GEOLOGICAL EVOLUTION AND PALEOENVIRONMENTS OF MADEIRA AND PORTO SANTO ISLANDS

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Introduction

Madeira/Desertas and Porto Santo, islands are oceanic volcanic islands, dating from the Miocene (to the Quaternary), being interpreted as a consequence of hot spot activity. Madeira/Desertas Island is the youngest of the set (the last volcanic eruptions took place about 5250 BP).

Porto Santo is the oldest. It is a Miocene Atlantic volcanic island that has been strongly uplifted and deeply eroded. Uplift and erosion has resulted in the exposure of the transition from the submarine to the subaerial stage if its volcanic evolution. This transitional phase is characterized by long periods of epiclastic activity, followed by erosion, sediment transport and resedimentation, punctuated by short-lived volcanic activity. The submarine sequence is composed of basaltic lava, pillow lava and hyaloclastites, interbeded with some fossiliferous detrital limestone lenses. The subaereal sequence is formed by basalts, trachytes to rhyolitic litotypes with prominent columnar jointing. The presence of fossiliferous levels outcropping at the top of the submarine complex characterize this transitional phase. The dating of the fossiliferous units is a key element in the understanding of the chronology of the volcanic evolution of Porto Santo.

Herein we discuss the different stages of evolution of these islands from the submarine to the subaerial stage of volcanic evolution, focusing on the biostratigraphical and paleoenvironmental characterization of the transitional phase of Porto Santo.

Geological Setting

Madeira, the Desertas and the Porto Santo islands are part of the volcanic belt that, together with other seamounts (Seine, Ampere, Coral patch, Ormonde) originate from the same hotspot. They are the youngest islands situated at the end of the hotspot track located in a 130 Myr old oceanic crust.

Madeira and Desertas islands belong to the same volcanic system that appeared around 10 MA ago.

Little is known about the evolution of the submarine stage of the Madeira/Desertas volcanic system apart from the morphology that characterizes shield volcanoes. This two armed volcanic rift system (with an angle of 110° between the arms) is more than 170 km long, rising from 4000 m depth and reaching an altitude of 1862m in Madeira Island. The submarine base of Madeira/Desertas comprises approximately 98.5 % of the total volume of the volcanic complex.

Deep submarine canyons that continue from inland valleys developed on the south coast of Madeira to 3440m depth. Prominent cinder cone fields (also on the south coast) are the most familiar morphological characteristic as well as deposits from giant landslides on the flanks of the volcanic system.

The oldest dated rocks (4.6 Ma) from Madeira island (Porto da Cruz) are thoelitic dykes belonging to the subareal stage of volcanic evolution. This stage can be dived into the basal, middle and upper units.

The basal unit corresponds to the oldest exposed rocks (> 4.6-3.9 Ma) and consists primarily of volcanic breccias and pyroclastic deposits and lava flows. A concentration of volcanic vents and east west oriented dike swarms in the centre of the eastern half of the island suggests that volcanism during the early Madeira rift phase originated primarily from an E-W oriented rift system.

The middle unit (3-0.7Ma) is composed of gently dipping thick lava sequences mainly alkalic basalts that cover most of the island and lasted till 0.7 Ma.

The upper unit (< 0.7Ma) represent the most recent volcanic activity and consists of scoria cones and intracanyon lava flows located in the western part of Madeira that developed from around 0.7 Ma to the last known eruption 6000 y.a.

The subaerial part of the island of Madeira corresponds to 4% to the total volume of the island. The eruption rates of Madeira/Desertas could be in the subaerial stage of volcanic evolution 95Km^3/Ma and in the submarine stage of evolution 5500 km^3/Ma. (Geldmacher *et al.* 2000)

The Desertas are deeply eroded wedge shaped islands of almost vertical dikes swarms, cinder cones and horizontal lava flows. The volcanic evolution of Desertas ridge developed from 3.3 Ma to 1 Ma (verbatin Hoernle K.) and is interpreted as an abandoned rift arm of Madeira/Desertas volcanic system.

