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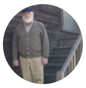

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Miocene intertidal zonation on a volcanically active shoreline: Porto Santo in the Madeira Archipelago, Portugal

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Short-term biological colonization of rockgrounds on the basaltic shorelines of oceanic islands has, as yet, been poorly explored. A Miocene sea cliff on Ilhéu de Cima off Porto Santo in the Madeira Archipelago of Portugal provides a case study showing intertidal zonation with two types of barnacles, serpulid worm tubes, two coral species, epifaunal bivalves and the trace fossils of endolithic bivalves. Large barnacles (*Balanus* sp.) and serpulids are limited to the upper 400 mm of a basalt cliff of 1.6 m in height. Small barnacles, possibly of the same species, extend to the base. The upper half includes the corals *Isophyllastrea orbignyana* and *Tarbellastraea reussiana*, to which many small, coral-inhabiting, barnacles (*Ceratoconcha costata*) are fixed. Borings identified as *Gastrochaenolites torpedo* appear through the bottom two-thirds of the cliff face. Rarely, *Gastrochaenolites lapidicus* is exposed in longitudinal section with borings up to 45 mm deep in solid basalt. Epifaunal bivalves, such as *Spondylus* sp., are limited to a middle zone. Associated with the sea cliff is an outer platform on which a multitude of *T. reussiana* colonies occur in growth position. The corals exhibit planar erosion over180 m^2. The shelf was faulted and cut by a basalt dike prior to the brief recolonization of *I. orbignyana*, found attached to low fault scarps. Habitation of the sea cliff was facilitated by rising sea level, but abruptly terminated by burial under volcanoclastic ejecta. ☐ *Basalt bioerosion*, *coastal dynamics*, *Ilhéu de Cima (Porto Santo)*, *Miocene intertidal zonation*, *volcanogenic perturbations*.

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Unconformities signifying former rocky shores can be detected and studied in exposures both small and large through the entire spectrum of the Phanerozoic rock record (Johnson 2006). Entire palaeoislands with laterally extensive unconformity surfaces are sometimes found exhumed. Examples include the Proterozoic Baraboo and Churchill quartzites in southern Wisconsin (USA) and northern Manitoba (Canada) that developed as archipelagoes in Cambrian and Ordovician/Silurian times respectively (Dott 1974; Johnson & Baarli 1987). Ordovician diorite formed the core of a late Silurian island from inner Mongolia, China (Johnson *et al.* 2001) and andesite was shaped into islands during the Late Cretaceous in Mexico's Baja California (Johnson *et al.* 1996). In all these examples, conglomerate deposits that abut unconformity surfaces amply demonstrate the power of coastal erosion. Fossil evidence for direct habitation on rocks by marine invertebrates also is widespread, although faunal zonation has proven difficult to verify. A clear example where gneiss boulders were colonized by marine invertebrates that partitioned their living space on a Late Cretaceous shore comes from Sweden (Surlyk & Christensen 1974). Doyle *et al.* (1997) illustrated the potential use of the barnacle species *Megabalanus tintinnabulum* (Linné 1758) from the Tabernas Basin (a Neogene intermontane basin in southern Spain) for the identification of the depth of deposition in a marine coarse-clastic and rocky foreshore facies, noting the rarity of fossil barnacles associated with rocky-shore settings. Former islands associated with epicontinental platforms or continental-shelf margins are the provenance for nearly all such studies.

