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THE MAIN CHARACTERISTICS OF THE MAGMATISM OF THE CAPE VERDE ISLANDS (*)

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(3 figures dans le texte)

RÉSUMÉ

La formation la plus ancienne reconnue jusqu'ici aux îles du Cap Vert est celle qui constitue la partie centrale de l'île de Maio (complexe central igné) : il s'agit de laves en coussins ayant une composition de tholéiite océanique. Des arguments structuraux, pétrographiques et géochimiques permettent d'affirmer que ce complexe igné représente un fragment de la croûte océanique de l'Océan Atlantique s'étant formé à la fin du Jurassique ou au début du Crétacé.

Le magmatisme qui s'est développé après le soulèvement de ce segment d'ancien fond océanique à la surface de l'océan se caractérise par une composition fortement alcaline, allant depuis des néphélinites et des néphélinites mélilitiques jusqu'à des basanites; en outre d'importantes intrusions de syénites néphéliniques et de carbonatites se sont mises en place dans certaines îles.

La genèse des laves alcalines est interprétée par une fusion de la pyrolite à phlogopite dans une partie profonde du manteau.

La transition depuis un volcanisme à composition de tholéiite océanique vers un magmatisme basique fortement alcalin est mise en relation avec l'apparition de fractures transverses dans l'Océan Atlantique.

ABSTRACT

The oldest rocks known on the Cape Verde Islands form the basement of the island of Maio; this « central igneous complex » is built up by pillow lavas of oceanic tholeiitic composition. Structural, petrographical and geochemical arguments support the hypothesis that this complex formed part of the ocean floor of the Atlantic Ocean during the Late Jurassic or Early Cretaceous.

After the uplift of that segment of ancient ocean floor to sea-level the lavas erupted on Maio became strongly alkaline. They range from nephelinites and melilite nephelinites to basanites and are accompanied by important intrusions of nepheline syenite and carbonatites.

The basic alkaline magmatism probably results from the fusion of phlogopite pyrolite in a deeper zone of the mantle.

An attempt is made to correlate the transition from oceanic tholeiitic to basic alkaline volcanism with the development of transverse fracture zones in the Atlantic Ocean.

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1. INTRODUCTION

Although oceanic islands have been studied for more than one hundred years, our present knowledge on ocean-floor spreading and plate tectonics is mainly the result of hardly two decades of intensive geological and geophysical prospection of ocean floors and ocean ridges. As a consequence of the abundant information provided by these recent deep-sea investigations a reinterpretation of all data available on oceanic islands became inevitable.

The dissimilarity between deep-sea volcanism and volcanism on oceanic islands and between different islands within the same oceanic basin, cannot be explained with a simple model of magma generation and magma evolution. In that respect a crucial position is taken by islands near continental margins. On such islands interactions may occur between the lower continental crust and the upper mantle at the moment of the break-up of the continents, when new oceanic areas are created.

From this point of view the Cape Verde Islands occupy a privileged position as they are located in the eastern part of the Atlantic Ocean, less than 500 km offshore the African continent. Most volcanic rocks of these islands are hyperalkaline in strong contrast with the tholeiitic ocean-floor basalts. Moreover on some islands alkali syenites and carbonatites are exposed, which are usually considered as rock types with continental affinities. These unusual rock compositions suggest that the Cape Verde magmatism is governed by completely different processes (as far as magma generation and evolution is concerned) than those acting in other areas of the Atlantic Ocean.

The purpose of the present paper is in the first place to study the magmatic evolution of the Cape Verde archipelago and to evaluate the possible influence of crustal material on its genesis. Further an attempt will be made to correlate the magmatic evolution with the main tectonic features which affected that part of the Atlantic Ocean since its opening about 135 million years ago.

2. CONCISE GEOLOGICAL AND STRUCTURAL OUTLINE OF THE ARCHIPELAGO

The major tectonic features of the Cape Verde archipelago are suggested by the linear distribution of the main islands of the group and correspond with WNW-ESE, WSW-ENE, N-S and E-W trending lines. Field observations as well as recent geophysical surveys support this hypothesis. The N-S fracture pattern is very conspicuous in the eastern part of the archipelago (Sal, Boa Vista, Maio) whereas the other trends are more evident on the westernmost islands.

