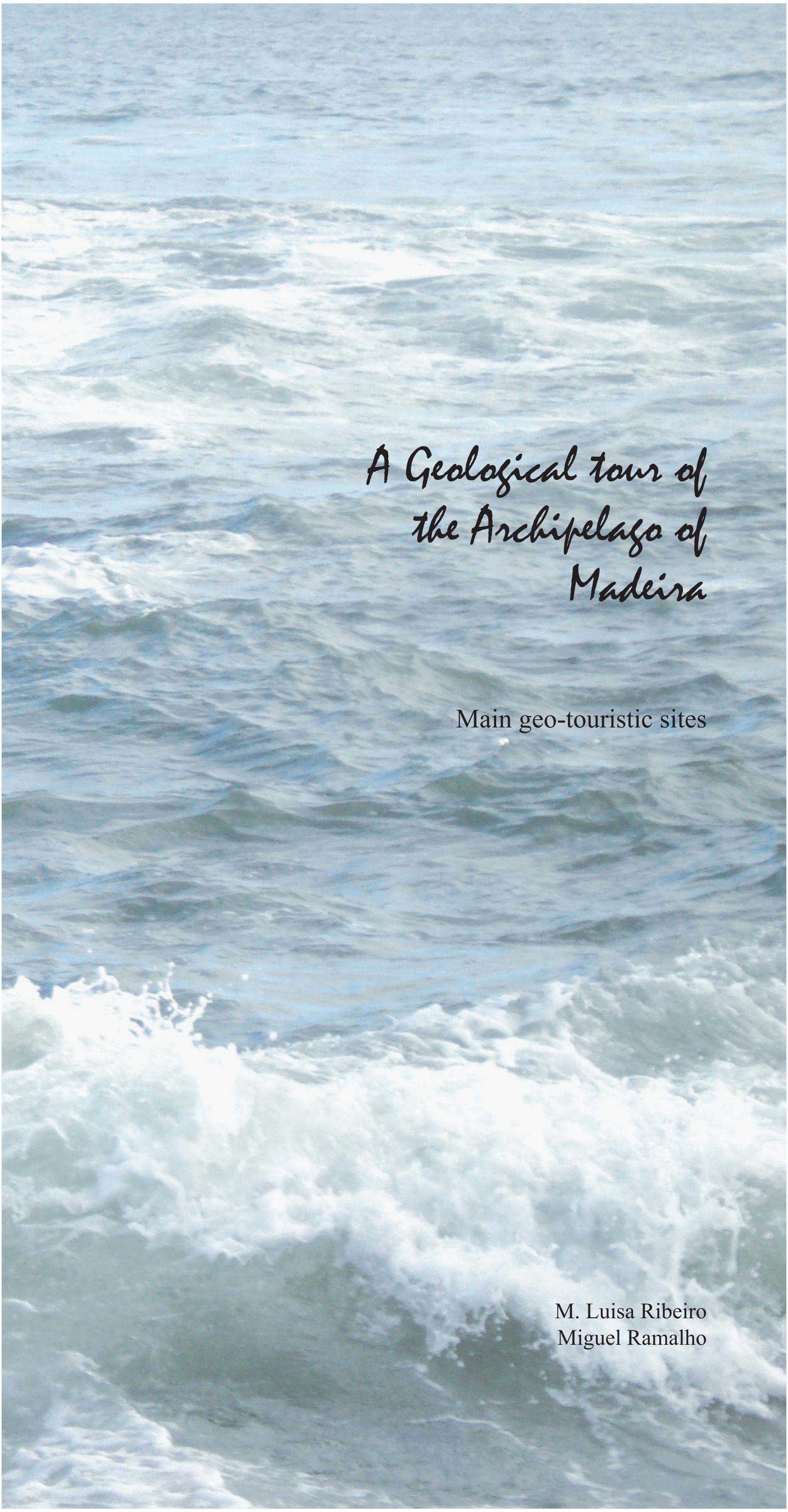

A Geological tour of the Archipelago of Madeira

Main geo-touristic sites

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PREAMBLE

This work was performed by INETinovação (the institution who preceded LNEG, National Laboratory of Energy and Geology) by request of the Direcção Regional do Comércio, Indústria e Energia da Região Autónoma da Madeira (DRCIERAM) with the purpose of encouraging cultural and scientific tourism on the two main islands of the Archipelago of Madeira.

The agreement between the two institutions, stated this work should be based on the geological maps of Madeira and Porto Santo, published, respectively in 1974 (Portuguese Geological Survey) and 1996 (Instituto Geológico e Mineiro). A simplified map at a reduced scale (1/80.000), with no need for additional mapping work, should be the outcome.

However, having been performed in different time periods and with distinct conceptions, the correlation of both maps was a difficult process.

In fact, in the geological map of Porto Santo by M. Portugal Ferreira and J. M. Cotelo Neiva, which was based on numerous absolute geochronological data, the adaptation work consisted in summarizing the information and also to present it with the same criteria previously defined for Madeira.

However, the geological map of Madeira had been published two decades before, by G. Zbyszweski, with the standard criteria for that time (stratigraphy and litostratigraphic correlation) without any absolute geochronological data. His mapping, performed at a 1/25.000 scale, kept in the Geology Department archive of LNEG is today an example of cartographic detail and is, therefore, priceless. However, when volcanic rocks are deposited/installed, they do not always follow the law of superimposition (which states that the recent strata always overlay the older strata) as it can be observed that in some places older volcanic materials overlay, or are interlayered, into more recent ones. In this case, geochronology is crucial.

Despite these problems, the geological map of Madeira has stood valid even after recently published geochronological data and, if some modifications have been performed in recent geological sketches, these refer to the most recent formations – scoriae and pyroclasts (examples: the NW–SE alignment of Fonte da Pedra, in the western edge of Paúl da Serra; the coastal alignment from Paúl do Mar to Ponta do Pargo). These corrections correspond, to geological interpretations given by different authors. Therefore, it was decided to keep the original cartography, summarized and adapted it to the established criteria.

1 LOCATION

The Archipelago of Madeira, as is commonly known the Archipelago of Madeira and Selvagens, is composed of two groups of islands: the Northern Group – situated in an oceanic environment, includes the islands of Madeira, Porto Santo and Desertas, and the Southern Group – located closer to the African continent and the Archipelago of Canaries with which it has geological affinities, includes the islands of Selvagens (Fig. 1).

The islands of the Archipelago are situated between the Abyssal Plain of Madeira to the West and the African Continent to the East. The Northern Group is part of a large submarine ridge, the Madeira – Tore Ridge, which extends for more than 1,000km in a NNE – SSW direction, located approximately 300km from the Portuguese mainland coast at the latitude of Nazaré (Fig. 2). The geochronological data indicate that this ridge was formed over a long period of time (over 103 My).

By observing the morphology of the oceanic depths of the Northern Group, it can be stated that there is some continuity between Madeira and Desertas, whereas the island of Porto Santo, 45km to the northeast, is separated from the others by depths exceeding 2,000m (Fig. 3).

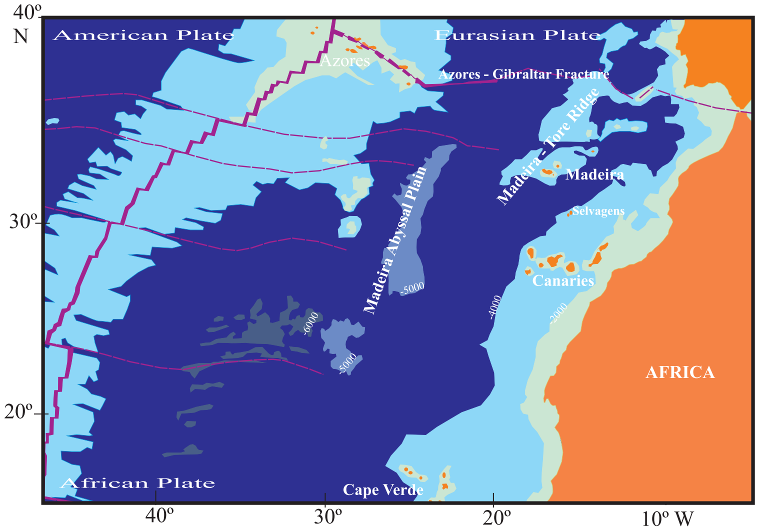


Fig. 1 – Location of the Archipelago of Madeira within the major geological units of the submersed part of the African Plate. In red: the Mid-Atlantic Ridge and major active faults. The ocean depths are represented by: green (0 – 2,000m), light blue (2,000 – 4,000m), dark blue (4,000 – 6,000m) and dark gray (more than 6,000m depth). The Madeira Abyssal Plain, with depths of around 5,000m, is highlighted.

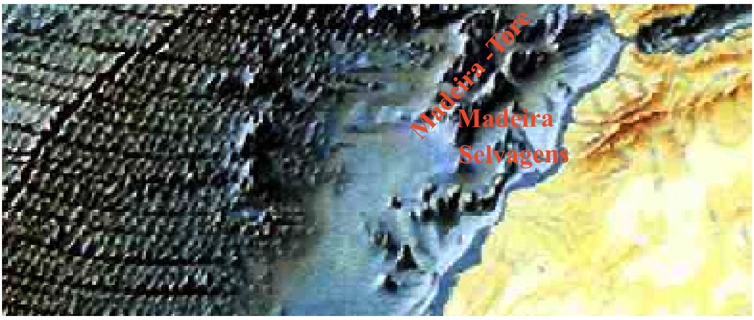


Fig. 2 – Location of the Madeira – Tore Ridge and the islands of Madeira and Selvagens between the Madeira Abyssal Plain and the African continent. This map is based on "Carte du fond des oceans" (Ed. Pierre Charron).

Another important information is the radial distribution that these islands display, with Madeira roughly orientated E-W, Porto Santo NE-SW and the Desertas NNW-SSE (Fig. 3). These data have been extensively used to constrain the origin of these islands, as is described below.

Generically, oceanic islands, such as the islands of the Archipelago of Madeira, correspond, in fact, to small subaerial parts of large volcanic edifices deep-seated onto the ocean floor, usually at great depths (Fig. 2).

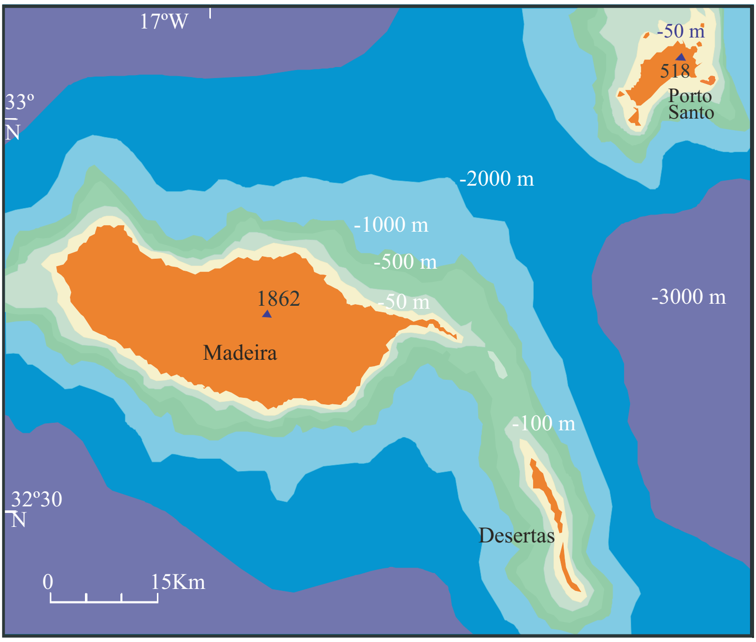
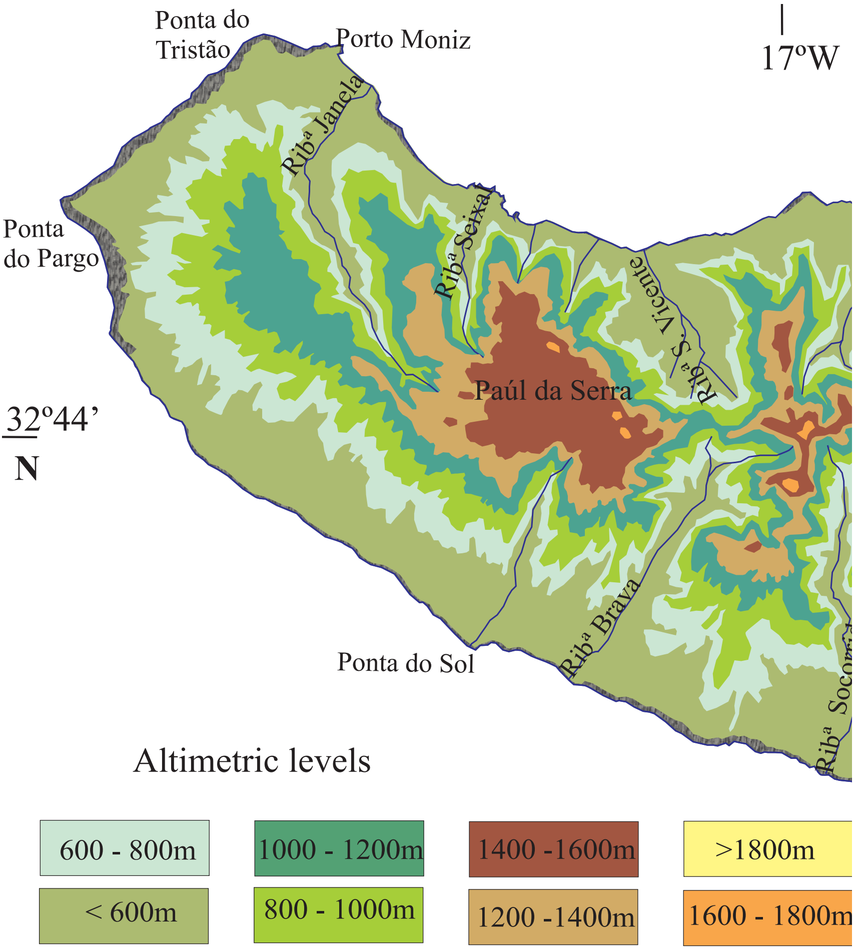


Fig. 3 – Between the Island of Porto Santo and the islands of Madeira and Desertas, ocean depth reaches more than 2,000m. In this map, bathymetry is represented by colour. (Map based on the Hydrographic Map of Madeira 1936-1938, Instituto Hidrográfico, Lisbon).

The volume of the volcanic edifice for the island of Madeira yields more than 9,000km³, whereas for Porto Santo a value of 5,000km³ is presented. This implies that the total subaerial part corresponds to only 4.2% and 0.1% of the entire volumes of Madeira and Porto Santo volcanic edifices, respectively.

All the islands of the Archipelago of Madeira are deep-seated in the ocean floor, which was generated by the separation of the African and American continents by the great fracture system known as the Mid-Atlantic Rift (Fig. 1 and 2). These islands are, for that reason, typical examples of intra-plate oceanic volcanism. This type of magmatism is very important for petrologists, since it constitutes the best sampling that represents the Earth's Mantle because it is not contaminated by crustal materials.



2 GENERIC MORPHOLOGICAL FEATURES OF THE ISLAND OF MADEIRA

The island of Madeira has an elongated form, with 57km E-W direction and 22km by N-S, covering a total area of 737km^2.

The morphology of the island of Madeira has been affected by the volcanic structures, the nature of its rocks (lithology), the sea level changes, the climate and the erosion. The combination of these factors led to the appearance of special geomorphological features – volcanic cones, deep depressions, cliffs, ravines, calderas, plateaus, terraces, etc., that often were named with local designations – “paúl”, “achada”, “curral”, “rechãs”, “leixões”, etc. The topography is vigorous, reaching 1,862m in Pico Ruivo, the highest peak in the island, and the valleys are very trenched. The “ribeiras” (creeks or streams), are side by side to huge cliffs and are tipically perpendicular to the coastline (Fig. 4). In general, they show a torrential regime

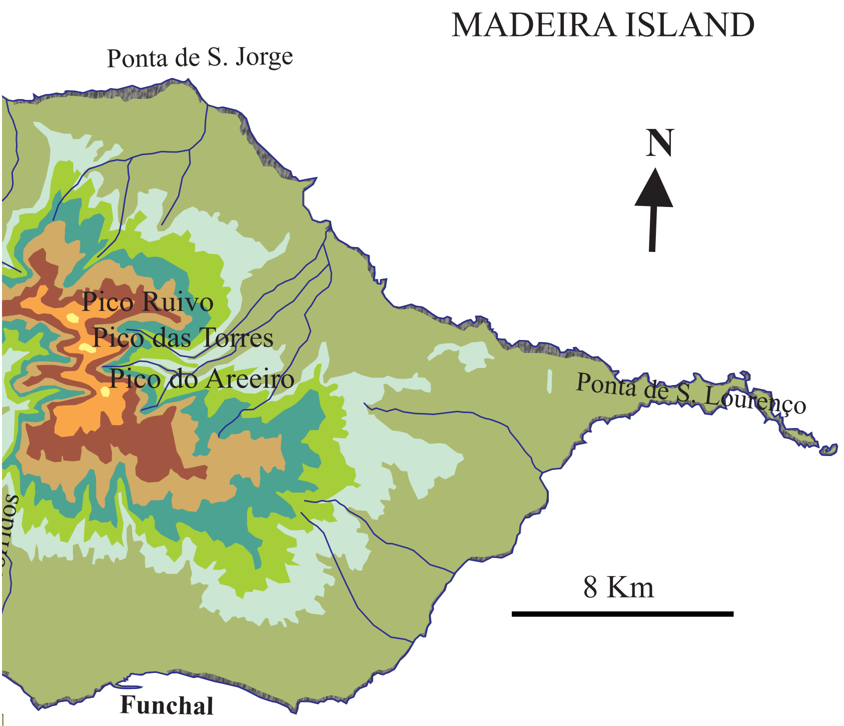


Fig. 4 – Topographic representation of the Island of Madeira with altimetry. Note the narrow region with an altitude of 1,000 and 1,200m, separating the Western part and the Eastern part of the island, near the headwaters of Ribeira Brava and Ribeira de São Vicente.

during the winter and are dry during the summer. This vigorous topography is due to the volcanic morphology of the island combined with the presence of very peculiar lithologies that correspond to intercalation with different thickness, of materials with distinct resistance – massive basalts, very resistant, and pyroclastic rocks (tuffs, breccias, ash, etc.), extremely easy to erode. When the erosion of the overlaying levels exposes pyroclastic rocks to the weathering agents, they very rapidly disaggregate and the resulting sediments are transported by rain to the streams. On the contrary, the basaltic lavas resist much longer to erosion and protect the underlying rocks. A peculiar aspect of this differential erosion is the occurrence of vertical basaltic dykes that stood *in situ* after the country rock has been completely eroded, forming "vertical walls" in the landscape of the highest regions of the island (e.g. Achada do Teixeira) (Photo 4).

Essentially, two main morphological units are distinguishable in the island of Madeira – the **Central Volcanic Massif** and the **Coastline.**

2.1 THE CENTRAL VOLCANIC MASSIF

The Central Volcanic Massif is composed, as the name indicates, of an imposing set of elevations of volcanic nature, whose highest peaks are located in the central part of the island. This set is subdivided in two parts – the Eastern and the Western Massifs – separated by the valleys of two important streams: Ribeira Brava that flows to the South and Ribeira de São Vicente that flows to the North (Fig. 4).

Encumeada, the upper part of the two basins, is one of the privileged places where it can be seen how those two streams are very close to intersect.

The WESTERN MASSIF consists of an extensive plateau, located between 1,300-1,500m above sea level, called Paúl da Serra. This plateau is deeply indented by the Ribeira do Seixal and Ribeira da Janela, the longest of the island.

At **Paúl da Serra**, a compact sub-horizontal basaltic level protects from erosion the rocks on which it rests, forming a spectacular erosion surface (Photo 1).

Photo 1 – The plateau of Paúl da Serra seen from the left bank of Ribeira da Janela.

Recently, in this region, it has been identified the action of glaciers of Würm age, the last glacial period, whose maximum ice coverage, occurred at, approximately, 18,000 years ago. Although Madeira is situated at fairly low latitudes, the possibility of the presence of glaciers in its highlands is not new. Recently, some authors presented morphological evidence of glacier action or, at least, snowfields in certain places. Paúl da Serra is the region most often cited for observation of glacial erosion forms, glacial ice circus or amphitheatre and moraines, including south of Fonte do Juncal, where large prismatic blocks of a basaltic flow have been removed from their original location by the combined effects of ice-melting/freezing of the country rock.

