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Volcanic history and $^{40}Ar/^{39}Ar$ and ^{14}C geochronology of Terceira Island, Azores, Portugal

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Abstract

Seven new $^{40}Ar/^{39}Ar$ and 23 new radiocarbon ages of eruptive units, in support of new geologic mapping, improve the known chronology of Middle to Late Pleistocene and Holocene volcanic activity on the island of Terceira, Azores and define an east-to-west progression in stratovolcano growth. The argon ages indicate that Cinco Picos Volcano, the oldest on Terceira, completed its main subaerial cone building activity by about 370–380 ka. Collapse of the upper part of the stratovolcanic edifice to form a 7 × 9 km caldera occurred some time after 370 ka. Postcaldera eruptions of basalt from cinder cones on and near the caldera floor and trachytic pyroclastic flow and pumice fall deposits from younger volcanoes west of Cinco Picos have refilled much of the caldera. The southern portion of Guilherme Moniz Volcano, in the central part of the island, began erupting prior to 270 ka and produced trachyte domes, flows, and minor pyroclastic deposits until at least 111 ka. The northern part of Guilherme Moniz Caldera is less well exposed than the southern part, but reflects a similar age range. The northwest portion of the caldera was formed sometime after 44 ka. Several well-studied ignimbrites that blanket much of the island likely erupted from Guilherme Moniz Volcano. The Pico Alto Volcanic Center, a tightly spaced cluster of trachyte domes and short flows, is a younger part of Guilherme Moniz Volcano. Stratigraphic studies and our new radiocarbon ages suggest that most of the Pico Alto eruptions occurred during the period from about 9000 to 1000 years BP. Santa Barbara Volcano is the youngest stratovolcano on Terceira, began erupting prior to 29 ka, and has been active historically.
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1. Introduction

Terceira, the third largest island in the Azores archipelago (Fig. 1), is constructed from three long-lived, overlapping stratovolcanoes and abundant, widely distributed basaltic vents. Each stratovolcano is built by basaltic to trachytic lava flows and pyroclastic deposits and each has nested summit calderas. The eastern two-thirds of the island is partially covered by pyroclastic deposits from the trachytic Lajes Ignimbrite erupted ~21 ka (Self, 1976; Nunes et al., 2000; this study). The easternmost volcano, Cinco Picos (Fig. 2) is deeply eroded, covered by post-caldera basalts, and inferred to

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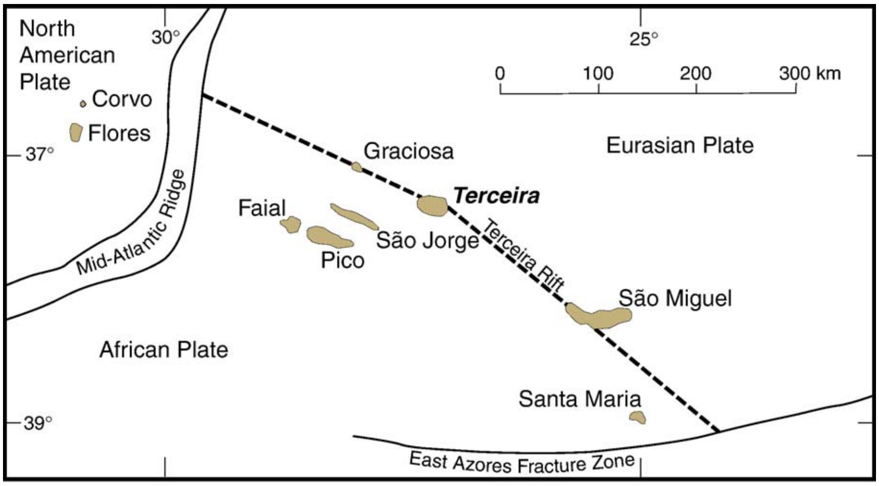

Fig. 1. Index map of the Azores archipelago and general trend of the Terceira Rift.

be the oldest on the island. The central volcano, Guilherme Moniz, and its active north flank, the Pico Alto Volcanic Center (PAVC), are intermediate in age and the sources of several pyroclastic deposits, including the Lajes Ignimbrite. Santa Barbara is the youngest stratovolcano on Terceira and occupies the western third of the island. Many trachytic and basaltic flows form lava deltas, suggesting that Santa Barbara is an actively growing volcano.

Basaltic vent deposits and flows are concentrated in the region between Santa Barbara and Guilherme Moniz Volcanoes, where some eruptions predate and most postdate the Lajes Ignimbrite. Additional basaltic eruptions occurred within the caldera and on the flanks of Cinco Picos Volcano. Other basaltic vents are scattered around most of the island. In contrast to São Miguel, where limited exposures of Pliocene rocks occur, our study and that of Lloyd and Collis (1981) show that exposed rocks on Terceira are all of Late Pleistocene and Holocene age.

2. Geologic setting and previous work

Terceira is located along the Terceira Rift, which marks the boundary between the Eurasian and African plates (Fig. 1). The boundary, a zone of divergence or a spreading center that underlies the Azores archipelago (Krause and Watkins, 1970; Searle, 1980), changes to one of convergence and, locally, transforms faulting toward the Iberian Peninsula (Grimison and Chen, 1986). Several workers (e.g., Schilling, 1975; White et al., 1976, 1979; Hawkesworth et al., 1979) have suggested that the Azores represents the track of a mantle plume or hotspot. Other workers (e.g., Nunes, 2000) have interpreted the distribution of Holocene eruptive vents on most of the nine major Azores islands to reflect a leaky transform fault that underlies the archipelago.

Structural features on Terceira mostly fall into two groups, those which are more or less aligned with the west-northwest-trending Terceira Rift and those that are radial or concentric to the three calderas (Lloyd and Collis, 1981). The Terceira Rift trace is diffuse and, to the extent known, not as clearly defined as it is in parts of the neighboring island of Sao Miguel, where it visibly cuts across the caldera of Sete Cidades volcano and where Kurz et al. (1990) were able to exactly locate the buried Eurasian–African plate boundary in the center of the island on the basis of He, Sr, and Pb isotopic data. The Rift on Terceira is likely a series of overlapping en echelon segments (Lloyd and Collis, 1981).

A relative chronology has been established by detailed geologic mapping (Zbyszewski et al., 1971; Moore and Rodrigues da Silva, in press) and volcanic stratigraphy studies (Self, 1976). Nunes (2000) described the general geology of Terceira and discussed several K–Ar and radiocarbon ages determined by previous workers. This study provides a chronology for critical field relationships identified during fieldwork for a geologic hazards assessment and accompanying map of Terceira (Moore and Rodrigues da Silva, in press) for the U.S. Department of Defense which, along with the Government of Portugal, operates the Lajes Air Base on the north flank of Cinco Picos Volcano.

