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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.

REVISION NOTES (for manuscript PALAEO7293)

We received the reviews for this manuscript on October 4, 2013 with a recommendation for major revision. After discussion among the co-authors, it was agreed that a significant part of the revision must feature two important elements: 1) a new stratigraphic log from the leeward, southeast side of the Cape Verdean island of São Nicolau, and 2) new thin sections of the fossil rhodoliths from our collections to determine the floral identity at least to genus level. In particular, one of the recommendations from Reviewer #2 was to incorporate a reference by Braga et al. (2010) outlining a distinction among different living and fossil coralline red algae that form as rhodoliths regulated by the original water depth. Identification of the Miocene rhodoliths from our stratigraphic profiles now adds a critical element to the story that serves to test the concept of depth relationships in fossil rhodoliths.

The earlier version of our paper included comments under section 2.3 (Previous paleontological studies) giving general observations on Miocene strata from the south side of São Nicolau not formalized in detail with a proper stratigraphic log. That part of the island is difficult to reach and only one member of our team had visited the place prior to our project. Our treatment of these incomplete data confused Reviewer #2, who inquired with a notation on line 525 of the original submission: "Where is the fossil content described in terms of paleobathymetry?" Also, in line 565, where it is asked whether a conclusion comes from the literature or an original observation by our team. Thus, one of our goals for the revised ms. was to provide the detailed stratigraphic log for a locality at Baía dos Barreiros (new Fig. 6). In order to do this, a member of our team (RSR) returned to São Niocolau in October/November to compile the data from this locality. Thus, we now submit a manuscript with a total of nine figures, an increase by one to accommodate the new profile from Baía dos Barreiros.

In the following commentary, we respond to the comments and suggestions offered by the journal's editor, Reviewer #1, and Reviewer #2. Original commentary is shown in black and our response is shown in red.

Editor's notes

All items specifically listed by the editor for correction have been complied with and corrected in the revised manuscript. Only one comment asked for modification of a particular figure:

Fig. 1: Please indicate latitudes and longitudes on map in upper right.

Done. Note that additional lines of latitude and longitude are already shown in the larger map for São Nicolau provided in Fig. 2.

Reviewer #1

The present paper is a good contribution and I find very informative and well organized. I feel the paper have a very long results section but I feel this need to be reflected in the discussion where I think there are no implications of the rhodolith sphericity data or other implications of their findings about rhodolith material.

NOTE: There is a contradiction between the editor's request for a shorter discussion and Reviewer #1 asking for the results to be better treated in the discussion. New results describing the stratigraphic log from Baía dos Barreiros have been added (lines 304-321). More to the point of the comment by Reviewer #1, a new section under the discussion (5.2 Composition and morphodynamics of São Nicolau rhodoliths) has been added (see lines 444-468). This addition is compensated for by removal of a large part of the discussion that reviewed information from published papers on other paleoislands (see excised lines 471-495).

Reviewer #2

The text is concise and well written. The stratigraphic and sedimentary data are well analysed and the illustrations represent a detailed account of the analysed stratigraphic sequences. So positive!

However, the readers would be greatly helped in understanding the studied scenario if a clear and detailed windward and leeward biotas are described and distinguished (even with tables). Rhodoliths are quoted in the highlights and in the abstract but a detailed description of the rhodolith assemblages is missing. The triangular diagrams do not really show a clear contrast among the rhodolith assemblages as stated in the highlights.

In terms of rhodoliths, there is largely one kind of assemblage – a transported assemblage – while some other details associated with the substrate indicate an *in situ* biota (trace fossils as borings). The faunal composition is quite simple and we don't believe that tables are the answer to this situation. Instead, we supply a more forceful statement regarding the differences between *in situ* and transported assemblages on both leeward and windward sides of the island.

The reviewer fails to understand the significance of the triangular plots that show extreme roundness. Possibly, there is a misunderstanding about these plots, thinking that some are for specimens from a windward setting as opposed to others from a leeward setting – when in fact all come from the windward side of the island. Allusion to naming things in tables also implies that the reviewer is looking for identification of the rhodoliths by genus and species. Using the new thin sections, we have accomplished this at the genus level. Only a single genus can be identified from our thin sections. We have returned to the thin-section studies published by

Torres and Soares (1946) that confirm *Lithothamnium* as the only genus so far identified with respect to rhodoliths from the island of São Nicolau. The paper by Braga et al. (2010) recommended to us by Reviewer #2 makes a compelling argument that many fossil identifications of rhodoliths to species level are unreliable. Thus, we feel comfortable keeping our identification at the genus level.

I find a number of problems with the presentation of the science (regarding the biotic content and the palaeoecological discussion/interpretation) and at this stage I would recommend its publication after major revision. Intensely negative! It should be returned to the authors for consideration for major revision with to the palaeoecology of the Upper Miocene-Pliocene marine assemblages. Nonetheless, the manuscript could be limited to deal with the stratigraphic and geological data. If this would be the case the authors should leave out the statements to the biogenic components of the limestone which are not really facies analysed in detail.

NOTE: We have adopted the suggestion by Reviewer #2 to emphasis the stratigraphic and geological data over "species" data in our revision. Thus, we consistently refer to biofacies mainly in a sedimentological sense – as opposed to species-level identifications. Comparison with living marine fauna is beyond the scope of this paper, because adequate biological work remains to be done in the Cape Verde islands.

I have added several comments and suggestions into the text (line commentary).

NOTE: It is *only* in the commentary addressed to specific lines in our manuscript that the reviewer's objections are hinted at.

Line 46 (Keywords): Rhodoliths – These are not really treated in detail in the study

Taxonomic considerations are now a part of this study, particularly in response to the paper by Braga et al. (2010), but only at a genus level for the rhodoliths.

Line 81: The paper by Halfor & Mutti (2005) is an over simplification of the rhodolith distribution in the fossil record. There are several examples that show thick Oligocene rhodolith deposits (see Braga et al., 2010).

NOTE: Halfor & Mutti (2005) are cited in the paper by Braga et al., (2010) with only a slight adjustment suggesting that maximum diversification occurred during the Early Miocene as opposed to the Middle Miocene. Furthermore, the Braga paper takes a particularly strong stand by arguing that the many species names for fossil rhodoliths currently in use are unreliable. This puts into question any attempt to determine the maximum time interval of rhodolith species diversity! HOWEVER, we can accept Braga's determination of an Early Miocene high.

Line 102: The "differences in biotas" are not really explored in detail in their study. It would need at least a table for comparisons between the fossil assemblages and the possible present-day counter parts.

Because the fauna differences are so striking, while at the same time involving so few "species" – tables are unnecessary. The strat columns are sufficient for this purpose. ALSO, with the visit by coauthor RSR to the locality at Baía do Barreiros – we are now able to add another stratigraphic section (Fig. 6) to emphasize the absence of whole rhodoliths on the south side of the island.

Line 151: interpreted – By means of what? This is in reference to the paper by Bernoulli et al (2007), where the age is interpreted on the basis of micro-fossils.

Line 248: attributed – Why attributed? Have you not checked the main building organisms? We substitute the word "assigned" for attributed and state that we have visited the locality and are able to confirm the main biogenic component.

Line 274: Subsection 4.3 on Fossil rhodolith shape analysis – The data of these analyses are not successively discussed and interpreted.

As per recommendation of Reviewer #1, we now include a section that further deals with these analyses under section 5.2. There (lines 447-448), we emphasize that limitation to the upper point of the triangle is among the most extreme we have ever found in both our own analyses and those of many other authors. It is as if the reviewer believes we are hiding data regarding other rhodoliths with other shapes. There are no other shapes to discuss in terms of the material available.

Lines 289-290: This is an interpretation and should be moved to the Discussion. OK

Line 297: former palaeoshore – How do you know the relationship with the former palaeoshore? Do you guess it from stratigraphic correlation or are there hints from the fossil content?

This is based on close physical relationship to basal substrate in addition to the changing nature of the faunal content -- and this is clearly shown in Fig. 2.

Lines 382-386: on reaching relatively high-energy conditions – Why? What are the evidences?

The preceding sentence clearly states the evidence.

Line 392: death assemblages – What are the evidences of this? This needs to be justified.

Living rhodoliths are rarely packed more than two deep. The reviewer does not seem to understand that we can keep track of the paleoshore by noting proximity to the basement rocks and also by observing the presence or absence of basalt-rock cores within the rhodoliths. Rhodoliths stacked deep against a paleoshore cannot represent living conditions! Furthermore, the data supplied in the paper by Braga et al. (2010) makes no reference what so ever to thicknesses of rhodolith beds. Rather, it supports the concept that different species of rhodoliths live in deeper, more offshore waters in contrast to species that live in shallower, nearshore waters. This distinction is reviewed in our discussion section and it helps strengthen our arguments now that we know we are dealing exclusively with forms belong to the genus *Lithothamnion*.

Line 414: Dott (1974) – What are the possible relationships between this example and the case study?

The relevance is that other studies find evidence of generally thick basal conglomerates on one side of a paleoisland (windward setting), but with reduced clast sizes or not at all present on the opposite side (leeward setting). In the revised paper, we cite Dott (1974) only to show that continental islands have been described dating as far back as the Cambrian.

Line 462: Rong et al. (2013) - Same criticism, but the reference is now removed.

Lines 442-433: deprived of sunlight – Coralline red algae can survive for a long time without light. What are the evidences for such a statement? This means a relatively abrupt mass mortality.

Yes, we have ample evidence from coastal deposits on Fuerteventura in the Canary Islands that an abrupt mass mortality of rhodoliths can take place through storm deposits. We have added this comment based on our experience with such contemporary deposits (see line 449).

Line 444: encrusting corals – does this mean that the encrusting corals thrived when the coralline algae did not?

Correct ! This is obvious from the photo in the original article, because the coral makes a lop-sided counterweight that makes it impossible for the rhodolith to move. The rhodolith was immobile at the time of coral encrustation. The present article under consideration is not the place to rehash information readily accessible in the published literature.

Line 452: whereas – There should be differences in the coralline taxonomic assemblages. No mention of this?

We have added information on the fossil genus identifications from the Hill of Oranges and Pedra de Agua localities on Ilhéu de Cima (Porto Santo, Madeira Archipelago) in the Madeira islands. In this particular case, the results only partially support the predictions of Braga et al. (2010).

Line 525: agree reasonable well with fossil content – Where is the fossil content described and interpreted in terms of paleobathymetry? This needs a clear description in the text.

The insertion of new text related in Fig. 6 in the results and discussion sections resolves this issue.

Line 547: shallow, sub-tidal marine biotas – These three marine biotas are not clearly defined / described / circumscribed in the text.

This is from the Conclusions section! There now exists a fourth strat section (Fig. 6) based on the recent fieldwork. By RSR. Furthermore, this issue is adequately treated (and in a novel way) under section 5.4 dealing with the use of volcanic sequences to gauge absolute water depth.

Line 565: Conclusion 2 – Is this a conclusion achieved by the present paper – or is it from the literature? Is there any evidence of this from the coralline taxonomic assemblages (i.e. deep-water coralline assemblages) or re-sedimented shoreward?

This aspect is resolved by addition of the new stratigraphic log from Baía dos Barriros (Fig. 6) and the confirmation that we are dealing with only a single genus of rhodoliths from the Miocene of São Nicolau.

Lines 567-568: Do you think this is due to paleoenvironmental reasons or to redeposition?

The red-algal fragments are due to redeposition and we have strengthened this argument through the addition of the new stratigraphic log from Baía de Barreiros (Fig. 6) and accompanying texts.

Line 586: no discrepancy indicated by fossil content – What fossil content would point out those water depths?

Citations related to trace fossils help reaffirm the depth measurements concluded from the overlying lava deltas.

Line 589: original water depth – This should be a more detailed discussion by comparison by fossil contents of the limestone. The fossil content should be described at a species level (or at least at genus level) in order to provide consistent comparisons with present-day counter parts.

New information on rhodolith genera is added and we re-emphasize other factors – such as the occurrence of very delicate bryozoans in the leeward setting.

Fig. 5: In the highlights, you state: “Shape analysis of abundant rhodoliths shows selection for transported forms.” This is not really evident in these diagrams where the dominating rhodoliths are spheroidal in shape. In a selected rhodolith assemblage, I would expect a more evident contrast between the shapes.

Again, the reviewer shows ignorance based on what the diagrams are intended to test and to show. If the reviewer is hoping to find differences in rhodoliths based on the premise of the Braga et al. (2010) paper, then he will be disappointed. We cannot add shapes to the triangular plots that do not exist. We have only one shape to exhibit and we re-emphasize that a kind of winnowing action is strongly implied.

Summary

All corrections required by the journal’s editor have been made. Reviewer #1 offered only a brief report that chiefly asked for a better discussion on the repercussions of our shape analyses (Fig. 5) in the discussion section. This has been done. Reviewer #2 found our contribution to be concise and well written. However, he/she had many criticisms that were spelled out only by the many notations added in the margins of our text. We believe that we have answered each and every one of those criticisms. Clearly, Reviewer #2 has a high regard for the 2010 paper by Braga et al. That paper sets out certain predictions regarding the depth preferences of rhodoliths by genera. We have taken pains to add to our present manuscript new data on generic identifications from our collections from São Nicolau – as well as a summary of the generic identifications previously reported in some of our earlier studies on fossil rhodoliths from the Canary and Madeira islands. Some references marked by Reviewer #2 as superfluous have been removed from the text and bibliography. The submitted “Highlights” have been amended to better reflect the key aspects of our study related to transported assemblages. We hope that sufficient information is now at hand to reconsider our manuscript for publication in PPP.

Palaeogeography, Palaeoclimatology, Palaeoecology

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

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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 ~~summarizes~~ combines previous data and new results from a detailed stratigraphic log based on ~~collected from~~ Upper Miocene limestone deposits on the island's south flank for comparison with ~~newly compiled~~ stratigraphic profiles of Upper Miocene limestone ~~with detailed stratigraphical logs~~ from the island's northeast quarter. ~~Also utilized are~~ New profiles from a Pliocene sandy limestone outcropping ~~exposed~~ 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 ~~coralline red algae~~ occur as ~~in~~ finer Miocene grainstone on the island's southern, protected side. ~~The Pliocene succession sequence gives added context to the diversity of marine invertebrates, including branching coral colonies and delicate ramose bryozoans that found shelter in a leeward setting. These~~ 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.

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

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 ~~emigrated to~~ 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~~, some of which~~ that demonstrate fossil evidence for contrasting exposed and sheltered biotopes (Johnson, 2002 ~~Johnson and Hayes, 1993; Rong et al., 2013~~). 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 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. (2013). 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 in sun-lighted waters. Evidence collected ~~more generally~~ on a global scale suggests that rhodoliths achieved peak domination in carbonate facies ~~through and soon after the~~ during ~~the~~ Early to Middle Miocene times ~~Climatic Optimum~~ (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 (Mayoral et al., 2013; Johnson et al., 2012, 2013; Amen et al., 2005; Zazo et al., 2002). 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. ~~distribution and incorporation of rhodoliths in limestone deposits of various kinds~~.

