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Gravitational, erosional and depositional processes on volcanic ocean islands: Insights from the submarine morphology of Madeira Archipelago

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ABSTRACT

The submarine flanks of volcanic ocean islands are shaped by a variety of physical processes. Whilst volcanic constructional processes are relatively well understood, the gravitational, erosional and depositional processes that lead to the establishment of large submarine tributary systems are still poorly comprehended. Until recently, few studies have offered a comprehensive source-to-sink approach, linking subaerial morphology with near-shore shelf, slope and far-field abyssal features. In particular, few studies have addressed how different aspects of the subaerial part of the system (island height, climate, volcanic activity, wave regime, etc.) may influence submarine flank morphologies. We use multibeam bathymetric and backscatter mosaics of an entire archipelago – Madeira – to investigate the development of their submarine flanks. Crucially, this dataset extends from the nearshore to the deep sea, allowing a solid correlation between submarine morphologies with the physical and geological setting of the islands. In this study we also established a comparison with other island settings, which allowed us to further explore the wider implications of the observations. The submarine flanks of the Madeira Archipelago are deeply dissected by large landslides, most of which also affected the subaerial edifices. Below the shelf break, landslide chutes extend downslope forming poorly defined depositional lobes. Around the islands, a large tributary system composed of gullies and channels has formed where no significant rocky/ridge outcrops are present. In Madeira Island these were likely generated by turbidity currents that originated as hyperpycnal flows, whilst on Porto Santo and Desertas their origin is attributed to storm-induced offshore sediment transport. At the lower part of the flanks (−3000 to −4300 m), where seafloor gradients decrease to 0.5°–3°, several scour and sediment wave fields are present, with the former normally occurring upslope of the latter. Sediment waves are often associated with the depositional lobes of the landslides but also occur offshore poorly-developed tributary systems. Sediment wave fields and scours are mostly absent in areas where the tributary systems are well developed and/or are dominated by rocky outcrops. This suggests that scours and sediment wave fields are probably generated by turbidity currents, which experience hydraulic jumps where seafloor gradients are significantly reduced and where the currents become unconfined. The largest scours were found in areas without upslope channel systems and where wave fields are absent, and are also interpreted to have formed from unconfined turbidity currents. Our observations show that tributary systems are better developed in taller and rainy islands such as Madeira. On low-lying and dry islands such as Porto Santo and Desertas, tributary systems are poorly developed with unconfined turbidite currents favouring the development of scours and sediment wave fields. These observations provide a more comprehensive understanding of which factors control

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the gravitational, erosional, and depositional features shaping the submarine flanks of volcanic ocean islands.

1. Introduction

The main volume of volcanic islands lies hidden beneath the sea and consequently their submarine flanks are far less studied than their accessible subaerial parts. The study of the submarine pedestals of volcanic islands is of great significance, because it can significantly improve our knowledge of island evolution, particularly if integrated with information on the development of subaerial edifices (Moore et al., 1989; Masson et al., 2002; Leat et al., 2010; Quartau and Mitchell, 2013; Saint-Ange et al., 2013; Quartau et al., 2015a). The advent of modern seafloor surveys during the 1980s, with sidescan and multibeam sonars, allowed the discovery of large-scale landslides (Moore et al., 1989; Masson et al., 2002), canyons and turbidite systems (Krastel et al., 2001; Sisavath et al., 2011), and sediment wave (Wynn et al., 2000a; Hoffmann et al., 2008) and scour fields (Hoffmann et al., 2011). Despite the vast range of published works, however, few comprehensive source-to-sink studies on ocean island volcanoes have focused on the development of their submarine flanks. Moreover, whether based on drilling (e.g., Schmincke and Sumita, 1998) or on the characterization of their submarine morphologies, most studies focus on a single island (e.g., Saint-Ange et al., 2013) or on a single process (e.g., Hunt et al., 2014). Consequently, works rarely relate subaerial conditions and shelf processes with the development of deeper submarine morphologies.

In this study, we make use of novel multibeam bathymetric and backscatter mosaics of an entire archipelago – which crucially extend from the nearshore to the abyssal plains – to gain a comprehensive insight on the origins of several gravitational, erosional and depositional features shaping the submarine flanks of volcanic islands. Furthermore, a correlation with the diverse physiographic conditions and geological evolution of each of the islands, allowed us to understand how these characteristics conditioned their present-day submarine flank morphologies. The case study of Madeira Archipelago is therefore particularly elucidative providing a unique insight onto the evolution of the submarine flanks of reefless oceanic volcanoes.