The islands are all capped with a subaerial sequence of alkaline Cenozoic lavas and pyroclastic rocks of basic composition including nephelinites, melilitites, basanites and olivine basalts. Phonolite plugs and pyroclasts are often associated with these basic rocks and constitute the most differentiated members of the alkaline series. Although Tertiary and Quaternary sediments are found on most islands, they are always of minor importance.

The islands aligned along the E-W direction are capped with large stratovolcanoes with well preserved morphology; their base rests on horizontal pillow-lava layers. As a result of the strong erosion which prevailed on the archipelago since the end of the Tertiary, the core of the Cenozoic volcanoes is frequently exposed and mainly consists of essexites, nepheline syenites and even carbonatites.

On the islands aligned along the N-S direction the cover of alkaline Cenozoic lavas is less complete, resulting either from a less extensive Cenozoic volcanic activity on these islands, or from a stronger uplift and erosion.

Although the denudation of the pre-Tertiary basement is quite uncommon it provides valuable information about the earliest history of the archipelago. In that respect the small island of Maio undoubtedly occupies a key-position among all Cape Verde Islands. On Maio one cannot only obtain data on the composition and the age of the older formations of the archipelago but also on the way of their emplacement. For that reason special attention will be paid to that island.

3. THE PRE-TERTIARY BASEMENT OF MAIO : AN UPLIFTED OCEAN-FLOOR SEGMENT

The pre-Tertiary basement of Maio is exposed in the central part of the island (fig. 1). Towards its periphery it is covered with tabular Paleogene and Neogene lavas and sediments or with a thin cover of Quaternary deposits.

The basement consists of volcanic formations (the so-called « central igneous complex ») which are overlain to the west and to the east by limestones showing an anticline structure. The strike of these limestone beds is approximately NNW-SSE. Some of them contain abundant layers of flint. Towards the top the limestones become argillaceous and grade into marls and clays. At their base pyrite concretions occur and the limestones tend to be more clayey and reddish in colour.

The limestone complex is underlain by hyaloclastites interbedded with limestone beds whose importance gradually diminishes towards the base. Finally the hyaloclastites pass into a homogeneous pillow complex. As there is no interstitial material the pillows fit well one another. The pillow complex is cut by numerous sills and breccious rocks appear in its upper part. In the central part of the igneous complex small essexite plugs, associated with nepheline syenites, occur. The extent of the central igneous complex approximately corresponds with the area covered by the lavas belonging to the 1st and 2nd phase as defined by SERRALHEIRO (1970).

The pillow complex of central Maio is probably the oldest formation of the whole archipelago. The age of the complex is unknown but paleontological data afforded by the overlying limestone beds support a minimum age of at least Early Cretaceous or even Upper Jurassic.

Besides the major anticline deformation, small folds of decametric amplitude affect the marls and clays of the upper part of the pre-Tertiary limestone complex. The axial planes of these folds are parallel to the axis of the major anticline. Another striking feature of the geology of Maio is the existence of a network of fractures along two main and almost perpendicular directions, N-S and E-W. The N-S trending fractures may be responsible for the uplift of the central part of the island.

The structure of the Early Cretaceous (or Upper Jurassic) pillow complex of Maio is obviously different from that characterizing much younger pillow deposits on the Cape Verde Islands such as those outcropping along the shoreline of southern S. Tiago. The latter are composed of cylindric lava pillows which are cemented by a fine matrix of hyaloclastites. The pillows of the central igneous complex of Maio, on the contrary, are piled up without interstitial material. Hyaloclastites may also occur in this case but only as well defined layers in some breccious beds on top of the pillow complex. Moreover the nature of the hyaloclastites is different in both localities. On S. Tiago island they consist of pillow debris whereas on Maio they are composed entirely of glassy shards.

