

K-Ar ages from the eastern Azores group (Santa Maria, São Miguel and the Formigas Islands)*

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Present estimates of the age of volcanic activity in the eastern Azores group are based on shelly fauna in a coquina zone separating the two basaltic sequences on Santa Maria. A Vindobonian (Middle Miocene) age has been assigned to the coquina zone. Our K-Ar data suggest that it was deposited 4-6 m.y. ago, i.e. Mio-Pliocene in age.

The basaltic series exposed below the coquina zone on Santa Maria is 6-8 m.y. old and probably much older. The post-coquina basaltic complex is 4 m.y. old and younger. The Nordeste basaltic complex in the NE part of São Miguel and the basaltic flows of the Formigas Bank are also 4 m.y. old and younger. We suggest that the three latter basaltic sequences are chronostratigraphic equivalents.

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K-Ar age studies of volcanic islands have been used to estimate rates of evolution and growth of volcanic edifices, e.g. McDougall (1964). Also, age limitations, by K-Ar means, placed on volcanic islands associated with mid-ocean ridge systems were applied to test the hypotheses of ocean floor spreading and to check the geophysically calculated spreading rates (McDougall & Wensink 1966, Abdel-Monem & Gast 1967, Dymond & Windom 1968). Within a single island the K-Ar ages add the dimension of time to the solution of the genetic relations among a variety of rock types. Within a group of volcanic islands the K-Ar dating technique represents one of the few methods applicable to inter-island stratigraphic correlation, since such correlations - based only on the chemical characteristics and petrographic similarities between rock units - could be very misleading.

In this study, the time framework for the volcanism of the Nordeste volcanic complex in the eastern part of São Miguel island will be established. Through inter-island correlation of K-Ar ages, the time framework of volcanism

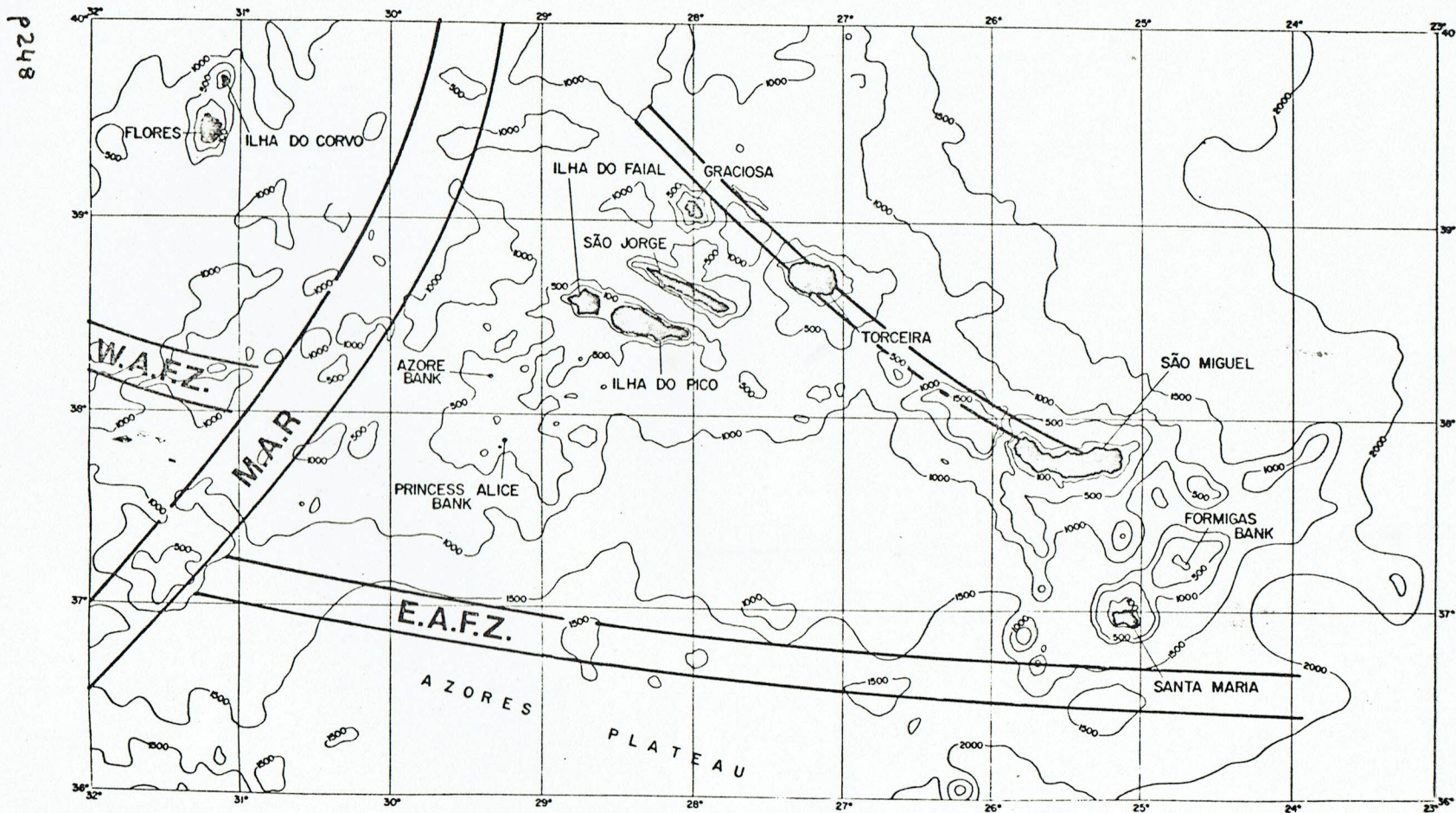
in the eastern Azores group, viz. Santa Maria, São Miguel, and the Formigas Islands, will also be established. Moreover, an attempt will be made to test the applicability of the K-Ar data to the crustal evolution in the vicinity of the Azores.

