AÇOREANA, 2007, Supl. 5: 112-125

NEOGENE SHALLOW-MARINE PALEOENVIRONMENTS AND PRELIMINARY STRONTIUM ISOTOPE CHRONOSTRATIGRAPHY OF SANTA MARIA ISLAND, AZORES

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ABSTRACT

The fossils of Santa Maria Island in the Azores archipelago represent one of the few shallow-marine communities of Neogene age between Europe and North America. Before the evolutionary and biogeographic implications of these fossils can be understood, however, their associated depositional environments and geologic ages must be determined. Here we present preliminary results from sedimentary facies analysis and strontium isotope chronostratigraphic analysis of sediments and fossils from two localities on Santa Maria Island that provide a window into shallow-marine environments and communities within the mid-Atlantic Ocean during the Neogene. Pedra-que-Pica on the southeastern corner of Santa Maria contains strata of fine-grained lithic calcarenite, coquina, and fine- to medium-grained lithic wacke that represent a regressive sequence from transition-zone to foreshore environments. The second locality at Pedreira do Campo on the southwestern-side of Santa Maria contains limestone and fine- to coarse-grained lithic arenite that represent a regressive sequence from shallow bank to shoreface-foreshore environments. Strontium isotopic results from Pedra-que-Pica and Pedreira do Campo indicate that these localities contain fossils that range from late Miocene to late Pliocene in age. Three molluscs collected from the coquina at Pedra-que-Pica have an average $^{87}Sr/^{86}Sr$ composition of 0.709018±0.000008 that represents an average estimated age of 5.51±0.21 Ma. Three pectinid bivalves collected from the limestone at Pedreira do Campo show a wide range in $^{87}Sr/^{86}Sr$ ratios, from 0.708885 to 0.709078, which represent estimated ages from 10.03 to 2.24 Ma, respectively. These results help to place the shallow-marine communities of Santa Maria Island into a geologic context that will aid our understanding of how these communities relate to the broader evolutionary and biogeographic history of the Atlantic basin during the Neogene.

INTRODUCTION

The Neogene Epoch was an important time when shallow-marine faunas of the former Tethys Sea evolved into separate and distinct Mediterranean, western Atlantic-Caribbean, and eastern Pacific communities. It was during the Neogene that the seaway between North and

South America closed (Emiliani *et al*., 1972; Keigwin, 1978), thereby dividing a once continuous marine province into distinct Pacific and Atlantic communities (Woodring, 1966; Vermeij, 1978; Vermeij and Petuch, 1986). Also during the Neogene, the remnants of the Tethys Sea continued to contract as the African tectonic plate collided with the Eurasian plate. Although many Neogene localities in the western and eastern Atlantic Ocean have been described, there are few opportunities to examine shallow-marine localities between these two ends of an ocean basin.

The Azores archipelago, located almost in the middle of the Atlantic Ocean, provides an opportunity to examine shallow-marine communities of the Neogene. The Azores archipelago consists of nine islands, but despite six centuries of occupation by people, only one island has been found to contain fossils (Mayer, 1864; Cotter, 1888-1892; Ferreira, 1955; Krejci-Graf *et al*., 1958; Zbyszewsky and Ferreira, 1962b; Ávila *et al*., 2002; Ávila, 2005). This is the island of Santa Maria, which is the southeastern-most island in the archipelago. The fossils and associated sediments of Santa Maria offer a window into shallow-marine communities and environments within the mid-Atlantic Ocean during the Neogene (Zbyszewski and Ferreira, 1962a; Serralheiro and Madeira, 1993; Ávila *et al*., 2002; Cachão *et al.*, 2003). In this study, we analyze the sedimentary facies of outcrops at two localities on Santa Maria (Pedra-que-Pica and Pedreira do Campo) in order to infer their depositional environments (paleoenvironments). We also analyze the strontium isotopic composition of fossil shells in order to estimate the geologic ages at these localities as a first step toward a Sr chronostratigraphy of the fossils and sediments of Santa Maria Island. This method of age dating is appropriate for the fossils of Santa Maria because past studies elsewhere have shown that the Neogene was a time of rapidly increasing $^{87}Sr/^{86}Sr$ in the global ocean and, therefore, particularly amenable to dating and correlating marine sediments using strontium isotopes (e.g. Hodell *et al*., 1991; Miller *et al*., 1991; Jones *et al*., 1993; Hodell and Woodruff, 1994; Mallinson *et al*., 1994; Oslick *et al*., 1994; Miller and Sugarman, 1995; Martin *et al*., 1999; McArthur *et al*., 2001). These results place the fossil communities at Pedra-que-Pica and Pedreira do Campo into a geologic framework in order to better understand the biogeography and evolution of these shallow-marine communities during the Neogene.