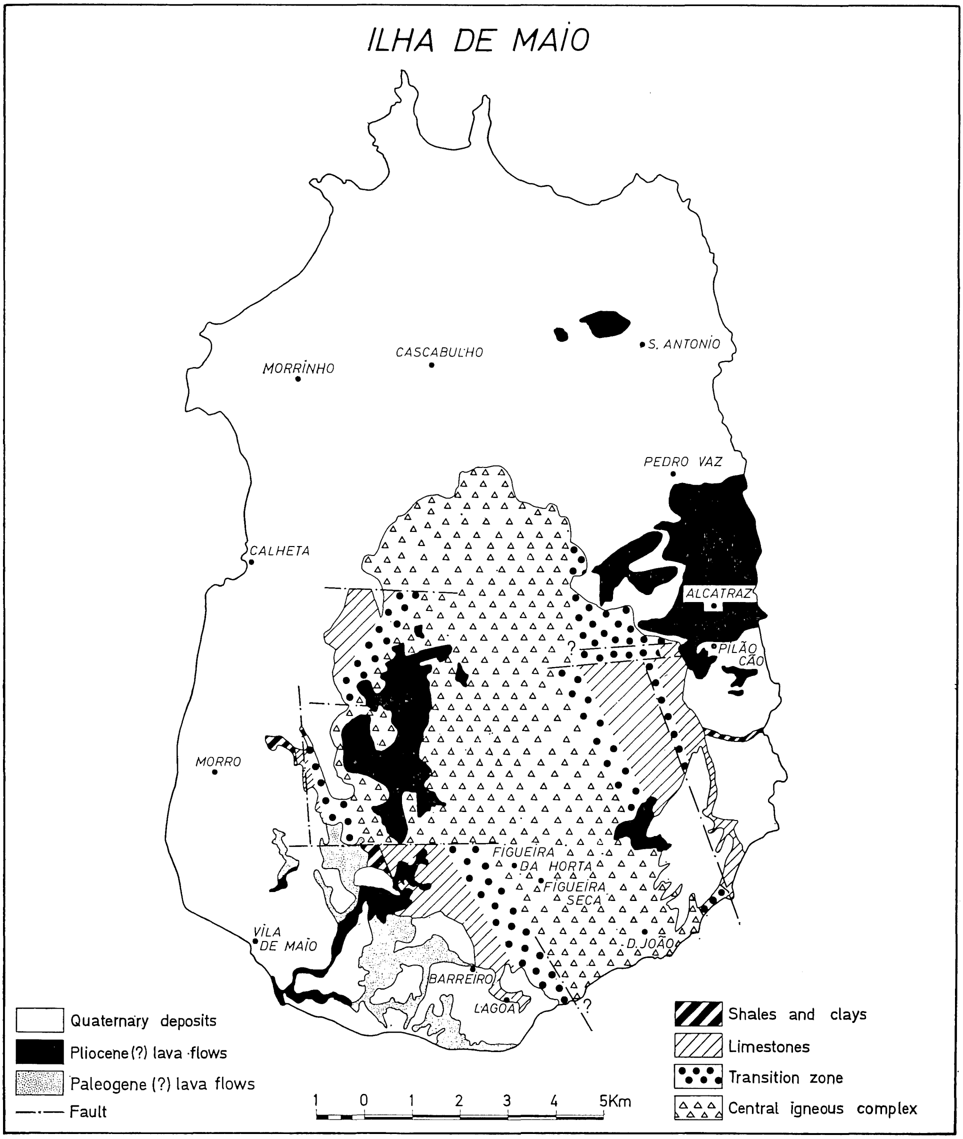

Fig. 1. — Generalized geologic map of Maio.

Furthermore it is worth mentioning that for both kinds of pillow formations the bathymetric conditions during the eruption were completely different. The pillows of southern S. Tiago are shallow-water deposits; those from Maio cooled at depths of more than 2000 m below sea-level as shown by the microfauna included in the overlying limestones (Teixeira, 1950; Cleintuar, personal communication).

With this in mind it can be very useful to compare now the structural, mineralogical and chemical characteristics of the pillow formation of Maio with those observed in present-day ocean-floor basalts.

As mentioned above, sills are common features in the central igneous complex of Maio. Locally they may be so numerous that it becomes quite difficult to recognize the pillow structure of the host rock. Everywhere on the island it is hard to establish a correct time relation between sills and pillows. Differences in composition and weathering state support the idea that the sills were injected during a long period of time. Some sills seem more or less contemporaneous with the pillows; others probably intruded much later. Whereas the sills are extremely abundant in the central igneous complex they appear only occasionally in the calcareous complex on top of them. This is in good agreement with deep-sea records which have shown that the injection of sills preferentially occurs at the contact between the volcanic layers and the sedimentary cover (McBirney, 1971).

