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Vertical movements of ocean island volcanoes: Insights from a stationary plate environment

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ABSTRACT

Uplift reconstructions based on the Cape Verde's geological record provide a unique opportunity to study the long-term isostatic movements associated with hotspot activity on a stationary plate environment. The archipelago is considered stationary with respect to its melting source so the hotspot-driven isostatic effects affecting the ocean islands are expected to be enhanced. In this study, Ar–Ar and U–Th geochronology techniques were used to date a set of palaeo-markers of sea-level from Santiago's and São Nicolau's edifices, two of the main Cape Verde Islands. A comparison between relative sea-level and eustatic sea-level (from a modern eustatic curve) was established to extract the vertical displacement undergone by the markers, and to reconstruct the uplift/subsidence history of each island. The resulting uplift reconstructions confirm that both Santiago and São Nicolau experienced a general uplift trend over the last 6 Ma, seemingly synchronous with the vigorous volcanic activity that built their exposed edifices. These islands, however, exhibit different uplift histories despite their common uplift trend. Several uplift mechanisms were tested and a local rather than regional mechanism is proposed as the main cause of uplift, generally unrelated with far-field effects of surface loading. This mechanism is probably associated with magmatic additions at crustal level.

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1. Introduction

Ocean island volcanoes are subject to vertical movements during their lifetime. The general view, mostly based on the prototypical Hawaiian model, is that islands are formed atop or on the frontal slope of hotspot swells (Detrick and Crough, 1978; Morgan et al., 1995) and subsequently subside under their own weight, creating a flexural moat (Menard and Ladd, 1963; Walcott, 1970; Watts and ten Brink, 1989). Towards the end of their main eruptive life, and as they move away from the melting source, islands gradually start to experience uplift as they pass over the flexural bulge created by new islands forming upstream (Detrick and Crough, 1978; Watts and ten Brink, 1989; Grigg and Jones, 1997). Erosion and mass-wasting events that redistribute the load over a larger area also cause uplift (Rees et al., 1993; Filmer et al., 1994). Older islands, as they move away from the flexural bulge and as the plate cools, start to re-subside, forming atolls and eventually disappearing under the sea's surface, becoming guyots (Darwin, 1842; Menard and Ladd, 1963; Detrick and Crough, 1978; Menard, 1983; Grigg, 1982). This view is strictly valid for island chains on fast-moving plates. What happens on stationary plates, when the islands' positions are fixed relative to the melting source? What vertical movements do they experience and what are the mechanisms that control these movements? To explore these issues, we studied the Cape Verde Archipelago, a group of islands that is approximately stationary in the hotspot reference frame (Burke and Wilson, 1972; McNutt, 1988; Sleep, 1990) and that lies on top of the largest bathymetric anomaly in the oceans: the Cape Verde Rise (Crough, 1978).

By understanding the history of vertical movements affecting ocean islands in both fast-moving and stationary plate environments, one can assess the individual contribution of the various mechanisms and gain insight into the processes that cause them. A way to trace those movements is to look for markers of past sea-level in the islands' geological record, and to correlate their present position with the sea-level height contemporaneous with their formation. A remarkable feature of the Cape Verde Archipelago is the relative abundance of sea-level palaeo-markers in the islands' stratigraphical sequence, making it an ideal place to research island freeboard (Ramalho et al., 2010). We have identified a number of strategic locations on the island of Santiago (in the southern chain), and on the island of São Nicolau (in the northern chain), to study and sample in detail. Here we present our vertical reconstructions that show significant differential uplift and test the possible contribution of each mechanism in the uplift process. Based on our calculations, we propose a

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local rather than regional mechanism to be responsible for significant island uplift.

2. Geological setting

The Cape Verde Archipelago is a group of ten volcanic islands situated 450–600 km off the west coast of Africa, 15° — 17° north of the equator (see Fig. 1). The archipelago is considered to be the result of a hotspot whose activity spans at least ~26 Ma (Torres et al., 2002a). Since the archipelago lies on the African plate, considered to be quasi-stationary in the hotspot reference frame (Burke and Wilson, 1972), it is stationary relative to the melting source. The islands themselves lie on 120–140 Ma seafloor (Williams et al., 1990) and form two chains disposed in a rough semi-arc clustered slightly off-center to the southwest of the bathymetric swell known as the Cape Verde Rise (McNutt, 1988; Monnereau and Cazenave, 1990). The swell is 1400–1600 km wide and ~2.2 km high and the region is associated with a positive geoid anomaly of 8–12 m (McNutt, 1988; Monnereau and Cazenave, 1990). The origins of the swell are still controversial but it seems it formed rapidly approximately 25 Ma ago since very few turbidites from theAfrican continental margin have reached the top of rise since then (Lancelot et al., 1978; Faugeres et al., 1989). The crustal and mantle structure beneath the islands seems to be characterized by an unevenly thickened crust (up to 22 km) underlain by a 60–80 km thick region of faster-than-average seismic velocities interpreted as a depleted swell root, residual from partial melting (Lodge and Helffrich, 2006). The crustal thickening seems to be confined to the islands' region (Ali et al., 2003; Pim et al., 2008), and the subsurface load associated with this thickening might be causing a regional uplift (of ~400 m) that restricts the amplitude of the flexural moat to just 1600 m (instead of the expected 2 km inflection) and tilts the moat infill outwards from the islands (Ali et al., 2003).

