PERGAMON

Geodynamics 28 (1999) 117–129

JOURNAL OF
GEODYNAMICS

Volcanic gaps and subaerial records of palaeo-sea-levels on Flores Island (Azores): tectonic and morphological implications

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Received 20 May 1997; received in revised form 31 July 1997; accepted 30 June 1998

Abstract

The morphological evolution of Flores Island, as commonly observed for volcanic islands, suggests (1) the balance between constructive processes (effusive and moderately explosive volcanic activities and tectonic uplifting movements) and destructive processes (marine abrasion, stream erosion, crater-forming volcanic explosions, caldera collapses and tectonic subsidence) and (2) the recurrent fluctuations of the sea-level.

Records of (a) gaps in the volcanic activity and (b) erosional and depositional marine activity are shown as:

— epiclastic deposits of marine origin
— erosional morphologies, such as abrasion platforms, terraces, cliffs and caves
— intensive palagonitization of the volcanic rocks
— vertical changes of the structures in the hydroclastic submarine formations.

Taking into account (1) the vertical crustal movements (uplift and subsidence) which may occur in volcanic domains and (2) the sequence of regressive–transgressive trends in the relative sea-level as expressed by indicators of pale-sea-levels, it is assumed that the morphological evolution of Flores Island comprehends three main stages.

The existence of important differences between the present-day altitudes of correlated marine records noted in Flores, in Santa Marie Island (Azores Archipelago) and Porto Santo Island (Madeira Archipelago) is related with their crustal behaviour and different volcanic and tectonic evolution. © 1999 Elsevier Science Ltd. All rights reserved.

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PII: S0264-3707(98)00032-5

1. Introduction

The present-day morphology of Flores Island, as of many other oceanic islands, is the result of a continuous unbalanced equilibrium between the constructive and the destructive processes (Azevedo and Ferreira, 1995b) (Fig. 1). The constructive processes are prevalent during the proto-insular and young insular stages; the destructive processes may be episodic during the constructive stages, but become predominant as the island gets older and older.

Besides the constructive–destructive equilibrium, the emerged area in each time of an oceanic island evolution depends largely on the eustatic sea-level fluctuations. The persistence of a regressive tendency or an island uprise may allow the preservation of records of the marine presence, such as uplifted terraces or notches.

In Flores Island, geomorphological and depositional records of past sea-levels are expressed in its subaerial domains. Their recognition and subsequent interpretation were supported and integrated on the wider frame of the geological and structural evolution of the Island, aimed to draw up of the volcanological map at the 1:15.000 scale.

2. Geographic, geotectonic and geochronologic setting

Flores is one of the nine islands of the Azores Archipelago. Together with Corvo they constitute the Western Group of this Portuguese archipelago, which is placed in the middle of North Atlantic Ocean at about 37° to 40°N, 24° to 31°W [Fig. 2(a)].

The azorean islands extend through a 600 Km belt aligned along WNW direction and belong to a major group of Atlantic Islands—Macaronesia Islands—that also includes Madeira, Canary and Cape Verde Archipelago Islands [Fig. 2(a)]