Comparable information on the biological and physical dynamics of former basaltic oceanic islands is surprisingly under-represented in the literature. Today, basaltic islands are abundant and closely related to the migration of oceanic crust over mantle

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hot spots (Morgan 1972). In the eastern North Atlantic off the coast of Africa, 75 basaltic islands with a composite area of 20,000 km^2 belong to Macaronesia and the Cameroon volcanic line. Few observations are recorded, however, on the dynamics between coastal sedimentation and colonization of the intertidal zone with respect to intermittent volcanism and related tectonics. Notably, Darwin (1844) briefly described limestone caught between basalt flows on the island of Santiago in the Cape Verde Archipelago. Few studies that go beyond Darwin's level of observation include details on the Azores and Canary islands regarding littoral deposits of Miocene to Pleistocene age related to volcanism (Azevedo & Ferreira 1999; Meco *et al.* 2007; Ávila *et al.* 2009). Schmidt & Schmincke (2002) compiled descriptions of Miocene volcanic flows and volcaniclastic deposits on Porto Santo, part of the Portuguese Madeira Archipelago, but acknowledged fossiliferous intercalations with minimum details.

The present contribution covers three aspects of rocky-shore development at a single locality on Ilhéu de Cima, a small satellite island of Porto Santo (Fig. 1). We aim to demonstrate clear examples of: marine invertebrate fossils preserved on basalt surfaces under the influence of intertidal to shallow-water zonation; bivalve borings in basalt and multi-phase colonization by coastal life in response to active volcanism and local tectonics. Our emphasis is on the palaeoecology of settlement patterns in the framework of events lasting only decades before termination by island volcanism or related tectonics. This perspective adds a distinctly different dimension to the study of rocky-shore dynamics in which the usual theme is mechanical erosion related to patterns of wind and wave erosion (Dott 1974; Johnson *et al.* 1996, 2001).

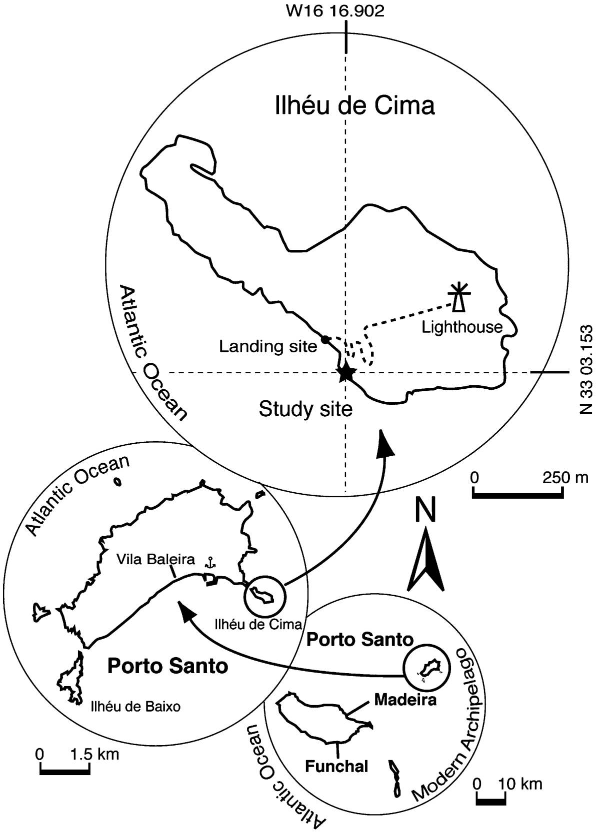

Fig. 1. Maps at various scales for the Madeira Archipelago, Porto Santo with its satellite islets, and Ilhéu de Cima with star showing location of the study site.

Location and geological setting

The Madeira Archipelago of Portugal is 650 km off the shores of Morocco. Porto Santo is an outlying island situated 50 km northeast of the main island of Madeira (Fig. 1). With a present day area of 41 km^2, Porto Santo is a deeply eroded island that occupies only about a third of its initial presumed area taking into consideration surrounding bathymetry. Ferreira (1997) produced a geological map of Porto Santo, including its several satellite islets. The second largest is Ilhéu de Cima with a perimeter of approximately 3 km and maximum elevation of 114 m. Fossiliferous sedimentary rocks occur in several places on the north and west sides of the island in association with the transition between two major volcanic units: a trachytic to basaltic submarine basal volcanic complex with ages ranging from 18.8 to 13.5 Ma and a subaerial alkali basaltic to hawaiitic complex dated between 14 and 10.2 Ma (Ferreira 1985). Based on calcareous nannofossil assemblages at Lombinhos on the east side of Porto Santo, Cachão *et al.* (1998) correlated sedimentary units to the Middle Miocene, Lower Serravalian (Calcareous Nanofossil biozone CN4 of Okada & Bukry 1980). A comparable age of about 14–15 Ma is projected for sedimentary intercalations with volcanic rocks on Ilhéu de Cima.