MATERIALS AND METHODS

We conducted fieldwork in May 2005 at two localities on Santa Maria Island, Pedra-que-Pica and Pedreira do Campo. Two stratigraphic sections were measured upsection using the method of eye height and Brunton compass described by Compton (1985). Pedra-que-Pica is located on the southeastern corner of

Santa Maria at Baixa do Sul (N36°55.806′, W25°01.482′), about 0.76 km west of the lighthouse on Ponta do Castelo (Fig. 1). The lower portion of the outcrop is exposed in a wave-cut platform about 1709 m^2 in area in the intertidal zone. The upper portion of the outcrop is exposed in a sea cliff that is several hundred meters in height.

Pedreira do Campo is located on the southwestern corner of Santa Maria (N36°56.818′, W25°08.119′), about 1.0 km east of Vila do Porto and about 1.4 km southwest of Pico do Facho (Fig. 1). The outcrop is exposed in an abandoned quarry that was formerly used to mine basalt for construction material. Pedreira do Campo is now part of a natural monument and the area is protected for its geological, paleontological, biological and cultural significance (Cachão *et al.*, 2003). Cachão *et al*. (2003) have recently described the international importance of the fossils and geology at Pedreira do Campo, particularly toward understanding the geologic history of the North Atlantic and the colonization of the Azores Islands by marine biota.

We analyzed three fossil specimens of molluscs (oyster, spondylid, and pectinid) from Pedra-que-Pica

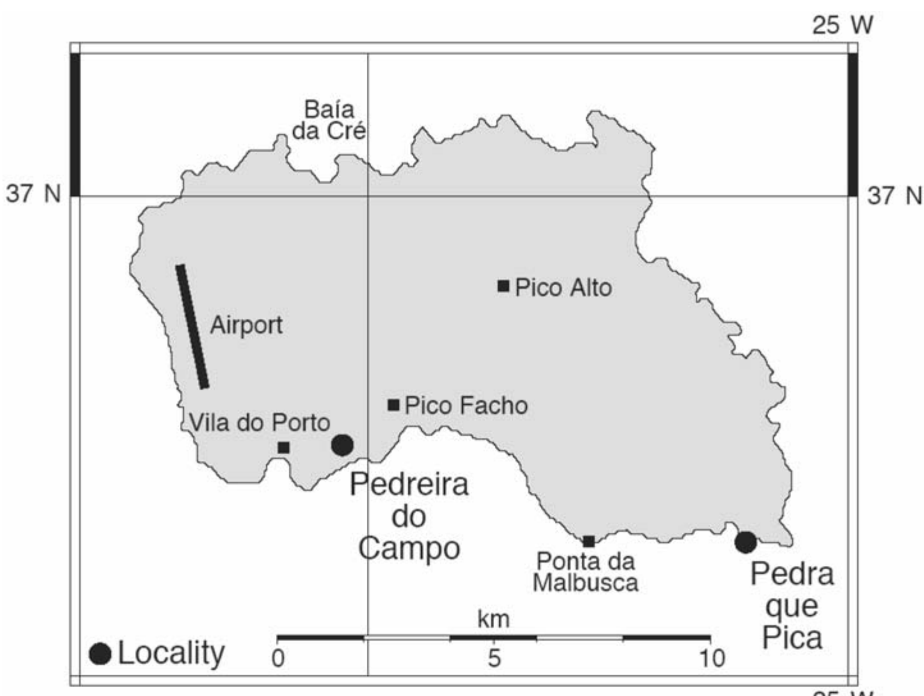

FIGURE 1. Map of Santa Maria Island, Azores, showing the location of Pedra-que-Pica and Pedreira do Campo.

