THE EMERGENT VOLCANISM OF FLORES ISLAND, AZORES (PORTUGAL)

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ARQUIPÉLAGO

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This paper provides a reconstruction of the early geological history of Flores Island, based on its comprehensive geological setting and the sequence of volcanic activity, which has changed from strictly submarine to emergent. The episodes of the Flores build-up processes are related to the tectonic framework of the western "branch" of the Azores Archipelago. The kinematic behaviour of this region suggests that the oceanic crust is here subdivided into distinct domains, each with independent vertical movements and specific evolution.

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O estudo de formações geológicas resultantes das fases finais do vulcanismo proto-insular da ilha das Flores (aqui designadas por Complexo de Base) permitiu a reconstituição dos processos de crescimento da proto-ilha. Com base na estrutura e litologia daquelas formações, esboçam-se as características, o enquadramento estrutural e a evolução da actividade vulcânica, inicialmente submarina e emergente nas fases finais, responsável pela construção da proto-ilha. Este período enquadra-se no contexto da evolução vulcânica e geotectónica das ilhas do Grupo Ocidental dos Açores, onde o comportamento cinemático sugere que a placa oceânica nesta região se encontra retalhada em domínios restrictos susceptíveis de sofrerem movimentos verticais independentes e de exibirem evoluções geológicas distintas.

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INTRODUCTION

The main objectives of the geological programme carried out on Flores Island were: *i*) to improve the geological map of the Island and; *ii*) to study the geological history of a volcanic island in connection with the processes related to the activity of a mid-ocean rift. The final stages of proto-island growth are particularly important in the construction of a volcanic island associated with a mid-oceanic ridge.

Flores occupies the western end of the islands of the Azores that extend for about 650 km, along a NW-SE alignment, between 25° and 30° W (Fig. 1A).

Flores and Corvo (a small island 16 km to the north), form the Western Group of the Archipelago, separated from the Central Group (Faial, Pico, S. Jorge, Graciosa and Terceira Islands) by the Mid-Atlantic Rift. The Eastern Group consists of two other islands: S. Miguel and Sta. Maria.

Tectonic and volcanic activities in this region are largely controlled by the location of the Mid-Atlantic Rift and by two transverse fractures that merge with the rift: *i*) the East Azorean Fracture Zone - EAFZ- that meets the rift south of the Azores and; *ii*) a fracture zone oblique to the former that defines the axis of the islands and joins the EAFZ East of Santa Maria.

These fracture zones, together with the Mid-Atlantic Rift, establish the boundaries of an active tectonic and volcanic domain usually referred as the "Azorean Microplate" (AzmP, Fig. 1A) lying at the triple junction, between the American, European and African Plates (see MADEIRA & RIBEIRO 1990).

The presence of seamounts, interpreted as submerged islands or aborted proto-islands, is common on the Azorean sea floor. A seamount, 50 km west of Flores, for instance, now lies at a water depth of 440 m (RYALL & al. 1983).

METHODS

This study concentrates on earliest volcanic materials uplifted on Flores and now exposed in several areas, mainly along the coast line to provide a record of part of the geological evolution of the island. Most of the old formations outcrop at the base of steep cliffs. They were mapped in detail and a careful sampling plan was adopted, based on macro and megascopic analysis, in order to minimise expected errors which could arise due to the random distribution of coarse pyroclastic material over small areas.

The study involved: *i*) a systematic survey of the lithology of the volcanic products and their stratigraphic sequence, and; *ii*) in the laboratory, petrographic and chemical analysis. Radiometric age determinations were also carried out both on lavas associated with submarine pyroclasts and in volcaniclasts of large dimensions. Some X-ray analyses were done for identification of the alteration products of the volcanic breccias. A portable magnetometer was used in the field to obtain information on the systematic polarity of the rocks (especially im-