2. Regional setting

Madeira Archipelago is located in the NE Atlantic, ∼1000 km SW of the Iberian Peninsula (Fig. 1). It comprises the islands of Madeira (737 km^2), Porto Santo (42 km^2), and Desertas (13 km^2). The island edifices are the result of intra-plate volcanism on the slow-moving Nubian plate, leading to a hotspot track extending to the NE (Geldmacher et al., 2000). Although administratively included in Madeira Archipelago, the Selvagens Islands (∼3 km^2) constitute, from the geological point of view, a distinct archipelago and will be presented in a future study.

Madeira is the youngest island, with volcanism extending from >7 Ma to the Holocene (Geldmacher et al., 2000; Mata et al., 2013; Ramalho et al., 2015). Subaerial Madeira extends 58 km in the WNW–ESSE direction and has an average width of 15 km (annotation 1 in Fig. 2). The island is an elongated shield volcano, which despite being highly dissected, is largely above 1200 m, reaching a maximum elevation of 1862 m at Pico Ruivo. This configuration of the island constitutes a barrier to the dominant NE trade winds, causing higher precipitation in the north-facing slopes (Prada et al., 2005). Notwithstanding this asymmetry, Madeira has a well-developed and deeply incised subaerial drainage system on both

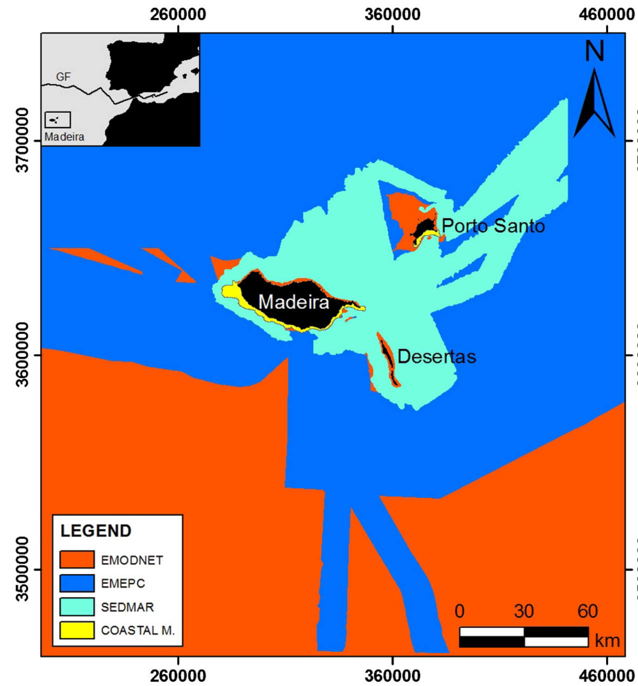

Fig. 1. Upper-right inset shows the location of Madeira Archipelago (GF – Gloria Fault) and main panel shows the sources of the different bathymetric datasets. Black areas represent the continental and island landmasses. Coloured areas represent the bathymetric sources: yellow, data from coastal management projects; light-blue, from SEDMAR; dark blue, from EMEPC; and orange, from EMODnet projects. This map and the following have UTM 28N coordinate system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

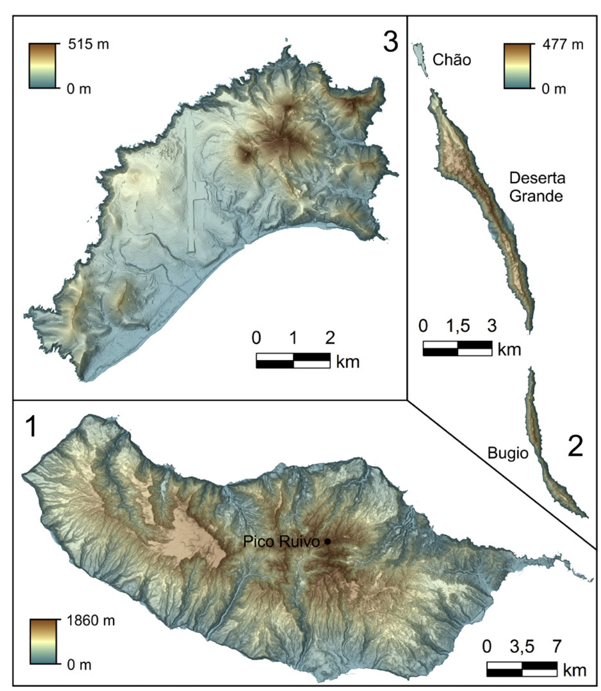

Fig. 2. Shaded relief images of the subaerial topography of the islands of Madeira (1), Porto Santo (2) and Desertas (3). Data is from Direção de Serviços de Informação Geográfica e Cadastro do Governo Regional da Madeira.