and three specimens of pectinid bivalves from Pedreira do Campo in order to determine the ratio of $^{87}Sr/^{86}Sr$ of the low-magnesium calcite composing the shell (Table 1). These data allow us to estimate the geologic age for each fossil specimen. For isotopic analyses, we first ground off a portion of the surface layer of each shell specimen to reduce possible contamination. Areas showing chalkiness or other signs of diagenetic alteration were avoided. Powdered low-magnesium calcite samples were drilled from the interior of each shell using a hand-held Dremel tool with a carbide burr. Approximately 0.01 to 0.03 g of powder was recovered from each fossil sample. The powdered calcite samples were dissolved in 100 µl of 3.5 N HNO_3 and then loaded onto cation exchange columns packed with strontium-selective crown ether resin (Eichrom Technologies, Inc.) to separate Sr from other ions (Pin and Bassin, 1992). Sr isotope analyses were performed on a Micromass Sector 54 Thermal Ionization Mass Spectrometer equipped with seven Faraday collectors and one Daly detector in the Department of Geological Sciences at the University of Florida. Sr was loaded onto oxidized tungsten single filaments and run in triple collector dynamic mode. Data were acquired at a beam intensity of about 1.5 V for ^{88}Sr, with corrections for instrumental discrimination made assuming $^{86}Sr/^{88}Sr=0.1194$. Errors in measured $^{87}Sr/^{86}Sr$ are better than ±0.00002 (2 sigma), based on long-term reproducibility of NBS 987 ($^{87}Sr/^{86}Sr=0.71024$). Age estimates were determined using the Miocene portion of Look-Up Table Version 4:08/03 associated with the strontium isotopic age model of McArthur *et al*. (2001).

RESULTS

Sedimentary Facies Analysis at Pedra-que-Pica

Pedra-que-Pica contains an exposure of 7.5 to 40.0 m of sediments that lie between two basalt flows. We

TABLE 1. Strontium isotope data and age estimates from Santa Maria Island, Azores.

Sample	Locality	87Sr/86Sr	error (%)	Age (Ma)*	Age range (Ma)*
PC1 A	Pedreira do Campo	0.709064	0.0010	2.78	3.88-2.36
PC1 B	Pedreira do Campo	0.709078	0.0010	2.24	2.58-1.89
PC1 C	Pedreira do Campo	0.708885	0.0010	10.03	10.34-9.75
PP1 I	Pedra-que-Pica	0.709027	0.0010	5.28	5.56-4.96
PP1 II	Pedra-que-Pica	0.709012	0.0008	5.67	5.82-5.49
PP1 III	Pedra-que-Pica	0.709016	0.0012	5.59	5.82-5.25

$^{87}Sr/^{86}Sr$ relative to NIST987 = 0.710248

* Ages from look-up tables in McArthur *et al*. (2001)

interpret the sediments and lower basalt flow as part of the Touril Complex as defined by Serralheiro *et al*. (1987) (Fig. 2). We interpret the upper basalt flow as part of the overlying Facho-Pico Alto Complex as defined by Serralheiro *et al*. (1987). The bottom of the Touril Complex was not seen at this locality as a result of being below sea level. The top of the Touril Complex was seen in contact with the overlying basalt of the Facho-Pico Alto Complex. The top of the Facho-Pico Alto Complex was not seen. Sediments of the Touril Complex at this locality are divided into four distinct facies. The base of the section is marked by brecciated basalt pillows that are overlain by a fine-grained, lithic calcarenite showing abundant bioturbation. Two sizes of *Thalassinoides* sp. are present: One size that is about 1 cm in diameter and another that is about 3 mm in diameter. Both types of burrows are vertical to subvertical and show branching. This facies is overlain by 1.5 to 3 m of coquina that is rich in large, disarticulated valves of spondylids, pectinids, and pycnodontids, as well as in barnacles, echinoids, bryozoans, calcareous algae, and coral. The coquina is structureless, except for some cross-lamination (1 cm) near the top of the coquina. Overlying the coquina is a thick unit of fine- to medium-grained, lithic wacke that is 4.0 to 32.5 m thick. The lithic wacke is well-stratified at the base and contains planar bedding about 1 cm thick. There are internal erosive surfaces within the lithic wacke where the planar bedding is discordant. Rare basalt clasts up to 30 cm in size are present in the lithic wacke. A boulder conglomerate containing basalt clasts overlies the lithic wacke at this location, as illustrated in Figure 2. The contact between these two units is erosive and the boulder conglomerate clearly infills a fluvial channel. About 50 m to the east beyond the channel, however, the lithic wacke is 32.5 m thick and is overlain by a basalt flow. Here, the lithic wacke grades upsection into an immature sandstone with less distinct bedding and more basalt clasts. There is relief along the contact between the lithic wacke and the overlying basalt flow of the Facho-Pico Alto Complex.