THE EASTERN MASSIF shows quite a different morphology compared to the Western Massif, being characterized by several peaks which reach high altitudes (Pico Ruivo, 1,862m, Pico das Torres, 1,851m, Pico do Areeiro, 1,818m, etc.). These elevations are due to the presence of coarse pyroclastic levels that have accumulated near their source vents and have been intruded by several basaltic dykes that form a dense network similar to an "inner skeleton" (Photo 2), preventing the erosion of the pyroclasts. The huge depressions that separate the various peaks occasionally display very special geomorphological characteristics such as the Curral das Freiras, in the upper part of Ribeira dos Socorridos (Photo 3). Here, the slopes between the 1,000-700m are almost vertical. The morphology of this depression has led some authors to hypothesize that it corresponds to a volcanic caldera. These deep depressions are nowadays interpreted as the result of the strong differential erosion between the lavas and pyroclastic rocks that occur in this location. Another significant depression of the same type is located in Serra da Água, in the upper part of Ribeira Brava.

In the highlands of the Eastern Massif, the erosion surface corresponding to Paúl da Serra is less preserved but nevertheless it is still possible to see small "**rechãs**" or "**achadas**" in areas where remnants of lava flows outcrop.

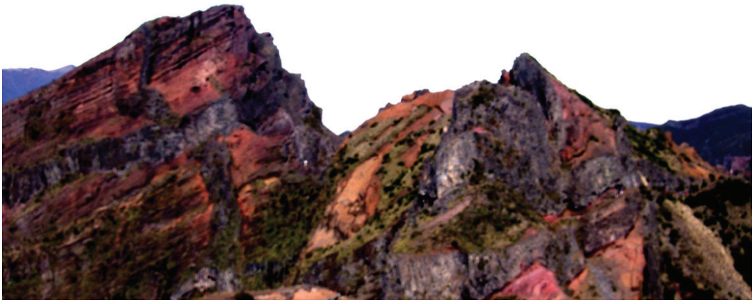


Photo 2 – Topographic characteristics of the region of Pico do Areeiro with a dense network of dykes intersecting and supporting pyroclastic units.

On the East side, the Massif gently dips towards **Ponta de S. Lourenço** which is a very elongated and narrow peninsula (Photo 5).

Photos 3 e 4 – The huge depression at Curral das Freiras (above) resulted from intense erosion of pyroclastic rocks that outcropped in the region. Below it is visible the “standing man”, a dyke in Achada do Teixeira that remains *in situ* and stand out in the topography because of its greater resistance to erosion, in contrast with its enclosing pyroclastic rocks.

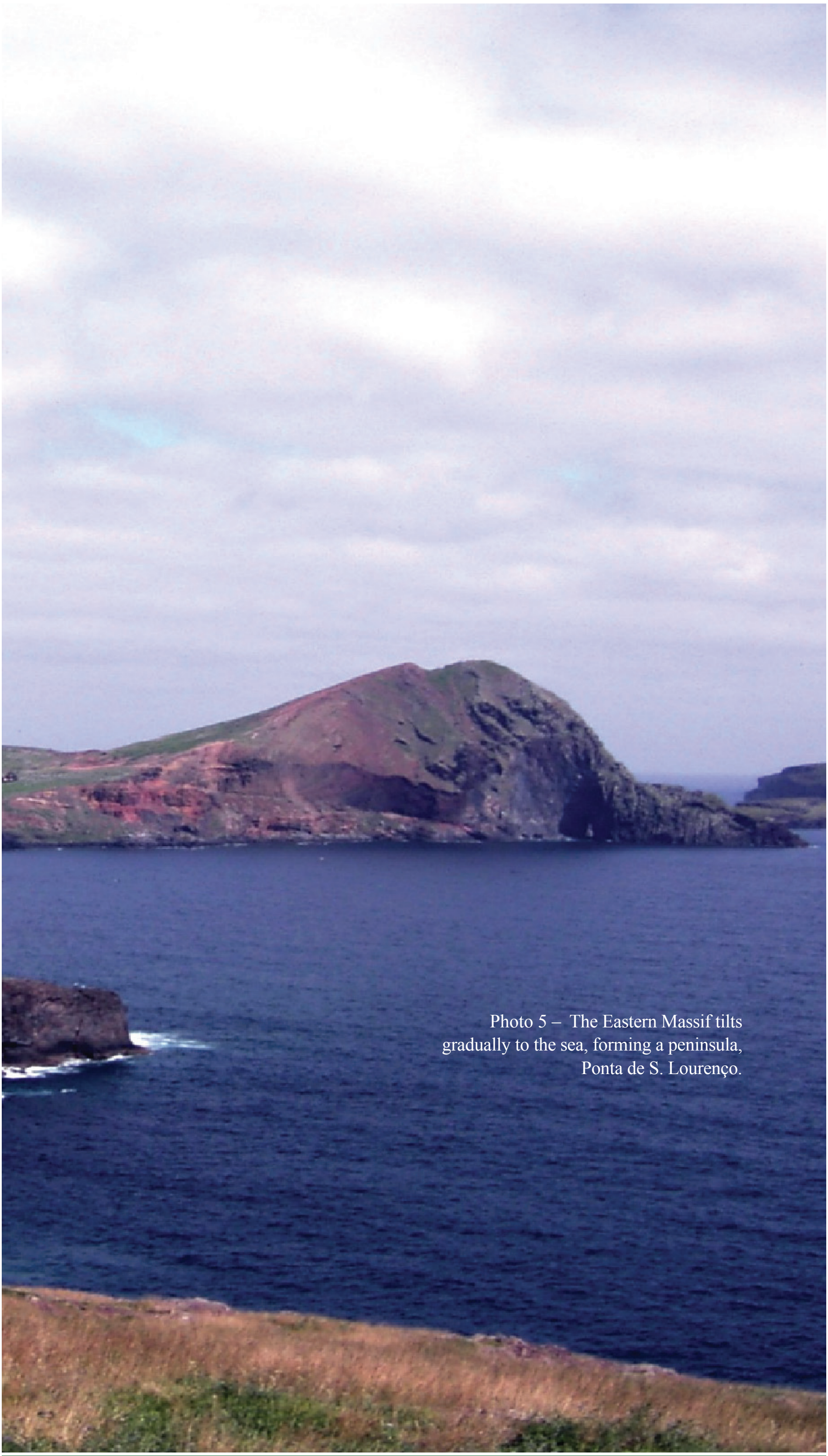


Photo 5 – The Eastern Massif tilts gradually to the sea, forming a peninsula, Ponta de S. Lourenço.

2.2 THE COASTLINE

The coastline of the island of Madeira, with the exception of Ponta de São Lourenço, is particularly steep (Photos 6 and 7), displaying high cliffs, especially in the Western and Northern coasts. Between Ponta do Pargo and Ponta do Tristão, the cliffs can be more than 250m high. The cliffs are intersected by gullies that locally, in the Northern and Western coasts, terminate at suspended valleys, due to the rapid retreat of the cliffs (Photos 8 and 9).

The Northern coast is more rugged than the Southern, which has been attributed to its more rapid retreat by the action of the prevailing winds - the trade winds. The almost continuous line of cliffs is intersected by the wide valleys of Porto Moniz, Seixal and S. Vicente whose morphologies were affected by the most recent volcanism.

Photos 6 and 7 – Aspect of the coastal cliffs northeast of Ponta do Pargo (left) and west of Madalena do Mar Village (right).

The retreat of the cliffs is due to the formation of rupture surfaces followed by their dismantling, sliding and accumulation of debris at the base of the cliffs. Examples of this phenomenon of accumulation deposits can be seen in Fajã da Areia (east of S. Vicente) and in Fajã do Barro (SE of Porto Moniz).

Sandy beaches are rare on the island, except in the region of Ponta de S. Lourenço. In this area, deposits of fine-grained aeolian sands occur with abundant calcareous shell fragments.

Photo 8 – “Véu da Noiva” is the popular name for the waterfall that runs all year from a suspended valley on the North coast, near the village of Seixal.

Photo courtesy of Diogo Rosa (LNEG).

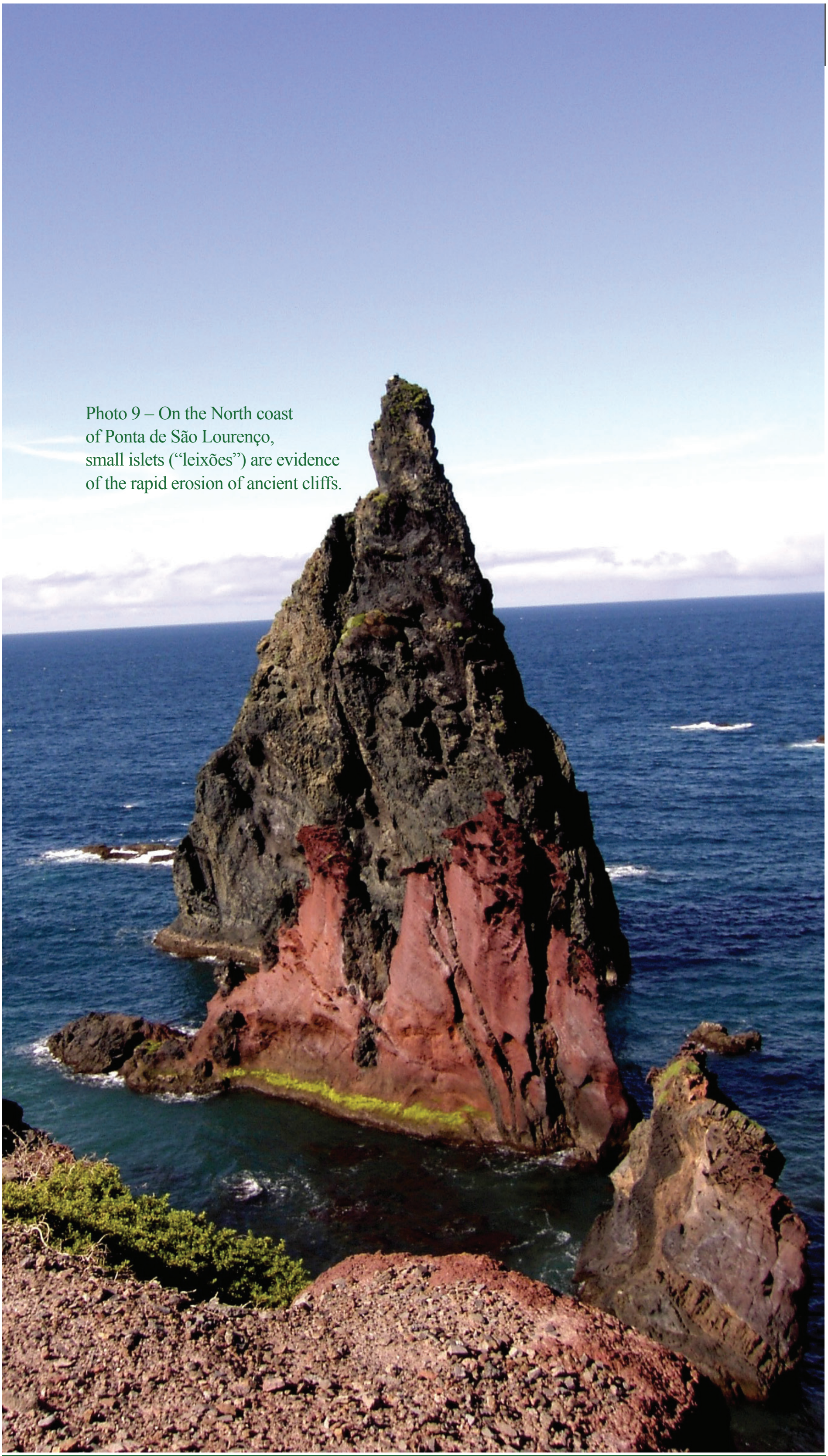


Photo 9 – On the North coast of Ponta de São Lourenço, small islets (“leixões”) are evidence of the rapid erosion of ancient cliffs.

3 THE MORPHOLOGY OF THE ISLAND OF PORTO SANTO AND ITS CONTRAST WITH THE ISLAND OF MADEIRA

The Island of Porto Santo, with its major islets, covers an area that slightly exceeds 42km², thus being much smaller than the Island of Madeira. In morphological terms, there is also a strong contrast between these islands. The Island of Porto Santo has a much lower altitude, approximately 518m above sea level at its highest point, Pico do Facho (Fig. 5). In relative terms, the Northern region of the island, where the highest peak is located, is relatively rugged, unlike the rest of the island where the altitude of 200 meters is rarely exceeded (Photos 10, 11).

Fig. 5 – Morphology of the Island of Porto Santo. The -100m bathymetric level limits the abrasion platform developed until the end of the Würm glaciation (18,000 years). During this period, when sea level was approximately 130m below the present level, the island was considerably larger than it currently is.

Another important morphological difference in relation to Madeira is the existence of a large central area, slightly tilted to the east. This area, covered by fine-grained sediment mainly deposited by the wind, separates the Northern and Southern regions of the island, where volcanic rocks crop out (Figs. 5 and 12).

The morphological contrast between the two islands has been interpreted to result mainly from the different lengths of exposure to the erosive agents. Indeed, the geochronological dating of rocks from the Island of Porto Santo has shown that its emergence has occurred more than 14 million years ago and, although its volcanic activity continued until about 8 million years, erosion began to act immediately.

The Island of Madeira, also according to geochronological dating, is much younger, showing absolute ages of 5.2 million years for the oldest known rocks.

So, given that erosion began to level the Island of Porto Santo much sooner, its effects are felt much more than in the Island of Madeira.

In the central part of the Island, the aeolian sediments occur at altitudes in excess of 200m, as in Pico de Bárbara Gomes, and reach a thickness of tens of meters, as can be seen, for example, on the West coast, in the road to Fonte da Areia. Its colours, internal and external structures and composition, contrast significantly with the igneous rocks on which they are deposited (Photos 12 and 13).

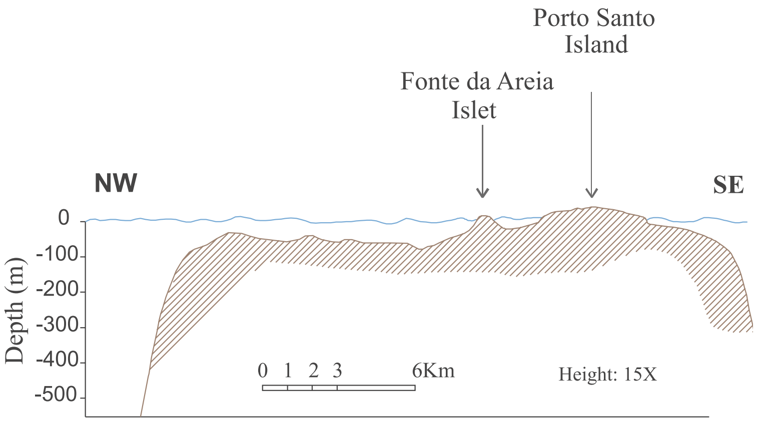


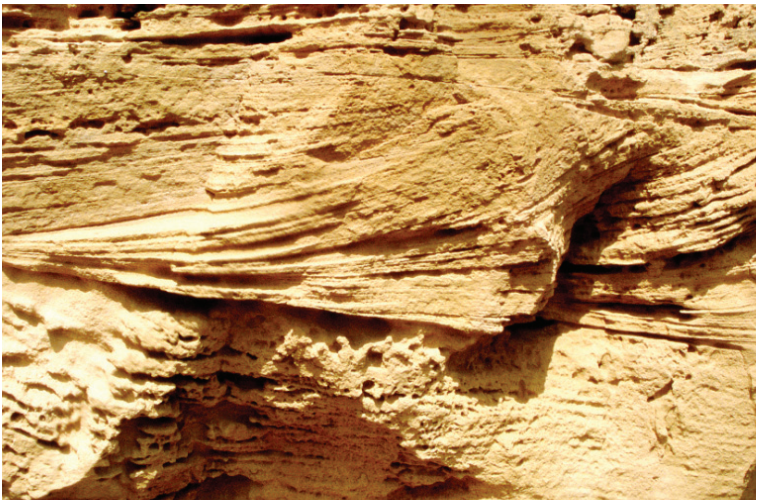
Fig. 6 – Schematic section showing the morphology of the submerged part of the island of Porto Santo and its vast platform between -50 and -100m, mainly developed in the Northern part of the island due to the predominant N winds.

Photos 10 and 11 – Geomorphological features of the Island of Porto Santo: flattened central region (above) covered by sand deposits, and the imposing Pico do Castelo (below), one of the hills of the Northern region.

The strong erosion is responsible for the major marine abrasion platform (between 50 and 100m depth) that surrounds the island and the islets that surround it – Ilhéu de Baixo or Ilhéu da Cal, Ilhéu de Cima and Ilhéu de Ferro, the largest, and also the Ilhéu de Fora, Ilhéu das Cenouras, Ilhéu da Fonte de Areia and others (Figs. 5 and 6; Photos 14, 15).

The marine abrasion platform of Madeira is, proportionally, much smaller than the one at Porto Santo (Fig. 3).

Except on the Easthern part were a long white sand beach occurs, the Porto Santo coastline is relatively steep, with generally inaccessible cliffs, where visitors can see an entire network of dykes that profusely intersect the country rocks which are composed of pyroclastic and lava flow deposits (Photos 16 and 17).



Photos 12 and 13 – In the Island of Porto Santo there is an extensive sedimentary cover, especially in its central region, often with a considerable thickness (above, Fonte da Areia) that overlies a level of altered volcanic tuffs. Below, a dune located south of Ribeira do Calhau (Porto dos Frades) shows oblique stratification, suggesting that the sands were transported from several directions.

Photos 14 and 15 – Aspects of the geomorphology of the Island of Porto Santo: above, a long white sand beach in the central region with the Ilhéu de Baixo or Ilhéu da Cal in the background; below, Ilhéu da Fonte da Areia emerging from the extensive marine abrasion platform that surrounds the Island of Porto Santo.

Photos 16 and 17 – Aspects of the coastal cliffs of the island of Porto Santo: Marinhas, on the West coast (left), and Morenos, on the Southwest coast (right).

4 GEOLOGY

A geologic map is a graphical representation of the distribution of the rock types, represented through a systematic and consistent criterion of age, their structures and other features, as interpreted by the authors. Additionally, the geological mapping of volcanic regions has some singularities, namely the presence of deposits without regional continuity, usually devoid of fossils for dating. This can be problematic for geologists, especially if they want to make regional correlations and do not have geochronological data (Photos 18, 19 and 20).

Among the various geological studies published regarding the islands of Madeira and Porto Santo, we highlight the geological maps, respectively by Zbyszewski *et al.*, 1974 (scale 1/50,000) and Ferreira & Neiva, 1996 (scale 1/25,000), because these publications were the starting point for all the works that followed. Among the latest studies, we point out the publications on the petrology of Madeira by J. Mata, or with his collaboration, between 1989 and 2006 that provide plentiful data on the mineralogical, geochemical, geochronological and isotopic composition of the igneous rocks of Madeira, and attempts to interpret its significance in petrologic and geodynamic terms. The geochronological data provided by this author helped to clarify the previous mapping carried out by Zbyszewski *et al.* (1974, 1975).

The geological map of the Island of Porto Santo was published in a more detailed scale, in which the stratigraphy is based on detailed geochronology and demonstrated through interpretative geological cross-sections. These cross-sections show lateral gradation of facies, gaps and overlaps, very difficult or even impossible to identify in volcanic regions where there are no geochronological data.

The geochronological data indicates that the oldest rocks of the Island of Porto Santo are from the lower Miocene, according to some authors (more than 19.3 million years old) or from the middle Miocene, according to others (more than 14 million years old). In Madeira, the oldest geochronological ages, known so far, do not exceed the 5.2 million years (lower Pliocene). Thus, despite some uncertainties regarding the ages of these islands, all authors acknowledge that the Island of Porto Santo preceded the island of Madeira by several million years (Fig. 7). The Desertas Islands, an extension to the southeast of Madeira, formed in a short episode during the evolution of this island.

This seems to indicate, as some authors have pointed out, a migration of the volcanism towards SSW, from the Island of Porto Santo to the Island of Madeira, between the Miocene and the Pliocene.

Photos 18 and 19 – The lava flows flowed through channels such as those observed, for example, in Paúl da Serra (above), and Ponta do Sol (below). These structures are distinguished because they show a large thickness variation from the centre towards their margins.

