NEW K-AR AGES, CHEMICAL ANALYSES AND MAGNETIC DATA OF ROCKS FROM THE ISLANDS OF SANTA MARIA (AZORES), PORTO SANTO AND MADEIRA (MADEIRA ARCHIPELAGO) AND GRAN CANARIA (CANARY ISLANDS)

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ABSTRACT

K/Ar-determinations, major and trace element chemical analyses and magnetic data are reported for rocks from Santa Maria (Azores), Madeira and Porto Santo, and Gran Canaria. Based on these data, the age of the basement of Santa Maria

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is believed to have formed between about 5.2 and 4.6 Ma, the unconformably overlying pillow complex interbedded with fossiliferous calcarenites about 3.8 to 3.3 Ma with the capping subaerial basalt being part of the same magmatic phase. The major erosional phase levelling the basement is thus approximately synchronous with the major Pliocene regression (R2) on Gran Canarıa (Lietz and Schminke, 1975), possibly indicating a widespread eustatic event. The upper part of the submarine, partly fossiliferous series of Porto Santo was dated as ca. 12 to 13 Ma and the Quaternary age for the major basalt formation in Eastern Madeira (Watkins and Abdel Monem, 1971) is confirmed. The agess of several formations on Gran Canaria were slightly revised.

Chemical differences between basement (shield) and later posterosional series on Gran Canaria are re-emphasized by the new data, while such differences are much less pronounced between the basement and younger series on Santa Maria.

I. - INTRODUCTION

The present study is a continuation of our previous studies on the age of volcanic rocks from volcanic islands in the central North-Atlantic (Lietz & Schmincke, 1975 ; McDougall & Schmincke, 1976 ; Feraud, 1977 ; Feraud *et al.*, 1980). It focusses on three main problems :

a) What is the temporal and structural relationship between the onset of volcanism and progression of volcanic islands and the three different structural environments represented : triple junction (Azores), proximity to passive plate boundary (Madeira group) and boundary between oceanic and continental lithosphere (Canary Islands) ?

b) Does the chemical composition of magmas change with time during the evolution of a volcanic island ?

c) Can the formation of calcarenites of shallow marine origin which occur on all three island groups be dated more precisely and do these represent one or more fluctuations in late Tertiary sea level of local or regional nature ?

II. - ANALYTICAL TECHNIQUES

K/Ar-ages were measured by Feraud on samples of 1 to 3,5 g. which were as fresh as possible, by experimental procedures of argon measurement described elsewhere in more detail (Feraud *et al.*, 1980 ; Feraud, 1977). The extraction and purification line, in pyrex, is directly connected to a modified THN 205 mass spectrometer. The mass fractionation is periodically measured by atmospheric air introduction. The atmospheric $^{40}Ar/^{36}Ar$ ratio is known with a precision better than $\pm$ 1 %. The argon amount of the blank is on the order of 1 to 3. 10^{-12}moles. The measurement reproducibility was tested in this study with samples MA 35 and M 41 (table 1, 2), and the measurements of standard are given elsewhere (Feraud *et al.*, 1980). K-concentrations were measured by atomic absorption in Montpellier by C. Dupuy and by X-ray fluorescence in Bochum. The constants compiled by Steiger and Jäger (1977) were used for the age calculations.

Total rock samples analyzed by Amdel (Australia) were prepared by crushing the rock to pass 22 B.S. mesh. The $-22+36$ B.S. fraction is screened out and 1/4 of this fraction is pulverised to pass 150 B.S. mesh. Aliquots of 250 to 300 mg of the pulverised fraction were used for potassium analysis and 8 to 10 g samples of the $-22+36$ B.S. mesh material are used for Argon analysis.

K was determined by atomic absorption after digestion of the sample in HF and H_2SO_4. A high concentration (approximately 2000 ppm Cs) of Cs_2SO_4 was added to each solution to act as an ionisation suppressant. Four or five measurements were made on each unknown solution and on standard solutions of higher and lower K concentration. Duplicate analyses, particularly for total rock samples, usually agree to within 0.5 %.

As was measured by isotope dilution using a high purity ^{38}Ar tracer. The isotopic ratios were measured using an extensively modified MS-10 mass spectrometer. Five or six sets of measurements were made for 40/38 and 38/36 ratios. Instrumental precision is normally high, giving a standard deviation of approximately 0.1 % for 40/38 and 0.3 % for 38/36. However, the analytical error of the Ar determination increases greatly when the percentage of radiogenic Ar relative to total Ar (i.e. radiogenic plus atmospheric) falls below 15-20 %.

Chemical Analyses : Major, minor and trace elements were analyzed by X-ray fluorescence methods on glass fusion beads, using a fully automatic Philips PW 1400. The fusion beads consist of rock powders (dried 110°C for 10 minutes and poured into a 34 mm diameter pellet mold). Fe (II) was determined by semi-automatic potentiometric titration of the hydrofluoric acid — silver perchlorate digested sample, with standard potassium bromide solution ; CO_2 by closed-system, coulometric titration of a barium perchlorate solution into which was passed the gases produced by passing oxygen over the sample roasted in a tube furnace ; and H_2O^+ by closed system, coulometric titration of a non-aqueous Karl-Fischer reagent into which was passed the inert carrier gas (here nitrogen) containing water stripped from the sample by heating in a Pt-crucible to 1300°C with an induction furnace.