Among the sedimentation structures which affect the Mesozoic limestones of Maio, slump structures are prominent. They appear as disharmonic folds with horizontal axial planes and bear witness of the uplift of the beds soon after their deposition. This uplift resulted in flowage and deformation of the poorly consolidated sediments.

Owing to the vicinity of the continent these slump structures might be interpreted as a response to movements within the continental slope. Such movements were probably very common in the period following the opening of the Atlantic Ocean. But in that case the question arises why no detrital sediments have been transported from the continent by the turbidity currents induced by the flexures. It appears therefore more plausible to assume that the slumping phenomena originated from deformation of the ocean crust.

Recent geophysical investigations around the Cape Verde archipelago (Dash *et al.*, 1976) have shown the existence of a N-S trending upheaval zone called Sal-Maio Ridge. It is delimited to the east, and perhaps less obviously to the west, by important fractures. Along these fractures a block has been lifted up on which Maio is located. Field observations in the Mesozoic limestone complex of Maio support that view and moreover indicate that the Sal-Maio Ridge already existed in Mesozoic times.

All these structural arguments lead to the concept that the central igneous complex of Maio not only represents a segment of the Atlantic proto-oceanic crust but also that that part of the Atlantic Ocean was affected by tectonic movements as early as Late Jurassic and Cretaceous times. Petrochemical and mineralogical data also support this hypothesis and will be discussed below.

The strongly alkaline trend of the Cenozoic magmatism of the Cape Verde Islands is well known and is demonstrated by a hasty petrographical study of Paleogene and Neogene lava flows of Maio. Nevertheless the deep-sea basalts from the central igneous complex of Maio are tholeiitic in composition. Although in that respect microscopical data do not yield irrefutable and definite arguments the mineralogy suggests tholeiitic affinities. The rocks are aphanitic to moderately porphyric basalts with phenocrysts of plagioclase, subcalcic augite and scace olivine in an almost entirely glassy matrix.

From the chemical point of view the similarity between the deep-sea basalts of Maio and ocean-floor basalts from all over the world is remarkable (De Paepe *et al.*, 1974). This relationship is particularly well demonstrated by the trace elements and especially by the rare-earth elements. The chondrite-normalized REE patterns of the Maio submarine basalts are very much alike. All rocks show an obvious light rare-earth depletion and the latter is progressively decreasing from the light towards the heavy lanthanides (fig. 2). Such patterns are typical for lavas from mid-oceanic ridges and ocean floors and contrast with the distribution patterns of these elements in Coryell-Masuda diagrams of alkaline basalts. Alkaline basalts display a relative enrichment of the light rare-earth elements as compared with the heavy lanthanides.

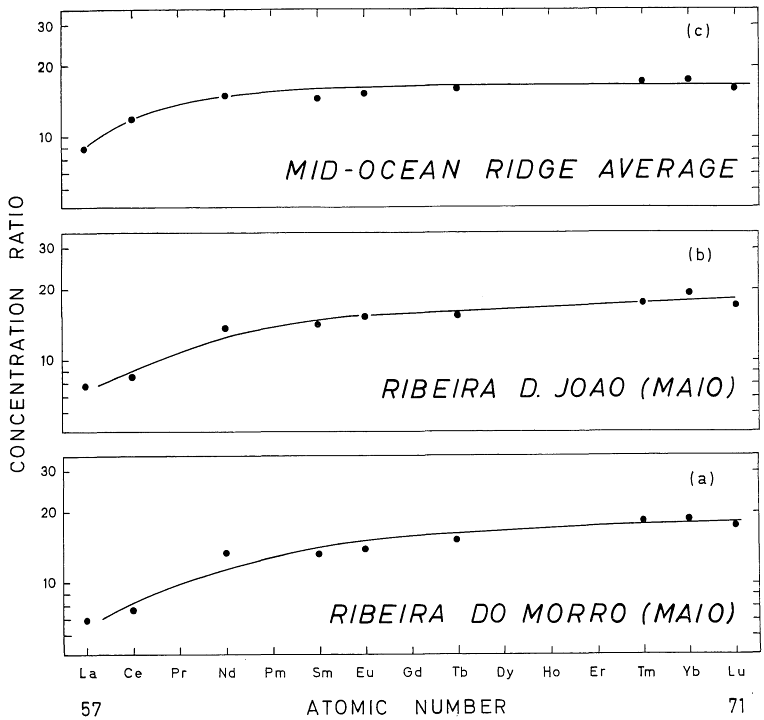

Fig. 2. — Chondrite-normalized REE patterns of tholeiitic basalts : (a) average of two tholeiites from the vicinity of Ribeira do Morro (De Paepe *et al.*, 1974); (b) average of three tholeiites from the surroundings of Ribeira D. João (De Paepe *et al.*, 1974); (c) mid-ocean ridge average (Schilling, 1971).