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 past biofacies around the margins of the island are due to physical constraints related to contrasting windward and leeward environments. Two tasks ~~goals~~ 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 ~~fossil biotas related to~~ former rocky shores. ~~The central hypothesis to be tested is that differences in biotas and related bioclastics around the margins of the island are due to physical constraints related to contrasting windward and leeward environments. Presence or absence of rhodoliths in the studied sections is but one factor considered among others that entail a range of ecological dynamics regarding additional biological components.~~

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 crude semi-arc (McNutt, 1988; Ramalho, 2011). Traditionally, the Cape Verde Islands have been classified into "windward" ~~comprising all the northernmost islands of Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and Boavista~~ and "leeward" islands ~~comprising the islands of Maio, Santiago, Fogo and Brava~~ 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~~, his table 1~~). In terms of elevation, São Nicolau is the fourth highest with a maximum elevation of 1,304 m (Mitchell-Thomé, 1972~~, his table 1~~).

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 ~~its~~ 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/sec. 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) are rare along the north coast. The island's largest ~~only substantial~~ sand beaches are found around Tarrafal de São Nicolau on the sheltered, southwest side of the island (Fig. 1).

2.2. History of volcanism

São Nicolau corresponds to an elongated shield volcano in an early post-erosional stage of development. The island's geomorphology and structure indicate development by composite fissure volcanism along two main rift arms. The more prominent is oriented E–W to WNW–ESE in direction, whereas the lesser is oriented N–S comprising the western portion of the island (Ramalho et al., 2010a). The island's volcanic history extends from the Miocene to the Quaternary (Macedo et al., 1988; Duprat et al., 2007; Ramalho et al., 2010a, b).

Emergence of the earliest landmass belonging to present-day São Nicolau occurred sometime during the Mid- to Late Miocene and corresponds to the Old Eruptive Complex. This unit, which remains undated, mostly comprises intensely palagonitized hyaloclastites pervasively intruded by a dyke swarm (Macedo et al., 1988; Ramalho, 2011). Marine sediments and submarine lavas rest unconformably above this unit. The first corresponds to shallow-water calcarenites (Monte Focinho Formation) with an estimated age ~~interpreted~~ between 11.8 and 5.8 Ma or even between 6.2 and 5.8 Ma (Bernoulli et al., 2007), whereas the latter corresponds to an entirely submarine volcanic unit (Figueira de Coxe Formation) that erupted between 6.2 and 5.8 Ma (Duprat et al., 2007; Ramalho et al., 2010b). The Figueira de Coxe Formation crops out at elevations in excess of 270 m above sea level attesting to episodic uplift that has affected São Nicolau since its first emergence above sea level (Ramalho et al., 2010a, b, c).

After a brief period of volcanic quiescence, uplift, and erosion, during which coastlines and adjacent shelves matured, the edifice of São Nicolau experienced a period of renewed and vigorous volcanic activity that corresponds to the Main Eruptive Complex (Macedo et al., 1988; Ramalho et al. 2010a, b). During this stage, coastlines rapidly expanded ~~considerably (and rapidly)~~ by lateral progradation of effusive lava deltas that covered large swaths of the pre-existing island shelf and preserved existing shelf sediments within the volcanic sequence. The main shield-building stage on São Nicolau lasted approximately 2.5 million years, from 5.0 to 2.5 Ma before present (Duprat et al., 2007; Ramalho et al., 2010b), a period during which coastlines constantly and rapidly shifted as volcanic activity and erosion counterbalanced each other. Finally, around 2.5 Ma, São Nicolau entered a period of slow erosional decay, interrupted by two intervals of volcanic rejuvenation that correspond to the Preguiça and Monte Gordo formations, respectively at 1.7–0.7 Ma and <100 ka (Duprat et al., 2007; Ramalho et al., 2010b).

2.3. Previous paleontological studies

Earlier studies on the paleontology of São Nicolau were conducted by Bebiano (1932), Torres and Soares (1946), Serralheiro and Ubaldo (1979), and Macedo et al. (1988). Torres and Soares (1946) identified some species of fossil rhodoliths belonging to the genus *Lithothamnion*, including material from Monte Focinho. A more recent study by Bernoulli et al. (2007) provided a reappraisal of the taxonomy and age of key fossils from the limestone at Monte Focinho near the island's south-central coast (Fig. 1). A Late Miocene age was established both on the basis of benthic foraminifera in the genus *Amphistegina* and planktic foraminifera ~~attributed~~ assigned to ~~various~~ species of *Globigerina, Globigerinoides, Globoratalia*, and other genera. The grainstone from this locality includes the abundant debris of cirripedean barnacles mixed with lesser amounts of coralline red algae fragments that accumulated below a steep, rocky shore.

~~Previously shown in part by Macedo et al., (1988), recent mapping by Ramalho et al. (2010a) traced a distinct band of Miocene limestone along São Nicolau's southeastern coast to Ponta Barroso (Fig. 1). Sea cliffs along this stretch of the coast are shear and difficult to access without the use of specialized climbing equipment. However, the exposure near the tip of Ponta Barroso is accessible by an arduous overland route. Field notes and field photos collected by one of us (RSR) at Ponta Barroso record the occurrence of fine-grainstone calcarenite with rare large echinoids and bivalves, as well as small pectens. Some rhodolith debris is restricted to the base of the unit. No whole rhodoliths were observed. The thickness of this unit is about 1 m, but varies up to a maximum of about 3 m in thickness.~~

3. Methods

The approximate size and configuration of the island of São Nicolau during the Late Miocene and immediately prior to the onset of the Main Eruptive stage at ~5.1 Ma (Ramalho et al., 2010b) was reconstructed using the present outcrop pattern of the Old Eruptive Complex and Figueira de Coxe Formation in conjunction with relative sea-level information extracted from the volcanic succession ~~sequence~~ at Castilhano (sometimes written Castilhiano). In this place, the first erupted lavas of the Main Eruptive Complex (dated at 5.09±0.07 Ma) preserved a paleo-coastline that presently can be found at ~100 m of elevation (Ramalho et al., 2010a,b). Thus, using ~~the sequence at~~ the Castilhano succession as a pivot point, the shape and dimensions of proto-São Nicolau were extrapolated around the perimeter defined by all outcrops of the Old Eruptive Complex and Figueira de Coxe Formation pene-contemporaneous in position ~~that can be found above ~100 m above present-day sea level~~. On the northern coast, where marine erosion already reduced the island considerably, the approximate position of the 100-m isobath was used to speculate where the northern limit of the ~~Late Miocene~~ island edifice was located during the Late Miocene.

Strip logs for stratigraphic sections modified after the standard format used by Shell Oil Company were compiled for four localities divided between the north and south shores of São Nicolau. In addition to rhodoliths, care was taken to register occurrences of shelly macrofossils and trace fossils. Samples also were collected for calcareous nannofossils, generally limited to finer grained and less indurated layers in the carbonate succession. The fine fractions from samples were concentrated in laboratory test tubes through overnight settling from a vigorously shaken half-sediment, half-tap-water suspension. The top fine fraction was extracted directly to a cover glass by a Pasteur pipette, spread into a rippled smear, and permanently mounted. Smear slides were scanned for coccoliths on a petrographic microscope (Zeiss Ortholux II-Pol) at x1250 magnification along a 3-cm column (approximately 5 mm^2). Calcareous nannofossil taxonomy follows criteria standardized by Perch-Nielsen (1985) and Bown (1998).

Rhodolith samples from two levels at Castilhano were collected for identification at the genus level using petrographic thin sections.

Whole rhodolith specimens from specific stratigraphic intervals were measured on site (to the nearest millimeter) across three principal axes (long, intermediate, and short). Data from these measurements were subjected to analysis based on the triangular plot among spherical, ellipsoidal, and discoidal shapes according to the format applied to rhodoliths by Bosence (1976, 1983) as modified from Sneed and Folk (1958).

4. Results

4.1. Island reconstruction for the ~~of a~~ Late Miocene ~~island~~

Coastline reconstructions for a Late Miocene (5.7–5.1 Ma) island indicate an elongated edifice approximately 25–33 km in length in an east-west dimension, and at least 8-10 km of maximum width in the north-south dimension (Fig. 2). The lack of outcrops of the Old Eruptive Complex and Figueira de Coxe Formation in an area east of Juncalinho and in the vicinities of Ribeira Alta precludes any more solid reconstructions for this part of the edifice.

4.2. North shore stratigraphy and paleontology

Stratigraphic profiles from the oasis at Castilhano and the canyon walls of Ribeira de Covoada de Bodela (Fig. 3) detail the onlap of carbonate deposits against rocky shores located on the northeast flank of Miocene São Nicolau (Figs. 1–2). Both sections are constrained below by the Old Eruptive Complex (intensely altered hyaloclastites and basaltic lava flows) and above by basaltic lava flows belonging to the onset of the Main

Eruptive Complex. Both sections include abundant rhodoliths and both replicate a fining-up pattern through the first 3-4 m at which point the Bodela section terminates. Thereafter, the Castilhano section recommences with renewed coarsening and rhythmic fining and coarsening in thick beds before a final fining-upwards sequence. The lower part of the carbonate succession at Castilhano is packed with rhodoliths that over-ride an irregular basalt surface with a topographic relief of about 1 m, including small overhangs of basalt under which rhodoliths are trapped (Fig. 4A and B). ~~In places, the original basalt surface features thin algal patches attributed to coralline red algae.~~ A basalt boulder above the unconformity exhibits a cluster of circular depressions 4 cm in diameter (Fig. 4C) that match the typical dwelling structures of regular echinoids assigned to the ichnospecies *Circolites kotoncensis*. Rhodoliths are less common in the stratigraphic interval between 2.5 m to 4 m above the unconformity, but thereafter resume in abundance (Fig. 3). An interval directly below the 4-m horizon features the trace fossil *Thalassinoides suevicus* (Fig. 4D).

Many rhodoliths reveal a small rock core of basalt in cross section (Fig. 4E). Sampled from a horizon 40 cm above the unconformity, the average maximum diameter of rhodoliths is 3.3 cm. Higher at a level 2.5 m above the unconformity, the average maximum diameter of rhodoliths registers an increase to 3.75 cm. The rhodoliths from these two levels are identified as belonging to the genus *Lithothamnion* (Davide Bassi, personal communication, 2013). Pectinid bivalves and *Spondylus* sp. together with broken tests of the echinoid *Clypeaster* sp. are more common in the upper half of the exposure than in the lower half. Loose plates of the cirriped barnacle *Balanus* sp. appear in the top two meters of the exposure.

At half the thickness of the Castilhano section, the Bodela section (Fig. 3) also exhibits an unconformity surface with about 1 m of relief on submarine basalt but is notably different in development of a distinct basal conglomerate with eroded clasts up to 45 cm in diameter (Fig. 4F). Rhodoliths with an average maximum diameter of 3.5 cm are plentiful through the overlying section, but not quite as abundant as found in the Castilhano section. In addition to *Pecten* sp. and *Spondylus* sp., ~~additional~~ associated bivalves include oysters encrusted on basalt boulders and the infaunal bivalves *Cardium* sp. and *Venus* sp. As at Castilhano, broken pieces of tests belonging to *Clypeaster* sp. occur, but also the spines of a cidaroid echinoid. Barnacles appear in the Bodela section attached only to bivalves. ~~Broken~~ Rare pieces of the finger coral *Porites* sp. represent a faunal element at Bodela not observed at Castilhano.

4.3. Fossil rhodolith shape analyses

Although the shallow-water marine assemblages ~~faunas~~ of Castilhano and Bodela are somewhat diverse, rhodoliths are the dominant element contributing to the limestone. Samples of whole rhodoliths varying in number from 35–40 specimens were extricated for measurements from narrowly defined stratigraphic intervals at both localities. Comparison shows that the most spheroidal rhodoliths come from an interval 40 cm above the base of the Castilhano section with a spread almost entirely restricted to the upper triangle in the larger triangular plot (Fig. 5A). Higher in the Castilhano section (2.5 m above the unconformity), rhodoliths are slightly larger in size and exhibit a slight tendency to more ellipsoidal shapes indicated by the spill-over of roughly half the sample into other sectors below and to the right of the upper triangle (Fig. 5B). The rhodolith sample from the Bodela section (Fig. 5C) comes from a level directly above the basal conglomerate (Fig. 3). In the range of shapes, it is more like the lower sample from Castilhano, but with a very few points that spill outside the upper triangle in a pattern similar to the upper sample from Castilhano. The majority of rhodoliths from both sections is highly uniform in size and shape. ~~, showing forms that are easily rolled by the movement of the water mass related to surface waves or bottom currents.~~

4.4. South shore stratigraphy and paleontology

A stratigraphic profile from Baía dos Barreiros (Fig. 6) details the onlap of carbonate deposits against rocky shores eroded in the Old Eruptive Complex located on the southeast flank of Miocene São Nicolau (Fig. 2). In this region, the carbonates crop out near the base of sea cliffs for 2.5 km from Baía dos Barreiros to Ponta Barroso (Fig. 2). Sediments constitute a 4 to 5 m evenly thick band, dipping about 10º to the south. In detail, however, the internal structure exhibits prograding foresets dipping about 15–20º to the south. Sediment composition is overwhelmingly dominated by intermediate-to-coarse rhodolith debris with very low amounts of lithics. Abraded rhodoliths are present but extremely rare, as well as other macrofossils. The succession generally exhibits a fining-up pattern, but terminates with a conglomerate that features pebbles derived from the Old Eruptive Complex (Fig. 6). Intervals with the trace-fossil *Thalassinoides* isp. occur at 1.25 m and 3.8 m above the base of the section; the trace-fossils *Sinusichnus* isp. and ?*Ophiomorpha* isp appear at a horizon 3 m above the base of the section. These trace-fossils are known to have a wide depth range in littoral to outer shoreface settings (Mayoral et al., 2013). An erosive unconformity is inferred at the top of the sedimentary succession, as shown by truncation of a basaltic dyke. The sediments along Baía dos Barreiros occur at the same stratigraphic position found at Castilhano and Ribeira de Covoada de Bodela. As such, these sections are considered to be pene-contemporaneous.

Extensive sedimentary outcrops on the south shore are exposed through the canyon of the Ribeira da Ponta da Pataca, located about 800 m south-southwest of the village of Preguiça (Fig. 1). Stratigraphic profiles for Pataca 1 (Fig. 6) and Pataca 2 (Fig. 7) are laterally continuous over 130 m and represent respective distal and more proximal settings in relationship to a former paleoshore. The thicker succession ~~sequence~~ at Pataca 1 commences 17 m above present sea level, whereas the thinner succession ~~sequence~~ at Pataca 2 starts at about 60 m above present sea level and follows inland along the narrow streambed of Ribeira da Ponta da Pataca. Well-defined beds near the top of the succession dip about 6 to 8º to the southeast. A pile of submarine sheet flows rest conformably above the fossiliferous sediments. The transition to subaerial flows is poorly observed as the outcrops are extensively covered by scree.