III. - RESULTS

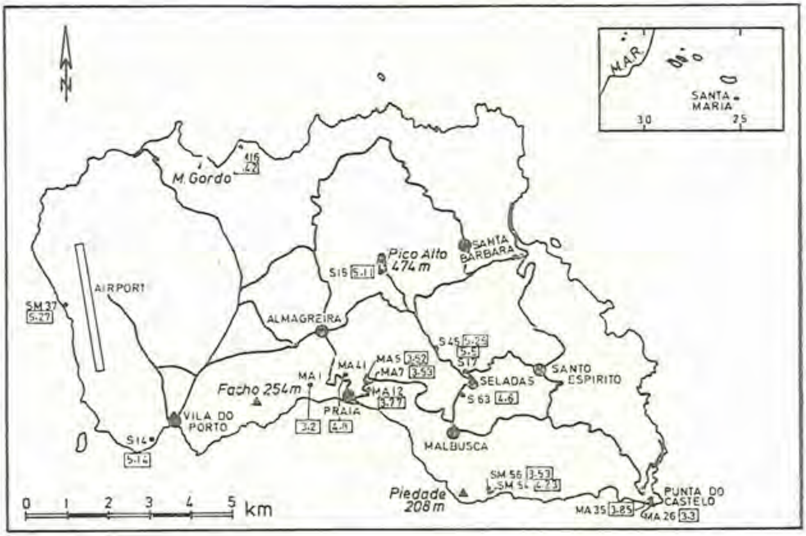

Fig. 1 — Map of Santa Maria (Azores islands, see inset) schowing K/Ar ages in Ma (boxes) and sampling localities. See table 1 for details.

SANTA MARIA

Santa Maria, the easternmost of the Azores islands, situated some 430 km east of the Mid Atlantic Ridge consists of a low mountain chain, running NNW-SSE, parallel to a dike swarm (Fig. 1). A large plateau cut by a NE-SW dike swarm close to Vila do Porto forms the western part of the island. This is the only island of the archipelago with fossiliferous sediments.

ZBYSZEWSKI & FERREIRA (1962b) proposed the following formations :

(1) Old basalt series cut by numerous dikes ;

(2) Volcanic breccias along a widespread erosional level near the town of Santana ;

(3) Fossiliferous sediments of Helvetian/Tortonian age ;

(4) Younger basaltic series covering the sedimentary rocks ;

(5) Young cinder cones.

SCHMINCKE & STAUDIGEL (1976) divided the island into three main formations :

(1) Volcanic basement (consisting of basaltic, especially ankaramitic lavas and dikes including some intermediate to trachytic rocks) levelled by marine erosion, the erosional surface dipping E below sea level in the southeastern part of the island.

(2) The submarine complexe, generally less than 100 m thick, consisting of interlayered pillow lavas, hyaloclastites, calcarenites, conglomerates, sandstones (partly terrestrial ?) and some subaerial lavas.

(3) Younger, subaerial volcanic series consisting of basaltic to intermediate lavas and scoria cones.

These authors describe the submarine complex, i.e. formations 2 and 3 of Zbyszewski *et al.* in more detail, presented chemical data and interpreted the pillow lavas as shallow marine terminal ends of subaerial lava flows.

Abdel-Monem *et al.* (1975) published K/Ar-age determinations of 8.12 and 6.08 Ma for the old (1) and 4.13 for the younger basaltic series (4). They assumed that the fossiliferous sediments (coquina) were deposited during a non-volcanic

interval from ca. 4 to 6 Ma. Feraud *et al.* (1980) measured K/Ar-ages of 4.2-4.9 Ma below the coquina zone and two ages of 5.1 Ma in the central chain and on the western plateau near Vila do Porto.

Basement complex

We have dated 5 samples from the basement complex (old series) : 3 basalt dikes (eastern part of the island, S 17, S 45, S 63), 1 benmoreite dike (Praia, MA 41), and 1 basalt flow (west coast, SM 37) (Fig. 2-3, tab. 1). Ages determined range from 4.6 to 5.5 Ma with the older age showing a large error due to the high atmospheric contamination of the sample. The new data together with 3 ages from this formation published by Feraud *et al.* (1980), clearly indicate that the lowermost basalts were emplaced during the very late Miocene to early Pliocene, i.e. between 5.5 and 4.6 Ma during a time period of at most 0.9 Ma. We believe our data give a more consistent age distribution of this formation than the ages of 8.12 and 6.08 Ma published by Abdel-Monem *et al.* (1975) because: (1) The data presented here and by Feraud *et al.* (1980) collected by three different groups and dated in two different laboratories show a high degree of internal consistency; (2) Basalt SM 37 (5.14 Ma) occurs about 70 m stratigraphically *below* SMA-3B (8.12 Ma) dated by Abdel-Monem *et al.* (1975). Mc. Dougall and Schmincke (1976) noted a similar discrepancy between their age data for the shield building basalts of Gran Canaria (Canary Islands) and those of Abdel-Monem *et al.* (1971), the later more detailed study showing the age data for the shield lavas to be both younger and much more tightly grouped than those of the earlier study. Many oceanic islands are constructed very rapidly during their first and often major phase of volcanic activity (shield phase) and the late Miocene to early Pliocene basement lavas of Santa Maria may represent the shield phase of this island.

Submarine complex

The basal complex is cut by a major erosional unconformity that is below sea level in the southeast and central northern part of the island, but rises to more than 70 m above sea level along the southern coast at Praia, the main section studied. The basement rocks are overlain by a series varying in thickness from ca. 50 to over 100 m that consists of variable amounts of conglomerates, sandstones, fossiliferous calcarenites, hyaloclastites and, locally, pillow lavas.

We have dated 2 samples from pillows in the central part of the series (MA 26 and SM 54), 2 samples from pillows from topmost lavas of the submarine series (SM 16, MA 7) and one sample from the base (MA 12). Ages range from 4.2 ± 0.1 Ma to 3.3 ± 0.3 Ma.

However, we regard the date of MA 26 (3.3 Ma) as too young, because (1) it is overlain by lava dated as 3.85 Ma and (2) because subaerial lavas overlying the submarine section are dated in neighbouring sections as around 3.5 Ma. This anomalously young age of MA 26 may be due to argon leakage from the glassy groundmass; the low Na/Ka-ratio of the rock also suggests that the glass has been hydrated and chemically changed, possibly accompanied by argon loss.

The age of SM 54 (4.12 Ma) may be too old because (1) the four other samples of the submarine complex give similar ages between 3.3 and 3.8 Ma and (2) major unconformities were not found between the rocks of this and those of the overlying series (see below), in contrast to the major unconformity at the base of the submarine series.