According to Schmidt & Schmincke (2002, p. 605), the north end of Ilhéu de Cima across from Porto Santo preserves foreset-bedded, steeply dipping pillow breccias overlain by, but connected with, horizontal flows interpreted as subaerial eruptions that entered the sea as a lava delta. Considered together with the diverse range of fossiliferous carbonates intercalated with volcanic deposits on the north and west sides of the island, it appears that Ilhéu de Cima was a separate island at least during part of its Miocene history. The study site described in this paper is the first in a series of projected studies on the Miocene palaeoshores of Ilhéu de Cima. It is approximately 150 m southeast of the only landing place on the islet (Fig. 1) and at an elevation 2–3 m above mean sea level.

Methods

Direct observations on fossils were made, on a grid measuring 400 mm by 400 mm, and applied to the vertical face of a Miocene sea cliff and an adjacent platform. Remains of organisms that colonized these rockground surfaces (see Wilson & Palmer 1992; for definition) were recorded to species level, where possible, and quantified. Bioerosion structures were identified to ichnospecies and quantified. Criteria used to distinguish *in situ* material from reworked material included: whether or not fossil bivalves are articulated; presence or absence of surface abrasion and rounding of coral colonies; orientation of corallites and presence or absence of encrusting coralline algae. Coral identification follows the taxonomy of Best & Boekschoten (1982) in their revision of Chevalier (1972). No fossils were collected, in compliance with guidelines for lands protected in the Parque Natural da Madeira.

Results

Table 1 shows the distribution of 217 fossils registered on the surface of a Miocene sea cliff within a sample 2 m in width × 1.6 m in height (3.6 m^2). The assemblage represents eight species or ichnospecies of marine invertebrates. By far the most abundant organisms preserved on the surface are barnacles. They include large and immature *Balanus* sp. (113 individuals) on basalt and *Ceratoconcha costata* Kramberger-Gorjanović (1889) (78 individuals) bioclaustrated exclusively on corals. Corals fixed to the basalt surface are conspicuous by size (eight colonies), as are borings in corals or other biocrust left as trace fossils (nine *Gastrochaenolites torpedo* Kelly & Bromley 1984). Two coral species were identified, both massive in growth form, but distinguished by different calyx diameters and shape. *Isophyllastrea orbignyana* (Mayer 1864) shows large and irregular-shaped calyxes (5–17.5 mm across) compared with *Tarbellastraea reussiana* (Milne-Edwards & Haime 1850) with more perfectly circular calyxes (2–4 mm). Bivalves, *Lima* sp. and *Spondylus* sp., are next in rank (six individuals). Serpulid worm tubes rank last in number (three individuals). Figure 2 shows part of the census area from a level 1 m above the base of the Miocene sea cliff. Additional photographs of bivalve borings from outside the census area are provided in Figure 3.

Crustose coralline algae were found to cover about 5% of the vertical surface, as differentiated from a non-descript carbonate crust that covered approximately 35% of the total area. More than half the surface area under study was exposed as bare basalt. An unknown proportion of bare basalt in the census may have been stripped of its carbonate crust and/or other distinguishable macrofossils as a result of recent erosion, but the spatial distribution of the remaining fossils still reveals a pattern of marked vertical zonation (Table 1). The large, encrusting barnacles (*Balanus* sp.) and the serpulid worms are restricted to the upper

Table 1. Spatial zonation of fossils on a Miocene sea cliff, Ilhéu de Cima (Porto Santo) based on census data from quadrats 400 × 400 mm. The basalt cliff face rises vertically 1.6 m and the width of the census area is 2 m (covered by five quadrates identified as 1–5 on the first three tiers.