The hydrothermal metamorphism which affects the pillow complex on Maio is a common feature in dredged ocean-floor basalts. In the submarine basalts on Maio this phenomenon is fairly well developed and results in the complete obliteration of the igneous texture with the formation of a metamorphic paragenesis in which only a few relicts of the primary mineralogy are preserved. The metamorphic reactions start with albitization of the plagioclase accompanied by neoformation of epidote and calcite : chlorite becomes the main constituent of the matrix. With an increasing degree of metamorphism biotite appears and finally the paragenesis consists of actinolite, albite, carbonates and epidote. Metamorphism is very irregularly distributed in the central igneous complex, but it appears that the metamorphic rocks are restricted to the vicinity of fracture zones, along which hydrothermal weathering occurs.

This kind of metamorphic reactions, as well as the relation between metamorphism and hydrothermal activity along fracture zones, confirms the statement that oceanic metamorphism is related to the presence of hot aqueous fluids

(MIYASHIRO, 1973). These fluids also seem to be responsible for the particularly high heat flow values occurring at some places of the mid-ocean ridges.

All these structural, geochemical and mineralogical arguments support the hypothesis that the central igneous complex of Maio once belonged to the oceanic crust of the Atlantic Ocean. This statement is in good agreement with recent geophysical data published by DASH *et al.* (1976) suggesting that the crust beneath the Cape Verde Islands — which at the present day shows a transitional character — was in the beginning of a purely oceanic nature. Features in favour of this theory are the typical oceanic nature of layer 3 of velocity 6.3 km/sec and the location of the magnetic quiet zone boundary (considered as the limit of opening of the ocean) at the east of the archipelago. On the other hand *Lamellaptychus angulocostatus atlanticus,* which characterizes the Mesozoic limestones of Maio, has also been found east of Cape Hatteras, North Carolina (RENZ, 1972). This may suggest that both localities were close together at the end of the Jurassic or at the beginning of the Lower Cretaceous (DASH *et al.*, 1976).

It is further worth mentioning that the stratigraphical sequences explored around the Cape Verde Islands during Leg 41 by the Glomar Challenger (LANCELOT *et al.*, 1975) are identical to those found in the North-American basin (Leg 11), and particularly that the basal carbonatitic sequence of the North-American basin is lithologically and stratigraphically nearly identical to the limestone complex outcropping on top of the central igneous complex of Maio.

4. GENETICAL CONSIDERATIONS ABOUT THE HYPERALKALINE MAGMATISM

The strongly alkaline trend of the Cenozoic volcanism on the island of Maio has been reported above. This trend is however not limited to that place of the archipelago and characterizes all Tertiary and Quaternary volcanic activity on the Cape Verde Islands.

The major part of the lavas fall in the range of basanites, nephelinites, melilitites and even phonolites, whereas the plutonic rocks are dominantly essexites and nepheline syenites, with associated carbonatites, the latter rock types outcropping principally on the islands of Fogo and Brava.

The origin of the alkaline volcanism sets a major problem for the genesis of the oceanic magmatism. If we consider the regional distribution of the different types of basaltic rocks within the Atlantic and Pacific Ocean it is conspicuous that, on the one side, the ocean floors are predominantly covered with oceanic tholeiites and that, on the other hand, oceanic islands are mainly covered with tholeiites of transitional character and by alkaline rocks. In some archipelagoes, such as Hawaii, nephelinites and melilitites may occur but the amount of these highly undersaturated rocks is always small and their occurrence is limited to a late magmatic or post-erosional stage. This contrasts with the abundance of strongly alkaline rocks on the Cape Verde Islands. Moreover nepheline syenites and carbonatites — which are rather unusual in an oceanic environment — become quite important. The case of the Cape Verde Islands is not unique as hyperalkaline rocks abound on both sides of the Atlantic Ocean, namely on the islands of Fernando de Noronha, Martin Vaz and the Bermudas as well as in the Canarian archipelago. On the Canary Islands however the alkaline trend is less distinct. All these islands are located near continental margins and their eccentric position — in the vicinity of a continent — may imply that material of the continental crust is involved in the genesis of strongly alkaline magmas.