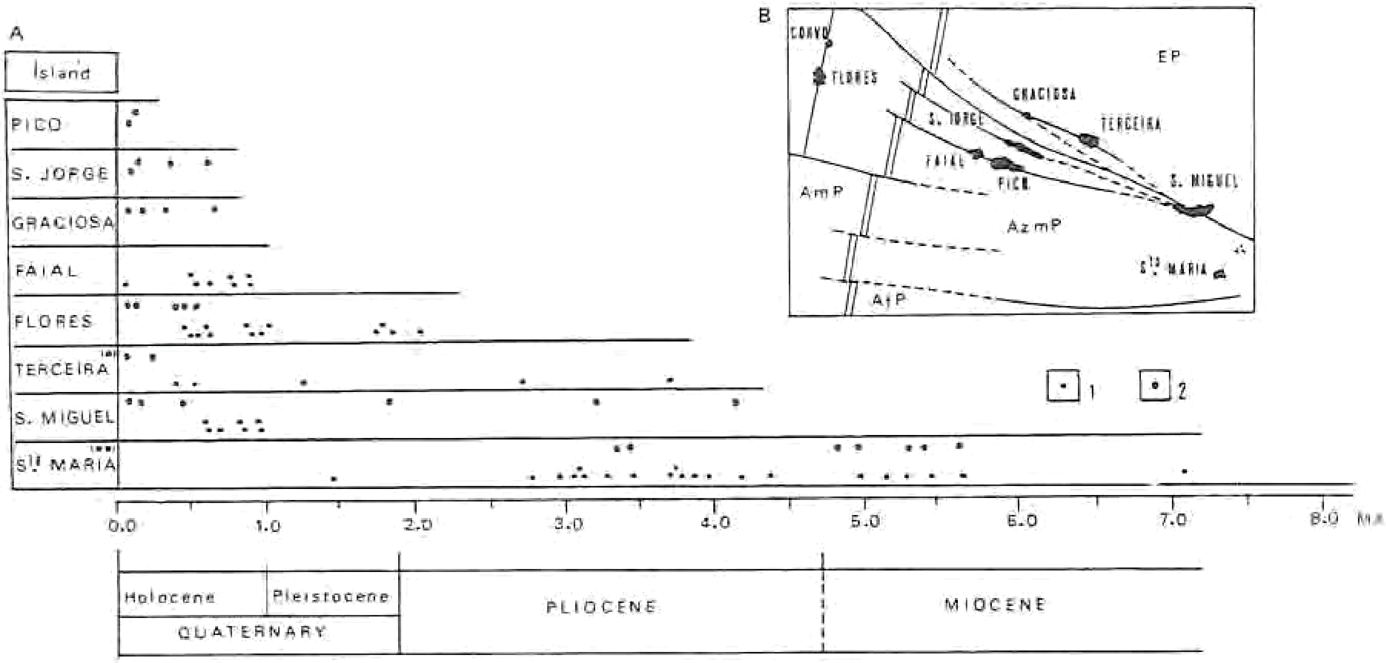

Fig. 1. A - Geotectonic setting of the Azores Archipelago (After FORJAZ 1988): EP - European Plate; AmP - American Plate; AfP - African Plate; Az mP - Azorean micro-Plate. B - The correlation of the Azorean Islands geochronological ages: (1) K/Ar ages obtained in Geochronological Laboratory, Coimbra University. (*) M. Portugal Ferreira, J. Ávila Martins (pers. commn.). (**) C. Costa (pers. commn.); (2) FÉRAUD & al. 1980, MORISSEAU 1985, ABDEL-MONEM & al. 1975.

portant in samples taken for age determinations).

Age determinations were made by the K/Ar method in the Laboratory of Geochronology of Coimbra University.

RESULTS

Chrono- and Lithostratigraphy

Radiometric ages relating to the Azores are given in Fig. 1B. Flores has the fourth oldest subaerial formations (about 2.00 Ma). Older ages are found only on Santa Maria, São Miguel and Terceira. For Corvo we anticipate a similar geochronological situation to that in Flores. The clear correlation between the ages of the oldest rocks found in each island and its increasing distance from the Mid-Atlantic Rift confirms the interpretation that progressive and symmetric movement of each island has taken place away from the Rift.

The geological formations of Flores Island were divided in two main groups (AZEVEDO & al. 1986): *i)* Upper Complex (UC) and; *ii)* Base Complex (BC).

Upper Complex (UC). This is composed of geological formations formed exclusively by subaerial volcanic activity, mainly phreatovolcanism (island stage). These formations occupy the highest stratigraphic levels and include pyroclastic deposits and lavas; their ages range from 0.65 Ma (K/Ar ages see AZEVEDO & al. 1986) to 0.02 Ma (C^{14} ages, see MORISSEAU 1985)(Fig. 2).

