A QUANTITATIVE STUDY OF FIVE THOUSAND YEARS OF VOLCANISM ON SAO MIGUEL, AZORES

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[Plates 1–4]

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The activity of the three stratovolcanoes on the island of Sao Miguel is documented by tephrochronology, and during the past 5000 years a total of some 57 volcanic eruptions have taken place, mostly of magnitudes 4–6 on Tsuya's scale. Approximately half were trachytic, and half basaltic. Each stratovolcano has a caldera within which each has had one historic eruption. The trachytic eruptions were predominantly explosive, and most took place from vents situated within the calderas. Isopach and isograde maps of most of the resulting pumice fall deposits are given. The basaltic eruptions produced both lava flows and pyroclastics, and isopach and isograde maps are given for some of the main fall deposits. The Agua de Pau volcano has had particularly large explosive eruptions, several of them (including Fogo A, the largest in the past 5000 years) being of plinian type.

The output of the three volcanoes over the 5000 years is equivalent to 4.6 km^3 of dense rock, at which rate the exposed parts of the volcanoes could have accumulated in 150000 years. At least half of the erupted material is trachytic, a proportion typical of the entire accessible parts of the volcanoes.

The 50 known eruptive vents of the past 5000 years are distributed in a zone 55 km long by 8 km wide which may lie above a major fracture zone. Some eruptive fissures trend obliquely across this zone, suggesting right-lateral movement along the fracture. Basaltic eruptions were confined to a much smaller area than in the preceding millennia perhaps due to the formation, at the time of the great Fogo A eruption 5000 years ago, of a broad trachytic magma chamber underlying the Agua de Pau and Furnas volcanoes which basaltic magma has since been unable to penetrate.

1. Introduction

Sao Miguel, the largest and most populated island in the Azores, has three active stratovolcanoes, Sete Cidades, Agua de Pau, and Furnas (figure 1), which have a long record of explosive eruptions. The resulting trachytic pumice fall deposits thickly mantle the slopes of the volcanoes and account for more than half of their visible bulk.

The wet-temperate climate of the Azores is such that luxuriant vegetation and soil soon develop on and effectively anchor any newly erupted pyroclastic material. The result is that a remarkably complete record of the explosive eruptions is preserved, in which the successive deposits are clearly demarcated by the soil horizons which separate them. The island is therefore ideal for tephrochronological study.

The technique of tephrochronology has hitherto been widely used only in Iceland, Japan and New Zealand. It can be more than simply volcanic ash stratigraphy, because the measurements of thickness, grain-size and constitution of the deposits which are necessary for correlative purposes can be of great volcanological value in studies on the style and scale of activity. It is the volcanological aspect which is the prime concern of this account.

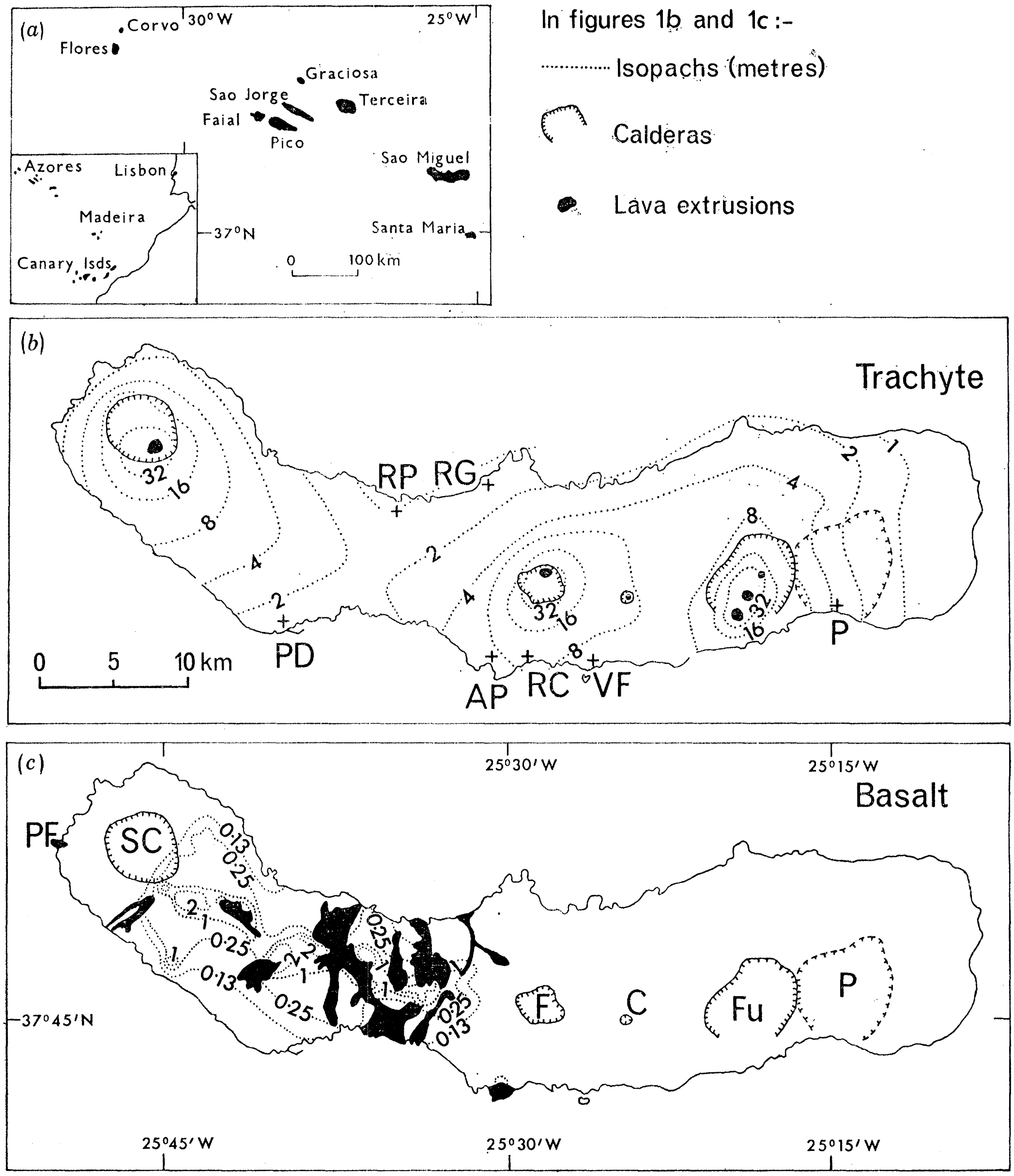


FIGURE 1 (*a*). Location map of Sao Miguel. (*b*) Map of Sao Miguel showing isopachs for the total thickness in metres of trachytic pumice deposits formed during the 5000 year period and also (solid black) the trachyte lava extrusions formed during the same period. Some of the principal towns are indicated (AP, Agua de Pau; P, Povoacao; PD, Ponta Delgada; RC, Ribeira Cha; RP, Rabo de Peixe; RG, Ribeira Grande; VF, Vila Franca do Campo). (*c*) Isopachs for the total thickness in metres of basaltic scoria deposits formed during the 5000 year period and also (solid black) the basaltic lava extrusions formed during the same period. The calderas are indicated (SC, Sete Cidades; F, Fogo; Fu, Furnas; P, Povoacao; also C, the Congro crater). PF, Ponta da Ferraria lava delta.

This paper, in conjunction with an earlier one describing the Fogo A and Fogo 1563 deposits (Walker & Croasdale 1971), documents the volcanic activity over the past five millennia of Sao Miguel's history. Fogo A is a particularly large and extensive deposit which gives a ^{14}C age of 4550 years B.P., and is a key to the unravelling of the recent volcanic history of the island. With a few exceptions this paper is concerned only with the events including and post-dating the Fogo A eruption.

The three volcanoes are roughly equal in size; each is 10–15 km in diameter at sea level, rises to 800 or 900 m, and has a volume above sea level of the order of 70 km^3. Each has a caldera, that of Sete Cidades being the finest, and Lagoa do Fogo (on the Agua de Pau volcano) the smallest and least well shaped. A fourth volcano which lies at the eastern end of the island is believed to be long extinct, and contains rocks as old as 3.25 million years (Abdel-Monem, Fernandez & Boone 1975).

Explosive trachytic eruptions in the period under review have taken place from vents in each of the three calderas, and from the maar-like crater of Lagoa do Congro on the eastern side of the Agua de Pau volcano. At least one explosive eruption has taken place in each caldera since the island was settled in the mid-fifteenth century. During the past 5000 years many basaltic eruptions have also taken place from vents located on the flanks of the two western volcanoes, notably in the low-lying ground between them referred to in this paper as the 'waist'. Several basaltic eruptions have also taken place since the settlement. Present activity is confined to fumaroles, hot springs and carbonated cold springs on Agua de Pau and Furnas.

The nine main islands in the Azores trend west northwest for 600 km and stand astride the Mid-Atlantic Ridge; they are related to the East Azores Fracture Zone which intersects the Ridge in this area. This zone is seismically very active and several destructive earthquakes occur in it each century. Five islands have had volcanic eruptions since the time of the settlement, and all are volcanic in origin, the rocks belonging to an alkali basalt/trachyte suite. All but the deeply eroded island of Santa Maria have one or more large Quaternary strato-volcanoes, the highest being the striking 2300 m cone on Pico, the others all having calderas. In addition, there are more than one thousand basaltic scoria cones in the Azores, many of them aligned along fissures, and several islands have off-shore ash-rings or tuff-rings due to surtseyan-type eruptions in shallow water.

The Servicos Geologicos de Portugal has published a geological map of Sao Miguel in two sheets on the scale 1:50000 (Zbyszewski, Almeida, Ferreira & Assuncao 1958; Zbyszewski, Ferreira & Assuncao 1959). There is an extensive literature on the geology of Sao Miguel, the relevant parts of which are referred to in the text. Good general accounts are given by Branco, Zbyszewski, Medeiros & Almeida (1957), Assuncao (1961), Jeremine (1957) and Zbyszewski (1961), and the historic volcanic activity is summarized by Weston (1964) and Machado (in Van Padang *et al.* 1967). The geology of a deep drill hole put down in 1973 is summarized by Muecke *et al.* (1974). The general tectonic setting of the Azores has been discussed by Krause & Watkins (1970).

