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Reply to comment by Marques et al. on "The insular shelves of the Faial-Pico Ridge (Azores archipelago): A morphological record of its evolution"

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1. Introduction

It is now widely accepted that shelves of reefless volcanic islands form essentially by wave erosion of the island slopes over periods that can encompass many glacial-interglacial cycles and thus varied sea levels [*Llanes et al.*, 2009; *Menard*, 1983, 1986; *Quartau et al.*, 2010; *Romagnoli*, 2013]. *Menard* [1986] was the first scientist to draw our attention to the correlation between island age and shelf width in contrast to the lack of correlation between island age and depth of shelf break. Furthermore, observations that the windward sides of islands have commonly wider shelves than leeward sides, despite no significantly different coastal (volcanic) age has further reinforced the view that wave erosion is the main process developing insular shelves [*Llanes et al.*, 2009; *Menard*, 1983, 1986; *Quartau et al.*, 2010, 2012, 2014, 2015b; *Ramalho et al.*, 2013; *Romagnoli*, 2013].

In this reply to *Marques et al.* [2016], we will show how the morphologies of the Azorean insular shelves are incompatible with their suggestion of having formed by volcanic progradation and rapid subsidence. Essentially, unless modified by recent volcanism, the shelf bedrocks beneath thin sand deposits present smooth surfaces that have lower gradients than the adjacent subaerial volcanoes and do not continue the subaerial volcano slopes as speculated by *Marques et al.* [2016] but instead lie well below them. Thus, insular shelves in the Azores show a typical wave erosional morphology, although often modified by volcanic progradation [*Quartau et al.*, 2010, 2012; *Quartau and Mitchell*, 2013; *Quartau et al.*, 2014, 2015a, 2015b]. The present-day depths of their shelf edges show that older portions of the islands have subsided, although their long-term (10^5-10^6 years) subsidence rates are normally one order of magnitude lower than the rates considered by *Marques et al.* [2016]. Although the Azores lie in a tectonically active region, deformation is concentrated along active faults that present normal slip-rate components, usually of the order of tenths of mm/a [*Madeira and Brum da Silveira*, 2003; *Madeira et al.*, 2015], and do not produce widespread subsidence as *Marques et al.* [2016] suggested.

2. Origin and Development of Reefless Insular Shelves

Shore platforms on reefless volcanic oceanic islands start to develop as soon as volcanism wanes [*Quartau et al.*, 2014]. They evolve into insular shelves as the surf line migrates landward and seaward with changing sea level (Figure 1) [*Quartau et al.*, 2010]. Erosion rates are fast initially because the majority of oceanic islands cliffs have low dipping effusive sequences of subaerial lava flows that are easily eroded. The flows usually exhibit columnar and slab jointing that, together with the weak contacts between them, promote wave quarrying and the dislodgment of jointed blocks. Likewise, clinker and pyroclastic layers between flows facilitate quarrying [*Ramalho et al.*, 2013]. This weakness explains how marine erosion can carve metric to decametric cliffs in young effusive structures in a matter of months or years (e.g., Surtsey Island) [*Romagnoli and Jakobsson*, 2015]. The best example in the Azores is the shelf surrounding Capelo Peninsula of Faial Island (Figure 2). It has average widths of 400–600 m [*Quartau et al.*, 2012] despite the peninsula not being