3. Field relationships

For purposes of this paper, we divide the volcanic rocks of Terceira into four zones (Fig. 2): the three

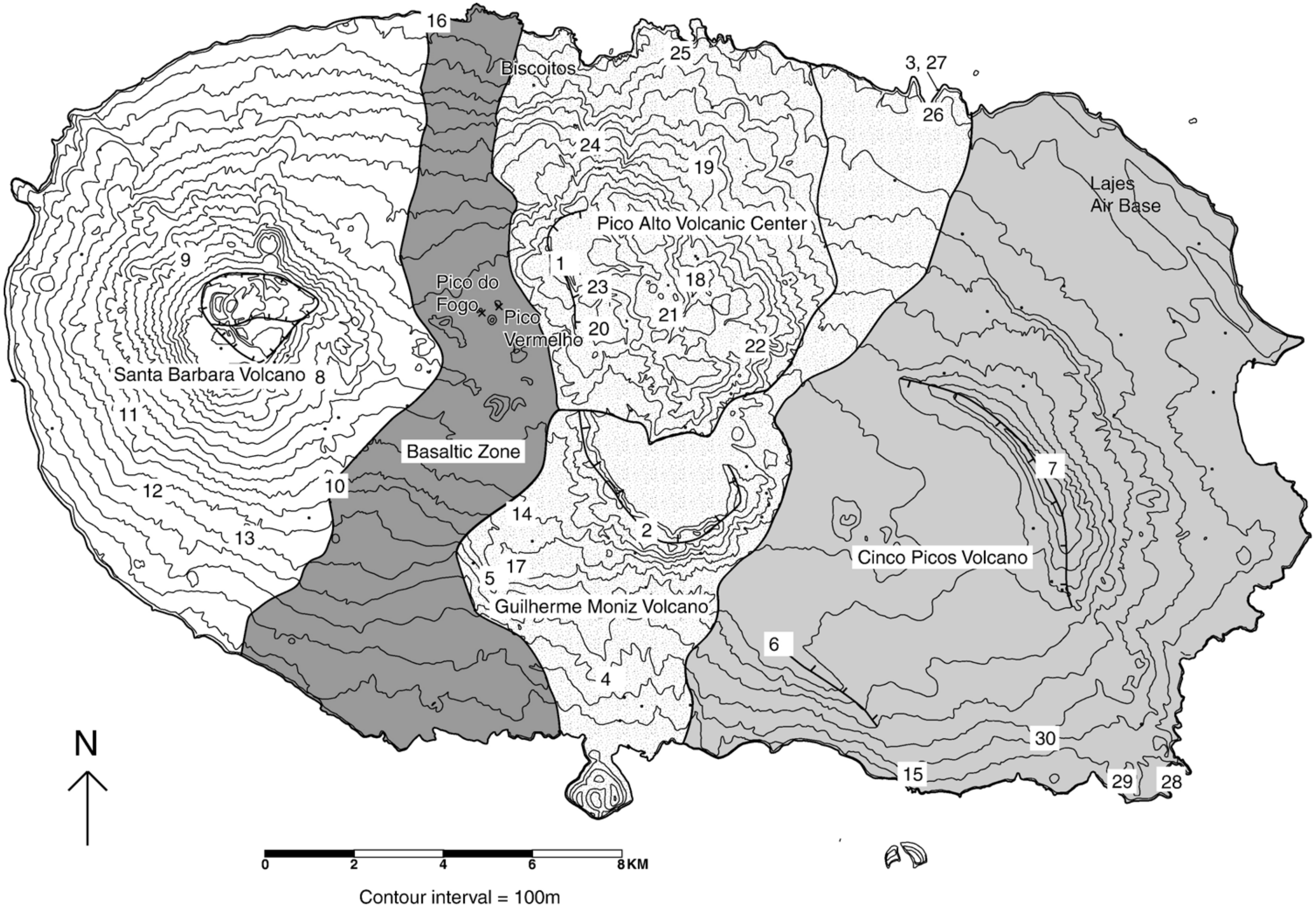

Fig. 2. Map delineating major volcanic centers of Terceira and geochronology sample locations, keyed to Tables 1 and 2.

stratovolcanoes of Cinco Picos, Guilherme Moniz (including the PAVC), Santa Barbara, and the area of mainly basaltic vents and flows between Guilherme Moniz and Santa Barbara (the “Basaltic Zone”). The general progression of the age of stratovolcano growth is from east to west, i.e., Cinco Picos is the oldest and Santa Barbara, the youngest. Contrary to this overall progression though, several monogenetic basalt eruptions at Cinco Picos occurred after the start of eruptions at Guilherme Moniz and Santa Barbara.

3.1. Cinco Picos Volcano

Cinco Picos Volcano is deeply eroded and partially obscured by younger lavas and pyroclastic deposits from post-caldera vents and the adjacent Guilherme Moniz Volcano. Collapse of the upper part of the edifice formed a 7 × 9 km caldera (Fig. 2), the largest in the Azores. Two remnants of the Cinco Picos Caldera rim rise above the younger cover. Postcaldera eruptions of basalt from cinder cones on and near the caldera floor and trachytic pyroclastic flow and pumice fall deposits from younger volcanoes west of Cinco Picos have continued in Late Pleistocene and Holocene time and refilled much of the caldera. On the north flank of the volcano, the Lajes graben and associated horsts provide significant structural and topographic relief and good exposures. Chemical compositions of rocks of the precaldera Cinco Picos stratovolcano range from olivine-poor basalt to low-silica trachyte. The deposit whose eruption may have been responsible for caldera collapse has not been recognized and probably is buried by younger volcanic deposits.

Infilling of Cinco Picos Caldera by newly erupted volcanic deposits likely began shortly after it formed and has continued into the Holocene. The main sources of fill material are the adjacent Guilherme Moniz Volcano and its associated PAVC, as well as at least 12 basaltic cones and flows that erupted on the Cinco Picos Caldera floor. Numerous pre- and postcaldera eruptions from the stratovolcano’s summit, flanks, and caldera sent ash into Cinco Picos Caldera. Larger Pico Alto eruptions, such as the Lajes Ignimbrite (Self, 1971), locally filled the caldera to a depth of at least several tens of meters. Self (1976) recognized the products of at least 40 Pico Alto eruptions, and most of them produced ash that fell in Cinco Picos Caldera.

The postcaldera basaltic cones and associated flows appear to be aligned along the buried, diffuse trace of the Terceira Rift (Lloyd and Collis, 1981). Petrographically, they differ markedly from the mafic lavas of the stratovolcanic edifice. The older lava flows are strongly feldspathic and aphyric or nearly so, whereas the younger basalts have conspicuous olivine and pyroxene phenocrysts. No postcaldera trachytic vents are exposed within the caldera. Postcaldera vents and flows of intermediate to trachytic composition are present on the east and southeast outer flanks of Cinco Picos.