The pyroclastic deposits are here named after the caldera or vent from which they originated, and where several came from the same source they are designated A, B, C . . . in sequence upwards from the arbitrary base-level of Fogo A (figures 2 and 3). The following account describes firstly the trachytic deposits of each of the three volcanoes, and secondly the basaltic scoria fall deposits which are normally accompanied by lava flows.

Three contoured maps are given for each fall deposit to show the thickness and the average maximum diameters of the three largest pumice and the three largest lithic clasts seen at each exposure. Samples from each deposit have been sieved, and frequency curves are given for a selection of these samples separated into their principal components (pumice, crystals and lithic fragments) by using the same procedure as adopted for Fogo A.

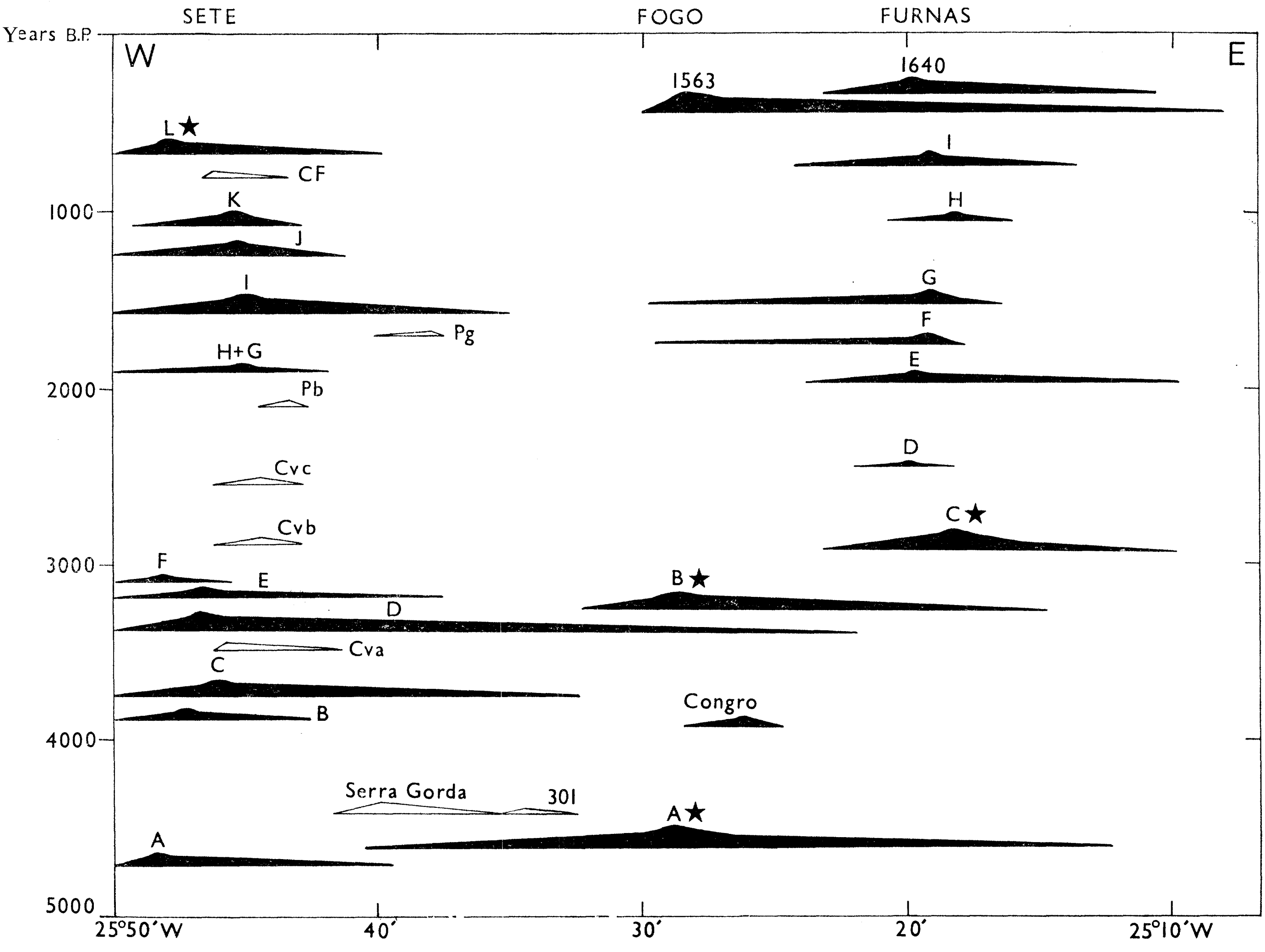


FIGURE 2. Diagram summarizing the chronological sequence of explosive eruptions on Sao Miguel during the past 5000 years. The width of the black bands show the approximate west to east extent of trachytic pyroclastic fall deposits and the thickness of each bar is crudely proportional to the thickness of the deposit. Stars indicate deposits for which radiocarbon ages are available. The open bars show some of the main basaltic pyroclastic fall deposits.

This paper is based on field work carried out between 1967 and 1971, by Booth on Sete Cidades and by Croasdale and Walker on the other two volcanoes. Age determinations on plant remains associated with the pyroclastic deposits have been made on seven samples by the Birmingham University Radiocarbon Laboratory (Shotton & Williams 1971, 1973; Shotton, Blundell & Williams 1968, 1969, 1970). Chemical analyses of samples collected by the authors have been made by B. M. Gunn (personal communication). The chemical characteristics of the volcanic rocks of Sao Miguel are discussed by Schmincke & Weibel (1972), and Schmincke (1973).

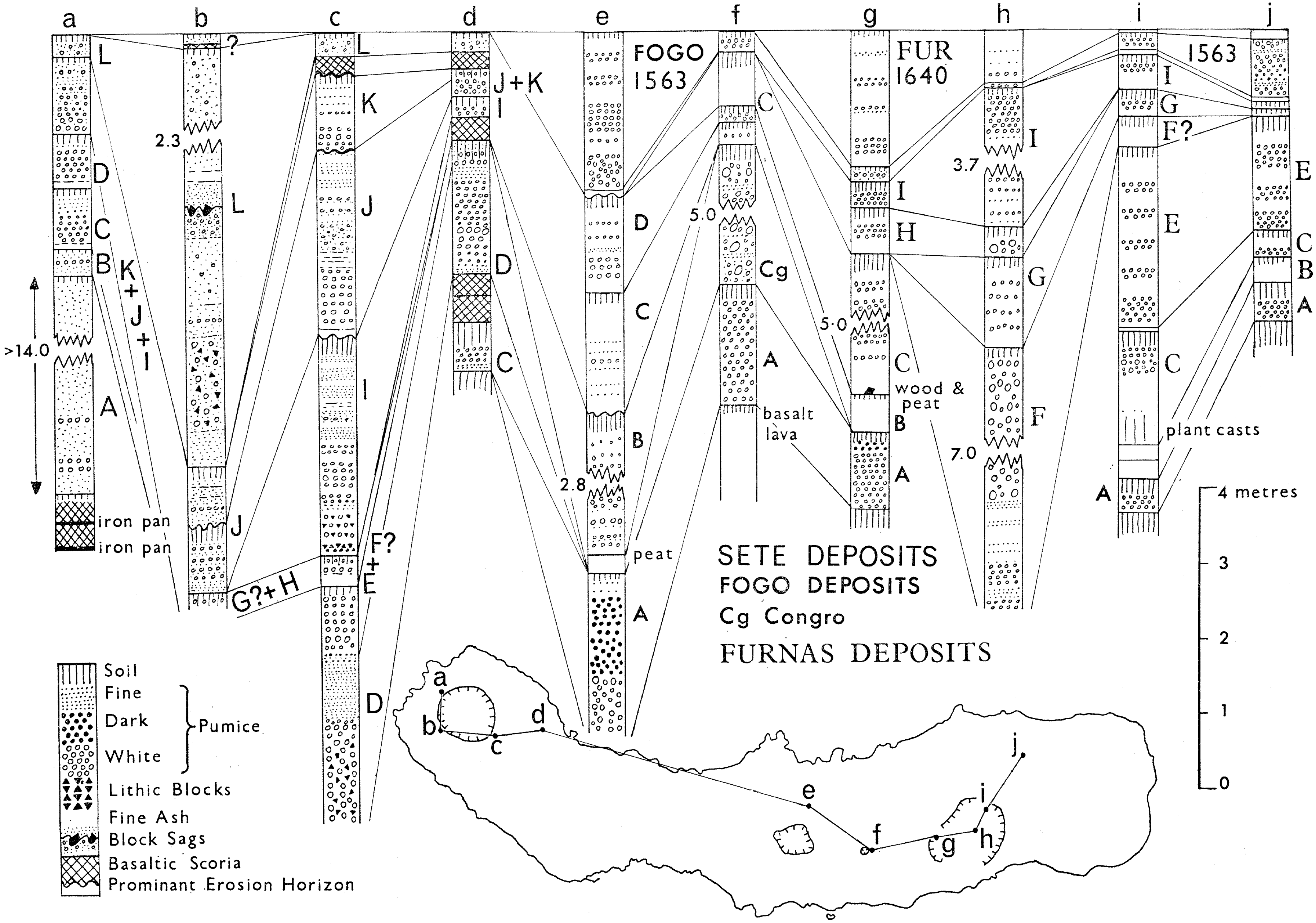


FIGURE 3. Selected sections showing stratigraphic successions and summarizing depositional features of the pyroclastic fall deposits of the past 5000 years. The three styles of lettering employed for the deposits identify the three source volcanoes. Location of the sections are shown on the map at the bottom of the figure.

2. The activity of the Sete Cidades volcano

The Sete Cidades volcano has a long record of prehistoric explosive trachytic eruptions and one possibly took place in the caldera in 1444. In addition three eruptions, presumably basaltic, took place in the sea off the western coast of Sao Miguel in 1638, 1682 and 1811, and one may have taken place on land in 1713. No fumaroles or solfataras can be seen today.