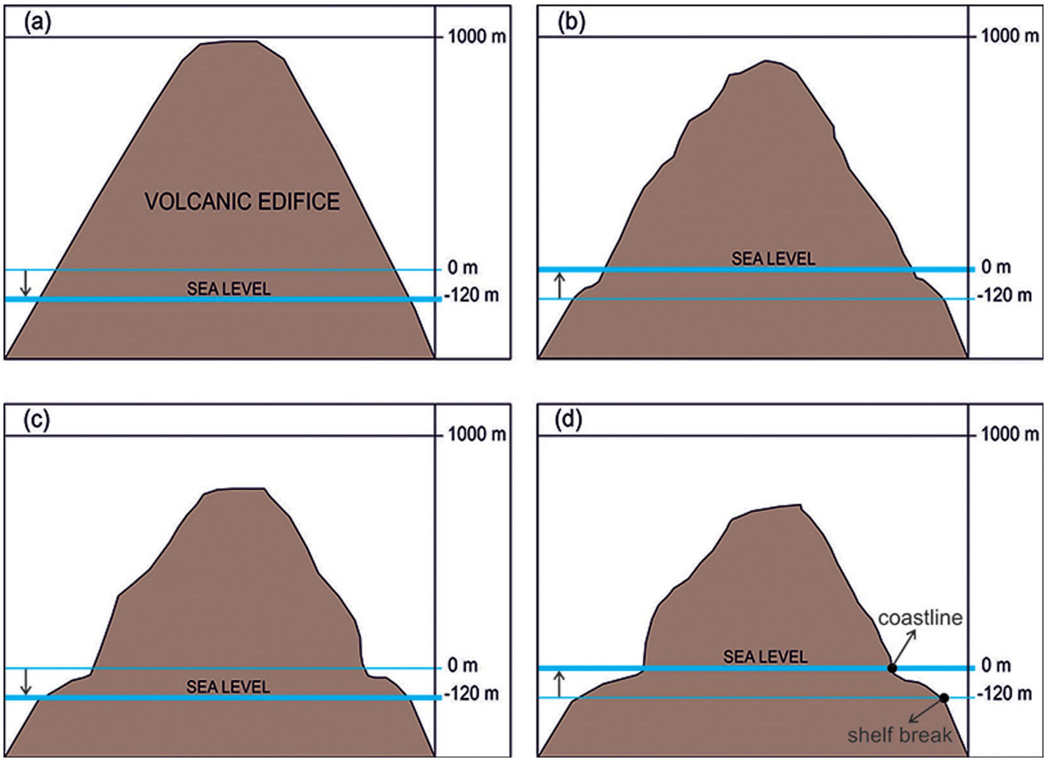

Figure 1. Formation of an insular shelf around a volcanic island through wave erosion during glacial-interglacial sea level oscillations (modified after *Quartau et al*. [2010]). Time increases from Figure 1a to Figure 1d. The vertical scale is significantly exaggerated.

older than 8 ka [*Di Chiara et al*., 2014]. However, as shelves widen, they trend toward a state of more gradual change, in which horizontal surf stresses causing cliff-line retreat are reduced because of wave attenuation across wider shelves [*Ramalho et al*., 2013; *Sunamura*, 1978; *Trenhaile*, 2001]. In addition, as island shelves widen, cliffs get taller. When such cliffs fail, they deliver material to the cliff foot, temporarily protecting them from wave erosion [*Dickson*, 2004; *Edwards*, 1941; *Sunamura*, 1992; *Trenhaile*, 1987]. Thus, cliff failures may delay erosion, making shelf widening discontinuous in time. Hence, average shelf erosion rates cannot be used indiscriminately to determine the age of an island. In order to interpret shelf widths of different islands, we need erosion and other process rates (such as uplift/subsidence) to be computed over comparable time scales.

3. Inferring Aspects of Island Geological Evolution From Shelf Morphology

During our research on the Azores, we have found that two main geomorphic characteristics (shelf width and shelf break depth) are useful to interpret and constrain the evolution of insular shelves and of the adjacent subaerial volcanic edifices [*Mitchell et al*., 2012; *Quartau et al*., 2010, 2012; *Quartau and Mitchell*, 2013; *Quartau et al*., 2014, 2015a, 2015b]. The edge of an insular shelf in the bedrock below unconsolidated sediment is normally a wave erosional feature that formed when sea level was at that lowered position. Shelf width increases through time as coastlines retreat with exposure to surf and thus, though not always linear, a relationship between shelf age and shelf width is often found. Other processes, however, can oppose or complicate this age-width relationship, such as those that fill in the shelf and make coastlines prograde, including posterosional volcanism and sedimentation and those that produce retreat of the shelf edge such as mass wasting [*Mitchell et al*., 2008, 2012; *Quartau et al*., 2010, 2012, 2014, 2015a, 2015b]. Despite these complications, shelf width appears to provide relative chronological constraints on the development of adjacent subaerial volcanic edifices that are compatible with radiometric dates [*Llanes et al*., 2009; *Menard*, 1983, 1986; *Quartau et al*., 2010; *Romagnoli*, 2013]. If the ages of the subaerial edifices are well constrained, the beginning of shelf incision and long-term coastline retreat rates can be estimated. In addition, shelf morphology coupled with the present-day coastline morphology can provide information on coastal