Tectonic and geologic setting

Krause (1965) and Krause & Watkins (1970) considered the Azores archipelago as being part of a linear tectonic feature stretching across the Atlantic Ocean. This tectonic feature consists of a seismically active east Azores fracture zone, the Azores archipelago, and the aseismic west Azores fracture zone.

The seismically active east Azores fracture zone extends from the Straits of Gibraltar and intersects with the Mid-Atlantic Ridge at the Azores. Heezen et al. (1959) previously considered the east Azores fracture zone, along with the Azores archipelago, to be an ill-defined and undeveloped extension (proto-ridge) stretching across the ocean, as it is

* Lamont-Doherty Geological Observatory Contribution.



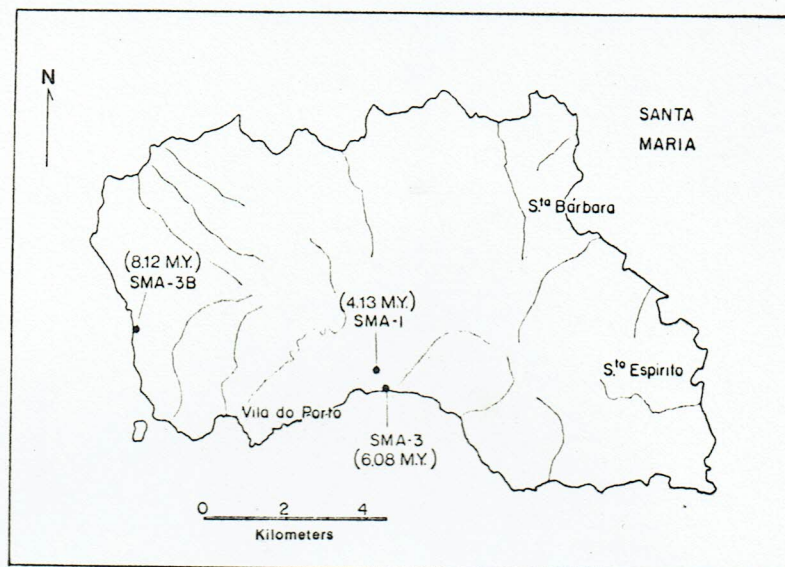


Fig. 2. K-Ar ages of Santa Maria Island.

associated with a shallow earthquake belt and a median rift valley. This simple picture was further complicated when Banghar & Sykes (1969) reported a part tensional and part strike-slip seismic event at the western end of the east Azores fracture zone that contrasts with a compressional seismic event at its eastern end. More recently, Krause & Watkins (1970) suggested that this fracture zone is the western extension of the 'Alpine' tectonic zone, the world's most active latitudinal tectonic element. They also suggested that its intersection with the Mid-Atlantic Ridge marks the apparent western limit of the 'Alpine' tectonic zone.