The caldera of Sete Cidades volcano is excentric, and has a diameter of 5 km and steep walls up to 550 m high. An incomplete ring of six cratered cones occurs within it, and the two main lakes (Lagoas Azul and Verde) on the caldera floor may in part occupy two other craters to complete the ring. These craters are post-caldera eruption centres from which showers of trachytic pumice and ash have thickly mantled the surrounding countryside. Two, Lagoa de Sao Tiago (figure 27, plate 1) and Lagoa Rasa, cut through an extrusive trachyte dome. Two of the deposits (Sete A and L, the latter related to the dissected ash-ring of Caldeira Seca, figure 28, plate 1) are unusually fine-grained and poorly sorted and are thought to have been erupted in a lake.

The Fogo A pumice, the arbitrary base-level for the present study, is seen as a thin bed on the easternmost slopes of the volcano where it rests on a particularly thick red-brown clay soil. This soil is widespread and distinctive, not only because it is unusually thick – it generally exceeds 1 m – but also because it is, in part, rich in feldspar crystals of platy habit up to 5 mm in size.

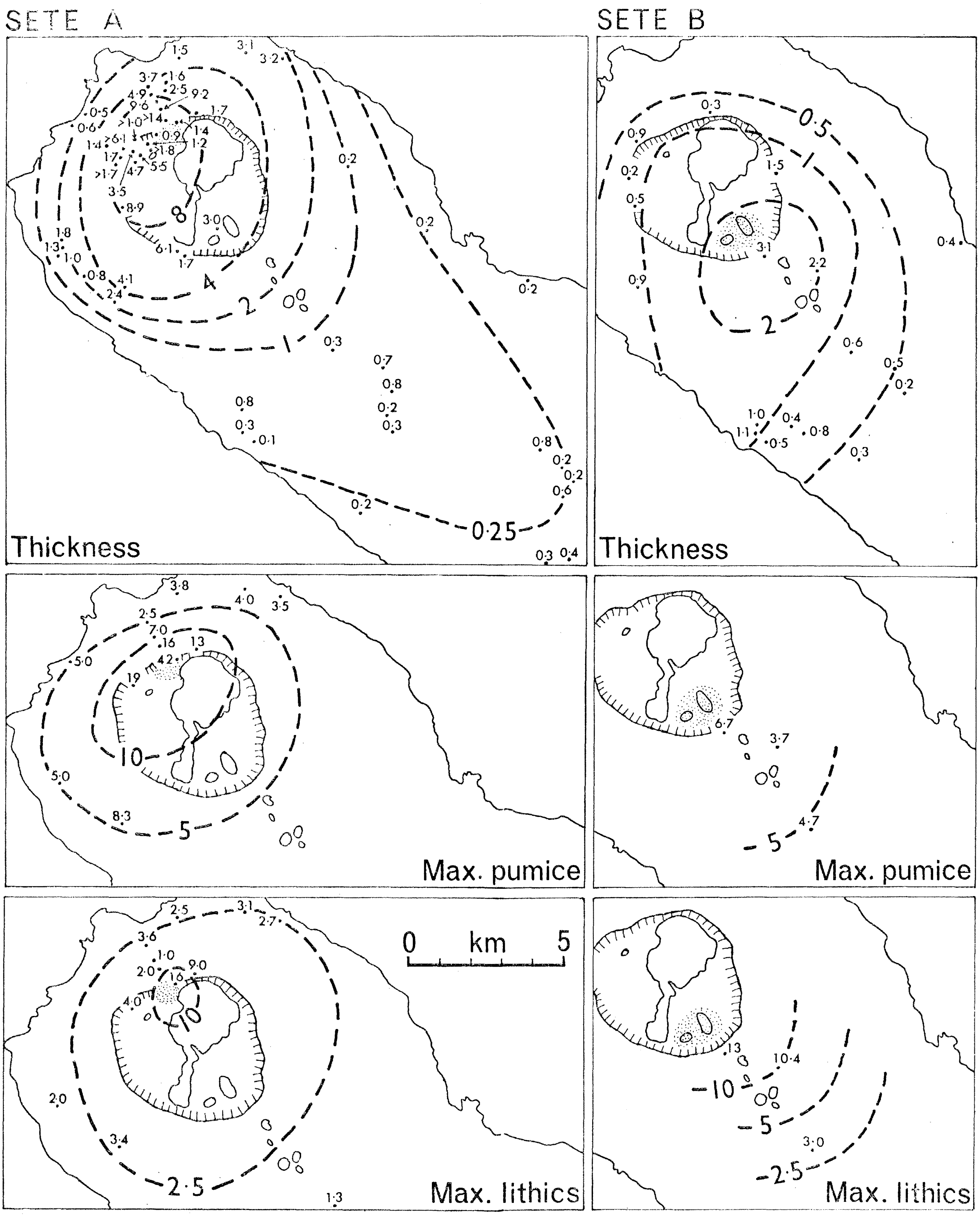
This study embraces the 12 trachytic deposits above this soil, designated Sete members A–L in chronological sequence. For only one, Sete A, is the age relative to Fogo A in doubt; the second, Sete B, rests on Fogo A. All 12 have originated within the caldera, and for some it is possible to identify their source crater. These deposits fall naturally into six groups separated by thick soil horizons indicating long repose periods. Within each group the soils between members are thin, and indicate closely spaced eruptions. These groups are described below in chronological order.

(a) *Sete A*

The first group is represented by a single ash deposit. It is magnificently exposed on the northwest rim of the caldera and along sunken roads running from there towards the coast, where it has a maximum thickness of more than 14 m. The maps (figure 4) indicate that the source is likely to be the Seara crater, though it could be a submerged vent in Lagoa Azul to the east. Near source the ash is distinctive on account of its unusually fine-grained, unsorted and ill-stratified nature, its grey-white colour, and the abundance of obsidian fragments in it. On the coastal road north of the caldera it is better sorted and shows normal grading. Locally it rests on two basaltic scoria deposits from nearby scoria cones.

(b) *Sete B and C*

These two members comprise the second group (figures 4 and 5). Of the two, C is the larger and more extensive and is traceable to as far as 22 km east southeast of the source, Lagoa Rasa. Where the deposits are thin the soil at the top embraces the entire thickness of C and part of B and the two cannot then be reliably separated. B is mostly concealed by younger deposits and the maps (figure 4) are therefore based on scanty data. The source of B is uncertain, but is probably either Lagoa Rasa or the Lagoa de Sao Tiago.



FIGURES 4–16. Dispersal maps of the principal pumice fall deposits. Three maps are given for each deposit: upper (thickness), thickness in metres; middle (max. pumice), average maximum diameter (in cm) of the three largest pumice clasts; lower (max. lithics), average maximum diameter (in cm) of the three largest lithic clasts. The stippled area indicates the probable location of the vent, and the hatched line indicates a caldera margin. Several lakes, both inside and outside the calderas, are also shown; most of them occupy craters. Grain size frequency curves (grain size given on a phi scale; $\phi = -\log_2 m$, where m is the grain size in mm) are given of selected sieve samples of some deposits from locations shown on one of the maps. Some of the frequency curves are subdivided to show the proportions of pumice (stippled), crystals (blank) and lithic fragments (black) for all but the finest fractions. The column of figures given with the frequency curves give: (top) sample number; (middle) median diameter in phi units; and (bottom) graphic standard deviation in phi units.

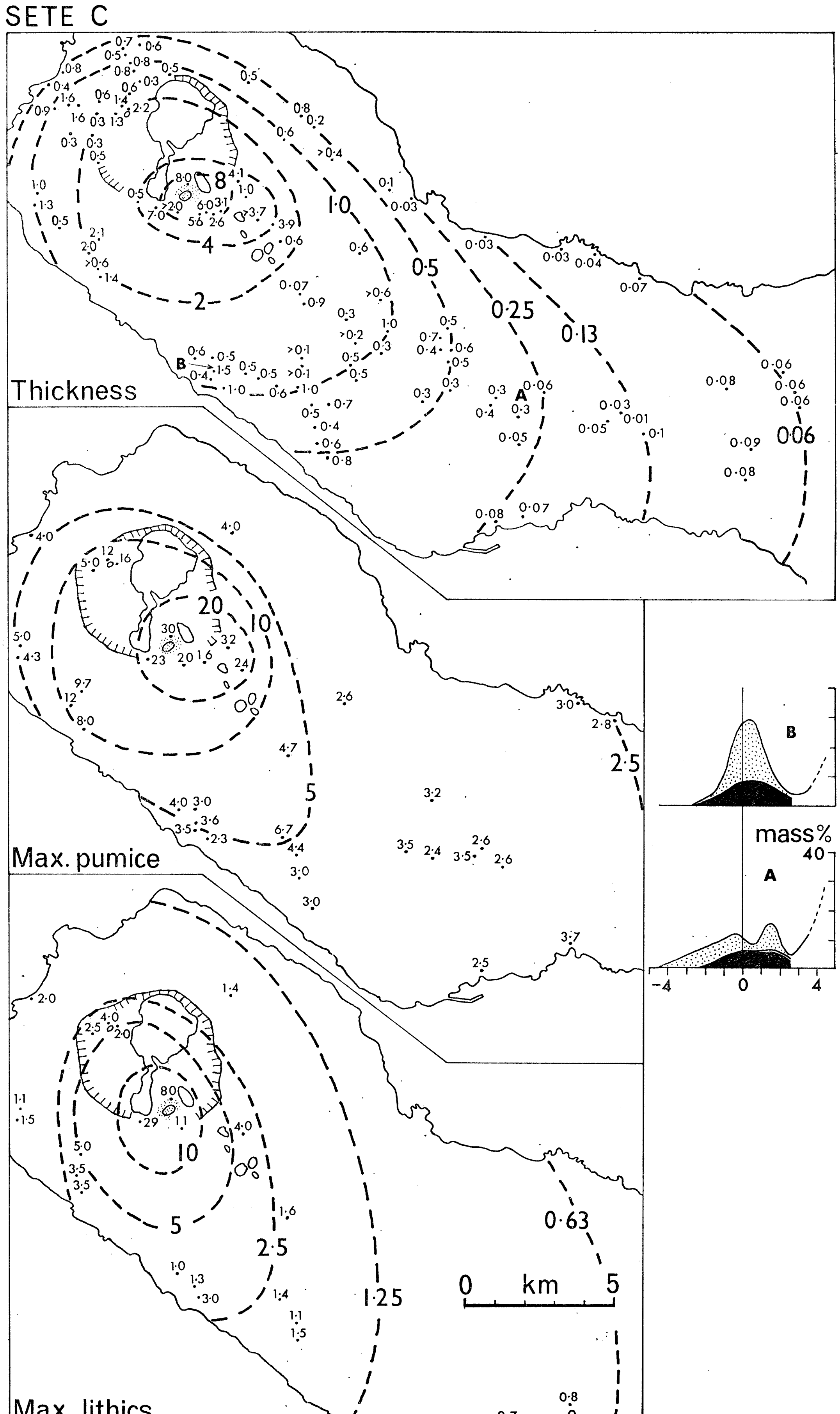

SETE C
Thickness
B
A
8
4
2
1·0
0·5
0·25
0·13
0·06
Max. pumice
20
10
5
2·5
Max. lithics
10
5
2·5
1·25
0·63
0 km 5
B
A
mass%
40
−4
0
4