We infer from the sedimentologic and fossil evidence that the deposits at Pedra-que-Pica represent a regressive sequence of transition zone to foreshore environments. The underlying pillow basalt indicates submarine volcanism. The cracked and weathered nature of the top of the pillow basalt indicates an interval of exposure before deposition of the overlying lithic calcarenite. This lower sandstone formed in transition-zone or lower shoreface environments, based on the abundant bioturbation and grain size. The overlying coquina represents one or more storm-lag deposits, where storms have winnowed out most of the sand, thereby leaving behind the larger shells. Most of the bivalves that we observed were concave down, suggesting winnowing. The overlying well-stratified sandstone most likely formed in a foreshore to upper

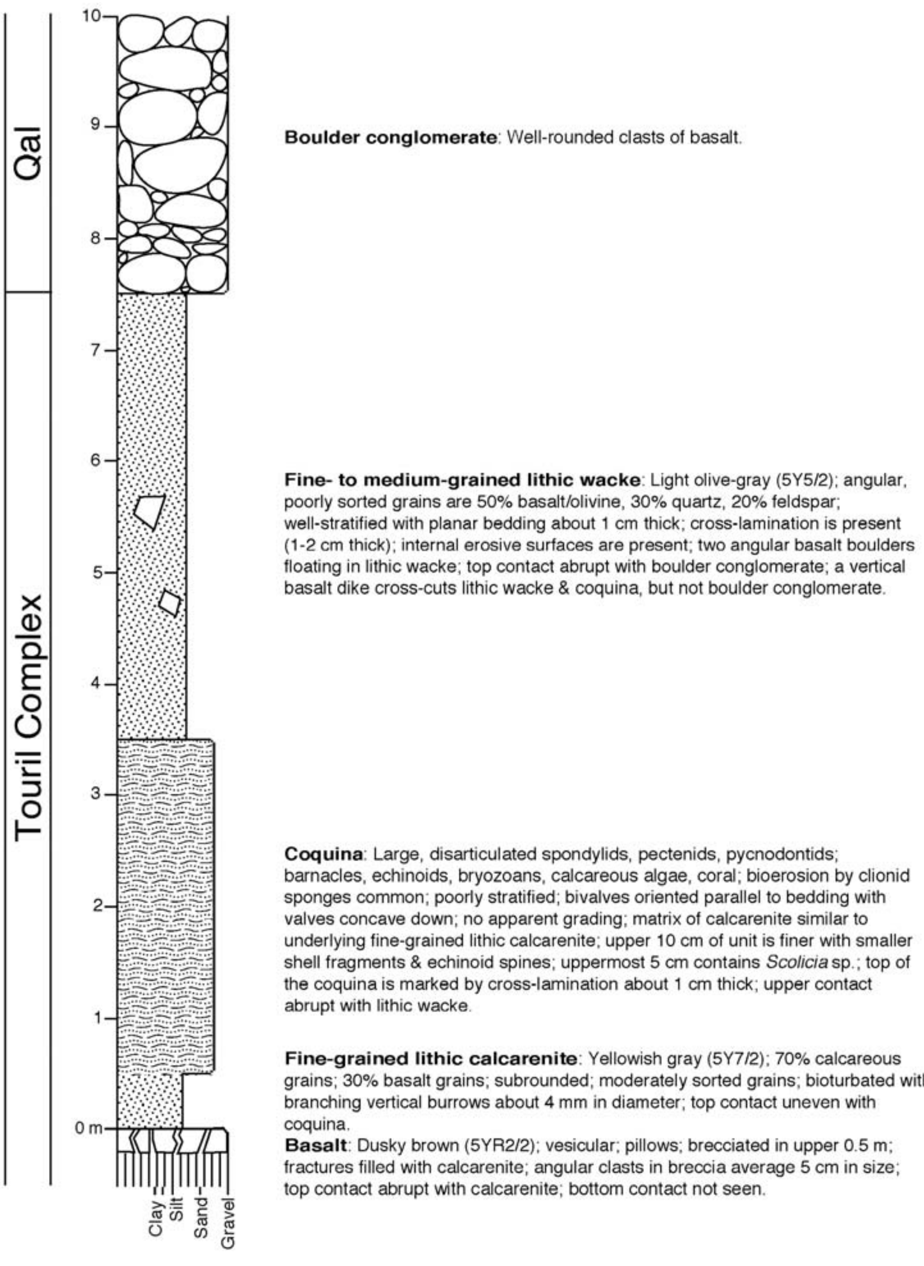

FIGURE 2. Stratigraphic section at Pedra-que-Pica, Santa Maria Island, Azores (N36°55.806′, W25°01.482′).

shoreface environment, based on the planar bedding, erosive surfaces, and general lack of bioturbation, which are all indicative of modern foreshore to upper shoreface environments (Reineck and Singh, 1975). The overlying basalt of the Facho-Pico Alto Complex represents a return to active volcanism in this area. The boulder conglomerate infilling the fluvial channel represents Quaternary alluvium.

Sedimentary Facies Analysis at Pedreira do Campo

Pedreira do Campo contains an exposure of 5 m of sediments that are within the Touril Complex of