At Pataca 1, the outcrop consists of three coarsening-up intervals with echinoid tests and spines present throughout. The initial coarsening-up sequence is a massive, very sandy and poorly sorted limestone or calcareous sandstone (Fig. 8A). Whole macrofossils are few, but the bivalve *Pinna* sp. is preserved in life position. In addition, short branching colonies of *Porities* sp. (Fig. 8B) occur together with thin, stick-shaped bryozoans of *Thalamoporella* sp. (Fig. 8C) that are commonly encrusted by a more delicate bryozoan attributed to *Metrarabdotos* sp. The trace fossils *Ophiomorpha nodosa* and *Macaronichnus segregatis* range through most of the initial interval. A second coarsening-up interval is a more pure limestone with higher fossil content that includes coral fragments and coquinas of *Argopecten* aff. *flabellum* (Fig. 8D). *Balanus* plates also are present. Many fossils are encrusted by bryozoans and serpulids. The trace fossil *Ophiomorpha nodosa* occurs at the very base of the interval, but otherwise trace fossils are absent. A third coarsening-up interval begins with minor basalt clasts and changes to a well-sorted lithic sandstone with little fossil content. Echinoids are the most common fossils in this interval, but *Balanus* plates also are present. The trace fossil *Skolithos linearis* (Fig. 8E) dominates the top 60 cm of this interval. The sediments seem to rest upon volcaniclastic breccia that may correspond to collapsed material and/or deposits of submarine debris flows.

The upper part of Pataca 1 is physically continuous with the lower part of Pataca 2. Being more proximal, however, Pataca 2 differs laterally in exhibiting a much higher content of basaltic clasts (Fig. 8F). The section shows a change from sandy limestone to calcareous sandstone (Fig. 7) with increasingly better sorting. The trace fossil *Thalassinoides suevicus* occurs near the base of the section. The lower layers are very fossiliferous, changing upwards to more bioclastsic content ~~broken shells~~. The gastropods *Strombus* sp. and *Turritella* sp. together with pectinid bivalves and barnacles are very common. Some coral colonies of *Tubastrea* sp. with conspicuous borings by pholad bivalves (Fig. 8G) are encrusted together with serpulids on basalt cobbles. The upper part of this section is formed by massive sandstone with fewer fossils. Echinoids spines, transported and worn *Porites* colonies and fragments of ~~broken~~ *Pecten* shells are present, as well as a sparse representation of the trace fossil *Ophiomorpha nodosa*.

4.5. Calcareous nannofossil biostratigraphy

Samples for age-diagnostic nannofossils were collected at three levels through the stratigraphic succession at Castilhano (see Fig. 3) both with and without rhodoliths. Species common to all three samples include *Dictyococcites antarticus, D. productus, Reticulofenestra haqii-minutula*, and *R. pseudoumbilicus*. The abundance of calcareous nannofossils showed an increase up-section, consistent with the transgressive nature of the succession. No species were exclusive to the horizon rich in rhodoliths. Species common to the upper samples but lacking from the lowest sample include *Calcidiscus leptoporus, Ciclicargolithus floridanus, Discaster* sp., small *Reticulofenestra* sp., *R. rotaria*, *Sphenolithus abies*, and *Syracosphaera* sp. The assemblage is compatible with a Late Miocene ~~an Upper Miocene position, in particular the~~ (Messinian) age (Bown, 1998). Notably, *R. rotaria* has a know First Appearance Datum (FAD) of 7.42 Ma and Last Appearance Datum (LAD) of 6.91 Ma.

A single sample was collected from the up-stream section at Ribeira Covoada de Bodela (see Fig. 3). The diversity of calcareous nannofossils is lower than that found at any level at Castilhano, but includes many of the same species indicative of correlation with the Messinian Stage.

Samples were collected at three levels through the Pataca 1 section (see Fig. 7). The sample from the lower layers is low in diversity with only three species: *Braarudosphaera* cf. *rosa, Coronocyclus nitescens*, and *Discoaster* sp. The sample from the middle layers proved to be barren of nannofossils. Finally, a sample from the upper layers yielded an assemblage including *Calcidiscus leptoporus, Coccolithus pelagicus, Helicosphaera carteri, Reticulofenestra productus, R. minuta, R. haquii-minutula, R. antarticus, R. pseudoumbilicus, Pontosphaera* sp. and *Umbilicosphaera* sp. This assemblage is compatible with a Pliocene position due to the presence of several reticulofenestrids, including *R. pseudoumbilicus* (Bown, 1998).

4.6. Summary of dichotomous biofacies

~~Using paleontological data collected by Bernoulli et al. (2007) on an Upper Miocene deposit at Monte Focinho near the south-central coast of São Nicolau (Fig. 1), it is instructive to draw contrasts with Upper Miocene deposits at Castilhano and Bodela (Fig. 3) near the island's present-day northeastern shore.~~ Using biofacies from the northerly Upper Miocene deposits at Castilhano and Bodela (Fig. 3), it is instructive to draw contrasts with the southerly pene-contemporaneous deposits from Baía dos Barreiros (Fig. 6), augmented by data collected by Bernoulli et al. (2007) from the south-central coast of São Nicolau. All four successions ~~three~~ are seated on the Old Eruptive Complex as defined by Macedo et al. (1988). ~~These deposits also signify the marine onlap of rocky shores that are Late Miocene in age.~~ Loose barnacle plates are present at the Monte Focinho and Castilhano localities, as well as whole barnacles attached to shells at Bodela, indicating an initially ~~a relatively~~ shallow-water source for the deposits. Likewise, dwelling structures eroded by regular echinoids in a basalt boulder at Castilhano (Fig. 4C) confirm such a relationship. In addition to the various benthic and planktic foraminifera recovered from the Monte Focinho section, Bernoulli et al. (2007) described a bioclastic grainstone that incorporates echinoid spines and bits of red algae, although the limestone's dominant signature comes from barnacle debris. No traces of whole or fragmentary rhodoliths were detected during our visit to the Monte Focinho locality.

Further comparisons may be drawn between the Miocene sequence at Castilhano and the Pliocene sequence at Pataca. The former registers two deepening phases of deposition on an open marine sublittoral platform signified by rhythmic fining-upward beds in the middle of the succession ~~sequence~~ (Fig. 3). In contrast, the Pataca 1 section records three coarsening-upward phases with considerably greater content of terrestrial lithics (Fig. 6). Of these, only the two upper sequences shallow sufficiently to reach relatively high-energy conditions. The presence of both whole and crushed valves belonging to pectinid bivalves indicates landward transport from an open, offshore area to the south, whereas barnacles record input from a closer, near-shore zone. This overall scenario has implications for the development of a distal delta on the leeward side of São Nicolau. The most striking omission from this Pliocene scenario is the complete lack of rhodoliths or rhodolith debris ~~brought landward from offshore areas~~. This is in marked contrast to the older Castilhano and Bodela sections on the windward side of São Nicolau, where ~~coralline red algae encrusted around basalt pebbles as~~ rhodoliths (Fig. 4F) constitute the primary carbonate signature showing shoreward transport against rocky shores. For the most part, these deposits signify death assemblages, because photosynthesis by the coralline red algae ceased for all but the top layer of rhodoliths in the transported package.

5. Discussion

5.1. Reconfiguration of a Miocene island

The coastline reconstructions for a Late Miocene island (Fig. 2) portray a smaller edifice than the present-day São Nicolau. This is not surprising, as these reconstructions correspond to a moment in time that immediately preceded the onset of the main shield building stage, during which the island grew considerably in size. Notwithstanding its this smaller size and the uncertainties associated with such extrapolations, it is possible to infer that São Nicolau already constituted a prominent east-west elongated volcanic edifice that extended from 25 to 33 km in length during the Late Miocene. This volcanic edifice essentially emerged above the sea surface by means of uplift and not summit volcanism, as attested to by onlap of a dominantly subaerial Main Eruptive Complex over the eroded remains of an entirely submarine edifice corresponding to the Old Eruptive Complex and Figueira de Coxe Formation.

5.2. Composition and morphodynamics of São Nicolau rhodoliths

The Upper Miocene rhodoliths from the northern shores of São Nicolau are characterized by three key traits. They are comparatively small, exceedingly well rounded, and are represented by the single genus *Lithothamnion*. As demonstrated through shape analyses (Fig. 5), these rhodoliths are among the most spherical detected so far in studies on living and fossil rhodoliths from the Cape Verde and Canary islands (Johnson et al., 2012). Practically, such shapes make good rollers that are susceptible to transport; therefore it is not surprising to find thick rhodolith accumulations on the windward side of paleoislands. According to Braga et al. (2010), the taxonomic composition of Miocene coralline assemblages and growth forms changes with depth that parallels present-day conditions. For example, the mastophoroid and lithophylloid rhodoliths are typical of shallower-water settings, whereas the melobesioids (which include *Lithothamnion*) tend to represent deeper-water settings. On this basis, it may be argued that the São Nicolau rhodoliths that typically nucleate around small basalt cores were transported shoreward from deeper waters.

The sedimentological signature imparted by rhodoliths on the paleoshores of Miocene São Nicolau are strongly related to physical transportation. On the northeast shore at Castilhano and Bodela (Fig. 3), relatively small rhodoliths were left intact but rolled shoreward by the action of strong surf to abut directly against rocky shores. In some cases, the rhodoliths fill spaces below bedrock overhangs. In contrast, the fact that only rhodolith debris is present on the leeward southern shores at Ponta Barroso and Baía dos Barreiros (Figs. 2 and 6) indicates that long-shore currents and wave refraction was the dominant influence in transporting materials to the southern shelf. The internal structure of these beds with distinct foresets suggests that sediments were deposited as clinoforms directed offshore to the south.

5.3. Comparison with other windward-leeward systems

~~Cambrian biotopes around former continental islands provide little or no evidence regarding the imposition of windward-leeward systems, but sedimentological relationships give some insight. Studying Precambrian–Cambrian unconformities exposed in the Baraboo district of Wisconsin, Dott (1974) reconstructed a windward-leeward system impacted by trade winds and storm winds that preferentially left a down-current trail of smaller quartzite pebbles on one flank of an archipelago while leaving much larger quartzite boulders in place around the island shores.~~

~~Sedimentological and palaeontological data collected by Rong et al. (2013) are related to the reconstruction of a Late Silurian continental island affected by prevailing~~

~~trade winds over the flooded Sino-Korean tectonic plate. Strata sitting on diorite around the palaeoisland's circumference feature coarse, diorite-derived conglomerate on the exposed, windward flank and silty limestone in direct contact with the unconformity surface on the opposite flank. Large stromatoporids are cemented on the unconformity surface and a fauna consisting of heliolitoid and tabulate corals occurs at or very close to the unconformity surface on the protected side of the island. None of the corals occur on the windward side where the conglomerate is well developed (Rong et al., 2013).~~

~~A windward-leeward system of opposing facies around small continental islands of Late Cretaceous age on the Pacific coast of Mexico's Baja California were described by Johnson and Hayes (1993). In this case, small rhodoliths with pebble-size cores of andesite eroded from the developing unconformity surface are embanked on the exposed flank of a paleoisland. Valves of a rudistid bivalve also are attached directly to the andesite surface on the same side of the island. These elements are absent from the opposite, leeward side of the palaeoisland, where instead oysters and bryozoans are encrusted on the unconformity and related andesite clasts in addition to cidaroid echinoids intact within the spaces among boulders.~~

Examples ~~cited above originate~~ from the literature (e.g. Johnson, 2002; Johnson and Baarli, 2012) typically relate to former islands on flooded continental shelves. The only case of a windward and leeward system previously studied from a fully oceanic setting on a basalt island comes from Porto Santo in the Madeira archipelago. At the Cabeço das Laranjas on the windward ~~one~~ side of Ilhéu de Cima off Porto Santo, thick Middle Miocene deposits of large rhodoliths represented by the genera Lithothamnion, Sporolithon, and Neogoniolithon are impounded against the original basalt shore

(Johnson et al., 2011). As in the Castilhano and Bodela sections on São Nicolau, rhodoliths in such transported deposits were deprived of sunlight and soon perished. ~~Life continued at the Cabeço das Laranjas in the sense that some rhodoliths at the top of the heap became the substrate for encrusting corals (Johnson et al., 2011, their fig. 4D~~). In contrast, the ~~opposite~~ leeward ~~rocky~~ shore of Ilhéu de Cima at Pedra de Água features a coeval Middle Miocene setting with coral colonies fixed in growth position on basalt mounds that rise above a sandy zone over which no more than one or two layers of rhodoliths are emplaced (Santos et al., 2012, their figs. 1 and 9). Nearly all the rhodoliths observed in cross-section at Pedra de Água are nucleated around large basalt pebbles, whereas many of the rhodoliths at the Cabeço das Laranjas lack a rock core. The rhodoliths at Pedra de Água are polyspecific from the genera *Lithophyllum* and *Sporolithon* and considered to have grown in shallow, subtidal waters close to the paleoshore (Santos et al., 2012), whereas those at the Cabeço das Laranjas were swept towards land from deeper waters by major storms of hurricane strength (Johnson et al., 2011).

5.3. Shifting Miocene wind and storm patterns

Based on stratigraphic data regarding variations in marine benthic $\delta^{18}O$ isotopes, related models for reconstruction of mean sea-surface temperatures, and sea-level variations pegged to ice-sheet models cited by De Boer et al. (2012, their fig. 1), the Middle Miocene Climatic Optimum (MMCO) stands out among major climatic shifts during the last 34 million years. Termination of this phase coincides with expansion of the East Antarctic Ice Sheet corresponding to distinct pulses dated to 13.8 and 13.2 Ma

(Westerhold et al., 2005). Global temperatures not only began to receded with the decline of the MMCO, but evidence from places as distant as the South China Sea and the Mediterranean Sea suggests that the Intertropical Convergence Zone (ITCZ) was pushed substantially northward from a position near the equator (John et al., 2003; Holbourn et al., 2010).

A displaced ITCZ could be expected to have a profound effect on climate in the developing Macaronesian archipelagos of the eastern North Atlantic, including the Cape Verde islands. In place of steady trade winds that normally arrive from the northeast, the flow of winds would shift to blow from the southeast. More typical of trade winds in the Southern Hemisphere, these would brush locally parallel to the West African coast and be more likely to stimulate sustained marine upwelling. More significant, the northward migration of the ITCZ should alter the general staging area and subsequent storm tracks of hurricanes in the North Atlantic. This scenario was employed to account for the occurrence of major storm deposits formed by Middle Miocene rhodoliths at Cabeço das Laranjas on Ilhéu de Cima off Porto Santo in the Madeira archipelago (Johnson et al., 2011). ~~The same post-MMCO scenario also accommodates the preservation of an *in situ* rhodolith field along a sheltered palaeoshore at Pedra de Água on Ilhéu de Cima (Santos et al., 2012).~~

Emerging Northern Hemisphere glaciations that intensified through post-Miocene times served to re-balance the ITCZ and facilitate its return to regions around the equator. A stable isotope study based on stratigraphy from the southeastern Atlantic (Vidal et al., 2002) shows a rapid decrease in $\delta^{18}O$ values consistent with a general warming trend in that part of the world already by Messinian time during the Late Miocene. Such a result suggests that a scenario similar to ~~more in keeping with~~ today's pattern of strong northeasterly trade winds across the Maraconesian realm, including the Cape Verde archipelago, was in effect by the end of the Miocene. Hence, present-day climate patterns dominated by persistent trade winds from the northeast against the island of São Nicolau (Brand, 2011) should serve as a reliable guide for comparison of windward and leeward coastal deposits of Late Miocene and Pliocene age around the island. ~~It is noteworthy that wave refraction from wind-driven waves along the eastern shores of Cape Verdian islands like Santiago are fully capable of transporting rhodoliths to the southeast flank, as shown by Pleistocene strata with abundant rhodoliths near Praia (Johnson et al., 2012). Likewise, it is notable from the Pleistocene record that northeast trade winds and local variations caused by topographic baffles are capable of delivering dune sand with extensive rhodolith detritus to the eastern and southeastern shores of Cape Verdean islands (Johnson et al., 2013).~~

5.4. Use of volcanic sequences to gauge absolute water depth

Effusive coastal volcanic successions ~~sequences~~ such as those resulting from the extrusion of lava-fed deltas provide additional ~~excellent~~ constraints on coeval sea level and consequently on paleo-water depths of bottomset sediments (Porebski and Gradzinski, 1990; Ramalho, 2011; Johnson et al., 2012; Meireles et al., ~~in press~~ 2013). During low- to moderate- effusion rates (Ramalho et al., 2013), lava flows entering the sea typically form structures similar to Gilbert-type deltas, with foresets of pillow lavas and hyaloclastites overlain by a topset of subaerial lavas; the passage zone between these two components of the delta thus marks very accurately contemporaneous sea level

(Porebski & Gradzinski, 1990; Ramalho, 2011). The vertical distance between the sedimentary bottomset (typically corresponding to marine sediments coeval of the eruption) and the passage zone, along the dip of the foresets, is thus a reliable way of estimating the palaeo-water depth of the sediments (Ramalho, 2011; Johnson et al., 2012; Meireles et al., ~~in press~~ 2013).