Subaerial Basalts

Subaerial basal lavas overlying the submarine series in 4 sections (Fig. 2) along the south coast (from west to east: MA 1, MA 5, SM 56, MA 35) were dated as 3.2, 3.5, 3.53 and

3.85 Ma. Possibly, the alkali basalt MA 35 (3.85 Ma) is part of the submarine series because of the higher age and its elevation above sea level. The ages nevertheless show that there is no major time gap between the submarine and subaerial lavas in the south. This is also suggested by the geological evidence. For example, topmost lavas of the submarine series have a pillowed base, evidence for eruption in very shallow water. Thus, the topmost pillow and the lowermost subaerial lavas may be part of the same eruptive interval, during which the first lavas filled up a shallow delta, while the later ones spread on dry land formed by the earlier flows.

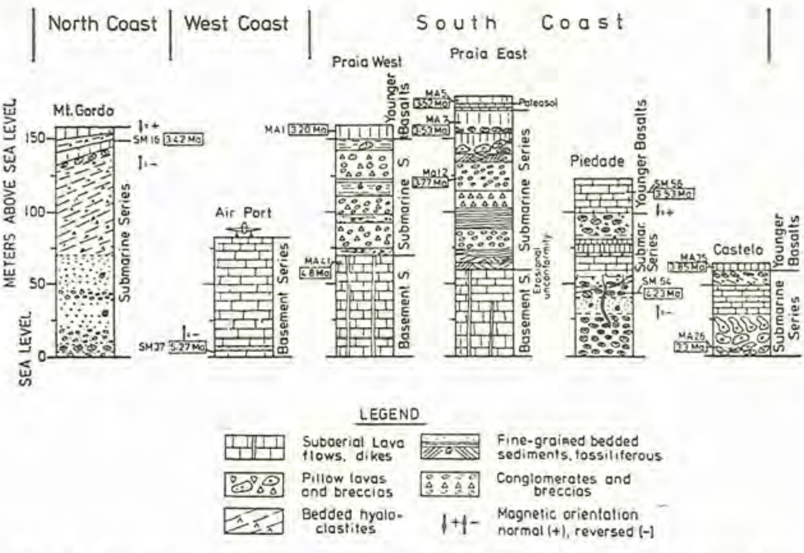

Fig. 2 — Stratigraphic sections of Santa Maria showing stratigraphic position of main samples dated and magnetic polarities as measured by fluxgate in the field. For locations of figures see Figure 1.

At Praia, the topmost lavas of the submarine series are slightly weathered and overlain by a paleosol that formed prior to eruption of lavas MA 1 and MA 5. The age difference

between these lavas which are chemically identical are not real and the evidence of minor weathering cannot be interpreted as representing a major time gap.

In conclusion, pillow and overlying subaerial lavas along the southern coast of Santa Maria were all emplaced about 3.3 to 3.8 Ma ago, about 0.5 to 1 Ma later than emplacement of the basement series.

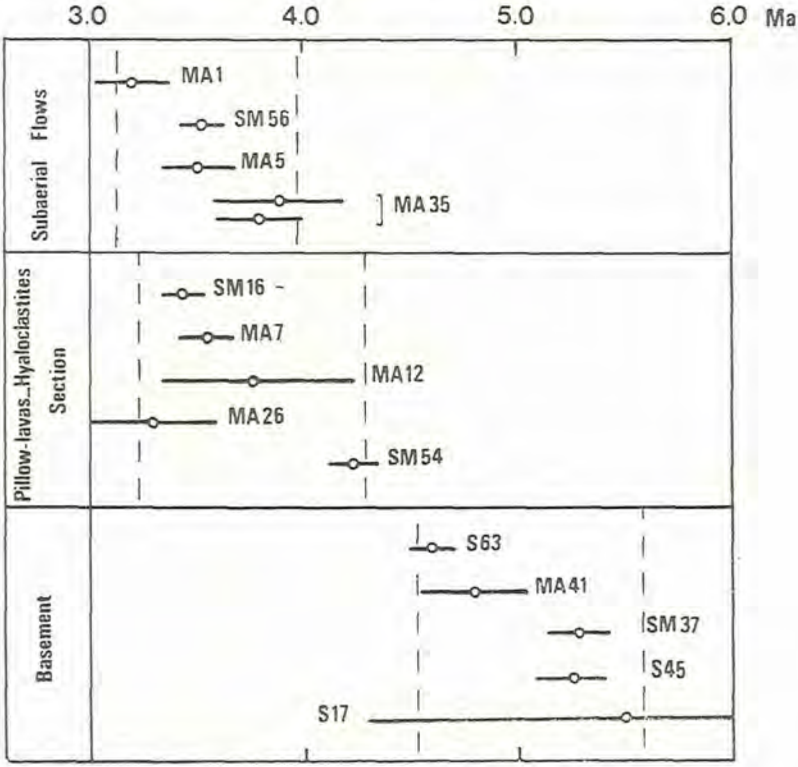

Fig. 3 — Distribution of ages measured within the three main rock formations of Santa Maria.

TABLE 2

K/AR AGES AND LOCALITIES OF MADEIRA ARCHIPELAGO SAMPLES

Island	*Formation*	*Sample*	*Rock type*	*Locailty*	K_2O %	*Weight* g	$^{40}Aatm$ / $^{40}Atotal$	*Radiogenic* ($X10^{-12}$ m
	Pico Ruivo	M 12	Alkali olivine basalt dike	Path Pico Arreira to Pico de Ruivo 1750 m abole sea level	1.0	2.0970	83.6	1.38
Madeira	basaltic	M 5	dito	dito about 1600 m	0.90	2.7000	90.5	1.60
	complex	M 4	dito	dito	0.83	2.2978	78.9	1.67
		M 3	dito	dito	0.80	2.1583	78.4	2.09
Porto Santo	Submarine basal complex	PS 4	Hawaiite lava flow, overlying main pillow series	Ribeira Dentro Barranco das Feiteras	0.6	1.5291	46.0	10.7
		M 41	Trachyte intrusion	Ribeira Dentro	1.27	2.1211 2.0743	42.1 44	23.0 23.1
		PS 2	Trachyte dike cutting upper pillow lavas	Ribeira Dentro Barranco das Feiteras	1.7	1.4724	18.3	32.2

Ages measured by FERAUD, G. and GASTAUD, J.