Cinco Picos Volcano has also grown outside its caldera. Several basaltic scoria deposits and associated short flows overlie exposures of the 21 ka Lajes Ignimbrite on the north flank. About twenty basaltic vents and three intermediates to trachytic domes and associated flows are concentrated on the east flank of the volcano. The youngest eruption appears to be that of Pico do Fonte Bastardo, where its flow is rough-surfaced and uneroded and appears to be only a few thousand years old (Rosenbaum, 1974).

3.2. Guilherme Moniz Volcano and Pico Alto Volcanic Center (PAVC)

Guilherme Moniz Volcano, in the central part of the island, contains primarily trachyte domes and flows, locally associated with relatively minor pyroclastic deposits. The elongate, 8 × 2 km, scallop-edged Guilherme Moniz Caldera (Fig. 2) may have formed as a result of multiple collapses that followed voluminous eruptions of trachytic ignimbrite. We have examined at least four (possibly six) such pyroclastic flow deposits, the Lajes Ignimbrite (21 ka, see below), the Angra Ignimbrite (dated by Shotton and Williams, 1973 at about 23 ka), and at least two older undated deposits on the south and northeast coasts.

The northern part of Guilherme Moniz Caldera is less well exposed than the southern part, owing to the burial by younger deposits. The Pico Alto Volcanic Center (PAVC) located north of the Guilherme Moniz Caldera, as described by Self (1976) and named and described by Lloyd and Collis (1981), is a younger part of Guilherme Moniz Volcano. The PAVC is a tightly spaced cluster of trachyte domes and short flows, many with associated pyroclastic flow and surge deposits that fill the caldera and extend down the northern flank of Guilherme Moniz Volcano. PAVC deposits limit the northern exposures of older Guilherme Moniz rocks mainly to discontinuous sea cliffs. We suggest that eruption of the Angra and Lajes Ignimbrites, and perhaps others, led to multiple episodes of caldera collapse.

The subaerial portion of Guilherme Moniz Volcano overlies the western flank of Cinco Picos, and the PAVC developed in the northern part of Guilherme Moniz Caldera sometime after eruption of the Lajes Ignimbrite (Self, 1976; Lloyd and Collis, 1981).

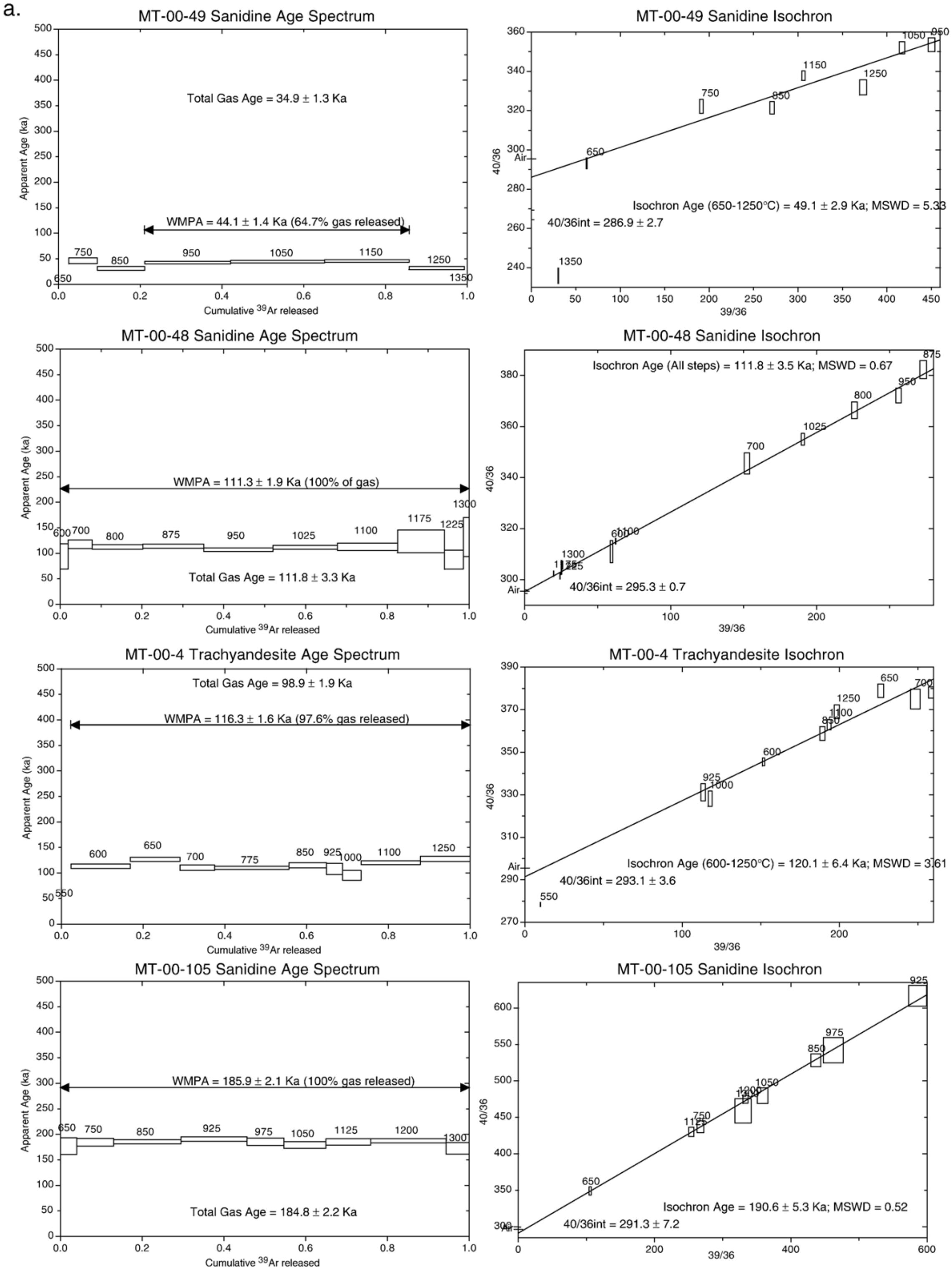

Fig. 3. Age spectra and isotope correlation plots for all $^{40}Ar/^{39}Ar$ data.