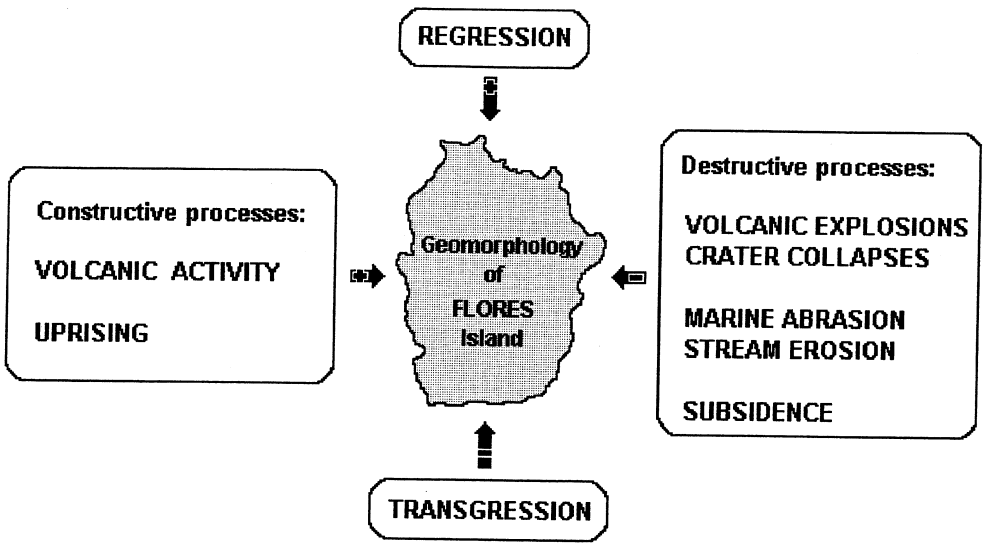

Fig. 1. Major processes (constructive and destructive) responsible for the geomorphological evolution of Flores Island.