		Rocky-shore biota									
Metres (cm)	Tier/ Quadrat	*Balanus* sp. (large)	*Balanus* sp. (small)	*Ceratoconcha costata*	Serpulid worms	*Isophyllastrea orbignyana*	*Tarbellastraea reussiana*	*Lima* sp.	*Spondylus* sp.	*Gastrochaenolites torpedo*	Biocrust (%)
120–160 (top)	4/4	44		25	3						25
	4/3	20									5
	4/2	19				1					40
80–120	3/5			17		1	3	3			75
	3/4			12		1	1			4	85
	3/3										5
	3/2										10
	3/1			24			1				30
40–80	2/5									1	15
	2/4										35
	2/3										70
	2/2							1	1		99
	2/1								1	1	55
0–40 (base)	1/5		30							3	70
	1/4										90
	1/3										25
	1/2										60
	1/1										55
Total		83	30	78	3	3	5	4	2	9	-

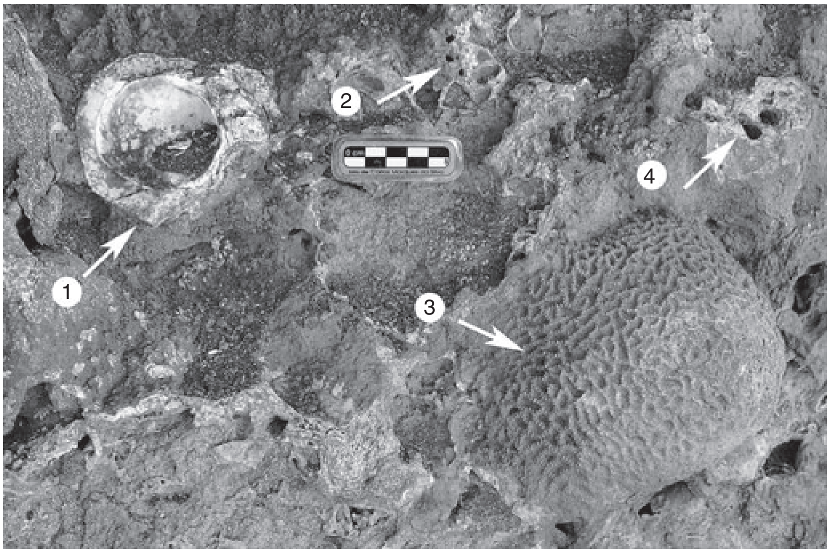

Fig. 2. Bivalve *Spondylus* sp. (1), large barnacles *Balanus* sp. (2), coral *Isophyllastrea orbignyana* (3) and bivalve borings *Gastrochaenolites torpedo* (4) in life position on a basalt rock face representing a Miocene sea cliff. Scale = 50 mm.

