Geology of Three Late Quaternary Stratovolcanoes on São Miguel, Azores

U.S. GEOLOGICAL SURVEY BULLETIN 1900

Prepared in cooperation with the
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Geology of Three Late Quaternary Stratovolcanoes on São Miguel, Azores

By RICHARD B. MOORE

Prepared in cooperation with the
Regional Government of the Azores

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Geology of Three Late Quaternary Stratovolcanoes on São Miguel, Azores

By Richard B. Moore

Abstract

Three Quaternary trachytic stratovolcanoes—Sete Cidades, Agua de Pau, and Furnas—are located on the island of São Miguel, Azores. Mafic vent deposits and associated lava flows are between the stratovolcanoes and on their flanks. Each volcano consists of interbedded ankaramite, basanitoid, alkali olivine basalt, hawaiite, mugearite, and tristanite cones and flows, as well as trachyte domes, flows, and pyroclastic deposits. Detailed geologic mapping and new radiocarbon and K-Ar ages indicate that Furnas, constructed entirely within the past 100,000 years, is somewhat younger than the other two volcanoes.

All three volcanoes have calderas that formed in the late Pleistocene as a consequence of voluminous eruption of trachytic pyroclastic flows and fall deposits. The outer caldera of Agua de Pau volcano is the oldest (26,500–46,000 years). The progression then is from west to east: the caldera of Sete Cidades is about 22,000 years old, the inner caldera of Agua de Pau is about 15,000 years old, and the caldera of Furnas is about 12,000 years old. Post-caldera activity has included emplacement of trachyte domes, associated with extensive Plinian and sub-Plinian pumice-fall deposits within the calderas, and eruption of more mafic lavas from vents on the flanks of the volcanoes. Each volcano has erupted during the past 500 years. Holocene eruptions have been most frequent on Sete Cidades and Furnas. Future eruptions present significant risk because a large population (150,000) now inhabits São Miguel. Furnas is particularly dangerous, partly because it has erupted five times during the past 1,100 years, most recently in A.D. 1630.

The three volcanoes range in subaerial volume from about 60 to 80 km^3. They were constructed at rates of about 0.02–0.03 km^3/century on Sete Cidades, 0.04 km^3/century on Agua de Pau, and 0.06 km^3/century on Furnas. Trachyte is volumetrically the most abundant rock type, ranging from about 72 percent of the exposed lavas on Sete Cidades to about 93 percent on Agua de Pau. Tristanites are most abundant on Furnas and reflect the generally higher K/Na on that volcano. Potassic hawaiites and mugearites are most abundant (about 18 percent by volume) on Sete Cidades.

New major element chemical and normative data for all mapped rocks from the three volcanoes demonstrate their alkalic (especially potassic) nature and indicate that virtually all mafic and many silicic rocks are nepheline normative. Peralkaline trachytes (including both quartz and nepheline normative types) are particularly abundant on Agua de Pau, where they constitute about 45 percent of the volume of all trachytes. They typically were erupted in large volume during short-lived events, most notably during the two caldera-forming episodes. In contrast, peralkaline trachytes are rare on Sete Cidades and Furnas volcanoes and make up less than 1 percent of their erupted volumes.

Variation diagrams illustrate some chemical differences among the volcanoes and suggest that most of the diverse rock types are related by fractionation of parental basanitoid. Incorporation of silicic material in mafic melts locally has resulted in hybrid lavas, especially on Agua de Pau.

Manuscript approved for publication January 31, 1991.

INTRODUCTION

The Azores straddle the Mid-Atlantic Ridge (fig. 1). Historic eruptions have occurred on five islands during the past 500 years (van Padang and others, 1967). Islands east of the Ridge, including São Miguel, are near the Azores fracture zone (called the Terceira Rift or Terceira Ridge by some workers), a seismically active spreading center (Krause and Watkins, 1970; Searle, 1980) near the triple junction of the African, Eurasian, and North American plates. The zone of plate divergence underlying the Azores archipelago changes to one of convergence between the Azores and the Iberian Peninsula (Grimison and Chen, 1986).

This report summarizes information gathered during 1:15,000- and 1:18,000-scale mapping (Moore 1983a, b, 1986) of an area of about 475 km^2 including Sete Cidades, Agua de Pau, and Furnas volcanoes on the island of São Miguel, Azores (figs. 1–3, 6, 8). New radiocarbon (<40,000 years B.P.; Moore and Rubin, 1991) and K-Ar (>40,000 years B.P.; E.H. McKee, U.S. Geological Survey (USGS),

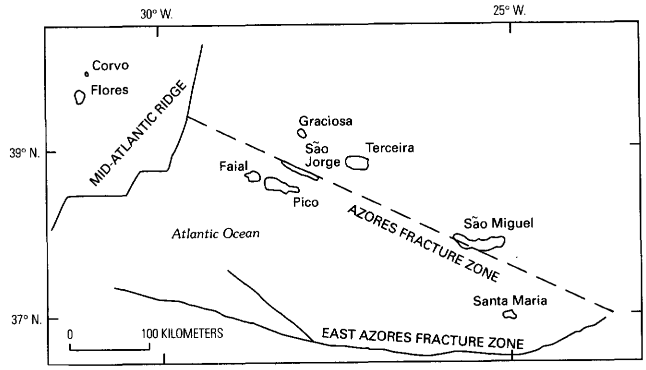


Figure 1. Location of Azores fracture zone and other major structures. Modified from Laughton and Whitmarsh (1975).

written commun., 1986) ages augment the stratigraphic data; all unreferenced ages in this report are from these two sources. Silica- and magnesia-variation diagrams using 357 new chemical analyses of rocks, representing every map unit, from the three volcanoes are presented.

The volcanoes are composed of lava flows, domes, and pyroclastic rocks of the alkali basalt–trachyte suite (Irvine and Barager, 1971). Eruptions of both mafic and trachytic lavas have occurred on Sete Cidades and Agua de Pau during the past 1,000 years, and Furnas has erupted trachyte five times during the past 1,100 years. These volcanoes are the targets of geologic, geophysical, and geochemical investigations by members of the USGS, in cooperation with the Regional Government of the Azores, in an effort to identify and assess the geothermal energy resources of São Miguel.

Zbyszewski and others (1958) and Zbyszewski and Ferreira (1959) published 1:50,000-scale geologic maps showing rock types on São Miguel. Moore (1990, 1991) presented a new geologic map (scale 1:50,000) of all of São Miguel and summarized the geology of the island. Walker and Croasdale (1970) and Booth and others (1978) studied widespread trachyte pumice deposits from the three volcanoes. Chemical analyses are presented by Esenwein (1929), Jeremine (1957), Schmincke and Weibel (1972), Schmincke (1973), Flower and others (1976), and White and others (1979). White and others (1976) described strontium isotope variations, and Hawkesworth and others (1979) evaluated strontium and neodymium isotope data. Storey (1981) discussed the petrologic evolution of the magma reservoir beneath Agua de Pau volcano during the past 4,600 years.

Acknowledgments.—Edward W. Wolfe (USGS) aided considerably with computer generation of the variation diagrams and also critically reviewed the manuscript. Debby Kay (USGS) did the rapid-rock chemical analyses. A.M. Rodrigues da Silva (Laboratorio de Geociencias e Tecnologia, Ponta Delgada, São Miguel) gave considerable logistical support. Wendell A. Duffield and Donald A. Swanson (USGS) critically reviewed the manuscript. This work was supported by the Agency for International Development (U.S. Department of State), the Regional Government of the Azores, and the U.S. Geological Survey.

STRUCTURE AND MORPHOLOGY

Normal faults are common on São Miguel; widespread trachyte pumice deposits mask them in most areas. Locally, faults displace unconsolidated pumice deposits as young as 361 (Furnas volcano) and 428 (Agua de Pau volcano) years. Most faults strike northwest or west-northwest and are part of the Azores fracture zone, the axis of which crosses Sete Cidades volcano on the western end of the island. The location of Sete Cidades probably was controlled by the fracture zone; fault scarps about 60 m high on the northwestern and eastern rims of the caldera are truncated by the caldera and apparently experienced major displacement at the time of caldera formation about 22,000 years ago.

Landforms on the three volcanoes are dominantly constructional; significant erosion occurs only on sea cliffs and on pyroclastic deposits in deep canyons cut near contacts between large trachyte domes and lava flows. Oversteepened slopes characterize many of these canyons, and a high probability exists for destructive mudflows during periods of heavy rainfall.

SETE CIDADES VOLCANO

Sete Cidades volcano is located on the western end of São Miguel (figs. 2, 3). Its subaerial volume is about 70 km^3, and its lavas have accumulated at an estimated rate of 0.02–0.03 km^3/century. An almost circular caldera about 5 km in diameter, with walls as high as 400 m, truncates its summit. Geologic mapping (fig. 3) indicates that pre-caldera rocks crop out chiefly in the caldera walls and in sea cliffs eroded into the flanks of the volcano. Post-caldera units are trachyte cones and pumice rings distributed across the caldera floor, and ankaramite, basanitoid, alkali olivine basalt, hawaiite, mugearite, and minor trachyte cones and flows erupted from flank fissures radial to the caldera. All trachytic vents on Sete Cidades are within a 7 by 4 km area, the smallest of the three stratovolcanoes, roughly centered on the caldera.

Sete Cidades lacks hot springs, which are prominent on Agua de Pau and Furnas volcanoes. Only two warm springs are known, near Mosteiros on the northwestern coast and at Ponta da Ferraria on the western coast. The latter has a temperature of about 50°C.

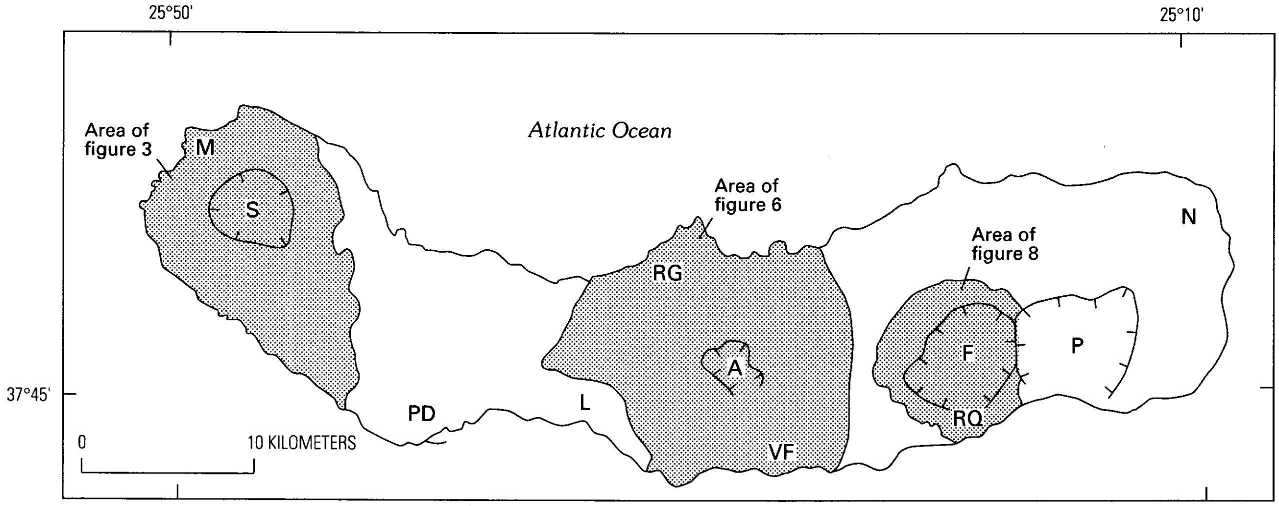


Figure 2. São Miguel, Azores. Hachured lines mark calderas: S, Sete Cidades; A, Agua de Pau; F, Furnas; P, Povoação (extinct). Major towns: M, Mosteiros; PD, Ponta Delgada; L, Lagoa; RG, Ribeira Grande; VF, Vila Franca do Campo; RQ, Ribeira Quente; N, Nordeste. Stippling indicates areas mapped at 1:15,000 scale (figs. 3, 6, 8).

Pleistocene Units

Pre-Caldera Units

The oldest subaerial rocks of Sete Cidades include trachyte and tristanite domes and flows exposed at the base of the caldera wall and in sea cliffs on the western and southern coasts. A trachyte flow at the base of the northwestern caldera wall (fig. 3) has a K-Ar age of 210,000±8,000 years, and a tristanite flow at the base of the section at Ponta da Ferraria (fig. 4), on the western coast, has a K-Ar age of 74,000±6,000 years. Figure 4 is a composite stratigraphic section in the vicinity of Ponta da Ferraria.

Flows of ankaramite, basanitoid, alkali olivine basalt, hawaiite, mugearite, and tristanite are interbedded with trachyte pyroclastic deposits that overlie the earlier domes and flows; these deposits form the major subaerial part of the stratovolcano. Trachyte pyroclastic deposits include pyroclastic flows, pyroclastic surges, mudflows, and pumice deposited during Plinian and sub-Plinian eruptions. Radiocarbon ages of charcoal recovered from beneath the flows and from within the pyroclastic units are greater than 29,000 years.

Caldera-Outflow Deposit

The caldera of Sete Cidades volcano formed approximately 22,000 years ago after eruption of several cubic kilometers of trachyte pumice. The volume of the caldera is about 6 km^3. The volume of the caldera-outflow deposit cannot be determined with certainty because of burial by younger lavas. An unknown but probably significant volume of pumice fell at sea. This eruption produced pyroclastic flows, locally welded, and pyroclastic surges directed primarily southeastward. The resulting composite deposit is more than 60 m thick 13 km southeast of the caldera but only 5 m thick on the western and northern flanks of the volcano. The welded pyroclastic flows crop out chiefly on the western, northern, and southern walls of the caldera.

A new roadcut on the western caldera wall provides the best exposure of the caldera-outflow deposit and overlying units (fig. 5). The caldera-outflow deposit and underlying and overlying deposits up to the Sete A pumice (terminology of Booth and others, 1978) are truncated by the caldera-bounding fault. Truncation of the beds that postdate the caldera-outflow deposit suggests that subsidence of the caldera continued incrementally (Walker, 1984) for some time after the major collapse.

Massive trachyte pumice deposited during an early Plinian phase of the caldera-forming eruption is exposed in the lowest 4 m of the roadcut. Strongly oxidized trachytic pyroclastic flows, 10–12 m thick and characterized by somewhat flattened black obsidian fragments in an orange fine-grained matrix, conformably overlie the Plinian pumice; a welded zone, here only 0.3 m thick and characterized by strongly flattened pumice fragments that are now obsidian, begins about 1 m above the base of this subunit. Above the caldera-outflow deposit is soil 10–30 cm thick that records perhaps several decades or centuries of weathering on the basis of comparison with modern soils developed on historic (A.D. 1563 Agua de Pau and A.D. 1630 Furnas) pumice deposits on São Miguel. A 2-m-thick Plinian deposit, consisting of large (to 0.7 m), dark- and

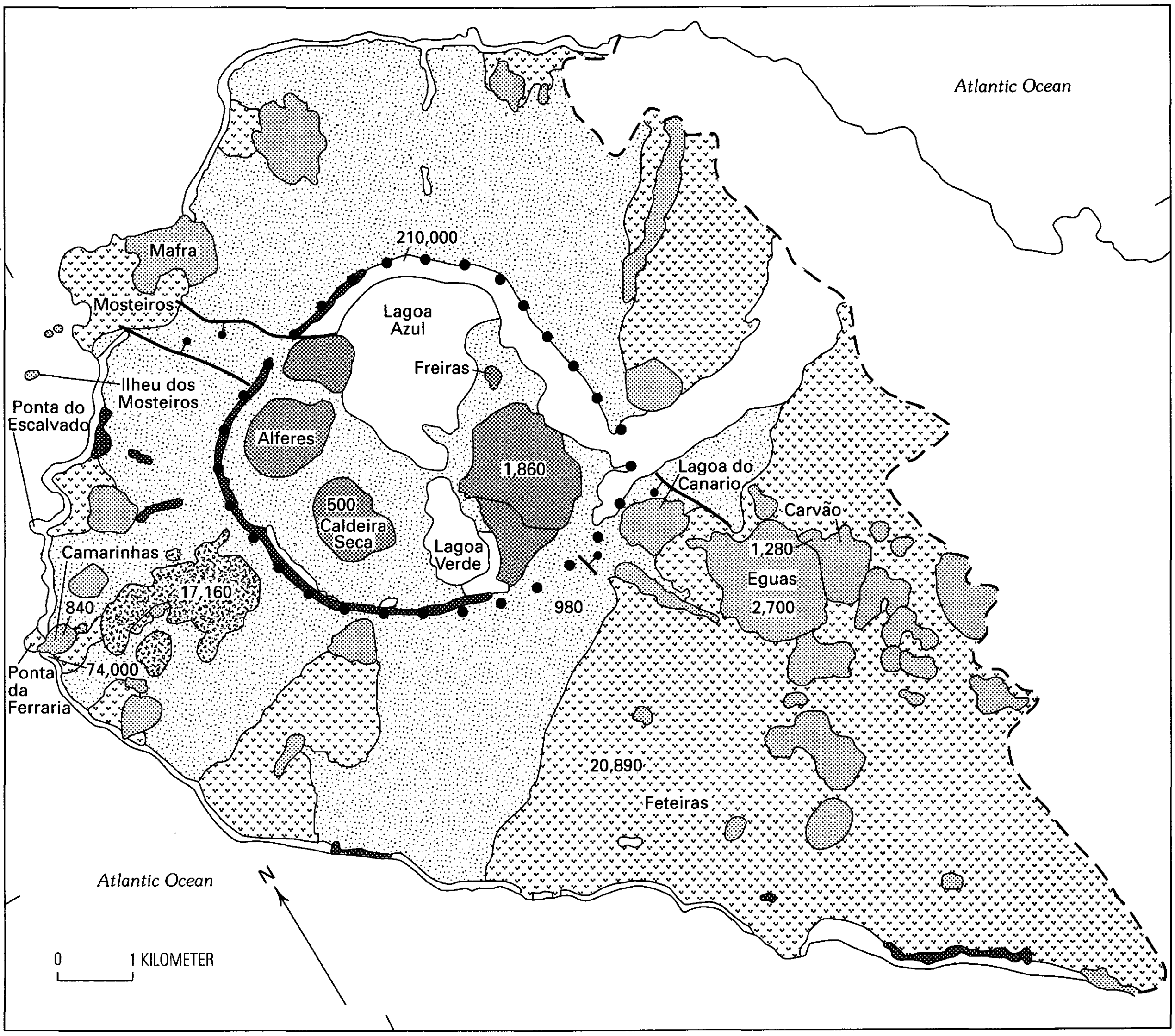


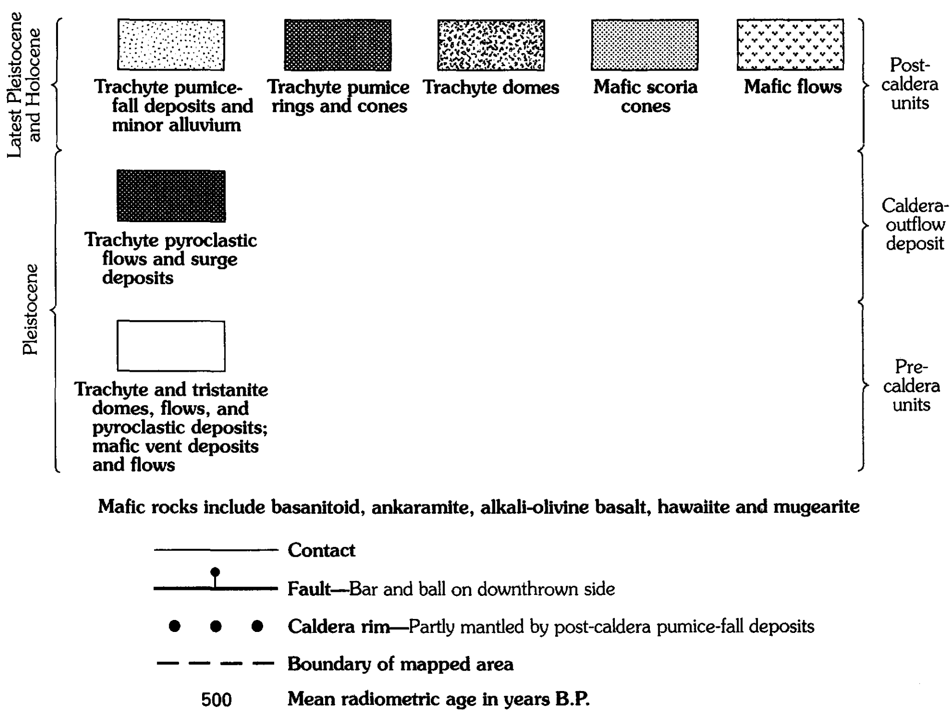
Figure 3 (above and facing page). Generalized geologic map of Sete Cidades volcano.

light-gray tristanite pumice fragments that are partly agglutinated and probably close to their source, overlies the soil. A 25–30-cm-thick layer of soil overlies the lower tristanite pumice. The top subunit of this group is coarse tristanite pumice, similar to the lower subunit, that overlies charcoal in the soil dated at 21,160±180 years B.P. The thickness of the soils between the dated charcoal and the caldera-outflow deposit suggests that only a few centuries elapsed between these eruptions. The age of the caldera-outflow deposit thus is believed to be about 22,000 years. Voluminous ignimbrites were erupted from Pico Alto volcano on Terceira at about the same time, 23,000 and 19,000 years B.P. (Self, 1976).

Outside of the caldera the caldera-outflow deposit generally is not welded and is recognized chiefly by its stratigraphic position and by the common occurrence of large (10–40 cm), slightly flattened, black obsidian fragments (formerly pumice) in a light-gray, fine-grained matrix. The thickest exposure of the deposit is about 13 km southeast of the caldera in almost inaccessible sea cliffs. Here, pumice fragments are not flattened to obsidian, the deposit is white to very light gray, and fine-grained cross-bedded surge deposits are common.

In most places (except in the new roadcut on the western caldera wall), the caldera-outflow deposit immediately underlies the Sete A pumice, a Plinian deposit probably from a trachyte cone in the northern part of Sete Cidades caldera (Booth and others, 1978). The caldera-outflow deposit is truncated by the caldera wall, whereas the Sete A pumice mantles it.

EXPLANATION



Post-Caldera Units

At the new roadcut on the western wall of Sete Cidades caldera (fig. 5), the oxidized pyroclastic flows and overlying coarse tristanite pumice are separated from the Sete A pumice by about 6 m of thinly bedded trachyte pumice deposits and soils interbedded with 6–8 m of alkali olivine basalt and potassic mugearite scoria and short flows from a nearby source.

Elsewhere on Sete Cidades, the caldera-outflow deposit is separated from the Sete A pumice by only a few mafic flows and at least one trachyte pyroclastic flow deposit. A potassic mugearite flow near Feteiras (fig. 3) on the southern flank of the volcano has a radiocarbon age of 20,890±240 years. A trachyte pyroclastic flow deposit on top of the sea cliff at Ponta do Escalvado, near the western end of the island, has a radiocarbon age of 17,160±130 years. This deposit probably is related to post-caldera trachyte domes and flows about 1.5 km southeast of Ponta do Escalvado.

Holocene Units

Trachytic Deposits

Sete Cidades volcano apparently was relatively inactive, except for the few eruptions noted above, during the approximately 17,000 years between formation of the caldera and deposition of the Sete A pumice. Such relative quiescence following caldera formation characterizes Agua de Pau and Furnas volcanoes as well.

Booth and others (1978) studied the products of 12 trachytic pyroclastic eruptions from Sete Cidades. They considered the age of the oldest eruption, Sete A, to be uncertain; the others, Sete B–L, rest on the 5,000-year-old Fogo A deposit from Agua de Pau volcano. I consider Sete A to be little older than 5,000 years, on the basis of the relatively thin (<20 cm) soil separating Sete A from Sete B.

Six vents, the eruptions of which formed cones or pumice rings, occur on the floor of Sete Cidades caldera in a roughly circular pattern (fig. 3); perhaps magmas rose along a concentric fracture that formed at about the same time as the caldera. Other vents may be submerged beneath Lagoa Azul (Blue Lake) and Lagoa Verde (Green Lake). Four of the six vents were sites of voluminous Plinian and sub-Plinian eruptions of trachyte pumice (Booth and others, 1978) that mantled the western part of São Miguel. The other two vents, Alferes and Freiras (fig. 3), erupted relatively degassed trachyte scoria of only local extent.

Most of the young pumice deposits on Sete Cidades that Booth and others (1978) studied have not been dated. The peralkaline Sete J deposit has a radiocarbon age of 1,860±120 years B.P. The next youngest deposit, Sete K, is older than the Carvão basanitoid cone and flow, dated at 1,280±150 years B.P.