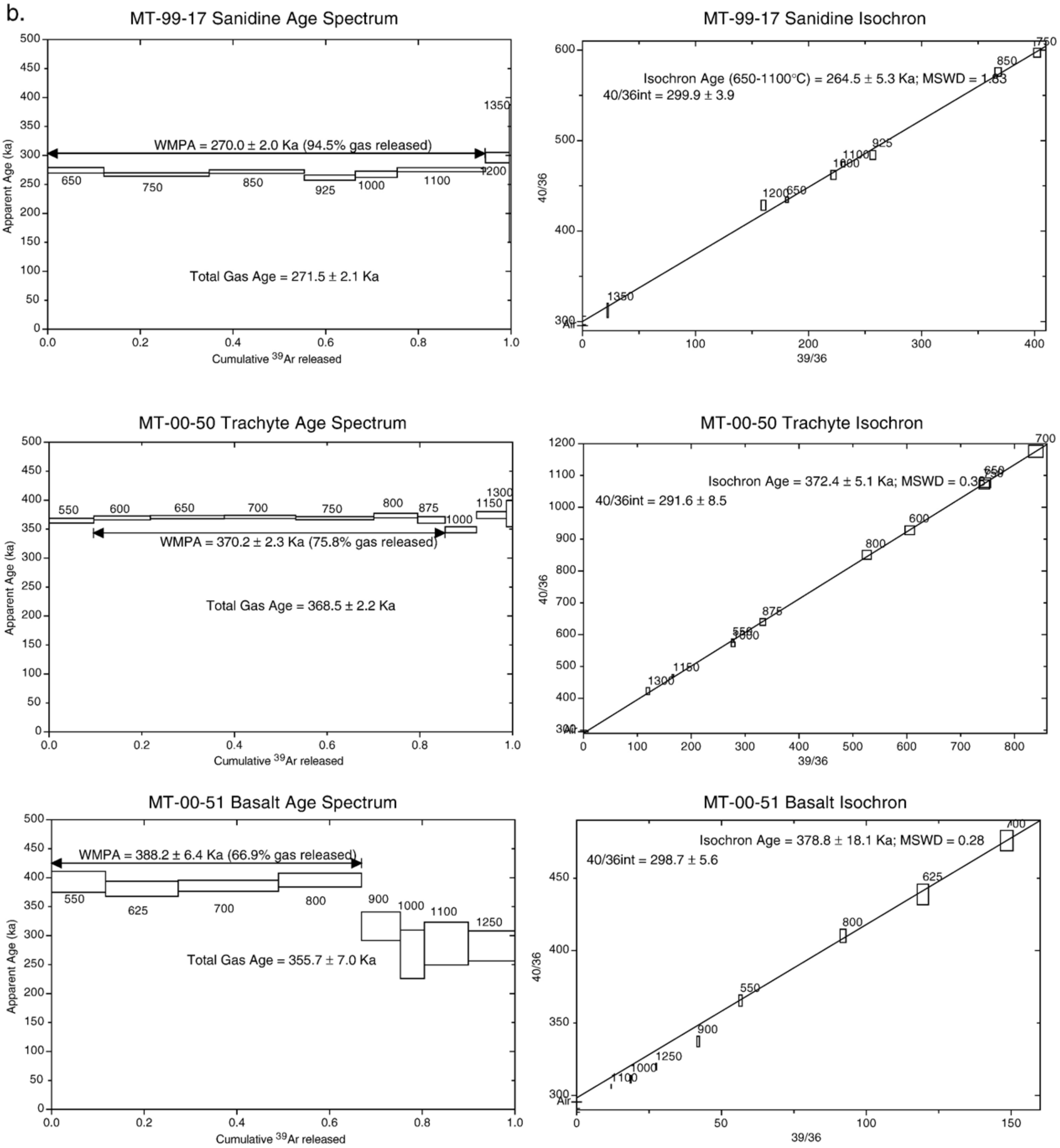

Fig. 3 (*continued*).

3.3. Basaltic eruptions between Guilherme Moniz and Santa Barbara Volcanoes

Monogenetic cones and spatter ramparts, virtually all with associated flows, of chiefly basaltic composition occupy about 80 km^2 in the area between Guilherme Moniz and Santa Barbara Volcanoes, which we call the "Basaltic Zone" (Fig. 2). This zone extends into the Guilherme Moniz Caldera south of the PAVC (see Zbyszewski et al., 1971; Lloyd and Collis, 1981), suggesting that part, at least, of the Guilherme Moniz magma reservoir has solidified. We also discovered previously unknown trachyte domes, nearly buried by basaltic vent deposits, in the center of this "zona baixa (low zone or area)" of Zbyszewski et al. (1971). All of these deposits are latest Pleistocene and Holocene in age (Self, 1976; Lloyd and Collis, 1981; this study).

The most recent eruption in this area occurred in 1761. It formed two small spatter-and-cinder cones, Pico Vermelho and Pico do Fogo, and extruded flows as much as 6 km to the north into the village of Biscoitos (Zbyszewski et al., 1971; Lloyd and Collis, 1981).

3.4. Santa Barbara Volcano

Subaerial eruptions of Santa Barbara, the youngest volcano on Terceira, probably began during the Late Pleistocene, perhaps within the past 100,000 years. The oldest exposed rocks are dominantly basaltic to intermediate in composition and crop out in sea cliffs on the north, west and south coasts. Ferreira and Azevedo (1995) reported ages of about 0.5–1.24 Ma for samples low on the northwestern sea cliff, but lava accumulation rates and the local stratigraphy suggest that these ages are too old and may reflect contamination by crustal xenoliths or xenocrysts.

The summit area of Santa Barbara is truncated by two nested calderas (Fig. 2). The outer caldera, about 2.5 × 2 km across and 150 m deep, likely formed after eruption of an extensive, lithic-rich trachytic pyroclastic-flow deposit. A younger but undated eruption, possibly the voluminous (1–2 ka; Self, 1976) Pico Rachado or Pico do Carneiro flank events, led to the collapse of an inner portion of the partly filled outer caldera. The inner caldera, about 2 km across, may be much younger than the outer one. The trachyte domes and flows that partly fill it have not been dated, but generally appear quite young (Self, 1976). Possibly, eruption of young large-volume trachyte domes and flows on the flanks of Santa Barbara, like Pico do Carneiro, Pico Rachado, and Ponta da Serreta, withdrew support under the summit area and led to caldera collapse.

The most recent trachytic eruption of Santa Barbara was the A.D. 1761 formation of eight low domes and short flows at Misterio dos Negros on the eastern flank of the volcano (Zbyszewski et al., 1971). The 1998–2000 basaltic eruption (Forjaz et al., 2000) occurred along a northwest-trending submarine ridge about 10 km west of the west coast of Terceira. The eruption was the first in the Azores since the 1957–1958 Capelinhos event on Faial. It also was noteworthy because hot fragments of highly vesicular pillow basalt floated on the surface of the ocean after being erupted at 500 m depth. Other isolated basaltic vents, mostly of Late Pleistocene age, occur on the north and south flanks of Santa Barbara Volcano.