At Castilhano (Fig. 3), a typical lava delta succession ~~sequence~~ with foresets of pillow lavas and hyaloclastites overly the marine sediments and the passage zone between overlying submarine and subaerial basalt occurs 25 m above the top of the limestone, pinpointing coeval stage of sea level around 5.09 Ma (Ramalho et al., 2010b). At Bodela (Fig. 3), the sedimentary sequence is overlain by massive submarine flows, and the passage zone between overlying submarine and subaerial basalt occurs 35 m above the top of the limestone in the Bodela section, suggesting a slightly deeper deposition than at Castilhano. Farther south at Baía dos Barreiros ~~Ponta Barroso~~, the passage zone is 95 m above the Upper Miocene limestone (Ramalho et al., 2010a), marking the terminal depth of that limestone as much deeper. At this locality, however, the value should be treated with caution, because an unconformity marked by a truncated dike occurs between the sediments and overlying lava flows. For these three localities, the passage zone between subaerial and submarine lava flows is coeval and signifies the same relative sea level now ~~uplifted~~ marked 100 m above the present ~~sea level~~. Measurements of accommodated water depth at the time carbonate deposition ceased at Castilhano, Bodela, and Baía dos Barreiros ~~Barroso~~ in the Late Miocene agree reasonably well with fossil content.

At Ribeira da Ponta da Pataca on the south-central coast, the observable passage zone in volcanics overlying Pliocene sedimentary strata is approximately 90 m above present-day sea level, indicating a possible coeval water column of 35 to 40 m for Pataca 2 (Fig. 7) and 60 to 70 m for Pataca 1 (Fig. 6). The difference in paleo-water depth at these two localities is an artifact of the natural slope on the Pliocene sea floor. Because the capping volcanic sequence shared by the two sections consists of a pile of low-angle submarine sheet flows, there may have been a time lapse between the moment of burial and the transition to subaerial flows at the passage zone above. Other possible disconformities may be hidden in the covered interval between the sedimentary strata and subaerial basalt. A hiatus of any duration may mask an intermittent rise in sea level. In any case, the *Skolithos* trace fossils at the top of Pataca 1 (Fig. 6) typically reflect a water depth shallower than suggested by the overlying passage zone. At Portinho da Mulher Branca near Praia on Santiago island, for example, *Skolithos* was related to an overlying passage zone indicating a water depth of only 12 to 15 m (Johnson et al., 2012). This discrepancy in conflicting water-depth indicators remains to be resolved either by extending the bathymetric range of the ichnofossil or by an obfuscating time gap.

6. Conclusions

Examples of contrasting windward and leeward settings from paleoislands are well documented, but mainly from continental shelves. The distribution and fossil content of surviving Upper Miocene limestone strata on São Nicolau are limited but adequate to outline patterns in intertidal to shallow, sub-tidal biofacies ~~marine biotas~~ in close proximity to rocky shores influenced by winds and waves around one of the windward volcanic islands in the Cape Verde Archipelago. Supplementary data from a comparatively thick Pliocene succession ~~sequence~~ on the island's south-central shore provide further insight on the potential richness achieved by biofacies in a setting better sheltered from wave shock. Four core conclusions highlight the results of this study. ~~with regard to marine life on the margins of a volcanically active oceanic island~~.

1. Limestone dominated by whole rhodoliths follows a distinct band correlated from the oasis at Castilhano to the canyon of the Ribeira de Covoada de Bodela on the northeast flank of São Nicolau. Relatively small in size, the rhodoliths were swept shoreward from a shallow bank situated nearby to the north or northeast. Many are nucleated around basalt pebbles eroded from an adjacent rocky shore. These ~~spherical~~ algal concretions accumulated in vast numbers as a transported assemblage deposited against the rocky shore, even pressed below overhangs in the bedrock ~~basalt~~. Although poor in calcareous nannofossils, the identified assemblage is compatible with a Late Miocene (Messinian) assignment. ~~This result is in rough agreement with the 5.09±0.07 Ma age determined by Ramalho et al. (2010b) for the pillow lavas immediately above.~~
2. Whole rhodoliths are absent from the coeval limestone at Baía dos Barreiros in southeast São Nicolau but extensive rhodolith sand is well developed as clinoform structures dipping seaward to the south. The more loosely equivalent limestone at Monte Focinho near the island's south-central shore also includes fine debris of coralline red algae mixed with crushed barnacles. A more sandy limestone deposit of Pliocene age at Ribeira da Ponta da Pataca on the south-central coast ~~of São Nicolau~~ includes elements such as the whole (and broken) valves of pectinid

bivalves, as well as whole branches of the *Porites* coral and delicate *Thalamoporella* bryozoan that are unusual or entirely absent from deposits on the north side of the island. A Pliocene age for the Pataca deposits based on calcareous nannofossils concurs with the age of basaltic lavas near the overlying passage zone dated at 3.06±0.17 Ma.

3. With a change after the Middle Miocene Climatic Optimum that brought the Intertropical Convergence Zone closer to the equator, the Late Miocene and Pliocene conditions at São Nicolau experienced steady winds from the northeast that generated ocean swell. Although smaller than today by perhaps 40%, the Late Miocene island still presented a long east-west oriented northern shore that felt the full impact of these conditions, much as today. Thus, the fossil deposits at Castilhano and Bodela represent accumulations on an exposed, windward coast, while those at Baía dos Barreiros and Pataca are indicative of a more sheltered, leeward coast.
4. Upper Miocene limestone beds near the northeastern coast at Castilhano and Bodela are overlain by submarine flows with passage zones to subaerial flows at intervals 25 m and 35 m above, respectively. Marine onlap of the carbonates concluded at those water depths with no discrepancy indicated by fossil content. Certain discrepancies with unconformities and trace fossils remain to be solved, as in the southern sucessions ~~the Pliocene Pataca sequence~~. Overall, however, the application of such transitions in volcanic flows to measure original water depth is a useful technique in the reconstruction of coastal conditions.

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679 **References**

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Figure Captions

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

Fig. 2. Reconstruction of São Nicolau during the Late Miocene at ~5.1 Ma.

Fig. 3. Stratigraphic profiles for localities at Castilhano and Ribeira de Covoada de Bodela on the northeast flank of Miocene São Nicolau.

Fig. 4. Upper Miocene deposits against basalt unconformities from the northeast part of São Nicolau showing details of faunal components: A) Irregular unconformity surface overlain by abundant rhodoliths at Castilhano (figure at right for scale), B) Small overhang of basalt filled with rhodolith limestone, C) Part of a basalt boulder above the unconformity surface with dwelling structures formed by regular echinoids assigned to the trace fossil *Circolites kotoncensis*, D) Trace fossil *Thalassinoides suevicus* from mid-section at Castilhano (see Fig. 3), E) Typical interval packed with rhodoliths many of which formed around basalt pebbles (arrows), and F) Basal conglomerate and overlying rhodolith limestone at Ribeira de Covoada de Bodela (figure at left for scale).

Fig. 5. Triangular plots showing the relative shapes of fossil rhodoliths: A, from the lower part of the section at Castilhano, B) from the middle part of the section at Castilhano, and C) from the lower part of the section at Bodela.

Fig. 6. Stratigraphic profile for the sequence at Baía dos Barreiros on the southeast flank of Miocene São Nicolau.

Fig. 7. Stratigraphic profile for the Pliocene coastal sequence at Ribeira da Ponta Pataca on the southwest flank of Miocene São Nicolau.

Fig. 8. Stratigraphic profile for the more inland Pliocene sequence at Pataca 2.

Fig. 9. Pliocene deposits capped by basalt from the southwest coast of São Nicolau at Ribeira da Pataca: A) Outcrop overview of Pataca 1 (see Fig. 7), B) Cluster of the coral *Porites* sp. from the lower beds, C) Ramose bryozoan *Thalamoporella* sp. from the lower beds, D) Disarticulated shells, mostly *Argopecten* aff. *flabellum* from the upper beds, E) Trace fossil *Skolithos linearis* from the top of the section, F) Outcrop overview of the Pataca 2 section (see Fig. 8), and G) Coral colonies of *Tubastrea* sp. bored by pholad bivalves from the middle of the section.

***Highlights (for review)**

- Late Miocene São Nicolau Island was impacted by NE trade winds as today.
- Windward biofacies are rich in rhodoliths nucleated on eroded basalt pebbles.
- Shape analysis of abundant rhodoliths shows selection for transported forms.
- Leeward biofacies are dominated by sand from crushed rhodoliths.
- Nannofossils, indicate L. Miocene Messianian and Pliocene ages for studied strata.
- Passage zone from submarine to subaerial flows tests the water depth for onlapped paleoshores.

Editor: *Palaeogeography, Palaeoclimatology, Palaeoecology*

Dear Editor Surlyk,

On behalf of my co-authors, I am re-submitting our manuscript "Miocene-Pliocene rocky shores on São Nicolau (Cape Verde Islands): Contrasting windward and leeward biofacies on a volcanically active oceanic island " for your reconsideration.

You will find all our new materials in good order, include a clean copy of the revised text, a copy showing where all changes have been made, and the detailed revision notes. The most significant addition to our study is a new stratigraphic profile from a strategic location on the SE flank of Sao Nicolau (new Fig. 6). All your suggestions regarding editorial changes have been made. Reviewer #1 offered only a brief report that chiefly asked for a better discussion on the repercussions of our rhodolith shape analyses (Fig. 5) for the discussion section, which we have done. Reviewer #2 has a high regard for the 2010 paper by Braga et al. That paper sets out certain predictions regarding the depth preference of rhodoliths by genera. We have taken pains to incorporate this paper into our ms. and to present new data on generic identifications from our São Nicolau collections –as well as to summarize the generic identifications previously reported in some of our earlier rhodolith studies in the Canary and Madeira islands.

We are a large group, but our contribution represents the confluence of several different areas of expertise by the various participants that range from interests in former rocky shores and coastal geomorphology to palaeogeography to nannofossil biostratigraphy to the intersection of rhodolith taphonomy and trace fossils. A novel aspect of our work involves use of the passage zone from submarine to subaerial flows that bury limestone deposits on a volcanic island as a meter-stick to gauge absolute water depth at the moment of local extinction.

A growing literature exists on the burial and exhumation of entire "fossil" islands from the geologic record. By far, most of the existing examples come from continental islands, some of which include evidence of windward/leeward relationships defined on the basis of sedimentological and paleontological criteria. Our contribution is one of the very few to consider the dynamics on oceanic, volcanic islands from the past.

All co-authors contributed to the revision of this paper and all gave their approval for the version now submitted for re-evaluation.

Respectfully,

Markes E. Johnson
December 6, 2013

Palaeogeography, Palaeoclimatology, Palaeoecology

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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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.

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

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 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. (2013). 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 (Mayoral et al., 2013; Johnson et al., 2012; Amen et al., 2005; Zazo et al., 2002). 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 km2, 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 1,304 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/sec. 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) are rare along the north coast. The island's largest sand beaches are found around Tarrafal de São Nicolau on the sheltered, southwest side of the island (Fig. 1).

2.2. History of volcanism

São Nicolau corresponds to an elongated shield volcano in an early post-erosional stage of development. The island's geomorphology and structure indicate development by composite fissure volcanism along two main rift arms. The more prominent is oriented E–W to WNW–ESE in direction, whereas the lesser is oriented N–S comprising the western portion of the island (Ramalho et al., 2010a). The island's volcanic history extends from the Miocene to the Quaternary (Macedo et al., 1988; Duprat et al., 2007; Ramalho et al., 2010a, b).

Emergence of the earliest landmass belonging to present-day São Nicolau occurred sometime during the Mid- to Late Miocene and corresponds to the Old Eruptive Complex. This unit, which remains undated, mostly comprises intensely palagonitized hyaloclastites pervasively intruded by a dyke swarm (Macedo et al., 1988; Ramalho, 2011). Marine sediments and submarine lavas rest unconformably above this unit. The first corresponds to shallow-water calcarenites (Monte Focinho Formation) with an estimated age between 11.8 and 5.8 Ma or even between 6.2 and 5.8 Ma (Bernoulli et al., 2007), whereas the latter corresponds to an entirely submarine volcanic unit (Figueira de Coxe Formation) that erupted between 6.2 and 5.8 Ma (Duprat et al., 2007; Ramalho et al., 2010b). The Figueira de Coxe Formation crops out at elevations in excess of 270 m above sea level attesting to episodic uplift that has affected São Nicolau since its first emergence (Ramalho et al., 2010a, b, c).

After a brief period of volcanic quiescence, uplift, and erosion, during which coastlines and adjacent shelves matured, the edifice of São Nicolau experienced a period of renewed and vigorous volcanic activity that corresponds to the Main Eruptive Complex (Macedo et al., 1988; Ramalho et al., 2010a, b). During this stage, coastlines rapidly expanded by lateral progradation of effusive lava deltas that covered large swaths of the pre-existing island shelf and preserved existing shelf sediments within the volcanic sequence. The main shield-building stage on São Nicolau lasted approximately 2.5 million years, from 5.0 to 2.5 Ma before present (Duprat et al., 2007; Ramalho et al., 2010b), a period during which coastlines constantly and rapidly shifted as volcanic activity and erosion counterbalanced each other. Finally, around 2.5 Ma, São Nicolau entered a period of slow erosional decay, interrupted by two intervals of volcanic rejuvenation that correspond to the Preguiça and Monte Gordo formations, respectively at 1.7–0.7 Ma and <100 ka (Duprat et al., 2007; Ramalho et al., 2010b).

2.3. Previous paleontological studies

Earlier studies on the paleontology of São Nicolau were conducted by Bebiano (1932), Torres and Soares (1946), Serralheiro and Ubaldo (1979), and Macedo et al. (1988). Torres and Soares (1946) identified some species of fossil rhodoliths belonging to the genus *Lithothamnion*, including material from Monte Focinho. A more recent study by Bernoulli et al. (2007) provided a reappraisal of the taxonomy and age of key fossils from the limestone at Monte Focinho near the island's south-central coast (Fig. 1). A Late Miocene age was established both on the basis of benthic foraminifera in the genus *Amphistegina* and planktic foraminifera assigned to species of *Globigerina, Globigerinoides, Globoratalia*, and other genera. The grainstone from this locality includes the abundant debris of cirripedean barnacles mixed with lesser amounts of coralline red algae fragments that accumulated below a steep, rocky shore.