Paleomagnetics

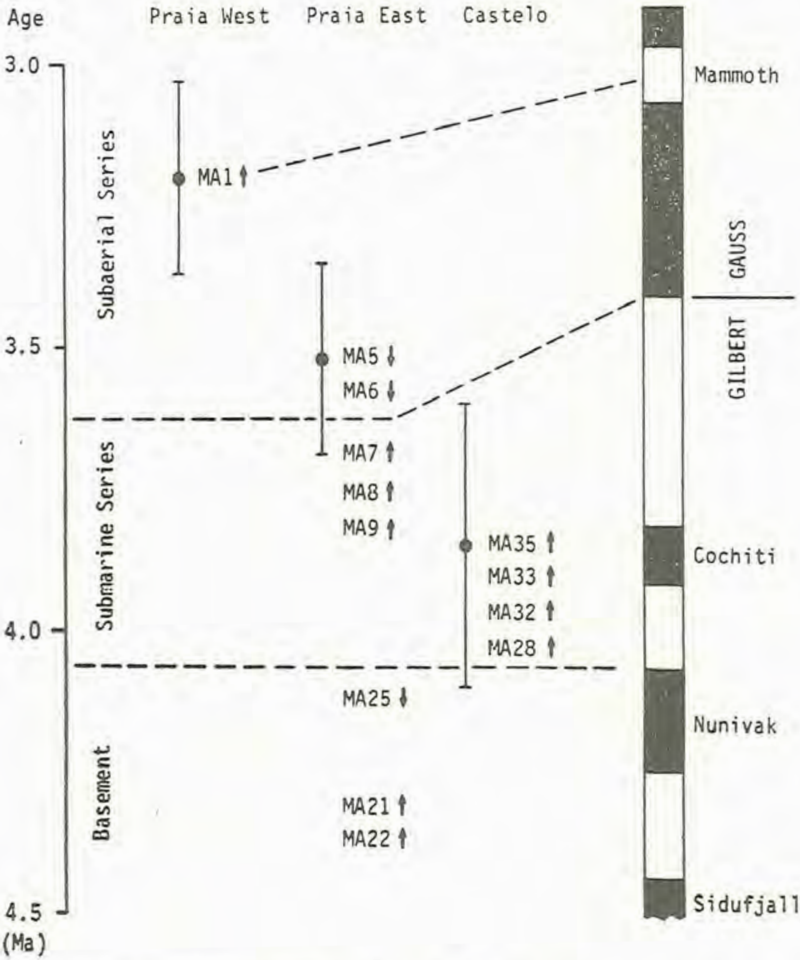

Fig. 4 — Paleomagnetic stratigraphy of Santa Maria volcanics. Geomagnetic polarity time scale of McDougall (1977) : positive polarity — black, negative polarity — white. Polarity of remanent magnetism of rocks : positive polarity : arrow down, negative polarity : arrow up. K/Ar ages according to table 1.

A paleomagnetic reconnaissance study was carried out on rocks of some sections in Santa Maria in order to provide aditional age control. The results are summarized in Figure 4. Nine lavas and dikes were sampled at the Praia sections comprising the entire sequence from the basement to the subaerial series. In addition, four lavas of the submarine section were studied from the Castelo section. On the average, stable remanent directions were determined from five samples per volcanic unit using an AF-demagnetization technique. The data will be published elsewhere in more detail.

The tentative identification of the polarity sequence as given in Figure 4 is based on the most recent polarity time scale of McDougall (1977) adjusted to the revised ^{40}K decay constant (Steiger and Jager, 1977). For this purpose, the radiometric ages obtained here on the basalt lavas MA 1, MA 5, and MA 35 (Table 1) were used as a general framework. Acceptable consistency of ages and magnetic polarities of these lavas with the earth magnetic field chronology is only achieved if the standard deviations of the K/Ar measureemnts are taken into account. The mean values of both MA 1 and MA 5 appear to be slightly too old. Due to the relative large experimental error, the age and polarity of MA 35 cannot directely be related to a specific polarity interval of the earth field.

The youngest rocks of the basement exposed in the Praia east section just below the erosional unconformity are a lava flow (MA 21) which is cut by a dike (MA 25). MA 25 has a positive, MA 21 a negative magnetic direction. The radiometric ages obtained indicate that most of the basement at Santa Maria formed during the negative Gilbert polarity epoch (about 5.4 to 3.4 Ma) MA 25 thus should mark one of the positive polarity events within this negative period. The Nunivak event ending at about 4.1 Ma seems to be the most plausible, but the evidence is insufficient to exclude the younger Cochiti or the older Sidufjall events ending at 3.8 and 4.4 Ma, respectively.

The K/Ar age range for the submarine complex including unit MA 35 from the Castelo section roughly covers the younger

(< 4 Ma) part of the Gilbert negative polarity epoch. The consistently negative polarity of all rocks studied from this formation further supports these age data. The time boundary between the submarine and subaerial series at least in the southern area of the island should be somewhere near the transition from the Gilbert to the Gauss positive geomagnetic polarity epoch (about 3.4 Ma). This is indicated by the change in magnetic polarity between lavas MA 7 and MA 6. The youngest lava in the Praia region (MA 1) most likely falls into the first negative polarity event within the Gauss epoch, the Mammoth event (3.17 to 3.07 Ma) which also would be in agreement with a K/Ar age of 3.20 ± 0.17 Ma (Table 1).

For several volcanic units from the Mt. Gordo, Airport, and Piedade section the directions of natural remanent magnetization have been determined on oriented handspecimen using a fluxgate magnetometer. Samples from the basement and submarine series show negative polarities, whereas the subaerial basalts have a positive magnetization (Figure 2). These results, therefore, are entirely consistent with the interpretation given above that the older formations were emplaced during the negative Gilbert geomagnetic epoch, the younger subaerial lavas during the positive Gauss period.

MADEIRA ARCHIPELAGO

Madeira archipelago lies at the southwestern end of the NE-SW complex Madeira-Tore Rise. It consists of the two islands Madeira and Porto Santo and three little Desertas islands.