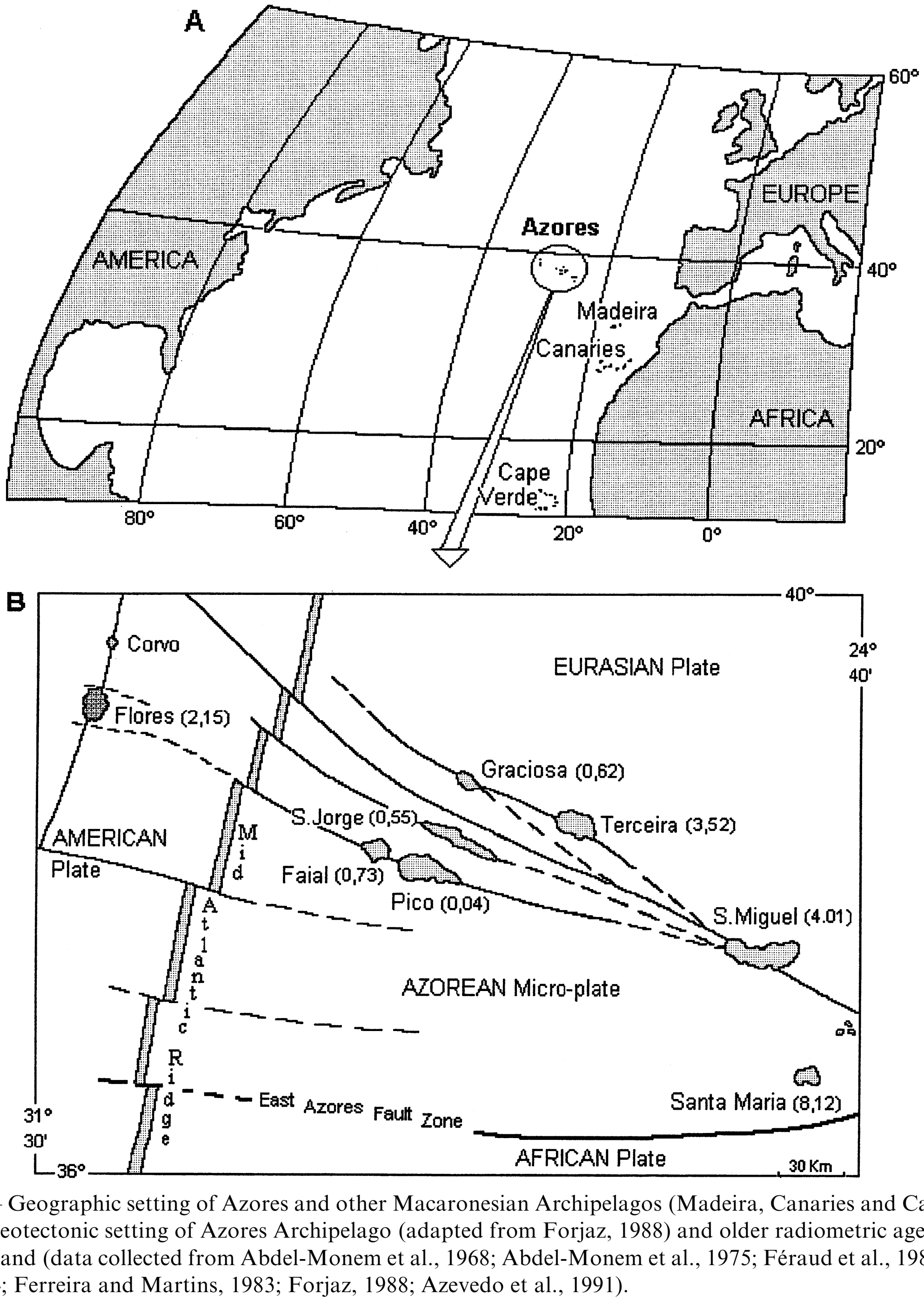

Fig. 2. **A**— Geographic setting of Azores and other Macaronesian Archipelagos (Madeira, Canaries and Cape Verde) and **B**— Geotectonic setting of Azores Archipelago (adapted from Forjaz, 1988) and older radiometric ages (Ma Bp) for each island (data collected from Abdel-Monem et al., 1968; Abdel-Monem et al., 1975; Féraud et al., 1980; Féraud et al., 1984; Ferreira and Martins, 1983; Forjaz, 1988; Azevedo et al., 1991).

All of the islands and seamounts from Azores Archipelago are the result of a volcanic process related to the confluence of three lithospheric plates—American, Eurasian and African—and are strictly associated to the Mid Atlantic Rift (MAR) and particularly to its transform faults.

Seven of these islands—Faial, Pico, S. Jorge, Terceira and Graciosa (Central Group) and S. Miguel and Santa Maria (Eastern Group) are rooted in the Eurasian Plate (Laughton and Whitmarsh, 1974), in a subdomain called Azorean Micro-plate (after Forjaz, 1988), which is limited westwards by the MAR, southwards by the East Azores Fault Zone and north–northeastwards by Graciosa–Terceira–S. Miguel Fracture (or Terceira Rift, after Machado, 1959). Contrasting with these seven islands, Flores and Corvo are rooted westwards of the MAR, in the North American Plate [Fig. 2(b)].

Several models for the tectonic regime of the Azorean Micro-plate were proposed on the basis of neotectonic, seismotectonic and paleomagnetic data interpretation (see for example: Machado et al., 1972, 1983; Hirn et al., 1980; Buforn et al., 1987; Madeira and Ribeiro, 1990, 1992), but they don't really include or give a detailed explanation for the tectonic regime of the western domain of Flores and Corvo. This lack of explanation is a consequence of: (1) the specificity of this azorean domain, particularly (1.1) the MAR westwards localization, (1.2) the NS direction of the volcanic building of Flores and Corvo, parallel to the MAR and approximately perpendicular to that observed for the other azorean islands (NWN), (1.3) the very moderate seismic activity (only two historical references, both from the sec. XVIII) and (2) a great scarcity of geophysical data for this Atlantic area. The main exceptions are the works of Serughetti and Rocha (1968), Krause and Watkins (1970) and Blakely (1974). Meanwhile, with the support of the 1:25 000 geologic map of Zbyszewsky et al. (1968), the recent lithological, structural and morphological evidences (Azevedo, 1997; Azevedo et al., 1991 and Azevedo and Ferreira, 1995a) and the new GPS data (Bastos et al., 1993) it is possible to advance the following aspects:

—Flores and Corvo Islands are two subaerial pits of the same volcanic building;
—The tectonic setting and volcanic processes of these two islands are, like those presented by the other islands, undoubtedly associated to the MOR (this is partially confirmed by the similarities found between geochemistry and isotopic data from Flores and Corvo and those from all the other azorean islands (Torre de Assunção et al., 1974), but the structural control induced by the transform faults, very clear in the eastern islands, is less evident here. However, the rectilinear nature of both the north and south Flores coastlines Fig. 4 may be the expression of this control.
—The main tectonic structures on Flores are sinistral N30–40°W and up-and-down N20–30°E faults (Azevedo, 1997); the NS major structure suggested in Forjaz (1988) has a secondary expression in subaerial domains.
—The occurrence of two important periods of vertical crustal movements which were strictly associated to the volcanic activity (Azevedo, 1997): (1) an uplifting, that was extensive to all the insular building and was related to the very intensive volcanism developed during the evolution from the proto-island to the island stage (emergent volcanism), (2) a structural collapse of to two or three big subaerial craters located in the central area of the island, which led to the build-up of large and shallow calderas (Azevedo, 1997).