For the Cape Verde Islands, recent geophysical investigations have shown that the crust underlying the archipelago presents an oceanic character and that the transitional thickness of the crust in that area of the Atlantic is only due to a depression of the Mohorovicic discontinuity caused by the accumulation of volcanic material erupted on or near the islands (DASH *et al.*, 1976). Unfortunately this statement does not allow to exclude entirely that the upper mantle has suffered some contamination by material of the continental crust which was possibly incorporated in the mantle at the moment of the continental break-up.

For this purpose the strontium isotopic rations of a series of lavas and intrusive rocks from the Cape Verde Islands have been measured; the analysed samples cover the whole range of chemical compositions found in Cape Verdian magmatic rocks (KLERKX *et al.*, 1974). The isotopic ratios vary between narrow limits from 0.7029 to 0.7033. This is appreciably lower than the ratios found in rocks from other oceanic islands and even close to values characterizing oceanic tholeiites. Therefore one can exclude a contamination by sialic material or an origin in a mantle with intermediate composition resulting from interaction with the continental crust.

Assuming that the Cape Verde magmatism is entirely oceanic, the question remains why its composition is so different from that of ocean-floor basalts and even rocks of most oceanic islands. In that respect some comments can be made with the help of the Sr isotopic data and other geochemical ratios such as K/Rb and Rb/Sr.

The isotopic ratios of all analysed rocks are quite constant whereas the $K_2O/K_2O + Na_2O$ values vary between 0.20 and 0.45. When these values are plotted on a $K_2O/K_2O + Na_2O$ versus $^{87}Sr/^{86}Sr$ diagram it appears that the most basic rocks from the Cape Verde Islands, namely the nephelinites and melilite nephelinites, join the variation trend defined by PETERMAN & HEDGE (1971) for all oceanic rocks (fig. 3). This probably means that the variation series originates from a parental magma whose composition is nephelinitic. According to experimental data nephelinitic magma types are generated by partial melting of a small fraction of pyrolite under hydrated conditions, at pressures between 18 and 37 Kb, corresponding to depths between 70 and 100 km (GREEN, 1970). Phlogopite may be considered as the hydrated phase in the mantle.

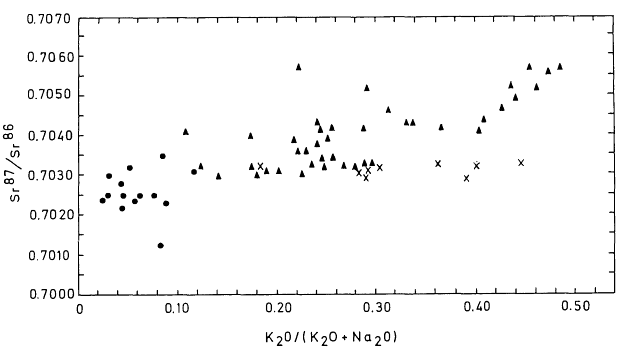

Fig. 3. — Variation of Sr^{87}/Sr^{86} versus $K_2O/K_2O + Na_2O$ in rocks from the Cape Verde Islands compared with oceanic basaltic rocks. Dots represent ocean ridge tholeiites (PETERMAN & HEDGE, 1971); triangles correspond to basaltic rocks of oceanic islands (PETERMAN & HEDGE, 1971) and crosses represent rocks of the Cape Verde Islands (KLERKX *et al.*, 1974).

This confirms the model of magma generation within the oceans as proposed by McBirney & Gass (1967). According to these authors there is a close correlation between the magmatism and the heat flow, and magmas generated in the outer parts of the oceans come from deeper zones of the earth mantle than magmas in more central parts.

Although more recent data on heat flow do not always support such a simple model it seems nevertheless applicable to those volcanic provinces, such as the Cape Verde Islands, which are located near inactive continental margins.