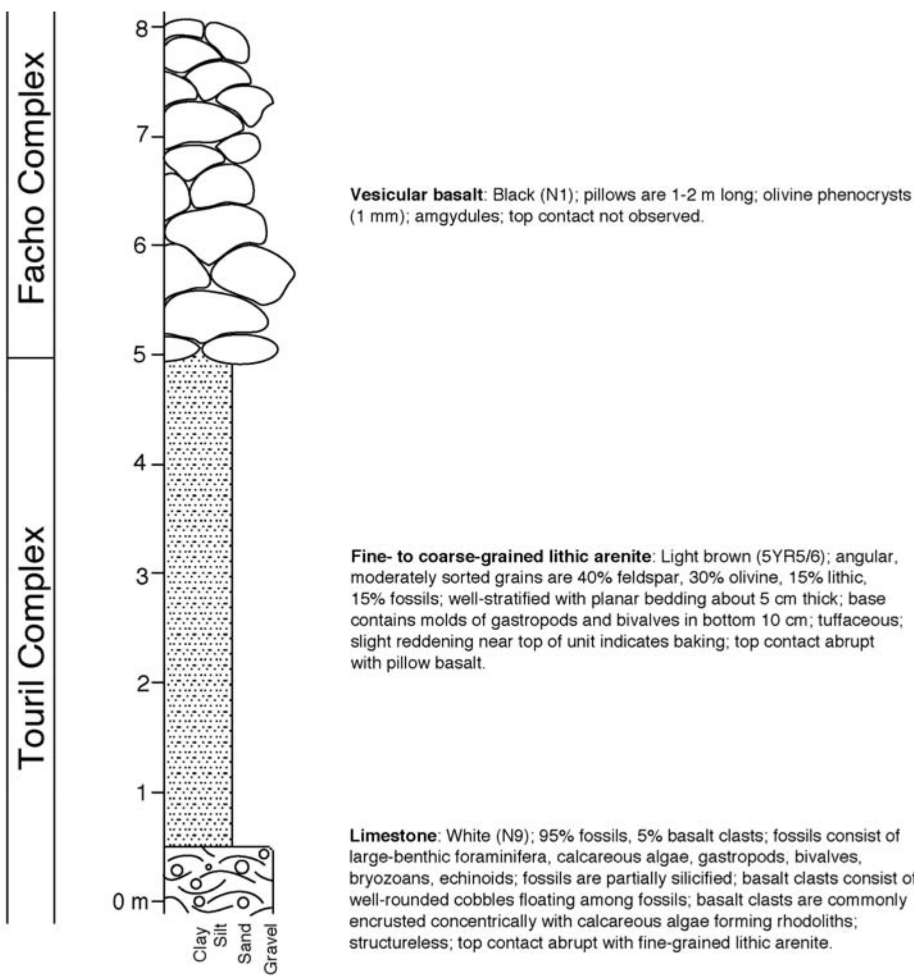

FIGURE 3. Stratigraphic section at Pedreira do Campo, Santa Maria Island, Azores (N36°56.818′, W25°08.119′).

Serralheiro *et al*. (1987) (Fig. 3). The bottom of the Touril Complex was not seen, but the top was seen. These sediments can be divided into two facies. The base of the section is marked by bioclastic limestone (calcirudite/skeletal grainstone) that is rich in large benthic foraminifera, bryozoans, gastropods, bivalves, and rhodoliths of calcareous algae. The base of the limestone is not exposed. Overlying the limestone is a well-stratified lithic arenite that is 4.5 m thick, which is overlain by about 20 m of pillow-basalt flows of the Facho Complex of Serralheiro *et al*. (1987). The top of the Facho Complex was not seen.