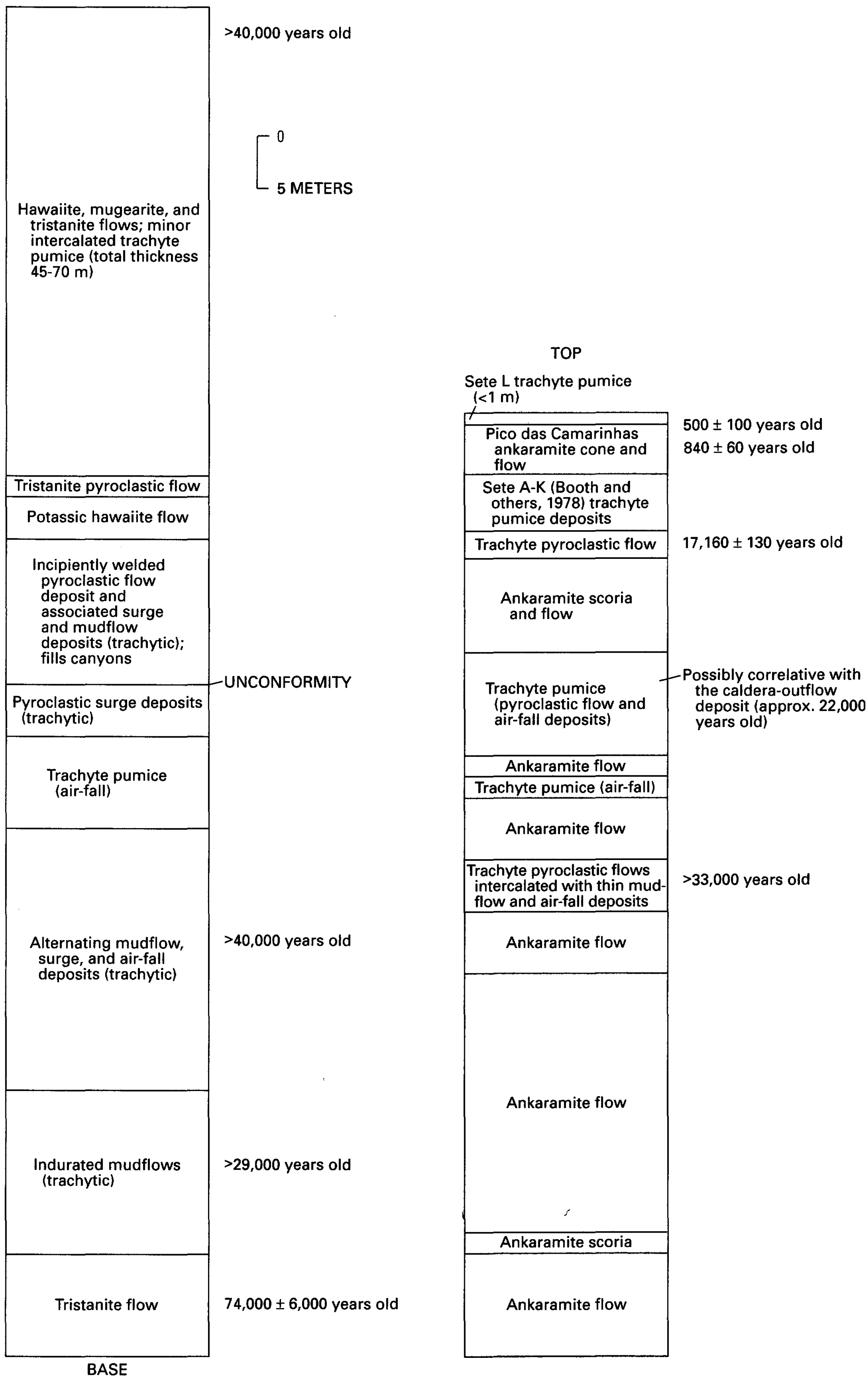


Figure 4. Composite measured stratigraphic section, sea cliff near Ponta da Ferraria on western flank of Sete Cidades volcano. Dips are approximately horizontal except on canyon-filling units.

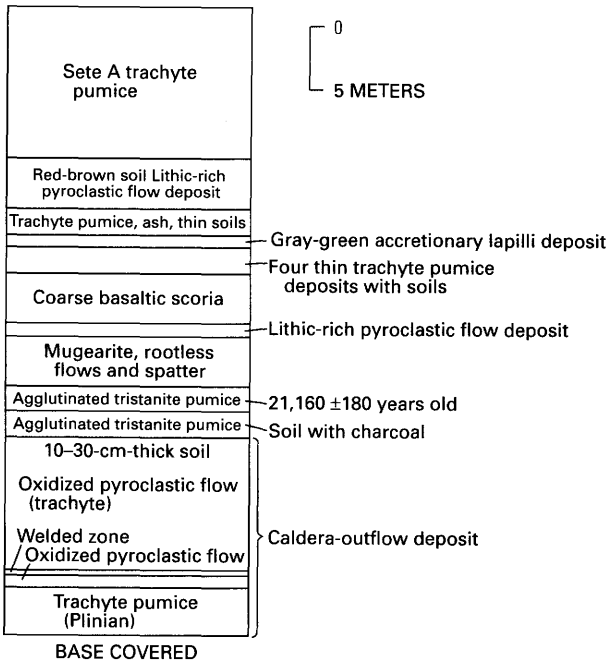


Figure 5. Measured stratigraphic section, roadcut on western wall of Sete Cidades caldera. All units dip approximately 17°W.

The youngest intracaldera eruption formed the Caldeira Seca pumice ring (fig. 3) and produced the peralkaline Sete L deposit. Shotton and Williams (1971) reported a radiocarbon age of 663±105 years B.P. for Sete L; a newly determined radiocarbon age of 500±100 years B.P. is similar to the previous determination and correlates with a reported eruption at the time of Portuguese discovery of the island in the middle of the fifteenth century (van Padang and others, 1967).

Assuming that the Sete A deposit is about 5,000 years old, the average dormant interval for the 12 trachytic pyroclastic eruptions of Sete Cidades that Booth and others (1978) studied is about 409 years. At least 780 years elapsed, however, between the Sete K and L eruptions, and the present dormant interval has lasted at least 540 years.

Mafic Flank Eruptions

Sporadic eruptions of ankaramite, basanitoid, alkali olivine basalt, hawaiite, and mugearite have occurred on Sete Cidades since formation of the caldera. Most mafic vents are concentrated along the trace of the Azores fracture zone extending southeast from the caldera (volcanic zone 2 of Moore, 1990, 1991). A few vents erupted along radial fissures on the flanks of the volcano.

Four young eruptions on and near Sete Cidades (fig. 3) have recently been dated. The ankaramite cone of Eguas, which forms the highest point on Sete Cidades about 2 km southeast of the caldera, is 2,700±250 years old. Pico do Carvão, 1 km southeast of Eguas, and its flow have a radiocarbon age of 1,280±150 years B.P. The basanitoid spatter rampart at Ferrarias, 1 km west of Eguas, is 980±90 years old, and did not form around A.D. 1444, as suggested by Zbyszewski (1961). The Pico das Camarinhas basanitoid cone and Ponta da Ferraria lava delta, products of the most recent subaerial mafic eruption on Sete Cidades, are 840±60 years old. This date and detailed mapping indicate that reports of subaerial eruptive activity on Sete Cidades around A.D. 1713 and perhaps at other times (van Padang and others, 1967) are not correct.

Surtseyan cones, remnants of which form the Ilheu dos (Islands of) Mosteiros near the northwestern coast of Sete Cidades (fig. 3), apparently erupted during the time that Sete A and younger trachyte pumice deposits accumulated. Hyaloclastite and deposits of basaltic accretionary lapilli from these vents are interbedded with trachyte pumice near the top of the sea cliff southwest of Mosteiros.

Lagoa do Canario (fig. 3) is a lake within a basanitoid maar about 0.5 km southeast of the southeastern caldera rim. The vent is within 300 m of a major fault marking the trace of the Azores fracture zone. Because the low cone surrounding the vent is thickly mantled by trachyte pumice, the composition of its juvenile material was unknown until it was exposed in roadcuts. These exposures also show that the maar is overlain only by the Sete I–L deposits.

Several vent deposits and associated flows, notably those of Eguas and Camarinhas, contain xenoliths of mafic and ultramafic rocks.

The absence of young mafic deposits within the caldera and the occurrence of recent trachyte eruptions there suggest that trachyte magma may still underlie it.

AGUA DE PAU VOLCANO

Agua de Pau volcano, a stratovolcano whose summit is 947 m above sea level, is located in the central part of São Miguel (fig. 2). Its subaerial volume of about 80 km^3 has increased at an estimated rate of 0.04 km^3/century. A prominent caldera 3 by 2.5 km across, with walls as high as 300 m, truncates its summit and contains Lagoa do Fogo (Fire Lake). The topographic margin of an older caldera, about 7 by 4 km across, is preserved locally on the western, northern, and eastern sides of the volcano. Stratigraphic relations, especially within the calderas, are generally less obvious on Agua de Pau than on the other two volcanoes because of burial by widespread thick Holocene pumice. Deposits predating both calderas crop out on all flanks of the volcano and in sea cliffs on the northern and southern coasts (fig. 6*A*). At least five eruptions of trachyte pumice have occurred from vents mostly within the inner caldera during the past 5,000 years (Booth and others, 1978). Mafic and trachytic lavas were erupted from vents on all flanks of the volcano, before and after formation of the calderas. No

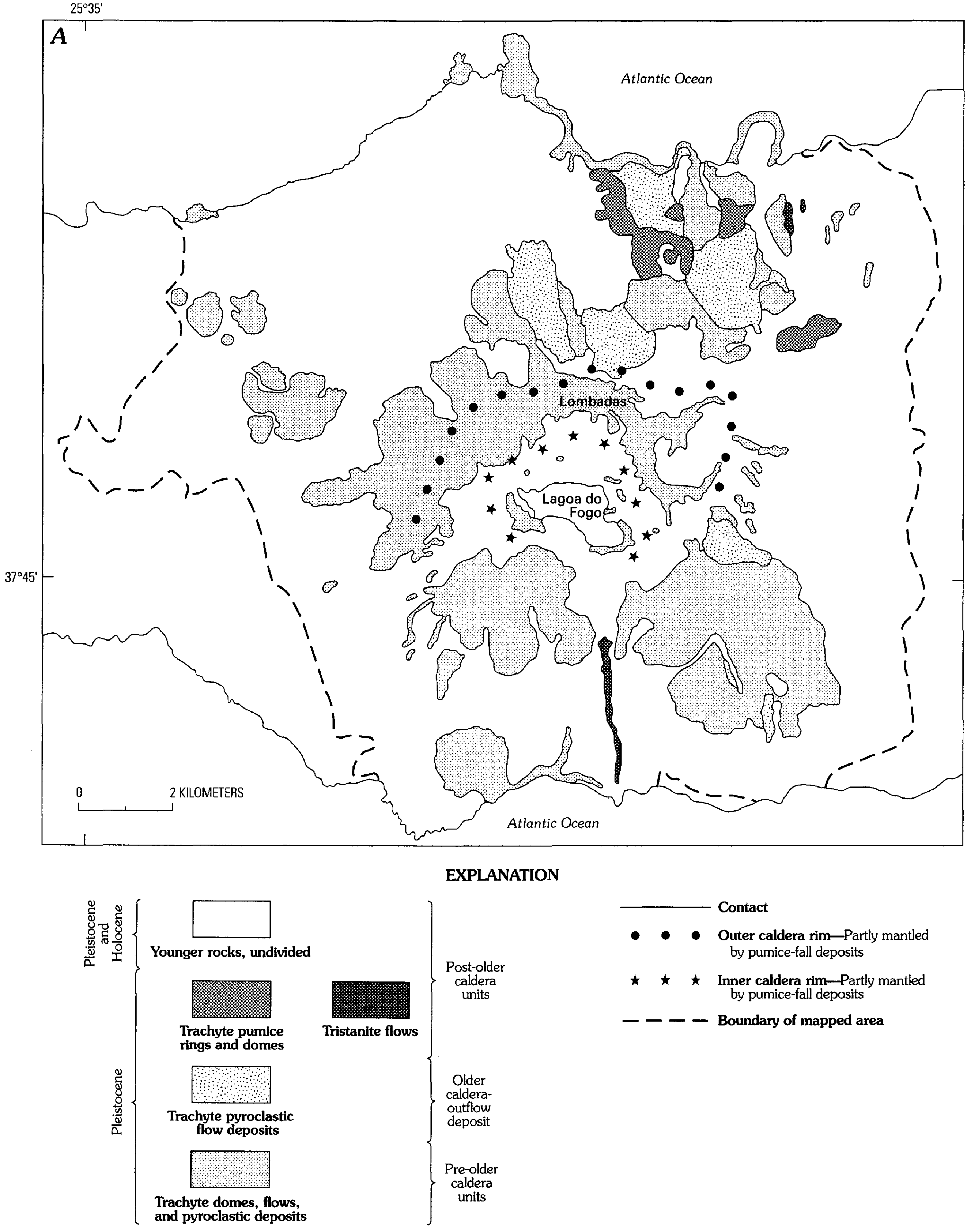


Figure 6 (above and following pages). Generalized geologic maps of Agua de Pau volcano. *A*, Units predating the younger caldera-outflow deposits. *B*, Younger caldera-outflow deposits. *C*, Units postdating the younger caldera-outflow deposits.

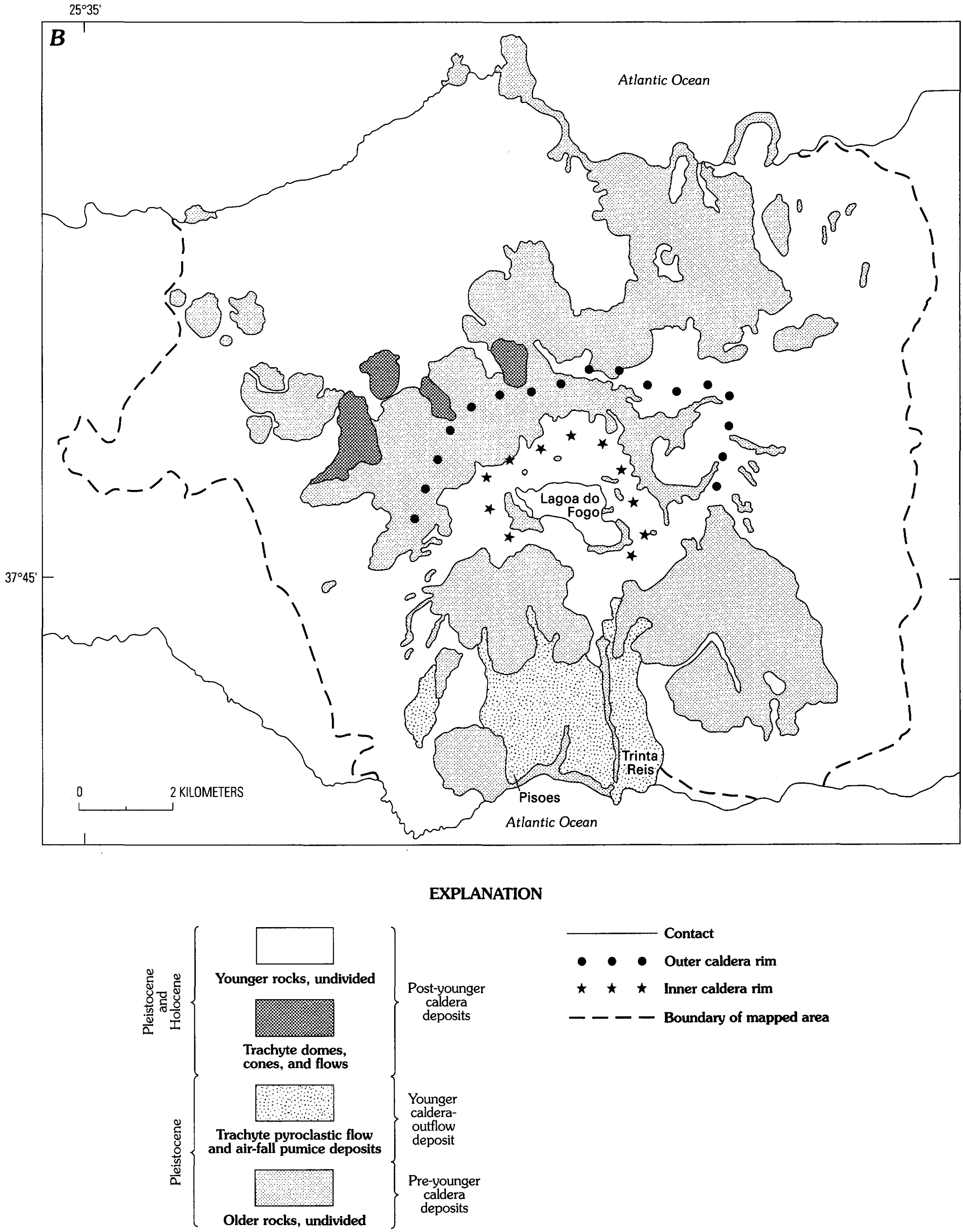


Figure 6. Generalized geologic maps of Agua de Pau volcano—Continued.

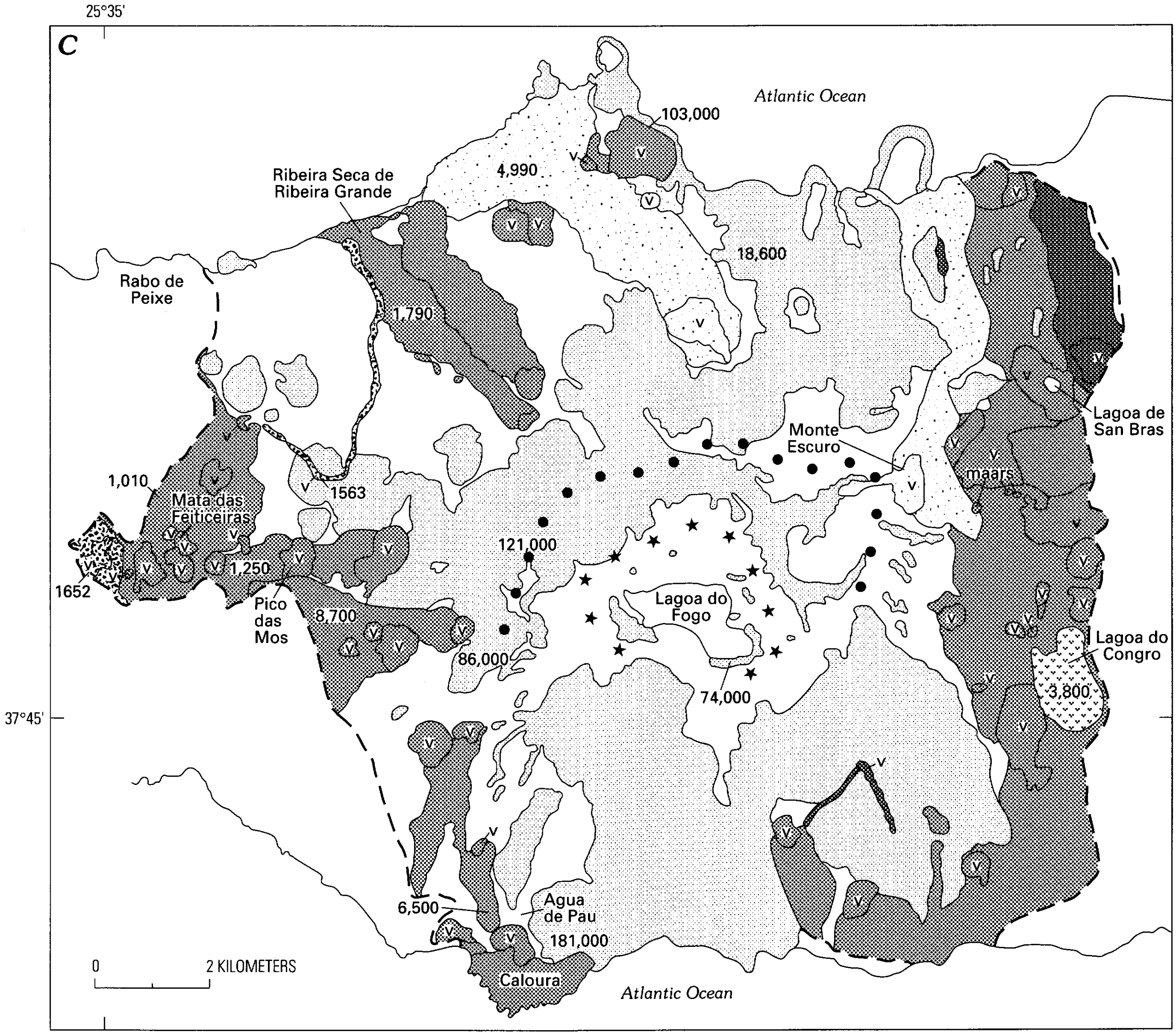


Figure 6. Generalized geologic maps of Agua de Pau volcano—Continued.

mafic vents are known within the calderas. Trachytic vents on Agua de Pau are within an area of about 17 by 14 km (fig. 6*A*), the largest of the three stratovolcanoes.

Several hot springs, with temperatures commonly near boiling, are on Agua de Pau, mainly on its northwestern flank (Zbyszewski and others, 1958; Zbyszewski and Ferreira, 1959). They are near intersections of northwest-trending faults and the outer caldera boundary. In addition, A.M.R. da Silva (written commun., 1984) recently found an inactive hot spring deposit on the southern flank of the volcano. The hot springs suggest that hot rock or magma associated with the late Pleistocene and Holocene eruptions is close to the surface. Six holes have been drilled to evaluate the geothermal resource, and more are planned.

Pleistocene Units

The oldest subaerial rocks of Agua de Pau volcano (fig. 6*A*) include a trachyte dome (181,000±15,000 years old; Gandino and others, 1985) on the southern coast, a trachyte flow (121,000±5,000 years old) near the summit, and trachytic welded tuffs (a representative one is 103,000±7,000 years old; Gandino and others, 1985) and associated mudflows on the northern coast. Xenoliths of welded tuff possibly correlative with that on the northern coast are common in late Pleistocene and Holocene pumice deposits erupted from within the inner caldera. Muecke and others (1974) obtained K-Ar ages of 117,000± 24,000 years (57 m depth) and 280,000±140,000 years (950 m depth) for

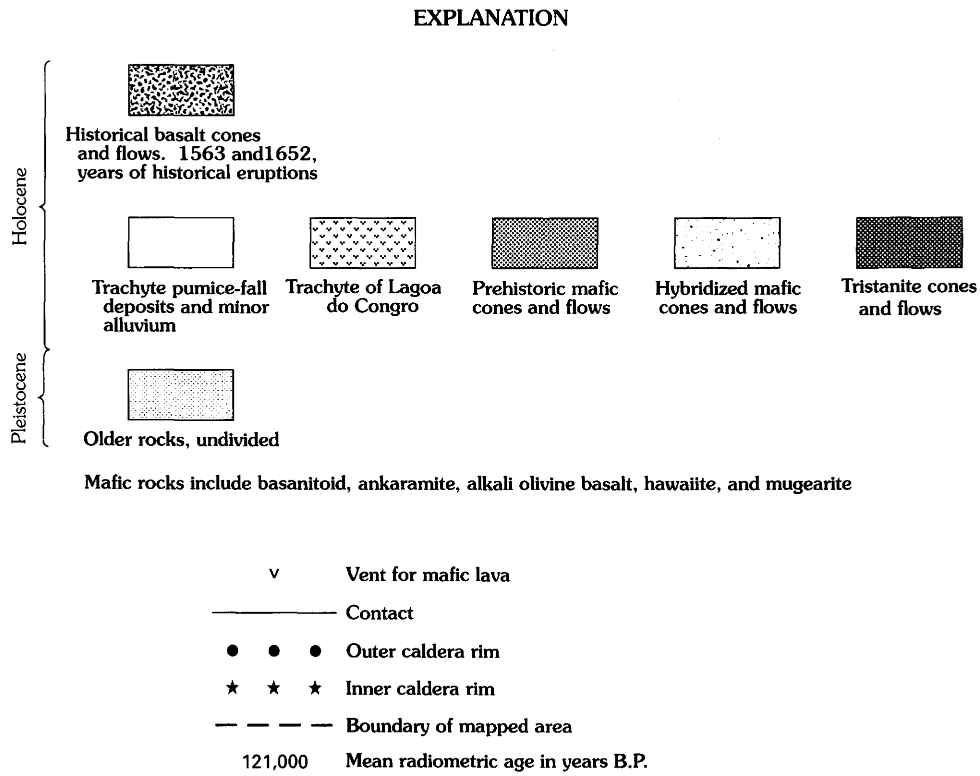


Figure 6. Generalized geologic maps of Agua de Pau volcano—Continued.

samples of drill core on the northwestern flank of Agua de Pau. These deposits formed during a period when Agua de Pau may have been much more active than it has been during the past 100,000 years (Muecke and others, 1974).

The main edifice of the volcano consists of trachytic lava flows, domes, and pyroclastic deposits that probably are about 40,000–100,000 years old (available K-Ar ages are 46,000–86,000 years; Gandino and others, 1985; E.H. McKee, written commun., 1986). Mafic eruptions occurred on the outer flanks of the volcano, outside the area of trachytic activity. One of the best exposures of the early trachytic deposits is in a sea cliff on the southern coast, where Booth and others (1978) recognized products of 65 separate explosive eruptions. Charcoal from soil beneath a trachyte flow near the base of this section (between units 4 and 5 of Booth and others, 1978) has a radiocarbon age greater than 40,000 years. Shotton and Williams (1973) obtained a radiocarbon age of more than 34,200 years for unit 14 of Booth and others (1978).

Older Caldera-Outflow Deposit

Collapse of the summit area may have occurred many times, but only two deposits clearly record such catastrophic events. The outer caldera formed after eruption of several cubic kilometers of welded and nonwelded pumice, now exposed mainly on the northeastern and southeastern flanks of the volcano (fig. 6*A*). Any correlative deposits on the eastern or western flanks are deeply buried by younger rocks. The volume of the outer caldera is about 5.5 km^3, and the estimated subaerial volume of the caldera-outflow deposit is about 5 km^3. An unknown but probably significant volume of pumice fell at sea.