Figure 5

In a track southwest of the caldera, B is 0.9 m and C is 2.0 m thick and the two are separated by a red gritty soil. B is well stratified, shows normal grading, and is quite rich in lithics, while C shows reversed grading, is very rich in lithics, and is on the whole finer-grained, with a well-bedded and very fine-grained top. The pumice in B is moderately porphyritic, in C only slightly so. In the area north of Ponta Delgada, B is the more prominent of the two and is a 'millet-seed' ash rich in crystals and lithic fragments, while C has been converted to a brown soil containing layers of creamy-white and partially decomposed pumice. On the coastal road northwest of the caldera where the group is 0.8 m thick, B is very thin and fine-grained, and C has a well-defined bed of pumice resting on the finer ash.

(*c*) *Sete D, E and F*

The third group comprises three members, D, E and F, which have a combined maximum thickness of 10 m between Lagoa de Sao Tiago and Lagoa Rasa and thin to 0.6 m 8 km southeast of the source (which is believed to be one of these craters). D (figure 6) is by far the largest and most extensive and is traceable to near Vila Franca, 33 km from source, where it is 0.1 m thick and contains pumice fragments up to 1 cm in size. E and F are seen in only a few sections.

D is a plinian deposit, very pumice-rich and coarse-grained, and fairly well stratified where thickest. In good road sections 4 km east of the source, where it is the most prominent pumice deposit seen, it is reversely graded and has a fine-grained and thinly stratified lower part and a coarse pumice middle and upper part. Reversed grading persists into the 'waist' region. The pumice is white and porphyritic.

The next member, E, is seen in scattered sections south of the caldera, where it is an even-grained and rather poorly stratified lithic-rich deposit in which the pumice is only slightly porphyritic. F has been seen only in three sections on the western rim of the caldera, where it is up to 0.16 m thick and contains pumice up to 1.5 cm in size.

(*d*) *Sete G and H*

The fourth group is in most places represented by a single member, G, but on the south-eastern rim of Sete Cidades caldera it comprises two, G and H, totalling 0.95 m thick and separated by a thin soil (figure 7). G is grey and fine-grained, with an impersistent coarse pumice base resting locally upon a well-defined erosion surface. The soil at the top of G contains coarse pumice and lithic fragments, together with obsidian chips. H is grey, well-bedded, fine-grained and lithic-rich, with a coarse central layer of pumice and lithics. Obsidian fragments are conspicuous among the latter.

The two deposits have a very limited dispersal; H can be distinguished at only a few points near the caldera rim, while G thins to less than 0.2 m at a distance of 10 km south southeast of the caldera. Their source is uncertain, but it may be either Lagoa de Sao Tiago or Lagoa Rasa.

(*e*) *Sete I, J and K*

The fifth group is represented by three members, I, J, and K (figures 7, 8, and 9) which have a combined thickness of 40 m between Lagoa de Sao Tiago and Lagoa Rasa but thin to less than 0.5 m at a distance of 9 km southeast of the caldera, and less than 0.3 m at a distance of 15 km. For the most part, these pumice deposits show normal grading, are well-bedded and

SETE D

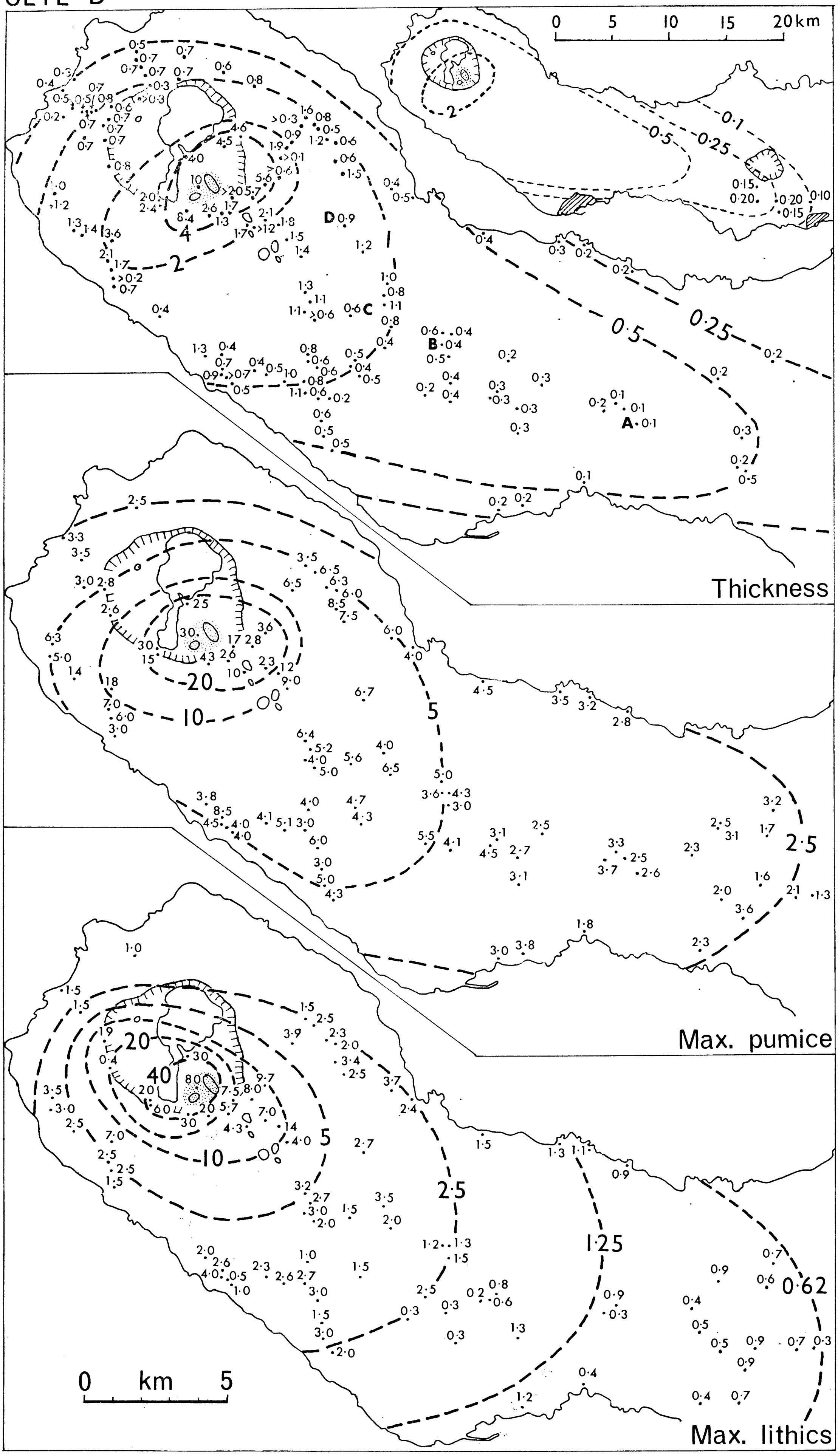


FIGURE 6. The extension of the deposit over the Agua de Pau volcano is shown on the reduced scale inset map (top right).