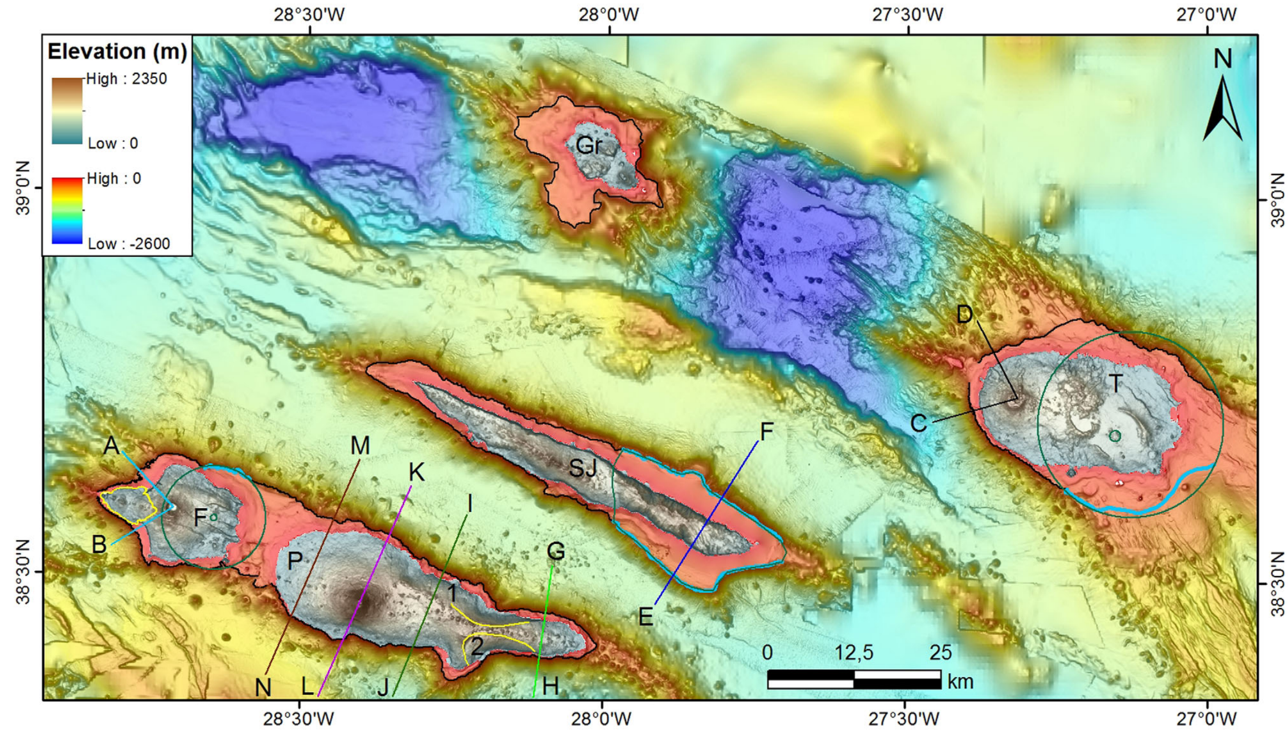

Figure 2. Elevation and bathymetry map of the central Azores islands (F, Faial; P, Pico; SJ, São Jorge; Gr, Graciosa; T, Terceira). Bathymetry is a compilation of data from *Casalbore et al.* [2015], *Chiocci et al.* [2013], *Mitchell et al.* [2003], *Quartau et al.* [2014, 2015a, 2015b], and the EMODNET web portal (http://portal.emodnet-bathymetry.eu). Topography is from Instituto Geográfico do Exército 1:25 000 maps. Black curves offshore represent the edges of the shelves surrounding the islands. Light blue curves offshore represent the deepest edges of the shelves surrounding the oldest volcanic edifices in Faial [*Quartau and Mitchell*, 2013], Terceira [*Quartau et al.*, 2014], and São Jorge islands, and green circles and polygons the hypothetical dimension of these edifices at the levels of their shelf edges. The depths of their shelf edges are used for calculating average subsidence rates of these edifices in Table 1. Yellow area on Faial represents the Capelo Peninsula. Yellow curved lines on Pico represent the (1) NE and the (2) SE landslide scars taken from *Quartau et al.* [2015b]. Red, green, blue, and black straight lines represent the location of the topographic profiles of Figures 5 and 6 (A–N).