The deposit fills canyons near the margins of the early trachyte flows. Welded tuff of the older caldera-outflow deposit overlies trachyte flows on the northern and southeastern flanks of Agua de Pau and underlies post-outer caldera, pre-inner caldera trachyte domes, pumice rings, and tephra on the northern flank. Along the road to Lombadas (fig. 6*A*), the welded tuff appears to be faulted at the caldera boundary.

The youngest dated pre-caldera trachyte flow is 46,000±6,000 years old, but stratigraphically younger trachyte flows underlie the older caldera-outflow deposit on the northern flank of the volcano. The deposit underlies a pumice ring and related central dome that have a radiocarbon age of 18,600±300 years B.P. Field relations suggest that the older caldera-outflow deposit predates a basanitoid flow dated at 26,500±500 years B.P., although that flow is outside the mapped areal extent of the caldera-outflow deposit. The deposit has been little eroded; incision of unconsolidated intracanyon pumice-fall deposits amounts to less than 50 m in a region of relatively heavy rainfall. The age of the older caldera-outflow deposit is thus uncertain but probably is about 30,000–45,000 years on the basis of the above described stratigraphic relations. The deposit may be correlative with a deep-sea tephra unit northeast of São Miguel dated by Huang and others (1979) at about 33,600 years B.P.

The recognizable part of the deposit is dominated by a welded zone, which locally exceeds 80 m in thickness on the northeastern flank of the volcano. In a sea cliff on the northern coast, nonwelded Plinian pumice and associated pyroclastic flows 5 m thick conformably underlie the welded zone. Closer to the caldera, on the northern flank, the thickness of the lower nonwelded pumice increases to about 50 m. Mudflows, which by analogy with younger deposits from major eruptions of Agua de Pau might be expected to overlie the welded zone, have not been found because of either erosional stripping or, more likely, burial by younger pyroclastic deposits.

Post-Outer Caldera Units

No evidence exists of eruptions within the outer caldera for about 15,000–30,000 years; however, a few eruptions of tristanite (fig. 6*A*) and possibly mafic lavas occurred from vents on the flanks of the volcano.

Three trachyte pumice rings, two with associated central domes, formed along a northwestern trend on the northern and northeastern flanks of the volcano (fig. 6*A*). The radiocarbon age of the northwestern ring is 18,600±300 years B.P. Morphologic expression, stratigraphic relations, and relative lack of erosion suggest that the other two vents are approximately the same age.

Younger Caldera-Outflow Deposit

The inner caldera apparently formed about 15,200 years ago when a large, southward-directed Plinian eruption resulted in deposition of extensive nonwelded pumice and locally welded pyroclastic flows. Emplacement of thick mudflows occurred near the end of this eruption. The welded pyroclastic flows, locally as thick as 3 m, crop out mainly along the southern sea cliff between Pisoes and Trinta Reis (fig. 6*B*). At Trinta Reis, xenoliths of syenite make up 10–20 percent of the rock. Elsewhere, the younger caldera-outflow deposit consists mainly of pumice-fall deposits more than 5 m thick and overlying mudflows commonly more than 50 m thick. Exposed remnants of the deposit are restricted to the southern flank of the volcano. The estimated subaerial volume of this unit is about 1.5 km^3, slightly more than that of the inner caldera; an unknown, but probably significant volume of pumice fell at sea. Radiocarbon ages of the basal Plinian deposit and of the overlying welded tuff are 15,190±280 and 15,180±150 years B.P., respectively. The caldera of Santa Barbara volcano on Terceira formed at about the same time (Self, 1976).

The evidence that a caldera formed at this time is less compelling than it is for the other three cases studied, chiefly because of burial by thick pumice deposits. The principal data suggesting that eruption of the 15,200-year-old unit was responsible for formation of the inner caldera are the somewhat greater volume of the deposit compared to the inner caldera, the lack of any other known eruption as a candidate, and the observation that the next major pumice deposit, Fogo A, mantles the caldera wall and rim.

Post-Inner Caldera Units

No significant eruptions within the inner caldera occurred for about 10,000 years; however, six trachyte domes and associated short flows formed just outside the outer caldera rim on the western and northwestern flanks of the volcano (fig. 6*B*). No deposit older than Fogo A (Walker and Croasdale, 1970) overlies the domes, which therefore could be either latest Pleistocene or Holocene in age.

Holocene Units

Fogo A

The inner caldera of Agua de Pau became active again about 5,000 years ago, when the voluminous Fogo A Plinian fall deposit (fig. 6*C*), pyroclastic flows, and late mudflows (Walker and Croasdale, 1970) were erupted. The Fogo A deposit rests directly on the 15,200-year-old caldera-outflow deposit on the southern flank of the volcano.

The Fogo A deposit displays complexities not previously recognized by Walker and Croasdale (1970) that indicate Fogo A may be the product of at least five separate eruptions. An artificial exposure about 3 km south of Lagoa do Fogo reveals an approximately 8-m-thick section of syenite-bearing Fogo A that contains four internal soils ranging in thickness from 2.5 to 15 cm, in addition to Plinian fall and pyroclastic surge deposits discussed by Walker and Croasdale (1970). The thicker soils in particular suggest that Fogo A formed over a significant period of time, perhaps several decades or centuries, rather than during a single short-lived event.

Moore and Rubin (1991) reported nine new ages of charcoal collected from pyroclastic surge beds, pyroclastic flow deposits, and the base of the basal Plinian bed of the Fogo A deposit. These samples are from different locations on all flanks of the volcano. The results (fig. 7) show considerable variation. The average of all the ages is 4,936 years, almost 400 years older than the average of two ages (4435, 4672 years) reported by Shotton and others (1968, 1969). The range in mean ages is from 4,480 to 5,380 years, which in itself suggests that more than one eruption occurred. The new ages cluster around 5,000 years, and I suggest that that is a more correct mean age than the ages reported by Shotton and others (1968, 1969). Whatever its age, the Fogo A deposit is a valuable chronostratigraphic marker bed because no other major trachytic eruptions are known on central and eastern São Miguel at this time.

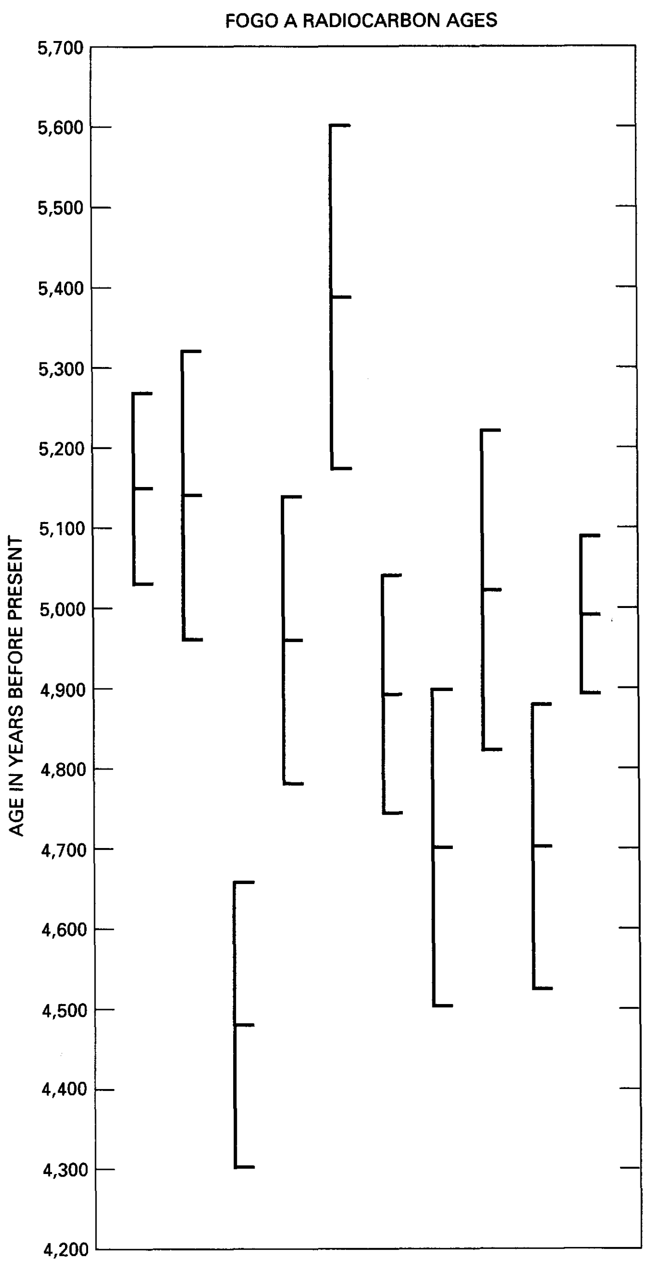


Figure 7. Radiocarbon ages of the Fogo A trachyte pumice deposit (Moore and Rubin, 1991). Brackets indicate one-sigma precision.

Post-Fogo A Pumice Deposits From Vents Within and Near the Inner Caldera

Booth and others (1978) and Walker and Croasdale (1970) described four post-Fogo A trachyte pumice fall deposits from Agua de Pau volcano, the latest in A.D. 1563. The average dormant interval between the five post-inner caldera eruptions was about 1,150 years (from about 5,000 to about 400 years B.P.), longer than at either Furnas or Sete Cidades volcanoes.

Eruptions at Lagoa do Congro

Lagoa do Congro occupies a maar on the eastern flank of Agua de Pau volcano, about 5.5 km east of Lagoa do Fogo (fig. 6C). Initial activity built a trachyte dome. Explosive eruptions of trachyte pumice destroyed part of the dome and an underlying basalt flow and formed a pyroclastic deposit that is locally more than 13 m thick. An exposure of the lower part of the deposit 250 m west of the crater rim shows three lithic-rich, coarse pumice beds separated by ash and two thin soils, which indicate short time intervals between major explosive events. A quarry 1.5 km southeast of the crater exposes the upper part of the deposit, which consists of 20 coarse pumice beds separated by 20 finer grained ash beds that include surge deposits (Booth and others, 1978). The basal pyroclastic deposit has a radiocarbon age of 3,800±400 years B.P., in agreement with the age inferred by Booth and others (1978) on the basis of soil development.

The last eruptive event at Lagoa do Congro was extrusion of a small trachyte dome and short flows on the floor of the crater. Ankaramite aa from a vent 1 km north of Lagoa do Congro later flowed down the northwestern wall of the crater, mantling it with inward-dipping flow units.

Mafic Flank Eruptions

Ankaramite, basanitoid, alkali olivine basalt, hawaiite, and mugearite were sporadically erupted from vents on the flanks of Agua de Pau during the Holocene. Most eruptions occurred west of Agua de Pau, in the zone of dominantly mafic lavas (volcanic zone 2 of Moore, 1990, 1991) that separates Agua de Pau from Sete Cidades volcano. A few eruptions occurred on the northern, eastern, and southern flanks. Dispersal of Holocene air-fall pumice mainly eastward by prevailing westerly winds resulted in thick mantles of pumice on mafic cones and flows (volcanic zone 4 of Moore, 1990, 1991) between Agua de Pau and Furnas volcanoes. A resulting illusion is that these cones are significantly older than the more prominent, thinly mantled cones and flows west of Agua de Pau.

Vents for Holocene mafic lavas, like those of Pleistocene age, are outside the area underlain by the trachytic

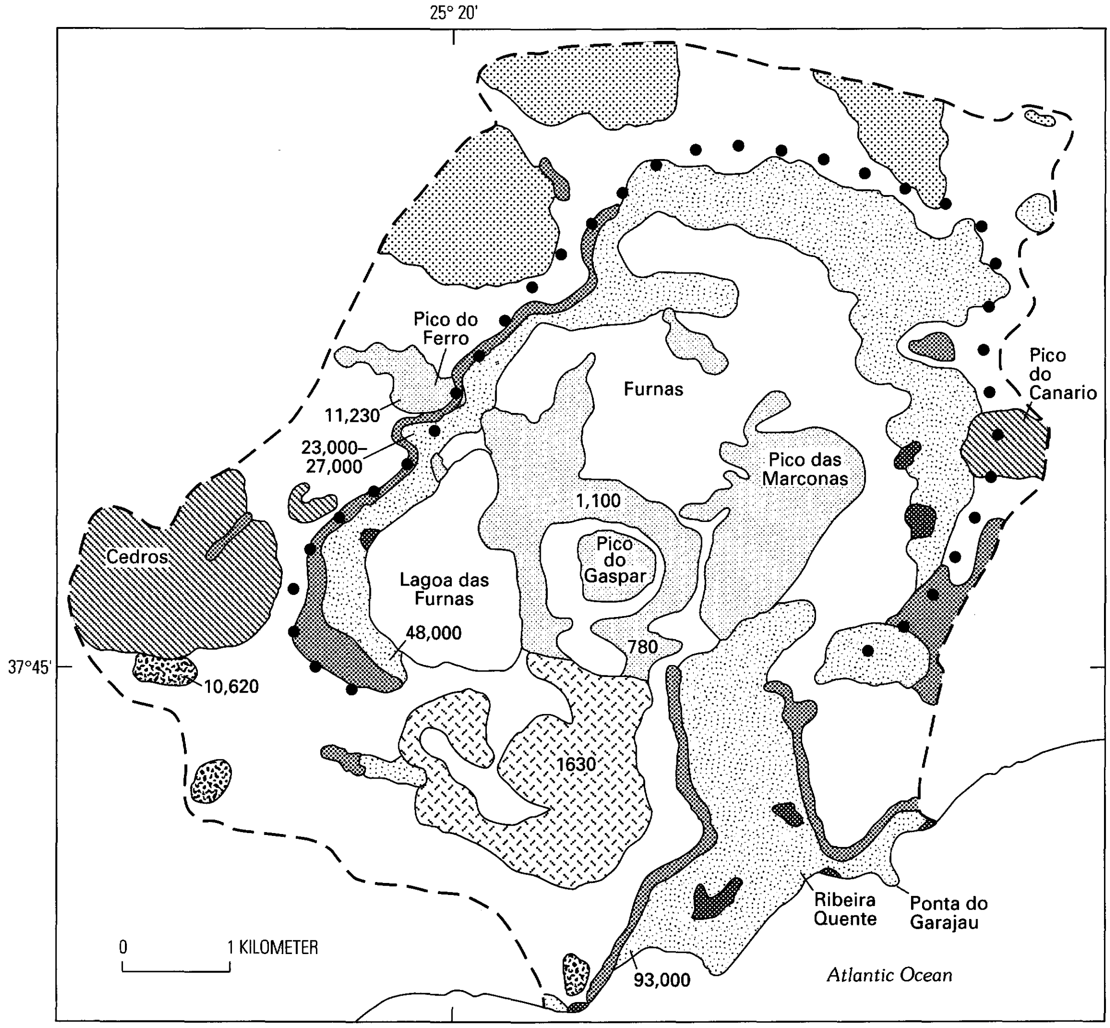


Figure 8 (above and facing page). Generalized geologic map of Furnas volcano.

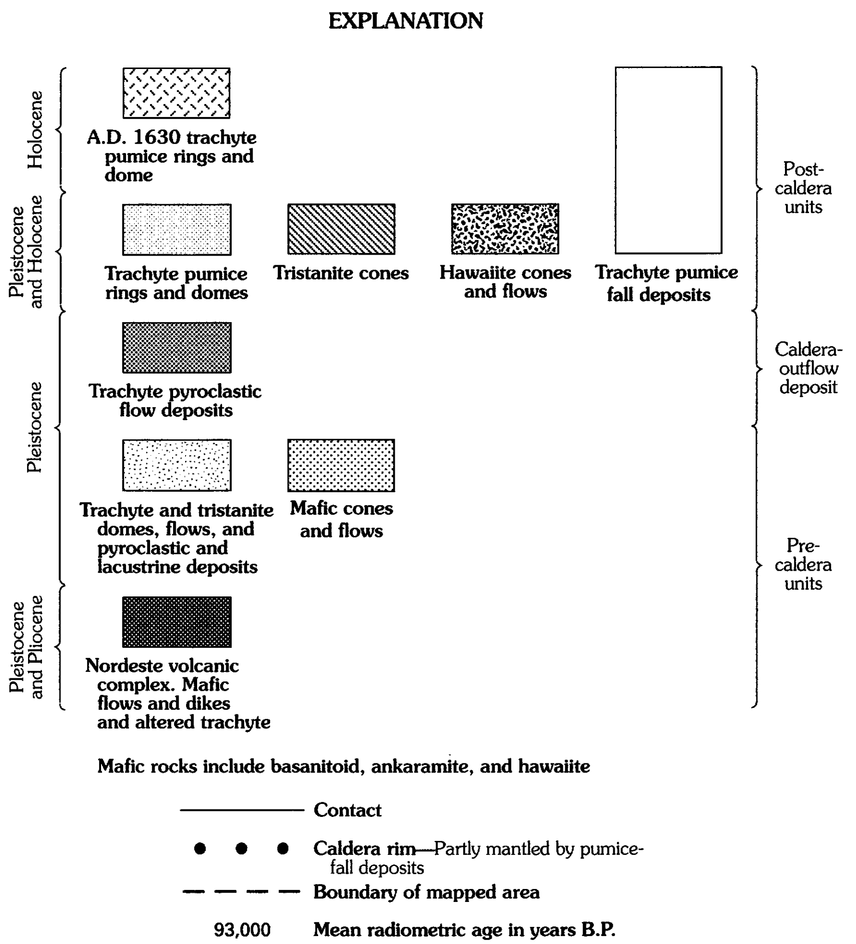
magma reservoir. As at Sete Cidades, the absence of mafic vents within the caldera suggests that trachytic magma may still underlie it.

Little systematic spatial or temporal distribution of lava types exists, although concentrations of vents for certain compositions occur locally. For example, vents and flows of ankaramite are concentrated on the western and southwestern flanks of the volcano, although at least three are on the eastern and southeastern flanks. Vents of potassic hawaiite are concentrated on the eastern flank.

Lagoa de San Bras, a maar about 7 km northeast of Lagoa do Fogo (fig. 6*C*), consists of palagonitic tuff overlying ankaramite spatter and rootless flows. Three other maars occur about 2 km southwest of Lagoa de San Bras. Two of these three vents are on the same west-northwestern trend as a large mafic cone at the eastern edge of the mapped area, and I believe that they formed at the same time in the latest Pleistocene or early Holocene.

At least four vents erupted hybrid lavas that represent a mix of trachytic and more mafic magma (basanitoid at three vents and hawaiite at one vent). The lava of basanitoid parentage has about 58 percent SiO_2 and the lava of hawaiitic parentage (Monte Escuro; fig. 6*C*) about 55 percent SiO_2. The basanitoid parentage is identified by titaniferous clinopyroxene in the groundmass, a high bulk-rock TiO_2 content, and ultramafic xenoliths. Three vents are within 1–2 km of the outer caldera boundary; possibly mafic magma rose along the margin of the trachytic magma reservoir and mixed with trachyte prior to eruption.

Ascent of mafic magma has been postulated to trigger eruption of overlying, more silicic melts at many volcanoes (Sparks and others, 1977). The A.D. 1563 trachyte Plinian eruption of Agua de Pau possibly was so initiated because extrusion of basanitoid from a vent 5.5 km west-northwest of Lagoa do Fogo immediately followed the trachyte eruption from the caldera (Weston, 1964). An extensive



hybrid flow from a vent about 4 km north of Lagoa do Fogo (fig. 6*C*) is interbedded with Fogo A trachyte pumice and has a radiocarbon age of 4,990±100 years (fig. 7). Ascent of this mafic magma may have triggered the Fogo A eruption.

Several radiocarbon ages of Holocene mafic lavas on the western side (volcanic zone 2 of Moore, 1990, 1991) of Agua de Pau volcano (fig. 6*C*) have recently been determined (Moore and Rubin, 1991). An ankaramite cone about 4 km west of Lagoa do Fogo is 8,700±200 years old. An ankaramite flow on the western side of the village of Agua de Pau, 6 km southwest of Lagoa do Fogo, is 6,500±100 years old. A potassic hawaiite flow that forms a lava delta in Ribeira Seca de Ribeira Grande, on the northwestern flank of the volcano, is 1,790±150 years old. The quarried basanitoid cone of Mata das Feiticeiras, about 8 km west of Lagoa do Fogo, is 1,010±120 years old. Pico das Mos, a basanitoid cone dated at 1,250±150 years B.P., is 2 km east of Mata das Feiticeiras.

A young alkali olivine basalt cone and flow in Caloura, on the southern coast of the island, overlies Fogo A trachyte pumice but has not been dated. Its flow formed a lava delta that includes the southernmost part of São Miguel.

Two eruptions of basanitoid have occurred near Agua de Pau volcano since the island was settled in the mid-fifteenth century. The A.D. 1563 eruption formed low spatter ramparts on top of Queimado, a relatively old trachyte dome about 6 km west-northwest of Lagoa do Fogo (fig. 6*C*). From that source, one small flow moved about 2 km northwest. The main flow went north about 5 km and inundated part of the village of Ribeira Seca de Ribeira Grande (Weston, 1964). In A.D. 1652 (Weston, 1964), Strombolian activity built a cinder cone and extruded flows about 10 km west of Lagoa do Fogo.

FURNAS VOLCANO

Furnas volcano, a stratovolcano about 800 m above sea level, occupies the east-central part of São Miguel (fig. 2). Its subaerial volume of about 60 km^3 has increased at an estimated rate of 0.06 km^3/century. A region of mafic and minor trachytic vents and associated flows about 8 km long (volcanic zone 4 of Moore, 1990, 1991) separates Furnas and Agua de Pau volcanoes. The Povoação caldera of the inactive Nordeste volcano adjoins the eastern side of Furnas. A caldera about 6 km in diameter, with walls as high as 0.5 km, truncates the summit of Furnas volcano and contains Lagoa das Furnas (fig. 8). Eruptive units predating the caldera crop out chiefly in the caldera walls and in sea cliffs on the southern coast. At least 10 eruptions of trachyte pumice have occurred from intracaldera vents during the past 5,000 years (Booth and others, 1978); these eruptions formed incomplete pumice rings and associated trachyte domes distributed across the caldera floor. Pre- and post-caldera cones of ankaramite, basanitoid, and hawaiite are outside the caldera, chiefly on its northern and western sides; some pre-caldera mafic flows crop out in the caldera walls. Post-caldera cones, domes, and flows of tristanite erupted just west of the caldera boundary and on the eastern caldera rim.

As at Sete Cidades and Agua de Pau volcanoes, no mafic vents are present within the caldera. The area that encloses only trachytic vents on Furnas volcano is about 8 by 6 km, intermediate in size between Agua de Pau and Sete Cidades. Despite the relatively small size of the volcano, Furnas apparently has a larger subjacent magma reservoir than does Sete Cidades. The relation between the modern Furnas magma reservoir and the apparently extinct Nordeste magma reservoir is unknown; the two volcanoes adjoin, and a connection at depth may once have existed.

Hot springs are prominent at Furnas and, along with its magnificent scenery, serve as the basis for a local tourist industry. The distribution of hot springs is shown by Zbyszewski and others (1958). Those on the northern shore of Lagoa das Furnas probably are related to the nearby caldera-bounding fault. Hot springs in the village of Furnas probably are associated with the Furnas C crater (Booth and others, 1978) or with radial fractures that formed during emplacement of the trachyte domes of Pico das Marconas (fig. 8). Hot springs along the upper Ribeira Quente (Hot River), 1 km southeast of the village, are associated with Pico das Marconas. The other principal location of hot springs is near the village of Ribeira Quente on the southern coast; here, they probably formed near faults associated with the southern caldera boundary. The hot springs suggest that a residual heat source associated with the frequent Holocene eruptions is close to the surface.

Pleistocene Units

Pre-Caldera Units

The Quaternary Furnas volcano overlies the 1- to 4-m.y.-old Nordeste volcanic complex (Fernandez, 1980), exposed near Ribeira Quente on the southern coast and locally at the base of the caldera wall. Roadcuts along the main highway between the villages of Furnas and Povoação expose highly weathered mafic flows and altered trachyte of the Nordeste complex on the eastern wall of Furnas caldera. Xenoliths of Nordeste mafic rocks are locally common in Plinian fall deposits of Furnas volcano.

The oldest known rocks of Furnas are late Pleistocene trachyte and tristanite flows and domes exposed at the base of the caldera wall and in sea cliffs near Ribeira Quente. A tristanite flow at the base of the section, directly overlying Nordeste basalt, near Ribeira Quente has a K-Ar age of 93,000±9,000 years, and a trachyte flow overlying Nordeste basalt near the base of the southwestern caldera wall is 48,000±4,000 years old. I conclude that Furnas volcano was built by almost exclusively subaerial eruptions during the past 100,000 years or less.

Sea cliffs west of Ribeira Quente expose pyroclastic units displaying much of the eruptive history of Furnas (fig. 9). Overlying the dated tristanite flow are 30 m of pyroclastic flows and mudflows whose radiocarbon ages are greater than 33,000 years. The next major deposit is a 40-m-thick mudflow whose radiocarbon age is 22,060±250 years B.P. The overlying section includes the caldera-outflow deposit, described below, and Holocene pumice-fall deposits.

The western caldera wall exposes a 250-m-thick section of mainly flows and pyroclastic deposits, which, like the southern coastal section, spans much of the eruptive history of the volcano. The sources for many of these units were nearby. Most of the sequence here postdates the 48,000±4,000-year-old flow.