We infer from the sedimentologic and fossil evidence that the deposits at Pedreira do Campo represent a regressive sequence of open-ocean environments grading upsection into a shallower foreshore or shoreface environment with subaqueous volcanism. The limestone most likely formed on a shallow bank or shoal within the photic zone, based on the photosynthetic organisms (rhodophytes and benthic foraminifera) and sedimentology. The absence of fine-grained terrigenous material suggests that

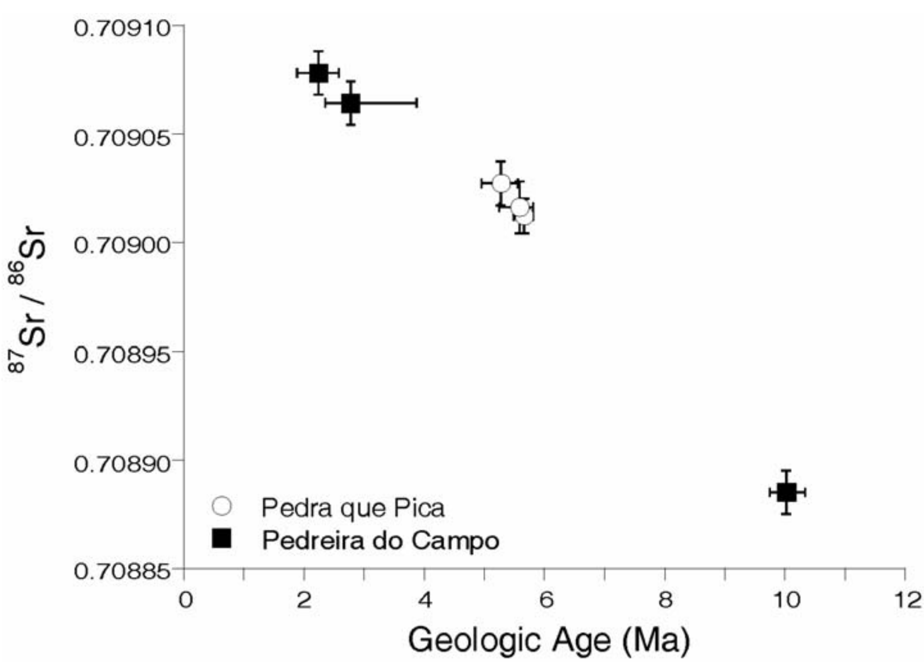

FIGURE 4. Scatter plot showing estimated geologic ages of Pedra-que-Pica and Pedreira do Campo as derived from measurements of the $^{87}Sr/^{86}Sr$ in fossil mollusc shells from these localities.

this bank or shoal was far from any subaerial sources of terrigenous sediment. The sandstone probably formed in a foreshore or shoreface environment, based on the planar bedding. The tuffaceous nature of the sandstone indicates that ash falls were a common occurrence from one or more nearby volcanoes.

