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The role of subsidence in shelf widening around ocean island volcanoes: Insights from observed morphology and modeling

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ABSTRACT

On reefless volcanic islands, insular shelves are thought to have formed essentially by the combined effects of wave erosion and glacio-eustatic sea-level oscillations. Subsidence, however, has also been recognized as having an important role in the development of these morphologies. Yet, few studies have quantified the relative contribution of subsidence to shelf generation and development, particularly to shelf width. A better understanding of this contribution, however, is key to understand the long-term evolution of coasts at volcanic islands, particularly given that subsidence may exacerbate the effects of marine erosion. In this study we assess quantitatively the role of subsidence in shelf development by comparing real cross-shore shelf profiles with modeled profiles using varied rates of subsidence. To achieve this, we used shelf bathymetric profiles from Faial and São Jorge islands in the Azores, which we compared with predictions of a numerical model of coastal erosion that has been calibrated previously against other field data. The first set of model runs was made to calibrate the model by determining the values that produced shelves with break depths, widths, and profile shapes that were similar to those observed. The second set of runs, which served to evaluate the contribution of subsidence to shelf widening, revealed that subsidence may have been responsible for increasing shelf widths by almost 2.5 times relative to shelves formed only by the combined effects of wave erosion and glacio-eustatic oscillations. Modeling shelf formation on the same islands but with increased subsidence rates up to 2.2 mm/yr resulted in shelf profiles up to 19 km wide, a value 3 to 6 times greater than observed on these islands. Our study therefore reinforces the idea that subsidence is a key contributor to the generation of broad insular shelves, given its role in enhancing coastal retreat. Our shelf evolution modeling also suggests that, notwithstanding the crucial role subsidence plays in increasing the width of shelves, on islands subjected to energetic wave regimes (as it happens in the Azores and Hawaii), modification by erosion is important enough to result in shelf morphologies that are not constructional in essence, but rather dominantly erosive surfaces. This study therefore contributes to a better understanding of how insular shelves and submarine terraces form and develop by proving important new quantitative insights of the role of subsidence on the generation of these morphologies.

1. Introduction

Continental and insular shelves are extremely important for our society in spite of their small size (cumulatively only cover ∼8% of the total oceans by area). They are areas of terrigenous sediment input from continents and islands, where economically important mineral deposits form (Rona, 2008) and significant carbon is sequestrated (Leithold et al., 2016). They are also the ocean area most used for navigation, recreation, fishing, aquaculture, mineral exploration and waste disposal (Chiocci and Chivas, 2014). Hence, small environmental changes to the coastal border of these systems can have a disproportionate impact on human activities. Following the development of single-beam echo-sounders, and into the 2nd half of the 20th century, the exploration of continental shelves rapidly expanded (e.g., Dietz and Menard, 1951; Emery,

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1965; Hayes, 1964; Hedberg, 1970; Inman and Nordstrom, 1971; Shepard, 1973; Vanney and Stanley, 1983). More recently, there has been an increasing interest in improving our knowledge of the processes affecting the formation and evolution of such shelf systems (e.g., Helland-Hansen et al., 2012; O'Grady et al., 2000; Paris et al., 2016; Schlager and Adams, 2001). The shelves of volcanic ocean islands, however, have received comparatively little attention since the seminal works of Menard (1983, 1986). The study of insular shelves is, however, crucial to our society given that most island populations depend on the marine biological and geological resources found in these environments, as well as on the income proportioned by coastal tourism. Additionally, insular shelves and coastlines are far more exposed to rapid change than their continental counterparts, posing more serious hazards to coastal communities (Ramalho et al., 2013). It is thus of primal importance to understand the role of different processes affecting coastal evolution and shelf development in these settings, particularly concerning marine erosion.

Volcanic oceanic islands are surrounded invariably by shelves, which are low-lying submarine zones that extend from the coast to the depth at which there is a marked increase in gradient to the submarine slopes of the volcanic edifice (Quartau et al., 2010; Ramalho et al., 2013). These shelves are thought to form mainly as wave eroded intertidal zones migrate landward and seaward with sea level changes. As a consequence, shelf width increases through time as coastlines retreat with marine erosion, leading to a common relationship between shelf age and shelf width (Menard, 1983; Le Friant et al., 2004; Llanes et al., 2009; Quartau et al., 2010). However, a closer look at the morphology of shelves reveals that they result from a more complex set of processes, including volcanism, tectonics and vertical movements, subaerial erosion, sedimentation and mass-wasting (Quartau et al., 2012; Ramalho et al., 2013). Therefore, the correlation between shelf age and shelf width is not always straightforward, especially on older islands where the combined effects of different processes can make their shelves geomorphologically more complex (Menard, 1983; Quartau et al., 2010, 2014, 2015; Romagnoli, 2013). For example, Quartau et al. (2010) used a model to investigate the role of mechanical wave erosion in the development of the shelf of Faial Island (Azores). They found that, although the shelf was mainly formed by wave erosion, other geological processes contributed to its development. The role of these processes, however, was only discussed qualitatively.