migration (recession by marine erosion and flank collapses or progradation by shelf infilling of volcanism and sediments) [*Meireles et al.*, 2013; *Mitchell et al.*, 2012, 2013; *Quartau et al.*, 2010, 2012; *Quartau and Mitchell*, 2013; *Quartau et al.*, 2014, 2015a, 2015b; *Ramalho et al.*, 2013]. High cliffs backing shelves, shelf erosional surfaces that in profile are sharply angular with the submarine slopes below the shelf edge, widespread sediment deposits, landslide indentations of the shelf edge, and the absence of submarine lava flows are evidence of an old age of the shelf and extended coastline recession [*Quartau et al.*, 2014, 2015b]. Shelves covered by submarine lava flow morphologies that do not show signs of surf erosion, with low adjacent coastlines that are commonly irregular in plan view, imply recent volcanic fill (denominated "rejuvenated shelves" in *Quartau et al.* [2015b]). This interpretation constrains coastline progradation in such areas after 6.5 ka, when sea level had risen close to its present-day position [*Quartau et al.*, 2014, 2015b]. Both cases exist in the detailed studies done so far in the Azores with a predominance of wave erosional shelves in Faial and Terceira Islands and rejuvenated shelves on Pico Island.

In the Azores, insular shelves carved into older edifices show much slower time-averaged coastal retreat rates than those carved over young edifices. Rates can differ by one order of magnitude depending on edifice age (or adjacent shelf width) [e.g., *Quartau et al.*, 2010]. Wave attenuation over wide shelves is probably the reason why old reefless volcanic islands take millions of years to be eroded completely to sea level. Some islands are long-lived because they have been uplifted [*Ramalho et al.*, 2010b]. There are excellent examples of old volcanic islands in the Atlantic (over 10 Ma) that have survived marine erosion due to uplift, such as Sal, Boavista, and Maio in Cape Verde [*Dyhr and Holm*, 2010; *Ramalho et al.*, 2010a; *Represas et al.*, 2012] and Fuerteventura in the Canaries [*Acosta et al.*, 2003; *Zazo et al.*, 2002]. Only Santa Maria in the Azores is of such an age and remains above sea level. The island has been volcanically inactive since 2.8 Ma and most of it is older than 4 Ma [*Sibrant et al.*, 2015]. The most obvious reason for its preservation despite coastal erosion is uplift, as the island started rising after 3.2 Ma and has already elevated ~200 m above its

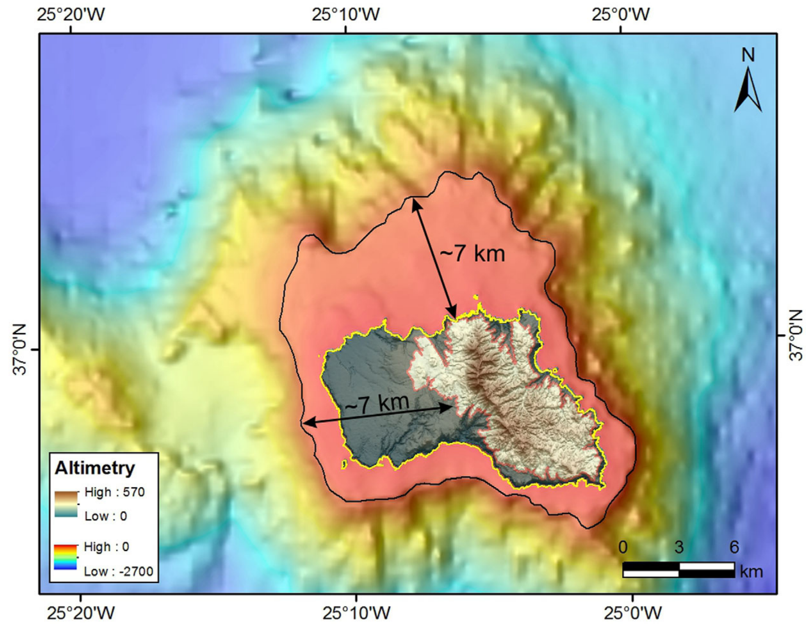

Figure 3. Elevation and bathymetry map of Santa Maria Island in the Azores. Bathymetry is from the EMODNET web portal (http://portal.emodnet-bathymetry.eu). Topography is from Instituto Geográfico do Exército 1:25 000 maps. Black curve offshore represents the edge of the insular shelf. The yellow line represents the present-day coastline while the pink line corresponds to the coastline 3.2 Ma ago based on ~200 m uplift [*Ramalho et al*., 2014]. Arrows represent the present-day width of the northern shelf and the width of the western shelf 3.2 Ma ago.

original level [*Ramalho et al*., 2014]. This uplift has almost doubled the area of the island since 3.2 Ma (Figure 3). Uplift and wave attenuation over a wide shelf on the northern (presently ~7 km) and western shelves (~7 km before uplift) opposed coastline retreat on the island's windward sides [*Quartau et al*., 2012; *Rusu and Guedes Soares*, 2012]. Although the S, SE, and E shelves of the island are narrow, their adjacent coasts have relatively high cliffs and lie on the leeward sides. Thus, they have probably experienced slower erosion rates due to their rare exposure to energetic surf but also because episodic failure has delivered considerable material to the cliff base, attenuating the effects of wave erosion.