A small canyon eroded into the caldera wall on the southern side of Pico do Ferro (fig. 8) exposes a stratigraphic section (fig. 10) that provides key information about the latest Pleistocene history of Furnas volcano. A basanitoid flow, probably from a vent west of the caldera, crops out at the base of the section. Carbonaceous sedimentary rocks of lacustrine origin, interbedded with thin pumice-fall deposits and pillow lavas of basanitoid and trachyte, overlie the basal flow. The sedimentary rocks include many algal mats containing at least five species of diatoms and a dicot indicative of shallow fresh-water conditions (Chaves, 1908; J. Platt Bradbury, USGS, written commun., 1984). The sediments were deposited in a lake of unknown size that probably was confined within a pumice ring or crater similar to those on the floor of the modern caldera. Radiocarbon ages of three separate lake beds are 23,000–27,000 years B.P. The basanitoid and trachyte pillow lavas apparently flowed into the lake from vents to the west.

Overlying the lacustrine deposits is an 18-m-thick tristanite flow containing ultramafic xenoliths. The caldera-outflow deposit caps this tristanite. Three younger tristanite flows that may have cascaded into the caldera form the top of the Pleistocene section; they came from post-caldera vents to the west and southwest and are overlain by Holocene pumice.

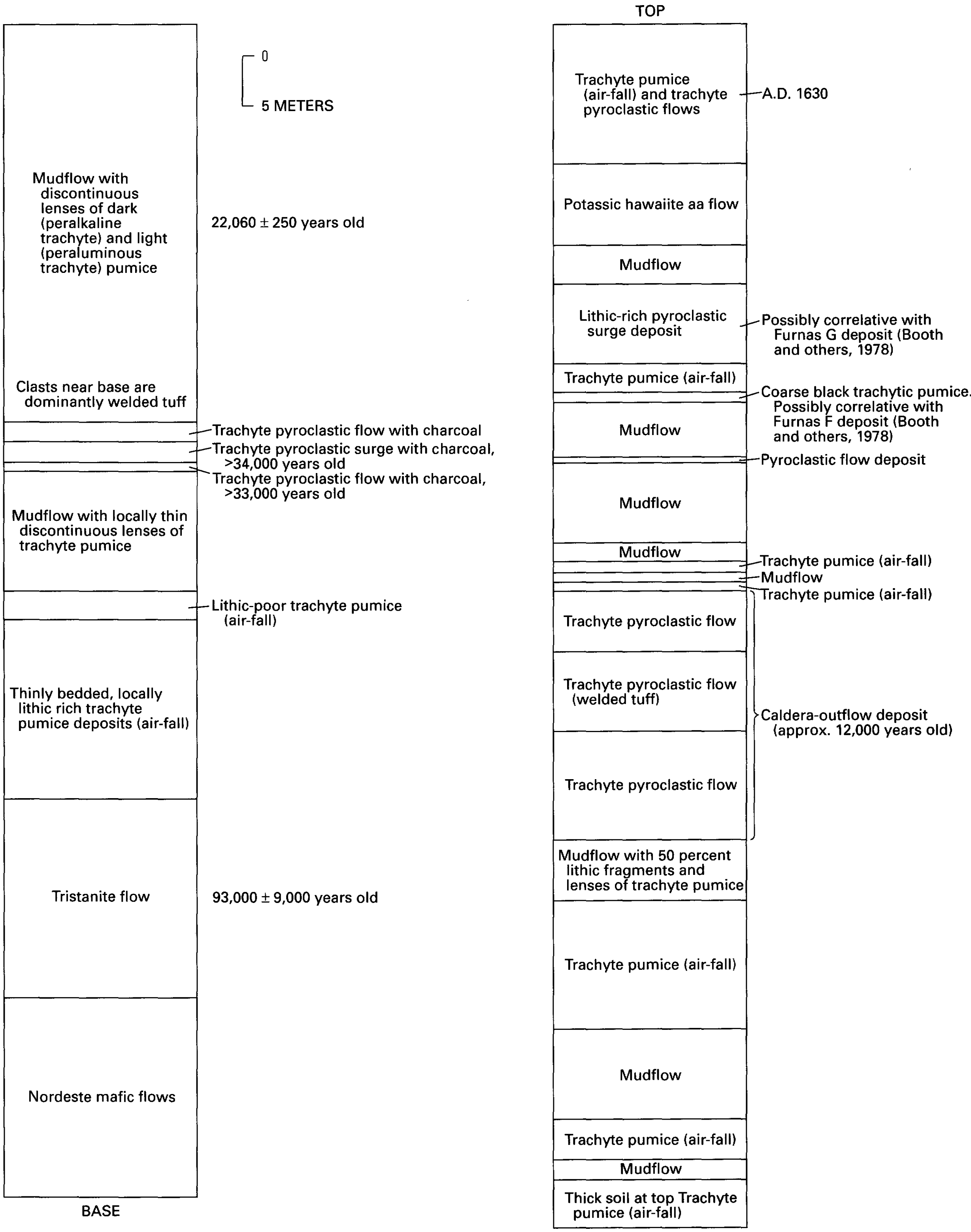


Figure 9. Composite measured stratigraphic section, sea cliff west of Ribeira Quente on southern flank of Furnas volcano. Units dip 0°–26°W.

Other lacustrine deposits, interbedded with potassic hawaiite pillow lava, crop out 2 km northeast of the section shown in figure 10, on the northern side of the village of Furnas. These deposits are older than the 2,900±120-year-old Furnas C deposit (Shotton and Williams, 1971; Booth and others, 1978), whose crater rim truncates them.

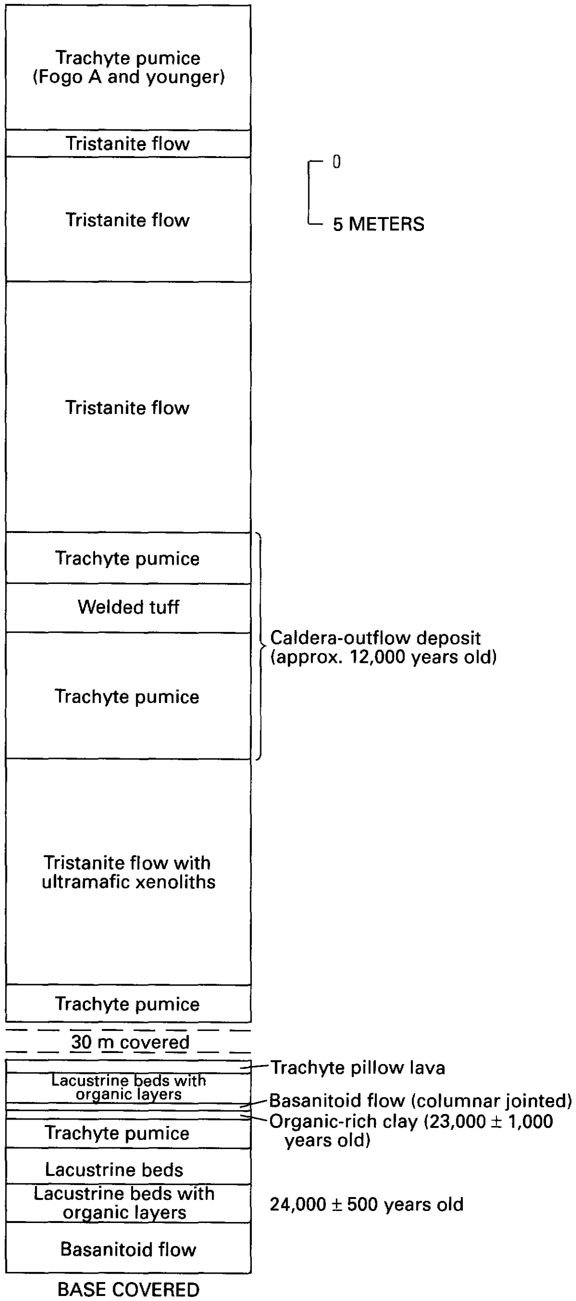


Figure 10. Measured stratigraphic section, western wall of Furnas caldera on southern side of Pico do Ferro. Dips are approximately horizontal.

Other major pre-caldera units exposed on the western and northern caldera walls are chiefly flows of ankaramite, potassic hawaiite, and tristanite from vents west and north of the caldera. These flows are interbedded with trachytic deposits, chiefly mudflows and pumice of Plinian or sub-Plinian origin.

Caldera-Outflow Deposit

The caldera of Furnas volcano formed about 12,000 years ago in response to ejection of trachyte pumice that formed a locally welded outflow deposit. This deposit is the uppermost unit truncated by the caldera wall in most places, except in the canyon whose stratigraphy is shown in figure 10; younger pumice-fall deposits mantle the caldera rim and wall. The caldera-forming eruption produced pyroclastic flows directed primarily south and east. A small exposure of the deposit also occurs 10 km north of the village of Furnas.

The caldera-outflow deposit is generally 25–50 m thick but ranges from 1 to 60 m. The welded zone is less than 1 to about 25 m thick. The estimated subaerial volume of the deposit is about the same as that of the caldera (7 km^3), but much tephra undoubtedly fell in the ocean.

The outflow deposit is at or just below the western caldera rim and locally is plastered against ankaramite cones just northwest of the caldera (fig. 8). It fills canyons on the southern flank of the volcano, near Ribeira Quente, and covers about half of the older Povoação caldera. This unit is the "Povoação ignimbrite" discussed briefly by Booth and others (1978) and Schmincke and Weibel (1972).

One of the best exposures of welded tuff is in an abandoned quarry on the western side of the Ribeira Quente, about 2 km northwest of the village of Ribeira Quente. The base of the deposit is concealed. The section consists of 9 m of densely welded tuff, 3 m of nonwelded pumice, and 14 m of densely welded tuff to the top of the quarry. Xenoliths of obsidian, trachyte, syenite, and basalt are present. Other good exposures are along trails west and east of the village of Ribeira Quente and at the beach in the village of Povoação.

The age of the caldera-outflow deposit is not known directly, but an overlying cluster of trachyte domes at Pico do Ferro (fig. 8) has a radiocarbon age of 11,230±100 years B.P. The soil separating the outflow deposit from the Pico do Ferro trachyte is only 10–15 cm thick and, by analogy with modern soils formed on historic pumice deposits of São Miguel, probably required only a few centuries to form.

Post-Caldera Units

Three tristanite cones, two with associated flows, and a cluster of seven trachyte domes postdate formation of the caldera; they were erupted from radial and concentric fractures that probably formed during caldera collapse. The cluster of domes, which includes Pico do Ferro, erupted along an arcuate fissure trending from N. 55° W. to due west; the fissure is approximately radial to the caldera but also is approximately parallel with a common regional fracture pattern on São Miguel. Truncation of the eastern dome at the caldera rim suggests either that caldera collapse was not yet complete when the dome formed or that part of the growing dome cascaded into the caldera.

The cone of Pico do Canario consists of tristanite pumice that is locally welded to dense obsidian. It formed atop the eastern Furnas caldera rim, and pumice cascaded into both Furnas and Povoação calderas.

Cones and flows of the Cedros area, about 1.5 km west of Lagoa das Furnas, consist of silica-rich tristanite. Five scoria cones erupted along fractures concentric to the caldera, and associated flows rafted scoria short distances from the vents. This unit overlies the caldera-outflow deposit in a deep canyon on the northeastern side of Cedros.

Tristanite scoria and a thick flow were erupted at another vent 300 m west of the caldera rim. The flow may underlie Pico do Ferro, but the contact is covered.

Except for the Pico do Ferro trachyte dome, the ages of these four post-caldera units are unknown but are either latest Pleistocene or Holocene. A potassic hawaiite cone that may overlie the Cedros tristanite has a radiocarbon age of 10,620±300 years B.P. (fig. 8).

Holocene Units

Trachytic Deposits

No known eruptions of Furnas volcano occurred for several thousand years after formation of the caldera; however, the earliest intracaldera eruptions have not been dated.

The oldest dated Holocene unit is a lake deposit about 1 km east of the village of Furnas, 200 m northeast of the junction of the roads to Ribeira Quente and Povoação. Fine-grained, thinly bedded, well-stratified lacustrine beds include lenses of black, fine-grained carbonaceous material. This deposit has not been recognized elsewhere, and it probably formed where a mudflow or pyroclastic flow dammed the ancestral Ribeira Quente. The radiocarbon age of one carbonaceous lens is 6,520±100 years B.P., an age not represented by known deposits elsewhere on the volcano.

At least ten Plinian and sub-Plinian eruptions of trachyte pumice, four of which accompanied emplacement of domes, occurred within the caldera during Holocene time. The stratigraphically oldest deposit forms an incomplete pumice ring, with a small central dome, on the northeastern side of Lagoa das Furnas (fig. 8). The lake occupies two adjoining shallow depressions that probably also mark vent locations. The Furnas A or B deposits of Booth and others (1978) possibly came from these vents.

The largest known Holocene pumice eruption produced the Furnas C deposit (Booth and others, 1978) 2,900±120 years B.P. (Shotton and Williams, 1971). The incomplete pumice ring that formed during this eruption crops out north and west of the village of Furnas. A late stage of the eruption produced thick mudflows that cover the northern part of the caldera floor.

The next major eruption on the floor of Furnas caldera formed the two trachyte domes of Pico das Marconas and associated pumice rings. Booth and others (1978) suggested that these vents were the sources of their Furnas E and H pumice deposits.

Pico do Gaspar is a trachyte dome about 1 km east of Lagoa das Furnas. Two nested incomplete pumice rings surround the dome. According to Booth and others (1978), these vents produced three widespread pumice deposits, Furnas F, G, and I. Charcoal from the F deposit in a quarry 1.5 km east of Pico do Gaspar has a radiocarbon age of 1,100±60 years B.P., and charcoal from the G deposit on the eastern caldera rim is 780±120 years old.

The most recent eruption of Furnas, in A.D. 1630 (Weston, 1964; van Padang and others, 1967), produced three partly nested, incomplete pumice rings and a central dome of trachyte on the southern caldera floor southeast of Lagoa das Furnas (fig. 8). The distribution and relative ages of the pumice rings indicate that the active vent moved west-northwestward about 1 km during the eruption, possibly along a concentric fracture related to collapse of the caldera. These vents lie near the southern caldera boundary, but the proximal deposits cover the rim. Vigorous mudflows swept down the Ribeira Quente and inundated the village at its mouth. Charcoal-rich pyroclastic flows characterize the base of the deposit at many localities. This charcoal yielded a radiocarbon age of 295±40 years B.P., in agreement with the known age of 320 years (before A.D. 1950). Other pyroclastic flows occur higher in the section, where they are interbedded with Plinian fall deposits.

At least 191 people reportedly were killed by the 1630 eruption, but accounts (Weston, 1964; van Padang and others, 1967) vary as to the cause: earthquakes preceding the eruption, hot pumice fall (probably actually pyroclastic flows), or mudflows. All of these events undoubtedly occurred, but mudflows sweeping down the valley to the village of Ribeira Quente likely caused the most deaths. The area of Ribeira Quente has been inundated repeatedly by mudflows and pyroclastic flows, most notably those associated with the caldera-outflow deposit, the Furnas C eruption, and the 1630 eruption.

Radiocarbon ages of the Furnas C and younger deposits permit estimation of the average dormant interval of Furnas volcano. Eight trachytic eruptions occurred between 2,900 and 320 years B.P., an average dormant interval of about 369 years. The interval decreased to only 195 years, however, during the period from 1,100 (Furnas F) to 320 years B.P., when five eruptions occurred. The present quiet interval has now lasted 320 radiocarbon years and 361 calendar years, and Furnas may be overdue for its next eruption.

Mafic Deposits

In contrast to Sete Cidades and Agua de Pau, post-caldera eruptions of mafic lavas have been rare on the flanks of Furnas. Potassic hawaiite cones (fig. 8), one dated at 10,620±300 years B.P., are on the southern side of the

Cedros tristanite cones. A potassic hawaiite flow, interbedded with pumice between the Furnas C and A.D. 1630 deposits, is on the southern flank of the volcano. This flow overlies consanguineous cinders from a nearby vent, buried during A.D. 1630 or an earlier eruption, just south of the southern caldera boundary.

PETROGRAPHY

Mafic Rocks

Mafic rocks on the three volcanoes include ankaramite, basanitoid, alkali olivine basalt, hawaiite, and mugearite.

Ankaramite contains abundant olivine and clinopyroxene and minor plagioclase phenocrysts in an intergranular to intersertal groundmass of plagioclase, clinopyroxene, olivine, opaque oxides, and interstitial residuum. Xenocrysts of orthopyroxene and amphibole are present in many samples, and late-stage biotite commonly fills vesicles.

Basanitoid has normative but not modal feldspathoids and thus is not termed basanite. Rocks are commonly aphyric but many contain scattered olivine and rare clinopyroxene and plagioclase phenocrysts in an intersertal to intergranular groundmass of the same minerals, opaque oxides, and interstitial residuum. Clinopyroxene in the groundmass is titaniferous (pleochroic brown or purple), reflecting the high bulk-rock TiO_2 content (generally >3.5 weight percent).

Alkali olivine basalt is less common than the other mafic rock types and is transitional among primitive basanitoid, accumulative ankaramite, and differentiated hawaiite and mugearite. Vent deposits and flows typically have a few volume percent of olivine>clinopyroxene>plagioclase phenocrysts in an intergranular to intersertal groundmass of the same minerals, opaque oxides, and interstitial residuum. Alkali olivine basalt is not easily distinguished in the field from other mafic rocks but is defined here as having less than 5 percent normative nepheline and less than 15 percent olivine and clinopyroxene phenocrysts.

Hawaiite typically has an intersertal to pilotaxitic or hyalophitic texture and is generally almost aphyric. A few samples contain less than 1 percent each of one or more of the following phenocryst minerals: olivine, clinopyroxene, plagioclase, amphibole, and biotite. Amphibole may be xenocrystic, for it invariably has rims of opaque oxides (opacite). Hawaiite is relatively rich in K_2O, as are most of the rocks on São Miguel (Schmincke and Weibel, 1972), and could be called trachybasalt.

Mugearite is relatively uncommon, although it occurs in vent deposits and flows on all three volcanoes. It is most abundant on Sete Cidades, where relatively old (>30,000 years) flows crop out chiefly in sea cliffs on the northern, western, and southern coasts. Mugearite appears completely transitional to hawaiite; samples of both generally have similar phenocryst populations and are indistinguishable in the field. Amphibole is an important phenocryst in the thick section of mugearite in the sea cliff south of Ponta da Ferraria (fig. 4).

Intermediate to Silicic Rocks

Tristanite, which generally has $K_2O/Na_2O \geq 1$ and SiO_2 of 55–58 percent, is relatively uncommon but occurs throughout the subaerial sequence on all three stratovolcanoes. Many tristanite vent deposits and flows are aphyric; others contain 1 percent or less of one or more of the following phenocrysts: olivine, clinopyroxene, sanidine, plagioclase, amphibole, biotite, and opaque oxides. Some, especially those containing olivine, may be hybrid mixtures of trachytic and more mafic magmas. A thick aphyric tristanite flow underlying the younger caldera-outflow deposit on the southern flank of Agua de Pau (fig. 6*A*) contains 5–10 percent late-stage biotite in vesicles.

Most trachyte contains phenocrysts of alkali feldspar (generally sanidine or anorthoclase), plagioclase, biotite, opaque oxides, green clinopyroxene, and rare zircon and apatite. Amphibole that is possibly xenocrystic is in several samples. One trachyte flow on the southern flank of Agua de Pau contains 40 volume percent sanidine phenocrysts. Sphene microphenocrysts are unusually abundant (as much as 2–3 percent) in several trachyte flows and domes from Agua de Pau. Storey (1981) reported that clinopyroxenes in young pumice deposits from Agua de Pau are generally salite and have low Al_2O_3, TiO_2, and Na_2O. Some trachyte is aphyric or almost so; most is in peralkaline domes on the western and northwestern flanks of Agua de Pau.

Syenite Xenoliths

Xenoliths of syenite as large as 0.5 m in diameter locally are common in trachyte pumice deposits of Furnas and Agua de Pau volcanoes. They are much rarer on Sete Cidades, although several dozen were observed in the sea cliff near Ponta da Ferraria. They are most readily found in alluvial deposits within the calderas and on the flanks of the volcanoes. I found xenoliths of syenite throughout the subaerial sequence on Agua de Pau, including ca. 100,000-year-old welded tuffs on the northern coast of São Miguel. They are particularly abundant in the 15,200-year-old younger caldera-outflow deposit, in which they locally make up 20 percent of the rock.

Cann (1967) discussed the mineralogy of several samples of Agua de Pau syenite; they chiefly contain sanidine, arfvedsonite, quartz, and aegirine, as well as minor biotite and zircon or dalyite. Some lack quartz and contain sodalite. Xenoliths of syenite at Furnas volcano are generally similar to those at Agua de Pau, but most lack quartz and contain sodalite.

E.H. McKee (written commun., 1986) dated a syenite xenolith from a trachyte pumice deposit on Furnas at 0.973±0.029 Ma. This relatively old age suggests that the syenite may have formed within Nordeste volcano.

Cann (1967) and Schmincke (1973) noted that syenite of Agua de Pau may contain either normative nepheline or quartz, and many samples are peralkaline; thus, the syenite generally matches the compositions of the extrusive rocks and is probably cognate.

Xenoliths of Mafic and Ultramafic Rocks

Xenoliths of mafic and ultramafic rocks are in several vent deposits and flows of basalt, basanitoid, and ankaramite on each volcano. The most remarkable sites are on Sete Cidades. The ankaramite cone of Eguas (fig. 3) and its flows contain thousands of xenoliths, including spinel lherzolite and dunite. Some samples have a relatively fine grained, recrystallized groundmass surrounding megacrysts of clinopyroxene, orthopyroxene, and kink-banded olivine. No garnet is known in these rocks or elsewhere on the three volcanoes. Some of these xenoliths may have been carried up from the mantle. Many, however, have cumulate texture and sufficient Na_2O to be nepheline normative; these may have formed in the conduit system of the volcanoes.

Pico das Camarinhas, an 840-year-old ankaramite cone near the western end of São Miguel, and its flow contain abundant xenoliths of hornblende gabbro, hornblendite, and pyroxenite.

The ankaramite cone of Mafra, 1 km east of the village of Mosteiros, and its flow contain common xenoliths of dunite (megacrysts of olivine in a finer grained, recrystallized groundmass of olivine and spinel) of possible mantle origin, wehrlite, olivine clinopyroxenite, green pyroxenite, black pyroxenite, websterite, and gabbro.

One of the most unusual occurrences of xenoliths is in the relatively old tristanite flow that forms Ponta do Garajau, 0.8 km east of Ribeira Quente on Furnas volcano (fig. 8). Xenoliths of olivine clinopyroxenite and syenite are common in a hybridized host that has 59.6 percent SiO_2 and phenocrysts or xenocrysts of sanidine, plagioclase, olivine, clinopyroxene, amphibole, and biotite. The clinopyroxenite contains normative, but not modal, nepheline and leucite; this is the only example of normative leucite among the rocks analyzed for this study.

MAJOR ELEMENT CHEMICAL COMPOSITIONS

Lava flows and pyroclastic materials of Sete Cidades, Agua de Pau, and Furnas volcanoes belong to the alkali basalt-trachyte suite (Irvine and Barager, 1971). Variation diagrams (figs. 11–13) based on 357 new chemical analyses show, for the most part, a continuum in chemical compositions among these rocks. Analytical data and normative compositions of representative rocks from the three volcanoes are given in table 1. A sample from each map unit has been analyzed.

Tholeiitic basalts are on the adjacent Mid-Atlantic Ridge but not on São Miguel (White and others, 1979). A few mafic rocks on all three volcanoes contain normative hypersthene and olivine, but these are either high-silica hawaiite, mugearite, tristanite, and hybrid rocks or ankaramite and basanitoid that have low alkali concentrations, possibly because of post-eruptive leaching. I consider them all to be alkali basalt or its derivatives, consistent with criteria of Poldervaart (1964).

Silica-Variation Diagrams

The Al_2O_3 versus SiO_2 variation diagram (fig. 11*A*) shows generally increasing alumina with increasing silica through the basalt range, reflecting the lesser abundance of olivine in more silicic compositions. The curve is relatively flat from about 50 to 62 percent SiO_2. Alumina then decreases with increasing silica in the most silicic rocks, which include peralkaline trachyte. Below about 62 percent SiO_2, rocks of Agua de Pau have generally lower alumina than do those of Sete Cidades and Furnas volcanoes.

The MgO versus SiO_2 variation diagram (fig. 11*B*) shows a wide range in magnesia contents of basaltic rocks, in accord with olivine-controlled differentiation. Above about 50 percent SiO_2, the curve is almost straight; the few deviations represent hybrid rocks, mainly from Agua de Pau, that result from mixing of mafic and trachytic melts.

The $FeO+0.9*Fe_2O_3$ versus SiO_2 variation diagram (fig. 11*C*) shows a fairly straight line. Basaltic lavas surrounding Agua de Pau have slightly higher iron contents than those on the flanks of the other two volcanoes. The greatest scatter is among the most silicic compositions on Agua de Pau, where magnesia abundances are undetectable.

Likewise, the $(FeO+0.9*Fe_2O_3)/MgO$ versus SiO_2 variation diagram (fig. 11*D*) emphasizes the marked iron enrichment above about 62 percent SiO_2, most prominent among the trachytic rocks of Agua de Pau.