3. Methods

The approximate size and configuration of the island of São Nicolau during the Late Miocene and immediately prior to the onset of the Main Eruptive stage at ~5.1 Ma (Ramalho et al., 2010b) was reconstructed using the present outcrop pattern of the Old Eruptive Complex and Figueira de Coxe Formation in conjunction with relative sea-level information extracted from the volcanic succession at Castilhano (sometimes written Castilhiano). In this place, the first erupted lavas of the Main Eruptive Complex (dated at

5.09±0.07 Ma) preserved a paleo-coastline that presently can be found at ~100 m of elevation (Ramalho et al., 2010a,b). Thus, using the Castilhano succession as a pivot point, the shape and dimensions of proto-São Nicolau were extrapolated around the perimeter defined by all outcrops of the Old Eruptive Complex and Figueira de Coxe Formation pene-contemporaneous in position. On the northern coast, where marine erosion already reduced the island considerably, the approximate position of the 100-m isobath was used to speculate where the northern limit of the island edifice was located during the Late Miocene.

Strip logs for stratigraphic sections modified after the standard format used by Shell Oil Company were compiled for four localities divided between the north and south shores of São Nicolau. In addition to rhodoliths, care was taken to register occurrences of shelly macrofossils and trace fossils. Samples also were collected for calcareous nannofossils, generally limited to finer grained and less indurated layers in the carbonate succession. The fine fractions from samples were concentrated in laboratory test tubes through overnight settling from a vigorously shaken half-sediment, half-tap-water suspension. The top fine fraction was extracted directly to a cover glass by a Pasteur pipette, spread into a rippled smear, and permanently mounted. Smear slides were scanned for coccoliths on a petrographic microscope (Zeiss Ortholux II-Pol) at x1250 magnification along a 3-cm column (approximately 5 mm2). Calcareous nannofossil taxonomy follows criteria standardized by Perch-Nielsen (1985) and Bown (1998). Rhodolith samples from two levels at Castilhano were collected for identification at the genus level using petrographic thin sections.

Whole rhodolith specimens from specific stratigraphic intervals were measured on site (to the nearest millimeter) across three principal axes (long, intermediate, and short). Data from these measurements were subjected to analysis based on the triangular plot among spherical, ellipsoidal, and discoidal shapes according to the format applied to rhodoliths by Bosence (1976, 1983) as modified from Sneed and Folk (1958).

4. Results

4.1. Island reconstruction for the Late Miocene

Coastline reconstructions for a Late Miocene (5.7–5.1 Ma) island indicate an elongated edifice approximately 25–33 km in length in an east-west dimension, and at least 8-10 km of maximum width in the north-south dimension (Fig. 2). The lack of outcrops of the Old Eruptive Complex and Figueira de Coxe Formation in an area east of Juncalinho and in the vicinities of Ribeira Alta precludes any more solid reconstructions for this part of the edifice.

4.2. North shore stratigraphy and paleontology

Stratigraphic profiles from the oasis at Castilhano and the canyon walls of Ribeira de Covoada de Bodela (Fig. 3) detail the onlap of carbonate deposits against rocky shores located on the northeast flank of Miocene São Nicolau (Figs. 1–2). Both sections are constrained below by the Old Eruptive Complex (intensely altered hyaloclastites and basaltic lava flows) and above by basaltic lava flows belonging to the onset of the Main Eruptive Complex. Both sections include abundant rhodoliths and both replicate a fining-up pattern through the first 3-4 m at which point the Bodela section terminates.

Thereafter, the Castilhano section recommences with renewed coarsening and rhythmic fining and coarsening in thick beds before a final fining-upwards sequence. The lower part of the carbonate succession at Castilhano is packed with rhodoliths that over-ride an irregular basalt surface with a topographic relief of about 1 m, including small overhangs of basalt under which rhodoliths are trapped (Fig. 4A and B). A basalt boulder above the unconformity exhibits a cluster of circular depressions 4 cm in diameter (Fig. 4C) that match the typical dwelling structures of regular echinoids assigned to the ichnospecies *Circolites kotoncensis*. Rhodoliths are less common in the stratigraphic interval between 2.5 m to 4 m above the unconformity, but thereafter resume in abundance (Fig. 3). An interval directly below the 4-m horizon features the trace fossil *Thalassinoides suevicus* (Fig. 4D).

Many rhodoliths reveal a small rock core of basalt in cross section (Fig. 4E). Sampled from a horizon 40 cm above the unconformity, the average maximum diameter of rhodoliths is 3.3 cm. Higher at a level 2.5 m above the unconformity, the average maximum diameter of rhodoliths registers an increase to 3.75 cm. The rhodoliths from these two levels are identified as belonging to the genus *Lithothamnion* (Davide Bassi, personal communication, 2013). Pectinid bivalves and *Spondylus* sp. together with broken tests of the echinoid *Clypeaster* sp. are more common in the upper half of the exposure than in the lower half. Loose plates of the cirriped barnacle *Balanus* sp. appear in the top two meters of the exposure.

At half the thickness of the Castilhano section, the Bodela section (Fig. 3) also exhibits an unconformity surface with about 1 m of relief on submarine basalt but is notably different in development of a distinct basal conglomerate with eroded clasts up to

45 cm in diameter (Fig. 4F). Rhodoliths with an average maximum diameter of 3.5 cm are plentiful through the overlying section, but not quite as abundant as found in the Castilhano section. In addition to *Pecten* sp. and *Spondylus* sp., associated bivalves include oysters encrusted on basalt boulders and the infaunal bivalves *Cardium* sp. and *Venus* sp. As at Castilhano, broken pieces of tests belonging to *Clypeaster* sp. occur, but also the spines of a cidaroid echinoid. Barnacles appear in the Bodela section attached only to bivalves. Rare pieces of the finger coral *Porites* sp. represent a faunal element at Bodela not observed at Castilhano.

4.3. Fossil rhodolith shape analyses

Although the shallow-water marine assemblages of Castilhano and Bodela are somewhat diverse, rhodoliths are the dominant element contributing to the limestone. Samples of whole rhodoliths varying in number from 35–40 specimens were extricated for measurements from narrowly defined stratigraphic intervals at both localities. Comparison shows that the most spheroidal rhodoliths come from an interval 40 cm above the base of the Castilhano section with a spread almost entirely restricted to the upper triangle in the larger triangular plot (Fig. 5A). Higher in the Castilhano section (2.5 m above the unconformity), rhodoliths are slightly larger in size and exhibit a slight tendency to more ellipsoidal shapes indicated by the spill-over of roughly half the sample into other sectors below and to the right of the upper triangle (Fig. 5B). The rhodolith sample from the Bodela section (Fig. 5C) comes from a level directly above the basal conglomerate (Fig. 3). In the range of shapes, it is more like the lower sample from Castilhano, but with a very few points that spill outside the upper triangle in a pattern similar to the upper sample from Castilhano. The majority of rhodoliths from both sections is highly uniform in size and shape.

4.4. South shore stratigraphy and paleontology

A stratigraphic profile from Baía dos Barreiros (Fig. 6) details the onlap of carbonate deposits against rocky shores eroded in the Old Eruptive Complex located on the southeast flank of Miocene São Nicolau (Fig. 2). In this region, the carbonates crop out near the base of sea cliffs for 2.5 km from Baía dos Barreiros to Ponta Barroso (Fig. 2). Sediments constitute a 4 to 5 m evenly thick band, dipping about 10º to the south. In detail, however, the internal structure exhibits prograding foresets dipping about 15–20º to the south. Sediment composition is overwhelmingly dominated by intermediate-to-coarse rhodolith debris with very low amounts of lithics. Abraded rhodoliths are present but extremely rare, as well as other macrofossils. The succession generally exhibits a fining-up pattern, but terminates with a conglomerate that features pebbles derived from the Old Eruptive Complex (Fig. 6). Intervals with the trace-fossil *Thalassinoides* isp. occur at 1.25 m and 3.8 m above the base of the section; the trace-fossils *Sinusichnus* isp. and ?*Ophiomorpha* isp appear at a horizon 3 m above the base of the section. These trace-fossils are known to have a wide depth range in littoral to outer shoreface settings (Mayoral et al., 2013). An erosive unconformity is inferred at the top of the sedimentary succession, as shown by truncation of a basaltic dyke. The sediments along Baía dos Barreiros occur at the same stratigraphic position found at Castilhano and Ribeira de Covoada de Bodela. As such, these sections are considered to be pene-contemporaneous.

Extensive sedimentary outcrops on the south shore are exposed through the canyon of the Ribeira da Ponta da Pataca, located about 800 m south-southwest of the village of Preguiça (Fig. 1). Stratigraphic profiles for Pataca 1 (Fig. 6) and Pataca 2 (Fig. 7) are laterally continuous over 130 m and represent respective distal and more proximal settings in relationship to a former paleoshore. The thicker succession at Pataca 1 commences 17 m above present sea level, whereas the thinner succession at Pataca 2 starts at about 60 m above present sea level and follows inland along the narrow streambed of Ribeira da Ponta da Pataca. Well-defined beds near the top of the succession dip about 6 to 8º to the southeast. A pile of submarine sheet flows rest conformably above the fossiliferous sediments. The transition to subaerial flows is poorly observed as the outcrops are extensively covered by scree.

At Pataca 1, the outcrop consists of three coarsening-up intervals with echinoid tests and spines present throughout. The initial coarsening-up sequence is a massive, very sandy and poorly sorted limestone or calcareous sandstone (Fig. 8A). Whole macrofossils are few, but the bivalve *Pinna* sp. is preserved in life position. In addition, short branching colonies of *Porities* sp. (Fig. 8B) occur together with thin, stick-shaped bryozoans of *Thalamoporella* sp. (Fig. 8C) that are commonly encrusted by a more delicate bryozoan attributed to *Metrarabdotos* sp. The trace fossils *Ophiomorpha nodosa* and *Macaronichnus segregatis* range through most of the initial interval. A second coarsening-up interval is a more pure limestone with higher fossil content that includes coral fragments and coquinas of *Argopecten* aff. *flabellum* (Fig. 8D). *Balanus* plates also are present. Many fossils are encrusted by bryozoans and serpulids. The trace fossil *Ophiomorpha nodosa* occurs at the very base of the interval, but otherwise trace fossils are absent. A third coarsening-up interval begins with minor basalt clasts and changes to a well-sorted lithic sandstone with little fossil content. Echinoids are the most common fossils in this interval, but *Balanus* plates also are present. The trace fossil *Skolithos linearis* (Fig. 8E) dominates the top 60 cm of this interval. The sediments seem to rest upon volcaniclastic breccia that may correspond to collapsed material and/or deposits of submarine debris flows.

The upper part of Pataca 1 is physically continuous with the lower part of Pataca 2. Being more proximal, however, Pataca 2 differs laterally in exhibiting a much higher content of basaltic clasts (Fig. 8F). The section shows a change from sandy limestone to calcareous sandstone (Fig. 7) with increasingly better sorting. The trace fossil *Thalassinoides suevicus* occurs near the base of the section. The lower layers are very fossiliferous, changing upwards to more bioclastic content. The gastropods *Strombus* sp. and *Turritella* sp. together with pectinid bivalves and barnacles are very common. Some coral colonies of *Tubastrea* sp. with conspicuous borings by pholad bivalves (Fig. 8G) are encrusted together with serpulids on basalt cobbles. The upper part of this section is formed by massive sandstone with fewer fossils. Echinoids spines, transported and worn *Porites* colonies and fragments of *Pecten* shells are present, as well as a sparse representation of the trace fossil *Ophiomorpha nodosa*.

4.5. Calcareous nannofossil biostratigraphy

Samples for age-diagnostic nannofossils were collected at three levels through the stratigraphic succession at Castilhano (see Fig. 3) both with and without rhodoliths. Species common to all three samples include *Dictyococcites antarticus, D. productus,* *Reticulofenestra haqii-minutula*, and *R. pseudoumbilicus*. The abundance of calcareous nannofossils showed an increase up-section, consistent with the transgressive nature of the succession. No species were exclusive to the horizon rich in rhodoliths. Species common to the upper samples but lacking from the lowest sample include *Calcidiscus leptoporus, Ciclicargolithus floridanus, Discaster* sp., small *Reticulofenestra* sp., *R. rotaria*, *Sphenolithus abies*, and *Syracosphaera* sp. The assemblage is compatible with a Late Miocene (Messinian) age (Bown, 1998). Notably, *R. rotaria* has a know First Appearance Datum (FAD) of 7.42 Ma and Last Appearance Datum (LAD) of 6.91 Ma.

A single sample was collected from the up-stream section at Ribeira Covoada de Bodela (see Fig. 3). The diversity of calcareous nannofossils is lower than that found at any level at Castilhano, but includes many of the same species indicative of correlation with the Messinian Stage.

Samples were collected at three levels through the Pataca 1 section (see Fig. 7). The sample from the lower layers is low in diversity with only three species: *Braarudosphaera* cf. *rosa, Coronocyclus nitescens*, and *Discoaster* sp. The sample from the middle layers proved to be barren of nannofossils. Finally, a sample from the upper layers yielded an assemblage including *Calcidiscus leptoporus, Coccolithus pelagicus, Helicosphaera carteri, Reticulofenestra productus, R. minuta, R. haquii-minutula, R. antarticus, R. pseudoumbilicus, Pontosphaera* sp. and *Umbilicosphaera* sp. This assemblage is compatible with a Pliocene position due to the presence of several reticulofenestrids, including *R. pseudoumbilicus* (Bown, 1998).

4.6. Summary of dichotomous biofacies

Using biofacies from the northerly Upper Miocene deposits at Castilhano and Bodela (Fig. 3), it is instructive to draw contrasts with the southerly pene-contemporaneous deposits from Baía dos Barreiros (Fig. 6), augmented by data collected by Bernoulli et al. (2007) from the south-central coast of São Nicolau. All four successions are seated on the Old Eruptive Complex as defined by Macedo et al. (1988). Loose barnacle plates are present at the Monte Focinho and Castilhano localities, as well as whole barnacles attached to shells at Bodela, indicating an initially shallow-water source for the deposits. Likewise, dwelling structures eroded by regular echinoids in a basalt boulder at Castilhano (Fig. 4C) confirm such a relationship. In addition to the various benthic and planktic foraminifera recovered from the Monte Focinho section, Bernoulli et al. (2007) described a bioclastic grainstone that incorporates echinoid spines and bits of red algae, although the limestone's dominant signature comes from barnacle debris. No traces of whole or fragmentary rhodoliths were detected during our visit to the Monte Focinho locality.

Further comparisons may be drawn between the Miocene sequence at Castilhano and the Pliocene sequence at Pataca. The former registers two deepening phases of deposition on an open marine sublittoral platform signified by rhythmic fining-upward beds in the middle of the succession (Fig. 3). In contrast, the Pataca 1 section records three coarsening-upward phases with considerably greater content of terrestrial lithics (Fig. 6). Of these, only the two upper sequences shallow sufficiently to reach relatively high-energy conditions. The presence of both whole and crushed valves belonging to pectinid bivalves indicates landward transport from an open, offshore area to the south, whereas barnacles record input from a closer, near-shore zone. This overall scenario has implications for the development of a distal delta on the leeward side of São Nicolau. The most striking omission from this Pliocene scenario is the complete lack of rhodoliths or rhodolith debris. This is in marked contrast to the older Castilhano and Bodela sections on the windward side of São Nicolau, where rhodoliths (Fig. 4F) constitute the primary carbonate signature showing shoreward transport against rocky shores. For the most part, these deposits signify death assemblages, because photosynthesis by the coralline red algae ceased for all but the top layer of rhodoliths in the transported package.