4. Influence of Subsidence in the Development of Insular Shelves in the Azores

The depth below sea level of the present-day erosional shelf break can be used to assess vertical movements of the adjacent island [*Quartau et al*., 2014, 2015b]. If this geomorphic marker is significantly deeper than the Quaternary lowstands (below −130 m), the island has subsided (Figure 4a). If it is significantly above those lowstands, and there is no geomorphological evidence of uplift (subaerial terraces, notches above high tide, spray or storm levels, submarine formations exposed above sea level, etc.), the shelf started to form during the period of sea level rise after the Last Glacial Maximum (LGM). In the latter case, a local sea level curve can be used to roughly infer the timing of shelf initiation (Figure 4b).

Marques et al. [2016] suggested that islands in the Azores develop through shoreline progradation of successive generations of coastal lava deltas over the slopes of the islands. The seaward progradation of lavas over steep offshore slopes generates lava-fed delta structures similar to Gilbert-type river deltas [*Jones and Nelson*, 1970; *Ramalho et al*., 2013]. Their characteristic morphology has a low-gradient topset of subaerial lavas and steep foresets of pillow lavas and hyaloclastites formed as lavas enter the sea. Since *Marques et al*. [2016] consider that the islands are subsiding very quickly (1–3 mm/yr), these structures would subside without being eroded and the slope break between their topsets and foresets should be preserved. Thus, this change of gradient would be morphologically equivalent to the shelf edge of wave erosional origin.

Assuming subsidence of 1–3 mm/yr as *Marques et al*. [2016] have done and a slope angle of the shield volcano of 5° for the oldest Topo volcanism of Pico (~186 ka according to *Costa et al*. [2015]), the slope break can be predicted to lie at −186 to −558 m and at a horizontal distance from the present-day coastline of 2.1 to 6.4 km, respectively. The first values (depth = −186 m and shelf width = 2.1 km) match those of the