Table 1
Terceira $^{40}Ar/^{39}Ar$ ages

Location (Fig. 2)	Sample	Volcano source	Separate, rock type	Integrated age (ka)	Plateau age (ka)	Steps used (%39 released)	Isochron age (ka)	Steps used (%39 released)	40/36 intercept	MSWD
1	MT-00-49	GM	Sanidine, trachyte	34.9 ± 1.3	**44.1 ± 1.4**	950–1150 (64.7%)	38.2 ± 8.9	950–1150 (64.7%)	302.6 ± 10.0	0.3
2	MT-00-48	GM	Sanidine, trachyte	111.8 ± 3.3	**111.3 ± 1.9**	600–1300 (100%)	118.1 ± 3.5	600–1300 (100%)	295.3 ± 0.7	0.67
3	MT-00-4	GM	Groundmass, trachyandesite	98.9 ± 1.9	**116.3 ± 1.6**	600–1250 (97.6 %)	120.1 ± 6.4	600–1250 (97.6%)	293.1 ± 3.6	3.6
4	MT-00-105	GM	Sanidine, trachyte	184.8 ± 2.2	**185.9 ± 2.1**	650–1300 (100%)	190.6 ± 5.3	650–1300 (100%)	290.6 ± 5.3	0.5
5	MT-99-17	GM	Sanidine, trachyte	271.5 ± 2.1	**270.0 ± 2.0**	650–1100 (94.5%)	264.5 ± 5.3	650–1100 (94.5%)	299.9 ± 3.9	1.83
6	MT-00-50	CP	Groundmass, trachyte	368.5 ± 2.2	**370.2 ± 2.3**	600–875 (75.8%)	372.4 ± 5.1	600–875 (75.8%)	291.6 ± 8.5	0.38
7	MT-00-51	CP	Groundmass, basalt	355.7 ± 7.0	**388.2 ± 6.4**	550–800 (66.9%)	378.8 ± 18.1	550–800 (66.9%)	298.7 ± 5.6	0.28

Bold entries indicate the preferred results.

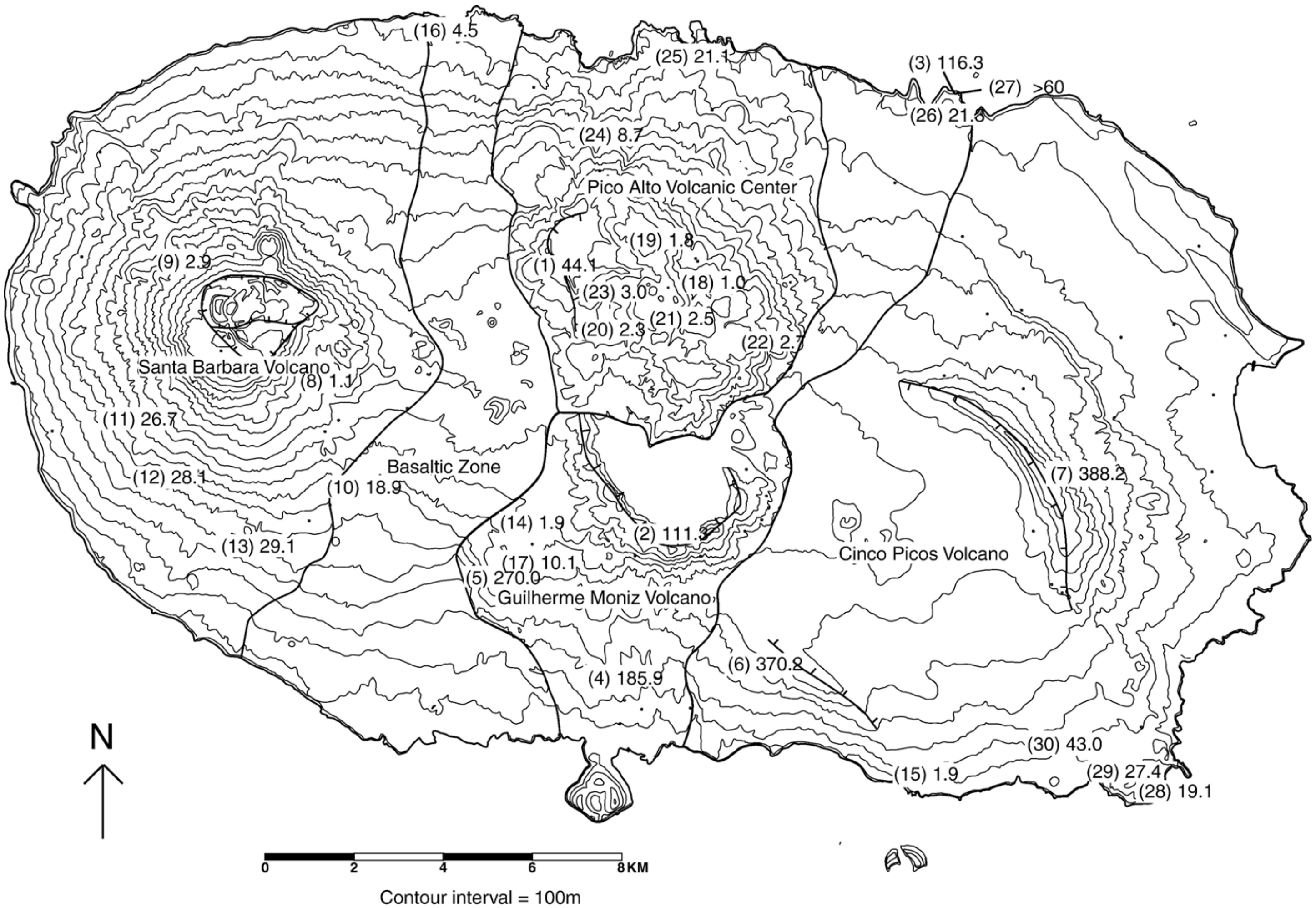

Fig. 4. Interpreted ^{40}Ar/^{39}Ar and radiocarbon ages plotted on topographic map (data of Tables 1 and 2). After the sample location in parentheses, ages are given in thousands of years (ka).

4. Dating techniques and sample preparation

For ^{40}Ar/^{39}Ar dating, we collected stratigraphically old lava flows or domes in order to determine the age of the oldest exposed rocks on the volcano, the youngest precaldera flow or dome in order to establish the approximate age of caldera formation, and trachyte domes and flows in densely populated areas in which renewed eruptive activity would constitute a significant volcanic hazard.