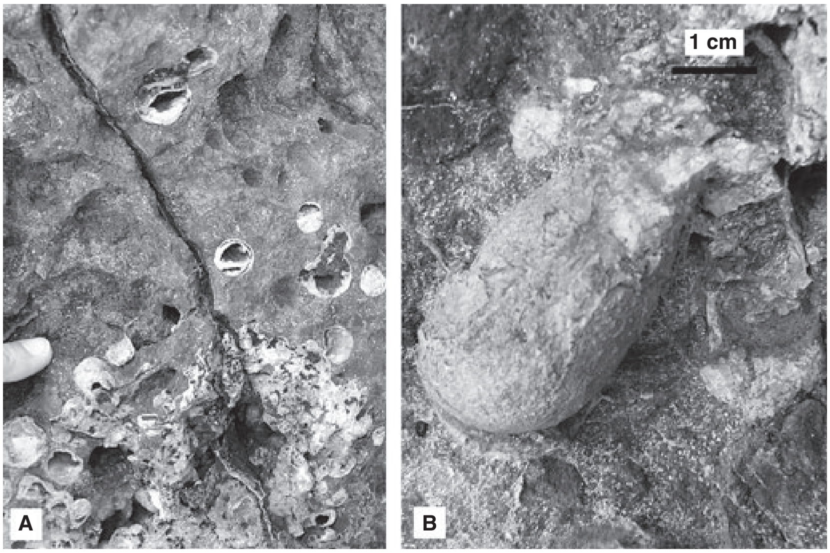

Fig. 3. Bivalve borings *Gastrochaenolites* on basalt. A, transverse sections through *Gastrochaenolites lapidicus,* with circular calcite fillings and cast linings near the surface of a sea cliff. B, longitudinal section showing the bulbous profile of *G. lapidicus.*

400 mm of the rock face. Coral colonies are limited to the upper half of the surface, but *T. reussiana* shows a preference for a zone between 0.8 and 1.2 m. *Gastrochaenolites torpedo* is distributed over the lower two-thirds of the surface, while the epifaunal bivalves (*Lima* and *Spondylus*) occupy a middle range. *Ceratoconcha costata* is hosted exclusively by coral colonies in the upper half of the rock surface. Other small barnacles (1–2 mm in diameter) are encrusted on the rock surface in the basal 400 mm of the profile, and higher between 0.8 and 1.6 m. The Miocene cliff top in the census area demonstrates an irregular surface with minor local relief on the order of 100–200 mm. A layer consisting of volcanic lapilli and finer tephra drapes the cliff top is 400 mm in thickness. Some large barnacles can be seen in cross-section, poking above the rock surface, but buried by volcanic material.

A distinct morphological feature that projects outward from a position below the vertical rock face is a platform with an exposed area of 180 m^2. The shelf is dominated by closely packed corals of *T. reussiana* preserved in growth position, but whose colonies are truncated by an erosion surface. At least three small vertical faults cut the surface with vertical displacements ranging from 240 to 600 mm (Fig. 4A). Separate blocks rise successively eastwards. A lenticular

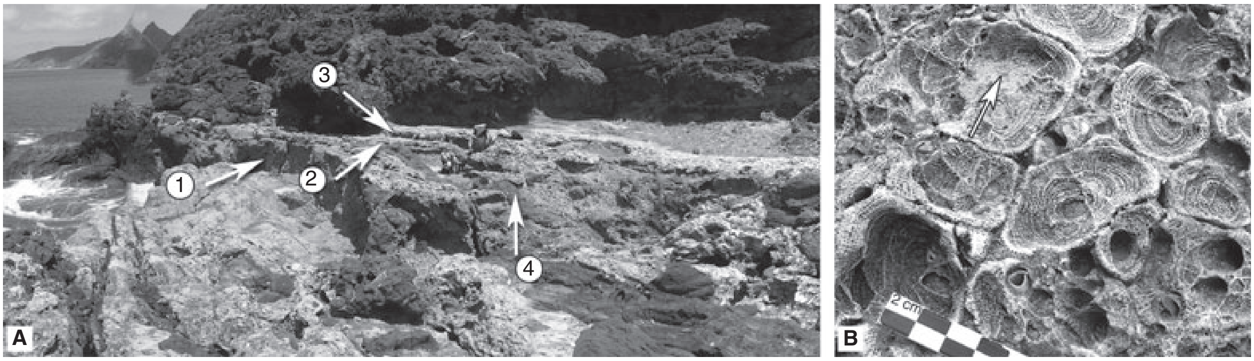

Fig. 4. Carbonate deposit on a shelf adjacent to Miocene sea cliff. A, numbers one to three points to small fault scarps and four points out a basalt dike cutting the platform (backpack for scale, centre). B, detail of *Tarbellastraea reussiana* corals showing truncated surface (arrow marks centre of growth for a large colony). Note lining of a boring (*Gastrochaenolites torpedo*) that protrudes above the surface near corner of the scale.

basalt dike that is 8.8 m long with a maximum thickness of 580 mm intrudes one of these blocks. The disrupted platform surface was recolonized by a few *I. orbignyana* corals, some of which can be found attached to exposed footwalls on low fault scarps. The relationships indicate that faulting and dike emplacement occurred after the surface was planed, but before re-colonization by second-generation corals.