Base Complex (BC). This complex comprises all the lavas and volcanoclastic deposits formed during the volcanic activity of the proto-island stage. These rocks are older than 0.65 Ma (Fig. 2). They include the "Old Pyroclasts" (ZBYSZEWSKI & al. 1968) and also the submarine lavas associated with them. The oldest (K/Ar) age, found in the BC formations in the NE side of the island, was around 2.15 Ma (Table 1).

The BC occurs: *i)* at the western side of Flores between Costa do Lagedo and Fajã Grande. These rocks are referred to as the

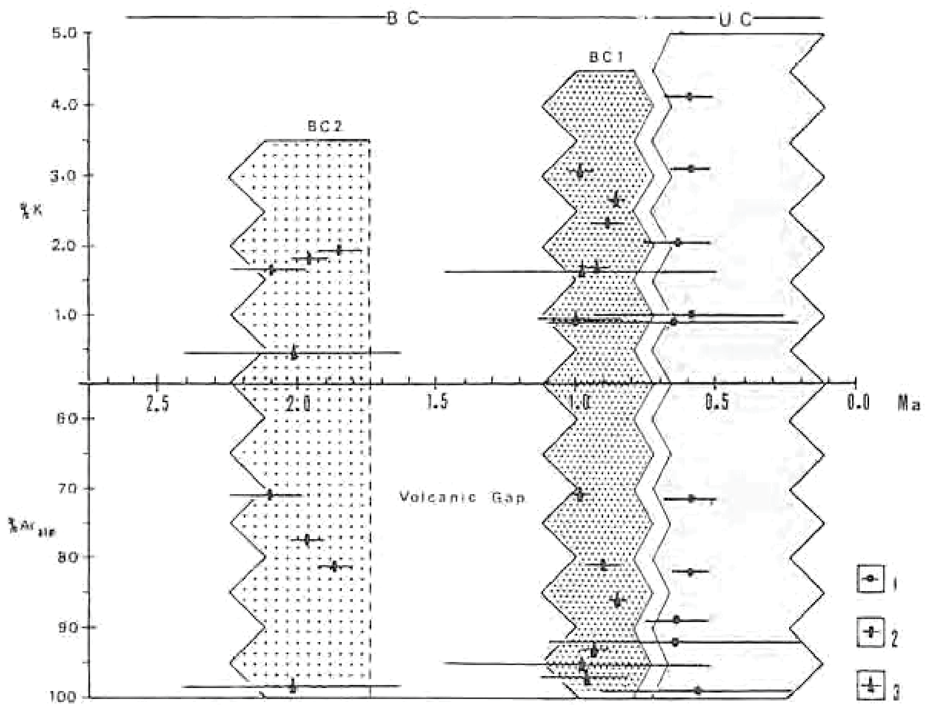

Fig. 2. Chronostratigraphy of Flores Island: UC- Upper Complex: BC- Base Complex (BC 1, BC 2); (1) UC K/Ar ages; (2) North- east BC K/Ar ages; (3) Southwest BC K/Ar ages.

Table 1. K/Ar ages from samples of Flores island, obtained in the Geochronological Laboratory, Coimbra University (The localities of the samples are shown in Fig. 3). (*) Results published in AZEVEDO & al. (1986)(**) Results published in AZEVEDO (1990)(***) Ar^{40} radiometric (^{cc}STP/G. 10^{-7})

Sample Structure	Lithology rad.	% K	Ar^{40***} rad.	% Ar atm.	Age Ma	Stratigraphy	
FS 140* Dique	Hawaiite	2.66	4.297	86.3	0.84 ± 0.02	BC 1	
FS 179* Lava-flow	Basalt	1.65	5.219	93.2	0.93 ± 0.05	BC 1	
FS 134* Lava-flow	Basalt	0.92	6.585	98.0	0.95 ± 0.19	BC 1	SW BC
FS 22* Dique	Benmoreite	3.09	3.019	71.5	0.98 ± 0.04	BC 1	
FS 146* Lava-flow	Basalt	1.58	1.748	95.8	0.98 ± 0.50	BC 1	
FS 228** Lava-flow	Basalt	0.44	1.106	99.9	2.04 ± 0.40	BC 2	
FS 21* Lava-flow	Hawaiite	2.39	4.247	81.9	0.86 ± 0.04		
FS 202 Lava-flow	Basalt	1.81	3.261	73.3	1.78 ± 0.05		NE BC
FS 226* Lava-flow	Basalt	1.85	4.490	77.7	1.96 ± 0.06		
FS 2 Lava-flow	Basalt	1.65	3.914	71.7	2.15 ± 0.15		