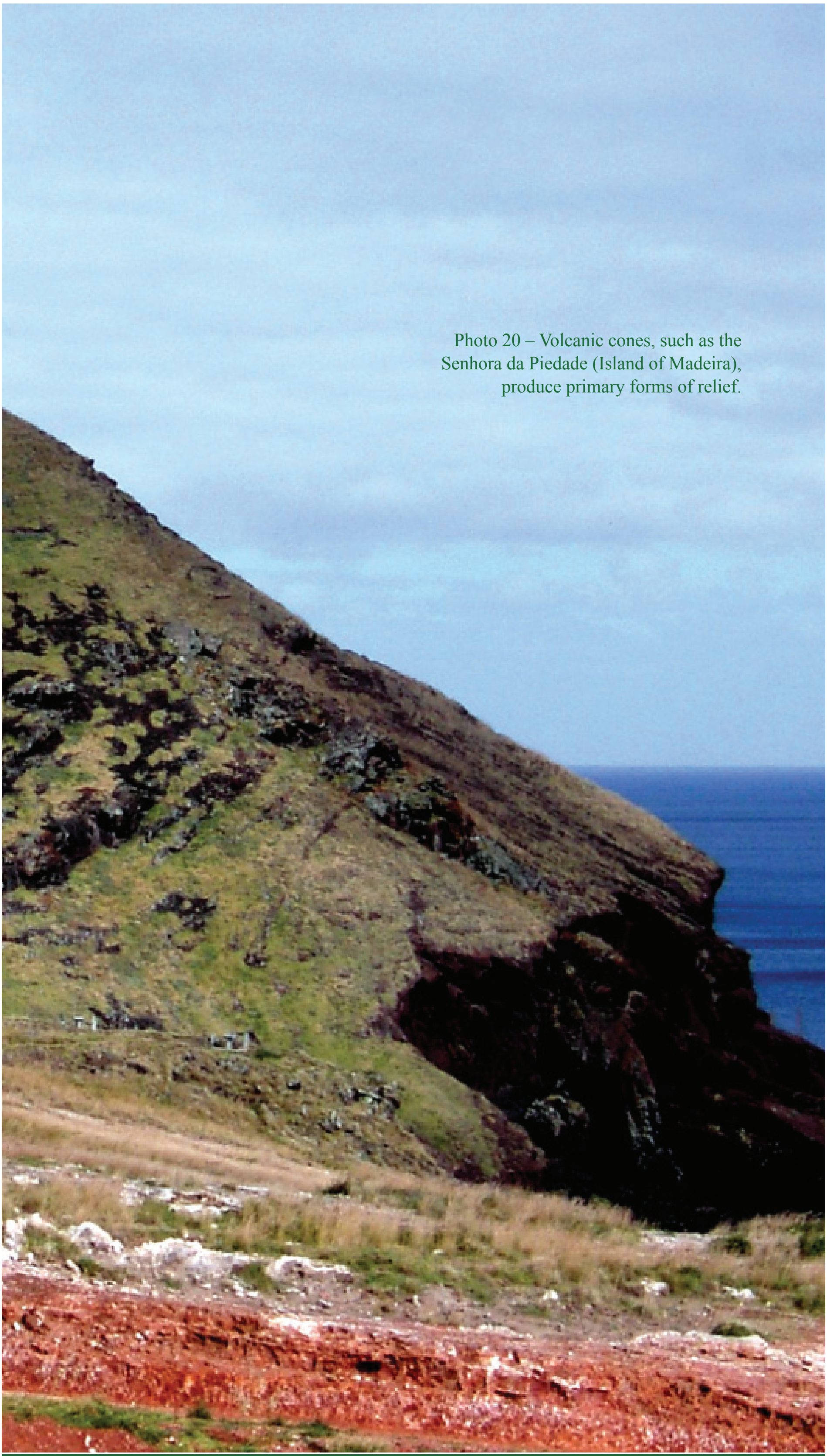
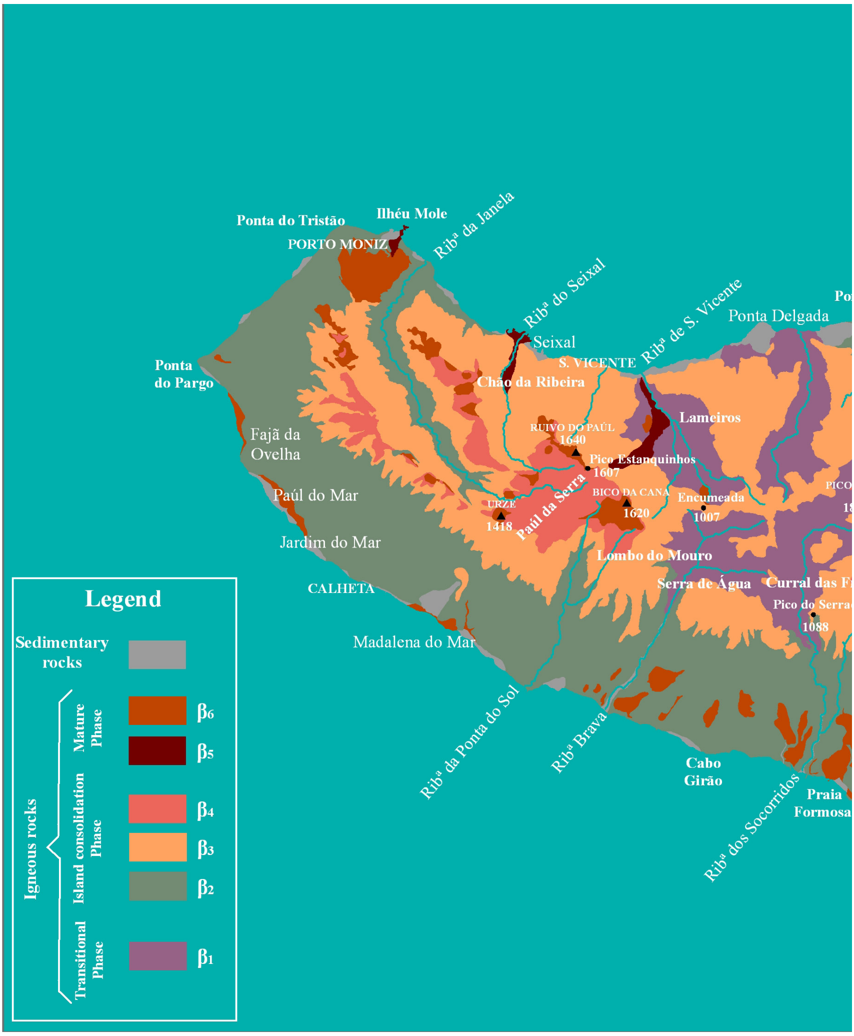


Photo 20 – Volcanic cones, such as the Senhora da Piedade (Island of Madeira), produce primary forms of relief.

EON	ERA	PERIOD	EPOCH	STAGE	GEOCHRONOLOGICAL AGE (MILLIONS OF YEARS)	SYNTHESIS OF THE GEOLOGICAL RECORD
PHANEROZOIC	CENOZOIC	QUATERNARY	HOLOCENE		0.0117	Madeira
			PLEISTOCENE	Upper	0.126	
				«Ionian»	0.781	
				Calabrian	1.806	
				Gelasian	2.588	
		NEOGGENE	PLIOCENE	Placencian	3.600	Desertas
				Zanclian	5.332	
			MIOCENE	Messinian	7.246	Porto Santo
				Tortonian	11.608	
				Serravallian	13.65	
				Langhian	15.97	
				Burdigalian	20.43	
				Aquitanian	23.03	

Fig. 7 – Comparative chronology of the volcanism on the islands of Madeira, Porto Santo and Desertas. Although this study is still in progress, there is a broad consensus regarding their relative ages: Porto Santo preceded Madeira whereas the Desertas islands were formed in a small time interval, during the formation of Madeira.



4.1 THE ISLAND OF MADEIRA

In the Island of Madeira, two main rock types crop out (Fig. 8) - the igneous, that can be called primary because they are directly linked to the volcanism that led to the island itself, and the sedimentary, which, although mostly associated with the erosion of the igneous, also have other origins – components transported by wind from the sea when the platform emerged, or, although very rare in Madeira but abundant in Porto Santo, corresponding to marine deposits with fossils, including corals.

In general, the distinction between these two rock types is relatively easy, except for some pyroclastic deposits and the sedimentary deposits correlated with them, either because they are derived from each other or because they are contemporaneous, often having components of both origins.

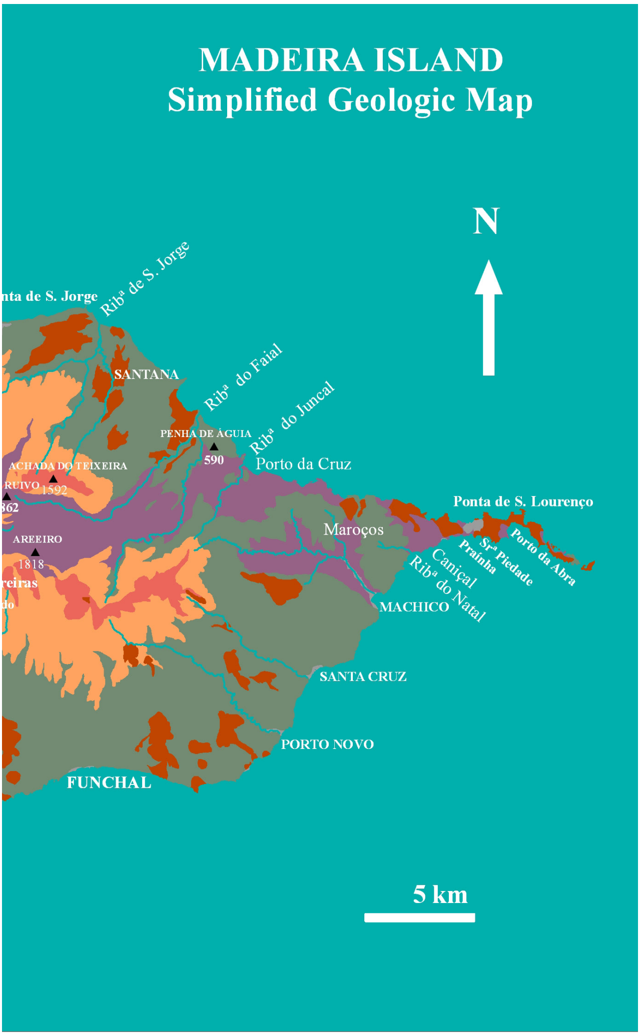


Fig. 8 – The igneous rocks of Island of Madeira are widely prevalent comparing with the sedimentary rocks.

SEDIMENTARY AND VOLCANIC - SEDIMENTARY ROCKS

The vast majority of sedimentary rocks correspond to the cover deposits that are scattered throughout the island, overlapping the earlier igneous materials, and correspond to slope, river and marine gravel deposits, beach sands, dunes, etc.

However, there are also deposits of mixed composition, containing gravel, and/or fine grained sediments, and fine-or coarse-grained volcanic components (Photos 21, 22). These deposits, wich sometimes contain fossils, are interlayered with pyroclastic levels of various sizes, or separating basaltic flow deposits. They have formed during periods of volcanic quietude, or in remote areas, away from the volcanic emission centres, being sourced from violent floods.

Photos 21 and 22 – Features of the deposits contemporaneous with the volcanism in the beach near Porto da Cruz; oblique stratification (left) and an example of the diversity of components included in pyroclastic rocks (right).

Photos 23 and 24 – Aspects of coarse-grained black sand in the mouth of Ribeira do Seixal.

Such deposits can be found in the valleys of Ribeira Brava, Ribeira da Fonte, Ribeira da Janela and Ribeira de São Bartolomeu and in Porto Moniz, in Ponta do Sol, Porto da Cruz, etc.

COVER DEPOSITS

These deposits correspond to colluvium, alluvium and aeolian deposits and consist mainly of gravel and sand that has accumulated at the base of the cliffs, in the stream courses and on the beaches, inlets of some creeks and in small coastal slopes (Photos 23 and 24).

The dismantling and collapse of the cliffs by erosion produces rock/debris falls that in coastal setting are named "fajãs" that consist mainly of boulders, gravel and other materials resultant from weathering of rocks (Photo 25).

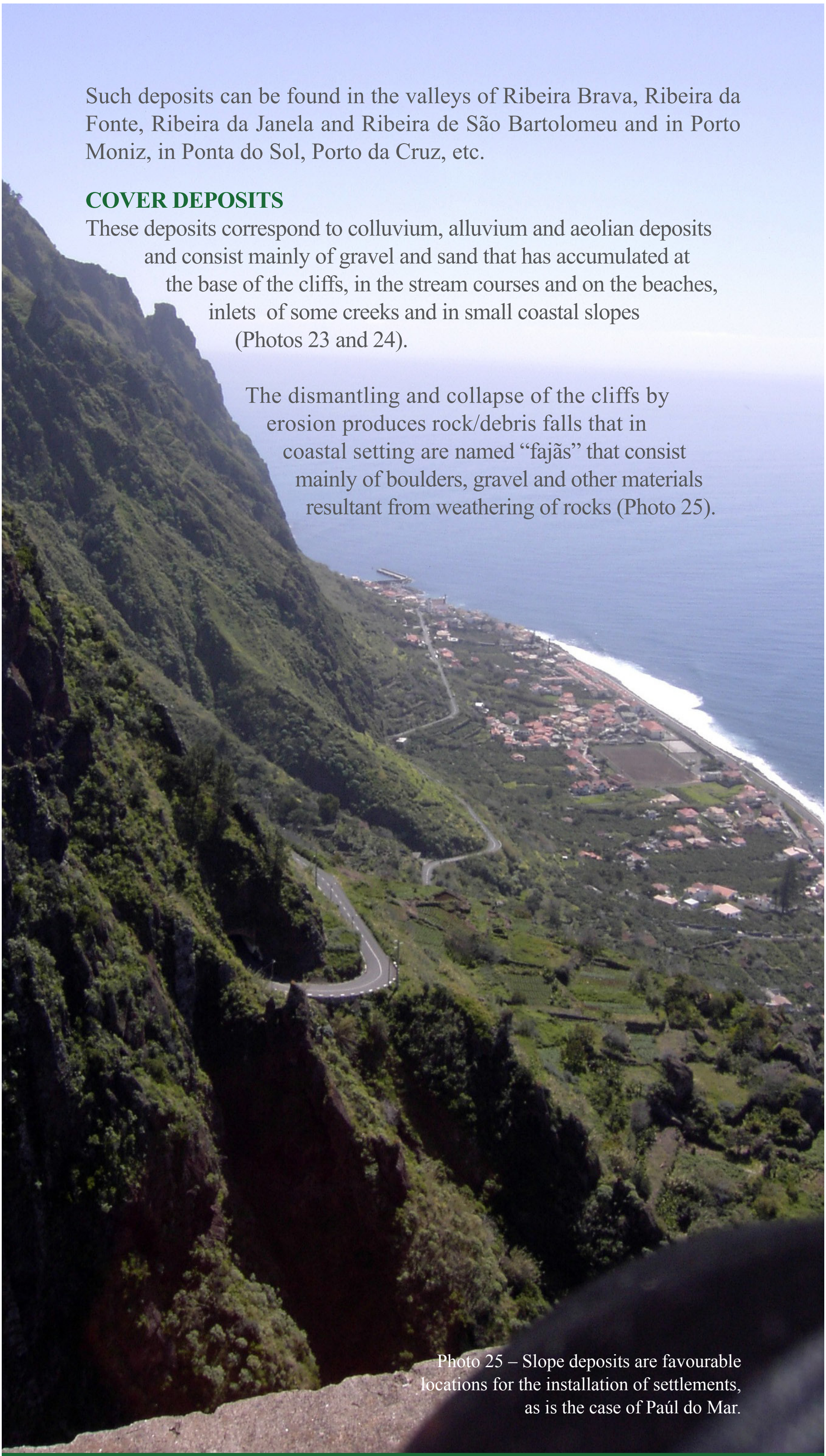


Photo 25 – Slope deposits are favourable locations for the installation of settlements, as is the case of Paúl do Mar.

Examples of these deposits are observed in: Fajã do Barro, Fajã das Contreiras, Fajã da Eira, Fajã Grande, Fajã dos Padres, etc..

In the Ribeira da Madalena, Ribeira Brava and Ribeira dos Socorridos valleys, in the Western part of the island, it is common to find torrential deposits with gravel and sand, whereas, for example, in Ribeira de S. Jorge, Ribeira do Faial and Machico, in the Eastern part, it is frequent to find alluvial deposits.

Gravel and beach sand deposits can be found in the river mouth of Ribeira de S. Vicente, Ribeira de Porto Novo and Ribeira Brava, and also in Paúl do Mar, Madalena do Mar, Câmara de Lobos, Praia Formosa, port of Funchal, Ponta dos Reis Magos and in the Santa Cruz, Caniçal and Porto da Cruz beaches.

Dunes are known in Ponta de S. Lourenço (Photo 26). These are supposed to have been formed at a time when the sea level was lower than the present level (during the Würm period the sea level was 130m below the present level). These deposits are mostly sandy with some clay intercalations, locally designated "branqueiros". They containing shell fragments of terrestrial molluscs and calcareous concretions in the form of petrified tree trunks and roots.

Fossiliferous limestones with coral fragments are known in the Eastern flank of Ribeira de S. Vicente and are associated with tuffs and agglomerates, interlayered in the regional igneous complex, that also contain various fossils (Photo 27). The geochronological dating of lavas that overlap these calcareous rocks, indicated a Pliocenic age. The intense exploitation of these deposits, for lime, led to their almost exhaustion.

An important fact to note is the altitude at which these limestone crop out (475m). It is well known that coral reefs form at sea level, therefore they were not formed at that altitude.

Photo 26 – Aspect of the consolidated dune in Prainha (Ponta de S. Lourenço), displaying calcareous crusts.

This means intense uplifting of the island after the Pliocene. If this uplift was 475m, or if it was combined with lowering of sea level, it is still a question to be answered.

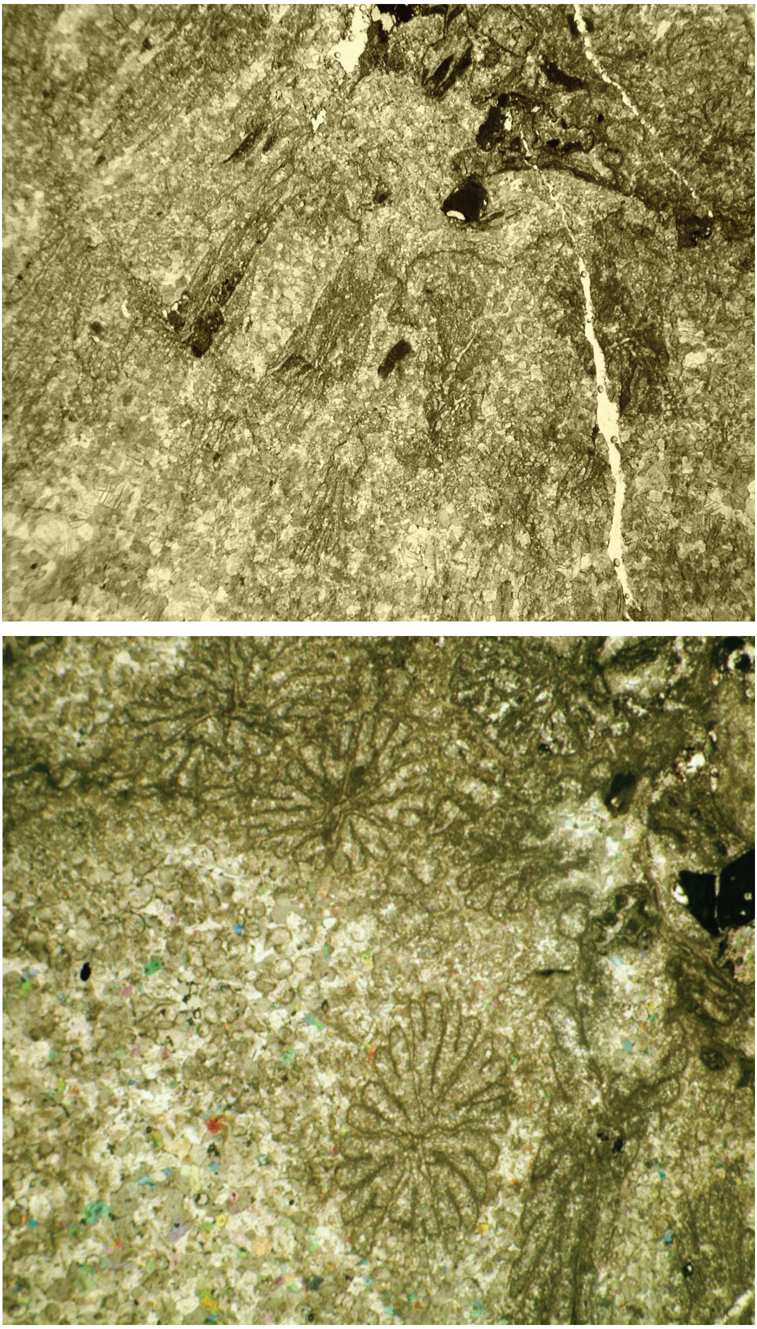
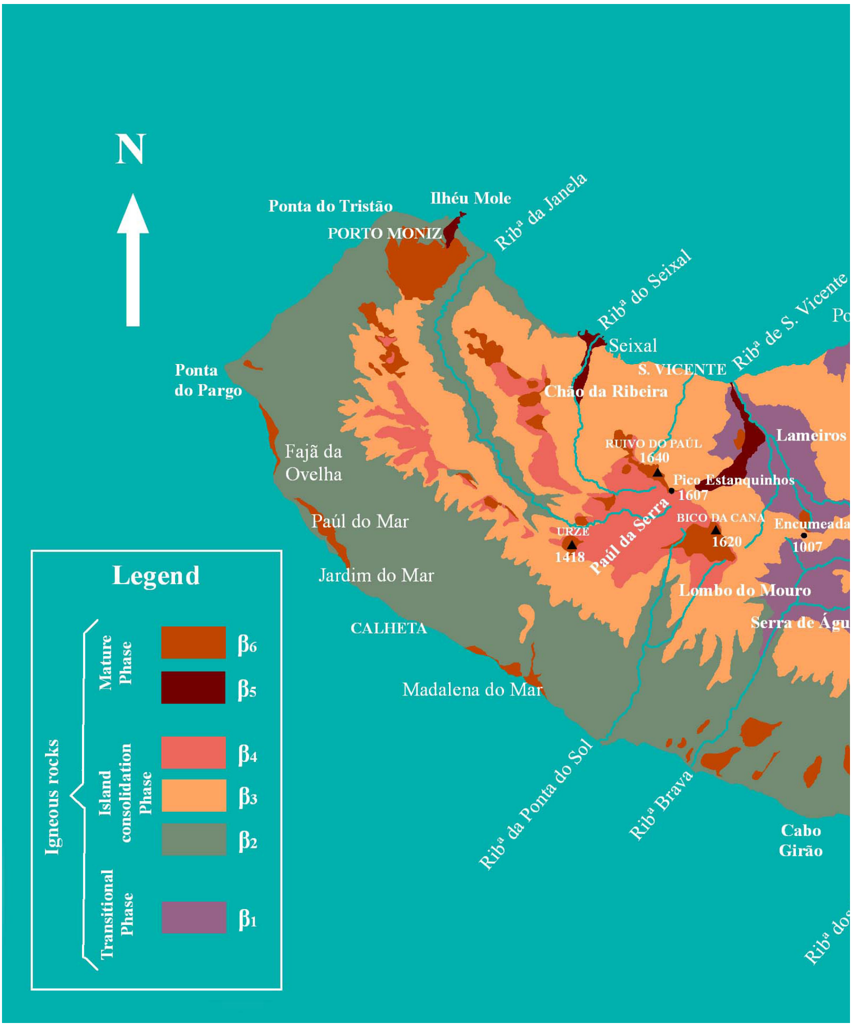


Photo 27 – Micrographic view of the reef limestones of Lameiros, S. Vicente (natural light, magnification 13X, approximately). Below, a cross-section of corals is visible.