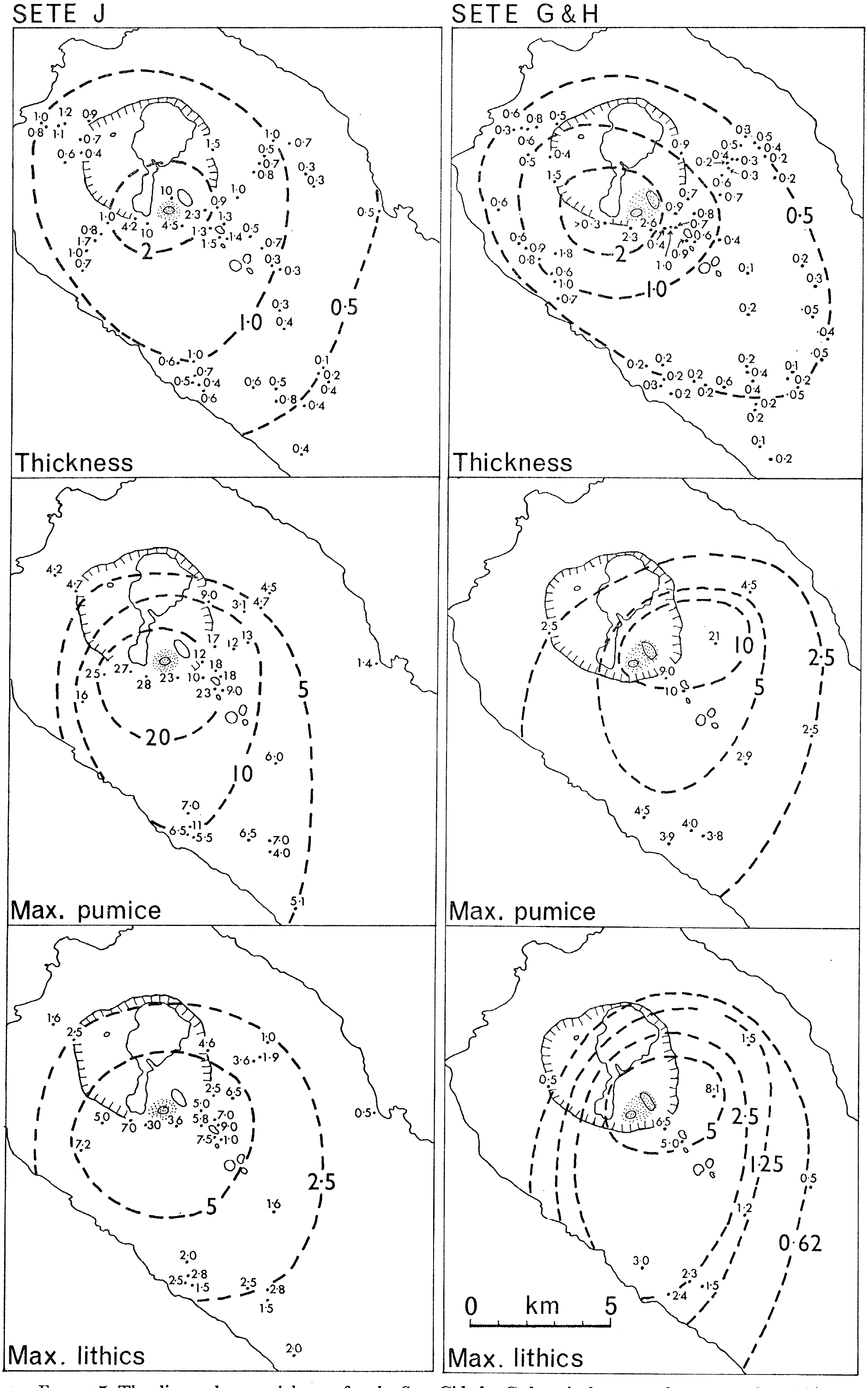


Figure 7. The dispersal maps right are for the Sete Cidades G deposit, but near the source where H is recognizable its thickness has been added to that of G.

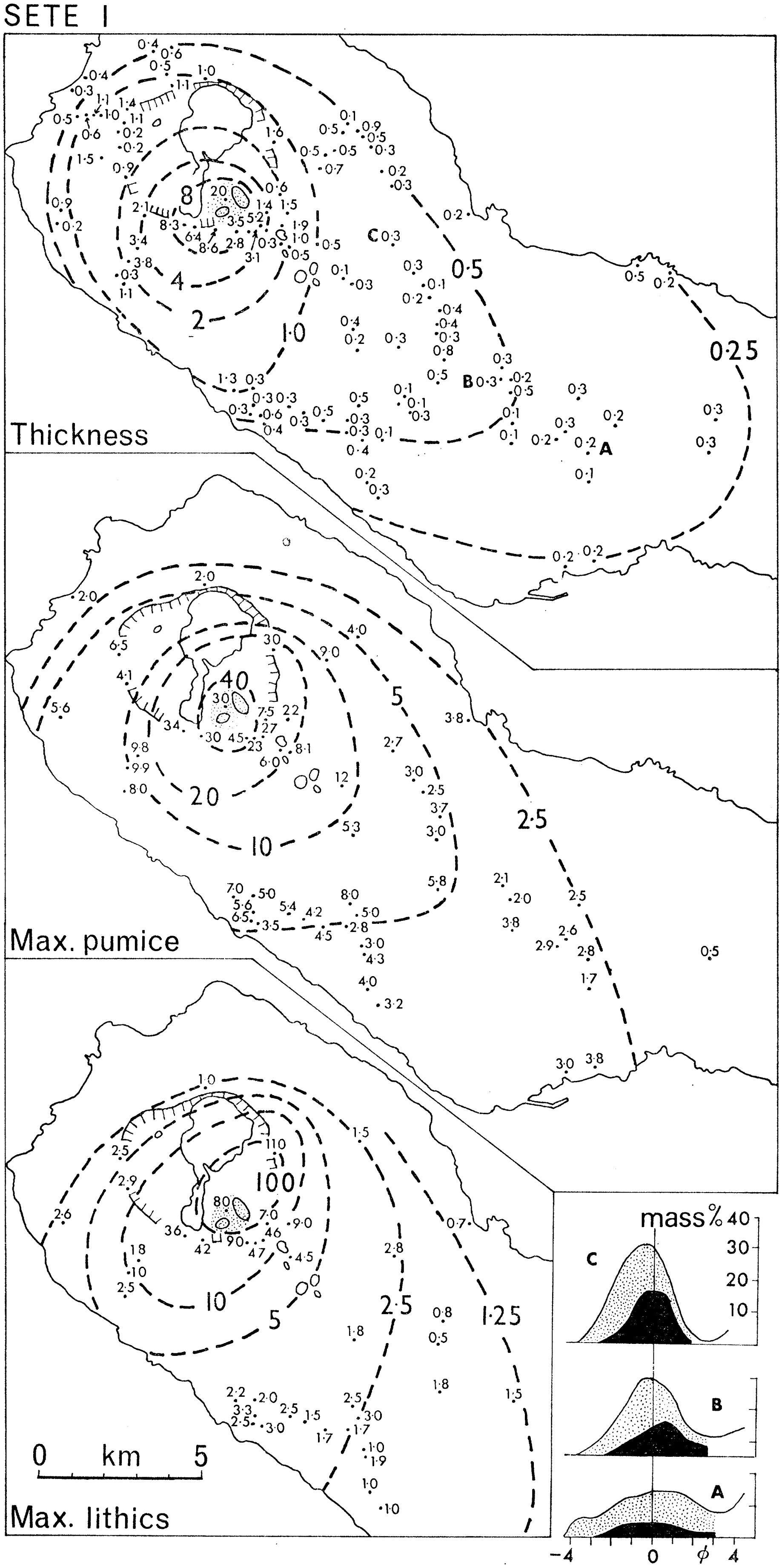


FIGURE 8

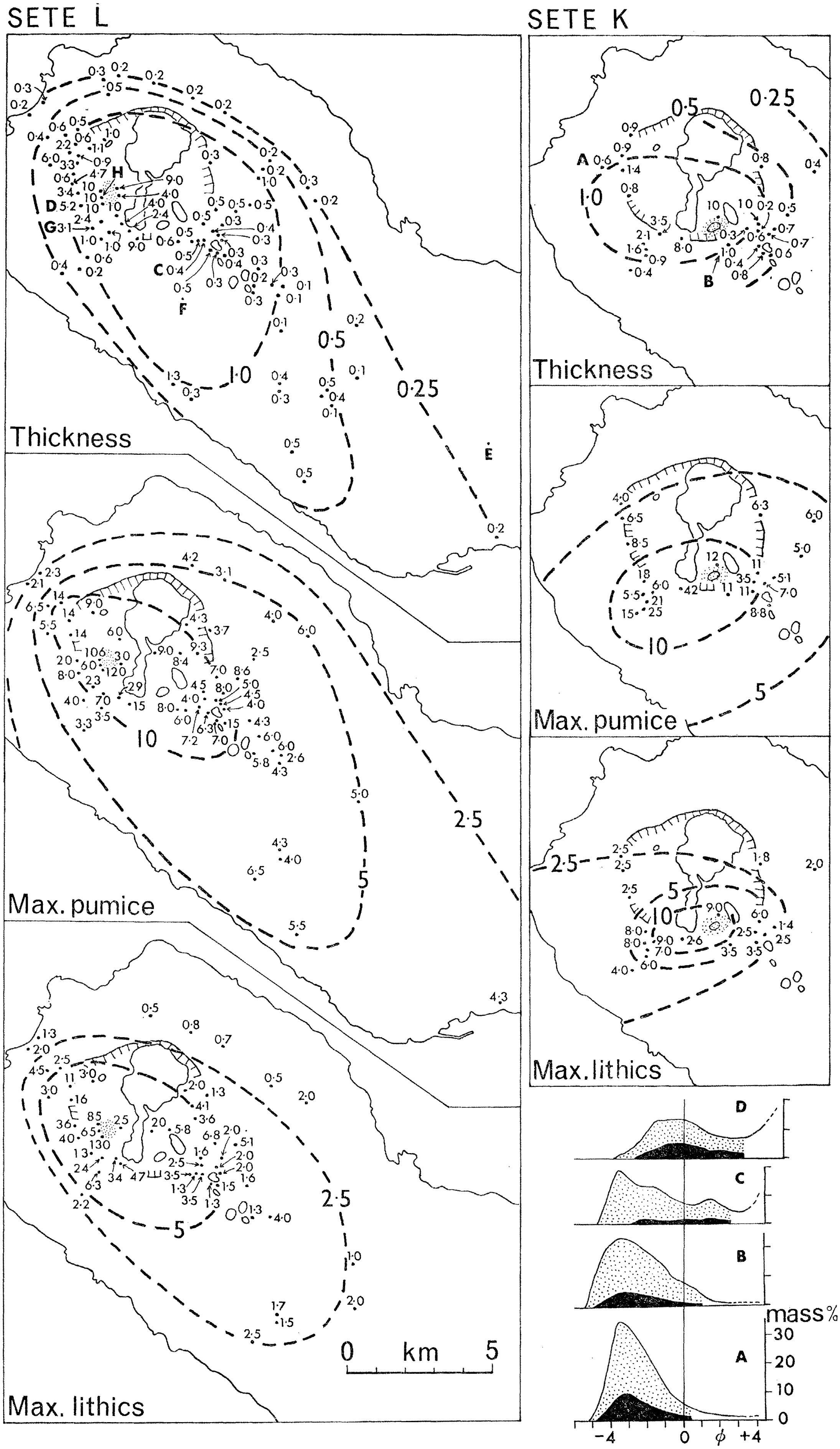

SETE L
Thickness
Max. pumice
Max. lithics
SETE K
Thickness
Max. pumice
Max. lithics
0 km 5
mass%
30
20
10
0
-4
0
ϕ
+4
A
B
C
D

Figure 9

rich in lithics. Their basal parts consist of an alternation of moderately coarse pumice and fine-grained ash beds, some of which may be rain-flushed. The pumice in I is very porphyritic, while subtle colour differences between the pumice in J and K allow them to be distinguished in the field. Prominent discordances commonly separate these members and indicate that vigorous erosion periods must have followed each eruption before vegetation had time to stabilize the loose pumice. Much of this eroded material was redeposited on the northeast slopes of the volcano as mudflows, some of which are well displayed in road sections midway down the slopes northeast of the caldera. The mudflows are not included on the isopach maps.