The older isotopic ages obtained for each azorean island are given on Fig. 2(b). Flores has the fourth oldest subaerial formations, presenting radiometric ages of about 2.2 Ma Bp (Azevedo et al., 1991). Only Santa Maria, S. Miguel and Terceira show older ages. This fact figures out the significative correlation between the ages of the oldest rocks found in each island and its increasing distance from the MOR, which confirms the progressive and symmetric divergence of the lithospheric plate.

The last volcanic activity of Flores occurred 0.003 Ma Bp (Morrisseau and Traineau, 1985) and according to Blakely (1974) and Needham and Francheteau (1974) the volcanic building of Flores and Corvo rest on a 9.0 Ma Bp oceanic crust (anomaly 5, after Krause and Watkins, 1970).

3. Build-up processes and gaps in volcanic activity

Flores, as all the other islands of the Azores Archipelago, is a typical volcanic build-up island whose volcanism is associated to MAR transform faults. There is a balance between the effusivity and the explosivity with predomination of the basaltic lavas and pyroclasts, but the differentiated products, such as hawaiites, mugearites, benmoreites, traquites and very seldom riolites as been already reported (Cas and Wright, 1987).

According to the geological and structural mapping (Azevedo, 1997 and Azevedo et al., 1991), the volcanic formations were organised in two major groups (called Complexes after Azevedo et al. (1986) to mean an assemblage of volcanic rocks, which present genetic and spatial affinities, but a wide variety of petrographic and geochemical characteristics, primary structures, morphologies, degrees and types of alteration):

1. The Base Complex (BC) that comprehends two major units: Base Complex 1 (BC1) and Base Complex 2 (BC2). These units (BC1 and BC2), which are the result of submarine and emergent proto-insular volcanism of Plio–Pleistocenic age, are mainly composed of volcanoclastic with some minor lava-flows at the top (Azevedo, 1988).
2. The Upper Complex (UC): includes all the subaerial volcanic formations and may be subdivided into three volcanic units (Azevedo and Ferreira, 1995): Upper Complex 1 (UC1), Upper Complex 2 (UC2) and Upper Complex 3 (UC3). The lower subgroup (UC1) was formed between 0.65 and 0.5 Ma Bp and is made up of extensive and sometimes very thick lava-flows alternating with subordinate pyroclast; its geochemical composition differentiated from basaltic into traquitic nature. The middle subgroup (UC2) whose age ranges from 0.4 to 0.2 Ma Bp, is mostly composed of basaltic and hawaiitic lava-flows. The upper subgroup (UC3) was build-up between 0.004 and 0.003 Ma Bp (Morrisseau, 1985) and includes basic pyroclast deposits, ashes with lithic fragments, which are the result of an intensive phreatovolcanism.

K/Ar radiometric ages (Azevedo et al., 1986, 1991; Ferraud et al., 1980) and ^{14}C data (Morrisseau, 1985) helped to define with some detail the evolution of the volcanic activity on Flores Island. The major periods of volcanism are shown on Fig. 3. They alternate with three main stages of quiescence, respectively located between 1.5 and 1.1 Ma, 0.5–0.4 Ma and 0.2–0.004 Ma Bp.