5. Discussion and conclusions

Our data show clearly that the alkaline magmatism is prevailing on the Cape Verde Islands since the upheaval of the archipelago. Earlier volcanic activity (Late Jurassic or Early Cretaceous) was essentially oceanic tholeiitic and resembles from any point of view oceanic volcanism occurring along mid-oceanic ridges.

At present one of the crucial questions on the Cape Verde magmatism is when the change from tholeiitic to alkaline magmatism took place and how significant such a drastic change may be in relation to the tectonic evolution of the Atlantic Ocean.

The earliest traces of the alkaline magmatism date back to the Mesozoic. They are found in the pyroclasts which occur near the contact between the central igneous complex of Maio and the overlying limestone beds. These rocks contain some titaniferous amphiboles. This mineral seems characteristic for the alkaline rock suite and is always absent in tholeiitic rocks. With the exception of a few sills, the Cretaceous limestone complex of Maio is devoid of volcanic rocks. This indicates that there was a long interruption of volcanic activity between the earlier phase of deep-sea volcanism and the subaerial Cenozoic alkaline volcanism which probably started soon after the uplift of the islands above sea-level. This has to be confirmed by absolute age determinations. Such determinations are in progress in order to date the stratigraphical positions of the old tholeiitic complex and the earliest phase of the alkaline magmatism, and also the numerous sills injected in the central igneous complex.

The change from tholeiitic to alkaline magmatic regime was probably induced by different geotectonic conditions. It has indeed been suggested that the presence of undersaturated lavas in an oceanic environment may be related to tectonic phenomena acting in the lithosphere (shear melting : Hawaii, Samoa) (Hawkins & Natland, 1975). Moreover in both oceanic areas and in rift zones (Afar) alkaline basaltic volcanism appears along transverse structures in contrast with the tholeiitic magmatism which characterizes axial structures (Barberi *et al.*, 1974; Melson & Thompson, 1971; Honnorez *et al.*, 1970; Rech. Géol. Afrique, CNRS, 1973-74). For this reason it seems reasonable to assume that within the Cape Verde area the appearance of alkaline basaltic rocks succeeding the tholeiitic ocean-floor basalts, as early as the end of the Mesozoic, is a result of the formation of important transverse zones in that part of the Atlantic Ocean.

It thus appears that the association of two types of magmatism is characteristic for the Cape Verde Islands. The earliest volcanism was oceanic tholeiitic in composition and ceased abruptly during the Early Cretaceous; from many points of view it resembles oceanic volcanism occurring along mid-oceanic ridges. After the upheaval of the ancient ocean floor to the surface of the ocean, probably during the mid-Tertiary, strongly undersaturated alkaline magmatism was active.

The region of the archipelago was tectonically active at different periods. The Mesozoic deposits, both volcanics and overlying sediments, have been deformed at the time of their formation. Another important tectonic phenomenon was the uplift of the islands to their present position at the surface of the ocean.

Further studies are needed to confirm the hypothesis that the development of the alkaline volcanism is related to the appearance of transverse fracture zones in the young Atlantic Ocean.

Although a general explanation has been suggested for the origin of the alkaline volcanism, conditions governing the development of important masses of nepheline syenite and carbonatite from a basic alkaline parental magma remain to be considered.

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REFERENCES

Assunção, C. T. de, Machado, F. and Gomes, R. A., 1965. — On the occurrence of carbonatites in the Cape Verde Islands. *Bol. Soc. Geol. Port.*, **16**, 179-188.

Assunção, C. T. de, Machado, F. and Serralheiro, A., 1968. — New investigations on the geology and volcanism of the Cape Verde Islands. *XXIII Intern. Geol. Congr.*, **2**, 9-16.

Barberi, F., Bonatti, E., Marinelli, G. and Varet, J., 1974. — Transverse tectonics during the split of a continent : data from the Afar Rift. *Tectonophysics*, **23**, 17-29.

Dash, B. P., Ball, M. M., King, G. A., Butler, L. W. and Rona, P. A., 1976. — Geophysical investigation of the Cape Verde archipelago. *J. Geoph. Res.* (in press).