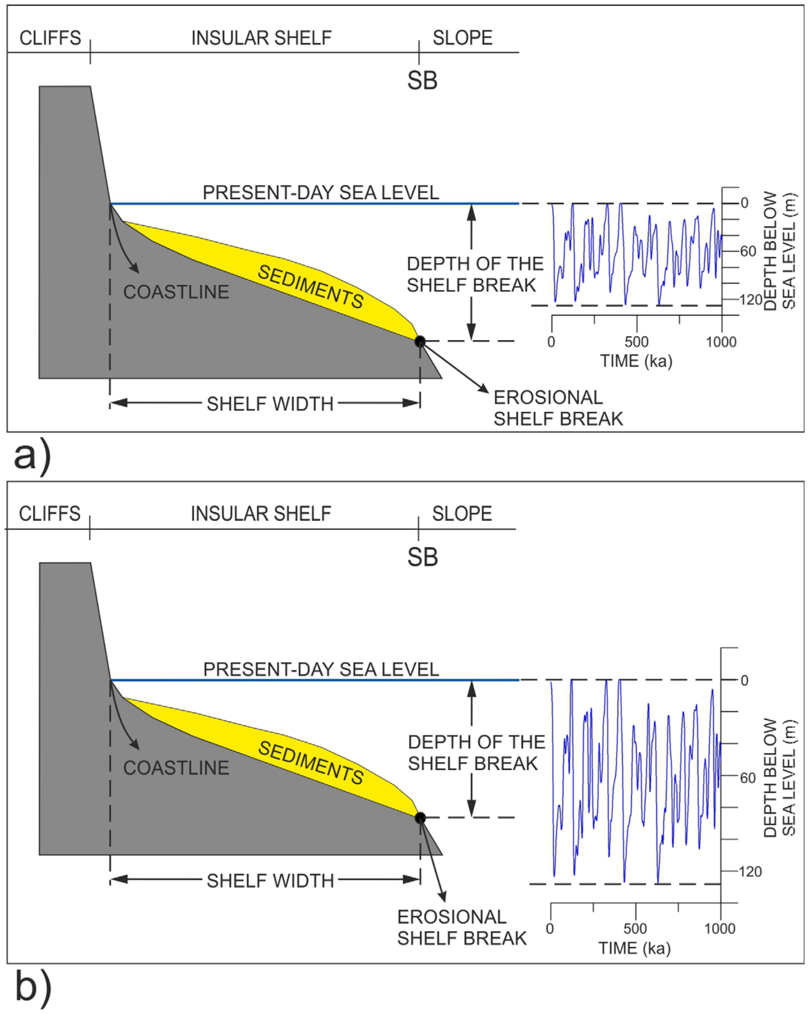

Figure 4. Schemes of an insular shelf showing the geomorphic markers used to infer islands' evolution. (a) Island that has subsided after the formation of its shelf, inferred from the depth of the erosional shelf break below the deepest lowstand sea levels. (b) Island that has uplifted or its shelf was formed during the rise of sea level after the LGM. Sea level curves in both Figures 4a and 4b are from *Bintanja et al.* [2005].

preserved shelf around Topo volcano at Pico [*Quartau et al*., 2015b]; hence, subsidence of 1 mm/yr could hypothetically explain the current shelf width and depth. However, NNE-SSW profiles across the subaerial and submarine topography of Pico Island clearly show that the theoretical very low-gradient view of the volcanoes composing the island considered by *Marques et al*. [2016] is unrealistic (Figure 5). Although there are a few places where the slopes of the volcanic edifices have gradients below 8° (the NW and E tips of the island), much of the island subaerial flanks are steeper than 8°. Even the submarine areas of Pico Island in front of the NE and SE landslide scars (1 and 2 in Figure 2, respectively) have already developed erosional shelves (see seismic profiles showing erosional morphologies in *Mitchell et al*. [2012] and *Quartau et al*. [2015b]). These landslides, dated by *Costa et al*. [2015] as being no younger than 70 ka, have most likely removed the older shelf in front of them, i.e., after these events, waves were able to carve new erosional shelves. Here and in other places around Pico where posterosional volcanic progradation has not been significant, an erosional morphology of the shelf is still perceptible [*Quartau et al*., 2015b]. Furthermore, the other islands in the central group of the Azores (Faial, São Jorge and Terceira) show high cliffs bordering wide shelves (Figure 6), and places where seismic profiles show clear low-gradient (eroded) platforms under the sedimentary cover (see profiles in *Quartau et al*. [2012, 2014]). In the Azores, wider shelves backed by high coastlines dominate but narrower shelves backed by low coastlines also coexist. These narrower shelves are also interpreted to have been formed by wave erosion, but recent volcanic progradation has partially filled the spaces left by erosion. This inference is supported by several examples of major shield or

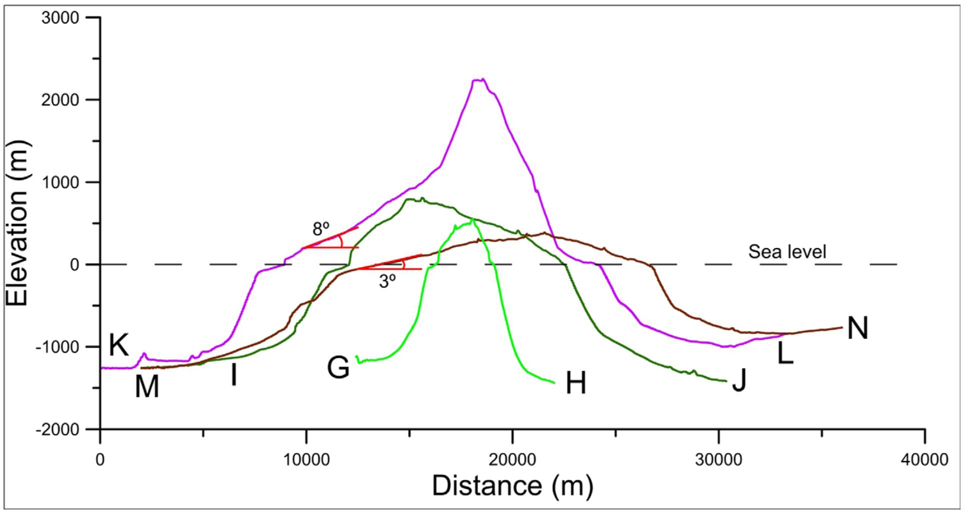

Figure 5. Topographic profiles perpendicular to the WNW-ESE development of Pico Island. Most of the island has subaerial flanks with gradients >8° and shows shelves with a wave erosional morphology. Profiles are located in Figure 2. Vertical exaggeration is ~5:1.