Porto Santo Island is older than Madeira/Desertas and comprises an eroded remnant of a much larger submerged edifice. It rises from water depths of more than 3000m with a flat top at 100m below sea level and reaches 517 m above sea level.

Porto Santo has been uplifted 350-400 m exposing the volcanic formations from the transitional of submarine to subaerial stage of evolution as indicated by pillow lava and hyaloclastitic breccia and coral patch reef located now at an altitude of 340 m. The majority of the exposed volcanic rocks were emplaced 14 and 10 Ma and are mainly alkali basalts intermediate rocks (mugearite, benmorites) and trachites and ryolites. At the base of exposed sections two superimposed lapilli cones are interpreted as having formed from numerous submarine to subaerial phreatomagmatic explosions. The lower basaltic and the upper mugearitic to trachytic sections are dominated by redeposited tephra and are called 'lapilli cone aprons'. Vertical growth due to accumulation of tephra, voluminous intrusions and pillowed lava flows produced ephemeral islands that were subsequently leveled by wave erosion.

Abundant biocalcarenite lenses at several stratigraphic levels represent periods of volcanic quiescence. The loose tephra piles became stabilized by widespread syn-volcanic intrusions such as dikes and trachytic to rhyolitic domes welding the volcanic and volcaniclastic ensembles into a solid edifice.

Scoria cones and tuff cones represent subaerial explosive activity. Basaltic lava flows built a resistant cap that protected the island from wave erosion. Some lava flows entered the sea forming lava deltas.

The island became consolidated by intrusion of numerous dikes and by emplacement of prominent intrusions that penetrate the entire volcanic succession.

Volcanic sedimentation ended with the emplacement of a debris avalanche after the last subaerial volcanic activity (Schmidt R. 2002).

Methodology

Since Mayer (1864), several palaeontological studies have been carried out in the islands of Madeira and Porto Santo (*e.g.* Henriques da Silva, 1959; Chevalier, 1972, 1975; Boekschoten and Best, 1981; Best and Boekschoten, 1982, etc.). These studies were strictly paleobiological, focussed on diferent paleontological groups (Gastropoda, Bivalvia, Echinoidea, Cnidaria, etc.).

The present work, however, is centered on the application of paleontological (biochronological, paleobiological and taphonomical) methodologies to the study of the evolution of volcanic islands, namely, of Porto Santo.

The paleontological studies had two main focuses: (1) the definition of the biostratigraphic positioning of the transitional phase, and (2) the paleoenvironmental interpretation of the transitional phase fossiliferous outcrops and its relations with active volcanism.

The biostratigraphic positionning was achieved by means of the analysis of Calcareous nannofossils biomarkers. The paleoenvironmental studies were based on a multiproxy paleobiological approach, using paleontological proxies ranging from phytoplankton (calcareous nannoplankton) and calcareous macro-algae (rodoliths), to mollusks (gastropods and bivalves), corals and to bioerosion structures on biogenic (corals) and rocky paleoshore substrates (basaltic lavas).

Taphonomic studies were also performed in the main sedimentary and volcano-sedimentary fossiliferous units, namely in the identification (taphonomic signature) of possible shallow tsunamigenic and peperite type deposits.

Biostratigraphy

The identification of calcareous nannofossil biomarkers allowed the definition of an age interval for the fossiliferous layers of *Lombinho de Cima (Serra de Dentro,* Porto Santo) within the biozone CN4 of Okada and Bukry (1980) (Middle Miocene, Middle Serravalian). This biostratigraphic age of these transitional phase fossiliferous sedimentary beds is in good agreement with radiometric $^{40}Ar/^{39}Ar$ ages, of approximately 14 Ma, obtained for the trachytic to basaltic submarine sequence in the northeast sector or the Porto Santo island (Geldmacher *et al.*, 2000).