IGNEOUS ROCKS

The vast majority of igneous rocks of Madeira correspond to volcanic products, although there are small outcrops of granular rocks (gabbros and monzo-gabbros with feldspathoids and essexites) proving the existence of fractional crystallization of small amounts of magmas inside the volcanic edifices. The largest outcrops of this rock types (not mapped at this scale), is located in the Porto da Cruz region, between Ribeira das Voltas and Ribeira de Massapez.

In general the constructional process of the Island of Madeira occurred in several stages. The main stages are represented in the geological map as volcanic complexes (β_1 to β_6) that consist of several lithologies (Fig. 9, see also digital terrain model Fig. 21).

The ages of the various mapped complexes have been determined by isotopic methods and are shown in Fig. 10.

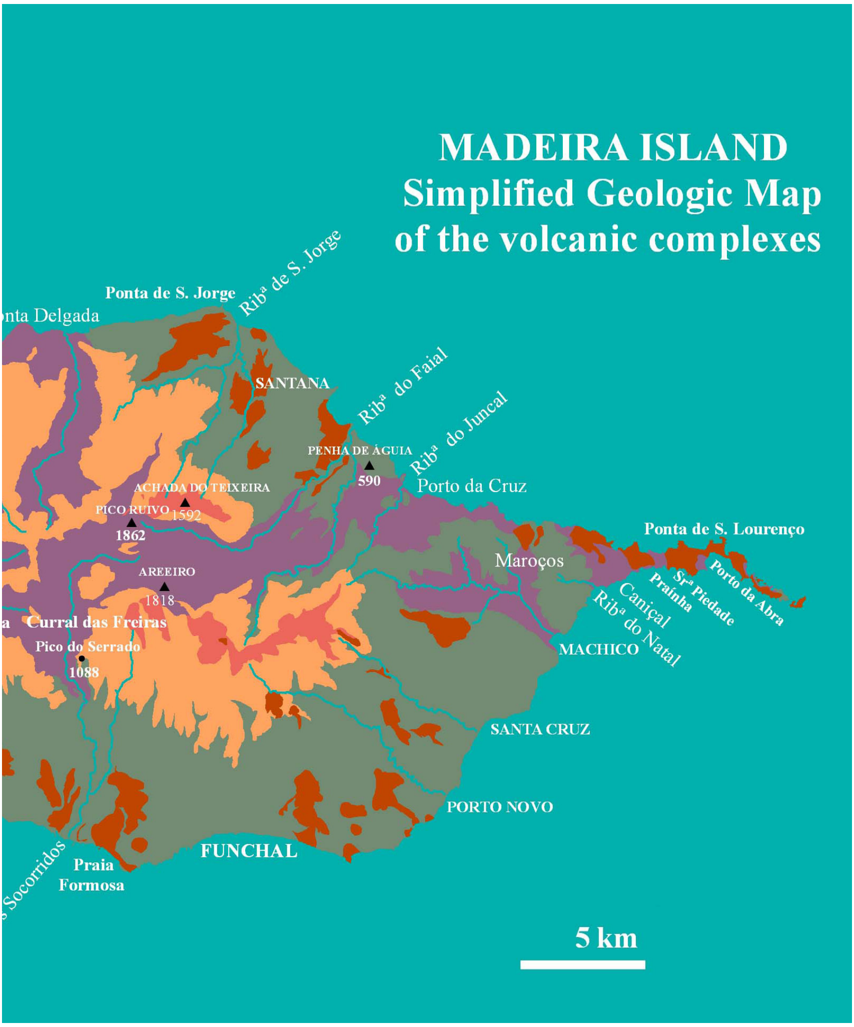


Fig. 9 – Volcanic complexes related to the different episodes of igneous activity in Madeira.

EPOCH	STAGE	AGE (Millions of years)	Madeira
HOLOCENE		0.0117	β 5,6
PLEISTOCENE	upper	0.126	
	Ion.	0.781	
	Cal.	1.806	β 2,3,4
	Gel.	2.588	
PLIOCENE	Plac.	3.600	β 1
	Zancl.	5.332	
MIOCENE			

Fig. 10 – Ages of the volcanic complexes of the Island of Madeira. β_1 is the oldest complex with an age of more than 2.5 My; β_2, β_3 and β_4 complexes have formed between 2.5 and 1 My; β_5 and β_6 complexes have an age of less than 1 My.

The geochronological results, summarized in Fig. 11, were determined in the Island of Madeira by several geologists. The locations where samples were collected are also shown in Fig. 11. As shown by the variability of ages, which is sometimes obtained in the same place, this method is not a universal solution to accurately determine the stratigraphy of the several mapped volcanic complexes.

The β_1 volcanic Complex is the oldest, with lithologies formed, probably, before the transition from the Miocene to the Pliocene age, as suggested by some fossils found in the interlayered reef limestones of Vale de S. Vicente (Photos 28, 29, 30 and 31).

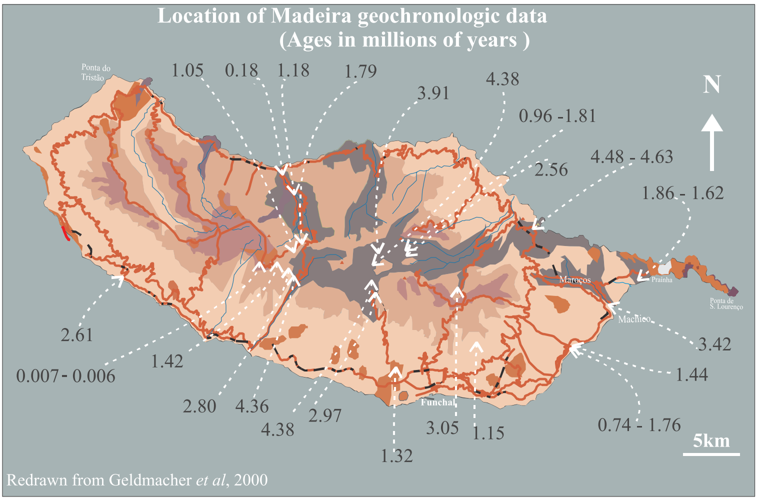
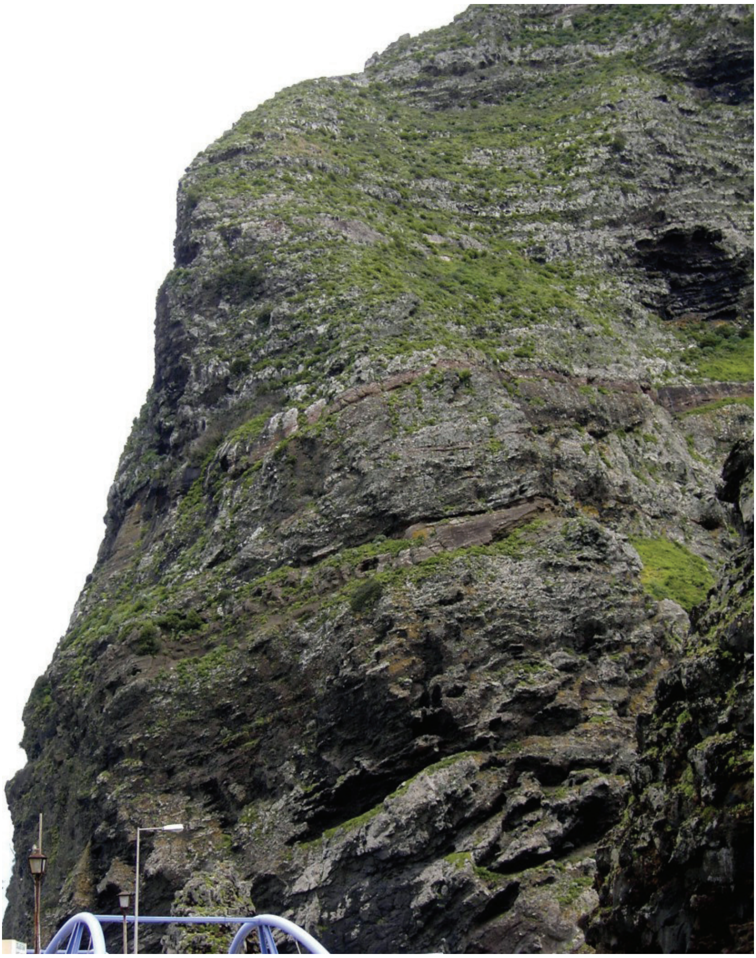


Fig. 11 – Summary of the geochronological data of Madeira (the main roads are in red to facilitate their locations) (see also Fig. 9).

This complex crops out in the deep valleys of many streams that, from São Vicente to Machico, flow to the Northern and Eastern coasts of the island and also in the upstream parts of Ribeira Brava and Ribeira dos Socorridos (Fig. 9).

The β_1 volcanic Complex can also be observed, for example, in the region of Curral das Freiras extending in several directions. It is mainly composed of coarse pyroclastic materials (with angular blocks, bombs, scoria, etc.), intercalated with some thin basaltic flows at the upper part, and is crosscutted by dense network of basic dykes.

The predominance of pyroclastic materials over the lava flows indicates that its origin is related to a particularly explosive phase of the island formation.



Photos 28 and 29 – Above, characteristics of the oldest Complex (β_1) on the cliff over the beach of Praia de S. Vicente and by the side of the road towards Pico do Areeiro (below).


Photos 30 and 31 – Chaotic pyroclastic materials in Complex β_1, between Caniçal and the mouth of Ribeira do Natal; intercalation of lava flows (on the left) and sedimentary intercalations (with a strong yellow colour) and a small open channel in the sediments (on the right).

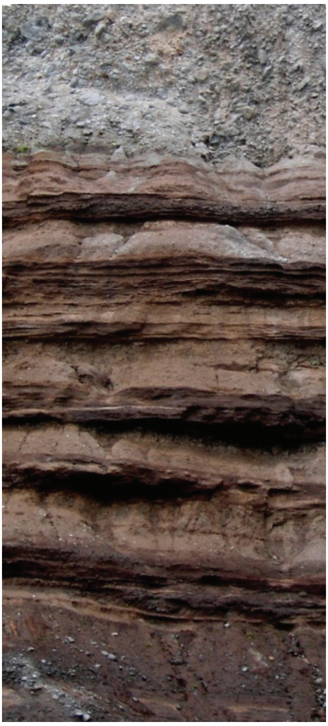
It is at the upper part of this complex, on the East bank of the Ribeira de S. Vicente, where one can find it interlayered with the fossiliferous marine limestone attributed to the lower Pliocene period, in the transition to the Miocene.

The β_2 Complex consists of lava flows intercalated with pyroclastic levels which become thinner away from their emission centres. Small outcrops of coarse pyroclastic rocks, show angular blocks that can reach 1m in diameter and occur at the highest peaks of the island - Areeiro and Ruivo. However, unlike in the previous complex, the β_2 lava flows are much more abundant, forming essentially stacks of lava flows interlayered with pyroclastic levels (Photos 32-35).

Vertical and parallel dykes of basic rocks intersect these deposits in several places. This complex crops out throughout the island, with minor exceptions in the Northern coastline, being the complex that has the largest exposure area (Fig. 9).

Photos 32 and 33 – Complex β_2 in Porto Novo (above) and in Maroços, showing spectacular columnar joints (below).

The β_3 Complex overlaps the previous, occupying a reasonable exposure surface, and is intersected by the large streams (Ribeira da Janela, Ribeira do Seixal, Ribeira de São Vincente, Ribeira do Porco, Ribeira do Faial, Ribeira dos Socorridos, Ribeira Brava and Ribeira da Ponta do Sol) that leave some isolated outcrops (Fig. 9). This complex corresponds to a sequence of basaltic lava flows and pyroclastic materials (Photos 36 and 37).

Photos 34 and 35 – From Pico do Areeiro to Faial, in Cruzinhas, metric lava flows of Complex β_2 overlapping the oldest complex can be seen (left). On the right, a mugearitic lava flow in Porto da Cruz (1.5 My) overlies metric layers of sediments with fossil plants (overview on page 92).


Photos 36 and 37 – β_3 Complex in the region between Encumeada (left) and Lombo do Mouro (right), where the basaltic intercalations show prismatic disjunction.

The β_4 Complex overlies the previous ones and occupies a rather restricted area of exposure. It also consists of wide range of alternating lava flows and pyroclastic materials (Photos 38 and 39).

The predominance of lava flows over pyroclastic rocks in the β_2, β_3 and β_4 complexes indicates that during the period of formation of these complexes, the volcanic activity was mainly effusive.

Photos 38 and 39 – β_4 Complex. Above, an aspect of the lavas that overlap the sequence of Encumeada. In the lower part of this sequence, on the roadside to Paúl da Serra, an intercalation of reddish pyroclastic rocks is present. Below, aspect of the lavas with spheroidal disjunction on the creek bed of Paúl da Serra.

Complex β_5 is mainly visible as the lava flows of Porto Moniz and in the valleys of Ribeira de São Vicente and Ribeira do Seixal (Photo 40).

Complex β_6 corresponds to the latest volcanic events and is represented by scoria cones, pyroclastic rocks and volcanic plugs and dykes (Photos 41 and 42). Geochronological results provided ages as young as 6,000 years (Bico da Cana, in the Eastern tip of Paúl da Serra).

It is interesting to note that some of the flows of this Complex (and possibly also of β_5 Complex), had their surface cooled while their inside kept flowing, leading to the formation of lava tunnels. These are modestly inclined, extending for hundreds of meters and can be visited at the so-called “Grutas de São Vicente”. In other locations (e.g. Cavalum), the tunnels are steeply inclined and are impossible to visit.

Photo 40 – Aspect of the volcanic cone of Ilhéu Mole, partially destroyed by the sea, and the lavas of Porto Moniz.

Photos 41 and 42 – Pico do Rabaçal (above), in Paúl da Serra and the volcanic cone of Senhora da Piedade (below), in the region of São Lourenço, are considered some of the most recent of the island.

The limited extent of complexes β_5 and β_6 suggests that the intensity of volcanism reduced gradually.

Except for one very dubious case in which "lights" were reported in a part of the island during a seismic crisis in the eighteenth century, no volcanic event has occurred in Madeira in the last 6,000 years. One cannot say that there will be no recurrence, especially given that the period of recurrence of volcanism on the island has been estimated at 10,000 to 15,000 years. However, the gradual reduction of the quantities of ejected volcanic material and the low seismic activity recorded in the island favours the idea of volcanic quiescence.

The major lithological variations previously identified allow the definition of three important steps in the formation of the Island of Madeira:

1st – **TRANSITION PHASE:** essentially explosive, during the period of transition from seamount to island;

2nd – **ISLAND CONSOLIDATION PHASE:** essentially effusive;

3rd – **MATURE OR EROSION PHASE:** with only local and decreasing volcanism.

4.2 THE ISLAND OF PORTO SANTO

At the Island of Porto Santo two main rock types also crop out; the igneous rocks, mainly basalts, directly linked to the volcanic origin of the island itself, and sedimentary rocks (Fig. 12).

However, one can distinguish some differences in the lithologies of these two islands.

SEDIMENTARY ROCKS

Contrary to what happens in Madeira Island, these rocks cover a significant area of the island (about one-third), and include limestones with varied types of marine fossils (Photos 43 and 44).

The marine platform that developed around the island, from the Miocene to the end of the Würm glaciation, has played a key role in the formation of these deposits (Figs. 5 and 6). The water temperature and the composition of basaltic rocks, rich in calcium, were the main factors leading to the large development of benthic organisms with a carbonate shell or skeleton. These shells and skeletons accumulated at the base of the platform, driven by ocean currents, were fragmented and deposited in specific locations, along with

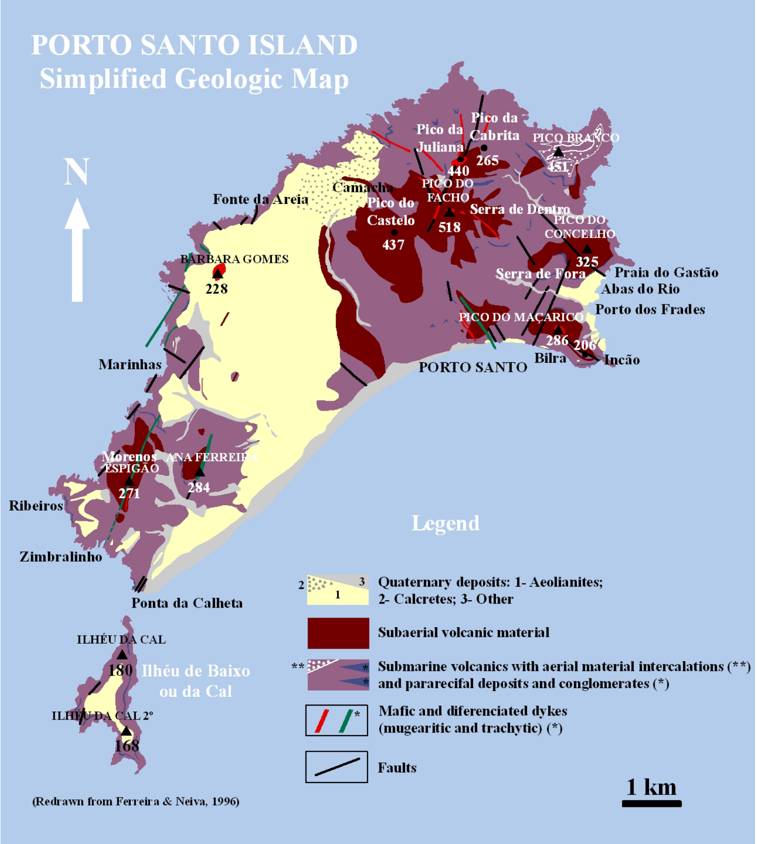


Fig. 12 – Schematic representation of the main geological units of the island of Porto Santo.

blocks of igneous rocks, forming breccias with limestone cement. On the other hand, erosion led to shell fragmentation, forming bioclastic sands. Finally, the wind, blowing mainly from the north, transported sediments to the sheltered regions of the onshore part of the island.

The sedimentary rocks include various types with a wide range of importance. The geological map illustrates the distribution of deposits contemporaneous with the submerged phase of the island - the fossiliferous limestone breccias and the sandy limestones and marls, as well as deposits from the Quaternary: calcarenite aeolianites (consolidated calcarenite dunes), sands from unconsolidated dunes, limestone crusts and beach, slope and alluvial deposits.