The CaO versus SiO_2 variation diagram (fig. 11*E*) shows a fairly straight line. Deviations at the basaltic end are for xenoliths of gabbro and peridotite, as well as for olivine-controlled differentiation and resulting variations in

Table 1. Chemical analyses and normative compositions for representative rocks from Sete Cidades, Agua de Pau, and Furnas volcanoes, São Miguel, Azores
[In weight percent]

	1	2	3	4	5	6	7	8
				Chemical analysis				
SiO_2	44.2	45.0	50.8	54.0	58.2	59.6	61.8	63.4
Al_2O_3	15.9	10.3	18.7	19.2	17.0	18.7	18.3	18.4
Fe_2O_3	2.8	3.4	2.2	1.8	2.9	2.5	2.5	2.4
FeO	10.0	7.4	6.5	4.9	2.8	1.8	1.2	0.76
MgO	5.6	17.2	3.9	2.3	1.5	1.9	0.41	0.45
CaO	10.7	10.0	7.3	4.8	3.0	2.9	0.87	0.68
Na_2O	2.6	1.8	4.5	5.7	5.3	5.3	7.9	6.8
K_2O	1.9	0.90	2.7	3.6	5.2	5.6	5.5	5.1
H_2O^+	0.34	0.08	0.19	0.18	0.48	0.19	0.66	0.06
H_2O^-	0.14	0.31	0.31	0.30	0.59	0.30	0.16	0.43
TiO_2	4.9	2.1	2.6	1.9	1.6	1.1	0.46	0.60
P_2O_5	0.87	0.44	0.81	0.57	0.51	0.23	0.05	0.08
MnO	0.17	0.14	0.16	0.22	0.14	0.15	0.25	0.21
CO_2	0.01	0.02	0.04	0.01	0.01	0.02	0.04	0.02
Sum	100.13	99.09	100.71	99.48	99.23	100.29	100.10	99.39
				Normative composition				
Q	—	—	—	—	—	—	—	0.71
C	—	—	—	—	—	—	—	0.71
Or	11.29	5.38	15.96	21.51	30.31	33.27	32.86	30.55
Ab	15.09	11.75	31.28	38.70	44.34	44.02	49.90	58.30
An	26.25	17.67	22.85	16.34	9.52	10.76	—	2.75
Ne	3.79	2.02	3.68	5.49	—	0.54	7.72	—
Ac	—	—	—	—	—	—	1.10	—
Ns	—	—	—	—	—	—	0.49	—
Di-Wo	8.91	12.38	3.27	1.62	2.04	0.87	1.58	—
Di-En	4.69	8.67	1.64	0.70	1.03	0.42	0.27	—
Di-Fs	3.96	2.66	1.56	0.92	0.97	0.43	1.44	—
Hy-En	—	—	—	—	1.18	—	—	1.15
Hy-Fs	—	—	—	—	1.10	—	—	4.00
Ol-Fo	6.54	24.43	5.66	3.57	2.74	3.04	0.53	—
Ol-Fa	6.09	8.26	5.94	5.12	2.83	3.37	3.11	—
Mt	2.00	1.70	1.35	1.06	0.78	0.65	—	0.48
Il	9.36	4.05	4.94	3.65	2.53	2.11	0.87	1.16
Ap	2.06	1.07	1.92	1.37	0.64	0.54	0.12	0.19

1. Basanitoid, basal flow on northwestern caldera wall, Furnas volcano.
2. Ankaramite, basal flow on sea cliff below Feteiras, Sete Cidades volcano.
3. Hawaiite, basal flow on sea cliff in Mosteiros, Sete Cidades volcano.
4. Mugearite, flow on sea cliff below Camarinhas cone, Sete Cidades volcano.
5. Hybridized basanitoid, flow on northern flank of Agua de Pau volcano.
6. Tristanite, basal flow on sea cliff east of Ribeira Quente, Furnas volcano.
7. Peralkaline trachyte, welded pumice of the Gaspar ring, Furnas volcano.
8. Trachyte, flow in Feteiras, Sete Cidades volcano.

phenocryst abundances. Ten samples of trachyte from Agua de Pau and one from Sete Cidades have no detectable CaO, another indication of their alkalic nature.

The Na_2O versus SiO_2 variation diagram (fig. 11*F*) shows considerable variation throughout the compositional range. Three samples of trachyte from Furnas have low Na_2O and probably are actually altered Nordeste rocks. The rest of the variation likely results from (1) olivine-controlled differentiation in the basaltic range, (2) differences in initial chemical composition or in degree of partial melting of the mantle source, (3) hybridization, (4) post-solidification leaching, or (5) some combination of these processes.

The K_2O versus SiO_2 variation diagram (fig. 11*G*) resembles the Na_2O-SiO_2 plot, except that (1) the generally higher K_2O in Furnas mafic and trachytic rocks is apparent and (2) above about 63 percent SiO_2 K_2O begins to decrease, mainly in Agua de Pau rocks, because of crystallization and removal of potassium feldspar (Storey, 1981).

The Na_2O+K_2O versus SiO_2 variation diagram (fig. 11*H*), on which is drawn the line separating alkalic basalts from tholeiites in Hawaii (Macdonald and Katsura, 1964), shows that São Miguel rocks are strongly alkalic. The eight rocks in the tholeiitic field include an altered Nordeste basalt, an olivine clinopyroxenite xenolith from Furnas, and six nepheline normative mafic and ultramafic xenoliths from Sete Cidades. Figures 11*E* and 11*H* can be combined to yield a Peacock (1931) index of about 49, further indication of the alkalic nature of the São Miguel rocks.

The K_2O/Na_2O versus SiO_2 variation diagram (fig. 11*I*) shows that, except for three highly potassic Furnas trachytes, the ratio increases only slightly with increasing silica. Higher K_2O in Furnas mafic and silicic rocks is apparent.

The TiO_2 versus SiO_2 variation diagram (fig. 11*J*) shows a generally straight line, except among basaltic compositions. Samples of basanitoid have typically high (>3.5 percent) TiO_2 contents, shown modally in titaniferous clinopyroxene phenocrysts and groundmass grains. Fractionation of clinopyroxene, as well as olivine and perhaps iron-titanium oxides, probably accounts for the variable TiO_2 contents in the basaltic range.

The P_2O_5 versus SiO_2 variation diagram (fig. 11*K*) shows wide scatter, especially below about 56 percent SiO_2. Two fields of Agua de Pau mafic rocks high and low in P_2O_5 can be distinguished. Apatite needles are present in most mafic rocks of São Miguel, and microphenocrysts of apatite are present in many trachytes. The reason for the wide scatter in figure 11*K* is not immediately apparent.

Magnesia-Variation Diagrams

The Al_2O_3 versus MgO variation diagram (fig. 12*A*) shows a relatively straight line throughout most of the compositional range. The exceptions are at the high-magnesia end, where some analyses are of ultramafic xenoliths that may not be cognate, and at the low-magnesia (trachytic) end, where alumina decreases somewhat in the most silicic rocks as feldspar is removed.

The $FeO+0.9*Fe_2O_3$ versus MgO variation diagram (fig. 12*B*) changes slope abruptly at about 12 percent iron and 5–10 percent MgO. This change reflects the decrease in iron as relatively forsteritic olivine is accumulated in ankaramites and ultramafic xenoliths. Departures from the general trend reflect, at the high-magnesia end, the analyses of ultramafic xenoliths and, in the basaltic range (about 5–15 percent iron), the effects of hybridization of diverse melts.

The CaO versus MgO variation diagram (fig. 12*C*) shows a general trend of increasing lime with increasing magnesia; the steep curve in the low-magnesia range flattens above about 8 percent MgO, where accumulation of olivine dominates. The diffuse pattern above about 15 percent CaO represents analyses of gabbroic and ultramafic xenoliths. The small cluster of Agua de Pau mafic compositions at about 6 percent iron and 7 percent MgO are hybrid rocks.

The Na_2O versus MgO (fig. 12*D*) and K_2O versus MgO (fig. 12*E*) variation diagrams are similar and show expected trends of decreasing Na_2O and K_2O with increasing magnesia. The Agua de Pau hybridized rocks are most obvious on figure 12*E*. The K_2O/Na_2O versus MgO variation diagram (fig. 12*F*) shows the generally higher K_2O in Furnas rocks and the expected trend of slightly decreasing K_2O/Na_2O with increasing magnesia.

The TiO_2 versus MgO variation diagram (fig. 12*G*) shows a peak in TiO_2 contents (3.5–>5 percent) at about 5–9 percent MgO, corresponding to basanitoid compositions. The scatter of points in this range reflects the dominance of olivine-controlled fractionation, although fractionation of titaniferous clinopyroxene may also be important. The cluster of low-TiO_2 hybrid rocks on the flanks of Agua de Pau is apparent.

The P_2O_5 versus MgO variation diagram (fig. 12*H*), similar to the TiO_2 versus MgO plot, shows a peak in P_2O_5 (0.7–1.6 percent) in basanitoids. The measurable P_2O_5 (commonly >0.1 percent) in the ultramafic xenoliths suggests they they may be cognate to the volcanoes because xenoliths representing fragments of mantle residuum probably would be depleted in incompatible P_2O_5.

AFM Diagram

The AFM plot (fig. 13) for the newly analyzed São Miguel rocks shows their alkalic nature, especially as compared to alkalic rocks from Hawaii (Macdonald, 1968). Most of the São Miguel mafic compositions are displaced toward the Na_2O+K_2O corner relative to Hawaiian compositions. A small field of four hybrid lava flows on the flanks of Agua de Pau can be distinguished. Several samples of Furnas trachyte and one from Sete Cidades are somewhat more alkalic than other samples of trachyte, although Furnas mafic rocks fall in an intermediate position. No clear distinction among the volcanoes is apparent.

DISCUSSION

The major element chemical data indicate many similarities and some significant differences among the rocks of Sete Cidades, Agua de Pau, and Furnas volcanoes. One important similarity is that basanitoid of somewhat variable composition is the most likely parental magma from which the other magmas were derived. Perhaps the two most important differences are the common development of peralkaline compositions on Agua de Pau and the generally increasing relative abundance of K_2O from west to east.

Figure 12*G* indicates that almost aphyric, high-TiO_2 basanitoid occupies a unique position among the analyzed rocks from the three volcanoes. From this composition, one trend leads, with decreasing MgO and TiO_2, to the more silicic differentiates (hawaiite to trachyte). Another trend is defined by decreasing TiO_2 and increasing MgO because of accumulation of olivine and low-titanium clinopyroxene in ankaramites. TiO_2 is lower in all rocks that trend away from basanitoid and so must be incorporated in minerals that have been removed. The most compelling field and petrographic evidence regarding the distribution of TiO_2 is that it is incorporated, under locally hydrous conditions, in biotite (Storey, 1981), basaltic hornblende–kaersutite, and ilmenite-titanomagnetite. These minerals are abundant and accompany plagioclase, pyroxene, and apatite in the common gabbro and hornblendite xenoliths in ankaramite of the Camarinhas cone.

Magnesia variation diagrams (fig. 12) (Schmincke and Weibel, 1972) suggest that olivine fractionation was important in controlling mafic compositions. However, hawaiite and more silicic rocks have been fractionated beyond olivine control, although olivine commonly is present as scattered microphenocrysts (sometimes xenocrystic) in even the most silicic compositions. The slope of many magnesia variation curves changes near 5 percent MgO, presumably because variation departs from simple olivine control at about that point. The scatter of points at higher magnesia contents suggests, however, that olivine fractionation is not the only process causing variation. The principal alternatives are (1) several parental magmas were generated beneath São Miguel that have different magnesia and other oxide contents resulting from different degrees of partial melting of a homogeneous mantle source or partial melting of an inhomogeneous mantle source, or (2) fractionation of other minerals (chiefly clinopyroxene and plagioclase but also orthopyroxene and opaque oxides) was important. Because microprobe data on mineral compositions are not yet available, quantitative modelling to test these hypotheses has not yet been attempted.

Peralkaline trachyte was erupted throughout the subaerial history of Agua de Pau from vents along radial and possibly concentric fractures on the western, southern, and northern flanks of the volcano, as well as from intracaldera vents. The development of volumetrically important peralkaline magmas on Agua de Pau and not on the other two volcanoes may be related to the relatively large subjacent magma reservoir of Agua de Pau, which I infer from the distribution of trachyte vents (fig. 6) and syenite xenoliths (Booth and others, 1978). In addition, alumina contents generally are lower throughout the compositional range on Agua de Pau as compared to the other two volcanoes (figs. 11, 12) (Schmincke and Weibel, 1972). Self and Gunn (1976) and Storey (1981) found that crystallization and removal of potassium feldspar, biotite, and clinopyroxene was largely responsible for producing peralkaline trachyte on Terceira and among the post-Fogo A pumice deposits on Agua de Pau; fractionation of plagioclase (Schmincke, 1982) must also have been important. Stratigraphic and radiometric data indicate that Sete Cidades, Agua de Pau, and Furnas volcanoes commonly had lengthy repose following major eruptions, especially caldera-forming episodes. Only on Agua de Pau, however, did caldera-forming eruptions produce peralkaline rocks in great volume. It is possible that peralkalinity typically characterized the late stage of magmatic cycles on Agua de Pau, as Storey (1981) found for the post-Fogo A pumice deposits. Perhaps potassium feldspar, biotite, clinopyroxene, and plagioclase were removed during early and intermediate episodes of a cycle, ultimately resulting in development of a peralkaline melt that erupted last in the cycle. Fisher and Schmincke (1984), however, presented evidence of common chemical zonation in silicic magma reservoirs, as shown by compositions of their erupted products; therefore, development of peralkalinity may be a relatively short-term process in large magma reservoirs.

Figure 12*F* illustrates the general increase of K_2O from west to east across the three volcanoes. This increase somewhat mimics the increase in $^{87}Sr/^{86}Sr$ found by White and others (1976) and Hawkesworth and others (1979) and suggests that increasing distance from the Mid-Atlantic Ridge or from the Azores fracture zone accounts for the increase in K_2O. This explanation does not hold, however, when older rocks are included. For example, Nordeste rocks (Fernandez, 1980) are not enriched in K_2O relative to Furnas rocks. In addition, White and others (1976) found normal (low) $^{87}Sr/^{86}Sr$ in Pliocene basalt from Santa Maria, the next island southeast of São Miguel. I suggest that the higher abundance of K_2O, particularly in Furnas rocks, may result from partial remelting of previously erupted or intruded rocks from Nordeste volcano, such as the ca. 1-m.y.-old syenite that McKee dated, during Furnas magmatic activity. Perhaps K_2O is lowest on Sete Cidades because only a small volume of previously emplaced silicic rock was available for remelting, as suggested by the relative absence of syenite xenoliths.

Preliminary study of available chemical data suggests that a mechanism similar to that proposed by Fernandez (1980) for the origin of Nordeste volcanic rocks produced the melts erupted by the three late Quaternary stratovolcanoes. Partial melting of 5–20 percent of mantle peridotite at depths of 35–70 km (Green and Ringwood, 1967) could produce parental basanitoid of somewhat variable composition. Crystallization and removal of olivine, pyroxene, and plagioclase in shallow (1–10 km) reservoirs leave more silicic melts (hawaiite, mugearite, tristanite, and trachyte). Accumulation of olivine and pyroxene results in ankaramitic magmas. The biotite- and amphibole-bearing magmas may have formed in reservoirs within 8 km of the surface (Eggler and Burnham, 1973). Evaluation of these processes awaits trace element, electron microprobe, and isotopic data.

The volume of subaerial basanitoid and related basaltic rocks between Sete Cidades and Agua de Pau volcanoes is about 30 km^3 and between Furnas and Agua de Pau volcanoes about 22 km^3. The volume of exposed trachyte on the three volcanoes is about 100 km^3 (table 2). Intrusive complexes of basaltic material may underlie São Miguel in sufficient volume to account for the abundant silicic rocks observed on the volcanoes.

Comparison of stratigraphic and chemical data for São Miguel with those for Terceira, the other Azorean island that has been studied in detail (Self, 1976; Self and Gunn, 1976), shows that:

1. Periods of particularly vigorous eruptive activity, commonly resulting in formation of calderas, occurred about 23,000–19,000 and 15,000–12,000 years B.P.

2. Chemical bimodality (basalt and trachyte) characterizes both islands: trachyte dominates, and intermediate compositions, though present, are volumetrically low.

Table 2. Estimated volumes of different rock types on the three late Quaternary stratovolcanoes of São Miguel

	Cubic kilometers	Percentage
Sete Cidades		
Ankaramite	1.14	3
Basanitoid	1.4	4
Basalt	0.9	2
Hawaiite + mugearite	7.3	18
Tristanite	0.5	1
Trachyte	28.4	72
Agua de Pau		
Ankaramite	1.0	2.1
Basanitoid	0.5	1.0
Basalt	1.0	2.1
Hybrid	0.3	0.6
Hawaiite + mugearite	0.35	0.7
Tristanite	0.5	1.0
Trachyte (peralkaline)	20.0	41.1
Trachyte (peraluminous)	25.0	51.4
Furnas		
Ankaramite	2.0	6.0
Basanitoid	1.0	3.0
Basalt	0	0
Hawaiite + mugearite	0.5	1.5
Tristanite	2.0	6.0
Trachyte	28.0	83.5

The output of Azorean volcanoes in general is low, but Sete Cidades, Agua de Pau, and Furnas together have erupted at least five times as much lava as the volcanoes on Terceira (Self, 1976; this paper) during latest Pleistocene and Holocene time. In contrast, volcanoes of somewhat similar composition in the Miocene and younger Canary Islands (Schmincke, 1982) have been constructed at rates 5–10 times greater than the Pliocene and younger Azores.

REFERENCES CITED

Booth, B., Croasdale, R., and Walker, G.P.L., 1978, A quantitative study of five thousand years of volcanism on São Miguel, Azores: Royal Society of London Philosophical Transactions, ser. A, v. 288, p. 271–319.

Cann, J.R., 1967, A second occurrence of dalyite and the petrology of some ejected syenite blocks from São Miguel, Azores: Mineralogical Magazine, v. 33, p. 227–232.

Chaves, F.A., 1908, Gisements de diatomees fossiles a Furnas (Ile de S. Miguel): Lisbon, Bulletin de la Societe Portugueses des Sciences Naturelles, v. II, fasc. 3.

Eggler, D.H., and Burnham, C.W., 1973, Crystallization and fractionation trends in the system andesite-H_2O–CO_2–O_2 at pressures to 10 kb: Geological Society of America Bulletin, v. 84, p. 2519–2532.

Esenwein, P., 1929, Zur petrographie der Azoren: Zeitschrift Vulkanologie, v. 12, p. 108–227.

Fernandez, L.A., 1980, Geology and petrology of the Nordeste volcanic complex, São Miguel, Azores: Geological Society of America Bulletin, v. 91, p. 675–680.

Fisher, R.V., and Schmincke, H.U., 1984, Pyroclastic rocks. Berlin, Springer-Verlag, 472 p.

Flower, M.F.J., Schmincke, H.U., and Bowman, H., 1976, Rare earth and other trace elements in historic Azorean lavas: Journal of Volcanology and Geothermal Research, v. 1, p. 127–147.

Gandino, A., Guidi, M., Merlo, C., Mete, L., Rossi, R., and Zan, L., 1985, Preliminary model of the Ribeira Grande geothermal field (Azores Islands): Geothermics, v. 14, no. 1, p. 91–105.

Green, D.H., and Ringwood, A.E., 1967, The genesis of basaltic magmas: Contributions to Mineralogy and Petrology, v. 15, p. 103–190.

Grimison, N.L., and Chen, W.P., 1986, The Azores-Gibraltar plate boundary—Focal mechanisms, depths of earthquakes, and their tectonic implications: Journal of Geophysical Research, v. 91, no. B2, p. 2029–2047.

Hawkesworth, C.J., Norry, M.J., Roddick, J.C., and 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, v. 280, p. 28–31.

Huang, T.C., Watkins, N.D., and Wilson, L., 1979, Deep-sea tephra from the Azores during the past 300,000 years; eruptive cloud height and ash volume estimates: Geological Society of America Bulletin, v. 90, p. 131–133.

Irvine, T.N., and Barager, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548.

Jeremine, E., 1957, Etude microscopique des roches de la region de Furnas (S. Miguel-Acores): Communications de la Service Geologique de Portugal, v. 38, p. 65–90.

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

Laughton, A.S., and Whitmarsh, R.B., 1975, The Azores-Gibraltar plate boundary, *in* Kristjansson, L., ed., Geodynamics of Iceland and the North Atlantic area. Dordrecht, Reidel, p. 63–81.

Macdonald, G.A., 1968, Composition and origin of Hawaiian lavas: Geological Society of America Memoir 116, p. 477–552.

Macdonald, G.A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, p. 82–133.

Moore, R.B., 1983a, Preliminary geologic map of Furnas volcano, São Miguel, Azores: U.S. Geological. Survey Open-File Report 83–395, scale 1:15,000.

______ 1983b, Preliminary geologic map of Sete Cidades volcano, São Miguel, Azores: U.S. Geological Survey Open-File Report 83–742, scale 1:18,000.

______ 1986, Preliminary geologic map of Agua de Pau volcano, São Miguel, Azores: U.S. Geological Survey Open-File Report 86–192, scale 1:18,000.

______ 1990, Volcanic geology and eruption frequency, São Miguel, Azores: Bulletin of Volcanology, v. 52, no. 8, p. 602–614.

______ 1991, Geologic map of São Miguel, Azores: U.S. Geological Survey Miscellaneous Investigations Series Map I–2007, scale 1:50,000.

Moore, R.B., and Rubin, M., 1991, Radiocarbon dates for lava flows and pyroclastic deposits on São Miguel, Azores: Radiocarbon, v. 33, no. 1, p. 151–164.

Muecke, G.K., Ade-Hall, J.M., Aumento, F., MacDonald, A., Reynolds, P.H., Hyndman, R.D., Quintino, J., Opdyke, N., and Lowrie, W., 1974, Deep drilling in an active geothermal area in the Azores: Nature, v. 252, p. 281–285.

Peacock, M.A., 1931, Classification of igneous rock series: Journal of Geology, v. 39, p. 54–67.

Poldervaart, A., 1964, Chemical definition of alkali basalts and tholeiites: Geological Society of America Bulletin, v. 75, p. 229–232.

Schmincke, H.-U., 1973, Magmatic evolution and tectonic regime in the Canary, Madeira, and Azores island groups: Geological Society of America Bulletin, v. 84, p. 633–648.

______ 1982, Volcanic and chemical evolution of the Canary Islands, *in* Geology of the northwest African continental margin. Berlin, Springer-Verlag, p. 273–306.

Schmincke, H.-U., and Weibel, M., 1972, Chemical study of rocks from Madeira, Porto Santo, and São Miguel, Terceira (Azores): Neues Jahrbuch fur Mineralogie, Abhandlungen, v. 117, no. 3, p. 253–281.

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

Self, S., 1976, The Recent volcanology of Terceira, Azores: Journal of the Geological Society of London, v. 132, p. 645–666.

Self, S., and Gunn, B.M., 1976, Petrology, volume, and age relations of alkaline and saturated peralkaline volcanics from Terceira, Azores: Contributions to Mineralogy and Petrology, v. 54, p. 293–313.

Shotton, F.W., Blundell, D.J., and Williams, R.E.G., 1968, Birmingham University radiocarbon dates, II: Radiocarbon, v. 10, p. 204.

______ 1969, Birmingham University radiocarbon dates, III: Radiocarbon, v. 11, p. 266.

Shotton, F.W., and Williams, R.E.G., 1971, Birmingham University radiocarbon dates, V: Radiocarbon, v. 13, p. 141–156.

______ 1973, Birmingham University radiocarbon dates, VII: Radiocarbon, v. 15, p. 451–468.

Sparks, S.R.J., Sigurdsson, H., and Wilson, L., 1977, Magma mixing; a mechanism for triggering acid explosive eruptions: Nature, v. 267, p. 315–318.

Storey, M., 1981, Trachytic pyroclastics from Agua de Pau volcano, São Miguel, Azores; evolution of a magma body over 4,000 years: Contributions to Mineralogy and Petrology, v. 78, p. 423–432.

van Padang, M.N., Richards, A.F., Machado, F., Bravo, T., Baker, P.E., and Le Maitre, R.W., 1967, Catalogue of active volcanoes-Atlantic Ocean: International Volcanological Association, pt. 21.

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

Walker, G.P.L., and Croasdale, R., 1970, Two Plinian-type eruptions in the Azores: Journal of the Geological Society of London, v. 127, p. 17–55.

Weston, F.S., 1964, List of recorded volcanic eruptions in the Azores with brief reports: Boletim do Museu e Laboratorio Mineralogico e Geologico da Faculdade de Ciencias, v. 10, fasc. 1, p. 3–18.

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

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

Zbyszewski., G., 1961, Etude geologique de l'Ile de S. Miguel (Acores): Communications de la Service Geologique de Portugal, v. 45, p. 5–79.

Zbyszewski, G., de Medeiros, A.C., de Almeida, F.M., and da Veiga Ferreira, O., 1958, Carta geologica de Portugal na escala de 1:50,000 (São Miguel): Servicos Geologicos de Portugal, Lisbon.

Zbyszewski, G., and da Veiga Ferreira, O., 1959, Carta geologica de Portugal na escala de 1:50,000 (São Miguel): Servicos Geologicos de Portugal, Lisbon.