stratovolcanoes in the Azores that are cut by waves forming erosional shelves (Figure 6). Subsequent lava flows may prograde the coastline partially filling these shelves [*Quartau et al*., 2010, 2012, 2014, 2015b]. Some of the best examples are the shelves bordering the Capelo volcanic fissure system on Faial (Figure 2), which in places show clear erosional morphologies while other sectors show significant volcanic progradation [e.g., *Quartau et al*., 2012, Figure 13]. Other evidence of the importance of surf erosion in shelf development in the Azores is the clear relationship between shelf width and exposure to wave energy around the coast of edifices with insignificantly different volcanic ages. The best example is the Caldeira volcano in Faial where shelf width around the edifice, mostly formed around 120 ka [*Hildenbrand et al*., 2012], varies between 800 m in the less exposed sector to 3 km in the more exposed sector [*Quartau et al*., 2012]. The above evidence in the Azores allows us to assert that surf erosion and volcanic progradation play dominant roles in the evolution of island shelves, with subordinate contributions from subsidence and flank collapses.

5. Short-Term Versus Long-Term Rates in Geomorphic Processes

Geomorphic and tectonic process rates are not independent of considered time intervals [*Gardner et al*., 1987; *Scott Snow*, 1992]. This is because changes commonly occur through the accumulation of discrete

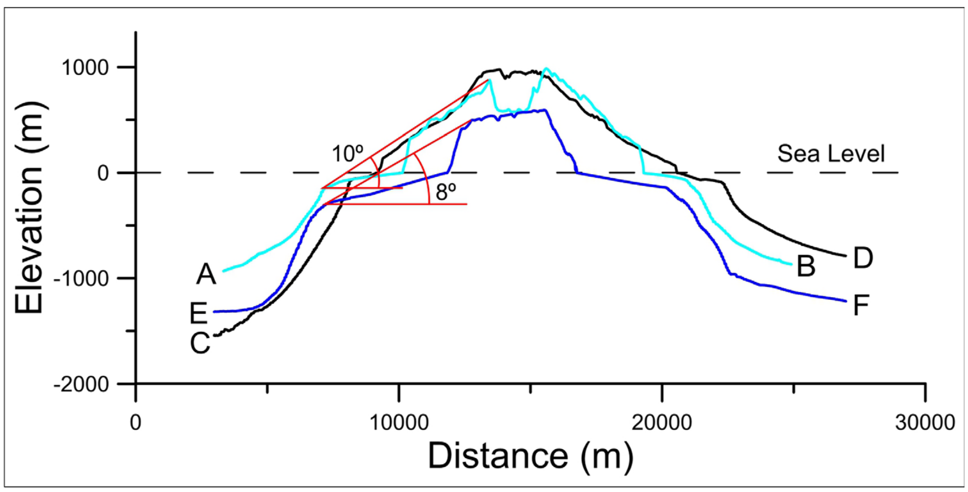

Figure 6. Examples of topographic profiles showing insular shelves at Faial (A–B), Terceira (C–D), and São Jorge (E–F) Islands, with a clear erosional morphology. Profiles are located in Figure 2. Vertical exaggeration is ~5:1.

Table 1. Estimated Subsidence Rates of the Oldest Volcanic Edifices at Terceira, Faial, and São Jorge Islands in Millimeters per Year (mm/a; Column 6) Calculated From the Difference (Column 4) Between Their Shelf Edge Depths (Column 2) in Meters (m) and the Depth of the First Lowstand (Column 3) After the Main Volcanic Phase (Column 1) and the Period of Time Since This First Lowstand Occurred (Column 5)

	Age of Main Volcanism (ka)	Shelf Edge Depth (m)		Depth of the First Lowstand After Main Volcanism (m)	Subsidence Suffered		Age of the First Lowstand (ka)	Subsidence Rate (mm/yr)	
		Average	Maximum		Average	Maximum		Average	Maximum
Cinco Picos (Terceira)	400	193	220	111.2	81.8	108.8	342.3	0.2	0.3
Ribeirinha (Faial)	850	199	282	103.7	95.3	178.3	795.4	0.1	0.2
Serra do Topo (São Jorge)	1320	254	349	61.2	192.8	287.8	1290.8	0.1	0.2

events rather than being gradual changes with constant rates [*Scott Snow*, 1992]. Thus, in general, a 10^4-10^5 years change in time interval will account for approximately one order of magnitude change in the rate of these processes [*Gardner et al*., 1987].