Madeira

Zbyszewski (1971, 1972) and Aires-Barros *et al.* (1974) define the following volcanic series from Madeira: a) A Miocene basal complex mainly of pyroclastic rocks of which the younger, more effusive part locally contains Vindobonian reef deposits.

b) Post-Vindobonian complexes that contain more lavas than pyroclastic rocks. c) A very effusive volcanism resulting in lava series, distributed in three different areas of the island. d) A young volcanic complex formed by cones and intracanyon lava flows. The petrology of the island has been discussed by Schmincke and Weibel (1972), Hughes and Brown (1972) and Aires-Barros *et al.* (1974). Major dike swarms with dominant directions mainly from E-W to NW-SE occur in several parts of the island (Zbyszewski, 1972, 1972). Watkins and Abdel-Monem (1973) have measured K/Ar-ages between 3.05 and 0.7 aM on lavas northeast of Funchal, but still older rocks may exist on the island.

We have dated four dikes, oriented approximately east-west most of which were described and analyzed by Schmincke and Weibel (1972), from the eastern central part of the island (table 2 ; figure 2 in Schminke and Weibel, 1972). The ages, ranging from 1.8 to 1 Ma, are very similar to those reported by Watkins and Abdel-Monem (1973) collected from the same general area. Thus, an important volcanic phase occurred on Madeira between about 1 and 2 m.y., possibly chiefly along E-W fissure zone in the center of the island.

Porto Santo

The geology of this small island, 45 km northeast of Madeira is not well known. Petrographic and chemical data were published by Aires-Barros *et al.* (1969) and Schmincke & Weibel (1972), and Lietz & Schwarzbach (1970) describe new localities of marine Tertiary fossils. Schmincke & Staudigel (1976) inferred that most of the exposed rocks of the island are submarine in origin and divided the submarine series into an older, trachytic series unconformably overlain by a basaltic — hawaiitic submarine to subaerial series. Submarine rocks occur at least as high as 300 m above sea level indicating either uplift of the island or lowering of sea level, or both.

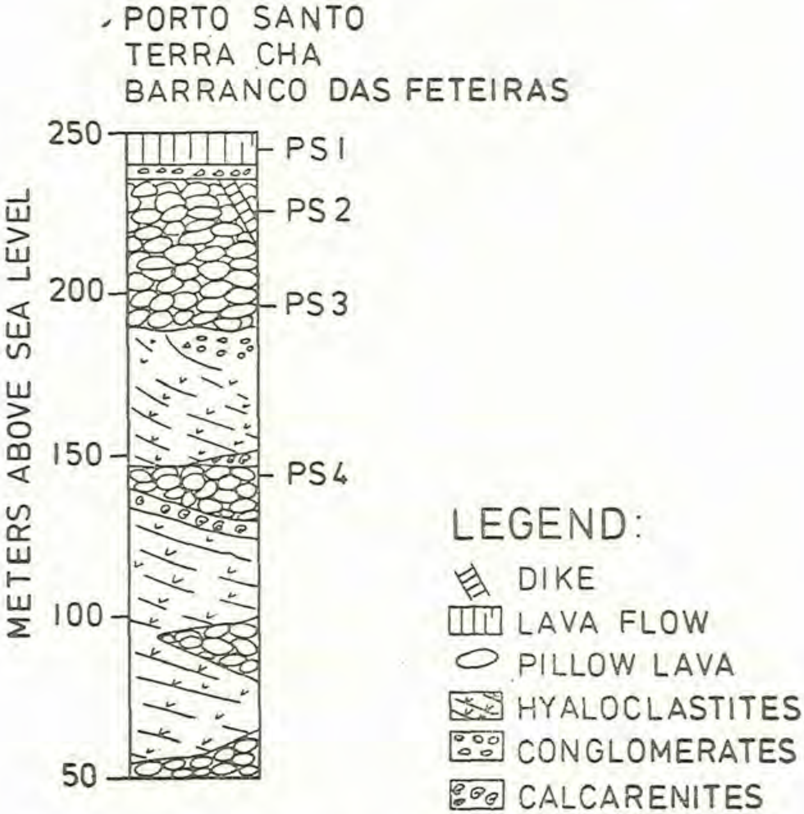

Fig. 5 — Stratigraphic section of submarine section of Porto Santo showing sample positions.

We have dated two trachyte intrusions, one below the basaltic pillow complex (M 41) and one cutting the pillow lavas (PS 2) and one basalt from the pillow series overlying conglomerate and fossiliferous beds (PS 4) (Fig. 4, table 2). All samples are from the Ribeira Dentro section, below Terra Chã, in the northeastern corner of the island (see figure 3 in Schmincke and Weibel, 1972). The ages are similar and range from 12.3 ± 0.4 to 13.1 ± 0.4; the age of 13.1 is probably

slightly too high since this trachyte is probably stratigraphically younger than the two other rocks. These ages are similar to those published by Macedo *et al.* (1974) of what they call upper submarine and subaerial basalts and mugearites dated as 13.1 to 12.6 Ma. These authors report ages of 15.7 to 16.4 Ma for older trachyte to trachyrhyolitic cryptodomes from this part of the island and younger trachytes dated as 13.8 Ma underlying the conglomerates and calcarenites. A more detailed comparison is impossible at present because the data by Macedo *et al.* (1974) are only available in abstract form.

Most exposed volcanic rocks of Porto Santo were emplaced during the middle Miocene, perhaps chiefly between approximately 12.5 and 13.8 Ma. Thus, the basement of Porto Santo is very similar in age to that of Gran Canaria, whose shield was constructed between 13.5 and 14 Ma (McDougall and Schmicke, 1976). At least the upper part of the submarine, seamount stage of Porto Santo is not much older than the overlying subaerial lavas, judging from the data presently available. This is an important point since in most islands such as Santa Maria and Gran Canaria, only the subaerial phase has been dated due to subsequent subsidence of the islands.

The timing of uplift of Porto Santo is still uncertain. Macedo *et al.* (1974) report ages of 11.2 and 12.4 for subaerial lavas, thought to have been erupted after uplift, but the question still remains whether these could be the subaerial part of the same magmatic phase and record emergence of the island above sea lever rather than uplift.