Four of the trachyte flows yielded pure sanidine separates and groundmass feldspar was concentrated from the remaining flows. Encapsulated packets of 80–105 mg of sanidine and 190–230 mg of groundmass were irradiated for 1h in the USGS-TRIGA reactor. Samples were shielded from thermal neutrons and neutron flux was measured using Taylor Creek sanidine (TCR-2) with an assigned age of 27.87 Ma (M.A. Lanphere, written communication). Argon was extracted from monitors with an argon ion laser and from unknowns with a Staudacher-type resistance furnace. Gas was cleaned with SAES ST-172 getters and analyzed on a MAP 216 mass spectrometer. Detailed step-heating experiments on all seven samples yielded simple plateau age spectra and isochron ages with intercepts easily within error of atmosphere. All ages are reported (Fig. 3, Table 1) with 1σ errors including errors in neutron flux, but not including errors in decay constants or monitor minerals. Spatial distribution of ages is shown in Figs. 4 and 5; full data tables and plots are available upon request.

For ^{14}C dating, charcoal was collected from within pyroclastic flow, pyroclastic fall, and surge deposits and in buried soils beneath lava flows as well as fragments entirely enclosed within lava flows. Charcoal samples were processed for radiocarbon analysis at the USGS radiocarbon laboratory in Reston, Virginia. Processed samples were dated by accelerator mass spectrometry (AMS) at Lawrence Livermore Laboratory's Center for Accelerator Mass Spectrometry (CAMS) in Livermore, California and at the NSF-Arizona AMS facility at the University of Arizona in Tucson. The charcoal samples were given a standard acid–alkali–acid (AAA) pretreatment when sample size was adequate. The AAA pretreatment consisted of a 2 h wash in 1 M HCl, an overnight wash in 0.1 M

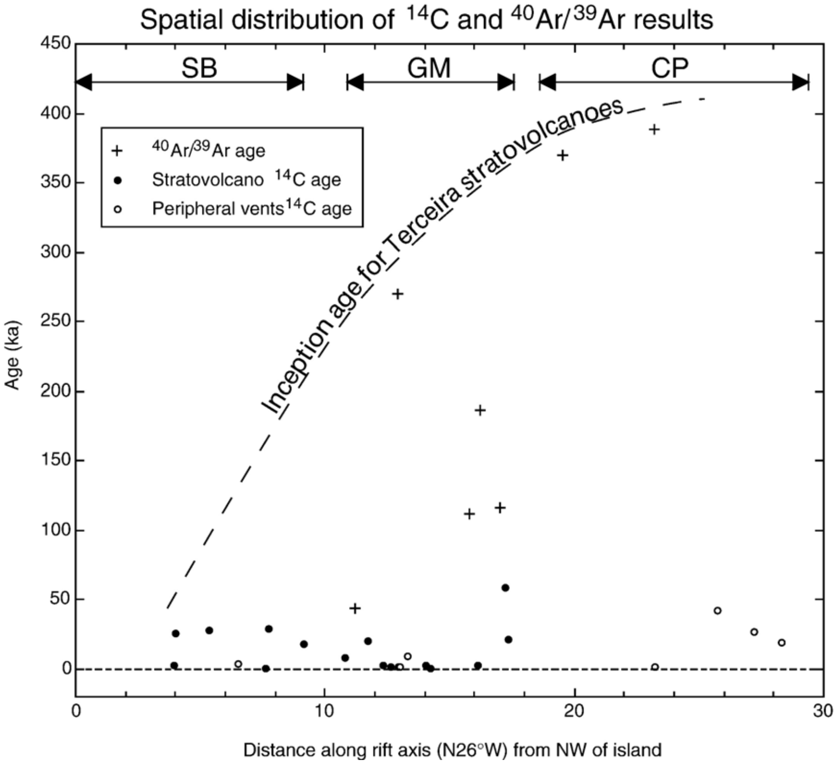

Fig. 5. Spatial distribution of geochronology results. Sample locations were projected onto a line parallel to the Terceira Rift (N26°W). Approximate locations of volcanic centers are shown (SB = Santa Barbara, GM = Guilherme Moniz, CP = Cinco Picos). Some samples (such as sample 15 erupted between SB and GM) project onto different centers.

Table 2
Terceira ^{14}C ages. pf, pyroclastic flow deposit. Laboratory location: A, University of Arizona; L, Lawrence Livermore. CP, Cinco Picos Volcano; GM, Guilherme Moniz Volcano; SB, Santa Barbara Volcano.

Location (Fig. 2)	Sample	Volcano source	Rock type	Unit name	WW (lab) #	Lab	Age (years BP)
8	MT-00-57	SB	trachyte pumice, fall	SE flank, 4th unit down in section	994	A	1130±40
9	MT-99-14	SB	trachyte pumice, pf	Lagoinha dome	2284	L	2890±50
10	MT-99-29	SB	basaltic trachyand. flow	Pico das Duas flow	2495	L	18,860±60
11	MT-99-15	SB	trachyandesite flow	flow near Doze Ribeiras	2285	L	26,670±130
12	MT-99-19	SB	lithic-rich trachyte pf	Santa Barbara pf	2287	L	28,110±160
13	MT-00-50	SB	trachybasalt flow	Pico das Seis flow	2791	L	29,110±120
14	MT-00-36	btw SB/GM	basalt flow	Galiarte (?) flow	946	A	1880±40
15	MT-99-31	btw SB/GM	basalt flow	Algar do Carvao flow	3685	L	1910±35
16	MT-99-29	btw SB/GM	basalt flow	Pico Gordo flow	2792	L	4480±40
17	MT-00-22	btw SB/GM	trachybasalt flow	Vareiras flow	2286	L	10,090±50
18	MT-99-4	GM	trachyte bomb	Quinta da Madalena	2281	L	1030±50
19	MT-00-39	GM	trachyte flow	Pico Alto	947	A	1760±40
20	MT-00-32	GM	trachyte pumice, pf	Biscoito Rachado	945	A	2330±45
21	MT-99-7	GM	trachyte pumice, pf	Biscoito Rachado	2282	L	2530±50
22	MT-00-41	GM	trachyte pumice, pf	poss. Biscoito Rachado	993	A	2680±45
23	MT-00-35	GM	trachyte pumice, pf	prob. Biscoito Rachado	992	A	2950±45
24	MT-99-40	GM	trachyte pumice, pf	Pico das Pardelas	2499	L	8670±50
25	MT-99-9	GM	trachyte pumice, pf	prob. Lajes Ignimbrite, village of Portela da Cruz	2283	L	21,130±80
26	MT-00-80	GM	trachyte pumice, welded pf	Lajes Ignimbrite, Porto da Vila Nova	3686	L	21,320±80
27	MT-00-3	GM	trachyte pumice, surge	basal pf deposit above flow 00-4, Porto da Vila Nova	2790	L	>59,600
28	MT-99-30	CP	basalt flow	Canada da Ponta flow	2496	L	19,120±50
29	MT-99-37	CP	basalt flow	Pico das Contendas flow	2498	L	27,410±190
30	MT-99-36	CP	basalt flow	Porto Judeu flow	2497	L	43,020±740

NaOH, and a final 2-h wash in 1 M HCl. Smaller samples were given shorter alkali washes (1–2 h) to preserve the minimum amount of carbon necessary for a radiocarbon analysis by AMS. Pretreated charcoal was converted to graphite deposited on iron, pressed into targets, and sent to an AMS facility for analysis. Radiocarbon ages with 1σ errors are listed in Table 2 and ages are plotted on Figs. 4 and 5.