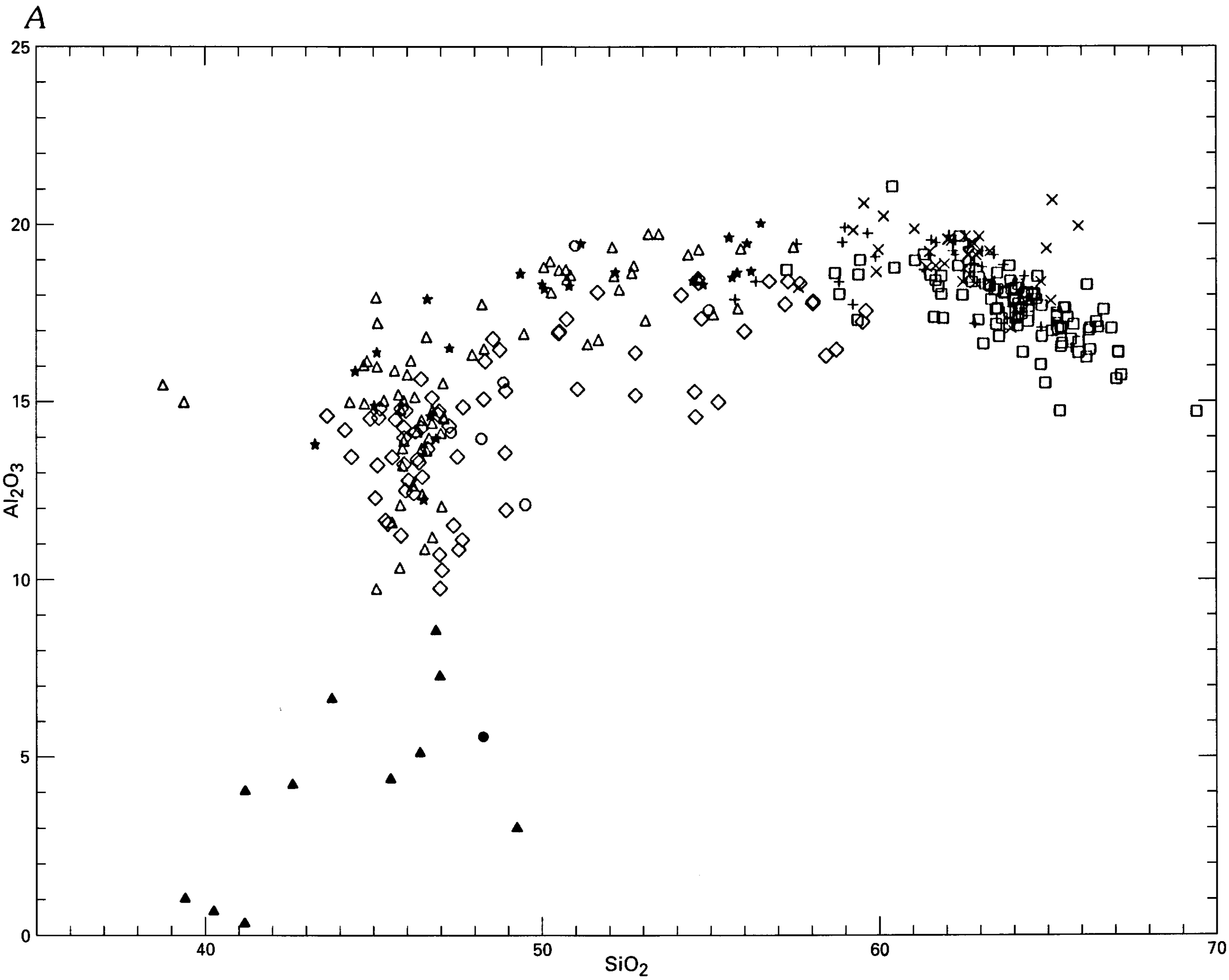


Figure 11 (above and following pages). Silica-variation diagrams (in weight percent). Symbols: □, trachytes and tristanites of Agua de Pau volcano; +, trachytes and tristanites of Sete Cidades volcano; ×, trachytes and tristanites of Furnas volcano (●, ultramafic or mafic xenolith); ◇, mafic rocks on the flanks of Agua de Pau volcano; △, mafic rocks on the flanks of Sete Cidades volcano (▲, ultramafic or mafic xenolith); ★, mafic rocks on the flanks of Furnas volcano; ○, Nordeste volcano.

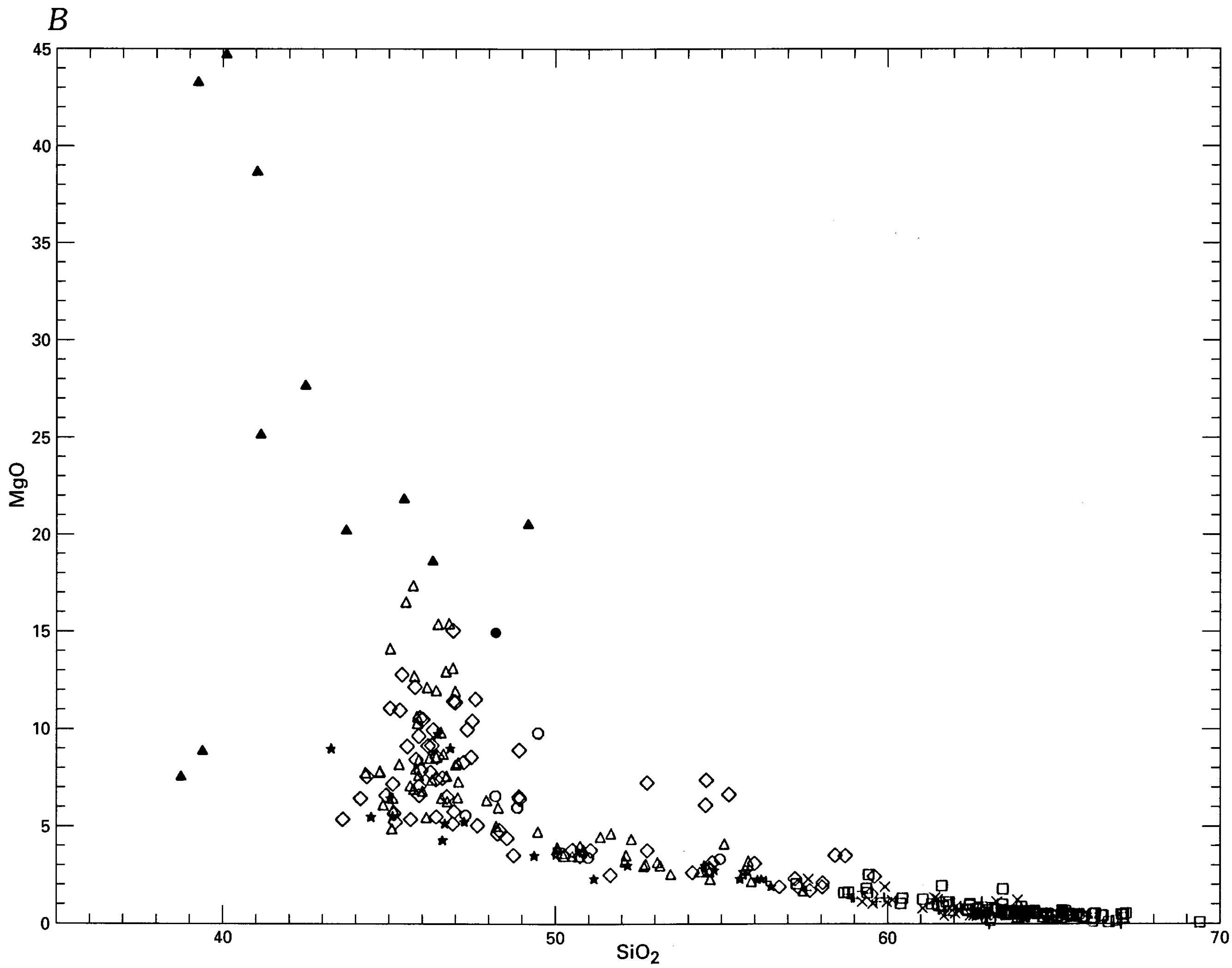


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

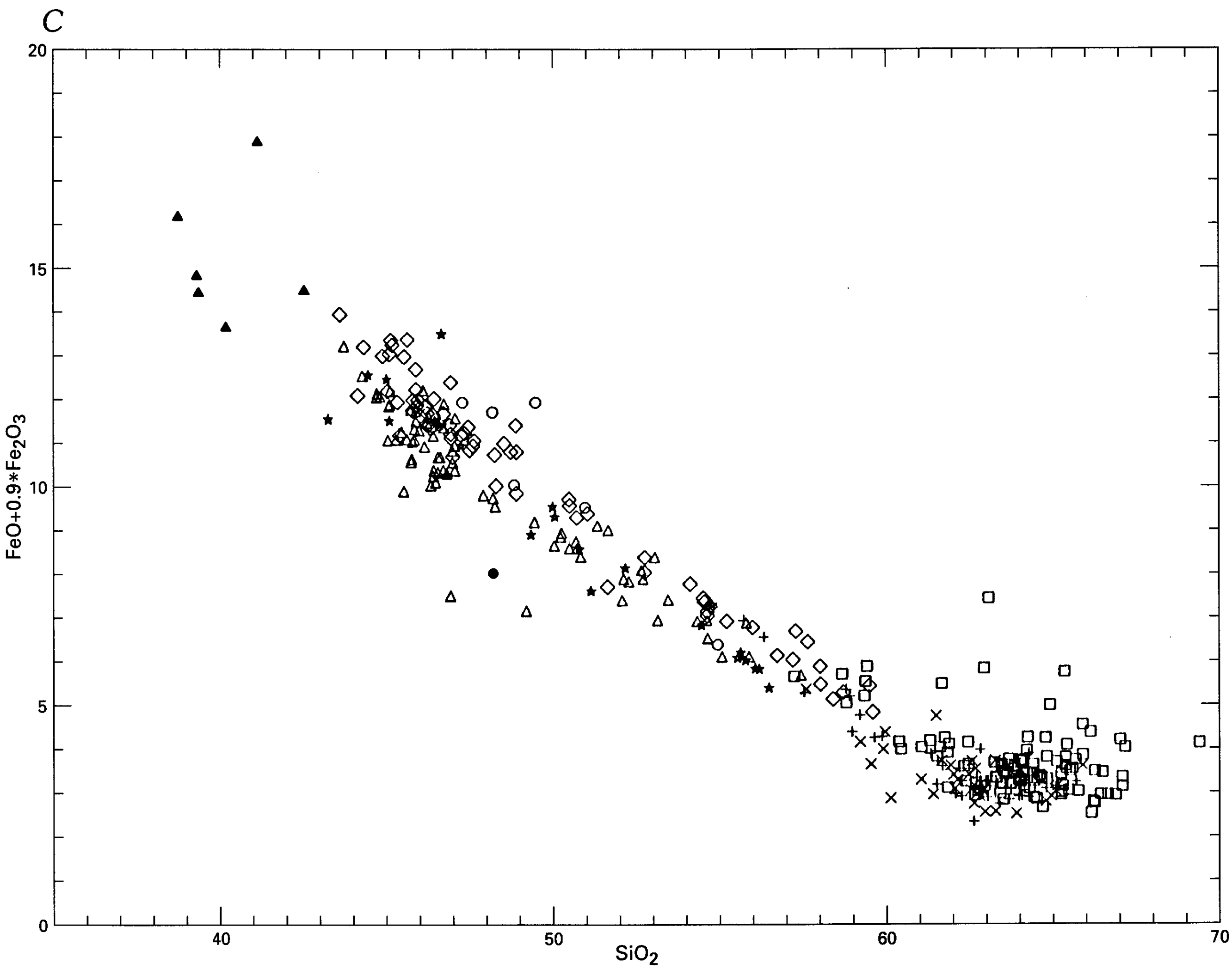


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

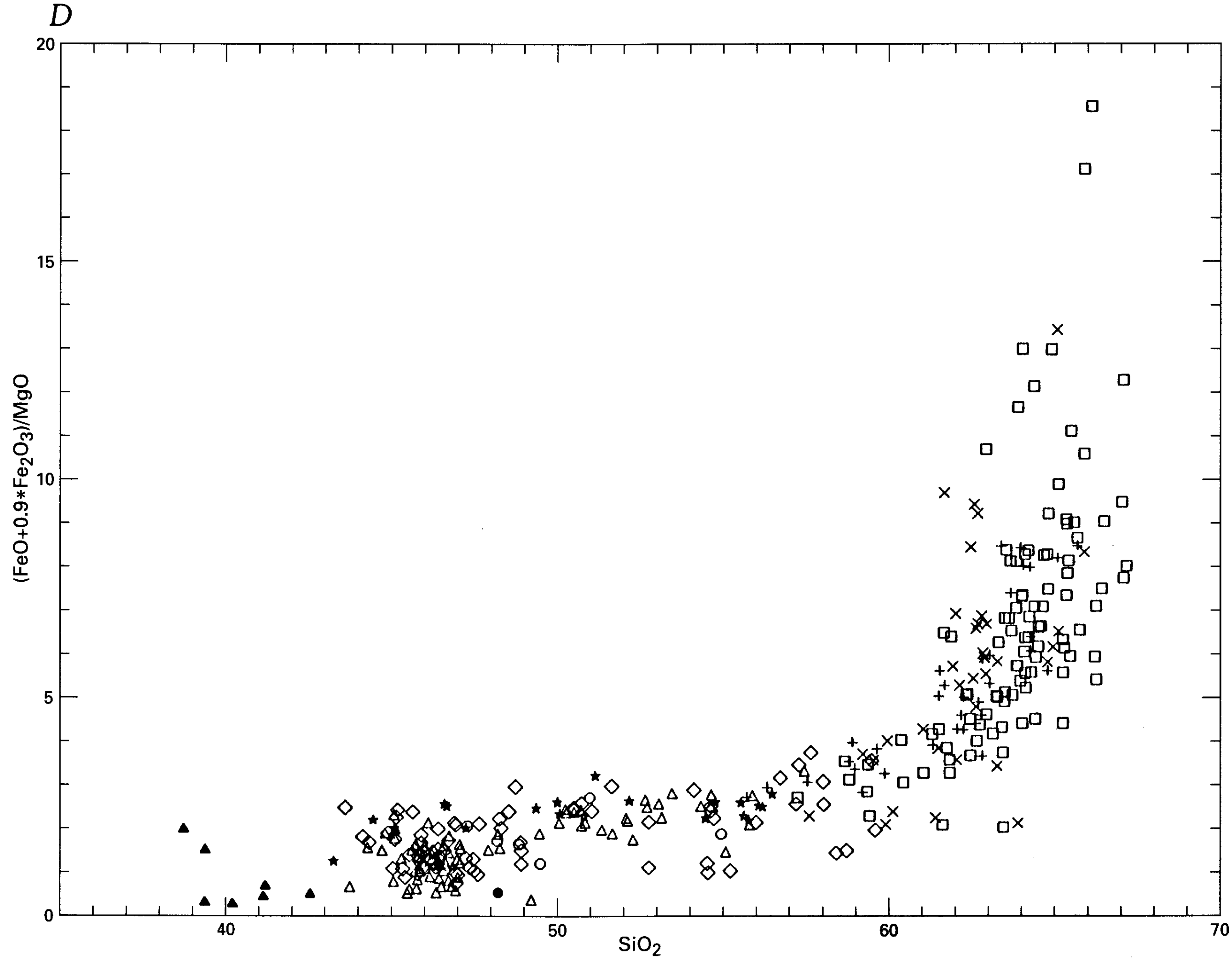


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

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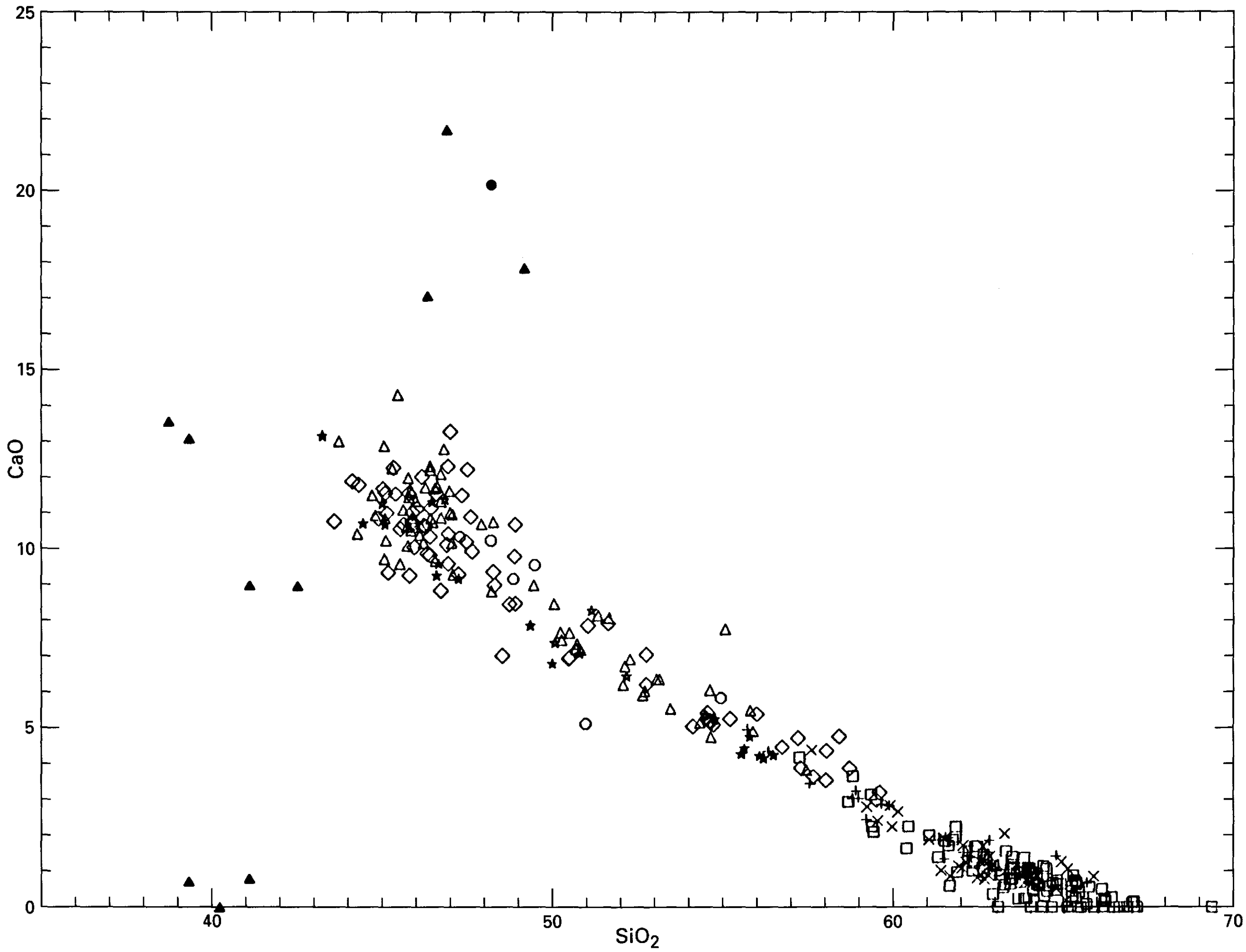


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

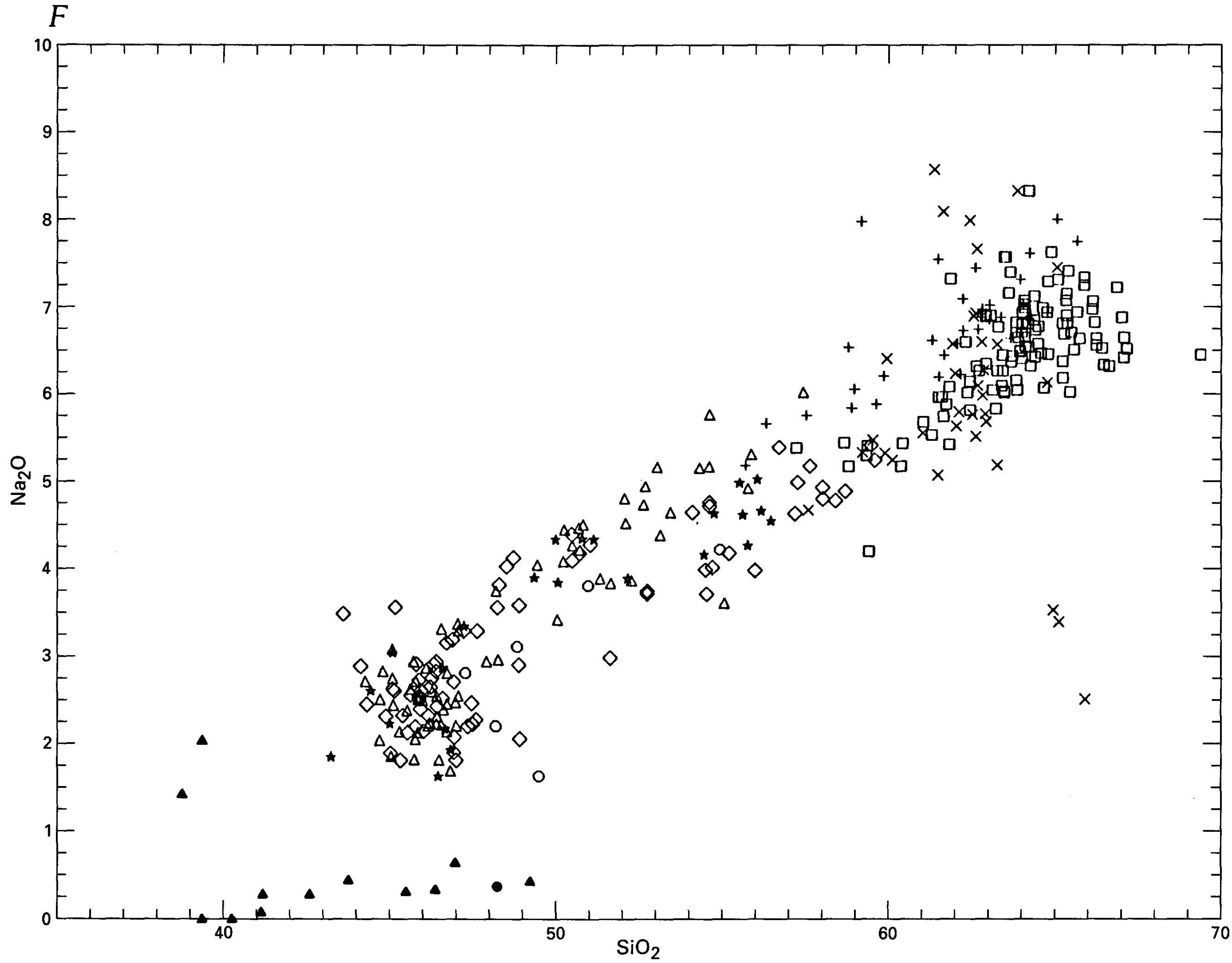
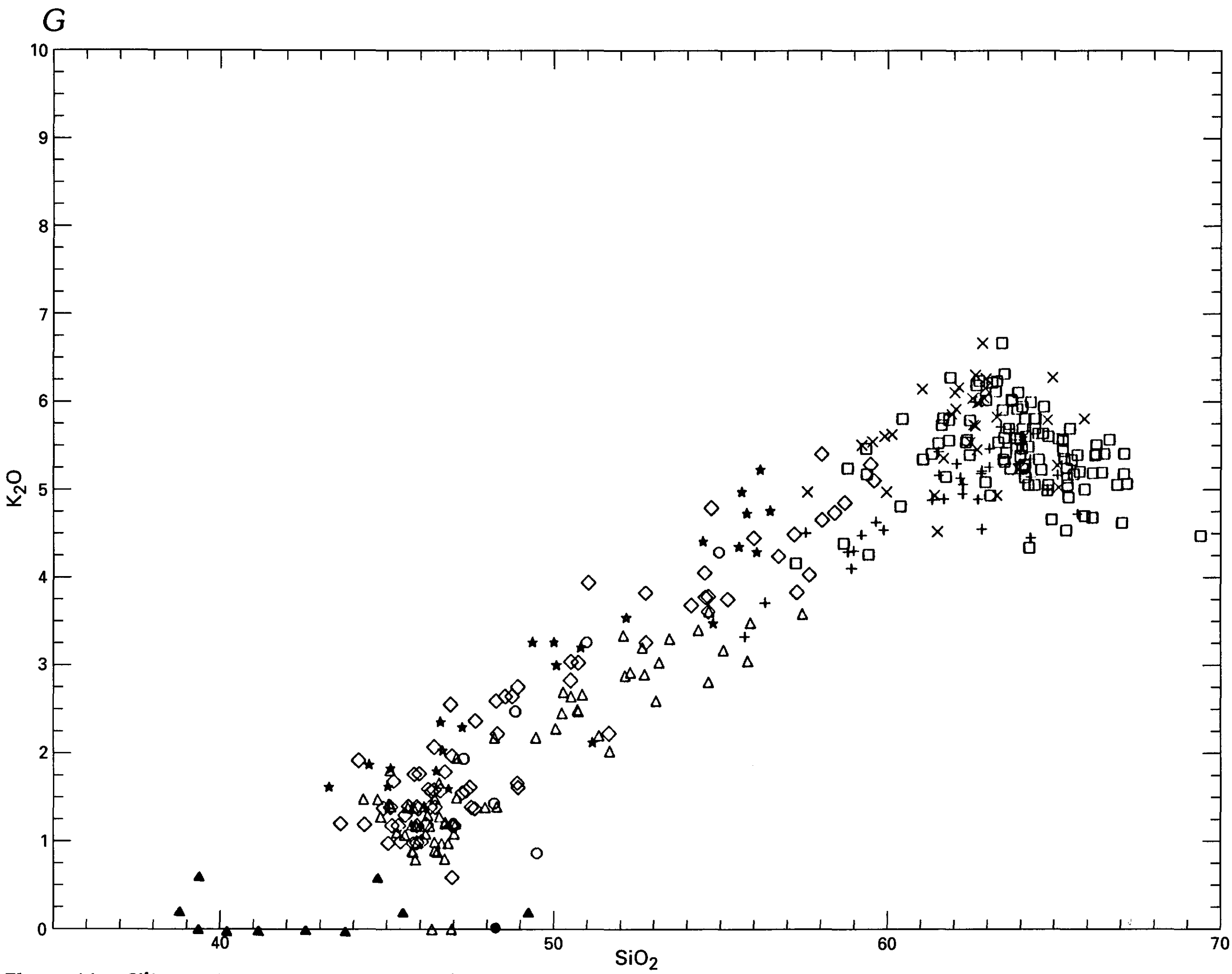


Figure 11. Silica-variation diagrams (in weight percent)—Continued.