The age of the first two (estimated by the fossil content and by isotopic methods) is attributed to the Miocene. Their fossils correspond to organisms of warm and shallow waters and the sediments resulted mainly from the accumulation of the fragments of their skeletons. These

Photos 43 and 44 – Above, overall view showing dunes fitting into the valleys, extending a few tens of meters of the slopes of the volcanic peaks (mouth of Ribeira da Serra de Dentro). Below, lumachella with large bivalves embedded in basalts from Ponta da Calheta.

organisms lived in the vast underwater shelf surrounding the island, on the volcanic basement coastline or even in small reefs developed around the former coastline.

FOSSILIFEROUS LIMESTONE BRECCIAS

Fossiliferous limestone breccias (also named as pararecifal deposits due to their high coral contents) occur throughout the island in outcrops distributed along the same altitudes attached to volcanic rocks and were formed by the accumulation of detritic elements from those same rocks and bioclastic elements, with carbonate cement (Photos 45 and 46). These rocks contain large amounts of fossils, largely corals that can reach a significant size (decimetric).

Photos 45 and 46 – Fossiliferous limestone breccias. Above, in the region of Incão, a breccia deposit with coral fossils; below, limestone breccia with various types of shells and blocks of basalt in the region of Ribeiros (Morenos).

SANDY LIMESTONES AND MARLS

The sandy limestones and marls are very scarce and could not be represented at the studied scale. It should be noted, however, as the most significant, the outcrop of Ribeira da Serra de Dentro. It is located near the road, about 500m to the north of the village of Serra de Dentro. On this site, one can observe a 60m thick level of sandy limestones and yellowish marls, with fossils and spherical concretions of calcified algae (locally known as "laranjas", meaning oranges) (Photo 47), followed by levels of conglomerates, mudstones and conglomeratic limestones.

The levels of sandy limestones are fossiliferous, occurring, among others: corals, bivalves, gastropods, echinoderms, calcified algae (*Lithothamnium*) and also shark teeth.

Photo 47 – Calcarenites and limestones in the region of Ribeira da Serra de Dentro, displaying spherical concretions (locally named “laranjas”) and layers of thin laminites, related to the presence of algae; with a detail on the right.

DUNES

The **calcarenite dunes** (or “calcarenite aeolianites” for some authors) are sedimentary units that cover the largest area of the island. These comprise consolidated and unconsolidated dunes, being the latter partially composed of loose sand resultant from the disaggregation of the previous. The consolidation of dunes occurs by dissolution of calcium carbonate from the shells and its deposition in the spaces between grains, cementing these.

The **consolidated dunes** are present in several sites, such as the central zone, although the best places where its internal structures can be seen are the coastline outcrops, particularly in the North and South sectors of Porto dos Frades (Photos 48 and 49) and near Fonte de Areia (Photo 50). At the latter location, where the unit is 60m thick, the consolidated dunes show horizontal, intersecting or oblique stratification, as well as

Photos 48 and 49 – Aeolianites of Abas do Rio; dune erosion forming a small dejection cone (left), irregular shape modelled by wind erosion (right).

levels of soils that may have carbonate crusts, accumulations of shells (*Helix*) or remains of roots.

These soil levels evidence phases of interruption of the aeolian sedimentation and probably correspond to periods of wetter climate; interbedded levels of angular pebbles corroborate the existence of violent torrents during these periods of intense rainfall.

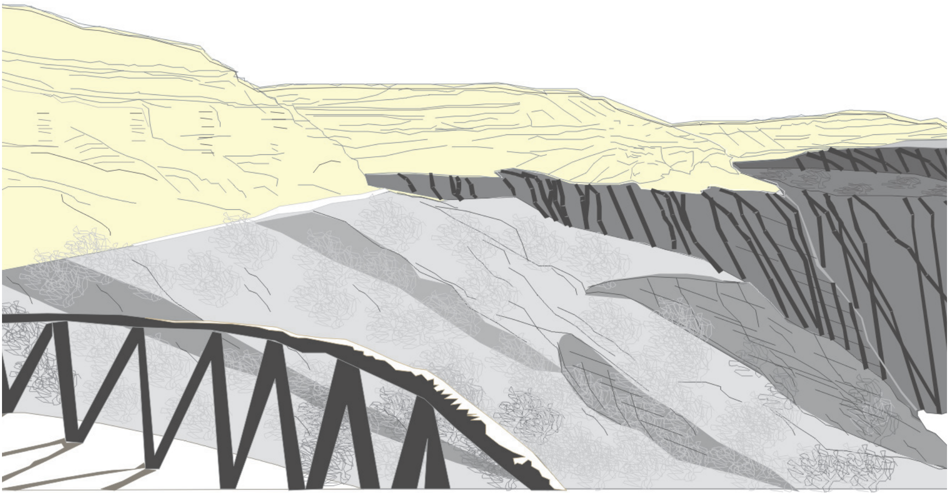


Photo 50 – In Fonte da Areia the contact of sandstones with the volcanic basement can be observed. Note the horizontal structure of the former (yellow) in contrast with the dense dyke network intersecting the latter pyroclasts (darker) (drawing on photography).

The **unconsolidated carbonate dunes** show calibrated fine to medium-grained sand, consisting of 80 to 90% of rounded shell fragments and 10 to 20% of minerals from volcanic rocks. The analysis of the surface of the sand grains show signs of wind transport when observed with the appropriate magnification.

LIMESTONE CRUSTS AND BEACH, SLOPE AND ALLUVIAL FAN DEPOSITS

Limestone crusts correspond to calcrete, formed by pedogenic processes similar to those described above for the consolidation of the dunes. They can be found throughout the island, and are particularly evident in many road outcrops. They are mostly found west and north of Camacha. However, they can also be observed north of the Ana Ferreira quarry and in the Northern bank of Ribeira da Serra de Fora.

The **beach deposits** resulted mainly from the accumulation of sand from the remobilization of the dunes that were transported by wind and rainwater. The 7km long sandy beach, from Ponta da Calheta to Porto

Santo, the largest of the archipelago, with fine and white sand is one of the attractions in the island.

The **slope deposits**, present mainly bellow the beach deposits, are composed of clusters of coarse-size materials, resulting from the dismantling of pyroclastic rocks, but may contain blocks of all types of volcanic and sedimentary rocks on the island, even dune rocks and fossiliferous breccias.

Alluvial fan deposits are scarce and occur in the riverbeds of the streams, especially in the Southeastern part of the island.

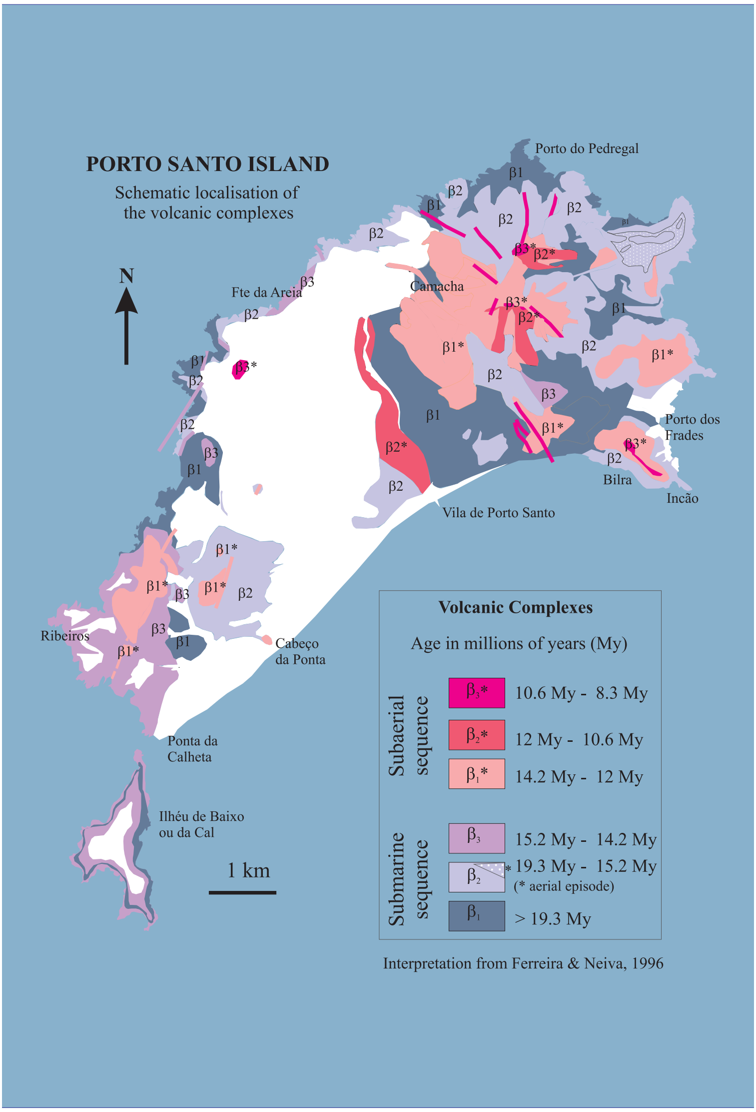


Fig. 13 – Schematic outcrop map of the volcanic complexes (submarine and subaerial) of the Island of Porto Santo. The sedimentary formations are shown in white.

Photos 51 and 52 – Features of the submarine sequences in the region of Calheta. Above, pyroclasts intersected by basaltic dykes of various ages, and in Praia do Gastão, below, contemporaneous, concordant, decimetre-thick pyroclasts and lava flows.

IGNEOUS ROCKS

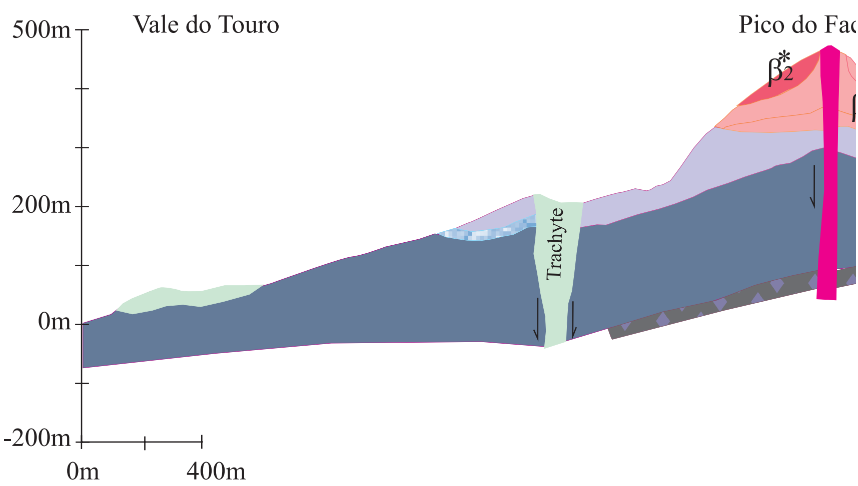
The igneous rocks constitute two major sequences that correspond to the submarine and subaerial phases of the evolution of the island, respectively (Figs. 12 and 13).

The first sequence includes the oldest rocks (more than 14.2 million years) and, the second, youngest sequence, includes rocks with about 8.3 million years (Figs. 12 and 13).

The **SUBMARINE SEQUENCE** comprises at least three distinct volcanic complexes, with basaltic and trachybasaltic flows interlayered with pyroclastites and hyaloclastites and other volcaniclastic deposits, which are associated with dome-flows and dykes of trachytes and trachyriolites (Fig. 14; Photos 51 and 52). One can observe the occurrence of pillow lavas, which indicate submarine deposition, for example, in Ponta da Calheta and in Zimbralinho (Photo 53).

Photo 53 – Although rare, pillow lavas can be observed in the submarine sequences of Praia da Calheta and Zimbralinho. They have a zoned structure, intersected by radial cracks occupied by gastropods.

Geologic cross section, North - South (approximately) running through Pico do Facho and Pico da Juliana

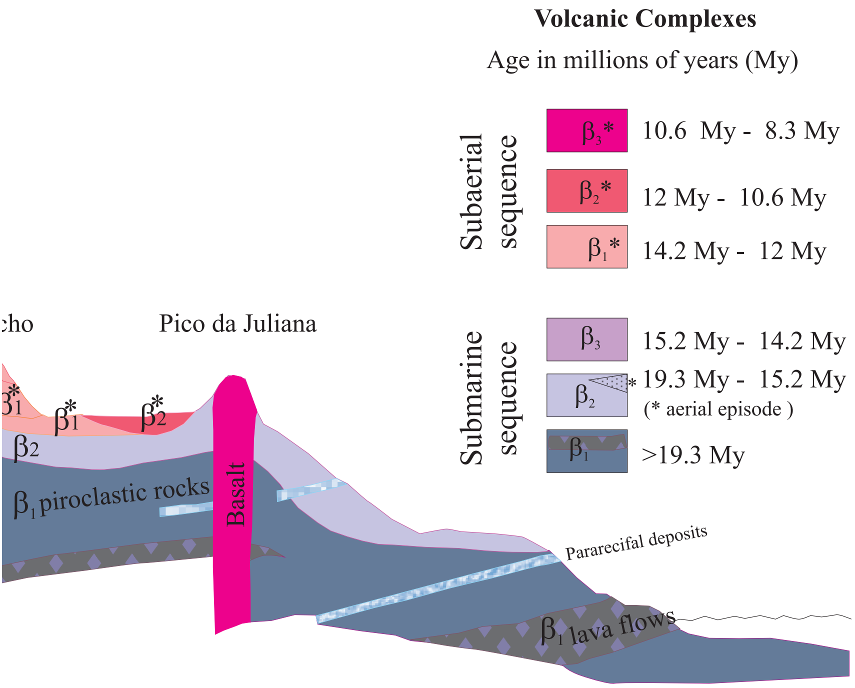


The different volcanic episodes are separated by intercalations of thin levels of pararecifal deposits, breccias with fragmented shells, conglomerates and other sediments.

The **AERIAL/SUBAERIAL SEQUENCE**, where three major volcanic complexes are distinguishable, contains basaltic clastolavas overlying subaerial basalts (Figs. 13 and 14). These intercalations are composed of trachytic rocks, in the form of domes and lava flows, mugearites and hawaiites. Trachyte and basalt dykes and basalt and gabbro plugs intersect the various lava flows (Photos 54 and 55).

In general, both sequences are observed in the Northern and Southern parts of the island. However, it is in the Northern part that the most ancient rocks crop out and a larger variety of lithotypes can be seen.

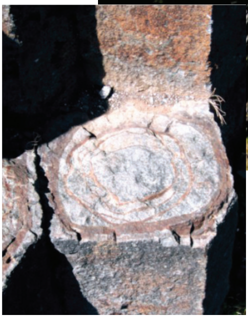
Some outcrops are noted for good exposure and great educational value. It is the case of the monumental column set of Pico de Ana Ferreira, on the Southern part of the island. There, exposed by the activity of an old quarry, one can observe giant hexagonal columns that resulted from the development of shrinkage surfaces during cooling and crystallization of the magmas (columnar jointing) (Photos 56 and 57).



Interpretation from Ferreira & Neiva, 1996

Fig. 14 – Geological cross-section showing the relationship between the eruptive complexes, intersected by volcanic chimneys (plugs), and respective pyroclastic cones.

Photos 54 and 55 – Subaerial sequences; trachytes of Pico de Baixo overlying sequences of lava flows and tuffs of various ages, in the Bilra region (on the left), basaltic scoria and pyroclasts, in Pico de Bárbara Gomes (on the right).



Photos 56 and 57 – The trachytic dyke of Pico de Ana Ferreira is noteworthy for its spectacular prismatic columns. The inset shows a detail of the “onion skin” alteration that can be observed within the basaltic prisms at the base of that structure.

5 MINERAL AND CHEMICAL CHARACTERISTICS OF THE LAVAS AND DYKES OF THE ARCHIPELAGO

Although the pyroclastic rocks are abundant, especially in the older complexes, the lava rocks are also significantly present in the islands of the Archipelago (Photo 58). In Madeira, there are not many rock types, with basalts, basanites and some mugearites as the most common. In Porto Santo, there is a large variety of rock types with occurrence of hawaiites, trachytes and trachyriolites in addition to the rock types identified in Madeira.

Photo 58 – Praia Formosa: metric intercalations of basaltic lava flows with scoria at the base, and thin layers of pyroclastic rocks at the base of the sequence (on the left); basaltic breccias (clasts smaller than 0.5m) (bottom right); lavas showing a vacuolar feature (upper right).

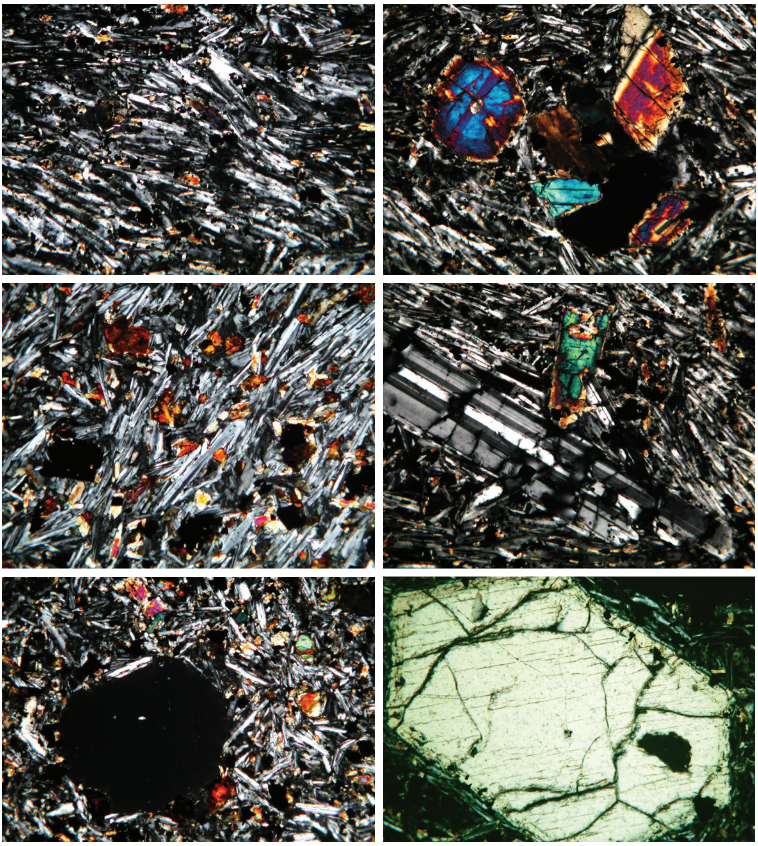


Photo 59 – Photomicrographs in polarized light (magnification 35X, approximately) of basaltic rocks. Above: microlitic texture with small elongated crystals of plagioclase (gray - black), with the same orientation of the lava flow (left), and clusters of olivine, pyroxene and oxides (right); Centre: the same texture but with much larger amount of oxides (black), olivine and pyroxene (various colours) (left) and phenocrysts of microlitic plagioclase (right) ; Bellow: vacuolar basalt (the rounded central black hole is a void left by gas loss) (left); clinopyroxene phenocryst (right).

The **BASALTS** are black or very dark, usually with very small grain size and often have vacuolar structures. Under the microscope, phenocrysts of olivine, pyroxene and plagioclase can be seen in a thinner matrix composed of the same minerals and also iron oxides (Photo 59). The percentages of these minerals can vary, producing the different types of basalts.

The **MUGEARITES AND TRACHYTES** (mostly present as dykes) are lighter, greyish or whitish, respectively. In the latter case, the plagioclase is more sodium-rich, olivine is very scarce or inexistent, and, replacing it, amphibole (brown hornblende) is present (Photo 60). Quartz is absent in most of the rocks from Madeira, though it may appear in some trachytes.