Southwest Base Complex (SW BC), and; *ii*) between Santa Cruz and Ponta Delgada and also in a small area close to Ponta do Albernaz. These rocks are referred to as the Northeast Base Complex (NE BC). These two domains occupy symmetric positions in a NNW-SSE alignment (Fig. 3).

Southwest Base Complex (SW BC). From lithological and structural studies and K/Ar age determinations (Fig. 2 & Table 1), we could identify two main groups (see AZEVEDO & al. 1986) in the Southwest Base Complex (SW BC): *i*) the upper group, to be called Base Complex 1 (BC1), with dates up to about 1.00 Ma for the oldest rocks, and; *ii*) the lower group, called Base Complex 2 (BC2), which shows K/Ar values corresponding to about 2.00 Ma.

The contact between BC1 and BC2 shows a geometric and lithologic unconformity. Both complexes are frequently crossed by basaltic and trachytic near-vertical dikes trending N 20°-30° W.

The Base Complex 1 (BC1) is formed by three different units (AZEVEDO & al. 1986): (*i*)Upper volcanic Breccia (UvB); (*ii*) Palagonitized Basalts and Hawaiites (pbH); (*iii*) Lower volcanic Breccia (LvB). These subunits of the BC1 crop out as three conformable near-horizontal bands.

The *Upper volcanic Breccia (UvB)* is composed of pyroclasts (blocks and lapilli) and angular autoclasts (5 cm to 1.5 m) of basaltic and hawaiitic composition within a palagonitized yellow matrix. The massive stucture and intensive lithification are very pervasive in this breccia. There is incipient lamination in the lowest levels. The highest levels show a gradual transition to subaerial deposits of the Upper subaerial

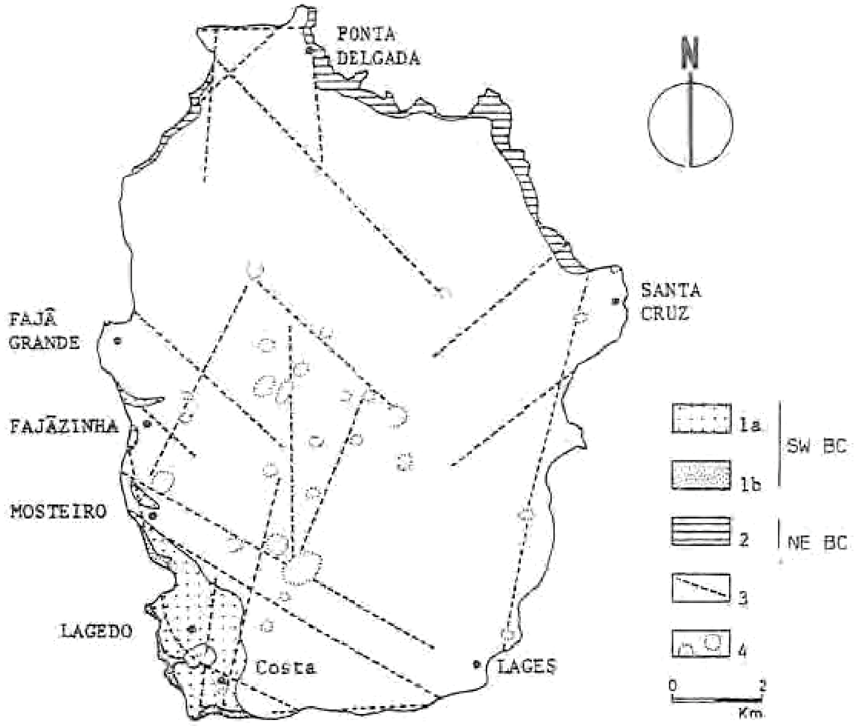

Fig. 3. Map of Flores Island showing: a) the BC formations (1a- Southwest BC1; 1b- Southwest BC2; 2- Northeast BC); b) the localization of the principal faults (3) and the volcanic calderas and craters (4); c) the localization of the dated samples.