The aseismic west Azores fracture zone intersects with the Mid-Atlantic Ridge at the Azores but with a slight northward offset from the eastern fracture zone (Fig. 1). It is a branched zone; the main branch follows a great circle trending south of the west and joins the Kelvin Seamounts Chain (Krause 1965).

The Azores archipelago is a group of volcanic islands that has a linear trend branching off the broadened Mid-Atlantic Ridge in an

ESE direction. It also makes an oblique angle with the direction of the east Azores fracture zone (Fig. 1). The exact location of the centre of the Mid-Atlantic Ridge at the Azores is not well defined. Heezen et al. (1959), however, stated that Flores Island stands astride the western flank of the ridge. Krause & Watkins (1970) presented a model analyzing the evolution of the oceanic crust in the vicinity of the Azores. They suggested the presence of a triple junction within a 'leaky transform system' with a NW-SE trend (Menard & Atwater 1968) superimposed on an ordinary spreading ridge system that has different spreading rates above and below the east Azores fracture zone.

The geology and petrology of the Azores Islands have recently been reviewed by Ridley et al. (1974). The islands are entirely volcanic, with the exception of a small coquina horizon exposed on Santa Maria Island. Calcareous fossiliferous lenses were also reported from the Formigas Banks by Zbyszewski et al. (1961). Zbyszewski & Ferreira (1962a) assigned a Vindobonian age to the marine fauna of the coquina zone. Using this time-marker, they extended the stratigraphic age assignment to the under- and overlying volcanic series. Furthermore, Zbyszewski & Ferreira (1962b) extended the stratigraphic correlation to the neighboring islands of São Miguel and Formigas.

Fig. 1. Regional map of the Azores archipelago. The approximate position of the Mid-Atlantic Ridge and the Tereira rift axis are from Krause & Watkins (1970).

Table 1. K-Ar data from the eastern Azores Islands.

Sample No.	Rock type	% K	Ar*/gm $\times 10^6$ Sec	Ar*/Ar _t	Age (m.y.)
<i>Santa Maria</i>					
SMA-3B	Alk. ol. basalt	1.17 +	0.379	0.04	8.12 \pm 0.85
SMA-3	Ankaramite	0.45 +	0.109	0.14	6.08 \pm 0.51
SMA-1	Alk. ol. basalt	0.63	0.104	0.22	4.13 \pm 0.35
<i>Formigas Bank</i>					
F-5	Basanitoid	1.13	0.210	0.16	4.65 \pm 0.36
F-7	Basanitoid	1.35	0.215	0.18	4.00 \pm 0.31
<i>Sao Miguel</i>					
10-A	Ankaramite	0.91	0.147	0.08	4.01 \pm 0.50
107-A	Alk. ol. basalt	1.45	0.183	0.15	3.17 \pm 0.28
181-A	Ankaramite	1.43 +	0.091	0.11	1.86 \pm 0.09
		1.22			
104-A	Trachybasalt	1.23 +	0.091	0.11	1.23 \pm 0.08
		1.87			
57-A	Tristanite	4.94	0.252	0.13	1.28 \pm 0.08
920-A	Tristanite	3.73	0.140	0.16	0.95 \pm 0.07
		3.74 +			

(1) K-determinations by XRF; (+) by atomic absorption.

(2) Ar-determinations by isotope dilution; Ar*=radiogenic argon; Ar_t = total argon.

(3) The decay constants used in the age calculations are: $\lambda_{\beta} = 4.72 \times 10^{-10} \text{yr.}^{-1}$; $\lambda_{\epsilon} = 0.584 \times 10^{-10} \text{yr.}^{-1}$; $\lambda_{\epsilon}/\lambda_{\beta} = 0.123$; K⁴⁰/K = 0.0119 atomic %.

(4) For experimental method details see Abdel-Monem (1969). For locations see Figs. 2, 3 & 4. Petrographic descriptions are available from the authors on request.

Volcanism in the eastern Azores group has been classified by Zbyszewski & Ferreira (1962b) into three major stages. The pre-Vindobonian stage consists of a primitive complex of basalts which are mainly ankaramites with interlayered tuffs, volcanic breccias and dikes cutting the basalts but not the fossil layer. The Vindobonian stage represents a period of relative quiescence and marine erosion and deposition during which intercalations of lava flows and coquina deposits were laid down. The post-Vindobonian stage consists of analcime basalts (with olivine and augite phenocrysts), basaltic basalts, hornblende and mafic andesite, trachytes and latites, and recent basalts. The last stage is considered to be still active.