From the horizontal platform surface, trials using the sampling grid yielded an average of nine *T. reussiana* colonies/quadrat. From a sample of 100 coral heads, the mean maximum diameter is 157 mm. The average number of *Gastrochaenolites*/quadrat was 28. In round numbers, the exposed shelf supported a population of 10,000 coral colonies of *T. reussiana* that were bored by 30,000 bivalves while some corals were still alive. The ichnospecies for these borings are identified as *Gastrochaenolites torpedo*, *G. lapidicus* Kelly & Bromley 1984 and *Gastrochaenolites vivus* Edinger & Risk 1994. All *Gastrochaenolites* traces are perpendicular to the host surface and truncated. Some *G. vivus* contain linings back filled with calcite. Also preserved on the coral surface are barnacle bioclaustrations (biologically claustrated, according to Palmer & Wilson 1988) made by *Ceratoconcha costata* and borings made by clionaid sponges (*Entobia* isp.). Cross-sections through coral heads show clear growth banding. If growth bands were laid down on an annual basis, individual colonies lived for 25–35 years. Corals of *I. orbignyana* are smaller in overall size compared with the *T. reussiana* colonies they replaced on the platform. In particular, the average colony height of *I. orbignyana* is <33% of *T. reussiana*, taking into consideration that most of the latter were truncated by erosion. Additional epifauna on the rockground includes bivalves, such as *Isognomon* sp. and *Spondylus* sp., with articulated remains preserved in growth position.

Discussion

The precise relationship between the vertical cliff face and horizontal platform canvassed for fossil content in this study is inconclusive. The two features may have been penecontemporaneous or the sea cliff may have been somewhat younger in development. The least complicated scenario is for the two features to have existed side-by-side with near-simultaneous erosional processes responsible for platform truncation and cliff retreat. In any case, occupation of the sea cliff by its signature barnacle populations occurred some time after the earliest colonization of the platform by the dominant coral *T. reussiana*. The entire platform surface may have become crowded with corals in <35 years, based on growth bands (Fig. 4B). The success of *T. reussiana* as a rapid colonizer on coarse-grained, unconsolidated biogenic sediment suggests it was an opportunistic species or thrived at a slightly greater water depth than *I. orbignyana*.

Local epirogenesis induced by volcanism lifted the reef platform, bringing it closer to mean sea level, where it was truncated and bioeroded prior to rigid fracturing related to lava injection. Re-occupation of the platform by sparse populations of *I. orbignyana* clearly occurred after platform deformation with some colonies growing directly on slip-fault planes. The smaller colony size of *I. orbignyana* compared with *T. reussiana* suggests that the recolonization phase was short. Coastal uplift was insufficient to neutralize a mid-Miocene rise in sea level that left *I. orbignyana* unable to fully occupy the faulted shelf, but allowed it to colonize surfaces higher on the sea cliff. Corals on other parts of the sea cliff suggest that *I. orbignyana* out-competed *T. reussiana* for living space.

In a study of Upper Miocene coral-reef sequences from many localities in southern Spain, Martin *et al.*

(1989) emphasized that *Porites* colonies established in silty sediments consistently preceded *Tarbellastrea* colonies through repetitious cycles in a basin dominated by fan deltas. They observed that '*Tarbellastraea* is never found as the initial colonizer, even when the natural substrate is firm' (Martin *et al.* 1989, p. 284). On Ilhéu de Cima, however, there is no *Porites* stage in the succession and *Tarbellastraea* is the initial colonizer on coarse-grained carbonate sediments over basalt. Here, *Isophyllastrea* colonies follow after *Tarbellastraea*, perhaps with a preference for somewhat shallower water.