5. Discussion of geochronologic results

All samples dated using ^{40}Ar/^{39}Ar yielded well-determined plateau ages with concordant isotope correlation (isochron) plots (Fig. 3, Table 1). Argon samples were selected to bracket critical events such as inception of stratovolcano growth or caldera collapse. Radiocarbon samples (all charcoal) were collected to establish growth ages on the youngest volcano, Santa Barbara, to understand the duration of activity in the active PAVC, as well as to constrain the ages of recent monogenetic eruptions across the island.

5.1. Cinco Picos Volcano

We dated five lavas from Cinco Picos Volcano, two from remnants of the Cinco Picos Caldera rim and three from basalt flows near the SE coast. The subaerial part of Cinco Picos began forming prior to about 370–388 ka (Table 1), the ages of the highest eruptive units on the exposed caldera rims on opposite sides of the volcano (Fig. 2). Ages determined by Feraud et al. (1980) are in broad accord with our new dates. Older ages inferred or reported by White et al. (1976), Ferreira and Azevedo (1995), and Forjaz (personal communication, cited by Nunes, 2000) range from about 0.75 Ma to 3.5 Ma and are not compatible with our analytical results or stratigraphic and morphologic observations (also see Lloyd and Collis, 1981). Accordingly, Cinco Picos rocks that are significantly older than the two samples we dated are unknown. It seems likely that the amount of time required for accumulation of the currently exposed part of the precaldera edifice was only a few tens of thousands of years, and that subaerial eruptions probably began between 500 ka and 400 ka. The age of the Cinco Picos Caldera collapse is dated only as younger than 370 ka.

The filling of the Cinco Picos Caldera began sometime after 370 ka and is continuing, primarily from Guilherme Moniz Volcano and the PAVC, but also cones and flows that erupted on the Cinco Picos Caldera floor. A basalt flow dated at 1.9 ka (Fig. 2, location 15) erupted at a vent north of the Guilherme Moniz Caldera and flowed across the Cinco Picos Caldera to the south coast of the island. We dated three of the approximately twenty basaltic vents (Fig. 2, locations 28, 29, 30) and associated flows by radiocarbon at 19 ka, 27 ka and 43 ka (Figs. 2 and 4; Table 2).

5.2. *Guilherme Moniz Volcano and Pico Alto Volcanic Center*

The subaerial part of Guilherme Moniz Volcano overlies the western flank of Cinco Picos and has been erupting for at least 270 ka. We dated four samples by $^{40}Ar/^{39}Ar$ from Guilherme Moniz Volcano and one sample from the west caldera rim remnant within the PAVC. The oldest sample (270 ka) that we dated (Table 1) is from a trachyte dome on the southwest flank (Fig. 2, location 5). Subaerial eruptions that built that flank occurred significantly earlier, but their exact age is not known. Another trachyte dome and associated flow (Fig. 2, location 4) is 186 ka. A thick trachyte flow on the south wall of Guilherme Moniz Caldera, dated at 111 ka, provides a maximum age of the Guilherme Moniz Caldera collapse. The 111 ka flow is overlain by poorly exposed thin trachyte flows and pyroclastic deposits, including a welded tuff that may be correlative with the Angra or Lajes Ignimbrite. A trachyte dome and associated flow on the northwest caldera wall (Fig. 2, location 1) comprise the principal precaldera eruptive unit in the summit area of that part of the volcano, and its 44 ka sanidine age places a maximum age on caldera collapse. The basal trachyandesite flow at sea level on the northeast flank of Guilherme Moniz yielded 116 ka. It is immediately overlain by a trachytic pyroclastic-surge deposit whose radiocarbon age exceeds about 60 ka. A thick section of trachytic pyroclastic deposits overlies this dated surge and culminates in the 21 ka Lajes Ignimbrite, which we collected nearby and dated. Previous radiocarbon dates on the Lajes Ignimbrite clustered around 19 ka (Shotton et al., 1974). The pyroclastic deposits that predate the Lajes Ignimbrite also likely came from Guilherme Moniz Caldera and may have contributed to its possibly incremental collapse (Walker, 1984). They are too young to have originated at Cinco Picos, geographically the only other possible source.

The Pico Alto Volcanic Center developed in the northern part of Guilherme Moniz Caldera after eruption of the Lajes Ignimbrite at 21 ka (Self, 1976; Lloyd and Collis, 1981). The oldest post-Lajes Ignimbrite deposit of the PAVC that Self (1976) described is his Terra Brava II, designated #5 on his correlation diagram and apparently about 18,000 years old. The oldest post-Lajes Ignimbrite unit for which we have a new radiocarbon age is the Pico das Pardelas deposit on the north flank, which erupted about 8700 years BP (Fig. 2, location 24) and is Self's number 10.

Our youngest new radiocarbon age for a PAVC deposit is about 1000 years BP for trachyte bombs from Quinta da Madalena (Fig. 2, location 18), near the center of the PAVC. It is not the youngest deposit, however (also see Self, 1976). Eruptions at PAVC appear to have continued intermittently almost to the time of human settlement about 500 years ago.

5.3. *Basaltic eruptions between Guilherme Moniz and Santa Barbara Volcanoes (the "Basaltic Zone")*

We have determined three new radiocarbon ages and redated another previously dated deposit in this area (Fig. 2, locations 15–18). These new dates agree well with Self's stratigraphic studies and the mapping of Zbyszewski et al. (1971) and Lloyd and Collis (1981) and lie between 1880 and 10,090 years BP. Our new mean age for the extensive flow from Algar do Carvao (Fig. 2, location 15) is 205 years younger than the previous determination reported by Zbyszewski et al. (1971). Other isolated basaltic vents, mostly of Late Pleistocene age, occur on the north and south flanks of Santa Barbara Volcano.

5.4. *Santa Barbara Volcano*

We dated six samples from Santa Barbara using radiocarbon techniques. Three of our newly dated Santa Barbara units are mafic to intermediate cones and flows that erupted relatively high on the volcanic edifice, although probably outside the area underlain by a trachytic magma reservoir.