Results and discussion

The analytical results are tabulated in Table 1 and the K-Ar ages are plotted in Figs. 2, 3, and 4.

Santa Maria Island (Lat. 37°42'N; Long. 25°31'W)

The island is the southernmost one in the Azores archipelago. It has a pear-shape outline. Physiographically, the island is divided into two regions separated by a central mountain chain extending in a NNW-SSE direction, the Serra Verde, which represents the backbone of the island. The western region is relatively plane and erosional surfaces are present at altitudes of 80 and 100 metres. The eastern region has more relief and the exposures of the coquina layer are confined to this region.

Zbyszewski & Ferreira (1962b) cited the geologic succession exposed on the western region from the oldest to the youngest formations as follows:

(1) Old basaltic complex consisting of lava flows separated from one another by thin layers of tuffs and breccias. This succession is well developed west of Vila do Porto with a dense system of basaltic dikes.

(2) The old basaltic complex is overlain by a thick complex of volcanic breccias, which forms a large platform east of the airport.

(3) A Miocene series consisting of volcanic breccias at the base followed by a series of intercalating agglomerates, tuffs, and richly fossiliferous limestone. This sequence is well developed NNE of Santanna and disappears to the west of the village.

(4) The post-Tortonian basalts that were extruded from Pico de Saramago and some other volcanoes overlie the Miocene series.

(5) Finally, a series of recent volcanic eruptions, which consists mostly of scoriae and cinder cones.

Three samples have been dated from this island (cf. Fig. 2). The oldest, SMA-3B, gave an age of 8.12 m.y. and was collected from below the airport runway about 70 meters above sea level. The second sample, SMA-3, was collected from the southern extremity of the island and at a short interval below the coquina zone. It gave an age of 6.08 m.y. These two samples, which represent the upper parts of the old basaltic complex, indicate the presence of a hiatus within this section and that the volcanic activity during that stage was terminated before the end of the Miocene. The third sample, SMA-1, was collected about 10 meters above the coquina zone (Fig. 2) and gave an age of 4.13 m.y.

The above data, though fragmentary, clearly put limitations on the age of the coquina zone. We suggest that the coquina zone was deposited between 4–6 m.y. ago, i.e. a Miocene–Pliocene deposit. The Miocene–Pliocene boundary is considered here to be 5 m.y. (Berggren 1969). The Vindobonian age assignment to the coquina zone (Zbyszewski & Ferreira 1962a) is, in our opinion, incorrect. After examining their list of identified planktonic forams, Dr. R. Saito of Lamont-Doherty Geological Observatory (pers. comm. 1970) stated that almost all those forams first appeared in deep sea cores in the Middle or Upper Miocene and continued to the present time. Only the two species *Globorotalia puncticulata* and *Globorotalia hirsuta* started in deep sea cores at about 4.2 and 6–5.5 m.y. respectively, based on the magnetic stratigraphy. The presence of these two species is consistent with our K-Ar data and stratigraphic assignment.

In summary, the K-Ar data suggest that the

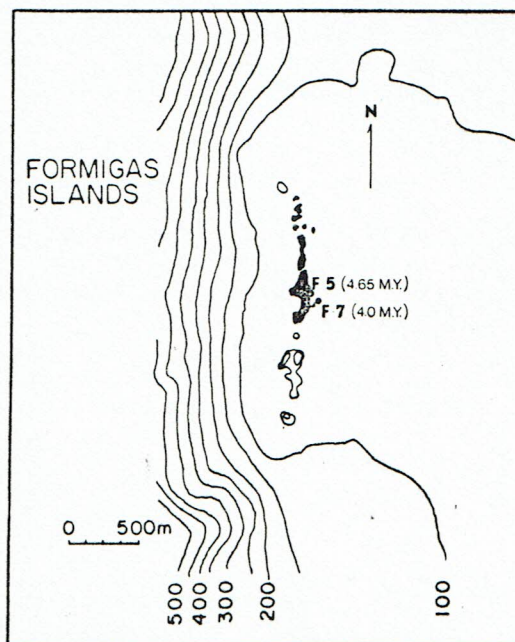


Fig. 3. Bathymetric map and K-Ar ages of the islets of Formigas (after Zbyszewski et al. 1961).

volcanic history of Santa Maria consisted of two extended periods of volcanicity separated by an interval of relative quiescence from 4–6 m.y. ago. This interval was characterized by intensive marine erosion and deposition of the coquina zone.