Examples of intertidal to shallow-water segregation on rocky shores remain rare, despite growth of a sizable literature on former rocky shores in recent years (Johnson 2006). Heretofore, the best example entails gneiss boulders with Late Cretaceous spondylid bivalves in an upper level, oysters in the middle, and serpulid worm tubes aggregated on the lowest levels at Ivö Klack in southern Sweden (Surlyk & Christensen 1974). The substrate surface studied at Ivö Klack was 1.7 m wide by 0.8 m high. Another example comes from Bahía San Antonio in Baja California Sur (Mexico), where vertical zonation occurs along a shoreline composed of granodiorite and andesite boulders occupied by Late Pleistocene molluscs differentiated over a vertical space of 1 m (Johnson & Ledesma-Vázquez 1999). By comparison, the Miocene example on Ilhéu de Cima (Porto Santo) is a sea cliff of solid basalt with organic encrustations and borings spanning a vertical distance of 1.6 m. Biodiversity on the Miocene sea cliff is intermediate between that registered on the Cretaceous and Pleistocene rock surfaces.

The occurrence of borings left in the basalt by endolithic bivalves was an unexpected discovery at the Miocene sea cliff on Ilhéu de Cima. In some places outside the census area (Fig. 3B), *G. lapidicus* is evident as having penetrated basalt to a depth of 45 mm. In other locations, *G. torpedo* borings were initiated on corals or algal crusts, but extended all the way through them into basalt. From the extensive literature on former rocky shores, the only other example of *Gastrochaenolites* in igneous rocks is from the Miocene near Sendai, Japan (Masuda 1968). The diameter and length of the Japanese borings are similar to those from the basalt of Ilhéu de Cima, and the shape of the Japanese borings is comparable with that of *G. lapidicus.*

Conclusions

Independent evidence suggests that, like today, Ilhéu de Cima was a separate island at least during part of its Miocene history of volcanism and intercalated fossiliferous deposits (Ferreira 1997; Schmidt & Schmincke 2002). This study was restricted to the palaeoecology of a single locality on the southwest shore of Ilhéu de Cima chosen on account of superbly preserved fossiliferous deposits related to a Miocene sea cliff and wave-cut platform.

Three core conclusions underscore unusual aspects of the study site in the context of broader studies on former rocky shores of all Phanerozoic ages (Johnson 2006).

1. The Miocene sea cliff is a genuine rocky shore composed of basalt (not a boulder deposit) with fossils that record distinct vertical zonation. Large barnacles (*Balanus* sp.) and serpulid worm tubes are restricted to the upper 400 mm of a rock face 1.6 m in height, while two colonial corals (*I. orbignyana* and *T. reussiana*) occupy the upper half of the rock face. Endolithic bivalve borings dominate the lower two-thirds of the rock face, while epifaunal bivalves (*Spondylus* sp.) are attached to the middle part.
2 Bivalve borings in igneous rocks are almost unheard of. This is only the second confirmed example in an igneous substrate, and it is represented by ichnospecies *Gastrochaenolites lapidicus* and *G. torpedo* in basalt. These borings represent an important source of new information regarding hard-substrate use strategy because until now, the only record of substrates bored by *Gastrocahenolites* were found in limestone.
3. A separate basalt shelf was rapidly occupied by coral colonies dominated by *T. reussiana*, prior to colonization of the Miocene sea cliff. The platform reveals a complex history of truncation across the tops of the coral heads and many *Gastrochaenolites* borings prior to being offset by small faults and intruded by an igneous dike. A shorter episode of re-establishment by corals (mainly *I. orbignyana*) and bivalves (mainly *Isognomon* and *Spondylus*) was forestalled by a rise in Miocene sea level that facilitated settlement on the vertical sea cliff. Such rapid events in ecological time are seldom recognized on former rocky shores, because so few examples of former volcanic islands have been studied.

Future studies on the Miocene geomorphology and palaeontology of Ilhéu de Cima are expected to demonstrate variations in the distribution of intertidal and shallow-subtidal biotas as related to strong hydrographic factors, in addition to volcanic disturbances.

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