The Azores lie within and about oceanic spreading centers [*Lourenço et al*., 1998; *Madeira and Ribeiro*, 1990], commonly resulting in morphologies where central volcanoes are dismembered by rifting. This is well expressed on Faial, Terceira, and São Miguel Islands [*Carmo et al*., 2015; *Madeira and Brum da Silveira*, 2003; *Madeira et al*., 2015], which are crossed by active faults defining graben structures, and less obviously on Graciosa, São Jorge, and Pico Islands due to recent volcanic covering, although the morphologic evidence of these faults is still present [*Hipólito et al*., 2013; *Madeira and Brum da Silveira*, 2003; *Madeira et al*., 2015; *Quartau et al*., 2015a]. Averaging multipoint GPS measurements to interpret island vertical displacements is an unreliable exercise because, depending on their location, the values at each point may show subsidence or uplift, as is the case on Terceira Island [*Miranda et al*., 2012]. Furthermore, the extrapolation by *Marques et al*. [2016] of vertical displacement rates based on only a decade of GPS measurements to hundreds of thousands or millions of years is even more unreliable. Not only do the depths of the shelf breaks of the Azores Islands suggest subsidence rates no greater than 0.3 mm/yr (Table 1), but GPS measurements often have uncertainties greater than the magnitude of the measured vertical movements [*Catalão et al*., 2011; *Mendes et al*., 2013; *Miranda et al*., 2012]. In addition, if their subsidence rates were applicable to $>$100 ka time scales, we would expect to observe shelf breaks deeper than 400 m in the Azores. Even assuming the lower subsidence rate value (1 mm/yr) for the Azores considered by *Marques et al*. [2016], shelf edges at the oldest parts of São Jorge, Faial, and Terceira would be at -1300, -850, and -400 m, respectively, but we have not been able to find any morphologic edges at these depths (Table 1). Multibeam bathymetry around these islands shows unequivocally that the deepest shelf edges are at around -200 to -400 m in areas presenting wide shelves, with no evidence of shelf collapse or associated mass-wasting deposits on these submarine slopes. One could perhaps argue that the subsided shelf edges may be covered by voluminous volcanic or mass-wasting deposits. However, even in the Hawaiian Islands, an archipelago known for spectacular landslides and voluminous volcanism, the submerged shelves (terraces) and adjacent edges are preserved at various depths down to -2000 m [*Faichney et al*., 2010; *Moore and Clague*, 1992].

In volcanically active islands, intrusions at different levels of the volcanic edifice may produce either local or island scale inversions between subsidence and uplift trends over varied time periods [*Ramalho et al*., 2015]. Furthermore, measurement over short-time intervals can bias the interpretations because one can be simply measuring eruption-related subsidence due to short-lived inflation-deflation cycles of volcanoes [*Baker and Amelung*, 2012]. Even deformation unrelated to eruptions is known to be highly variable in both magnitude and direction, over time scales ranging from a few days to a few years [e.g., *Bartel et al*., 2003]. In Hawaii, deep drilling has shown that the rapid subsidence rates (caused by the extreme loads of the islands) are not necessarily constant through time. Over various time intervals of several thousand to tens of thousands years, edifice growth has varied greatly as also have subsidence rates [*Lipman and Moore*, 1996]. Therefore, rates from only a decade of GPS vertical movements in the Azores cannot be simply extrapolated to 10^5-10^6 year time scales.

6. Conclusions

The information provided by the interpretation of high-resolution bathymetry and seismic profiles coupled with the analysis of subaerial stratigraphy and geomorphology provides a much stronger case for discriminating between competing theories for the development of insular shelves in the Azores.

The depth of the shelf break at the oldest parts of the islands shows that long-term subsidence rates cannot be greater than 0.3 mm/yr in the Azores. In addition, the overall morphologies of the central volcanoes that compose the islands are very different from those suggested by *Marques et al*. [2016]. Instead of low angle shields, these volcanoes have steep subaerial slopes and have wide shelves incising their nearshore submarine areas. Beneath the unconsolidated sediment cover, the bedrock surface typically has low gradients and does not continue the profile of the subaerial edifices. A few localized areas in Pico Island where posterosional volcanic progradation has occurred do meet *Marques et al*. [2016] morphological view. However, even there, although partially covered by lava deltas, multibeam bathymetry and seismic profiles commonly reveal an erosive morphology.

Based on integrated offshore and onshore morphological evidence, we conclude that the insular shelves of the Azores are mainly formed by wave erosion, although they can be significantly modified by volcanic progradation as in the case of Pico Island. Subsidence and large-scale flank collapses play a secondary role in the evolution of these shelves.

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Erratum

In the originally published version of this article, several authors' affiliations were listed incorrectly. The affiliations have since been corrected and this version may be considered the authoritative version of record.