The Formigas Bank (Lat. 37°23'N;
Long. 24°45'W)

The islets of Formigas are located about 30 km to the NE of Santa Maria. They extend in a N–S direction. Zbyszewski et al. (1961) stated that the orientation of the Formigas islets and their submarine topography, which is very much steeper to the west than to the east, cf. Fig. 3, suggest that they probably represent a tectonic feature.

The islets consist of flows of porphyritic olivine basalt which sometimes contain irregular lenses of calcareous fossiliferous sediments. Zbyszewski et al. (1961) stated that the marine fauna in the calcareous sediments is similar to that on Santa Maria. A dike of more compact nature with a N–S orientation (basaltic basalt with andesitic tendency) is also present.

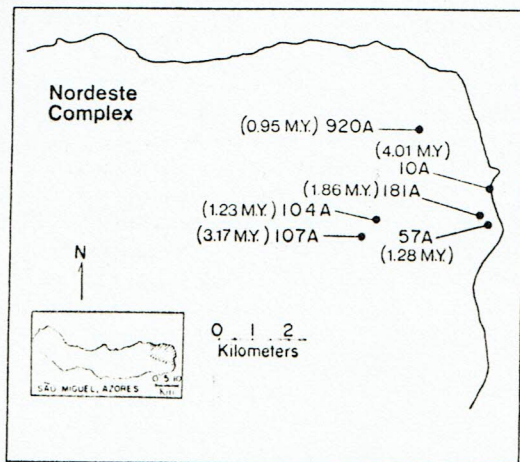


Fig. 4. K-Ar ages of the Nordeste volcanic complex, São Miguel Island.

Two samples have been dated from the major islet (cf. Fig. 3). Sample F-5 was collected at the light house and gave an age of 4.65 m.y. Sample F-7 was collected by a scuba diver at 35 meters depth in front of the light house and gave an age of 4.0 m.y. The two ages are in good agreement and suggest that the Formigas islets are probably the stratigraphic equivalents of the post-coquina basalts on Santa Maria.

São Miguel Island (Lat. $36^{\circ}58'N$; Long. $25^{\circ}31'W$)

This is the largest island in the Azores archipelago and has a long narrow elliptic shape. Physiographically, the island is made up of a composite of volcanic complexes. The field relationships among them suggest that the volcanic activity has moved westward with time. The regional geology and petrography of the island have been studied by Zbyszewski (1961) and Assunção (1961), respectively. This present study is only concerned with the Nordeste basaltic complex in the NE part of the island (cf. Fig. 4). Details of the geology and petrology of the Nordeste complex have been studied by Fernandez (1969, 1973) and Boone & Fernandez (1971).

Briefly, the Nordeste basaltic complex exposes a composite thickness of about 1100 meters of lava flows – chiefly trachybasalts and

ankaramites. The absence of interstratified sediments and pillow structures, coupled with abundant evidence of incipient stream valley cuttings between eruptions, indicates the sub-aerial development of the complex. The volcanic sequence shows the differentiation trend basalt–trachybasalt–tristanite–trachyte. The stages of differentiation are not reflected directly by the position of the flows. Nevertheless, the oldest flows are the least differentiated. The differentiates – trachybasalt, tristanite and trachyte – are characterized by the absence of the feldspathoids, i.e. reflecting a silica-saturated but not over-saturated path of differentiation.

The eruptive formations of the Nordeste basaltic complex and their K-Ar ages, from the oldest to the youngest, are as follows:

(1) *The lower basalts.* This series makes up the bulk of the shield. Its base is unexposed, but the total exposed thickness is about 150 meters. The flows are predominantly of the aa-type. Most of them are one or two meters thick and are of limited areal extent (about 100 square meters). The flows rest conformably upon each other with no signs of erosion, suggesting rapid accumulation. Petrographically, the lavas range from olivine basalt to olivine–andesine trachybasalt. The majority are ankaramitic and picritic in nature. The series is cut by two sets of dikes – a more basaltic set in the inland areas and a trachybasaltic one in the coastal regions.

Two samples from this series were dated (cf. Fig. 4). Sample 10-A, which represents the oldest exposed lava flow, gave an age of 4.01 m.y., and sample 107-A, which also represents a lava flow near the base of the series, gave an age of 3.17 m.y. The two ages are consistent with the field relationship. They also suggest that this series is probably the stratigraphic equivalent of the post-coquina basalts and not the pre-coquina ones as suggested by Zbyszewski & Ferreira (1962b).