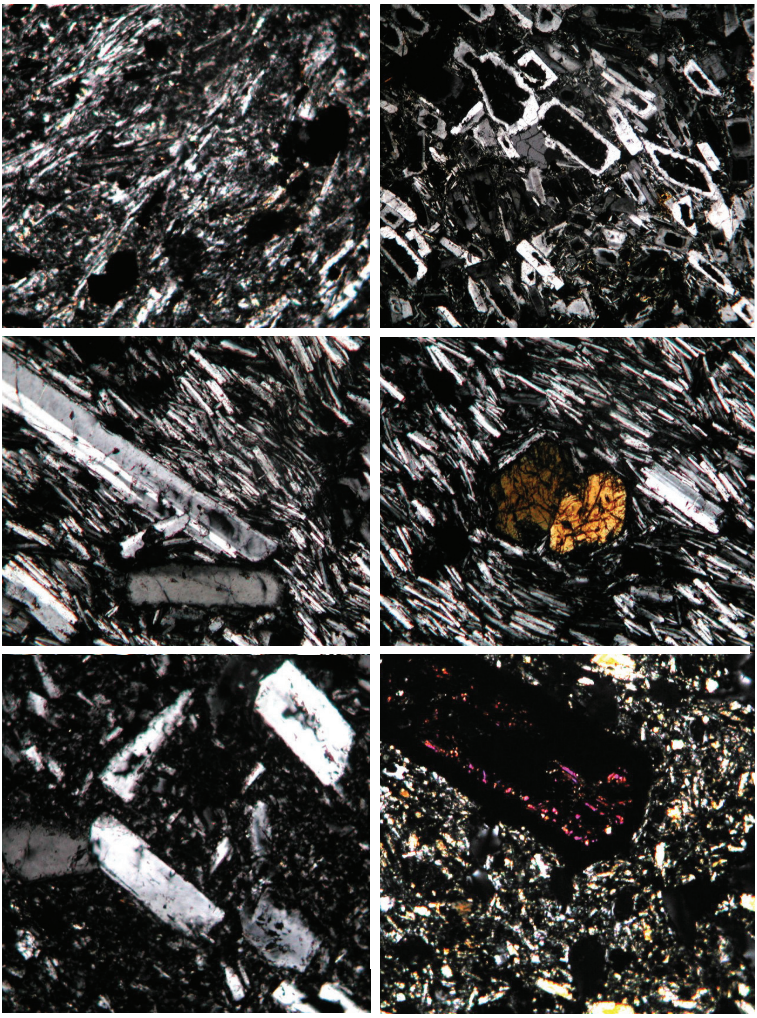


Photo 60 – Photomicrographs in polarized light of volcanites from Porto Santo, showing the typical mineralogy and textures. Above: trachyte of Fonte da Areia, with small elongated crystals of plagioclase ($\simeq$ 0.25mm) oriented as the lava flow (left), and trachyte of Pico de Baixo with zoned feldspar crystals ($\simeq$ 1mm) (right); Centre: trachyte from Pico da Cabrita, with porphyritic texture and microlitic matrix (feldspar $\leqslant$ 1mm), and brown amphibole (right); Bottom: trachyte of Pico da Cabrita with porphyritic texture and very fine matrix (feldspar $\leqslant$ 0.5mm) (left), and basalt from Pico de Bárbara Gomes, with porphyritic texture (the coloured crystal is pyroxene, $\simeq$ 1mm) (right).

The chemical composition of igneous rocks of Madeira can be part of the so-called alkaline sequences (enriched in alkalis compared to silica contents when compared with the other known sequences - tholeiitic and calc-alkaline). (The Canary Islands, St. Helena Island, the archipelagos of Cape Verde and São Tomé are examples of the same type of magmatism).

6 FORMATION OF OCEANIC ISLANDS

The comprehensive study of the geochemical signatures (major and trace elements and some isotopes) of the alkaline sequence of Madeira was done by J. Mata (1996). The mineralogical and geochemical studies performed by this specialist on volcanic islands from the Atlantic, indicate that the magma that has originated the Island of Madeira resulted from a mantle plume formed at a depth of about of 125km (within the asthenosphere). This mantle plume crossed the thick lithospheric mantle, becoming contaminated, before erupting on the seafloor, forming a seamount that evolved to the current oceanic island (Fig. 15).

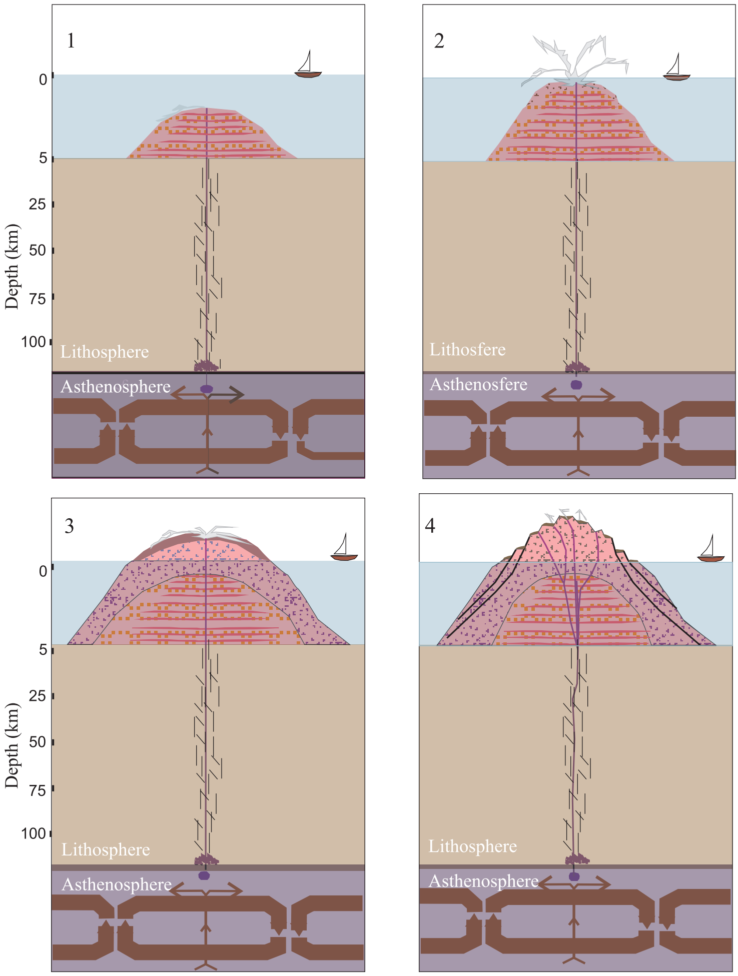


Fig. 15 – The emplacement of a mantle plume in today's location of the Island of Madeira led to the formation of the island. Of the main stages of the development of an oceanic island: 1 - submarine, 2 - transitional; 3 - subaerial/island consolidation phase; 4 - mature/rejuvenation, the last three are recorded in Madeira. The submarine stage (seamount) was only identified in Porto Santo (modified after Mata, 1996).

During the formation of an oceanic island by this process, there are usually several phases that are summarized below:

The **SUBMARINE PHASE** corresponds to the formation of a mountain (seamount) that grows on the ocean floor by the emission of molten rock from the mantle. In submarine settings pillow lavas are characteristic structures that form in the lava flows. At great depths the lavas have to overcome significant pressure to be emplaced and therefore, the pillow lavas are more flattened and elongated;

The **TRANSITION PHASE** occurs when the height of the water column above the seamount no longer exerts enough pressure to prevent the explosion of magma that reaches the sea floor. The eruptions can be explosive, forming large amounts of very heterogeneous pyroclastic materials;

The **ISLAND CONSOLIDATION PHASE** corresponds to periods of lava emission that alternate with explosive volcanic periods;

The **MATURE OR REJUVENATION PHASE** occurs after some volcanic quietude that is concomitant with erosion of the island and corresponds to late volcanic episodes and reactivation of earlier structures (Figs. 8, 9 and 11).

In **MADEIRA ISLAND**, the last three phases can be observed.

However, in **PORTO SANTO**, pillow lavas were identified, indicating effusive eruptions in submarine environment. Therefore, in this island all phases can be recognized.

If the final destiny of volcanic islands is the total erosion and subsequent disappearance, both islands still have many years to live, but it is not prudent to facilitate this process!

6.1 TECTONICS AND THE FORMATION OF THE ARCHIPELAGO

For the type of volcanoes which are believed to have existed in the archipelago of Madeira, the volcanic materials are expelled from the magma chamber, where magma accumulates, through a central conduit, and often through secondary conduits. The magma that does not reaches the surface forms dykes (Fig. 16).

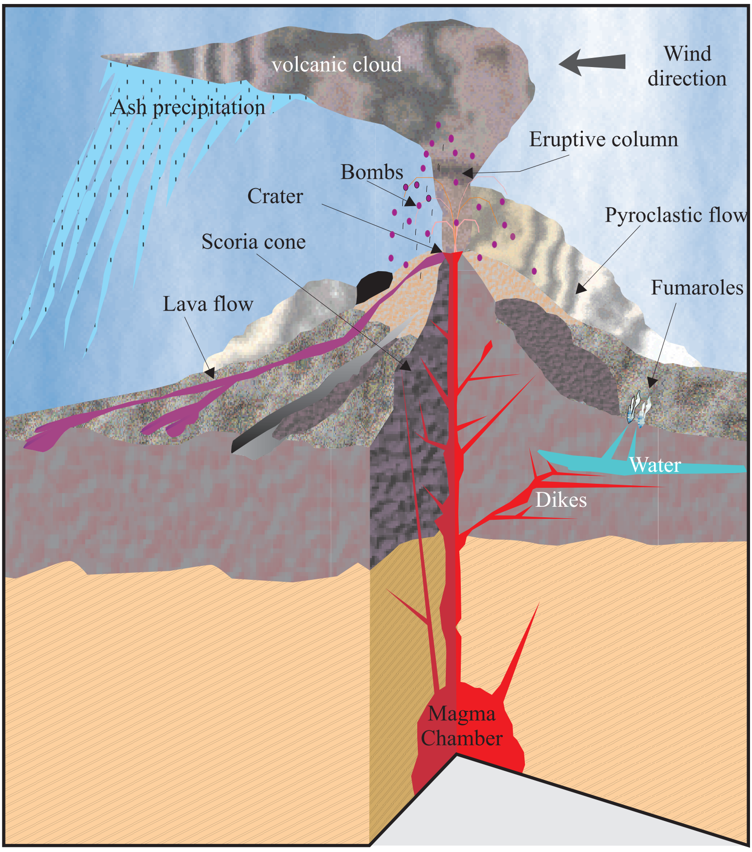


Fig. 16 – Schematic cross-section of a volcanic edifice with the identification of the different structures, types of materials erupted and associated rocks.

The volcanoes central conduit usually corresponds to the intersection of major lithospheric faults, to the intersection of a major fault with secondary faults, or even to the places, within these structures, where magma can escape. The conduits are successively activated by the rising magmas.

On the **ISLAND OF MADEIRA**, lineaments of dykes, late secondary volcanic cones, and major faults, roughly oriented E-W and NNE-SSW, have been identified by several authors, and control the main coastline orientation (Photos 61 and 62). However, there is considerable controversy regarding the role of these tectonic structures. Some authors believe they were crucial for the transport of magmas and consider them as the original structures that led to the appearance of the "hot spot". Other authors consider that these structures are due to extensional activity, possibly related to thermal relaxation and gravitational adjustments. Ponta de São Lourenço is a good place to observe some displaced dykes and pyroclastic layers by fault movements.

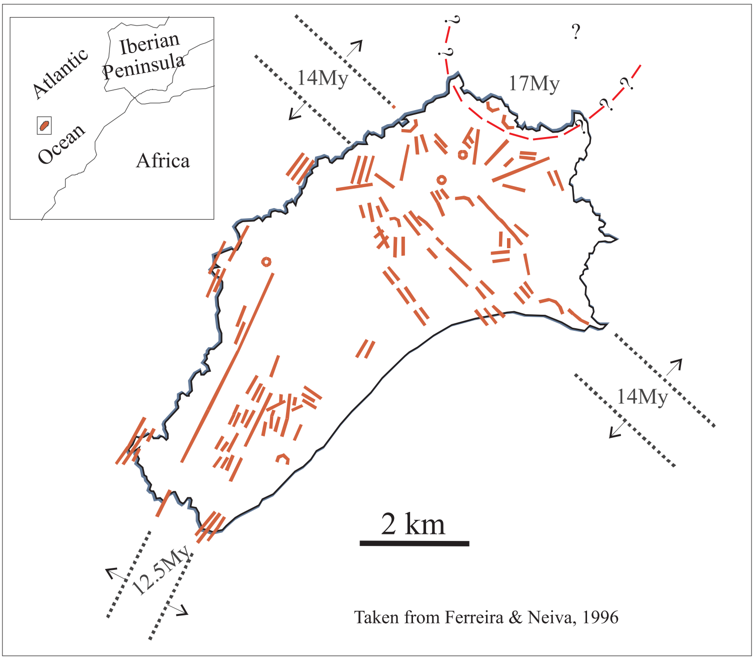


Fig. 17 – Sketch of the Island of Porto Santo, showing the major dyke alignments, plugs and calderas (in red) and the inferred tectonic movement in the time interval between 20 and 12.5 million years.

Regarding Porto Santo, various structures were observed, suggesting various tectonic movements (Fig. 17; Photo 63).

In the Northern part of the island, dykes with NW-SE direction are abundant, whereas in the southern part, the direction of the dykes is dominantly NNE-SSW. These observations and the geochronological ages obtained for the dykes, indicate that there was crustal extension orthogonal to those directions, respectively, at 14 and 12.5 My. Moreover, it is probable that a large crater was active at 17 My in the Northern part of the island (Fig. 17).

Although, there is still no full explanation for the formation of the mantle plumes, some models have been developed by geologists and geophysicists for the Madeira region.

The “hot spots” or mantle plumes correspond to phenomena within the Earth’s mantle that remains active for long periods of time, tens or hundreds of millions of years, in certain fixed locations of the mantle. Usually, they form lineaments or leave a trail of volcanic activity due to the motion of the overlying tectonic plates. Thus, if we measure the direction of the alignment of a hot spot from the oldest to the most recent volcano, we can say that the movement of the overlying tectonic plate was in the opposite direction.

Some geologists believe that the several parallel lineaments of volcanoes of the same type that exist in the Eastern Atlantic, where Madeira is located, began to form around 70 million years ago (Fig. 18). The lineament of volcanoes or of the products of their activity, according to these authors, would have started in Monchique (Algarve, Portugal) and extends along a succession of seamounts until it reaches Porto Santo and, finally, Madeira. These authors envisage a movement of the African Plate in the opposite direction (as mentioned above) with a rotation pole situated north of the Azores.

Moreover, magma ascent produces mecanichal stress towards the surface, often leading to the installation of rift structures (name usually given to a structure corresponding to an elongated depression). The most common of these structures are the triple rifts (with three branches disposed at 120° angle from each other). Geologists use these tectonic structures, observable at a regional and local scale - faults, fractures, alignments of dykes and volcanoes, etc., to infer the stresses that produced them and, thus, to understand the underlying geological phenomenon.

Although this model, envisaging a rift structure in the archipelago and the alignment of hot spots from the south of mainland Portugal to Madeira, may be interesting, it does not has the consensus of experts and even has many detractors.

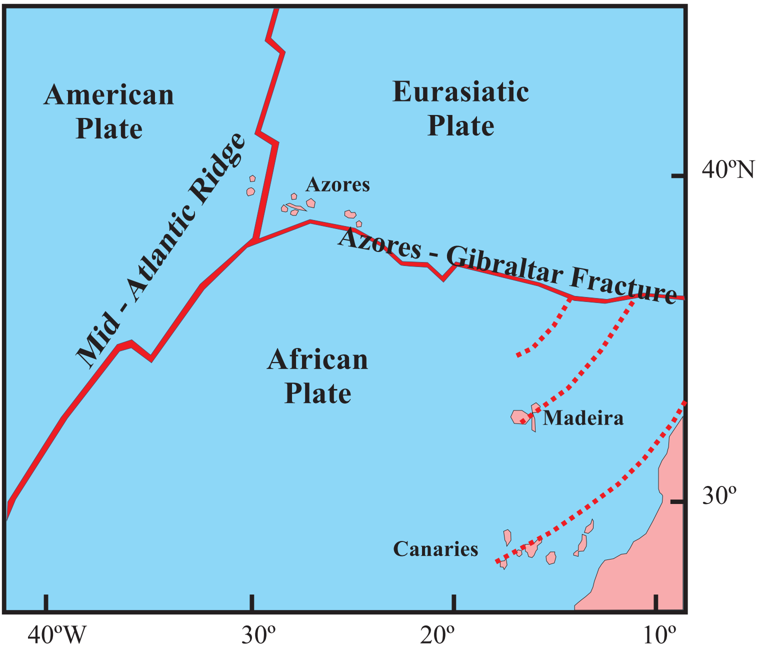
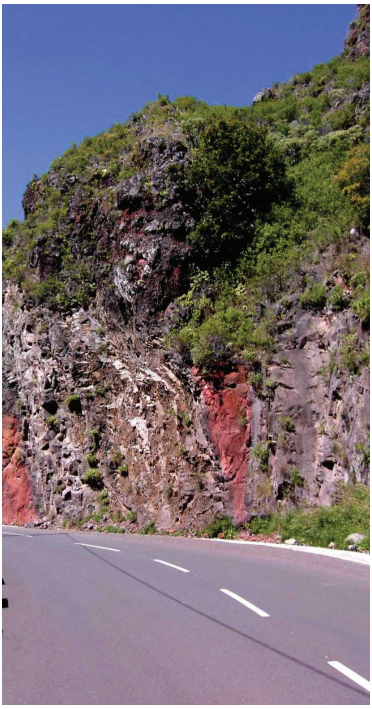


Fig. 18 – Is the Archipelago of Madeira the result of a "hot spot" below the African Plate that is moving to NNE?



Photos 61 and 62 – Left: deformed rocks in the vicinity of Fajã da Ovelha (Island of Madeira). Right: detail of the development of a planar structure in the Northern contact of the dyke (with lighter colours in the picture).

Photo 63 – Some structural features observed on the Island of Porto Santo suggest strong tectonic movements. In Ponta da Calheta, for example, the basalts were slightly curved and strongly laminated.

7 FEATURES OF ROCK ALTERATION AND OTHER SINGULARITIES

The alteration of volcanic rocks produces truly interesting aspects that often serve as artistic inspiration. Below, we include some images, and their locations.

Photo 64 – Alteration of basalts in the outcrops at the parking lot at the end of the road that leads to Ponta de S. Lourenço (Island of Madeira). The white material is calcium carbonate (calcium is relatively abundant in these rocks and, when altered in dry weather, is included in carbonates).

Photo 65 – Another feature of the alteration of basalts in Ponta de S. Lourenço (Island of Madeira). In these cases, some spheroid layering structures were preserved.

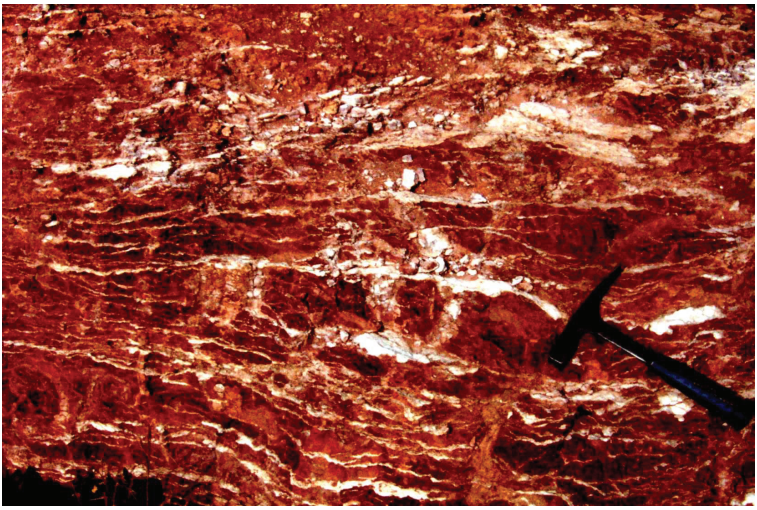


Photo 66 – Another type of structures related to alteration corresponds to the precipitation of calcium carbonate dissolved by rainwater in thin layers between the levels of pyroclastic rocks. Such features can be seen on either side of the road to Ponta de S. Lourenço (Island of Madeira) and in the roadsides of the Island of Porto Santo.

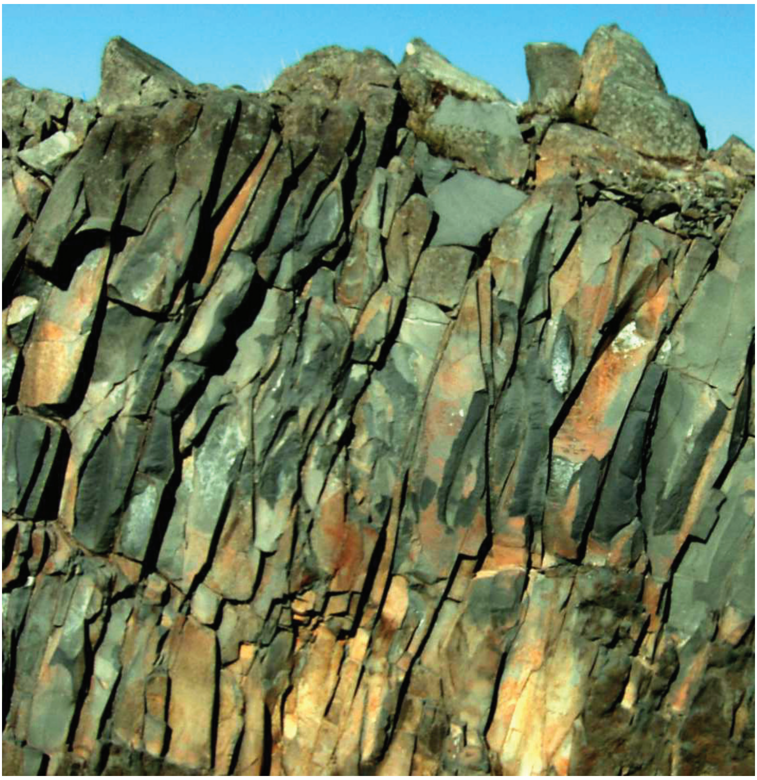


Photo 67 – Metric size basaltic dyke of Pico do Areeiro, which is strongly fractured and shows alteration clay minerals of various colours within its fractures (Island of Madeira).