$^{87}Sr/^{86}Sr$ Chronostratigraphy

Strontium isotopic results from Pedra-que-Pica and Pedreira do Campo indicate that these localities contain fossils that range from late Miocene to late Pliocene in age (10.0 to 2.2 Ma) (Fig. 4, Table 1). The three fossil shells collected from the coquina at Pedra-que-Pica have an average $^{87}Sr/^{86}Sr$ composition of 0.709018±0.000008 that represents an average estimated age of 5.51±0.21 Ma, which is Messinian age in the late Miocene. The three fossil shells collected from the limestone at Pedreira do Campo show a wide range in $^{87}Sr/^{86}Sr$ ratios, from 0.708885 to 0.709078, which represent estimated ages from 10.03 to 2.24 Ma, respectively (Fig. 4).

DISCUSSION AND CONCLUSIONS

The fossils of Santa Maria Island in the Azores archipelago represent one of the few shallow-marine communities of late Neogene age between Europe and North America in the north Atlantic Ocean. The rarity of similar localities makes our results important in the consideration of the evolutionary and biogeographic history of shallow-marine faunas in the north Atlantic. Both localities studied in this report contain deposits that formed in shallow-marine environments, with Pedra-que-Pica representing a regressive sequence from transition-zone to foreshore environments, and Pedreira do Campo representing a regressive sequence from shallow bank to shoreface-foreshore environments. Although both localities contain regressive sequences, they differ in their sedimentology. Pedra-que-Pica contains abundant terrigenous sediment that is clearly derived from volcanic and bioclastic sources. Pedreira do Campo, on the other hand, contains limestone with very little terrigenous input, but with abundant photosynthetic organisms (large benthic foraminifera and rhodophytes). We infer from this pattern that Pedra-que-Pica was very near emergent land, whereas Pedreira do Campo was not as close to emergent land, but was instead on a shallow bank or shoal either isolated or on the windward edge of Santa Maria Island. If the former was the case, then the sediments at Pedreira do Campo may record the complete submergence of Santa Maria Island between eruptive phases, with the last eruptive phase re-establishing an emergent island in the Pliocene (represented by the overlying Facho-Alto Pico Complex).

The estimated geologic ages of these two localities are different as well (Fig. 4). Pedra-que-Pica is latest Miocene in age, whereas Pedreira do Campo is either as old as late Miocene or as young as late Pliocene.

The Sr ratios determined from the three specimens collected from the coquina at Pedra-que-Pica form a tight cluster, giving an estimated age of 5.51±0.21 Ma. This estimated age is very interesting as it coincides with the Messinian salinity crisis, when the Mediterranean Sea is believed to have desiccated several times during the Messinian age (Adams *et al*., 1977; Hsü *et al*., 1977; Krijgsman *et al*., 1999).

The Sr ratios from the three specimens collected from the limestone at Pedreira do Campo, however, do not form a tight cluster but are scattered, with two specimens clustering at about 2.5 Ma and the other specimen indicating a much lower Sr ratio and older age date of 10 Ma. There are three possible alternative explanations for the pattern observed in the specimens from Pedreira do Campo. First, there may have been significant time-averaging at Pedreira do Campo. An older shell from a late Miocene deposit may have been reworked into a younger death assemblage during the late Pliocene at Pedreira do Campo. Second, it is possible that some of the shells analyzed may have undergone diagenetic alteration that may have altered the ratio of $^{87}Sr/^{86}Sr$. Future work will need to further exclude the possibility of diagensis. Third, local volcanism may have affected the Sr ratio of the seawater locally where the molluscs lived on the open bank. The three shells from Pedreira do Campo are from limestone that is overlain by a thick section of tuffaceous sandstone and pillow basalt. Perhaps hydrothermal activity associated with nearby submarine volcanism altered the ambient Sr ratio of the water for short periods of time during formation of the limestone, such that some shells may have a lower Sr ratio than other shells that reflect global Sr ratios more accurately. Sr ratios from mid-oceanic, ridge flows and pillow-basalt fluids are comparatively lower than ratios from rivers bringing Sr to the ocean from eroded crustal (sialic) rocks (Faure and Mensing, 2005). If seawater with lower Sr ratios surrounding the Azores from periods of high submarine volcanism or active vent flows was incorporated into shell calcite by the molluscs, it could have lowered their ratios and made them appear artificially older. Further work is clearly needed in order to test each alternative hypothesis in order to better understand the preliminary results from Pedreira do Campo.