(2) *The ankaramites.* This series is composed of thick flows (5–150 meters) characterized by abundant pyroxene and olivine phenocrysts; there are also plagioclase rich ones. The flows show unconformable relationships with the underlying lower basaltic series as observed in the vicinity of Farol do Arnel. No samples were investigated from this series.

(3) *The upper basalts.* This series is composed of thin basaltic flows reaching a total thickness of approximately 150 meters. The flows generally have conformable relationships with the over- and underlying series. They sometimes lie directly on the lower basaltic series, e.g. in the vicinity of Nordeste. The rock types of this series grade upward from slightly porphyritic olivine-andesine trachybasalt to aphyric olivine tristanite to the least abundant thin trachyte flows. The tristanites are commonly exposed on the valley walls and as valley fillings forming canoe-shaped bodies.

One sample (181-A, cf. Fig. 4) taken from a flow marking the base of this series, gave an age of 1.86 m.y., which is consistent with the field stratigraphy. The span of time, 12.15 m.y., between the oldest flow in the lower basaltic series and the first eruptions of the upper basaltic series constitutes the period during which most of the exposed Nordeste complex was emplaced (Fernandez 1969). This includes the Nordeste ankaramites and the early flows of the upper basaltic series. The major unconformity which separates the lower basaltic series from the Nordeste ankaramites is bracketed by the 3.17 m.y. and 1.86 m.y. dates.

(4) *The trachybasalts and tristanites.* The flows of this series show field relationships similar to the trachybasalt-tristanite members of the underlying series. They are also present as small plugs intruding the upper basaltic series. Sometimes the contacts of these late differentiates are not well exposed.

Three samples from this series were dated (cf. Fig. 4). Sample 57-A came from a tristanite intrusion, 104-A from a trachybasalt dike cutting the upper basaltic series, and 920-A from a tristanite flow capping the upper basaltic series. They gave the ages 1.28 m.y., 1.23 m.y., and 0.95 m.y., respectively. The ages are consistent with the field relationships. The emplacement of the mafic dike at 1.23 m.y. and the earlier intrusion of the tristanite plug indicates the absence of normal succession of mafic rocks followed by salic ones. The youngest flow in the series – 0.95 m.y. – is tristanitic in composition and represents by its radiometric age and stratigraphic position the latest outpouring of lava in the Nordeste region.

(5) *Explosive volcanism.* The final phases of

volcanism on São Miguel were of the explosive type. Pyroclastic material poured out from the huge cones and calderas and covered most of the island. Most of these calderas are now lakes. The explosive phase gave way to a scoriaceous type of volcanism which is now represented by numerous small cones aligned along major fissures.

To summarize, the K-Ar ages are consistent with the field interpretations of the Nordeste basaltic complex. The data also suggest that the complex is Plio-Pleistocene in age and is probably the stratigraphic equivalent of the post-coquina volcanics on Santa Maria island.

Summary and conclusions

(1) The basaltic complex exposed on the western region of Santa Maria represents the oldest rocks in the east Azores group, and the only Miocene volcanism in this part of the archipelago. It is 6–8 m.y. old and probably much older.

(2) The coquina zone exposed on Santa Maria and the calcareous sediments found on the Formigas Bank were deposited between 4–6 m.y. ago. The assignment of time limits to this horizon is significant, since it has been used as a paleontologic-stratigraphic time-marker in inter-island correlations (Zbyszewski & Ferreira 1962b).

(3) The volcanic complex exposed above the coquina zone on the eastern region of Santa Maria, the Nordeste basaltic complex exposed on the NE part of São Miguel, and the basalt flows of the Formigas Bank are all 4 m.y. old and younger. We here suggest that these complexes are chronostratigraphic equivalents.

(4) It is apparent that the oldest rocks in this part of the Azores archipelago are the farthest, in a perpendicular direction, from the ESE-axis of the Terceira rift zone (cf. Fig. 1). If there is any support for the model of Krause & Watkins (1970) suggesting the presence of a NE-SW secondary spreading center in the vicinity of the Azores, it should come from this observation. Their estimation of a 25 m.y. old minimum age for Santa Maria is not really in great conflict with the K-Ar data presented here, if we take into consideration that the subaerial portions of the volcanic edifices avail-

able for direct sampling are negligible compared to the submarine ones (cf. Abdel-Monem & Gast 1967).

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