Photo 68 – These interesting structures of organic substitution can be seen in Senhora da Piedade (Madeira). They correspond to fossils, probably of roots and stems, replaced by calcite. Above, view of a set of such structures, and, below, a detail.

Photo 69 – Prismatic columns in Maroços (Island of Madeira). Note the polygonal outline of the section of the columns. The alteration allows the growth of vegetation, which contributes with a magnificent colouration.

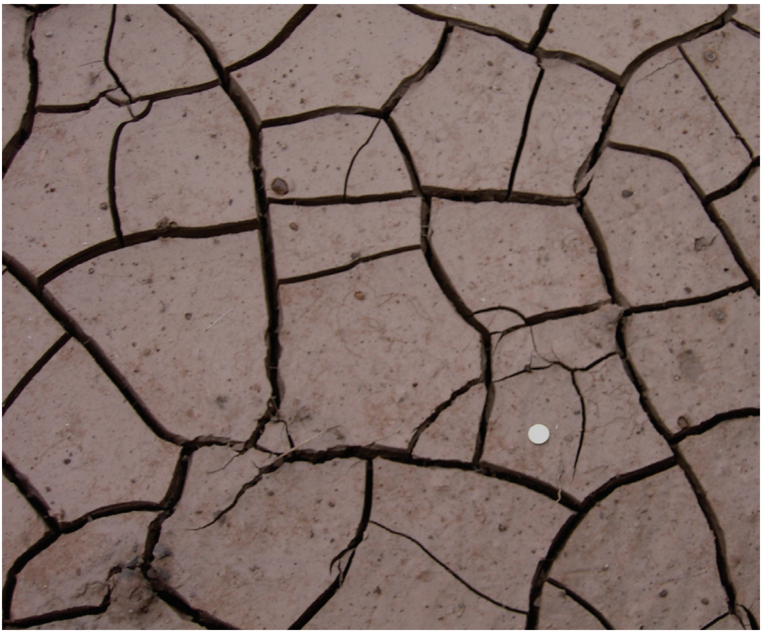


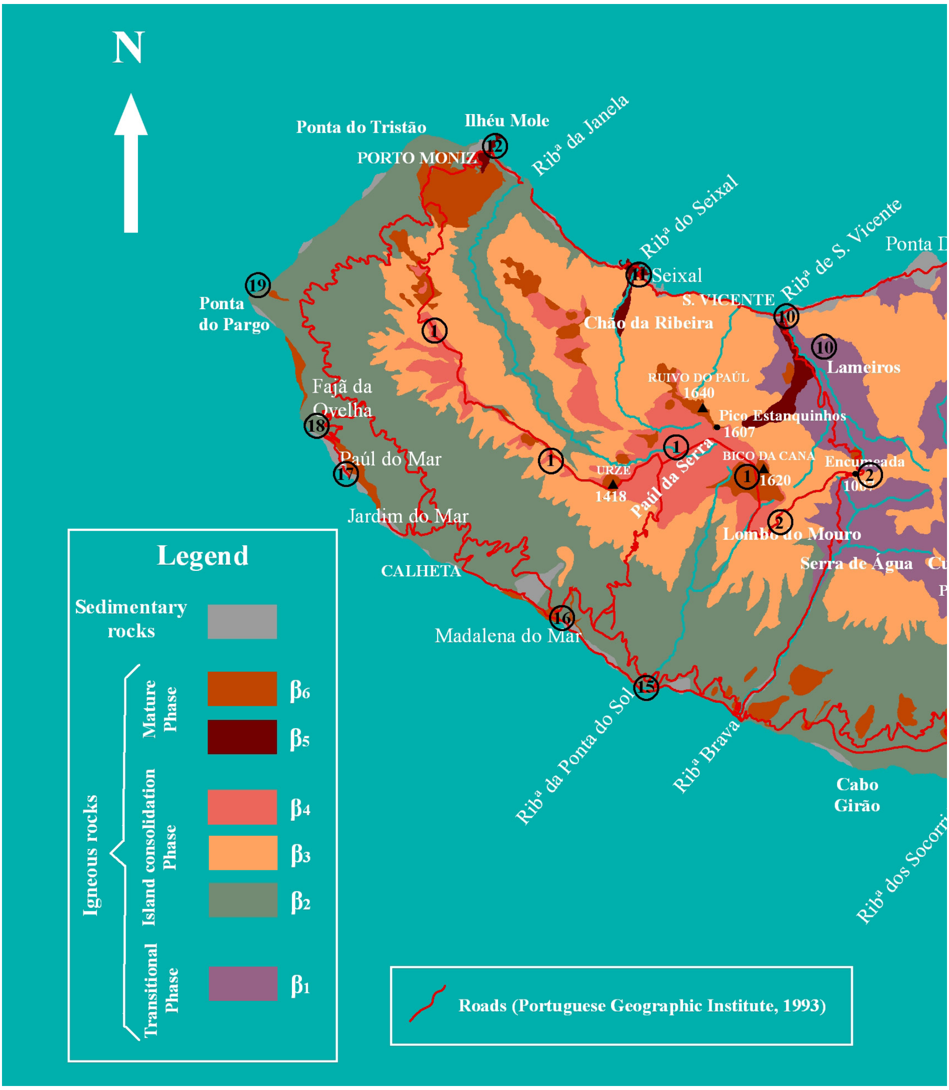
Photo 70 – Modern clay sediment (Porto da Cruz) with shrinkage cracks due to water loss by evaporation. Some authors argue that the columnar structures formed in the basalts result of a similar process, by shrinkage of the exposed surfaces during cooling.

Photo 71 – A curious fountain decorated with numerous replacement structures of roots and stems by calcium carbonate, often found in calcarenite dunes, can be seen in the region of Ribeiros, on the SW of the Island of Porto Santo.

8 MAIN SITES WITH GEO-TOURISTIC INTEREST

ISLAND OF MADEIRA

1 - Paúl da Serra – Paúl da Serra is a plateau, corresponding to an erosion surface formed due to the resistance to erosion of a lava flow which overlies rocks that are easily eroded by meteoric weathering. This spectacular surface is evident at altitudes of 1,400/1,500m, namely along the road which reaches Encumeada from S. Vicente or Ribeira Brava, and can be photographed from the road located on the left bank of Ribeira da Janela (Photo 1). On the road cuts along that same road, small channels that transported lava are visible (Photo 18). Along the bottom of small streams which flow on this plateau and along the road cuts, aspects of the erosion of the basaltic lava flows, such as spheroid layering, can be seen (Photos 38 and 39). From this plateau, small volcanic cones of the most



recent eruptions of the island emerge (the most recent was dated in Bico da Cana, providing an age of 6,000 years). Recently, geomorphological evidence has led some authors to infer the existence, during the Würm period (18,000 years ago), of persistent snow in certain places, namely in Paúl da Serra. Evidence of the previous existence of an ice amphitheatre and glacial moraines are described to the south of Fonte do Juncal, where large blocks of a prismatic basaltic lava flow were apparently removed from their original site by the combined effects of freezing-thawing of the surrounding rocks.

2 - Encumeada – This site is one of the most significant points of the morphology of the Island of Madeira. Here you can see how the retreats of Ribeira Brava and of Ribeira de S. Vicente, the former running south and the latter running north, are very close to intersection, and thus, close to dividing the island into two parts. The Volcanic Complex β_3 that

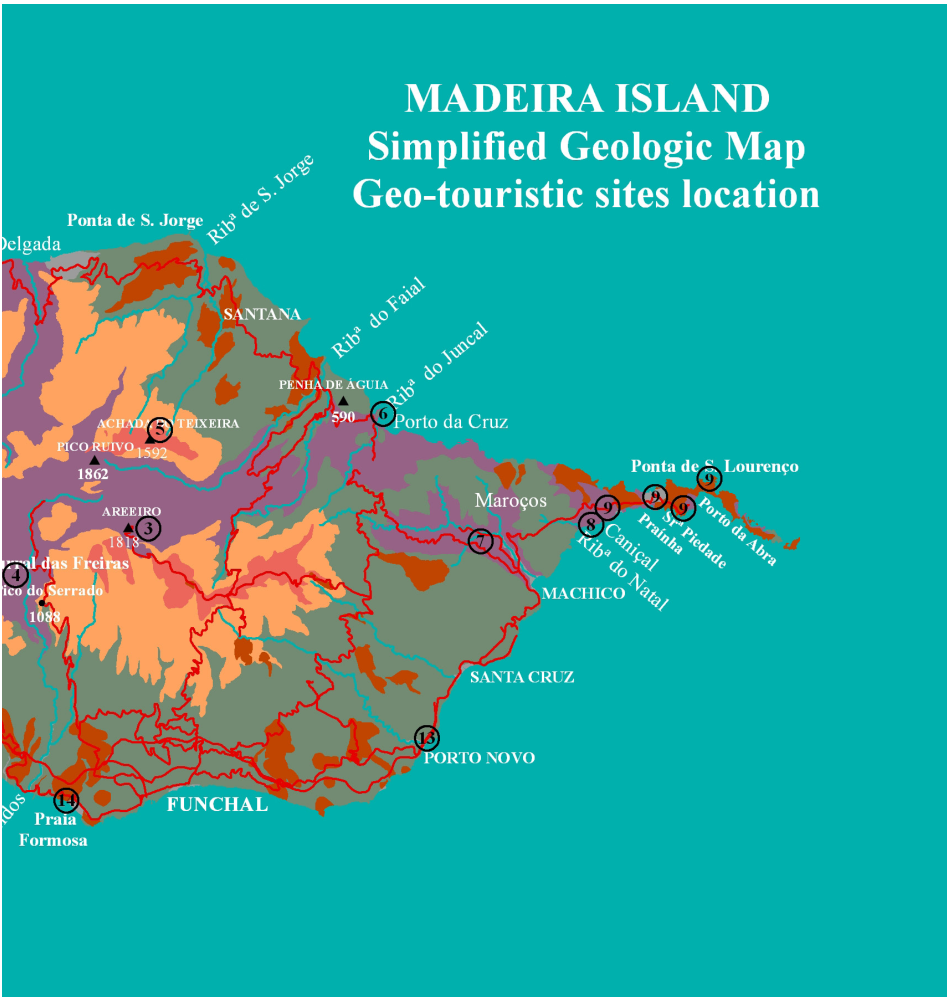


Fig. 19 - Rough localization of the main geo-touristic sites.

still outcrops in this region, has many intercalations of lava flows that overly and protect from erosion the underlying rocks, mainly pyroclasts of the basement Complex β_1. The weathering agents will have their work facilitated as soon as the more resistant layers of Complex β_3 have disappeared. Other points that are also displaying this process, although less accessible, are located, for example, in the region between Pico das Torrinhas and Pico das Eirinhas, in the headwaters of the creeks Ribeira de Urzal and Ribeira dos Socorridos. Moreover, in the same region, as soon as you start to go up to Paúl da Serra, immediately by the side of the road, is an old quarry in basaltic rocks with beautiful columnar jointing (Photo 36). Following the same road to Paúl da Serra, in the region of Lombo do Mouro, you will have a rough idea of the nature of the volcanic Complex β_3 and of the persistence of the lava flows in relation to their pyroclastic intercalations that are easier to erode. These are less noted in the landscape (Photo 37).

3 - Pico do Areeiro – Pico do Areeiro, at a height of 1,818m, is a very important tourist attraction, accessible year round. Here you can observe the nature and structure of the oldest volcanic complex in the island (Photos 2 and 29). This complex consists mainly of pyroclastic rocks with intercalated lava flows, intersected by a dense network of basaltic dykes. These dykes, with variable directions and dips intersect each other (Photo 2) and offer very good resistance to the erosion of the older volcanic complex of this region. In the parking lot, near the access to the trigonometric beacon, one can see a basaltic dyke whose fractures show very interesting clay alteration (Photo 67).

4 - Curral das Freiras – Curral das Freiras is a vast depression that resulted from the intense erosion of pyroclastic rocks of the older volcanic complex that outcropped in the region. These rocks, being more fragile than the surrounding rocks, were easily eroded providing the current depression. The best place to observe this morphological structure is from the Eira do Serrado (Photo 3). The huge depression of Curral das Freiras, with its special geomorphological configuration of steep slopes (approximately 300m) has led some authors to consider the hypothesis of it being a volcanic caldera. Today, however, it is known that these deep depressions are only a consequence of the strong differential erosion between the lavas and pyroclastic rocks that crop out there. Another significant depression of the same type is found in Serra da Água, uphill from Ribeira Brava.

5 - Achada do Teixeira – Known as “homem em pé” (standing man), corresponds to a metre thick basalt dyke which remains *in situ*, “stripped” of its host rock. It is outstanding because of its height and the extension of the outcrop (tens of meters). It is the result of the dykes’ greater resistance to erosion in comparison with the pyroclastic rocks which originally hosted it (Photo 4).

6 - Porto da Cruz – At this site one can see a variety of interesting geological features, the most well known are mugearitic lava flows, whose light colour contrasts with those of other volcanic rocks of the island of Madeira. These rocks outcrop on either side of the beach at the mouth of Ribeira do Juncal, in Rochão and Cães. On the latter, the mugearites cover sediments with oblique stratification and a diversity of lithic components (Photos 21, 22 and 35). Although rare, plant fossils were found in these sediments. The age indicated by geochronological dating of these mugearites is 1.5 million years.

In this site, at the base of the hill corresponding to Cães, one can observe modern clay sediments. These sediments generally show shrinkage cracks due to water loss by evaporation (Photo 70).

7 - Maroços – In Maroços (Machico), near the entrance to the new tunnel of Cales, a huge basalt outcrop displaying spectacular columnar jointing can be seen (Photos 33 and 69). These structures were developed, according to some authors, like the shrinkage cracks in the modern sediments of the previous site, as the result of the gradual cooling of the lavas that originated the basaltic rocks.

8 - Caniçal and mouth of Ribeira do Natal – The observation of the mouth of Ribeira do Natal in Caniçal, gives us an idea of the violence of the volcanic explosions during the transition from a submarine mountain to an island, as evidenced by the poorly calibrated nature of the deposits, sometimes with metric-size blocks (Photos 30 and 31). Such deposits are known as "lahar", an Indonesian term used to describe mixtures of rock fragments and water sliding down the slopes of volcanoes along the streams. When in motion, these mixtures correspond to a mass of clayish cement which carries blocks that can reach tens of meters in diameter. These mixtures move at high speeds and therefore represent a great danger for the inhabitants of the villages that are on their route.

9 - Ponta de S. Lourenço – This corresponds to a narrow peninsula extending from the Eastern Massif (Photo 5). On the Northern side, small islands, called "leixões", sometimes showing beautiful rocks with contrasting colours, are the evidence of the rapid erosion of ancient cliffs (Photo 9).

This entire peninsula, where the dry climate favours observation, has multiple sites of interest:

The small volcanic cone of Senhora da Piedade is a primary geomorphological feature from the most recent volcanic activity on the island. The building of the marina allows to observation of the inside of this cone with its central conduit (Photos 20 and 42).

Immediately to the west of the volcanic cone of Senhora da Piedade, very good examples of structures of organic replacement can be observed. These correspond to fossil roots and stems replaced by calcite (Photo 68).

The view from Porto da Abra, which is a large bay facing the SE, comprises splendid cliffs with various and colourful rocks (lavas and tuffs) intersected by several metric-thick dykes. Geologists find evidence of regional extensional tectonics.

A dune of thin and clear sand, consisting of large quantities of shell particles displaying oblique stratification, formed in the sheltered area of Prainha as the result of the accumulation of sand carried by sea winds (Photo 26).

Other interesting aspects relate to rock alteration visible due to the drier climate of this peninsula, when compared to the rest of the island. Outcrops near the parking lot at the end of the road that leads to Ponta de S. Lourenço display beautiful aspects of the so-called spheroid or “onion skin”. The whitish material is due to a higher concentration of calcium, a relatively abundant element in the country rocks and that during the process of alteration in dry weather, is included carbonates (Photos 64 and 65). Other type of structures related to alteration can be observed, for example, on the road to Ponta de S. Lourenço and correspond to the precipitation of calcium carbonate, dissolved by rainwater, in layers between the pyroclastic deposits (Photo 66).

10 - São Vicente – The town of São Vicente is located at the mouth of the creek with the same name. Upstream, this creek, reaches the area of Encumeada where it is very close to intersect Ribeira Brava, which flows in the opposite direction towards the South coast. It is interesting to observe the valleys of these two creeks close to their source and to feel that the erosion will inevitably lead to the division of the island into two parts, by the deepening of the two valleys.

Also, the caves and Centre of Volcanism of São Vincente constitute, by themselves, a reason to visit this town. Here, some lava tubes, left empty by the material that flowed through them, have been cleared to provide an interesting 700m underground pedestrian tour which highlights some aspects of the volcanism of Madeira.

Another geological feature to consider on this site is the great cliff adjacent to the beach of S. Vicente which gives an idea of the mainly pyroclastic nature, with lava intercalations, of the volcanic Complex β_1, the oldest of the island (Photo 28).

Finally, from the point of view of the geology of the Island of Madeira, there is also another point of great interest in the vicinity of this town. It is a metric, severely degraded, outcrop - the reef limestones of Lameiros (Photo 27).

This outcrop is part of an old quarry exploited for the production of lime. This limestone reef, which is currently at an altitude of 475m, represents an interesting problem concerning the development of the Island of Madeira and oceanic islands in general, because the reef structures were formed at sea, well below its current altitude. This means that the island endured a pronounced lifting after the Pliocene. However, the amplitude of this elevation, considering that there was a sea level retreat, is a problem that needs to be further studied.

11 - Seixal – At the beach of this village, situated at the mouth of creek with the same name, the structures and textures of the lava flows of complex β_5 can be seen. These flows reached the sea through the valley of that creek from an altitude of about 550m. These relatively recent lava flows (dating provided an age of 390,000 years) have scoria-type structures such as “Aa“ (Hawaiian expression that means “stony” or “that is burning”), characterized by irregular vesicular surfaces, resulting from the rapid loss of gases.

Near Seixal, the rapid retreat of coastal cliffs as the result of the strong sea erosion caused by the trade winds, led to the development of hanging valleys in very high cliffs. The best known example in the island - the “Véu da Noiva” waterfall - is located to the east of Seixal (Photo 8).

12 - Porto Moniz – In this town, as in Seixal, there is a lava flow (β_5) and the remains of a volcanic cone (Photo 40). The geochronological dating of this lava has given an age of 120,000 years, younger than the lava flow which was dated in Seixal. The view from the top of the road, when you arrive in Porto Moniz, is spectacular and allows the observation of the arrival of the lava flow to the sea. The same viscous scoria structures, visible in Seixal, can also be seen.

The small volcanic cone of Ilhéu Mole, near the coast, is, as its name implies (“mole” = soft), mainly made of pyroclastic rocks and contrasts with the lavas around them.

13 - Porto Novo – The banks of Ribeira de Porto Novo, near the mouth, allow a good observation of the lava flows of Complex β_2 (Photo 32).

14 - Praia Formosa – In this region, volcanic Complex β_2 was locally intersected by the youngest Complex β_6. The latter includes the volcanic cones of Pico de S. Martinho, Pico dos Barcelos, Ponta da Cruz, etc. A walk on the beach (Praia Formosa) allows geologists to observe the contacts between the two complexes. The less experienced, however, can observe on the slopes the lithologies of the most recent complex arranged in alternating layers of lava flows and pyroclasts, volcanic breccias, some vacuolar aspects of lava flows, and also the presence of scoria and volcanic breccias, formed and dragged while the lava was moving (Photo 58).

15 - Ponta do Sol – In this place, the cliff that includes the tunnel deserves some attention. It corresponds, in fact, to a large channel where lava flowed, as shown by the wide variation in thickness from the centre to the margins of the structure. It is also interesting that there is a incipient structure, roughly columnar and approximately vertical in the thicker part of the channel, which seems to indicate *in situ* residence of the lava in this area (Photo 19).

16 - Madalena do Mar – Here, two water lines converge and limit the beach. To the west one can see a beautiful coastal cliff carved into volcanic Complex β_2. It consists of an sucession of metric lavas and pyroclastic rocks, with a wide range of colours. Here, the lithological sucession of this complex is somewhat different than what we see, for example, in Porto Novo, where the basaltic lava flows are thicker and more frequent.