5. Discussion

5.1. Reconfiguration of a Miocene island

The coastline reconstructions for a Late Miocene island (Fig. 2) portray a smaller edifice than the present-day São Nicolau. This is not surprising, as these reconstructions correspond to a moment in time that immediately preceded the onset of the main shield building stage, during which the island grew considerably in size. Notwithstanding its smaller size, São Nicolau already constituted a prominent east-west elongated volcanic edifice that extended from 25 to 33 km in length during the Late Miocene. This volcanic edifice essentially emerged above the sea surface by means of uplift and not summit volcanism, as attested to by onlap of a dominantly subaerial Main Eruptive Complex over the eroded remains of an entirely submarine edifice corresponding to the Old Eruptive Complex and Figueira de Coxe Formation.

5.2. Composition and morphodynamics of São Nicolau rhodoliths

The Upper Miocene rhodoliths from the northern shores of São Nicolau are characterized by three key traits. They are comparatively small, exceedingly well rounded, and are represented by the single genus *Lithothamnion*. As demonstrated through shape analyses (Fig. 5), these rhodoliths are among the most spherical detected so far in studies on living and fossil rhodoliths from the Cape Verde and Canary islands (Johnson et al., 2012). Practically, such shapes make good rollers that are susceptible to transport; therefore it is not surprising to find thick rhodolith accumulations on the windward side of paleoislands. According to Braga et al. (2010), the taxonomic composition of Miocene coralline assemblages and growth forms changes with depth that parallels present-day conditions. For example, the mastophoroid and lithophylloid rhodoliths are typical of shallower-water settings, whereas the melobesioids (which include *Lithothamnion*) tend to represent deeper-water settings. On this basis, it may be argued that the São Nicolau rhodoliths that typically nucleate around small basalt cores were transported shoreward from deeper waters.

The sedimentological signature imparted by rhodoliths on the paleoshores of Miocene São Nicolau are strongly related to physical transportation. On the northeast shore at Castilhano and Bodela (Fig. 3), relatively small rhodoliths were left intact but rolled shoreward by the action of strong surf to abut directly against rocky shores. In some cases, the rhodoliths fill spaces below bedrock overhangs. In contrast, the fact that only rhodolith debris is present on the leeward southern shores at Ponta Barroso and Baía dos Barreiros (Figs. 2 and 6) indicates that long-shore currents and wave refraction was the dominant influence in transporting materials to the southern shelf. The internal structure of these beds with distinct foresets suggests that sediments were deposited as clinoforms directed offshore to the south.

5.3. Comparison with other windward-leeward systems

Examples from the literature (e.g. Johnson, 2002; Johnson and Baarli, 2012) typically relate to former islands on flooded continental shelves. The only case of a windward and leeward system previously studied from a fully oceanic setting on a basalt island comes from Porto Santo in the Madeira archipelago. At the Cabeço das Laranjas on the windward side of Ilhéu de Cima off Porto Santo, thick Middle Miocene deposits of large rhodoliths represented by the genera *Lithothamnion*, *Sporolithon*, and *Neogoniolithon* are impounded against the original basalt shore (Johnson et al., 2011). As in the Castilhano and Bodela sections on São Nicolau, rhodoliths in such transported deposits were deprived of sunlight and soon perished. In contrast, the leeward shore of Ilhéu de Cima at Pedra de Água features a coeval Middle Miocene setting with coral colonies fixed in growth position on basalt mounds that rise above a sandy zone over which no more than one or two layers of rhodoliths are emplaced (Santos et al., 2012, their figs. 1 and 9). Nearly all the rhodoliths observed in cross-section at Pedra de Água are nucleated around large basalt pebbles, whereas many of the rhodoliths at the Cabeço das Laranjas lack a rock core. The rhodoliths at Pedra de Água are polyspecific from the genera *Lithophyllum* and *Sporolithon* and considered to have grown in shallow, subtidal waters close to the paleoshore (Santos et al., 2012), whereas those at the Cabeço das Laranjas were swept towards land from deeper waters by major storms of hurricane strength (Johnson et al., 2011).

5.3. Shifting Miocene wind and storm patterns

Based on stratigraphic data regarding variations in marine benthic δ18O isotopes, related models for reconstruction of mean sea-surface temperatures, and sea-level variations pegged to ice-sheet models cited by De Boer et al. (2012, their fig. 1), the Middle Miocene Climatic Optimum (MMCO) stands out among major climatic shifts during the last 34 million years. Termination of this phase coincides with expansion of the East Antarctic Ice Sheet corresponding to distinct pulses dated to 13.8 and 13.2 Ma (Westerhold et al., 2005). Global temperatures not only began to receded with the decline of the MMCO, but evidence from places as distant as the South China Sea and the Mediterranean Sea suggests that the Intertropical Convergence Zone (ITCZ) was pushed substantially northward from a position near the equator (John et al., 2003; Holbourn et al., 2010).

A displaced ITCZ could be expected to have a profound effect on climate in the developing Macaronesian archipelagos of the eastern North Atlantic, including the Cape Verde islands. In place of steady trade winds that normally arrive from the northeast, the flow of winds would shift to blow from the southeast. More typical of trade winds in the Southern Hemisphere, these would brush locally parallel to the West African coast and be more likely to stimulate sustained marine upwelling. More significant, the northward migration of the ITCZ should alter the general staging area and subsequent storm tracks of hurricanes in the North Atlantic. This scenario was employed to account for the occurrence of major storm deposits formed by Middle Miocene rhodoliths at Cabeço das

Laranjas on Ilhéu de Cima off Porto Santo in the Madeira archipelago (Johnson et al., 2011).

Emerging Northern Hemisphere glaciations that intensified through post-Miocene times served to re-balance the ITCZ and facilitate its return to regions around the equator. A stable isotope study based on stratigraphy from the southeastern Atlantic (Vidal et al., 2002) shows a rapid decrease in δ18O values consistent with a general warming trend in that part of the world already by Messinian time during the Late Miocene. Such a result suggests that a scenario similar to pattern of strong northeasterly trade winds across the Maraconesian realm, including the Cape Verde archipelago, was in effect by the end of the Miocene. Hence, present-day climate patterns dominated by persistent trade winds from the northeast against the island of São Nicolau (Brand, 2011) should serve as a reliable guide for comparison of windward and leeward coastal deposits of Late Miocene and Pliocene age around the island.

5.4. Use of volcanic sequences to gauge absolute water depth

Effusive coastal volcanic successions such as those resulting from the extrusion of lava-fed deltas provide additional constraints on coeval sea level and consequently on paleo-water depths of bottomset sediments (Porebski and Gradzinski, 1990; Ramalho, 2011; Johnson et al., 2012; Meireles et al., 2013). During low- to moderate- effusion rates (Ramalho et al., 2013), lava flows entering the sea typically form structures similar to Gilbert-type deltas, with foresets of pillow lavas and hyaloclastites overlain by a topset of subaerial lavas; the passage zone between these two components of the delta thus marks very accurately contemporaneous sea level (Porebski & Gradzinski, 1990; Ramalho, 2011). The vertical distance between the sedimentary bottomset (typically corresponding to marine sediments coeval of the eruption) and the passage zone, along the dip of the foresets, is thus a reliable way of estimating the palaeo-water depth of the sediments (Ramalho, 2011; Johnson et al., 2012; Meireles et al., 2013).

At Castilhano (Fig. 3), a typical lava-delta succession with foresets of pillow lavas and hyaloclastites overly the marine sediments and the passage zone between overlying submarine and subaerial basalt occurs 25 m above the top of the limestone, pinpointing coeval stage of sea level around 5.09 Ma (Ramalho et al., 2010b). At Bodela (Fig. 3), the sedimentary sequence is overlain by massive submarine flows, and the passage zone between overlying submarine and subaerial basalt occurs 35 m above the top of the limestone in the Bodela section, suggesting a slightly deeper deposition than at Castilhano. Farther south at Baía dos Barreiros, the passage zone is 95 m above the Upper Miocene limestone (Ramalho et al., 2010a), marking the terminal depth of that limestone as much deeper. At this locality, however, the value should be treated with caution, because an unconformity marked by a truncated dike occurs between the sediments and overlying lava flows. For these three localities, the passage zone between subaerial and submarine lava flows is coeval and signifies the same relative sea level now marked 100 m above the present. Measurements of accommodated water depth at the time carbonate deposition ceased at Castilhano, Bodela, and Baía dos Barreiros in the Late Miocene agree reasonably well with fossil content.

At Ribeira da Ponta da Pataca on the south-central coast, the observable passage zone in volcanics overlying Pliocene sedimentary strata is approximately 90 m above present-day sea level, indicating a possible coeval water column of 35 to 40 m for Pataca

2 (Fig. 7) and 60 to 70 m for Pataca 1 (Fig. 6). The difference in paleo-water depth at these two localities is an artifact of the natural slope on the Pliocene sea floor. Because the capping volcanic sequence shared by the two sections consists of a pile of low-angle submarine sheet flows, there may have been a time lapse between the moment of burial and the transition to subaerial flows at the passage zone above. Other possible disconformities may be hidden in the covered interval between the sedimentary strata and subaerial basalt. A hiatus of any duration may mask an intermittent rise in sea level. In any case, the *Skolithos* trace fossils at the top of Pataca 1 (Fig. 6) typically reflect a water depth shallower than suggested by the overlying passage zone. At Portinho da Mulher Branca near Praia on Santiago island, for example, *Skolithos* was related to an overlying passage zone indicating a water depth of only 12 to 15 m (Johnson et al., 2012). This discrepancy in conflicting water-depth indicators remains to be resolved either by extending the bathymetric range of the ichnofossil or by an obfuscating time gap.

6. Conclusions

Examples of contrasting windward and leeward settings from paleoislands are well documented, but mainly from continental shelves. The distribution and fossil content of surviving Upper Miocene limestone strata on São Nicolau are limited but adequate to outline patterns in intertidal to shallow, sub-tidal biofacies in close proximity to rocky shores influenced by winds and waves around one of the windward volcanic islands in the Cape Verde Archipelago. Supplementary data from a comparatively thick Pliocene succession on the island's south-central shore provide further insight on the potential richness achieved by biofacies in a setting better sheltered from wave shock. Four core conclusions highlight the results of this study.

1. Limestone dominated by whole rhodoliths follows a distinct band correlated from the oasis at Castilhano to the canyon of the Ribeira de Covoada de Bodela on the northeast flank of São Nicolau. Relatively small in size, the rhodoliths were swept shoreward from a shallow bank situated nearby to the north or northeast. Many are nucleated around basalt pebbles eroded from an adjacent rocky shore. These algal concretions accumulated in vast numbers as a transported assemblage deposited against the rocky shore, even pressed to fill spaces below overhangs in the bedrock. Although poor in calcareous nannofossils, the identified assemblage is compatible with a Late Miocene (Messinian) assignment.
2. Whole rhodoliths are absent from the coeval limestone at Baía dos Barreiros in southeast São Nicolau but extensive rhodolith sand is well developed as clinoform structures dipping seaward to the south. The more loosely equivalent limestone at Monte Focinho near the island's south-central shore also includes fine debris of coralline red algae mixed with crushed barnacles. A more sandy limestone deposit of Pliocene age at Ribeira da Ponta da Pataca on the south-central coast includes elements such as the whole (and broken) valves of pectinid bivalves, as well as whole branches of the *Porites* coral and delicate *Thalamoporella* bryozoa that are unusual or entirely absent from deposits on the north side of the island. A Pliocene age for the Pataca deposits based on calcareous nannofossils concurs with the age of basaltic lavas near the overlying passage zone dated at 3.06±0.17 Ma.

3. With a change after the Middle Miocene Climatic Optimum that brought the Intertropical Convergence Zone closer to the equator, the Late Miocene and Pliocene conditions at São Nicolau experienced steady winds from the northeast that generated ocean swell. Although smaller than today by perhaps 40%, the Late Miocene island still presented a long east-west oriented northern shore that felt the full impact of these conditions, much as today. Thus, the fossil deposits at Castilhano and Bodela represent accumulations on an exposed, windward coast, while those at Baía dos Barreiros and Pataca are indicative of a more sheltered, leeward coast.
4. Upper Miocene limestone beds near the northeastern coast at Castilhano and Bodela are overlain by submarine flows with passage zones to subaerial flows at intervals 25 m and 35 m above, respectively. Marine onlap of the carbonates concluded at those water depths with no discrepancy indicated by fossil content. Certain discrepancies with unconformities and trace fossils remain to be solved, as in the southern sucessions. Overall, however, the application of such transitions in volcanic flows to measure original water depth is a useful technique in the reconstruction of coastal conditions.

Acknowledgments

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Figure Captions

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

Fig. 2. Reconstruction of São Nicolau during the Late Miocene at ~5.1 Ma.

Fig. 3. Stratigraphic profiles for localities at Castilhano and Ribeira de Covoada de Bodela on the northeast flank of Miocene São Nicolau.

Fig. 4. Upper Miocene deposits against basalt unconformities from the northeast part of São Nicolau showing details of faunal components: A) Irregular unconformity surface overlain by abundant rhodoliths at Castilhano (figure at right for scale), B) Small overhang of basalt filled with rhodolith limestone, C) Part of a basalt boulder above the unconformity surface with dwelling structures formed by regular echinoids assigned to

the trace fossil *Circolites kotoncensis*, D) Trace fossil *Thalassinoides suevicus* from mid-section at Castilhano (see Fig. 3), E) Typical interval packed with rhodoliths many of which formed around basalt pebbles (arrows), and F) Basal conglomerate and overlying rhodolith limestone at Ribeira de Covoada de Bodela (figure at left for scale).

Fig. 5. Triangular plots showing the relative shapes of fossil rhodoliths: A, from the lower part of the section at Castilhano, B) from the middle part of the section at Castilhano, and C) from the lower part of the section at Bodela.

Fig. 6. Stratigraphic profile for the sequence at Baía dos Barreiros on the southeast flank of Miocene São Nicolau.

Fig. 7. Stratigraphic profile for the Pliocene coastal sequence at Ribeira da Ponta Pataca on the southwest flank of Miocene São Nicolau.