At Lagoa do Canario, 1 km southeast of the caldera (figure 29, plate 2), each deposit has a base rich in lithics interbedded with thin layers of clay-like white ash and overlain by a coarse pumice bed about 0.4 m thick, which in turn is overlain by well-bedded, lithic-rich deposits.

The distribution maps indicate that the source of J is Lagoa de Sao Tiago crater, and of K is Lagoa Rasa. There is insufficient evidence to determine which of these craters is the source of I.

(*f*) *Sete L*

The sixth group is represented by a single member, L (figure 9). The source is the prominent ash-ring of Caldeira Seca (figure 28), 600 m across and 100 m high, deeply gullied by erosion and with the ridges truncated by new-cut fields of pasture-land. The ash, which is well seen around the crater and on the southwestern rim of the caldera, closely resembles Sete A in being fine-grained, unsorted, poorly stratified and rich in obsidian fragments. Bands of coarse pumice are occasionally found at the base and on the rim of the caldera a coarse-grained bed with well-formed block sags lies 3 m above the base. Sporadic exposures enable the ash to be traced to a distance of 17 km southeast of the source, where it is 0.2 m thick.

Sete L is the youngest trachytic deposit recognized on the volcano. A ^{14}C age of A.D. 1287 (Birm-181, Shotton & Williams 1971) was given by plant remains in it on the flank of Caldeira Seca. Fries (1968) gives a ^{14}C age of A.D. 1100 for a core sample from the centre of Lagoa Azul. The depth of burial of the sample, about 50 cm, is less than would be expected if the material pre-dated the Caldeira Seca eruption. An eruption is doubtfully reported from this general area in the mid-fifteenth century: between 1439 and 1460 (Weston 1964), or in 1444 (Machado in Van Padang *et al.* 1967). It is possible that this eruption produced the small cone on the eastern side of Lagoa Azul.

3. The activity of Agua de Pau (Fogo) volcano

The volcano is named after the Serra de Agua de Pau, a group of hills which culminate in a rounded peak 949 m high and enclose a depression (the Fogo caldera) containing Lagoa do Fogo. The slopes of the volcano are very thickly mantled with pyroclastic deposits, five of which have been erupted in or near the caldera during the period under review. The first and most prominent is the Fogo A pumice, and the most recent is that produced by the eruption of 1563. One other fall deposit originated from the small maar-like crater of Lagoa do Congro which though it lies nearly midway between the Agua de Pau and Furnas volcanoes, is regarded as a flank vent on the former.

Lagoa do Fogo appears to occupy a line of contiguous craters which may date from the 1563 eruption. Just northeast of the lake, within the caldera, is what appears to be a trachyte dome truncated by the lake; there is such a thick mantle of 1563 pumice on it, however, that the presumed trachyte is concealed. This possibly occupies part of the vent of the Fogo A eruption. One of the post-A deposits, Fogo B, is thickest and most coarse-grained 2 km north of Lagoa do Fogo and its vent is presumably located there, outside the Fogo caldera, though no well-defined crater has been recognized.

In the following account the single deposit from Congro and three from Fogo (B, C and D) are described in chronological sequence.

(*a*) *Fogo A*

This, the first and largest deposit formed during the 5000 year period, is not further considered having been described elsewhere (Walker & Croasdale 1971).

(*b*) *The Congro deposit*

This is dispersed mainly south and east of the Lagoa do Congro crater, on the rim of which it exceeds 10 m in thickness (figure 10). In a pit (figure 31, plate 3) a short distance southeast of the crater it consists of coarse-grained pumice beds alternating with about 20 fine-grained beds, each a few centimetres thick, some of which are probably pyroclastic surge deposits. In a small roadside pit 2.5 km south southeast of the crater the deposit is much thinner though still coarse-grained, with pumice blocks up to 30 cm in size, and the number of fine-grained beds has decreased to five. The deposit is conspicuously rich in lithics. Two samples, one from each of the exposures mentioned, contain 50 % by mass of lithics, and the content is higher still off the axis of dispersal. The crater has been drilled through basalt and trachyte lavas, and the lithic pyroclastic debris appears to be of similar rocks. A small extrusive dome of dark-coloured trachyte occupies part of the crater and is thought to represent the final stage of the Congro eruption.

(*c*) *Fogo B*

The Fogo B deposit is coarsest, and attains its maximum thickness of 10 m, in an area 2 km north of Lagoa do Fogo, being widely dispersed east and north of the presumed source there (figure 11). It is a large deposit and, like A, is distinctive because small feldspar crystals of equant habit are abundant in it. It is distinguished from A by the absence both of syenite clasts (these are common in A) and of a dark-coloured pumice at the top.

Where thickest, the basal third of B is a fine-grained and very poorly sorted ash, some at least being rain-flushed. The middle third is a coarse pumice breccia rich in lithics (40 % of one sample are lithics), interrupted by a number of fine-grained beds, some of which are rain-flushed. The top third consists mostly of fine-grained bedded ashes. In an exposure 11 km east northeast of the source B is 1 m thick and mostly very fine-grained, though a thin pumice bed in the lower part contains pumice fragments up to 2.5 cm in size.

Plant remains are found at the base of B at a number of exposures, and wood from a road cutting 3 km northeast of Lagoa do Fogo gave a radiocarbon age of 3242 years B.P. (Birm-125; Shotton *et al.* 1970). A photograph of this exposure appears in pl. 1 (*a*) of Walker & Croasdale (1971); on this photograph the Fogo B deposit is labelled 2, and the beds labelled 3 and 4 are Fogo C and D respectively.

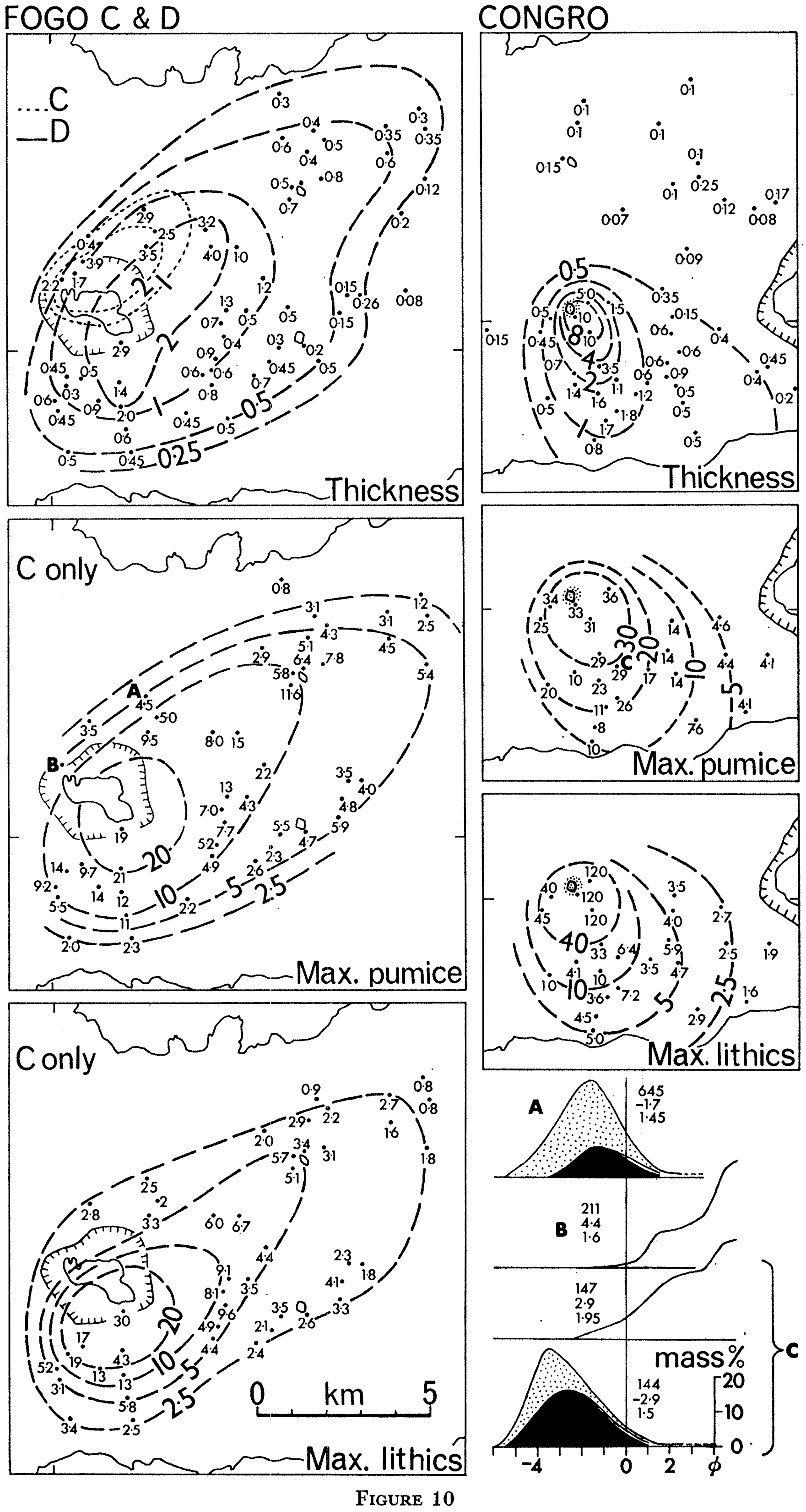

FOGO C & D
CONGRO
C
D
Thickness
Thickness
C only
Max. pumice
Max. pumice
C only
Max. lithics
Max. lithics
0 km 5
A
B
C
mass%
ϕ