Paleoenvironments

The paleoecological interpretation of the fossil assemblages from the sedimentary beds characterizing the transitional phase indicate the existence, during this phase, of several diverse and quite distinct shallow marine paleoenvironments: coral reef *(Ilhéu da Cal or Ilhéu de Baixo)* and patch-reef environments *(Ribeiro Salgado, Serra de Dentro and Ilhéu de Cima)* (Fig. 1); back reef/mangrove, pebble/boulder shore (Lombinhos at Serra de Dentro) and beach environments *(Ilhéu de Cima)*.

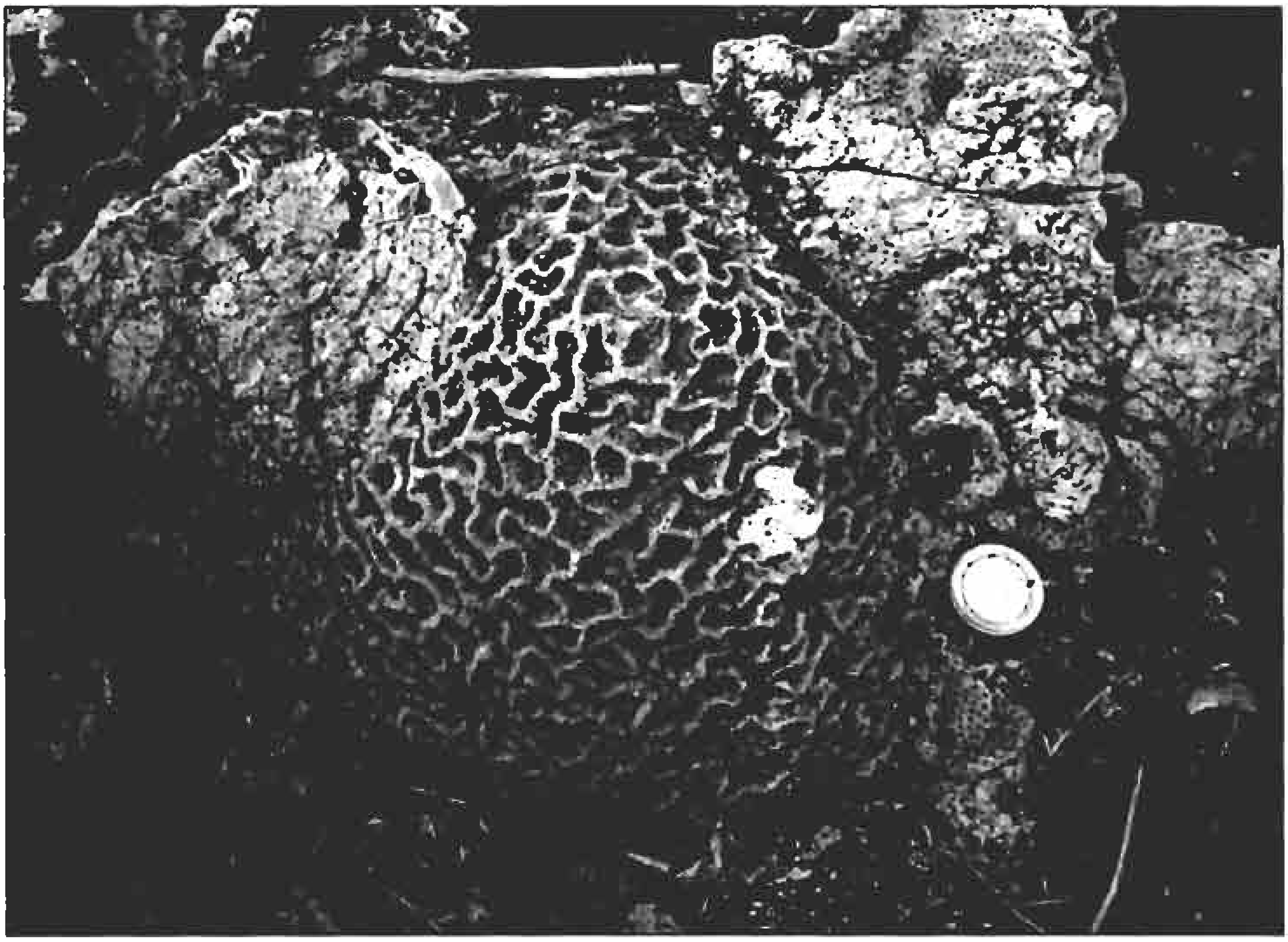

***Figure 1:** In situ colonial coral with attached Spondylus bivalve, on the top left corner. Patch-reef facies of Ilheu de Cima.*

A common feature to most of the Miocene marine sedimentary units that outcrop in the volcanic island of Porto Santo, and in its surrounding islets (*e.g.*, Ilhéus de Cima, Ilhéu de Baixo), is the presence of large rodoliths, locally called *laranjas* (oranges). At the *Ilhéu de Cima* two distinct types of fossil rodolith assemblages can be found. At *Pedra do Sol* the rodoliths are associated with *Clypeaster* echinoids, *Spondylus* bivalves and coral patch-reefs. Rodoliths are dominated by at least two species of *Lithothamnion*, many encrusting bryozoans, some serpulid worm tubes and rare Peyssonneliacean algae. Growth forms are mostly columnar. Rare crustose forms occur formed by *Lithoporella melobesioides*. The second assemblage type occurs at *Cabeço das Laranjas* were rodoliths, mainly composed by *Sporolithon and Lithothamnion*, constitute the major component of the fossil content of these layers (Fig. 2) with densities of more than 80 specimens per square meter (Cachão *et al.*, 2000).

At *Ribeiro de Água (Morenos)* a pyroxene-rich sandstone with serpulid crusts in the contact with the basaltic substrate, suddenly changes into a highly heterometric sedimen-