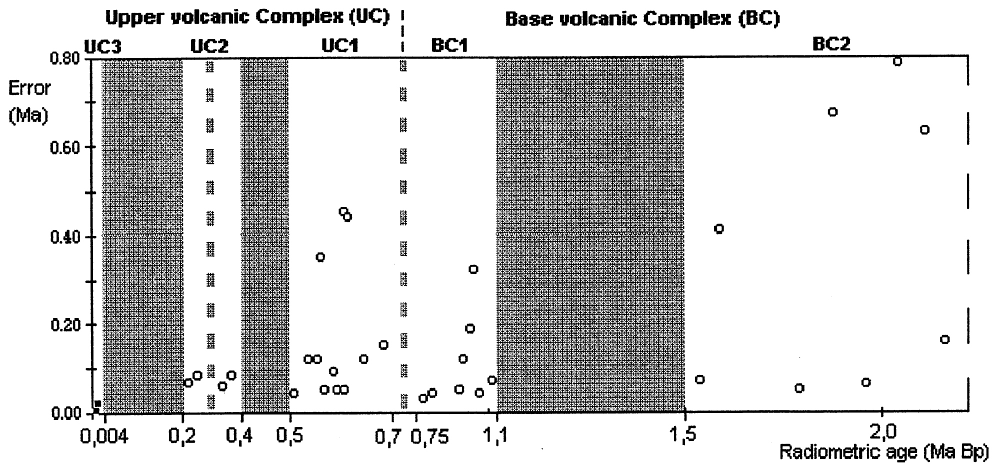

Fig. 3. Radiometric ages (K/Ar determinations in circles (Azevedo et al., 1986; Azevedo et al., 1991; Ferraud et al., 1980) and ^{14}C determinations in small squares (Morrisseau, 1985), periods of volcanic activity (white bars) and volcanic gaps (grey bars) figured out in Flores Island.

4. Subaerial records of paleo-sea-level and paleo-coastlines

Depositional and geomorphological records indicative of paleo-sea-levels have been observed along coastal sectors of Flores (Zbyszewsky, 1976 and Azevedo and Ferreira, 1995), located between the present-day coastline and the 300 m a.s.l. (Fig. 4 and Table 1), as:

1. Epiclastic marine deposits, such as beach deposits and conglomeratic levels.
2. Erosional morphologies, such as abrasion platforms and wave cut-terraces (with the local name "fajãs").
3. Intensive palagonitization of some volcanic rocks, particularly visible in the volcanic breccias, which mean a long-period of interaction with the sea-water.
4. Vertical changes in the compositional facies and depositional structures of the submarine rocks, such as a sudden shift from lava-flows to volcanic breccias and tuffs, or from autoclastic to pyroclastic deposits that could mean a quick change in the environmental conditions of volcanism, for example a quick reduction in the dimension of water column and consequently, in the hydrostatic pressure. These situations are particularly common on the volcanic sequences built-up during the transition from the submarine to subaerial volcanism or vice-versa.

Fossilised abrasion cliffs, stream terraces with eustuarine conglomerates and wave-cut caves may also be used to infer sea-level fluctuations.

These lithological and morphological markers have been classified into five groups on the basis of their Table 1:

1. Chrono and lithostratigraphic setting, in particular their relationship with their incasing volcanic rocks;
2. Relationship with the quiescent periods of volcanism;
3. Present-day altitudes, discarding the amount of the vertical crustal movements;