The exposed geology of the Cape Verdes is complex and is still imperfectly known. There is no evident hotspot track but there is possibly an age progression in the southern chain, from east (older and denuded islands) to west (younger and prominent islands), as suggested by the geomorphology of the edifices and the age of the oldest exposed lithologies (see Fig. 2). Due to the islands' stationary position relative to the melting source, their volcanic lifetime is relatively long, characterized by several periods of volcanism with decreasing volumetric output and intercalated with long (1–4 Ma) periods of quiescence (see Fig. 2). Historical volcanism (<500 a) is known only on Fogo, whose latest eruption occurred in 1995, but most islands exhibit products erupted during the Quaternary.

The presence of eroded basement complexes, with uplifted portions of ocean-floor (Serralheiro, 1970; Paepe et al., 1974; Serralheiro, 1976; Stillman et al., 1982; Gerlach et al., 1988; Davies et al., 1989) and large pockets of plutonic rocks (Serralheiro, 1976), denotes early cycles of volcanism that normally precede the main shield-building stage and are still poorly known. These might be relics of the seamount and/or emergent island stages and may attest to significant vertical movements. However, their advanced state of alteration and profuse dyke swarms make their study extremely difficult and discourages dating. Outstanding examples of these basal lithologies include Maio's old sequence, with Jurassic MORB basalts and Jurassic/Cretaceous deep-sea sediments, folded, faulted and interpreted as uplifted seafloor possibly associated with the intrusion of the island's Central Igneous Complex (Serralheiro, 1970; Stillman et al., 1982), and Sal's Ancient Eruptive Complex, a submarine volcanic sequence with intercalated pelagic sediments (Silva et al., 1990; Ubaldo et al., 1991; Torres et al., 2002b; Ramalho et al., 2010).

In Cape Verde, in contrast with many other archipelagos (e.g. Staudigel and Schmincke, 1984; Klügel et al., 2005), evidence for significant positive movement is not restricted to the basement complexes. The relative abundance of sea-level palaeo-markers extends throughout the stratigraphic sequence of many islands, suggesting significant differential uplift throughout the archipelago (Ramalho et al., 2010). The islands of Santiago and São Nicolau are two noteworthy examples of seemingly uplifted edifices, whereas, for example, Santo Antão and São Vicente seem not to have experienced uplift (Ramalho et al., 2010). For this paper we have focused our study on Santiago and São Nicolau because of their unique geological records, their central position in the archipelago, and their evolutionary similarities (see Figs. 2, 3). Fig. 3 compares the volcanostratigraphy of these two islands, with information regarding the main uplift tracers found on the island, including their present elevation. For a detailed description of sea-level markers and discussion of relative sea-level from Santiago and São Nicolau refer to Ramalho et al. (2010).

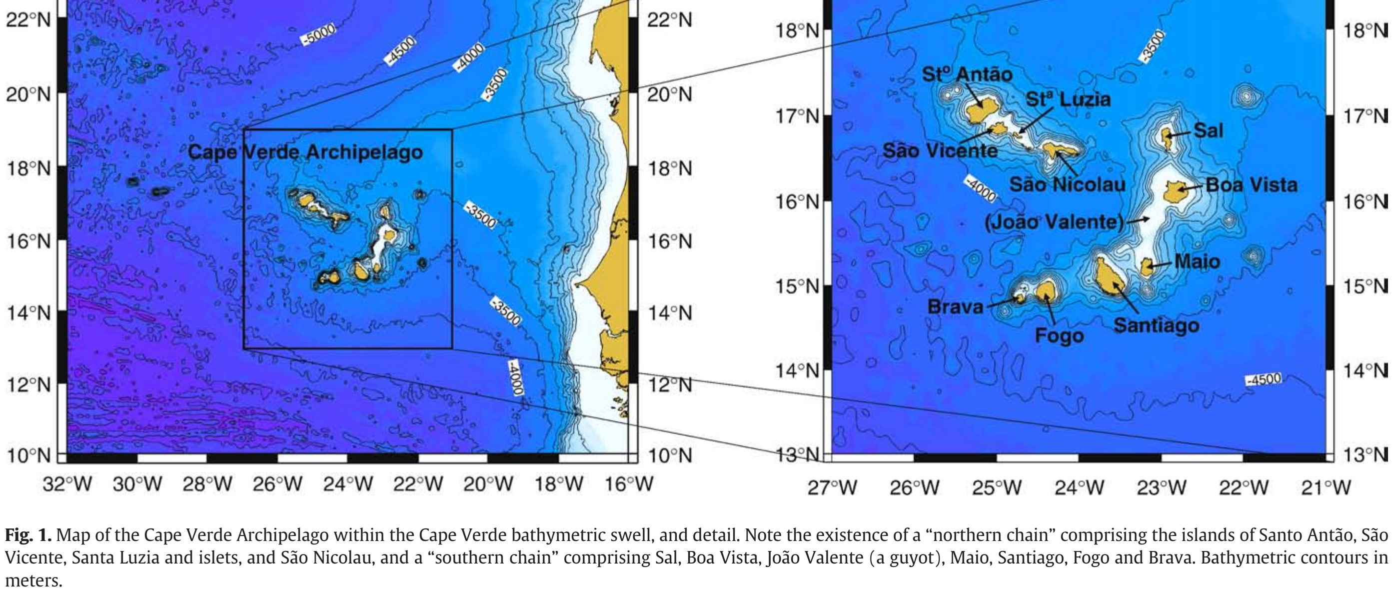

Fig. 1. Map of the Cape Verde Archipelago within the Cape Verde bathymetric swell, and detail. Note the existence of a "northern chain" comprising the islands of Santo Antão, São Vicente, Santa Luzia and islets, and São Nicolau, and a "southern chain" comprising Sal, Boa Vista, João Valente (a guyot), Maio, Santiago, Fogo and Brava. Bathymetric contours in meters.

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