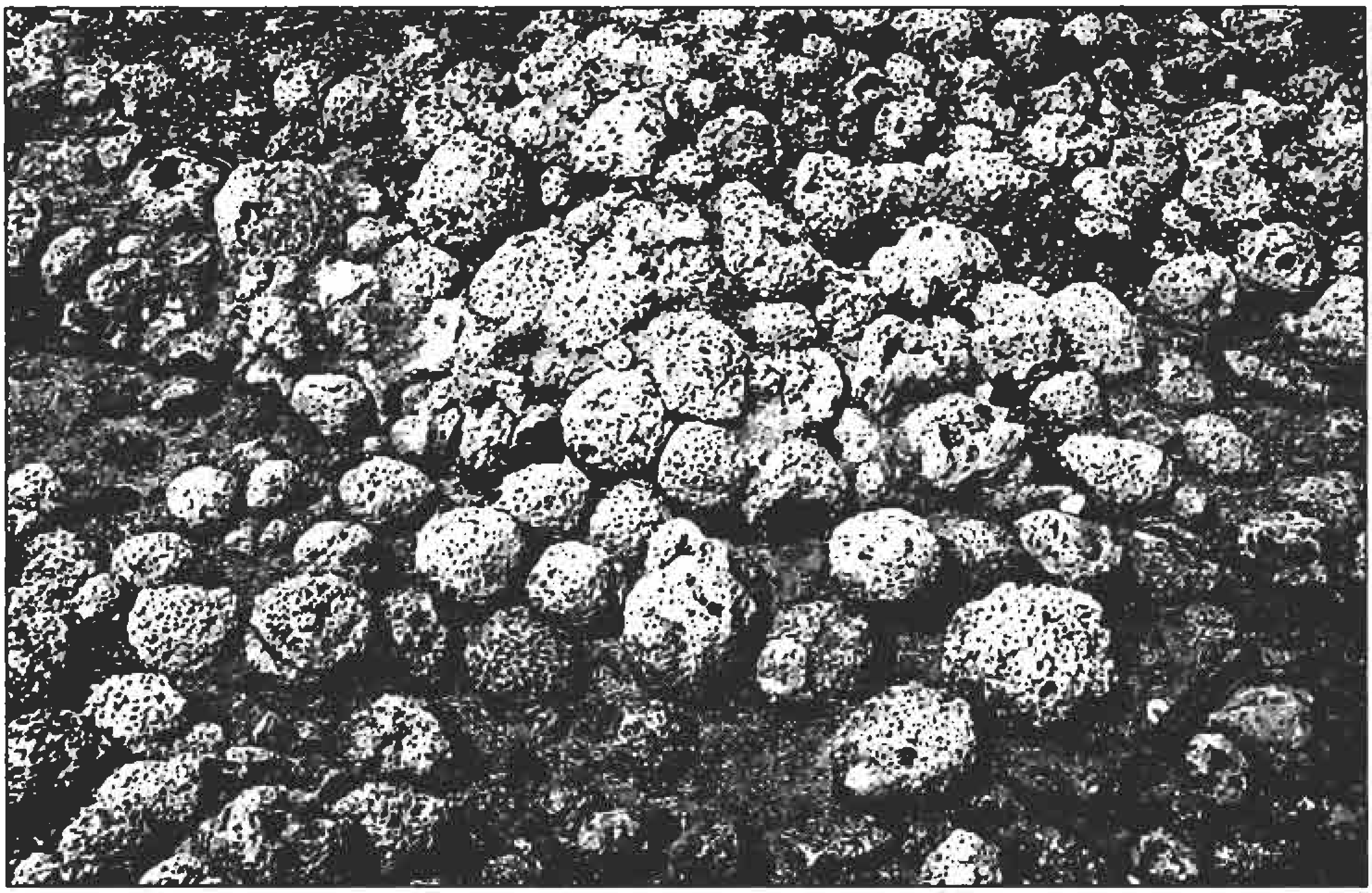

Figure 2: Massive in situ rodolith (Rodophyta algae) accumulation. High-energy productive rich coastal facies. Cabeço das Laranjas, Ilhéu de Cima, Porto Santo.

tary unit associated to an unusual fossil assemblage composed, among other elements, of well preserved shells of nautiloids and tests of spatangoid echinoids incorporated in a poorly sorted very coarse conglomerate with metric boulders. These litho, bio and taphofacies are unique in Porto Santo and may indicate deposition during a high-energy single catastrophic (probably tsunamigenic) event.

At *Ilhéu de Cima* there are facies composed of mingled sediments and basaltic lavas which may be considered as a peperite produced when channeled surface magma flows intruded on unconsolidated and wet marine coastal biogenic sediments.

Future Perspectives

Due to the very shallow high-energy nature of most of the sedimentary facies of Porto Santo the biostratigraphic markers of calcareous nannofossils are in several cases not possible to obtain. In this circumstances $^{86}Sr/^{87}Sr$ isotope dating age model will be applied to mollusk calcite shells to confirm or detect distinct stratigraphic units.

In order to characterize shallow subtidal rocky paleoshores environments based on bioerosion structures, on both organic (corals) and rocky (basalt) substrates will be further developed.

Geological Heritage

Parallel to the scientific studies, efforts are been made to accomplish a Paleontological Heritage Inventory and promote Geological and Paleontological Heritage as an important part of the Natural Heritage of the Madeira Archipelago. The sites of geological importance of Madeira and Porto Santo are related to particular volcanic landforms and structures (xenoliths, volcanic cylinder cones, columnar jointing, pillow lava, lava tubes, palaeosoils and erosional forms) and sedimentary rock landforms (fossil dunes, marine terraces, fossiliferous stratigraphic sequences, coastal karsts) (Rodrigues *et al.*, 1998, 2000).

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