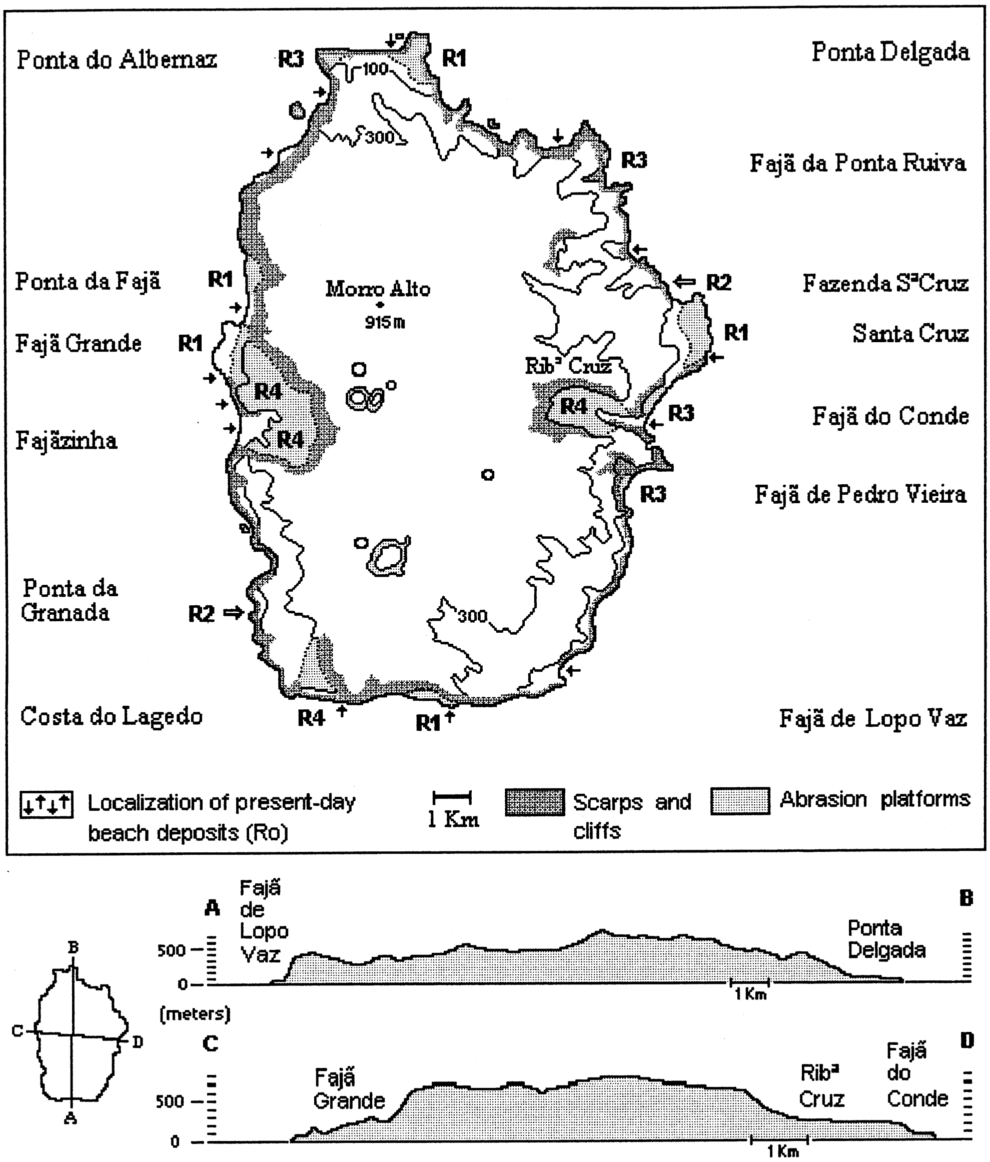

Fig. 4. Localization of the depositional and geomorphological records of marine erosional and depositional activity (see Table 1 for description).

4. The available data for the North-Atlantic climatic temperatures and sea-level fluctuations with particular attention to the warm peaks occurred during the inter-glacial stages.
5. geomorphological characters.

The present-day beaches and scarps are called Ro and the other groups are named as R1, R2, R3 and R4 according to their increasing comparative ages.

Table 1
Main characters of paleo-sea-level records (see Fig.4 for records localization)

Group	Depositional-geomorphological characters and their basis (see Fig.3)	Altitude (m.a.s.l.)	Chronostratigraphic settings	Epoch
Ro	Present-day beaches and abrasion cliffs	0	Present-day	Holocene
R1	· Santa Cruz platform	35 - 45	Younger than **UC2** (0.2 Ma Bp) The platforms and deposits are over-imposed on the UC2 youngest units	PLEISTO-CENE
	· Platform and epiclastic deposits of: - Ponta Delgada - Ponta da Fajã - Fajã Grande - Fajã de Lopo Vaz			
R2	· Conglomerates of:	15 - 20	Between 0.23 and 0.27 Ma Bp. The conglomerates are intercalated between two lava-flows with 0.23 and 0,27 Ma Bp (K/Ar ages from Azevedo, 1997)	
	- Fazenda de Santa Cruz - Ponta da Granada (Zbyszewsky, 1976)			
R3	· Cliffs and wave-cut terraces of:	c.a. 100	Younger than **UC2** (≅ 0.35 Ma Bp) The platforms are over-imposed on the UC2 oldest units	
	- Fajã do Conde - Fajã de Pedro Vieira - Fajã da Ponta Ruiva · Platform and epiclastic deposits of Ponta do Albernaz			
R4	· Platforms, cliffs and a very few caves and coarser epiclastic marine deposits of: - Fajã Grande-Fajãzinha - Costa do Lagedo	c.a. 250	Younger than **UC1** (0.5 Ma Bp) The records are over-imposed on the UC1 units	
	- Ribeira da Cruz		Older than **UC2** (≅ 0,25 Ma Bp) The platforms are partially filled with UC2 formations	