FIGURE 10

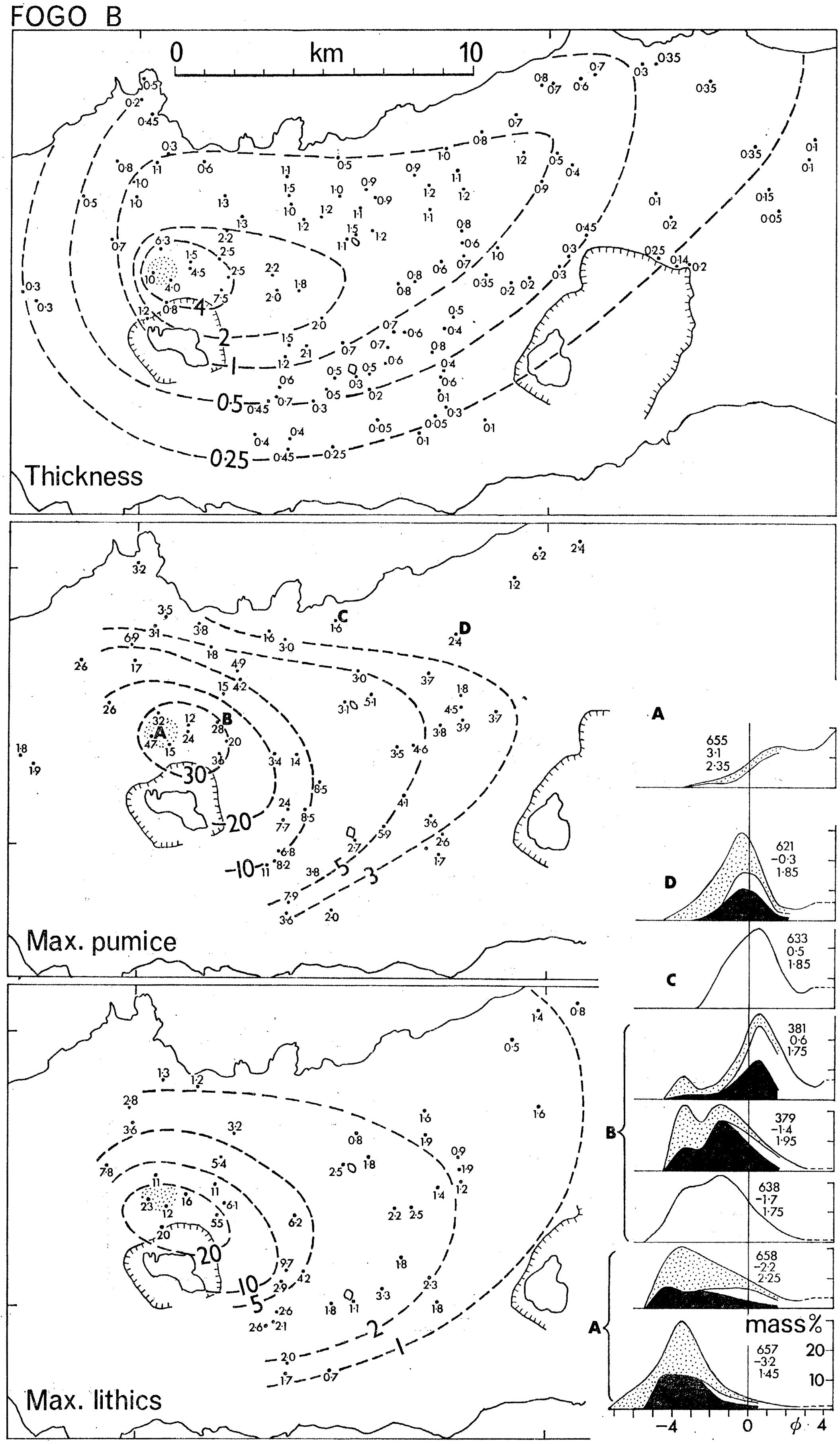


FIGURE 11

(*d*) *Fogo C and D*

Fogo C is a fine-grained ash, rich in accretionary lapilli, recognized in a few sections north of Lagoa do Fogo where its maximum thickness is 2.2 m on the northwest rim of the caldera. Figure 10 gives the approximate positions of the 1 and 2 m isopachs.

Fogo D is distinctive for two reasons. Firstly its pumice is more dense and mafic than normal, yellow or yellow-brown in colour and moderately rich in platy feldspar phenocrysts up to 5 mm and exceptionally 10 mm in size. Secondly it is very rich in lithics, and in most exposures the pumice, because of its density, is only slightly larger than the lithics. D is generally well stratified and fine-grained, although coarse beds occur at most exposures. To judge from the isopach and isograde maps (figure 10) the source is located near the southern end of Lagoa do Fogo, and may have been obliterated by the Fogo 1563 eruption.

(*e*) *Fogo* 1563

The large and well-defined pumice deposit correlated with the known eruptive event of the year 1563 has been described elsewhere (Walker & Croasdale 1971) and is not further considered here.

4. The activity of Furnas volcano

Furnas is morphologically the least distinctive of the three stratovolcanoes on Sao Miguel. It does not form a cone but is merely an elevated tract which occupies the ground between the Agua de Pau and Povoacao volcanoes. Its caldera measures 6 km in maximum diameter but is a well-defined feature only in its northern part where the walls are 250 m high. On the southern side any caldera rim is partly buried below a great thickness of young pyroclastics, and partly obliterated where cut through by the deep gorge of Ribeira Quente. To the northwest there is a probable older caldera rim situated 1 km outside the present one. The flat ground between the two rims contains near-horizontal pyroclastics and one prominent lava flow together with a group of small trachyte domes. The present caldera has a scalloped outline here and the main road from Furnas to Ribeira Grande follows the ridge between two embayments.

Young trachytic pyroclastic fall deposits are very prominent and a thickness of 20–100 m is seen in many sections. The caldera contains two well-defined ash-rings, Covu du Burra and Gaspar, and a third less well-defined one, Pico das Marcondas. Each is a moated structure with a central extrusive dome of trachyte. Part of the village of Furnas lies in a flat-floored depression which could be an explosion crater. The latest eruption was that of Cova da Burra in 1640, and numerous fumaroles occur in and south of the caldera (see figure 24*c*).

The Fogo A pumice, seen in a few exposures within the caldera and in many around the rim, forms a datum which permits the unravelling of the pyroclastic sequence, and the Fogo B and 1563 pumice deposits are also spread partly across the Furnas volcano. A total of 17 different trachytic pyroclastic fall deposits have been identified above Fogo A, of which ten are due to explosive eruptions within the caldera and are called the Furnas A–J members in sequence upwards. These ten are described below. At least two are accompanied by trachyte extrusive domes. There is no evidence that basaltic eruptions took place anywhere on the volcano during this period.

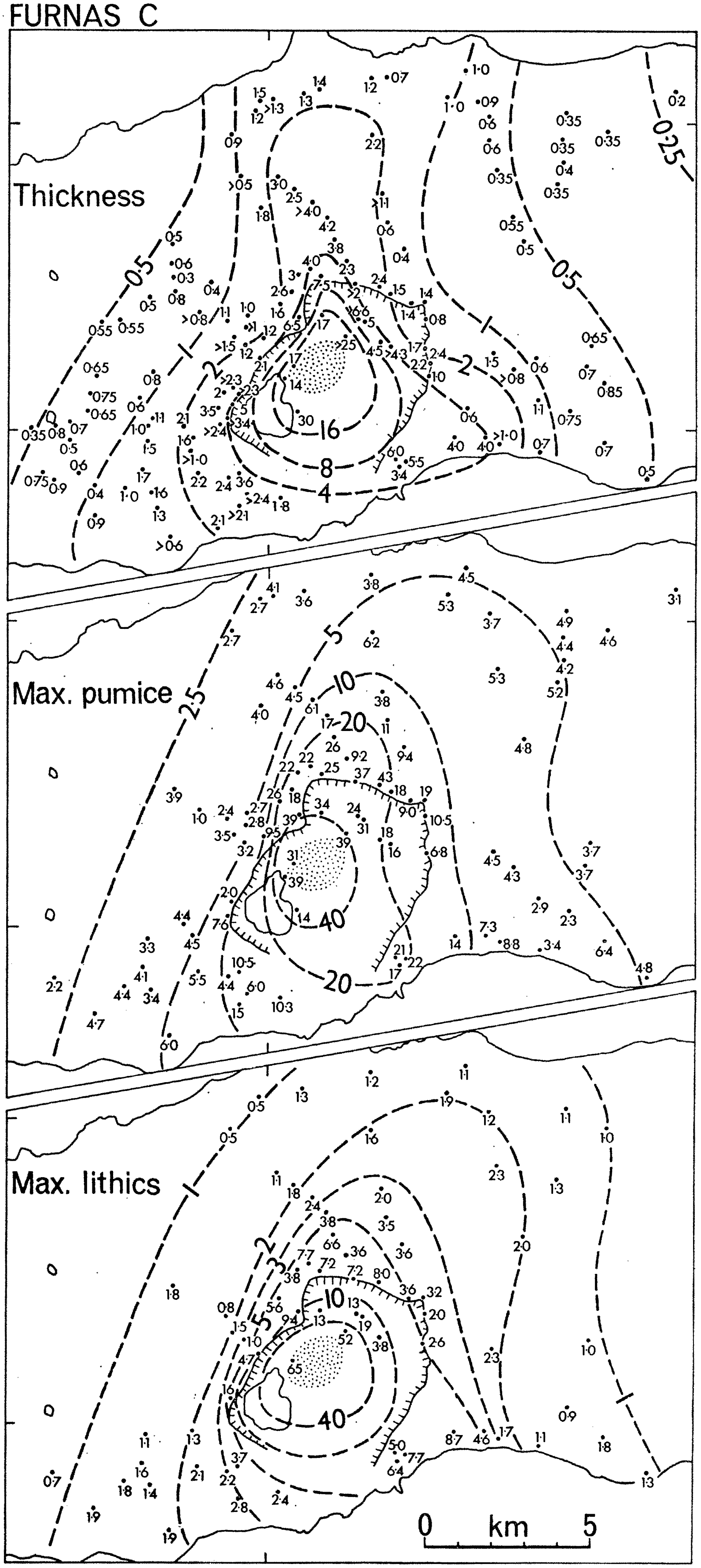

FURNAS C
Thickness
0·25
0·5
2
4
8
16
Max. pumice
2·5
5
10
20
40
Max. lithics
1
2
3
5
10
40
0 km 5

FIGURE 12

(a) *Furnas A and B*

These two thin and fine-grained deposits, locally separated from Fogo A by a thin crystal-rich ash identified as Fogo B, are both seen in the northern part of the caldera floor where their combined thickness exceeds 2 m. In other exposures only one occurs and it is not certain which of the two it is. For example a single ash 1.4 m thick containing pumice up to 2.5 cm in diameter is seen northeast of Ribeira Quente. The ash seen north of the caldera is normally a sticky grey clay which in places carries vertical, limonite-stained tubular structures interpreted as the remains of buried grass stems. On the caldera rim west of Lagoa das Furnas the ash contains rootlets and has wood fragments at the top buried by the Furnas C ash, and a ^{14}C age of 2900 years given by a sample of this wood (Birm-225; Shotton & Williams 1971) dates the succeeding deposit, C.