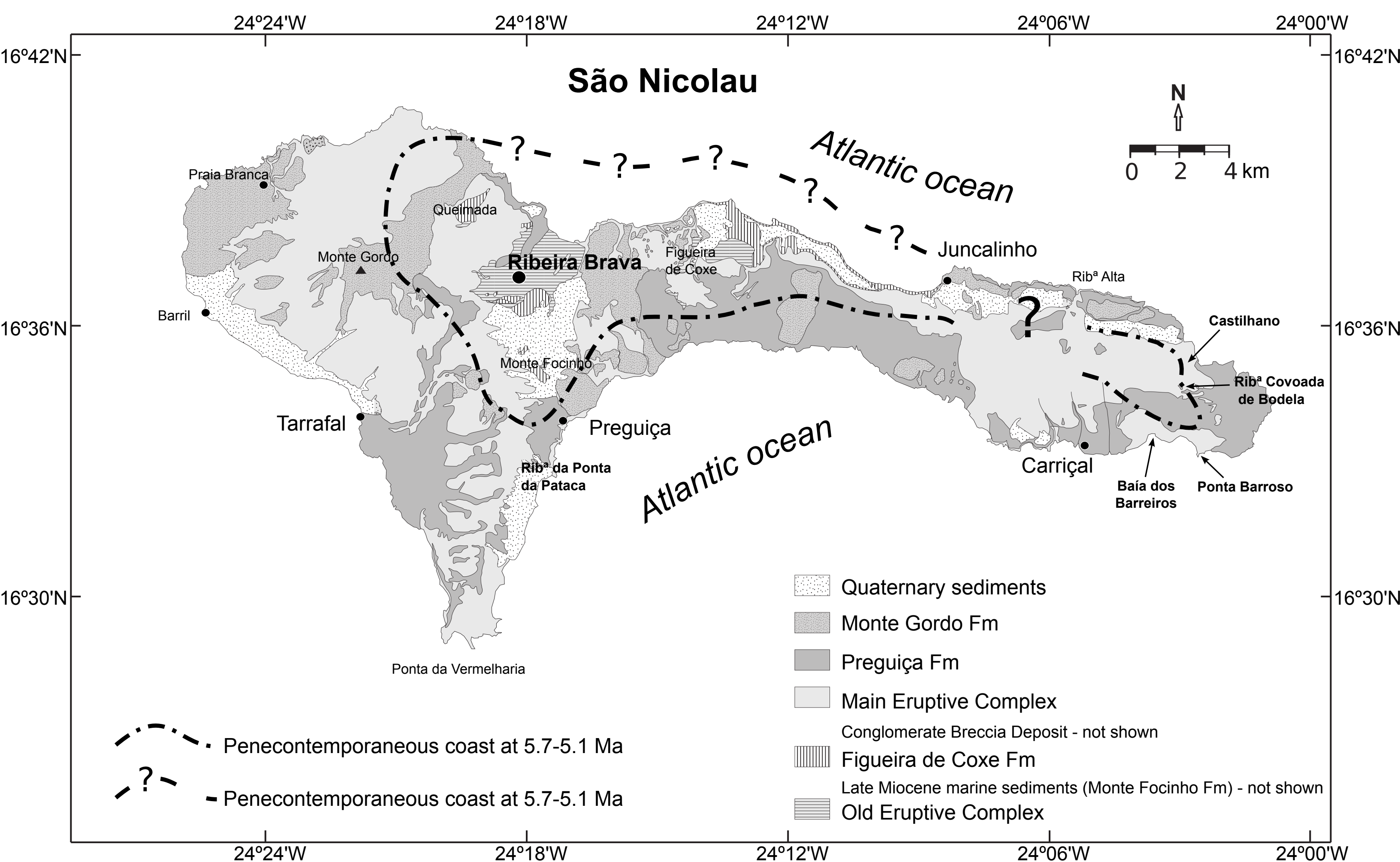
Fig. 8. Stratigraphic profile for the more inland Pliocene sequence at Pataca 2.

Fig. 9. Pliocene deposits capped by basalt from the southwest coast of São Nicolau at Ribeira da Pataca: A) Outcrop overview of Pataca 1 (see Fig. 7), B) Cluster of the coral *Porites* sp. from the lower beds, C) Ramose bryozoan *Thalamoporella* sp. from the lower beds, D) Disarticulated shells, mostly *Argopecten* aff. *flabellum* from the upper beds, E) Trace fossil *Skolithos linearis* from the top of the section, F) Outcrop overview of the Pataca 2 section (see Fig. 8), and G) Coral colonies of *Tubastrea* sp. bored by pholad bivalves from the middle of the section.

Figure 1

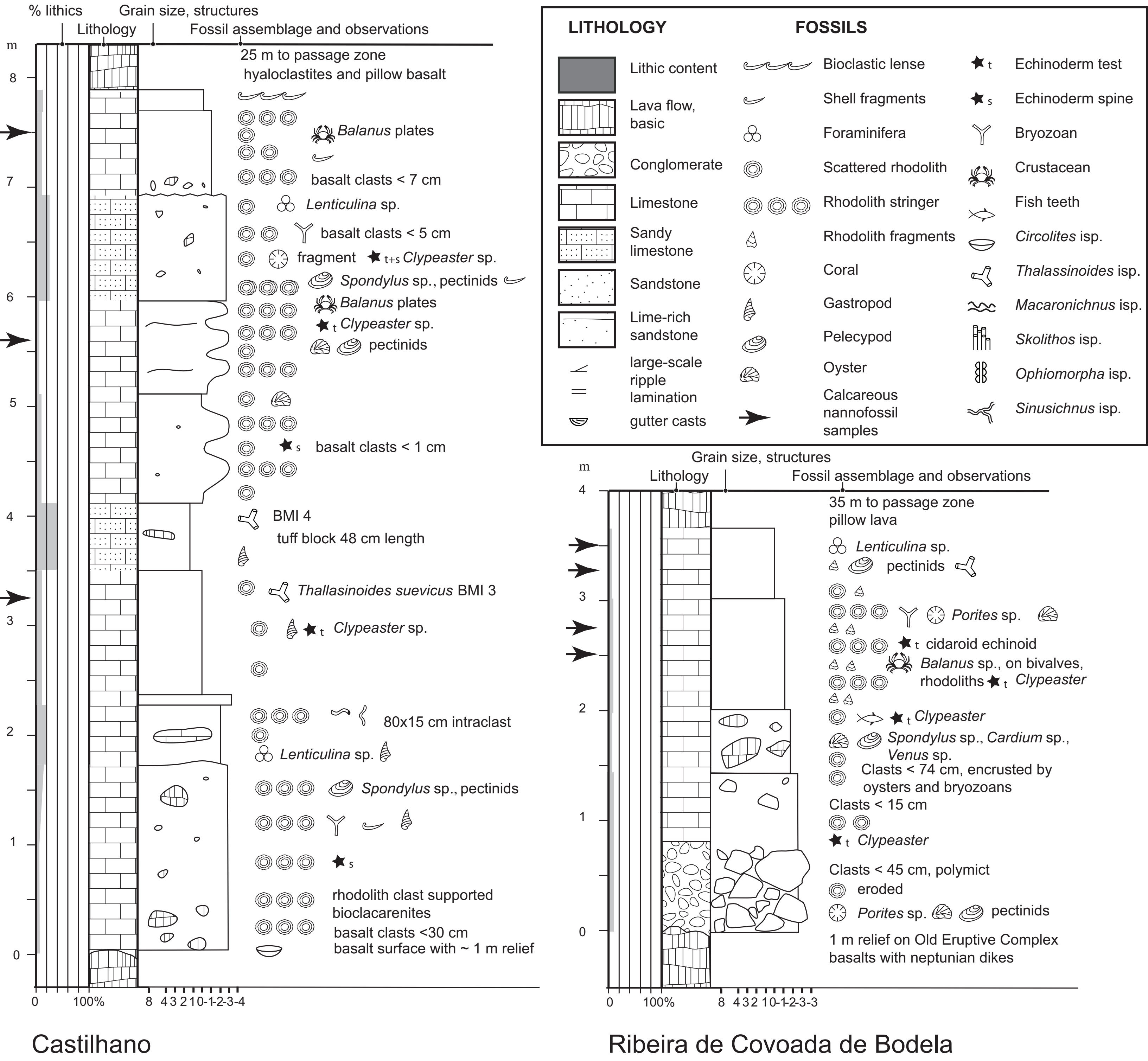

N
- 4000
- 2000
- 5000
Mauritania
Nuakchott
Cape Verde Rise
- 2000
Cape Verde Is.
Senegal
Dakar
25°
15°
30°
20°
0
400 km
Atlantic Ocean
windward Islands
Santo Antão
Sal
São Nicolau
Boavista
leeward islands
Maio
Fogo
Santiago
Atlantic Ocean
São Nicolau
Monte Gordo
Ribeira Brava
Juncalinho
Castilhano
Barril
Monte Focinho
Covoada de Bodela
Tarrafal
Preguiça
Carriçal
Pataca (1 and 2)
Ponta Barroso
Baía Barreiros
0
5 km

Figure 2



24º24'W
24º18'W
24º12'W
24º06'W
24º00'W
16º42'N
16º36'N
16º30'N
São Nicolau
N
0 2 4 km
Atlantic ocean
Atlantic ocean
Praia Branca
Queimada
Monte Gordo
Ribeira Brava
Figueira de Coxe
Juncalinho
Ribª Alta
Barril
Castilhano
Monte Focinho
Ribª Covoada de Bodela
Tarrafal
Preguiça
Ribª da Ponta da Pataca
Carriçal
Baía dos Barreiros
Ponta Barroso
Ponta da Vermelharia
Quaternary sediments
Monte Gordo Fm
Preguiça Fm
Main Eruptive Complex
Conglomerate Breccia Deposit - not shown
Figueira de Coxe Fm
Late Miocene marine sediments (Monte Focinho Fm) - not shown
Old Eruptive Complex
Penecontemporaneous coast at 5.7-5.1 Ma
Penecontemporaneous coast at 5.7-5.1 Ma

Figure 3



% lithics
Grain size, structures
Lithology
Fossil assemblage and observations
m
25 m to passage zone hyaloclastites and pillow basalt
Balanus plates
basalt clasts < 7 cm
Lenticulina sp.
basalt clasts < 5 cm
fragment
t+s Clypeaster sp.
Spondylus sp., pectinids
Balanus plates
t Clypeaster sp.
pectinids
s basalt clasts < 1 cm
BMI 4
tuff block 48 cm length
Thallasinoides suevicus BMI 3
t Clypeaster sp.
80x15 cm intraclast
Lenticulina sp.
Spondylus sp., pectinids
s
rhodolith clast supported bioclacarenites
basalt clasts <30 cm
basalt surface with ~ 1 m relief
0
100%
8 4 3 2 1 0 -1 -2 -3 -4
Castilhano
LITHOLOGY
FOSSILS
Lithic content
Lava flow, basic
Conglomerate
Limestone
Sandy limestone
Sandstone
Lime-rich sandstone
large-scale ripple lamination
gutter casts
Bioclastic lense
Shell fragments
Foraminifera
Scattered rhodolith
Rhodolith stringer
Rhodolith fragments
Coral
Gastropod
Pelecypod
Oyster
Calcareous nannofossil samples
t Echinoderm test
s Echinoderm spine
Bryozoan
Crustacean
Fish teeth
Circolites isp.
Thalassinoides isp.
Macaronichnus isp.
Skolithos isp.
Ophiomorpha isp.
Sinusichnus isp.
Grain size, structures
Lithology
Fossil assemblage and observations
35 m to passage zone pillow lava
Lenticulina sp.
pectinids
Porites sp.
t cidaroid echinoid
Balanus sp., on bivalves, rhodoliths
t Clypeaster
t Clypeaster
Spondylus sp., Cardium sp., Venus sp.
Clasts < 74 cm, encrusted by oysters and bryozoans
Clasts < 15 cm
t Clypeaster
Clasts < 45 cm, polymict
eroded
Porites sp.
pectinids
1 m relief on Old Eruptive Complex basalts with neptunian dikes
0
100%
8 4 3 2 1 0 -1 -2 -3 -3
Ribeira de Covoada de Bodela