Complex. The maximum thickness of this unit is about 100 meters.

Palagonitized Basalts and Hawaiites (pbH). The basalts of this unit are porphyritic rocks, strongly palagonitized. They occur between Lagedo and Costa do Lagedo. The lava flows, each 1 to 5 meters thick, are sometimes interleaved with pyroclastic levels.

The hawaiites occur between Mosteiro and Lagedo and at Fajazinha. They show subaphyritic texture, no vesiculation and are densely jointed. The thickness of this unit never exceeds 50 meters.

The Lower volcanic Breccia (LvB) is mostly composed of pyroclasts and autoclasts. Some epiclasts can be found in the Mosteiro area. The dimension of the fragments ranges from a few centimeters to 0.8 meters. The clasts are supported by a palagonitized matrix. An important secondary lithification is present in some areas. An incipient stratification with alternating layers of small and large fragments is common in this breccia. The topmost levels consist of ash laminae and poorly lithified lapilli and ash. In the lowest level one may find massive blocks without matrix. The whole unit is variable in thickness and dips gently toward the west.

Base Complex 2 (BC 2). In this complex two units have been mapped (AZEVEDO 1988): *i) Basalts and Hawaiites* (bH); *ii) Stratified volcanic Breccia (SvB).* Both units dip about 20° towards the Northeast.

The *Basalts and Hawaiites (bH)* unit is a 20 meters thick succession of basaltic and hawaiitic lavas with intercalated pyroclastic material, where single flows never exceed 4 meters. In some places pillow structures can be found. The thickness of the pyroclastic levels are always less than that of adjacent lava flows. All these rocks are strongly palagonitized.

The *Stratified volcanic Breccia (SvB)* occurs in a small zone of the western cliffs of Lagedo. It is totally composed of well stratified volcanic breccia, with frequent large autoclasts and a minor amount of pyroclasts. The clasts range from 1 to 10 centimeters in size and are all covered by a thick film of alteration products.

The supporting matrix is strongly palagonitized and lithified. A "double-grading" structure (CAS & WRIGHT 1988) is particularly well developed in this breccia, the uppermost levels of which are entirely composed of lithified volcanic ashes.

The section of this unit where seen above sea level is nearly 15 meters thick.

Northeast Base Complex (NE BC). The exposed area of this Base Complex is smaller than that of the SW BC. Both Complexes have some characteristics in common, particularly the high proportion of volcanoclastic deposits. The stratigraphy of this Complex, however, is more irregular than that of the SW BC.

The base of the NE BC is usually formed by a succession of thick basaltic and hawaiitic lava-flows. The middle levels are mainly of pyroclasts and autoclasts supported in a palagonitized matrix, rather simillar to the SW BC volcanoclastic deposits. Fining-up granulometric sequences are very common. These may end up in tuff deposits. The upper levels are formed by a sequence of thin basaltic lava flows interleaved with laminae of thin pyroclastic material.

There is a good correlation between the geochronology of the SW BC and the NE BC (Fig. 2 and Table 1). The oldest volcanic formation is seen in the NE BC, near Ponta Delgada.

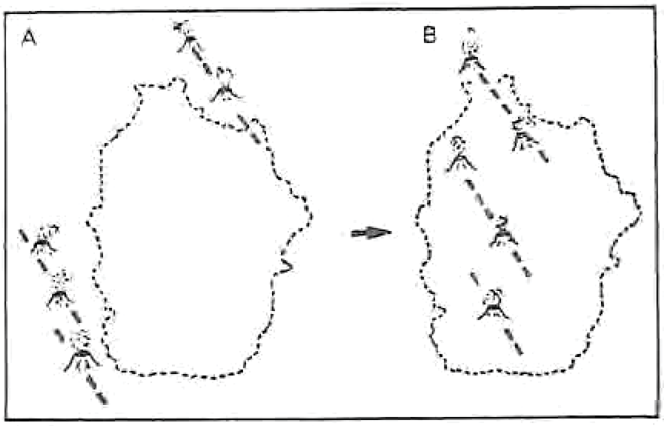

Fig. 4. A simplified picture showing the probable rotation of the feeder centers during the building up process of the BC: A- BC 2 feeder centers localization; B- BC 1 feeder centers localization.