Of the two nested summit calderas on Santa Barbara, the outer one is thought by Self (1976) to have formed about 25,000 years ago. Our date of about 28 ka (Fig. 2, location 12) for a widespread lithic-rich pyroclastic flow deposit on the south flank of Santa Barbara somewhat supports Self's suggestion, for a caldera wall, had it been there, might have blocked egress of the flow to the south.

Unfortunately, we have few new radiocarbon dates of Santa Barbara post-Lajes Ignimbrite trachytic eruptions (Table 2). Our age of about 2900 years BP for a pyroclastic flow from the Lagoinha dome is younger than Self's (1976) age based on stratigraphic criteria. Our age of about 1100 years BP on burned forest duff indicates an eruption at that time, but we are uncertain which one. This eruption may correlate with a linear series of domes extending down the east flank of the volcano (Zbyszewski et al., 1971; Lloyd and Collis, 1981). We also identified three subsequent Santa Barbara eruptions that deposited pumice at this locality high on the eastern flank.

6. Conclusions

The spatial distribution of argon and radiocarbon dates (Figs. 4 and 5) reflects the patterns of volcanism on Terceira. It supports field relationships outlined here and previous assertions (e.g. Lloyd and Collis, 1981; Nunes, 2000) of an east to west relative progression. The oldest dated sample from each stratovolcano provides minimum ages on each major center, and those flows likely erupted within a few tens of thousands of years of the inception of subaerial volcanism. Each adjacent volcanic center appears to have overlap in age. Santa Barbara and Guilherme Moniz volcanoes are both still active and the ages of the oldest Guilherme Moniz samples and the two Cinco Picos samples are similar. Samples dated from caldera rims provide maximum ages on caldera formation events.

Radiocarbon samples from peripheral basalt vents across the island reflect continuing volcanism away from magma chambers associated with the stratovolcanoes. Monogenetic cones and flows are concentrated near the presumed trace of the Terceira Rift (Lloyd and Collis, 1981) and our geochronology reflects only a modest fraction of these deposits. The young (<50 ka) ages on these deposits result from our sampling, not a recent change in volcanic behavior. Young ages (<5 ka) on domes and flows of the PAVC and the upper reaches of Santa Barbara Volcano reflect the significant hazard these centers pose.

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References

Feraud, G., Kaneoka, I., Allegre, C.J., 1980. K/Ar ages and stress pattern in the Azores: geodynamic implications. Earth and Planetary Science Letters 46, 275–286.

Ferreira, M.P., Azevedo, J.M., 1995. Evolucão geologica do arquipelago dos Acores baseada na geocronologia: Seminario "Geologia Atlantica". Associacao Portuguesa de Geologos, Ponta Delgada, 9 pp.

Forjaz, V.H., Rocha, F.M., Medeiros, J.M., Meneses, L.F., Sousa, C., 2000. Noticias sobre o vulcão oceanico da Serreta, Ilha Terceira dos Acores: Ponta Delgada, Nova Grafica, Lda., 40 pp.

Grimison, N.L., Chen, W.P., 1986. The Azores–Gibraltar plate boundary—focal mechanisms, depths of earthquakes, and their tectonic implications. Journal of Geophysical Research 91 (B2), 2029–2047.

Hawkesworth, C.J., Norry, M.J., Roddick, J.C., Vollmer, R., 1979. ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr ratios from the Azores and their significance in LIL-element enriched mantle. Nature 280, 28–31.

Krause, D.C., Watkins, N.D., 1970. North Atlantic crustal genesis in the vicinity of the Azores. Geophysical Journal of the Royal Astronomical Society 19, 261–283.

Kurz, M.D., Kammer, D.P., Gulesserian, A., Moore, R.B., 1990. Isotopic variations within oceanic islands: He, Sr, and Pb isotopes in basalts from Sao Miguel, Azores (abs). Transactions of the American Geophysical Union (EOS) 71 (17), 657.

Lloyd, E.F., Collis, S.K., 1981. Geothermal prospection-Ilha Terceira, Acores: Geological report: Geothermal Energy New Zealand Ltd., under contract to the Secretaria Regional do Comercio e Industria, Governo Regional dos Acores, 96 pp.

Moore, R.B., Rodrigues da Silva, A.M., in press. Assessment of geologic hazards, Terceira Island, Azores, Portugal: U.S. Geological Survey Open-File Report, 16 p. plus 1:25,000-scale map.

Nunes, J., 2000. Notas sobre a geologia da Ilha Terceira. Acoreana 9 (2), 205–215.

Nunes, J.C., Forjaz, V.H., Oliveira, C.S., 2000. Geological mapping of Terceira Island (Azores) urban centres as a way to better understand the seismic response of buildings. Actas do II Simposio de Meteorologia e Geofisica da APMG, Evora (Portugal), 8 pp.

Rosenbaum, M.S., 1974. Basaltic volcanism in south-east Terceira, Azores. Geological Magazine 111 (5), 409–420.

Schilling, J.-G., 1975. Azores mantle blob: rare-earth evidence. Earth and Planetary Science Letters 25, 103–115.

Searle, R., 1980. Tectonic pattern of the Azores spreading center and triple junction. Earth and Planetary Science Letters 51, 415–434.

Self, Stephen, 1971. The Lajes Ignimbrite, Ilha Terceira, Acores. Comunicações dos Serviços Geológicos de Portugal 55, 165–184.

Self, Stephen, 1976. The recent volcanology of Terceira, Azores. Journal of the Geological Society (London) 132, 645–666.

Shotton, F.W., Williams, R.E.G., 1973. Birmingham University radiocarbon dates. Radiocarbon 15, 462.

Shotton, F.W., Williams, R.E.G., Johnson, A.S., 1974. Birmingham University radiocarbon dates. Radiocarbon 16, 293.

Walker, G.P.L., 1984. Downsag calderas, ring faults, caldera sizes, and incremental caldera growth. Journal of Geophysical Research 89 (B10), 8407–8416.

White, W.M., Schilling, J.-G., Hart, S.R., 1976. Evidence for the Azores mantle plume from strontium isotope geochemistry of the Central North Atlantic. Nature 263, 659–663.

White, W.M., Tapia, M.D.M., Schilling, J.-G., 1979. The petrology and geochemistry of the Azores Islands. Contributions to Mineralogy and Petrology 69, 201–213.

Zbyszewski, G., Candido de Medeiros, A., da Veiga Ferreira, O., e Torre de Assuncão, C., 1971. Carta geologica de Portugal na escala de 1/50,000-Ilha Terceira. Servicos Geologicos de Portugal, Lisboa.