GRAN CANARIA

Gran Canaria, one of the two central large volcanic islands in the Canarian archipelago has a long and complexe geologic history from the Middle Miocene to the Recent (Schmincke, 1976). The subaerial part of the island was constructed during

three main magmatic phases: (1) The major and shield forming phase produced moderately alkalic basalts overlain by several hundred km^3 of rhyolitic to nepheline phonolitic ignimbrites and lava flows and lasted from about 14 to 12 Ma with some extrusive and intrusive activity extending to about 8.7 Ma; (II) During the second main phase more alkalic basanitic to phonolitic magmas were erupted, the different formations being named Roque Nublo Group, emplaced chiefly between 4.4 and 3.5 Ma; (III) Nephelinites (Los Llanos Formation) were erupted around 2.8 Ma, with melilite nephelinite following at 1.8 Ma, and still younger basanites.

The first K/Ar data were published by Abdel-Monem *et al.* (1971) and more detailed studies were presented by Lietz & Schmincke (1975) and Mc Dougall & Schmincke (1976).

Mogan Formation

A widespread but thin alkali basalt («trachybasalt») formation interbedded with the trachytes and alkali rhyolites of the middle Mogan Formation mapped in southwestern and eastern Gran Canaria (Schmincke, 1969) was dated as 12.5 Ma by Mc Dougall & Schmincke (1976), contrasting with ages of 13.1 to 13.8 of under- and overlying ignimbrites and lava flows. The new age determination of basalt from the same formation but from another locality, sample 719: 13.7 ± 0.2 Ma (table 3) fits perfectly with the stratigraphic succession (see Fig. 4 in Mc Dougall & Schmincke, 1976) and support the interpretation that the sample dated by Mc Dougall & Schmincke had lost some radiogenic argon.

El Tablero Formation

Lietz & Schmincke (1975) had recognized a minor but widespread nephelinite formation, which they dated as 4.86 ± 0.15 Ma, that occurred after a long erosional hiatus in the

islands history, but prior to onset of Roque Nublo volcanism. Their age determination was confirmed by Mc Dougall & Schmincke (1976) who presented ages of 5.0 and 5.5 Ma for different specimens from the same flow at Tazartico. A prominent nephelinite intracanyon flow remnant occurs at San Nicolas at the foot of La Tabladas Terrace, post-dating phonolitic conglomerate but predating Roque Nublo conglomerate (E in Fig. 50 and 51 in Schmincke, 1976). The age of this flow, sample 799 : 5.07 ± 0.10 Ma, (table 3) is identical to that of Lietz & Schmincke (1975). There is now very strong evidence that the deep canyons in southern Gran Canaria were not only in existence at Roque Nublo time (Schmincke, 1968) but at least as early as 5 Ma ago and probably earlier (6 Ma ago ?) since the eruption of the nephelinite flow here dated must have been preceded immediately by a phase of moderate canyon cutting following a phase of widespread accumulation of thick conglomerate sheets of the Arguineguin formation. Since intrusives of the older Tejeda formation are as young as 8.7 Ma (Mc Dougall & Schmincke, 1976), the main phase of deep erosion on Gran Canaria must have occurred between about 8.7 and 6 (?) Ma ago, possibly caused by a major drop in sea level or rise of the island or both.

Roque Nublo Formation

The lowermost lava of the Roque Nublo Group in the western half of the island, moderately alkalic basalt, chemically different from the bulk of the overlying Roque Nublo volcanics, was date as 4.4 ± 0.15 Ma by Lietz & Schmincke (1975). A chemically similar basalt from the base of the group on the eastern half of the island has been dated as sample 1419 : 4.29 ± 0.10 Ma (table 3) in the present study. It is likely that these chemically distinct lavas were erupted at the same time from vents in the central part of the island, perhaps closer to 4.3 than 4.4 Ma, as previously assumed.

TABLE 3

K/AR AGES AND LOCALITIES OF GRAN CANARIA SAMPLES

Formation	*Sample*	*Rock type*	*Locality*	K_2O %	*Weight* g	$^{40}Aatm$ / $^{40}Atotal$	Ar^{40} / K^{40}	*Radiogenic argon* ($X10^{-12}$ moles/g)	*Age* (Ma)
Mogan	719	Alkali basalt lava flow T 4	M. Cedro, west side 580 m above sea level	1.64	6.4964	36.0	0.0007968	32.34	13.7 ± 0.2 (2)
El Tableros	799	Nephelinite intracanyon flow	San Nicolas, Las Tabladas Terrace, ca. 80 m above sea level	2.31	4.1068	66.3	0.0002953	16.90	5.07 ± 0.10 (2)
Roque Nublo	1419	Alkali basalt lava flow	St. Lucia, road to Temisas, basal flow Roque Nubli Fm	1.18	6.9940	66.7	0.0002498	7.291	4.29 ± 0.10 (2)
Los Llanos	1449	Nephelinite intrusion	Marteles Caldera, bottom at western canyon entrance	1.0	2.5006	56.0		4.15	2.88 ± 0.09 (1)
Los Llanos	1450	Nephelinite dike South	Marteles Caldera -slope Morro de la Caldera, NW-SE orientation	0.65	1.9657	67.65		2.42	2.59 ± 0.14 (1)
Post	HS307	Nephelinite pillow lava	La Isleta, west coast, ca. 6 m above sea level	1,14	2.6302	78.6		1.68	1.02 ± 0.08 (1)

(1) *ages measured by FERAUD, G. and GASTAUD, J.*

(2) *ages measured by Amdel*

n.a. not available.