5. Volcanic, tectonic and morphological evolution

Taking into account (1) the volcanic sequences Fig. 3, (2) the vertical crustal movements (uprises and subsidences) of neo or volcano-tectonic origin (refered in par.2), (3) the sequence of subaerial marine records (refered in par.4), (4) the general eustatic sea-level and palaeo-temperature fluctuations (based on Emiliani oxygen-isotope stages, in Nilsson, 1983) and (5) palaeoclimate data obtained on North Atlantic cores (Ruddiman, 1977 and Ruddiman and

McIntyre, 1981; Ruddiman and McIntyre, 1984), it is possible to divide the subaerial morphological evolution of Flores Island into three main stages. Herein for each stage or sub-stage the volcanism, crustal movements and sea-level fluctuations are refered.

5.1. ***Stage 1*** *(0.75 to 0.4 ma bp). During this major period two sub-stages might be considered:*

5.1.1. ***Sub-stage 1.1*** *(0.75 to 0.55 Ma Bp)*

5.1.1.1. Volcanic activity. It was very intensive and of the emergent type, i.e., predominantly explosive and corresponding to the evolution from the proto-island to the island stage (Azevedo et al., 1991). The BC1 to lower UC1 units record this activity.

5.1.1.2. Crustal vertical movements It is here affiliated an important tectono-volcanic uprise, whose amplitude might have exceed 100 m. This uplift is interpreted as being connected to the intensive volcanism of this period, but could be a consequence of an isostatic compensation between two small adjacent blocks of the lithosfer (Azevedo et al., 1991). As a matter of fact, it should be noticed that the subsided island (a seamount with a present-day depth of 450 m), which is located 50 kilometres westwards of Flores Island, shows a tectonic evolution (Ryall et al., 1983) opposed to that figured out for the Flores Island: while an uprise process dominated in Flores Island, the seamount subsided at about the same rate, thus supporting the concept of an isostatic compensation between the two adjacent domains of the oceanic crust.

5.1.1.3. Sea-level fluctuation In spite of the uncertain global eustatic sea-level and palaeotemperature fluctuations for the North Atlantic during this time lapse (Nilsson, 1983), the development of a warm period—correlative to Mindel, Elster or Anglian Glacial Stage—and the consequent regression tendency of the sea-level, accelerated the emergency of the island. Based on the present-day data it is impossible to figure out the accurate amplitude of this regression, but taking into account the association between the volcano-tectonic uprise and the regressive tendency of the sea-level, the upsurge of the island during this sub-stage should have been of the order of a few hundreds of meters, probably c.a. 400 m. This is confirmed by the present-day occurrence of BC1 volcanic formations at 400 m a.s.l. It should be recalled that the BC1 units were built-up during proto-island emergent volcanism (Azevedo et al., 1986; Azevedo et al., 1991).

5.1.2. ***Sub-stage 1.2*** *(0.55 to 0.4 Ma Bp)*

5.1.2.1. Volcanic activity. It comprehends the last period of the UC1 volcanism, which was characterised by the extrusion of large amounts of lavas from two or three large volcanic centres. It was followed by a long lasting period of volcanic quiescence (0.5 to 0.4 Ma Bp).

5.1.2.2. Crustal vertical movements During this sub-stage there happened an inversion in the uprising tendency. The very large amounts of lava extruded during the UC1 last phases of volcanism might explain the subsidence of the whole island and particularly the collapse of its central zone, which led to the formation of volcanic calderas.

5.1.2.3. Sea-level fluctuation The development of a general transgressive period-correlative to the Interglacial Stage that preceded a cold period that might be correlated to the Mindel Glacial Stage (Nilsson, 1983) was responsible for an important erosion of the subaerial domain of the island.

The group of records R4 should have been formed during one of the peaks of this transgressive tendency. The 250 m a.s.l. of R4 records figures out that the amplitude to this transgression should have been less than 200 m. The neo and tectonic subsidence of the island amplified the trangressive amplitude in this specific domain, as to reach 200 m a.s.l.

5.2. ***Stage 2*** *(0.4 to 0.2 Ma Bp)*

5.2.1.