From all the mechanisms recognized as having a role in shelf development, perhaps none has fueled more discussion than subsidence. Researchers in general agree that subsidence influences shelf development (e.g., Menard, 1983; Ramalho et al., 2013, 2017; Quartau et al., 2014; Trenhaile, 2014), but its importance is still debated (e.g., Marques et al., 2016; Quartau et al., 2016). Ocean island volcanoes are generally expected to subside by varying amounts, and only very rarely are subjected to significant uplift trends (Ramalho et al., 2010a, 2010b). Significant subsidence is expected to occur particularly during the early shield building stages, when rapidly-growing volcanic edifices load the underlying lithosphere, causing plate flexure (Watts and ten Brink, 1989). Towards the end of the shield–building phase, when volcanoes reach their maximum size, subsidence related to flexural loading supersedes volcanic growth and volcanoes usually begin to submerge without additional topographic growth (Huppert et al., 2015). This subsidence is expected to wane rapidly (on a geological timescale) once a volcanic edifice is built, as viscous relaxation of the lithosphere gives way to its longer-term flexural strength (Brotchie and Silvester, 1969; Walcott, 1970; McNutt and Menard, 1978; Minshull et al., 2010). Islands are also generally subjected to longer-term, slower-acting subsidence on account of cooling of the underlying lithospheric plate (Stein and Stein, 1992), which may be enhanced if the lithosphere is significantly heated and 'reset' by magmatism (Detrick and Crough, 1978). The global variation of seafloor depth is generally controlled by the oceanic plates' thermal evolution, in which oceanic lithosphere cools as it spreads away from mid-ocean ridges, becoming denser as it ages, therefore resulting in a predictable bathymetric profile, with depth roughly equivalent to age$^{1/2}$ and asymptotically trending to equilibrium at $\sim$70 Ma (Stein and Stein, 1992). Long-term island subsidence is thus dominantly controlled by thermal subsidence of the underlying plate, except when volcanic island edifices are built on stable $>$70 Myr-old lithosphere. Magmatism and hotspots swells may affect this trend by means of rejuvenating the lithosphere or more importantly by causing uplift through either the accumulation of buoyant melt residue underneath the lithosphere (Morgan et al., 1995; Ramalho et al., 2010b) or through dynamic topography (Sleep, 1990; Ribe and Christensen, 1999; Pim et al., 2008). Hotspot swell decay, however, contributes to island subsidence, at least on fast-moving plates with respect to the melting source (Morgan et al., 1995; Ramalho et al., 2013). Considerable tectonic subsidence may also affect islands that are located in diffuse extensional or transtensional plate boundaries, as on some of the Azores Islands and in Iceland (Islam et al., 2016; Madeira et al., 2015; Marques et al., 2013).

Given these diverse mechanisms, it is not surprising that subsidence influences shelf development. However, different researchers have considered the role of subsidence in shelf development to be dominant or secondary relatively to the combined effects of marine erosion and glacio-eustatic oscillations. Marques et al. (2016), for example, suggested that subsidence takes a leading role in shelf formation, to the point that shelf morphology is essentially constructional in nature. According to this view, the shelf break corresponds to the transition between the subaerial and submarine slopes of the volcanic edifice, i.e. between subaerial and submarine lava flow sequences that have been submerged by rapid subsidence. This model might be applicable to the rare cases of island coastlines subjected to very slow marine erosion rates (e.g. the case of the younger Galapagos Islands) and/or very fast subsidence. However, its applicability to other settings has been questioned because of erosive insular shelf profiles (upwards-concave and with gradients that are significantly lower than the subaerial slopes of the volcanoes), high coastal cliffs, and possibly overestimated subsidence rates (Quartau et al., 2016). Notwithstanding these considerations, the relative role of subsidence in insular shelf development remains largely unquantified, and constitutes an important scientific question.

The purpose of this study was to quantitatively assess the role of subsidence in the formation of insular shelves. A wave erosion model was used to simulate the cross-shore shelf profiles of two subsiding islands in the Azores, to determine their rates of subsidence and to compare these profiles with those produced under otherwise similar conditions on stable landmasses. The model was also used to investigate the effect of variable rates of subsidence on insular shelf formation and on the age of the shelf breaks formed under oscillating sea level conditions during the Quaternary.

2. Materials and methods

2.1. The Azores as a case study

The Azores Archipelago is a group of relatively young volcanic islands that straddle the triple junction between the Eurasian (Eu), Nubian (Nu), and North American (NA) tectonic plates (Laughton and Whitmarsh, 1974). In the Azores, volcanism is mainly tectonically controlled and occurs along faults (fissure volcanic systems) or at fault intersections (central volcanoes), often resulting in volcanic edifices with varied ages and complex morphologies