TABLEAU IX

Comportement biologique du Bifénox

Produits [1]	*Date du traitement*	*Stade au moment du traitement*	*Doses appliquées dil. dans 360 l eau/ha*	*Etat de propreté des parcelles* — Date			*Etat végétatif de la céréale* — Date					*Rendements récoltés 15.7.83*	
				18.12.82 Stade E [2] Dicot.	13.04.83 Stade H Dicot.	29.04.83 Stade K Dicot.	16.10.82 Stade CD	18.11.82 Stade E	23.12.82 Stade F	13.04.83 Stade H	29.04.83 Stade K	Rendements moyens kg/ha	Rendements comparés au témoin
S.C. à 480 g/l de Bifénox	04.10.82	Pré-emerg.	1,67	4,8	6,8	8,0	1,0	1,7	1,0	1,0	1,0	7.879	100,5
S.C. à 480 g/l de Bifénox	04.10.82	Pré-emerg.	3,33	4,5	6,5	7,8	1,0	3,0	1,0	1,0	1,0	7.689	98,1
S.C. à 480 g/l de Bifénox	10.11.82	D	1,67	—	6,5	8,0	—	4,0	1,0	1,0	1,0	7.975	101,7
S.C. à 480 g/l de Bifénox	10.11.82	D	3,33	—	5,5	6,7	—	6,0	1,0	1,0	1,0	8.252	105,3
S.C. à 180 g/l de Bifénox + 420 g/l MCPP	13.04.83	HI	4,25	—	—	4,7	—	—	—	—	1,7	8.238	105,1
S.C. à 180 g/l de Bifénox + 420 g/l MCPP	13.04.83	HI	8,50	—	—	3,7	—	—	—	—	1,0	8.351	106,5
Témoin				9	9	9	1,0	1,0	1,0	1,0	1,0	7.839	100,0

(1) Appliquées après 3,5 l/ha d'une S.C. 500 g/l chlortoluron en pré-émergence le 04.10.82.
(2) D'après l'échelle phénologique élaboré par W. FEEKES.

Los Llanos Formation

A widespread formation of nephelinites and olivine nephelinites covers much of central and eastern Gran Canaria, unconformably overlying Roque Nublo rocks (Schmincke, 1976). Two ages in Lietz & Schminke (1975) range from 2.6 to 2.8 Ma, while data in Mc Dougall & Schmincke from nephelinites in the center and southeastern part of the island range from 2.5 to 3.0 Ma, with flows in the eastern part of the island as young as 2. Ma. A plug-like intrusion at the upper entrance of Marteles caldera (Schmincke *et al.* 1973) was dated as sample 1449 : 2.9 ± 0.09 Ma and a northwest-southeast striking dike at the northern rim of Marteles caldera as sample 1450 : 2.59 ± 0.14 Ma (table 3). These data are well within the range of previous ages for this formation and indicate that the major phase of nephelinitic volcanism (Los Llanos formation), at least in the center of the island, occurred between about 2.6 and 2.9 Ma. Nephelinitic eruptive activity appears to have shifted eastwards subsequently.

Post — Los Llanos basanites

Quaternary basanitic volcanoes occur scattered over much of the northeastern half of Gran Canaria with previous ages ranging from about 2.2 Ma to subrecent (Lietz & Schmincke, 1975 ; Mc Dougall & Schmincke, 1976). A nephelinitic pillow lava from the peninsula of La Isleta, just north of Las Palmas, that records and old sea level whose elevation was very similar to the present one (Furnes & Sturt, 1976) was dated as 1.02 ± 0.08 Ma (sample HS 307 : table 3). This age is similar to that of a basanitic intracanyon flow cut into a thick conglomerate fan at the north coast (P 17 : 1.26 ± 0.05 Maç; Lietz & Schmincke, 1975). Thus, there is evidence for uplift or lowering of sea level or both during the middle Quaternary, as

recorded by formation of the thick conglomerate/conglomerate fan and its subsequent erosion prior to 1.2 Ma ; however, very little *net* change with regard to sea level appears to have occurred during the past about 1 Million years. It is still uncertain if this basanitic volcanism occurred in several distinct phases or more or less continuously during the Quaternary.

IV. - DISCUSSION

Structural evolution

The present results confirm the age of about 5 Ma proposed by Feraud *et al.* (1980) for the exposed volcanic basement of Santa Maria, and show that the volcanic activity continued until 3.2 Ma or more recently. These authors showed that a model with a small fixed sublithospheric hot spot beneath a moving lithosphere is contradicted by the observed age patern of the Azores archipelago. If the exposed basement of Santa Maria is assumed to represent the major shield building phase and the oldest ages reported for the other islands by Abdel-Monem *et al.* (1975) and Feraud *et al.* (1980) be taken as the first shield phase of these islands, a mobile «hot spot» with a large dimension (Feraud *et al.*, 1980) is more likely.

Three of the five basement ages are of basaltic dikes, trending northwest-southeast probably representing the feeders for the dated basement series. Although the southeast part of this dike swarm is quite parallel to the apparent major volcano-tectonic direction of the Azores, another basaltic northeast-southwest trending dike swarm occurs on Santa Maria near Vila do Porto, but has not been dated. Using ling range sonar and other geophysical surveys, Searle (1980) showed the existence of a tectonic trend in the western part of the Azores area that is about N 119-124 $\pm$ 6° similar to that proposed

by Feraud *et al.* (1980). Although a more thorough evaluation of the importance of the dated dike direction in the area of Santa Maria in terms of the lithospheric stress pattern must await dating of the Vila do Porto dike swarm, the Azores archipelago does not seem to be generated by a simple linear plate boundary oriented N 150° E.

According to Searle (1980), the African plate changed motion with respect to Europe about 36 Ma ago from a southeast to a west-southwest direction. The Azores spreading center, extending from the Gloria Fault (Azores-Gibraltar fracture zone) along the Terceira Rift to the North Azores fracture zone formed at about the same time. The data presented here, together with those of Feraud *et al.* (1980), clearly show that all of the Azores islands are much younger, the oldest probably being not older than ca. 5.5 Ma.

The Madeira archipelago belongs to the impressive Madeira-Tore Rise stretching 1400 km from Madeira in the south-°est to the Tore Seamounts in the northeast. Lavas from Josephine Seamount, at the intersection of the Tore Madeira Rise and the Azores-Gibraltar Zone, about 600 km NNE of Madeira were dated by Wendt *et al.* (1976) with ages ranging from 8 to 13 Ma. The rocks are altered and therefore the measured ages should be regarded as minimum ages. However, the oldest ages are very similar to our ages of Porto Santo. Because the only ages measured all along the east part of the Azores-Gibraltar Zone are older than 30 Ma Feraud *et al.* (1977) it seems that the Tore-Madeira Rise has been active about 12-13 Ma ago in at least three places. It is not known if the uplift of Porto Santo discussed above is related to post-early Miocene uplift of Gorringe Bank (near Josephine Seamount) and other parts of the Tore-Madeira Rise, interpreted as resulting from compression between the African and Eurasian plates along the East Azores Fracture Zone (Laughton *et al.* 1975 ; Bonnin, 1978).