De Paepe, P., Klerkx, J., Hertogen, J. and Plinke, P., 1974. — Oceanic tholeiites on the Cape Verde Islands : Petrochemical and geochemical evidence. *Earth Planet. Sci. Lett.*, **22**, 347-354.

Green, D. H., 1970. — A review of experimental evidence on the origin of basaltic and nephelinitic magmas. *Phys. Earth Planet. Interior*, **3**, 221-235.

Hawkins, J. W. and Natland, J. H., 1975. — Nephelinites and basanites of the Samoan linear volcanic chain : their possible tectonic significance. *Earth Planet. Sci. Lett.*, **24**, 427-439.

Honnorez, J. and Bonatti, E., 1970. — Nepheline gabbro from the Mid-Atlantic Ridge. *Nature*, **228**, 850-852.

Klerkx, J. and De Paepe, P., 1971. — Cape Verde Islands : Evidence for a Mesozoic oceanic ridge. *Nature Phys. Sci.*, **233**, 117-118.

Klerkx, J., Deutsch, S. and De Paepe, P., 1974. — Rubidium, strontium content and strontium isotopic composition of strongly alkalic basaltic rocks from the Cape Verde Islands. *Contr. Mineral. and Petrol.*, **45**, 107-118.

Lancelot, Y. and Seibold, E., 1975. — The eastern North Atlantic. *Geotimes*, **20**, 7, 18-21.

Machado, F., Azeredo Leme, J., Monjardino, J. and Seita, M. F., 1968. — Carta geológica de Cabo Verde, notícia explicativa da folha da ilha Brava e dos Ilheus Secos (na escala 1/50.000). *Garcia de Orta* (Lisboa), **16**, 123-130.

McBirney, A. R., 1971. — Oceanic volcanism : a review. *Rev. Geoph. Space Phys.*, **9**, 523-556.

McBirney, A. R. and Gass, I. G., 1967. — Relations of oceanic volcanic rocks to mid-oceanic rises and heat flow. *Earth Planet. Sci. Lett.*, **2**, 265-276.

MELSON, W. G. and THOMPSON, G., 1971. — Petrology of a transform fault zone and adjacent ridge segments. *Phil. Trans. Roy. Soc. London*, A **268**, 633-664.

MELSON, W. G., HART, S. R. and THOMPSON, G., 1972. — St. Paul rocks, Equatorial Atlantic : petrogenesis, radiometric ages and implications on sea-floor spreading. *Geol. Soc. Am. Mem.*, **132**, Hess Memorial Volume, 241-272.

MITCHELL-THOME, R. C., 1974. — The sedimentary rocks of Macaronesia. *Geol. Rundschau*, **63**, 1179-1216.

MIYASHIRO, A., 1973. — Metamorphism and metamorphic belts. G. Allen and Unwin, 492 pp., London.

PETERMAN, Z. E. and HEDGE, C. E., 1971. — Related strontium isotopic and chemical variations in oceanic basalts. *Bull. Geol. Soc. Am.*, **82**, 493-499.

PITMAN III, W. C., LARSON, R. L. and HERRON, E. M., 1974. — The age of the ocean basins (two charts and summary statement). *Geol. Soc. America*.

RECHERCHES GÉOLOGIQUES EN AFRIQUE, 1973-1974. — *CNRS*, **2**, Paris.

RENZ, O., 1972. — Aptychi (Ammonoida) from the Upper Jurassic and Lower Cretaceous of the western North Atlantic : *in* HOLLISTER, C. D., EWING, J. I. *et al.*, 1972. *Initial Reports of the Deep Sea Drilling Project*, XI, 607-620. Washington.

RONA, P. A., BRAKL, J. and HEIRTZLER, J. R., 1970. — Magnetic anomalies in the Northeast Atlantic between the Canary and Cape Verde Islands. *J. Geophys. Res.*, **75**, 7412-7420.

SCHILLING, J.-G., 1971. — Sea-floor evolution : rare-earth evidence. *Phil. Trans. Roy. Soc. London*, A **268**, 663-706.

SERRALHEIRO, A., 1970. — Geologia da Ilha de Maio (Cabo Verde). Junta de Investigações do Ultramar, 103 pp., Lisboa.

TEIXEIRA, C., 1950. — Notas sobre a geologia das Ilhas Atlanticas. *Ann. Fac. Ciên. Porto*, **33**, 193-233.