Figure 4
Click here to download high resolution image

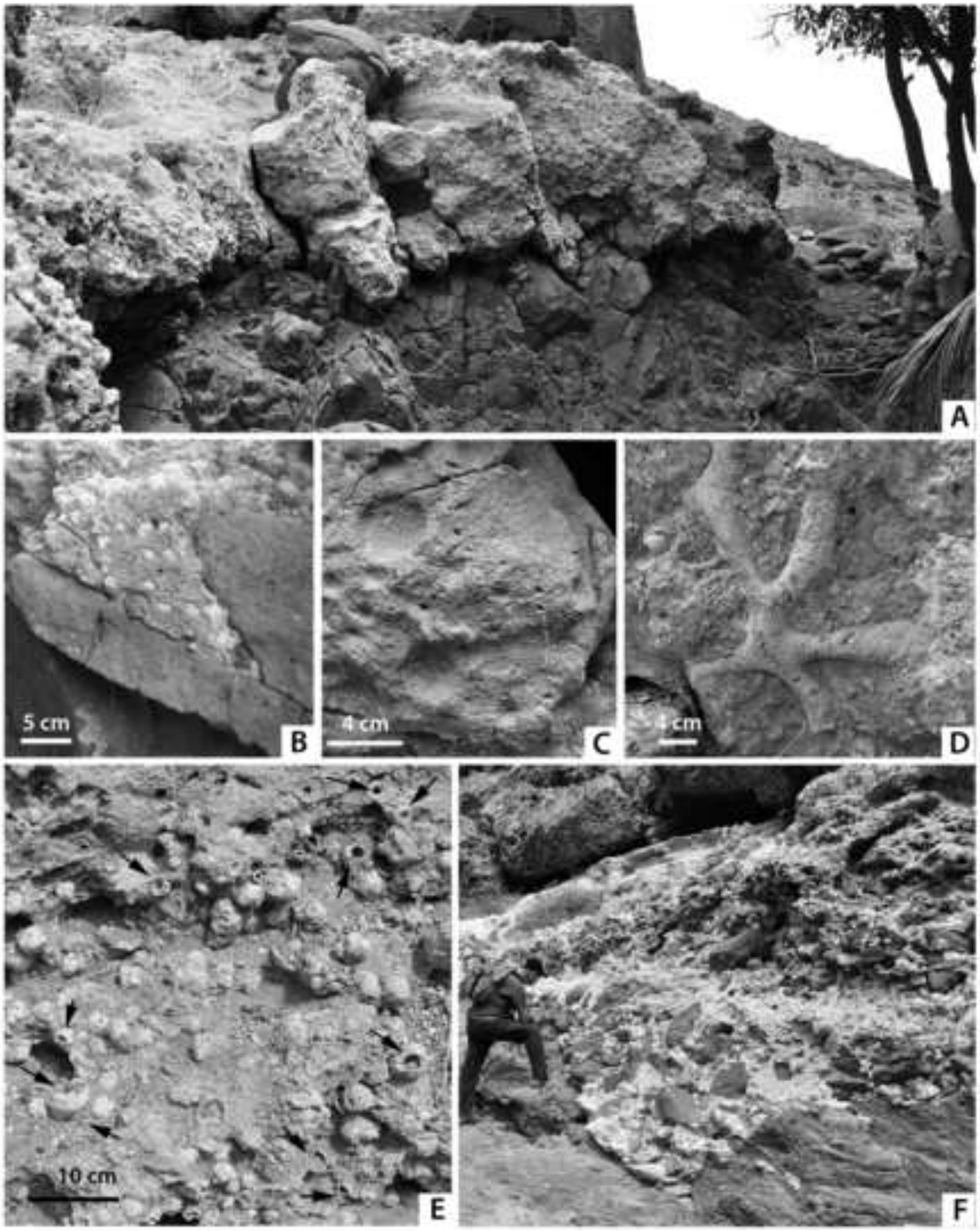


Figure 5

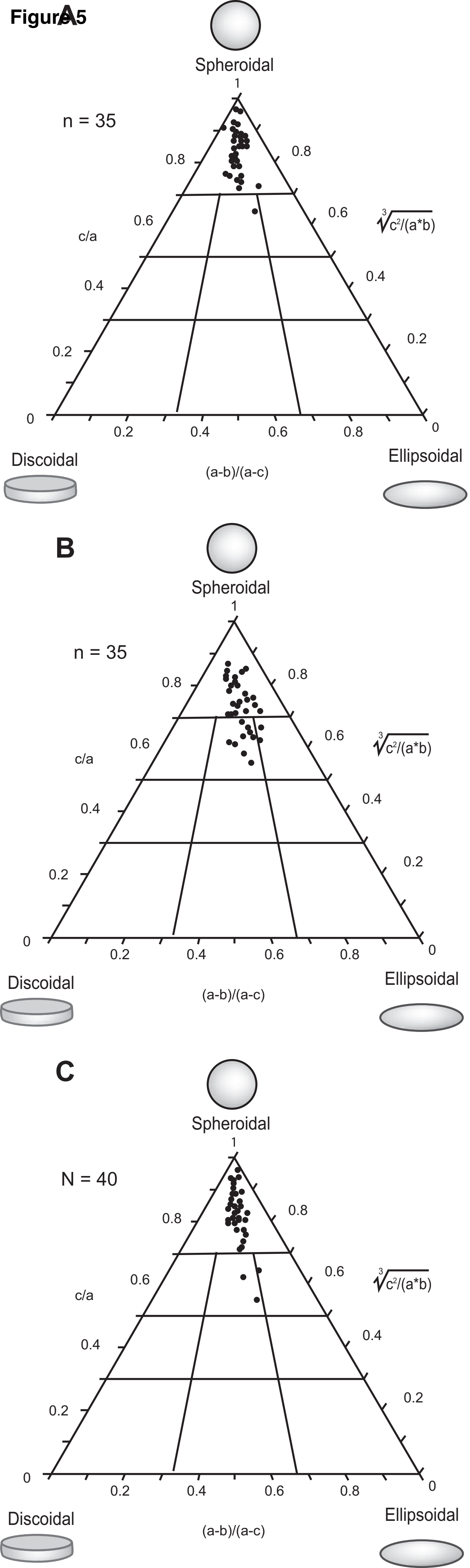

A
Spheroidal
n = 35
c/a
$\sqrt[3]{c^2/(a*b)}$
(a-b)/(a-c)
Discoidal
Ellipsoidal
B
Spheroidal
n = 35
c/a
$\sqrt[3]{c^2/(a*b)}$
(a-b)/(a-c)
Discoidal
Ellipsoidal
C
Spheroidal
N = 40
c/a
$\sqrt[3]{c^2/(a*b)}$
(a-b)/(a-c)
Discoidal
Ellipsoidal

Figure 6

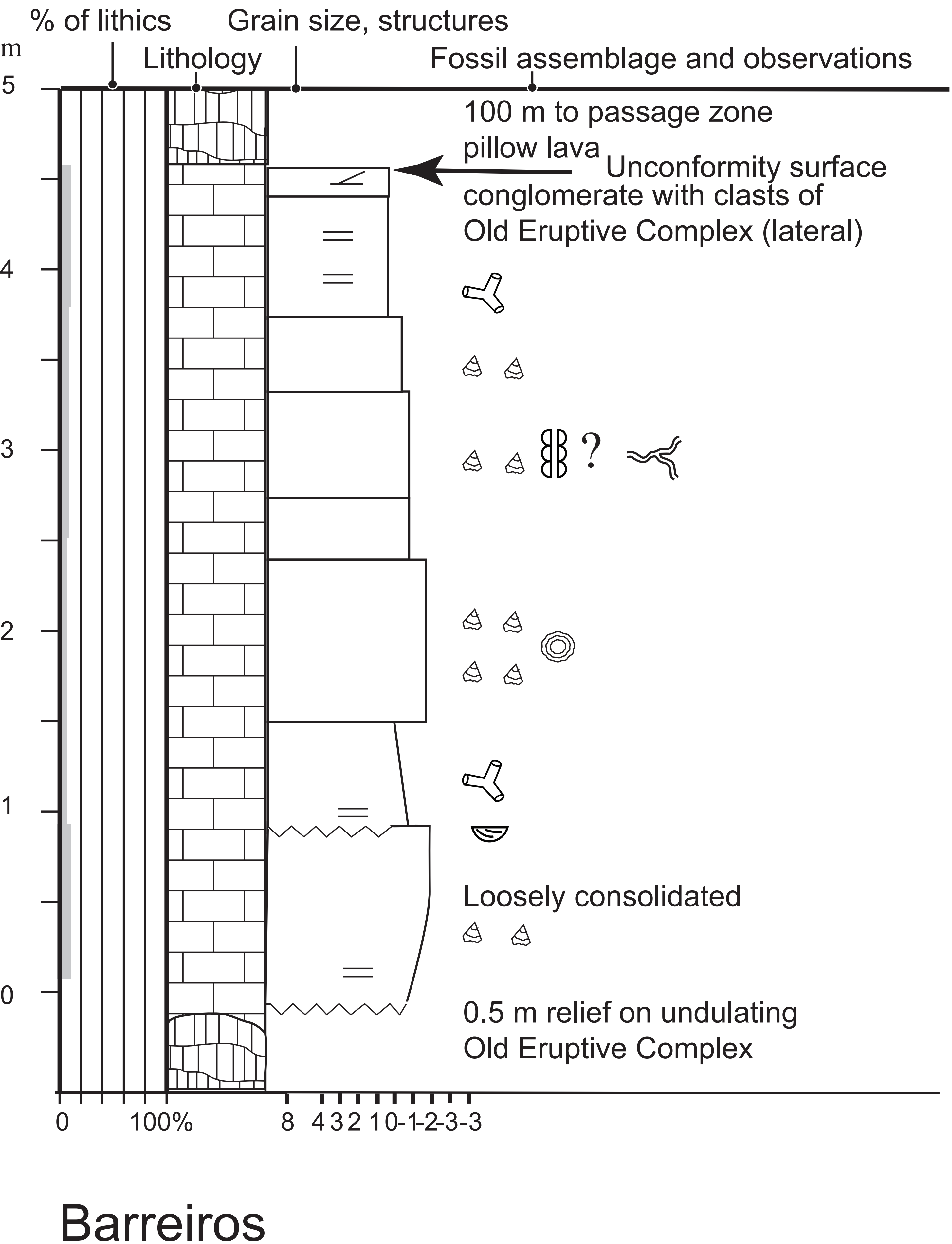
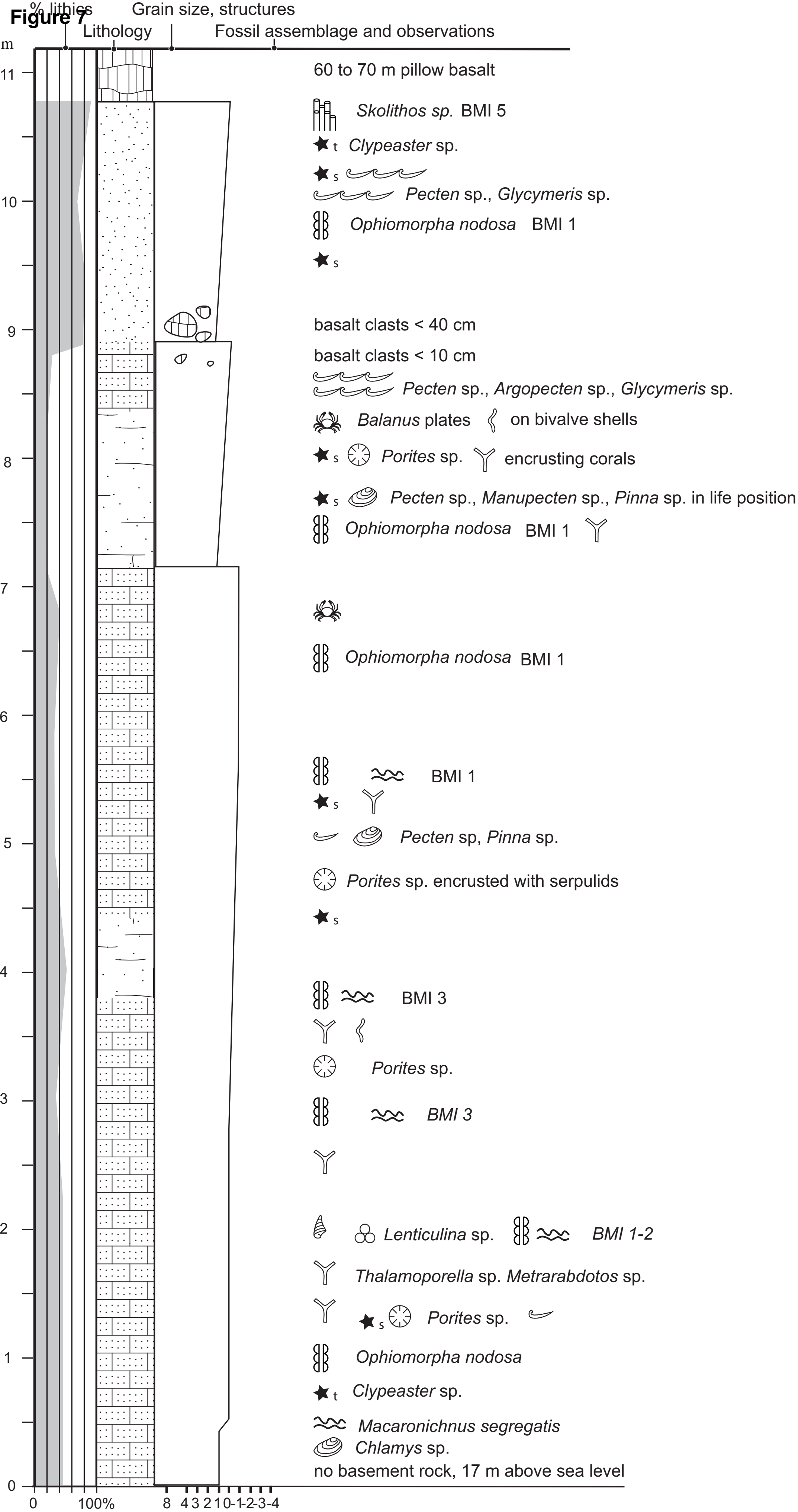

% of lithics
Grain size, structures
Lithology
Fossil assemblage and observations
m
5
4
3
2
1
0
100 m to passage zone
pillow lava
Unconformity surface
conglomerate with clasts of
Old Eruptive Complex (lateral)
?
Loosely consolidated
0.5 m relief on undulating
Old Eruptive Complex
0
100%
8
4 3 2 1 0 -1 -2 -3 -3
Barreiros

Figure 7



Pataca 1

Figure 8

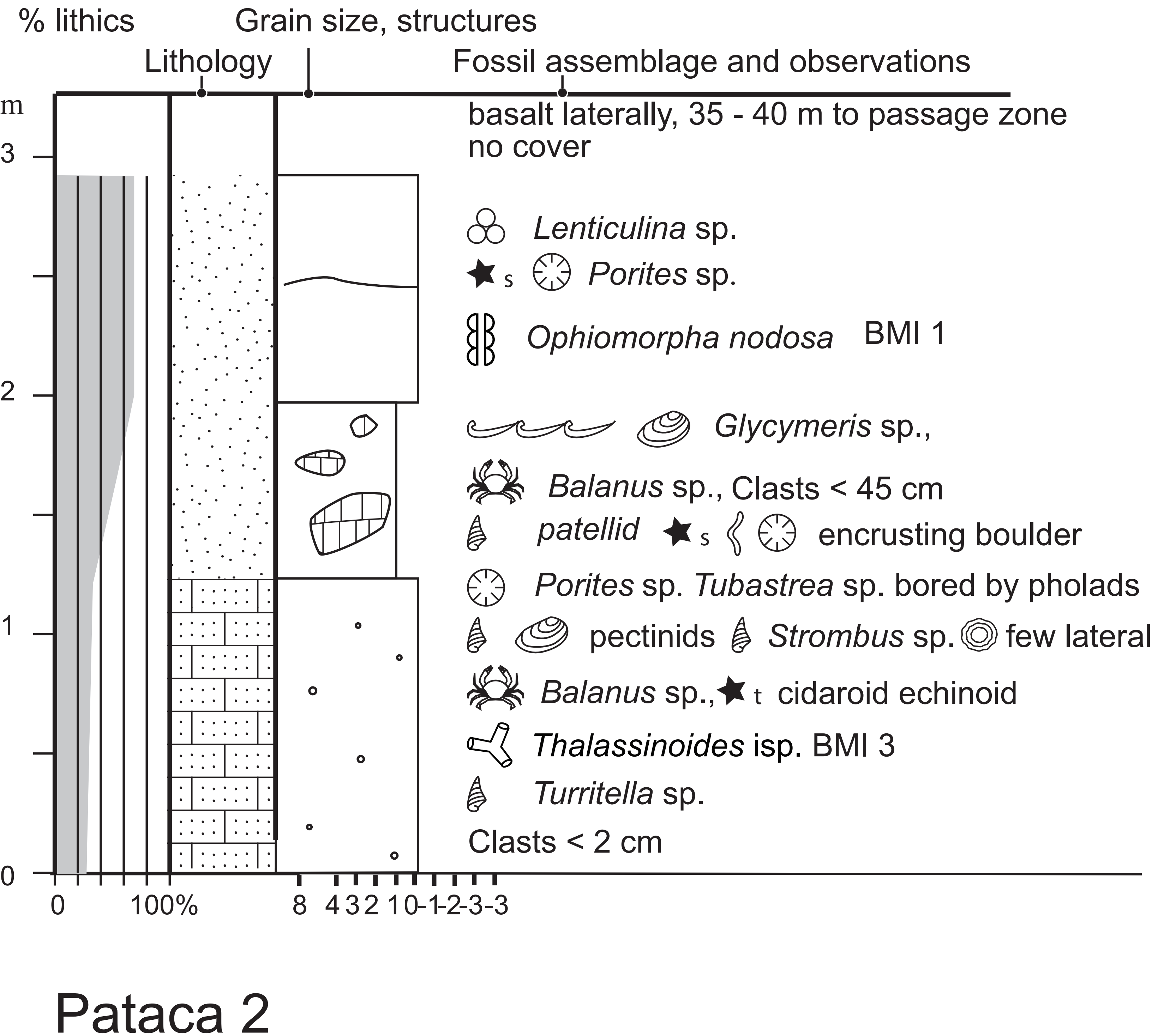

% lithics
Lithology
Grain size, structures
Fossil assemblage and observations
m
3
2
1
0
0
100%
8 4 3 2 1 0 -1 -2 -3 -3
basalt laterally, 35 - 40 m to passage zone
no cover
Lenticulina sp.
s Porites sp.
Ophiomorpha nodosa BMI 1
Glycymeris sp.,
Balanus sp., Clasts < 45 cm
patellid s encrusting boulder
Porites sp. Tubastrea sp. bored by pholads
pectinids Strombus sp. few lateral
Balanus sp., t cidaroid echinoid
Thalassinoides isp. BMI 3
Turritella sp.
Clasts < 2 cm
Pataca 2

Figure 9
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