Between Santa Cruz and Ponta Delgada the BC formations dip approximately 20° to the South-southeast. In Ponta do Albernaz the breccia deposits clearly dip toward the North-northwest.

DISCUSSION

The volcanic setting and buildup processes of the Base Complex

The volcanic processes which were directly or indirectly responsaible for the buildup of the BC are here interpreted as being initially submarine but trending toward emergent during the final phases. The volcanism alternated between explosive and effusive activity, with a clear predominance of the explosive processes.

The volcanic setting

The symmetric relationship between the SW BC and the NE BC reflects the influence of the strong NNW-SSE stuctural lineaments (Fig. 3) on the localization and evolution of the volcanic centers. Later activity along these alignments controlled the volcanism of the Upper subaerial Complex (UC).

The dip of the oldest formations of both the NE BC and the SW BC (BC 2) suggests that the localization of their volcanic feeders were outside the present island (Fig. 4A): towards North and Northeast for the NE BC and toward West and Southwest for the SW BC. Later on, the feeder centers migrated toward the Island (Fig. 4B). This is inferred from the structure of the BC 1 (SW BC) and of the Ponta do Albernaz NE BC. The marked angular and lithological discontinuities between BC 2 and BC 1 also indicate such a migration.

The initial feeder centers cannot be located with precision since the pristine volcanic morphology has been largely obliterated by marine erosion and by later subaerial volcanism.

The processes of volcanic buildup

The great variation in the structures and rock types that comprise the BC volcaniclastic

deposits point to many processes involved in the buildup (AZEVEDO 1988).

The large volume of the volcaniclastic deposits resulted from: *i*) very active and long-lasting feeder centres; *ii*) highly efficient fragmentation processes and; *iii*) quiet deposition on the ocean floor surrounding the volcanic centers.

The volcanic clasts present in the BC deposits evidence the importance of pyroclastic and autoclastic processes. In SW BC, three distinct phases of fragmentation could be defined, reflecting the migration of the volcanism from deep to emergent levels:

i) The period of autoclastic fragmentation, with a particular emphasis on thermal granulation, which requires a very deep volcanism (Fig. 5), probably reaching below the Pressure Compensation Level (PCL)(FISHER 1984). The lower stratigraphic levels (SvB of BC2), composed exclusively of autoclasts, resulted from this type of volcanism.

ii) The domain of steam explosions (WOHLETZ 1983), resulting from a volcanism at variable depths between the PCL and the VFD (Volatile Fragmentation Depth) (FISHER & SCHMINCKE 1984); the large amount of pyroclasts in the upper levels of SW BC (LvB of BC1) (Fig. 5) are the result of this type of volcanic activity.

iii) The domain of the magmatic and steam explosions, controlled by an upper VFD and emergent volcanism that produced the materials that constitute the highest levels of the BC on Flores.

The presence of abundant rounded clasts shows that epiclastic processes were also active.

The considerable thickness and the high incidence of massive fabrics in all the volcaniclastic deposits (for example, in SvB and LvB of BC1) suggest a rapid succession of submarine volcaniclastic flows. In turn, the occurrence of such a large amount of volcaniclasts associated with a supporting matrix, suggests transportation by debris-flow (AZEVEDO 1988, 1990).

The presence in some levels (base of LvB and BC 1) of large volcanoclasts without a supporting matrix suggest the development of coarse grain-flows. On the other hand, the oc-

