sips 9.0 software to produce high-resolution digital elevation models (DEMs) with variable cells size depending on the water depth (1 m for shallow water to 8 m at ~250 m).

A total of 2008 km of high-resolution seismic profiles (Fig. 3) was also acquired between −25 m and −300 m using an Applied Acoustic Engineering AA 200 Boomer™ plate and a receiver array consisted of a single-channel streamer with 8 hydrophones. Most of the seismic profiles were acquired using 100/200 J of output energy, depending on the water depth. Seismic survey lines parallel to bathymetry have line spacing varying with depth (between 20 and 200 m), whilst seismic lines perpendicular to the coastline were regularly spaced at ~250 m.

3.2. Terrace mapping

Multibeam bathymetry and seismic profiles were combined with an existing onshore topographical model (generated from a 1:5000 scale digital altimetric database) in a GIS environment, allowing for