Our results for Pedra-que-Pica are in general agreement with previous studies, but there are differences. Results are mostly congruent with previous work that inferred a late Miocene to early Pliocene age for the sediments of the Touril Complex, based on biostratigraphy (e.g. Krejci-Graf *et al*., 1958; Zbyszewski and Ferreira, 1962b). Our results are also congruent with the K/Ar radiometric ages determined by Abdel-Monem *et al*. (1975). They dated the basalts underlying the "coquina zone" (presumably Touril Complex of Serralheiro and Madeira, 1993) as being 6-8 Ma or older, and the basalts overlying the "coquina zone" as being 4 Ma or younger. These ages for the underlying and overlying basalt flows bracket our average Sr age date of 5.51±0.21 Ma for the sediments at Pedra-que-Pica. However, our estimated age for the sediments at Pedra-que-Pica are older than the K/Ar age dates determined by Feraud *et al*. (1980, 1981, 1984) for what they described as the "pillow complex interbedded with fossiliferous calcarenites," which Serralheiro and Madeira (1993) inferred as containing the Touril Complex. Feraud *et al*. (1981, 1984) determined that these rocks are 3.8 to 3.3 Ma, which is 1.7 to 2.2 million years younger than our average estimated age for the sediments at Pedra-que-Pica. Finally, our results are in agreement with the geologic review of Serralheiro and Madeira (1993), who inferred that the fossiliferous sediments in the Touril Complex were Messinian to early Pliocene in age, based on the previous studies and their own geologic field work. Results from Pedreira do Campo are not in agreement with previous studies, which further indicates that the initial results from Pedreira do Campo need to be treated with caution.

These results and conclusions help to place the shallow-marine communities of Santa Maria Island into a geologic context that will aid our understanding of how these communities relate to the broader evolutionary and biogeographic history of the Atlantic basin, as well as that of the world, during the late Neogene. Future work must include: (1) Sr age dating of additional samples from Pedreira do Campo in order to better resolve its age; (2) Sr age dating of samples from new exposures, such as those at Ponta da Malbusca and Baía da Cré; (3) correlating the different exposures of fossiliferous sediments around the island through Sr age dating and geologic field work; and (4) ultimately creating a Sr chronostratigraphic framework for Santa Maria Island that will help to resolve the discrepancies between the previously published age dates for the Touril Complex.

ACKNOWLEDGEMENTS

We thank Mr. Pombo (Vila do Porto) for information about the fossils of Santa Maria. We also thank F. Cecca (University Paris VI) for discussions and help in the field and Clube Naval de Santa Maria for providing sea transportation to reach the locality at Pedra-que-Pica. MXK thanks A.M. de Frias Martins and Sérgio P. Ávila for inviting him to participate in the 1st Atlantic Islands Neogene International Congress, June 2006. We are grateful to the University of the Azores for providing funding for this work, as well as to the University of Florida for funding the Sr analyses. We also acknowledge financial support from the organizers of the 3rd Workshop "*Palaeontology in Atlantic Islands*" and from FCT (Portuguese Science Foundation), SRAM (Secretaria Regional do Ambiente e do Mar, Governo Regional dos Açores), DRCT (Direcção Regional da Ciência e Tecnologia, Governo Regional dos Açores) and Câmara Municipal de Vila do Porto.

S.P. Ávila was supported by grant SFRH/BPD/22913/2005 (FCT - Fundação para a Ciência e Tecnologia) of the Portuguese government.

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