Magmatic phases on Atlantic islands

Systematic changes in the chemical composition of magmas erupted during successive phases occur on several Atlantic islands (Schmincke, 1973, 1981). The chemical data reported here for Santa Maria rocks are insufficient to fully characterize the different formations dated. Nevertheless, lavas of the basement formation are less alkalic than those of the younger pillow complex and subaerial lavas but the difference is much less pronunced than that between magmatic phases on Gran Canaria (Schmincke, 1981). Interestingly, the time gap between the basement and the pillow lavas is less than 1 Ma, while the ages of the pillow and capping basalts are experimentally indistinguishable. The major unconformity cutting the basement series is possibly generated by processes such as regional sea level changes unrelated to geodynamic processes beneath Santa Maria governing generation and eruption of magmas. Tre existence of scoria cones on Santa Maria, however, shows that even younger volcanoes exist on this island. A more thorough evaluation of the chemical evolution of Santa Maria must thus wait until a fuller documentation of chemical composition of rocks of different ages is aavilable. The question of why several magmatic phases are more common in islands like the Canary Islands compared to the Azores is discussed more fully elsewhere (Schmincke, 1981).

Perhaps the most characteristic feature of the chemical composition of Porto Santo magmas is their low K-content and their high Na/K-ratio, similar to that of Madeira (Schmincke & Weibel, 1972). The age data here presented clearly show that magmas generated in the mantle beneath the Madeira Archiplago have possessed this feature for at least as long as about 13 Ma. Data are insufficient to show whether magmas erupted along other parts of the Madeira-Tore Rise also show this particular chemical composition. The problem of mantle heterogeneity in this part of the Atlantic is discussed by Schmincke (1981).

The temporal evolution of magma chemistry on Gran Canaria can now be documented in more detail than before. Nephelinite lavas represented by very small local flow remnants of the El Tablero Formation as much as 30 km apart were erupted in many parts of Gran Canaria almost exactly 5 Ma ago. This supports the suggestion that these may represent the final post-erosional nephelinite phase following the Miocene shield and subsequent more alkalic phases (Schmincke, 1976). The second phase of nephelinitic volcanism following upon the Roque Nublo magmatic phase, originally thought to have occurred between 2.8 and 2.8 Ma (Lietz & Schmincke, 1975), later modified by Mc Dougall & Schmincke as having occurred between 2.8 and 2.1 Ma, does indeed appear to have erupted chiefly between about 2.6 and 2.9 Ma, at least in the highlands of Gran Canaria.

The Quaternary pillow lava from La Isleta, whose chemical composition is very similar to that given in Furnes & Sturt (1976) is extremely Ti- (and Fe)rich-even for a Ti-rich province such as the Canary Islands. Because of the otherwise mafic composition this chemical feature must be «primary» rather than due to low pressure fractionation of phases such as olivine. The lava is chemically similar to the nephelinites of the El Tablero and Los Llanos formation (Schmincke, 1976; Lietz & Schmincke, 1975; this report) and differs chemically from the basanite P 17 (Lietz & Schmincke, 1975) of similar age indicating that nephelinite and basanite magmas were erupted side by side on Gran Canaria during the early Quaternary.

Sea level changes

If the basement age of Santa Maria is taken as ranging from about 4.6 to 5.2 Ma (disregarding the older, less reliable age of 5.5 Ma) and the overlying pillow basalt/sediment complex as having formed between about 3.3 and 3.8 Ma, the major regression (or uplift) that caused the thorough erosion

of the basement must have taken place during the uppermost Miocene early Pliocene. It coincides roughly with the second major regression on Gran Canaria (R 2) believed to have occurred between about 5 and 4.3 Ma (Lietz & Schmincke, 1975), reinforcing their tentative interpretation that it might be the result of a widespread lowering of sea level at this time rather than vertical movement of the islands. The subsequent transgression, however, is not easily correlated, data from Gran Canaria arguing for a rapid transgression around 4.3 Ma and age of the upper fossiliferous bed as about 4.2 Ma (Lietz & Schmincke, 1975) while the Santa Maria pillow lavas and interbedded calcarenites are more likely to have been emplaced between 3.5 and 4 Ma. Small K/Ar age descrepancies between stratigraphically equivalent lavas, slight alteration in some rocks and the likelihood that onset and duration of volcanism may have differed appreciably between both islands, even if transgression may have been synchronous, make it impossible at present to decide if the formation of the fossiliferous, Clypeaster-bearing calcarenites of Gran Canaria and Santa Maria and thus the transgressions are exactly synchronous or not. Interestingly, maximum *present* elevations of marine beds/pillows of these formations are nearly identical for both islands, about 130 m for Gran Canaria and 150 m for Santa Maria. Moreover, the new K/Ar-ages show that the fossiliferous sediments on both islands are not of Middle Miocene age as assumed in the older literature but of Lower//Middle Pliocene age.

On the other hand, the age of the Porto Santo calcarenites, suspected to be older (Vindobonian) than those on Santa Maria and Gran Canaria on paleontological grounds (Lietz & Schwarzbach, 1970) are now certainly ca. 12.5 to 13.5 Ma old, about 3 times as old as those on Gran Canaria and Santa Maria. There is a great need for dating the lavas underlying calcarenites that have been reported from neighbouring Madeira for over 100 years and that are believed to be co-eval with those of Porto Santo (Mitchell-Thome, 1976). Madeira does not

seem to have experienced a rather long volcanic history, judging from its youthful morphological appearance, and all K/Ar-age determinations available (Watkins & Abdel-Monem, 1971 ; Macedo *et al.*, 1974 ; this report) are younger than about 4 Ma. The occurence of Miocene sediments on Madeira must thus be regarded with some scepticism.

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