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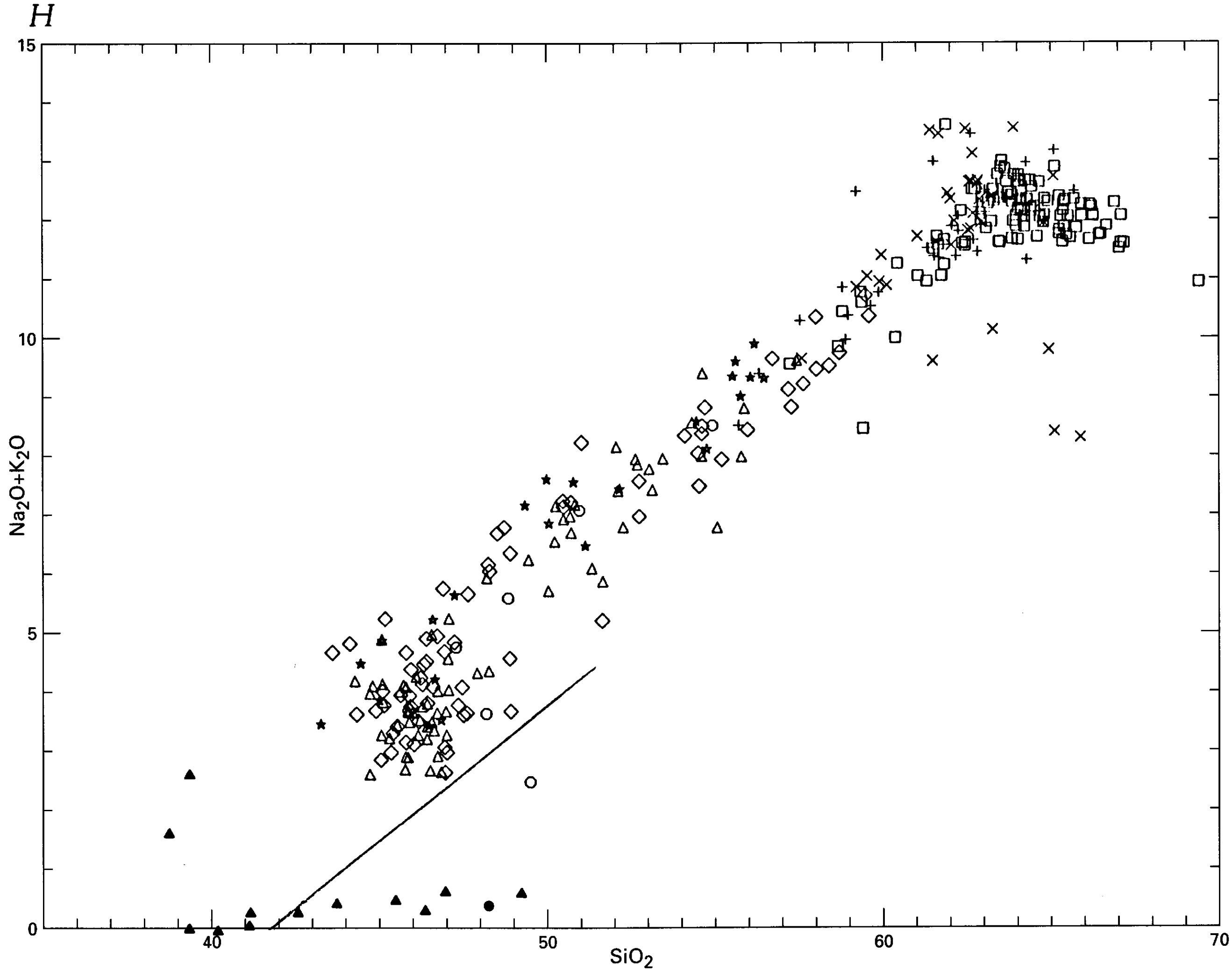


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

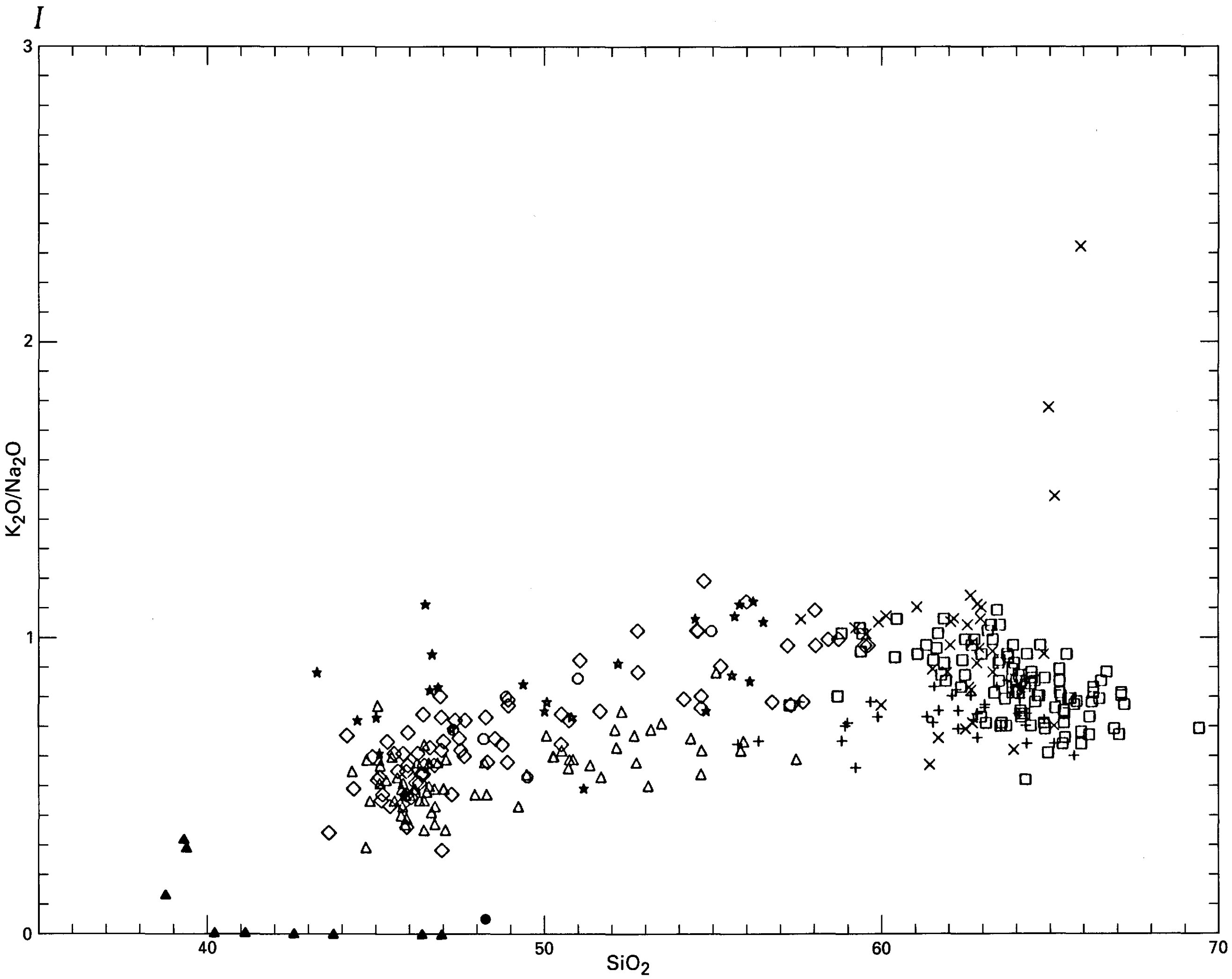


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

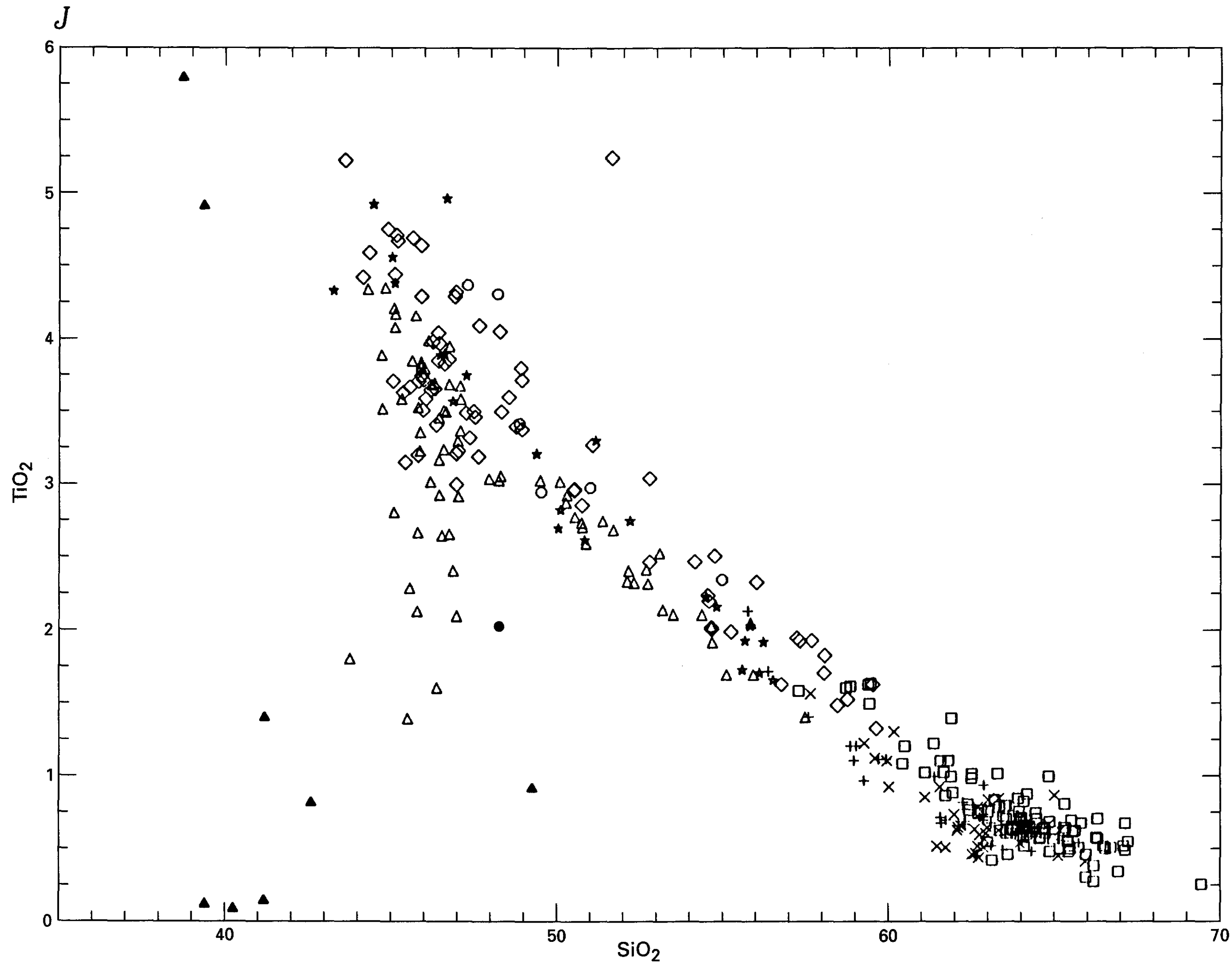


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

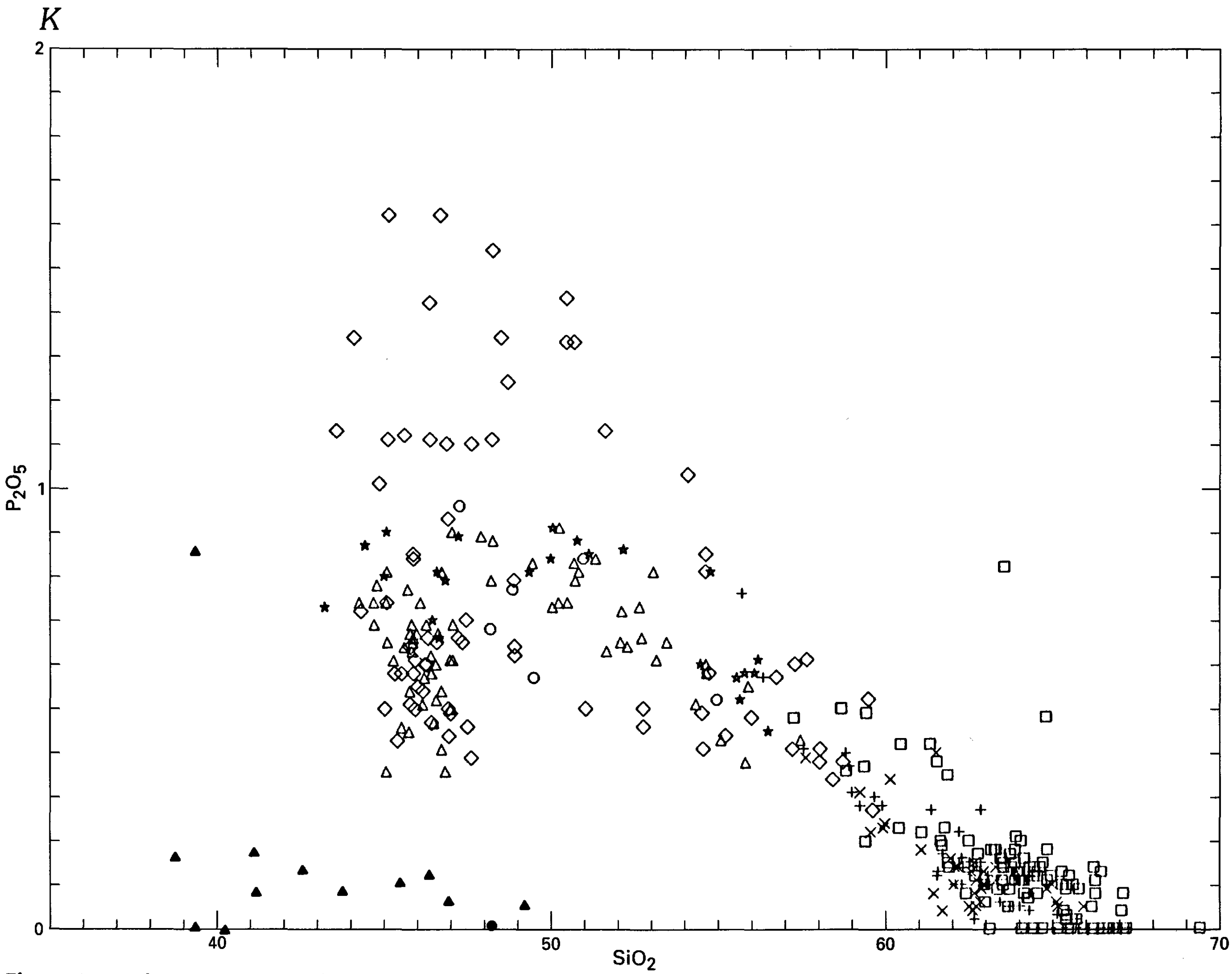


Figure 11. Silica-variation diagrams (in weight percent)—Continued.

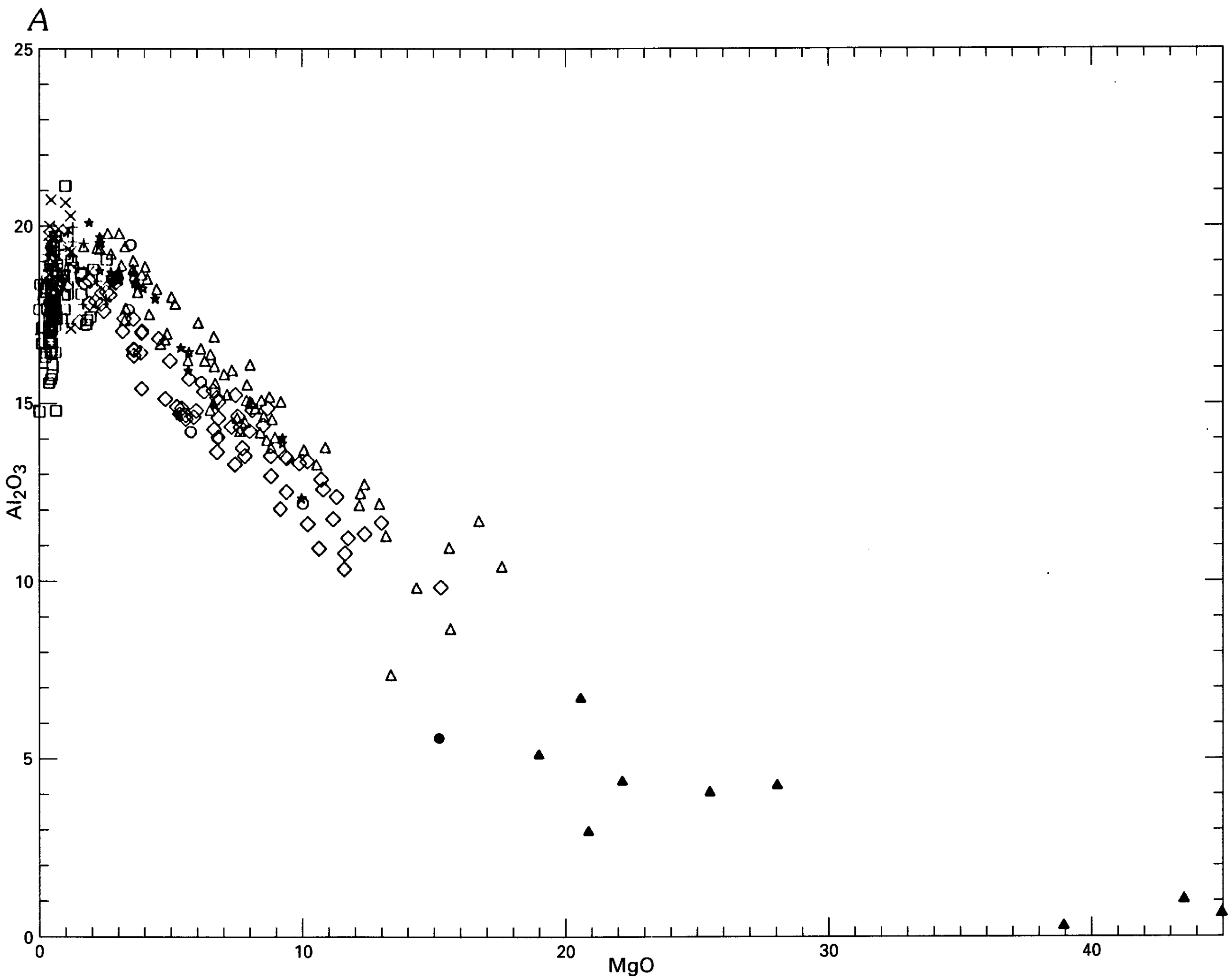
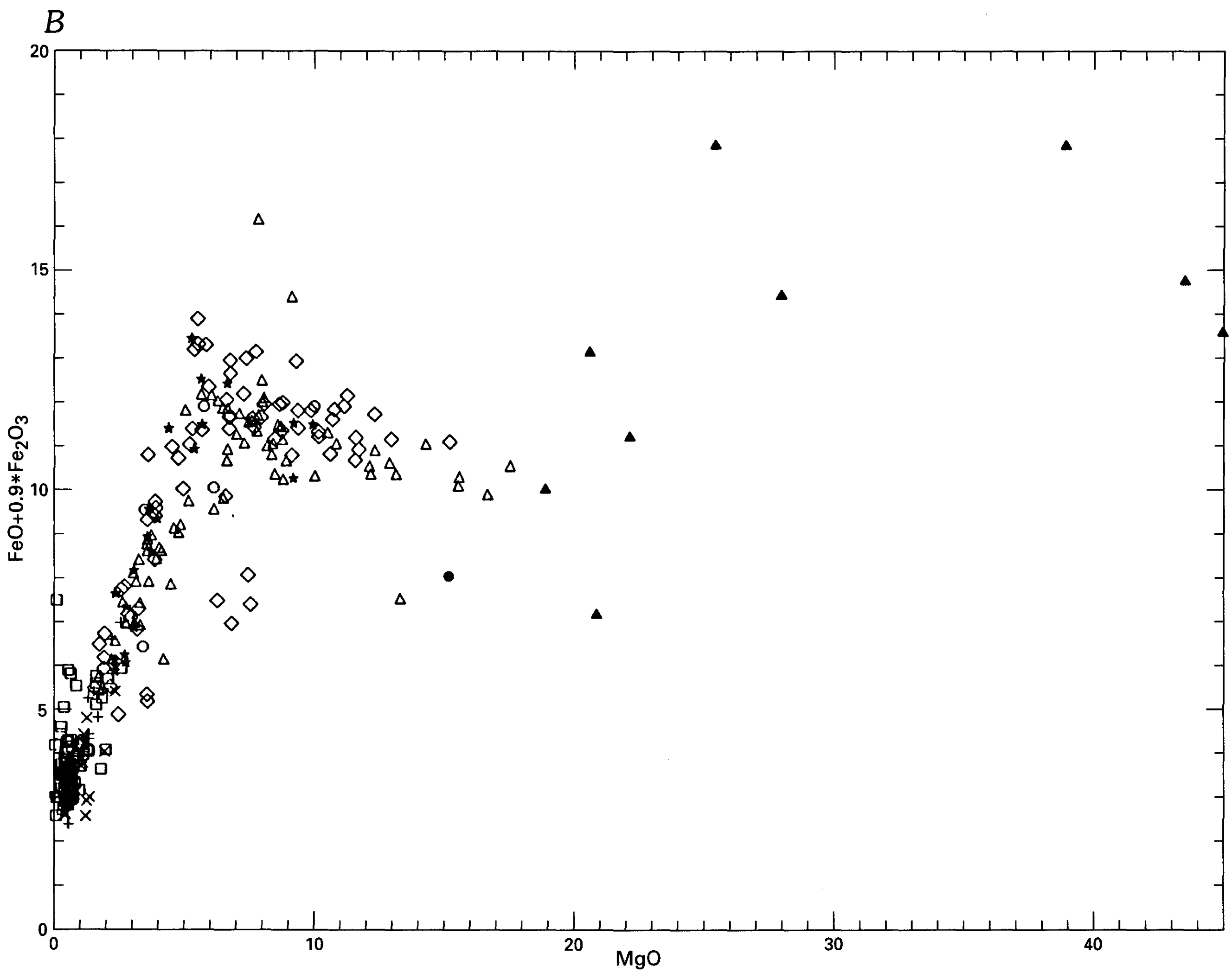


Figure 12. Magnesia-variation diagrams (in weight percent). Symbols as in figure 11. Symbols: □, trachytes and tristanites of Agua de Pau volcano; +, trachytes and tristanites of Sete Cidades volcano; ×, trachytes and tristanites of Furnas volcano (●, ultramafic or mafic xenolith); ◇, mafic rocks on the flanks of Agua de Pau volcano; △, mafic rocks on the flanks of Sete Cidades volcano (▲, ultramafic or mafic xenolith); ★, mafic rocks on the flanks of Furnas volcano; ○, Nordeste volcano.