17 e 18 - Paúl do Mar e Fajã da Ovelha – On the road up from Paúl do Mar to Fajã da Ovelha, as soon as the altitude allows the watching in the opposite direction, it is worth stopping. The view to Paúl do Mar is spectacular (Photo 25). The huge cliff leaves no doubt about the dismantling and collapse with the consequent formation of slope deposits – fajãs – which provided good conditions for settlements to be established, as is the case of Paúl do Mar. Another interesting observation on this road is the outcrop of dykes displaying evidence of strong deformation (Photos 61 and 62).

19 - Ponta do Pargo – From the village of Ponta do Pargo there is a road that leads to the lighthouse. In this place, one gets a splendid view of the stunning straight coastal cliff, losing itself on the horizon (Photo 6). The small top with a trigonometric beacon corresponds to a small recent volcanic cone. There are also some slope deposits, for example, the Fajã Nova, immediately to the NE.

ISLAND OF PORTO SANTO

1 - Bilra - Incão – A stroll between the marina of Porto Santo to Ponta da Galé and to Porto dos Frades, along a newly opened road, provides a preliminary idea of the geology of the island of Porto Santo.

Starting from the marina, the visitor finds mainly pyroclastic deposits intercalated with basaltic lava flows from the volcanic complexes related to the submarine development of the island and some slope deposits. The latter consist of alteration products of volcanic rocks, particularly of the tuffs, which were transported by gravity and streams, and were accumulated at the base of the slopes. These often include blocks of volcanic rocks of various sizes and sometimes with intercalations of dune sands.

Looking at the landscape, towards the cliff, basalt lava flows and basalt and trachyte dykes belonging to the subaerial volcanic complexes stand

Fig. 20 – Location of the main geo-touristic sites.

out (Photo 54). Blocks from the dismantling of these structures can be observed along the slopes, some reaching the road that follows the base of the cliff.

Continuing the route, between Bilra and Incão, it is possible to observe the fossiliferous limestone breccias, also known as reef deposits. These rocks, which always occur associated with submarine volcanic complexes, constitute small and narrow outcrops dispersed throughout the island. They occur embedded in the volcanic substrate at specific altitudes, often in the form of breccias with carbonated cement, with elements of volcanic rocks and large amounts of fossils, either intact or broken, particularly corals which can occur in decimetric size blocks (Photo 45).

2 - Porto dos Frades – Continuing along the same path from Ponta da Galé to the mouth of Ribeira do Calhau (Porto dos Frades). In this site is interesting to observe the consolidated calcarenite dunes and the loose sands, the latter often forming dunes.

Here, the consolidated aeolian sands reach various altitudes and show horizontal, oblique or cross-bedded stratification (Photos 13, 48 and 49). The study of the internal stratification of fossil dunes allows the determination of the direction of winds in the past.

The consolidation of the dunes is due to the dissolution of calcium carbonate from the shell fragments by rainwater, which then precipitates and acts as a binding agent between the grains, even if many empty spaces remain, which increases the porosity of these rocks. This calcium carbonate can also form levels of calcareous crusts ("laginhas de cal"). In this site, near the mouth of the stream there is also a lime oven, confirming the use of these rocks as a geological resource in the past.

If we continue to walk north towards Praia do Gastão, one finds the rocks of the oldest volcanic complexes (submarine stage) with beautiful outcrops of pyroclastites interlayered with lava flows (Photo 52) and sometimes intersected by imposing basalt dykes.

3 - Ribeira da Serra de Dentro – This site is the best outcrop of sandy limestones and marls in the island of Porto Santo. It is located on the left margin of Ribeira da Serra de Dentro, along the road, about 500m N of the village of Serra de Dentro. In this site the layers dip approximately 30° to NW. They consist of a series of yellowish sandy limestones and marls with a thickness of a few tens of meters, and containing fossils and centimetric spheroid concretions of coralline algae ("laranjas" = oranges) followed by levels of conglomerates and clays and conglomeratic limestones. These levels of sandy limestones are fossiliferous, containing, among others: corals, bivalves, gastropods, echinoderms, crustaceans, coralline algae (*Lithothamnium*) and also shark teeth (Photo 47). All these fossils are considered to reflect warm and shallow waters, with these deposits resulting from the accumulation of carbonate mud formed from the degradation of the carbonated shells and other organisms that lived at the bottom of the vast platform developed around the island, or fixed to the volcanic coastline substrate. It is not possible to exclude the contribution of the dismantling of some reefs that grew close to the coast. The age of these levels, obtained by the study of the fossils and also by isotopic methods, is attributed to the Miocene.

Rocks of the same type also crop out at Ilhéu de Cima, Ilhéu de Baixo and Ilhéu de Ferro.

4 - Pico de Bárbara Gomes – This site is an isolated outcrop of volcanic material in the central region of the island, covered mainly by deposits of aeolianitic calcarenites.

The volcanic rocks present at Pico de Bárbara Gomes are mainly basalts, scoriae and pyroclastic rocks, corresponding to the subaerial sequences of the island (Photo 55).

5 - Miradouro do Pico do Castelo – Viewpoint of Pico do Castelo - Is a very good site to get an overview of the Island of Porto Santo. The central region, flattened, appears between the base of the elevations of the Northern region, where this imposing peak is located, and the Southern region (Photos 10 and 11). You can also enjoy a good view of the vast beaches that stretch along the SE coast of the island, and which are its major tourist attractions (Photo 14).

6 - Fonte da Areia – Although consolidated dunes crop out in various parts of the island, one of the best places to see its internal structure is in Fonte da Areia (Photos 12 and 50).

Here, this unit is about 60m thick and corresponds to a beautiful sequence of consolidated aeolian sands showing horizontal, oblique or cross-bedded stratification, as well as levels of ancient soils, which may have carbonate crusts, accumulations of snail shells (*Helix*) or roots.

The levels of old soil evidence episodes of interrupted wind deposition and probably correspond to periods of wetter climate. There are also levels with unrolled pebbles, transported during floods caused by intense rainfall.

The consolidated dunes are composed of sand particles, including for the most part (80-90%), round fragments of calcareous marine shells, and a smaller fraction (10-20%) of clasts from volcanic rocks. These sand particles are generally medium to fine-grained well calibrated grains, showing evidence of long wind transport. The source of this sandy material was the long platform extending to N of the island. When this platform was exposed, during a sea level drop, the Northern winds eroded it and transported the sand to dry land where it accumulated in sheltered places.

The age of the consolidated dunes, determined by isotopic methods, is attributed to the end of the last glacial period of the Quaternary (Würm), during which, as we know, great climatic oscillations were felt due to the ice ages, as reflected in the rise and drop of the sea level.

These dunes cover the volcanic substrate, abundantly intersected by dykes, as can be seen in the coastal cliffs (Photo 50).

7 - Pico de Ana Ferreira – The trachytic dyke of Pico de Ana Ferreira deserves a special mention for the spectacular development of its columnar jointing. Differentiation allowed the formation of hexagonal prisms, which, when altered, show “onion skin” (Photos 56 and 57). Some authors associate the formation of these structures to the mechanism that forms desiccation cracks, by shrinkage of the colder surfaces with fluid loss.

8 - Ponta da Calheta – In this site is interesting to see some aspects of the pyroclasts interlayered with basaltic lava flows (submarine sequences), intersected by spectacular basaltic dykes of various ages (Photo 51). Radial structures evidence the presence of pillow lavas in this site.

A lumachella embedding basalts occurs a few meters from the beach of Ponta da Calheta (Photo 44).

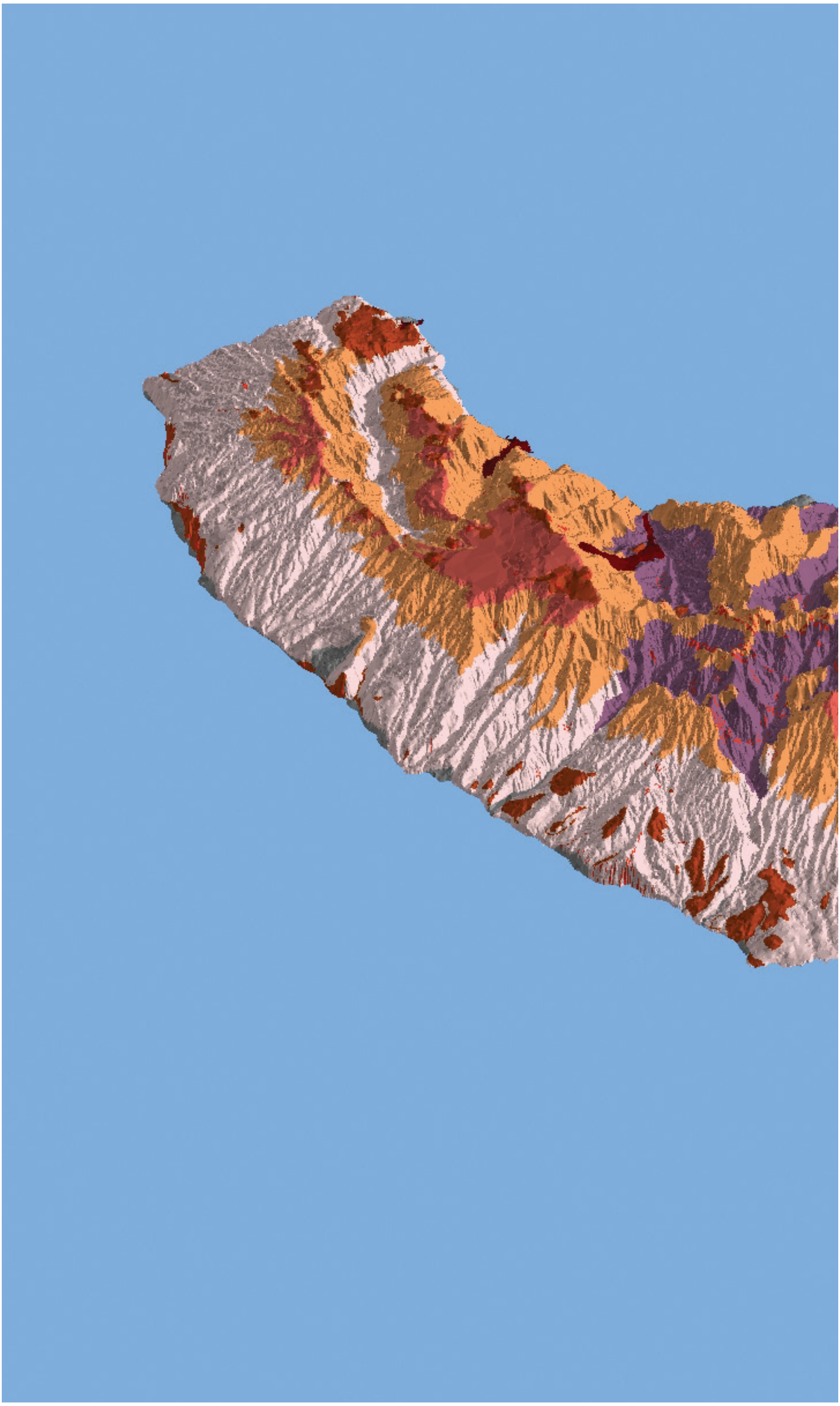
In this site is also possible to observe deformed and slightly curved laminar basalts, enhanced by calcium carbonate, indicating a strong tectonic movement (Photo 63).

9 - Zimbralinho – In this small beach, submarine volcanic sequences can be observed. This is the best place to observe pillow lavas that can only be found in the submarine sequences of this island of the Archipelago of Madeira. They have a zoned structure, intersected by radiated cracks where modern gastropods lived (Photo 53). It is also possible to recognize the trachyte dyke that goes from Pico do Espigão to Zimbralinho. On the way down to the beach, a metric-size dyke shows a well-developed columnar jointing.

10 - Morenos - Ribeiros – In this region, there are spectacular features of the ancient volcanic complex along the coastal cliff. The submarine phase of the island is intersected by an abundant network of dykes. Given the incoherent nature of these deposits, mainly pyroclastic during this stage, the dykes serve as support pillars (Photo 17).

On the way to Ribeiros a curious fountain decorated with several organic replacement structures (roots and stems replaced by calcium carbonate) can be seen, built with pieces that were collected in the sedimentary deposits (Photo 71). On this site, by the sea, aspects of the fossil-bearing limestone breccias with various types of shells, blocks of basalt, etc., embedded in basaltic rocks, can be seen (Photo 46).

11 - Marinhas – Here, as in Morenos, there are spectacular features of the ancient volcanic complex along the coastal cliff, whose lithologies, mainly pyroclastic, are intersected by numerous dykes, forming a tight network (Photo 16).



GEOLOGY OF MADEIRA ISLAND

On 3D digital terrain model

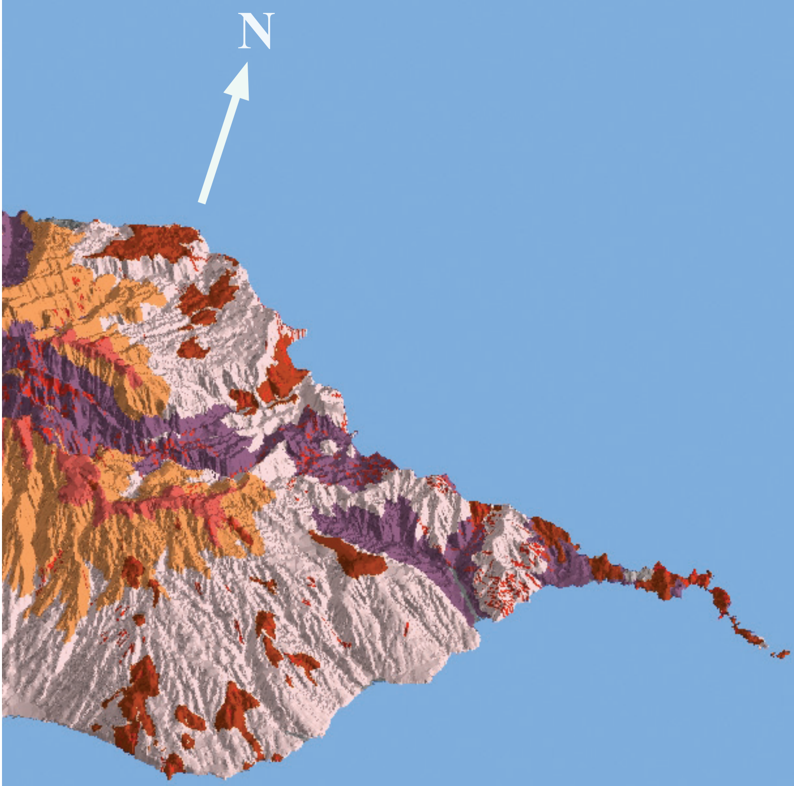


Fig. 21 – 3D digital terrain model and geological mapping by LNEG. Modified from the topographic map of Instituto Geográfico Português, scale 1:50,000; vertical exaggeration: 2X.

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GLOSSARY

Achada. (regional designation). Flattened region on a mountain top.

Asthenosphera. Part of the Earth's upper mantle that lies between 250km depth and the outermost layer of the mantle, the mantle lithosphere, that together with the continental and oceanic crust is part of the lithosphere.

Azoic. Sediment with no fossils.

Basic Magmas. Magmas with silica (SiO_2) contents lower than 54%. These magmas are originated by melting of the mantle and are the source of many rocks, such as basalts and gabbros.

Benthic. Organism that lives on the dependence of the sea floor (on the surface or inside it).

Branqueiros. (regional designation). Also called "paus fósseis" (fossil woods). Calcareous concretions in the form of petrified tree trunks and roots that occur in the dunes of the Eastern region of Madeira (Ponta de S. Lourenço) and in the northeast of Porto Santo (in this case, also occur in ball-shape and are designated as "bonecas"). They are the result of calcium carbonate precipitation in roots and trunks within the soil.

Cenozoic. Referring to the Cenozoic Era, which corresponds to the time interval that began 65 million years ago until the present time.

Clastolavas. Volcanic rock where it is possible to identify fragments of lava ejected from the crater in the liquid state, slightly cooled before accumulating.

Continental crust. Part of the Earth's outer layer that comprises the continents, including the continental platforms. It can be more than 80km thick.

Curral. Corral.

Differential erosion. Erosion affects the outcrops differently as the lithologies are more or less vulnerable to the action of the weathering agents, causing the more resistant to be prominent in relief.

Aeolianite. Detritic sedimentary rock consisting of grains of sand accumulated by wind and later consolidated by calcareous cement (consolidated dune).

Erosion. Alteration and disaggregation of rocks and consequent levelling of the relief by the action of external agents (rain water, ice, wind, thermal amplitude, etc.).

Essexite. As the teralite, they are varieties of coarse-grained alkaline gabbros. It is a gabbro with feldspathoids, with a composition and texture that varies considerably. Both types have the same composition but in different proportions. There is no consensus on these proportions. They compositionally gradate to diorites and monzonites with feldspathoids and to ultramafic rocks. Essexite has more plagioclase and less feldspathoids than teralite. Both contain equivalent amounts of potassium feldspar.

Example of composition of an essexite: 20% sodium orthoclase, 28% plagioclase, 20% nepheline, 30% mafic minerals and 2% apatite.

Facies. Collection of features of a rock (mineral, chemical, paleontological or structural) that characterize it, and that reflects the conditions of its formation and/or evolution.

Fault. Discontinuity surface in rocks where one side moved in comparison to the other, disrupting their normal succession.

Femic. Mnemonic consisting of "Fe" corresponding to iron oxide and "m" for magnesium: describes the minerals containing these two elements as essential components, such as olivine, most amphiboles and pyroxenes, as well as the most common accessory minerals from igneous rocks such as magnetite, hematite and ilmenite. It is synonymous of "ferromagnesian".

Ferromagnesian. See Femic.

Geodynamics. Area of Geology that studies the spatial-temporal evolution of the regions.

Geomorphology. Geomorphology is the science related with understanding of the Earth's land surface and the processes by witch it is shaped. Geomorphologic feature - is a typical form of relief.

Hawaiite. Rock of the trachybasalt group: rock of basaltic composition ($44\% < SiO_2 < 54\%$), enriched in alkalis ($5.9\% < Na_2O + K_2O < 7.2\%$). Rock of the alkaline sequence.

Hyaloclastite. Volcaniclastic rock generated by the accumulation of non-explosive volcanic glass that resulted from the rapid cooling of basaltic liquids in contact with water.

Hyalotuffs. Pyroclastic rocks formed by phreatic-magmatic and groundwater explosions from basaltic volcanoes in shallow waters.

Igneous rocks. Rocks that result from the cooling of magmas.

Leixões. (regional designation). Small islets along the coast.

Limestone. The mineralogical (and chemical) composition of sedimentary rocks is variable. Therefore, for convenience of study, the most common groups (or sequences) are defined. Limestone is a rock that has calcium carbonate minerals exceeding 50% of its composition. However, when studying a primarily non-calcareous sequence, that designation is often given to a rock that stands out for its higher content of calcium carbonate.

Lithology. Set of physical characteristics of a rock, such as the mineral composition, grain size, colour, texture and more.

Lithosphere. Terrestrial layer that comprises the continental and oceanic crusts and the portion of the upper mantle immediately below. It can be up to 200km thick below the continents and about 80km below the oceans.

Lumachella. Designation of a limestone or marl (usually) formed by significant accumulation of fossils, normally shells.

Mafic. Rock, usually igneous, consisting essentially of femic minerals. Some authors make no distinction between mafic and femic minerals.

Mantle. Internal layer of the Earth located between the core and the crust, which extends to a depth of 2,900km. It has been divided into two parts, upper mantle and lower mantle, as located above or below the 670km depth seismic discontinuity, respectively. The mantle is generally solid with local partial melting that originates the magmas that ascend to the crust.

Massapez or salão. (regional designation). Names given to the mixture of clays and carbonates resultant from the alteration of volcanic ash. Was used as cement in the past to build rudimentary buildings.

Mesozoic Era. Period of time that extended from 250 million to 65 million years ago.

Mugearite. Rock of the trachybasalt group: rock of basaltic/intermediate composition ($46\% < SiO_2 < 57\%$), enriched in alkalis ($7.2\% < Na_2O + K_2O < 9.2\%$), integrated in alkaline sequences.

Oceanic crust. Part of the outer layer of the Earth located beneath the oceans. It is mainly composed of igneous rocks (basalts and gabbros), generally covered by thin layers of sediments.

Paúl. Swamp.

Rechã or achada. (regional designation). Flattened region on top of a mountain.

Rhyolite. Acid rock ($58\% < SiO_2 \leqslant 76\%$), with alkalis between $5\% < Na_2O + K_2O < 12\%$.

Tectonics. Area of Geology that studies the structure of rocks (faults, folds, etc.) within the lithosphere and the movements that created those structures.

Trachyte. Rock with an intermediate/acid composition ($58\% < SiO_2 < 69.5\%$), enriched in alkalis ($9.1\% < Na_2O + K_2O < 11.5\%$).

Porto da Cruz
Mugearitic lava flow
(1.5 million years) on top of
sediments with plant fossils.