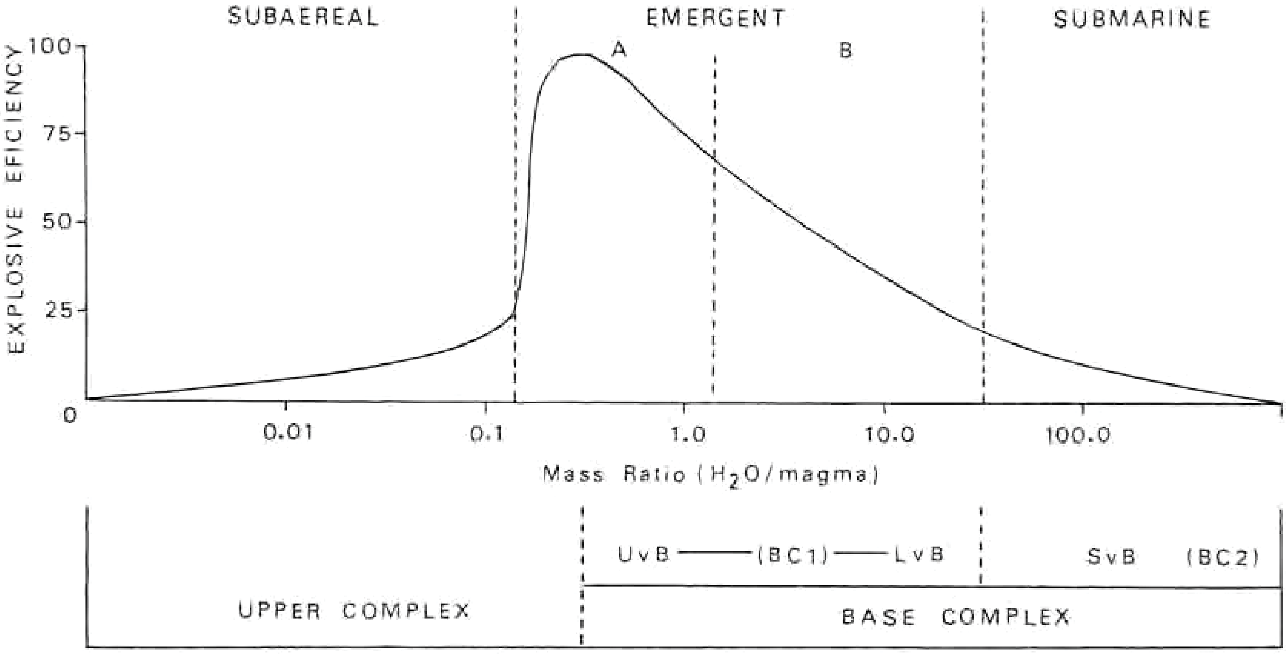

Fig. 5. Attempted correlation between the BC explosive volcanism, represented by the BC volcanic breccias (UvB- Upper volcanic Breccia and LvB- Lower volcanic Breccia of BC 1; SvB- Stratified volcanic Breccia of BC 2), and the theoretical diagram of volcanic explosive efficiency: A - emergent volcanism resulting of a periodic inundation of the vent; B- emergent volcanism resulting of a permanent inundation of the vent (WOHLETZ 1983, CAS & WRIGHT 1987).

currence of some restricted level composed of very fine fragments (SvB of BC 2) indicate the development of turbidity currents and mud-flows. Other mechanisms, however, such as ballistic projection, should not be ruled out.

The rarity of pillow-stuctures in the BC lavas is explained by a limited time of extrusion and restricted thickness of these lava flows. Another reason might be a high gradient of the ocean floor at the eruption centers.

CONCLUSIONS

Summary of the evolution of the western group of the Azores

The results of this study allow us to draw general conclusions concerning style, time and space of the sequential phases of the volcanic growth of Flores, which rests on a 9.0 Ma old ocean floor (KRAUSE & WATKINS 1970), at a distance of about 180 Km from the Mid-Atlantic Ridge.

At the present time the Western Group of the Azores is composed of Flores and Corvo. However, about 5.0 Ma ago, another island emerged from the Atlantic, only to subside later, becoming a seamount (depth 450 m) 50 km west of Flores (RYALL & al. 1983).