5.2.1.1. Volcanic activity. It comprehends the last major volcanic episode of this island, the UC2 volcanism Fig. 3.

5.2.1.2. Crustal movements No important vertical tectonic movements was registered throughout this stage.

5.2.1.3. Sea-level fluctuations A regressive tendency related to a climatic cold period-correlative to the Emiliani Stage 8 or to the Mindel, Anglian or Elster Glacial Stages (Nilsson, 1983)—was followed by a transgression during a warm period correlative to the Emiliani Stage 7 or to Interglacial M/R, Holstein and Hoxnian Stages (Nilsson, 1983).

The chrono and lithostratigraphic settings of the R3 and R2 records (see Table 1) suggest that they were probable constructed during two short pauses in the overall UC2 volcanic activity, thus corresponding to two intermediate stabilization episodes on the general transgressive tendency.

5.3. ***Stage 3*** *(0.2 Ma until the present)*

5.3.1.

5.3.1.1. Volcanic activity. After a long volcanic quiescent period (0.2 to 0.004 Ma Bp), there occurred a short period of volcanism, the UC3 volcanism (0.004 to 0.003 Ma Bp).

5.3.1.2. Crustal movements It is probable that the slow rate subsidence of a normal oceanic crust, which is the result of the thermal contraction (Sclater et al., 1971) was extensible to the oceanic crust in Flores area, at least after the ending of the major steps of insular volcanism—UC3 and UC2 volcanism.

5.3.1.3. Sea-level fluctuations According to the data available after the study of some North Atlantic oceanic drilled cores which represent this period (see for example Ruddiman, 1977; Ruddiman and McIntyre, 1981; Ruddiman and McIntyre, 1984; Heinrich, 1988; Rodrigues and Dias, 1989 and Baas et al., 1997) the palaeotemperatures and the eustatic sea-level went throughout an oscillatory evolution that includes two major cold periods (the first is correlative to Riss, Saale and Wolstonian Glacial Stage and the last one corresponds to the Last-Glacial Stage) intercalated by two warm periods (equivalent to the Last-Inter-Glacial Stage and to the Post-Glacial Stage).

The group of records R1 might register the peak of one intermediate transgressive period. According to the its chronostratigraphic setting (see Table 1) this transgression will correspond to the Emiliani Stage 5 or to the Last Interglacial (Eem) period (Nilsson, 1983), which have been dated in North Atlantic cores between 0.127 Ma and 0.073 Ma Bp (Ruddiman and McIntyre, 1984).

6. An attempt for the correlation with Santa Maria and Porto Santo Islands

In spite of the fairly well known volcano-tectonic setting and evolution for the Macaronesian Islands (Azores, Madeira, Canaries and Cape Verde Archipelago) [Fig. 2(a)], which is expressed by a good number of papers and other scientific works, the scarcity of investigation on eustatic sea-level and palaeo-climate (palaeotemperature) fluctuations is evident. Meanwhile, similar records of paleo-sea-level have been identified in Santa Maria Island (Serralheiro and Madeira, 1990), the oldest and the eastern island of the Azores Archipelago [Fig. 2(b)], and in Porto Santo Island (Ferreira, 1997), the oldest island of Madeira Archipelago [Fig. 2(a)]. In both situations, the sequence of records confirmed the general regressive–transgressive evolution (eustatic sea-level and palaeotemperature fluctuations) described for Flores (see par. 5). However, the present-day altitudes of correlated records expresses great differences between Flores and the other two Islands, where they lie at lower heights. This setting may be explained taking into account the differences in the crustal behaviour and tectonic evolution of the three volcanic islands. As a matter of fact, contrasting with the other two islands, Flores can be considered as being a very young island, whose last volcanic activity—UC3 volcanism—is dated of 3,000 years Bp, while in Santa Maria the volcanism stopped during the Middle Pliocene (Serralheiro and Madeira, 1990) and in Porto Santo it ceased in the Middle to Upper Miocene (c.a. 9 Ma Bp, Ferreira, 1997). As in these two older islands there is no evidence of important neo-tectonic uprises, either the lower heights of the correlative abrasion platforms should be explained as a consequence of the normal slow rate subsidence of the oceanic crust (Sclater et al., 1971).

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