Palaeogeography, Palaeoclimatology, Palaeoecology 395 (2014) 131–143

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Miocene–Pliocene rocky shores on São Nicolau (Cape Verde Islands): Contrasting windward and leeward biofacies on a volcanically active oceanic island

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ARTICLE INFO

Article history:
Received 8 June 2013
Received in revised form 11 December 2013
Accepted 19 December 2013
Available online 28 December 2013

Keywords:
Coastal deposition
Miocene
Pliocene
Rhodoliths (Rhodophyta)
Northeast Trade Winds
Volcanic islands

ABSTRACT

North Atlantic islands in the Cape Verde Archipelago off the coast of West Africa commonly feature an elongated N–S shape in which reduced northern coasts and longer eastern shores absorb the brunt of wave activity and long-shore currents generated by prevailing North East Trade Winds. Located in the middle windward islands, São Nicolau is unusual in profile with an elongated E–W configuration that offers a broad target against high-energy, wind-driven waves. Conversely, the south shore of São Nicolau provides relatively wide shelter in a leeward setting. Reconstruction of the proto-island prior to the onset of the Main Eruptive stage during the Late Miocene at ~5.1 Ma reveals a moderately smaller island with essentially the same E–W orientation. This study combines previous data with results from a detailed stratigraphic log based on Upper Miocene limestone deposits on the island's south flank for comparison with stratigraphic profiles of Upper Miocene limestone from the island's northeast quarter. Logs from a Pliocene sandy limestone outcropping on the south-central coast of São Nicolau give added context to the diversity of marine invertebrates, including branching coral colonies and delicate ramose bryozoans that found shelter in a leeward setting. Whole rhodoliths contribute the main fabric of carbonates deposited against rocky shores on the northern, exposed side of the Miocene island, whereas only traces of worn rhodoliths and rhodolith sand occur as in finer Miocene grainstone on the island's southern, protected side. Miocene and Pliocene carbonate deposits were terminated by submarine flows on an actively growing volcanic island. The passage zone from submarine to subaerial flows on the island's flanks makes a useful meter-stick to gauge absolute water depth at the moment of local extinction by volcanic activity.

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1. Introduction

Islands are singular landscapes where the limits of habitability are proportionate to size and distance from the nearest mainland (MacArthur, 1972). However arrayed in the seas or oceans that surround them, islands also enforce restrictions on life subject to the wider field of prevailing winds, ocean currents, storm tracks, and other climatic factors typical for any given geographic realm. Coral species that colonized the big island of Hawaii, for example, thrive on the leeward Kona Coast where ocean swell from the South Pacific is moderate compared to rough conditions on the windward Hamakua Coast where wave shock energized by persistent trade winds prohibits coral growth (Dollar and Tribble, 1993). On continental islands closer to a mainland, variations in physical factors between exposed, outer rocky shores and sheltered inner shores regulate the distribution of marine organisms, as found for example around the Channel Islands of southern California (Littler et al., 1991). The geological record is capable of preserving whole islands that demonstrate fossil evidence for contrasting exposed and sheltered biotopes (Johnson, 2002). Due to plate tectonics and the re-cycling of oceanic crust, the geologic record is biased in favor of continental islands leading as far back as the Cambrian (Dott, 1974). In contrast, hotspot oceanic islands are transient features due to island subsidence and strong marine erosion. Consequently, their onshore record typically does not extend beyond Miocene times (Menard, 1986). Their mid-ocean geography, however, makes them prime localities to look at present and past coastal biotopes and sedimentary processes in an oceanic setting, as well as places to gain insights on ancient patterns of wind and ocean currents.

All 20 Miocene and 15 Pliocene examples of biotas associated with rocky shores from localities around the world surveyed by Johnson and Baarli (2012) come from continental shelves. Rocky-shore biotas

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0031-0182/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.palaeo.2013.12.028

from oceanic islands, however, are becoming better known. Santos et al. (2011) described a rocky shore from the Middle Miocene of Porto Santo in Madeira (Portugal) that features a biota with intertidal zonation. Additional studies on Miocene carbonates from Porto Santo include those by Johnson et al. (2011), Santos et al. (2012), and Baarli et al. (in press). The coastal carbonates of Porto Santo and many other oceanic islands in the northeast Atlantic Ocean often incorporate whole rhodoliths or sediments eroded from rhodoliths. These coralline red algae are non-attached and spherical to sub-spherical in shape due to concentric growth accruing with circumrotary movement in benthic settings under sun-lighted waters. Evidence collected on a global scale suggests that rhodoliths registered peak domination in carbonate facies during Early to Middle Miocene times (Halfar and Mutti, 2005; Braga et al., 2010).

Island groups from the North Atlantic realm of Macaronesia, which include the Azores, Madeira (with the Selvagens), Canary, and Cape Verde archipelagos, have a volcanic history tracing back to the Miocene or older. Additionally, many of the Macaronesian islands were subjected to uplift, making them particularly rich in exposed marine sedimentary and volcanic sequences (Ramalho et al., 2010a,b; Ávila et al., 2012; Meireles et al., 2013). Like Madeira, the fabric of Miocene and younger limestone deposits from many of the other island groups is enriched by rhodoliths and rhodolith-derived sediments (Zazo et al., 2002; Amen et al., 2005; Johnson et al., 2012; Mayoral et al., 2013). A theme of overarching regional interest concerns the degree to which the strong Northeast Trade Winds pervasive across much of Macaronesia influenced the formation of rhodolith limestone.