From our own studies of Flores island and from the findings of RYALL & al. (1983) and SERUGHETTI & ROCHA (1968), it is possible to reconstruct the evolution the Western Group of the Azores, (Fig. 6):

i) Sea floor stage. Volcanism to form the ocean floor started 10 Ma ago in the vicinity of the island that now corresponds to the seamount (BLAKELY 1974), and 9.0 Ma ago in the vicinity of Flores and Corvo (KRAUSE & WATKINS 1970).

ii) Proto-island stage. This stage developed locally following formation of the volcanic ocean floor. The emergent volcanism of this phase lasted until 5.0 Ma ago at the site of the western bank and until 0.65 Ma ago in Flores.

iii) Island stage. The basalts formed during this stage to form the western bank were formed 4.81 ± 0.20 Ma ago. In Flores this stage

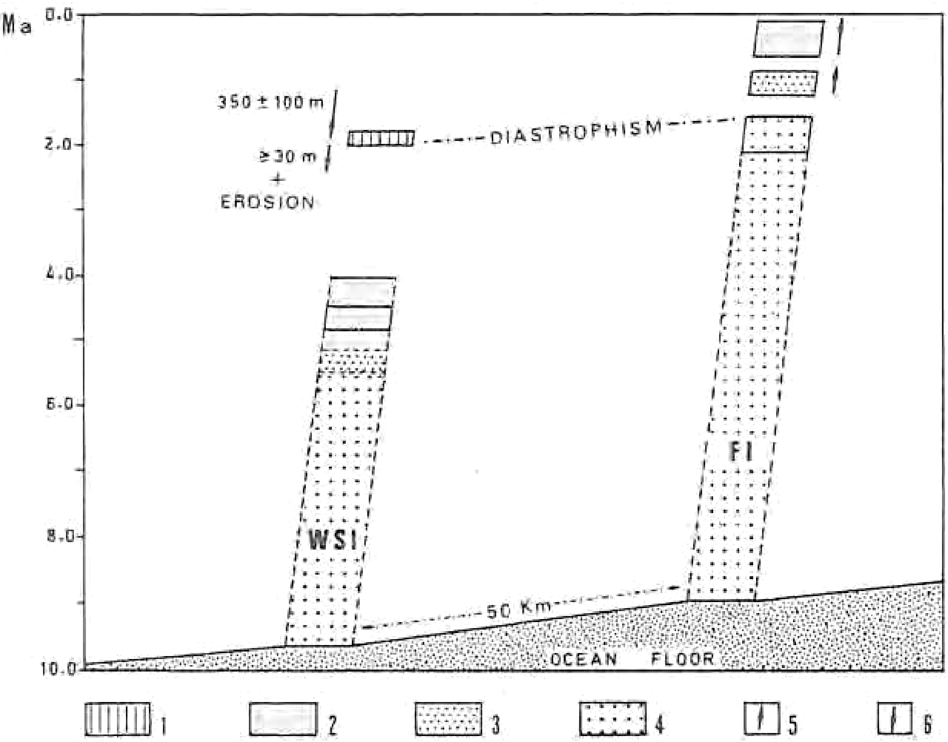

Fig. 6. Synopsis for the geologic evolution of Flores (FI) and Westwards Subsided Island (WSI) (seamount): 1- Carbonates; 2- Subaerial volcanism; 3- Emergent volcanism; 4- Submarine volcanism, Proto-island volcanism; 5- Uprise; 6- Subsidence.

started 0.65 Ma ago and continued until 0.2 Ma ago (MORISSEAU 1985). This subaerial volcanism was associated with uplift.

Although both the western seamount and Flores, went through similar stages of evolution initially, their later evolution was quite different:

The seamount that was built up 50 Km west of Flores eventually subsided at least some 30 meters and was significantly eroded, to form a submarine plateau covered by biogenetic carbonates, with fossils the age of which is about 1.8 Ma. The continuation of downward movement took the plateau to the position it now occupies at a depth of 440 meters.

As regards Flores island, there is no evidence of any post-volcanic subsidence and its present geotectonic stability is remarkable.

This rather diverse kinematic evolution for two very close domains on the same plate (American) suggests that: *i*) the plate is to be considered as composed of very restricted domains, like a big puzzle; *ii*) for each of the sub-domain, the initial buildup process may be similar, but their subsequent evolution is different; *iii*) the uplifts and subsidences need to be studied at a local level and they must be carefully examined before any wide interpretation is attempted.

In spite of a East-West trending fracture system on Flores, no such structure is known to occur between the two islands (Flores and Corvo) and the Mid-Atlantic Rift. It is, after all, a well known region for its seismic stability. However, it is possible that healed ancient fractures may exist. Such a structure is recognised in relation to the western branch of the EAFZ, between Santa Maria Island and the Middle Rift, and may have played an important role in the volcanism of that area.

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