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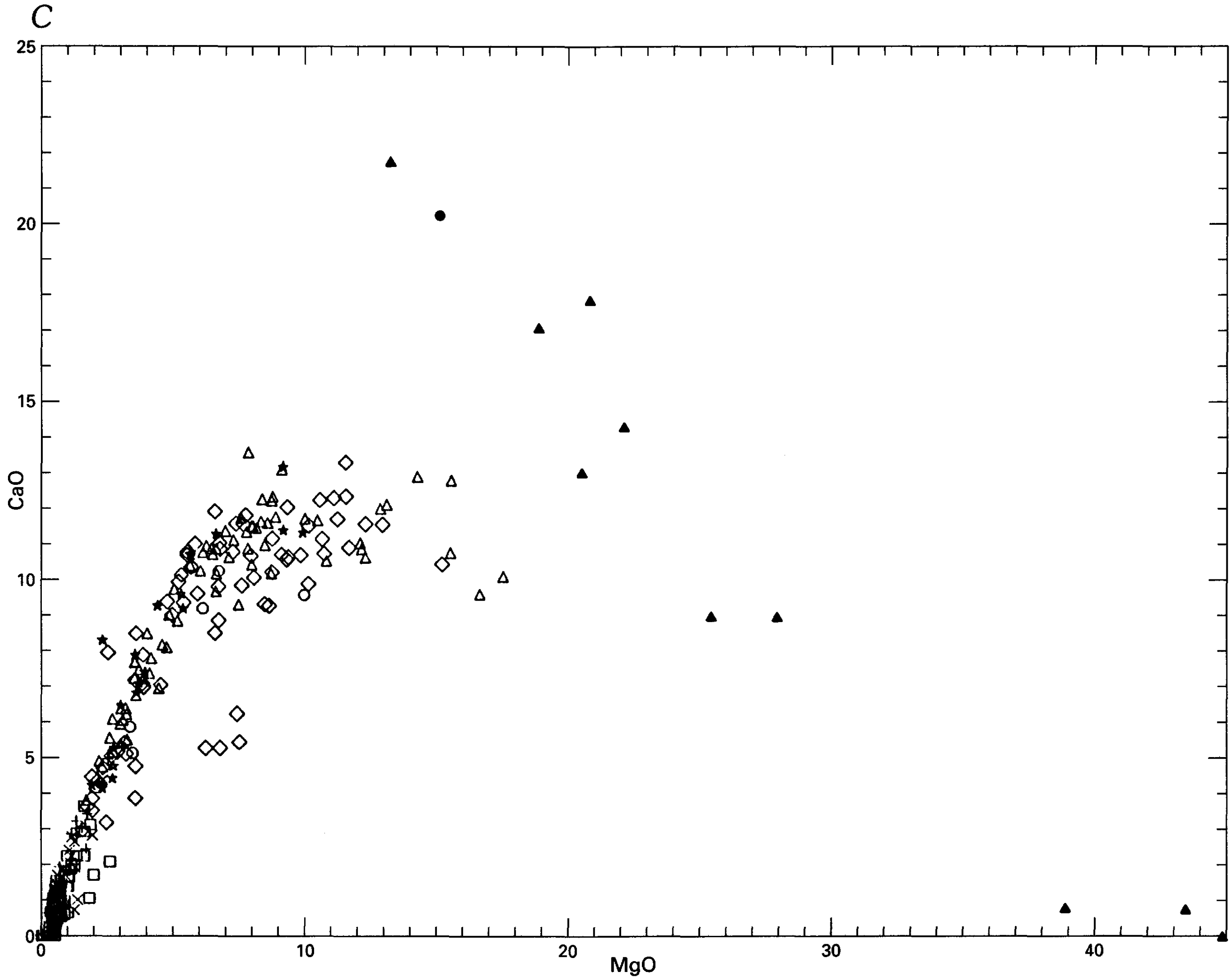

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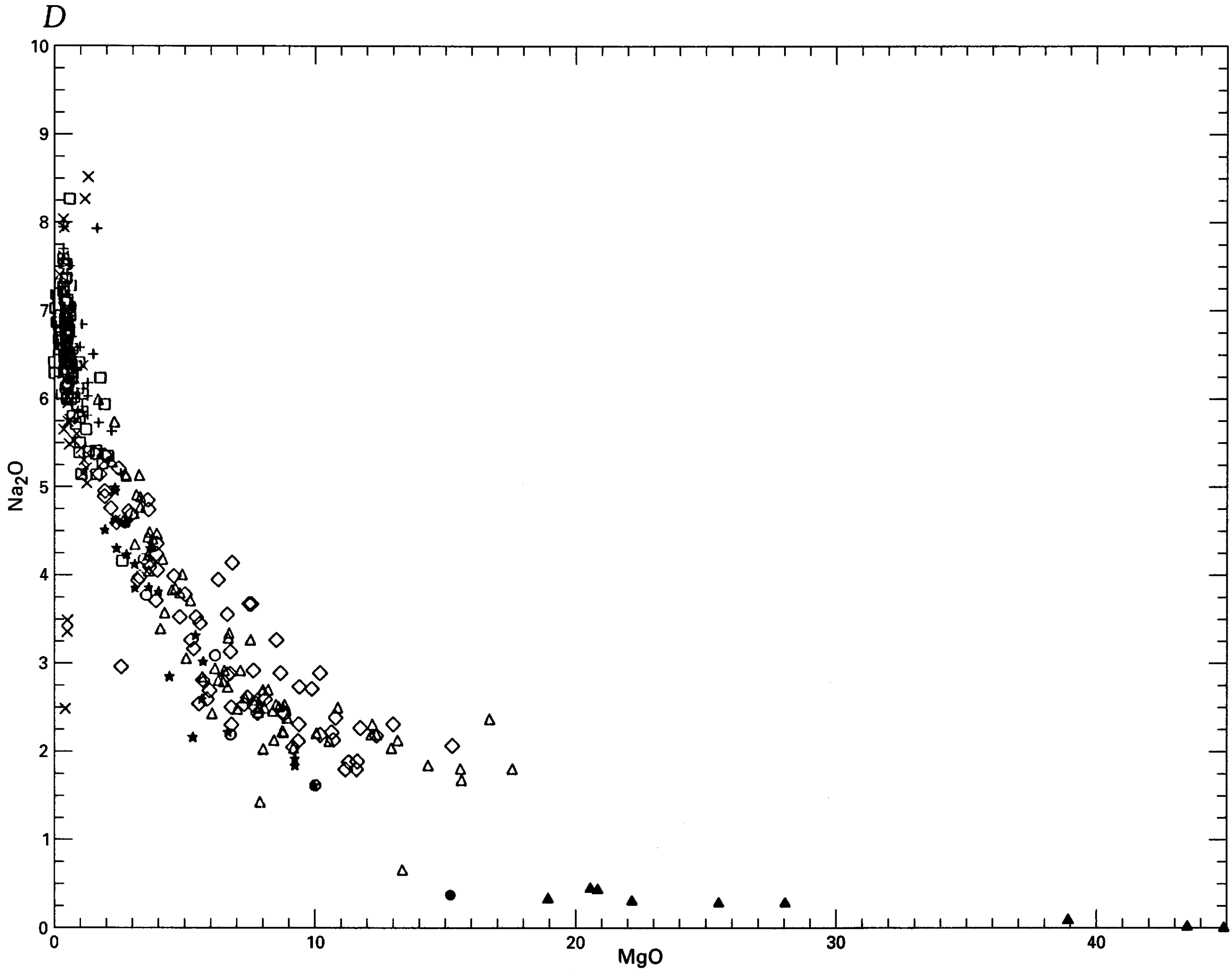

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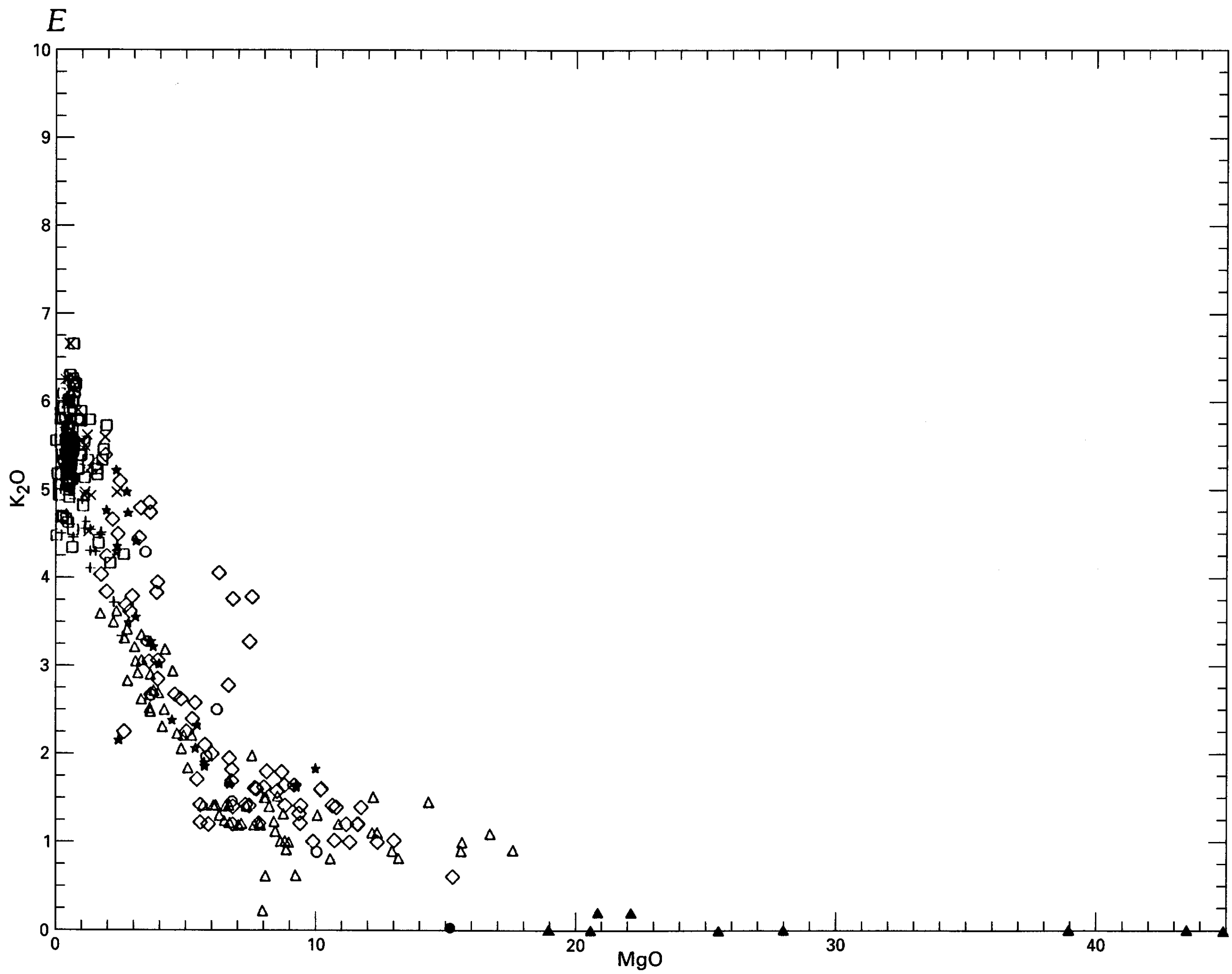

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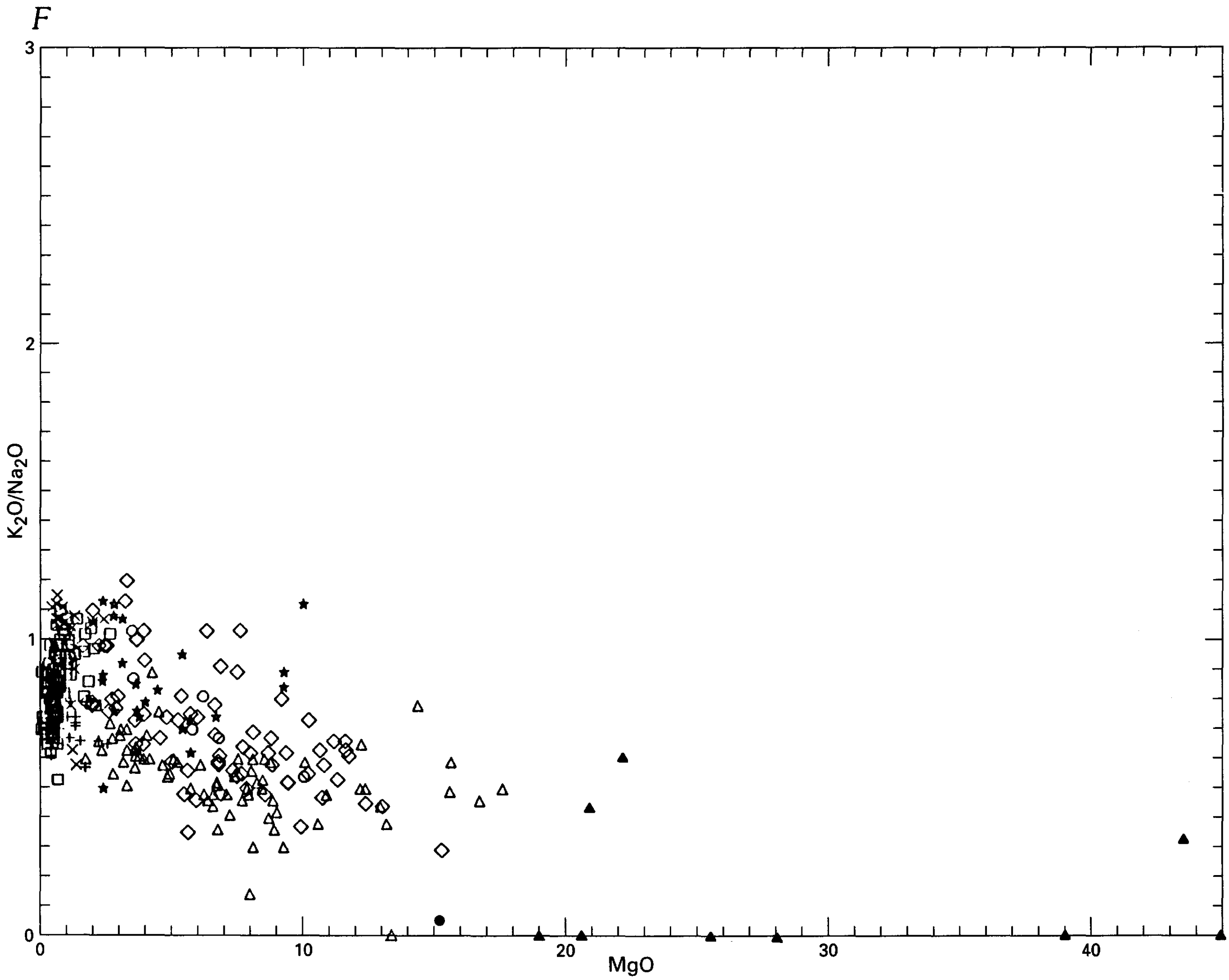

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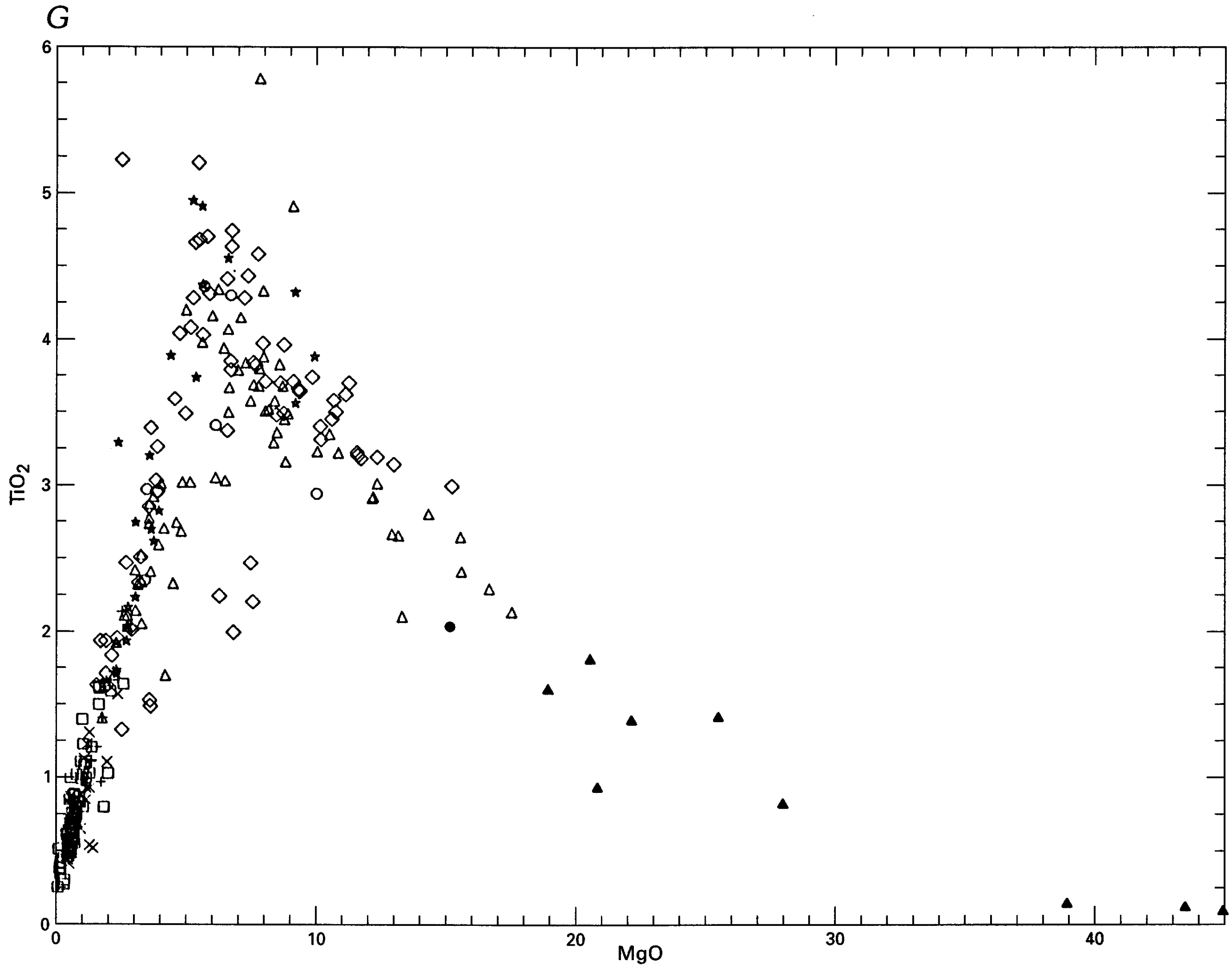

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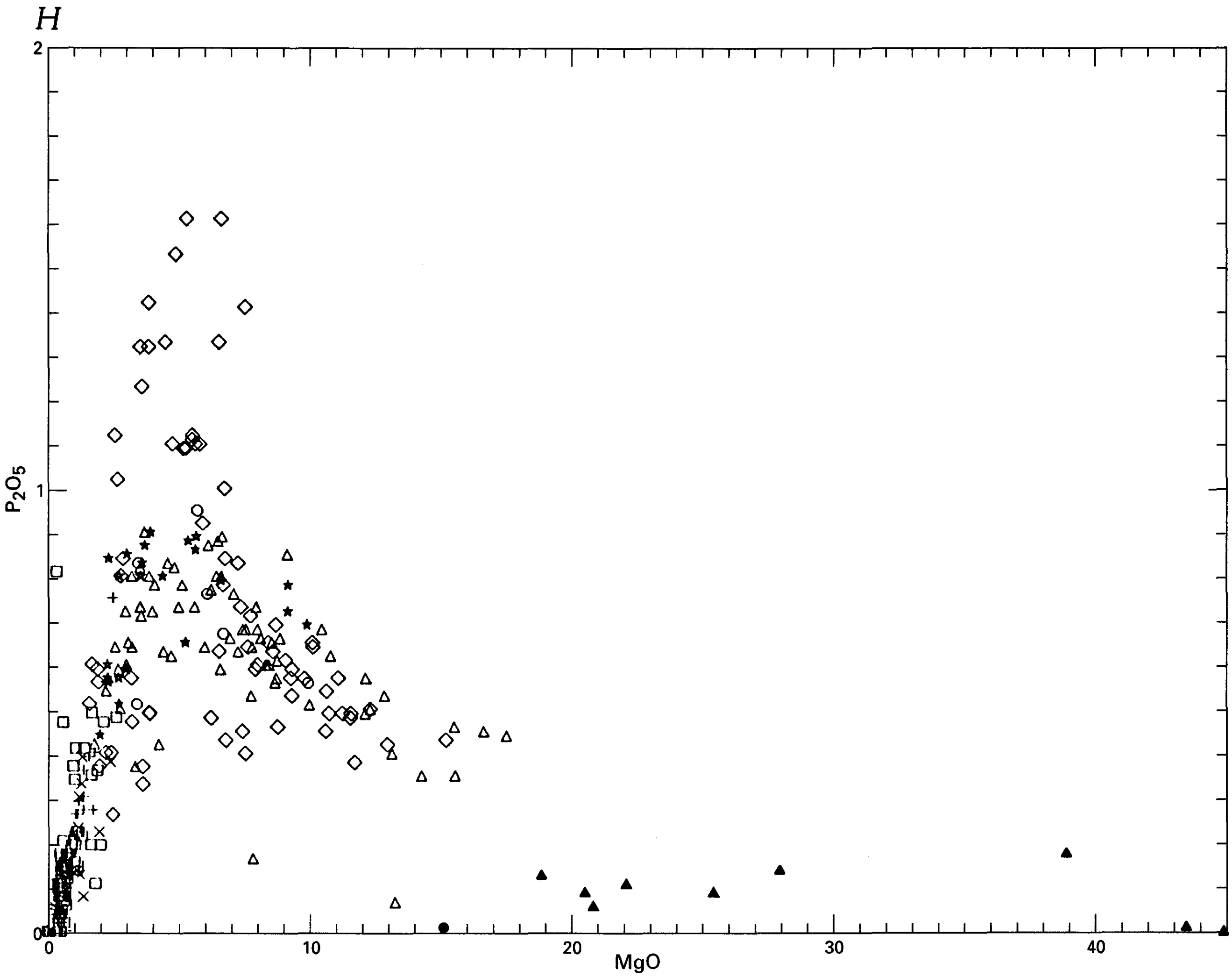

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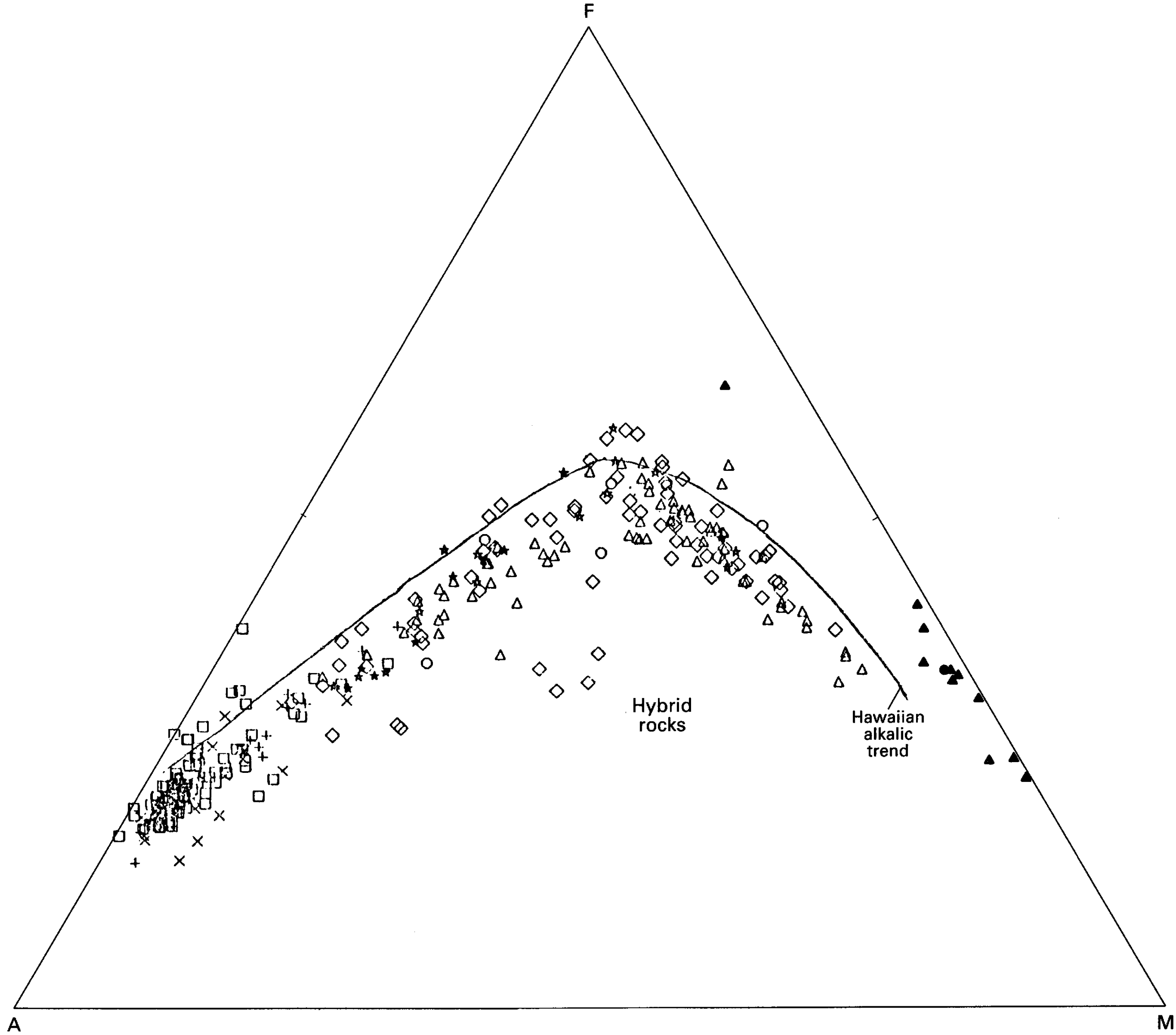

Figure 13. AFM ternary diagram. A, Na_2O+K_2O; F, $FeO+0.9*Fe_2O_3$; M, MgO. Symbols: □, trachytes and tristanites of Agua de Pau volcano; +, trachytes and tristanites of Sete Cidades volcano; ×, trachytes and tristanites of Furnas volcano (●, ultramafic or mafic xenolith); ◇, mafic rocks on the flanks of Agua de Pau volcano; △, mafic rocks on the flanks of Sete Cidades volcano (▲, ultramafic or mafic xenolith); ★, mafic rocks on the flanks of Furnas volcano; ○, Nordeste volcano.

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