This study is focused on São Nicolau, one of the principal windward islands belonging to the Cape Verde Archipelago in southern Macaronesia off the West African coast of Senegal. The goal of this study is to test the hypothesis that differences in biofacies around the margins of the island are due to physical constraints related to contrasting windward and leeward environments. Two tasks shape the project's organization: 1) to reconstruct the approximate size and configuration of the proto-island of São Nicolau during the Late Miocene and immediately before the onset of the Main Eruptive Complex (after Macedo et al., 1988), and 2) to compile detailed stratigraphic profiles for Miocene and Pliocene sections that include biofacies associated with former rocky shores.

2. Geographic and geologic settings

2.1. Physical geography

São Nicolau is one of 15 volcanic islands in the Cape Verde Archipelago dispersed over a prominent seafloor anomaly called the Cape Verde Rise (Fig. 1). Due to an almost-stationary position with respect to its melting source, the archipelago corresponds to a cluster of islands arrayed in a west-facing semi-arc (McNutt, 1988; Ramalho, 2011). Traditionally, the archipelago has been classified into windward and leeward islands with respect to the dominant NE trade winds. São Nicolau is one of the windward islands and it ranks fifth largest in size with an area of 343 km^2, which is slightly above the median compared to the 14 other Cape Verdean islands (Mitchell-Thomé, 1972). In terms of elevation, São Nicolau is the fourth highest with a maximum elevation of 1304 m (Mitchell-Thomé, 1972).

The location of São Nicolau within the north-central part of the archipelago and the island's overall shape make it an appropriate subject for this study. In particular, the north shore of São Nicolau is unusual for a roughly east–west alignment that extends over a distance of 45 km (Fig. 1). No other island in the group makes such a broad target for the steady trade winds arriving out of the northeast. With little difference between winter and summer seasons, the north shore of São Nicolau is subject to winds that reach 5–6 on the Beaufort Scale (Brand, 2011), which equates to wind speeds between 8 and 10.8 m/s. Intervals of calm are seldom met on this shore. Crossing an enormous fetch, the trade winds that reach São Nicolau produce ocean swells with wave heights that run between 3.5 and 6 m (Brand, 2011). The present-day wind field and sea-surface dynamics make conditions on the windward rocky shore highly energetic. Scouring of the shore is intense and even small pocket beaches (as at the mouth of Ribeira Alta east of Juncalinho)

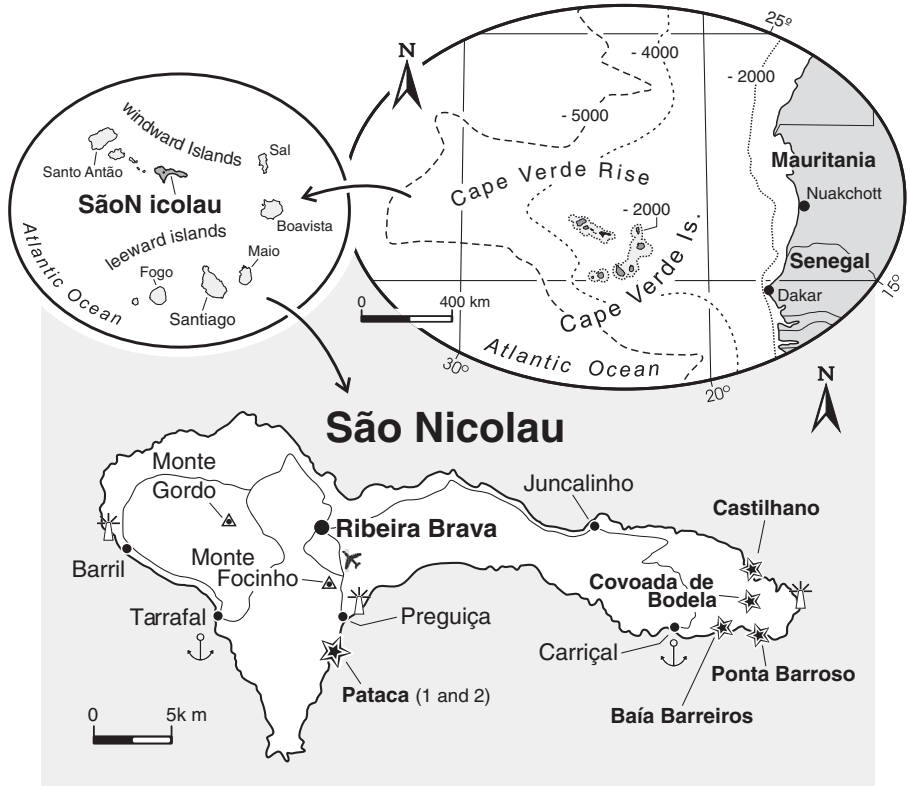

Fig. 1. Maps at various scales for the North Atlantic Cape Verde Rise with details shown for the Cape Verde archipelago and the island of São Nicolau.

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