(b) *Furnas C*

This, the largest Furnas member, is widely dispersed and a thickness of 2 m persists almost to the north coast (figure 12). It is well stratified (figure 33, plate 3) and consists of an alternation of coarse trachytic pumice and fine ash beds, the latter often rich in accretionary lapilli and regarded as rain-flushed. The pumice is practically non-porphyritic, and loose sanidine crystals are sparse. A fine grained and often argillized layer 0.5–1.0 m thick generally occurs at the base and usually contains limonite-stained vertical tubular structures (similar to those in the preceding ash); there is some doubt as to whether it is a part of C or another ash separated from it by an interval of a few years.

Traced towards Furnas village, C increases rapidly in thickness and more than 25 m is seen on the northeast outskirts beside the Ribeira Grande road, in a deep road cut into the western side of Gaspar crater, and on the north side of Lagoa das Furnas. The flat-floored depression on which part of the village is built is thought to be the crater from which C came. The form of the crater can no longer be clearly seen on the southern and eastern sides where it is thickly blanketed by younger pyroclastic deposits.

(c) *Furnas D*

This very thin ash, up to 0.3 m thick, is seen in a few exposures on the northeast rim of the caldera. It is generally rich in lithics, the maximum size of which is about 2 cm. The scanty data suggests a source within the caldera and a northerly dispersal.

(d) *Furnas E*

Member E is well stratified and closely resembles C but has porphyritic pumice. It is best seen in road cuttings around the northeast rim of the caldera, where the maximum thickness is 2.4 m, and northeast of the caldera it is locally the most prominent pumice deposit (figure 13). The exact location of the source is uncertain, but is probably Pico das Marcondas, and the trachyte extrusive dome on this hill could date from the same eruption.

(e) *Furnas F*

Member F is unusual in that lithics are more abundant than pumice, and the pumice is dark grey, denser, more mafic, and richer in phenocrysts than in any other Furnas deposit. Where thin, as in exposures on the northwestern rim of the caldera, the pumice is either thoroughly decomposed or is yellow-coloured due to weathering.

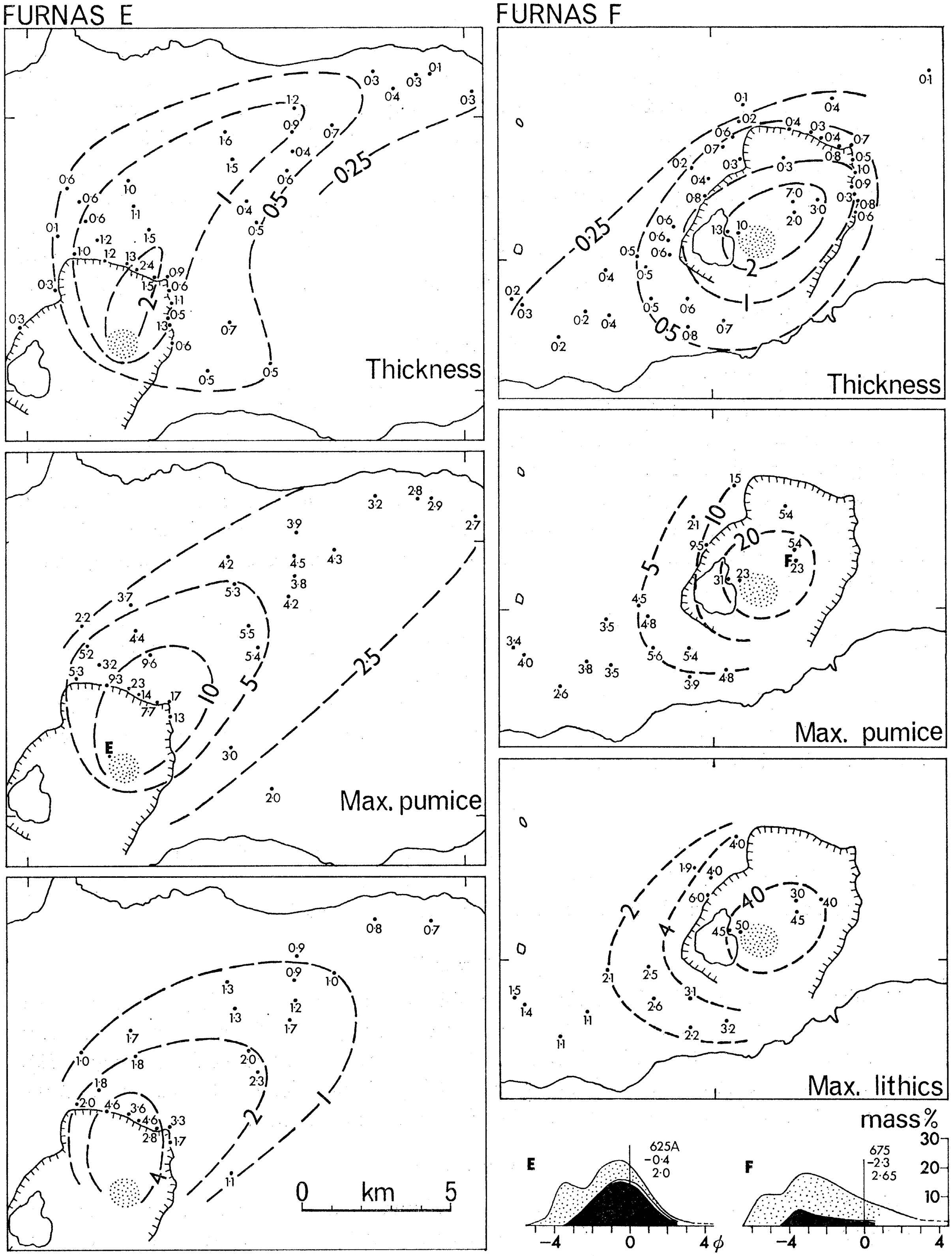

FURNAS E
FURNAS F
Thickness
Max. pumice
Max. lithics
0 km 5
mass %
625A
−0·4
2·0
675
−2·3
2·65
E
F
−4
0
4 ϕ

FIGURE 13

The correlation of F is in many places uncertain. More than 7 m of extremely coarse debris interpreted as F is seen at two points situated on either side of Gaspar crater, and this crater is believed to be the source (figure 13). At one point, on the inner western wall of the crater, it is a chaotic deposit extremely rich in lithic blocks up to 75 cm in diameter. At the other, in a sunken lane just southeast of the therapeutic baths at Furnas, the deposit is richer in pumice which reaches 60 cm in size. Fine-grained beds also occur here.

(*f*) *Furnas G*

This is a well-stratified deposit, distinctive in most exposures because it has a pale-coloured pumiceous base and a dark-coloured sandy top. Significant features are that it is thin, 1.5 m being the maximum observed thickness, and never coarse-grained: at only three points have pumice larger than 10 cm and lithics larger than 4 cm been seen. Another feature is the richness in lithics, especially in the upper part, in which obsidian chips are prominent.

The isopach and isograde maps (figure 14) suggest that Gaspar crater is the source. The pumice, moreover, is dark-coloured and porphyritic rather similar to that of F, which suggests a common source. A soil which must have taken several hundred years to form separates G from F.

(*g*) *Furnas H*

Member H is one of the coarsest yet least extensive of all the Furnas deposits (figure 14). It is a moderately lithic-rich pumice breccia and is best seen on Pico das Marcondas and in the river valley below, with a maximum exposed thickness of less than 5 m. In a track cutting on the northern slope of the hill it contains carbonized wood. The pumice has a moderate content of phenocrysts of platy feldspar and biotite. A sandy ash less than 0.1 m thick found at the same stratigraphic level in several exposures north of Lagoa das Furnas may be part of H.

Member H is thought to be due to a brief but violent explosive eruption on Pico das Marcondas. The hill is an extrusive dome of trachyte with remnants of a crater rim preserved in places around the north and east sides; H is however appreciably younger than the extrusion, being separated from it by other deposits.

(*h*) *Furnas I*

Member I consists of two parts which have been mapped separately (figure 15). The lower part is pumice-rich and reaches its maximum exposed thickness of over 6 m in pits just south of Furnas, where pumice and lithic clasts reach 40 cm in size. It thins to 0.5 m on the north-eastern rim of the caldera, where it is very fine-grained. The upper part is a very pure and homogeneous pumice bed which is very distinctive and easily mapped. The pumice fragments tend to be platy, phenocrysts of platy feldspar up to 8 mm in size are abundant, and lithics are virtually absent.

Member I followed H very closely; locally however there is an incipient soil and plant remains are seen in an exposure near some fumaroles north of the main road northeast of Pico das Marcondas. The two parts of I are thought to represent two phases of the same eruption, though it is possible that they represent two eruptions separated by too short a time for the formation of a recognizable soil.

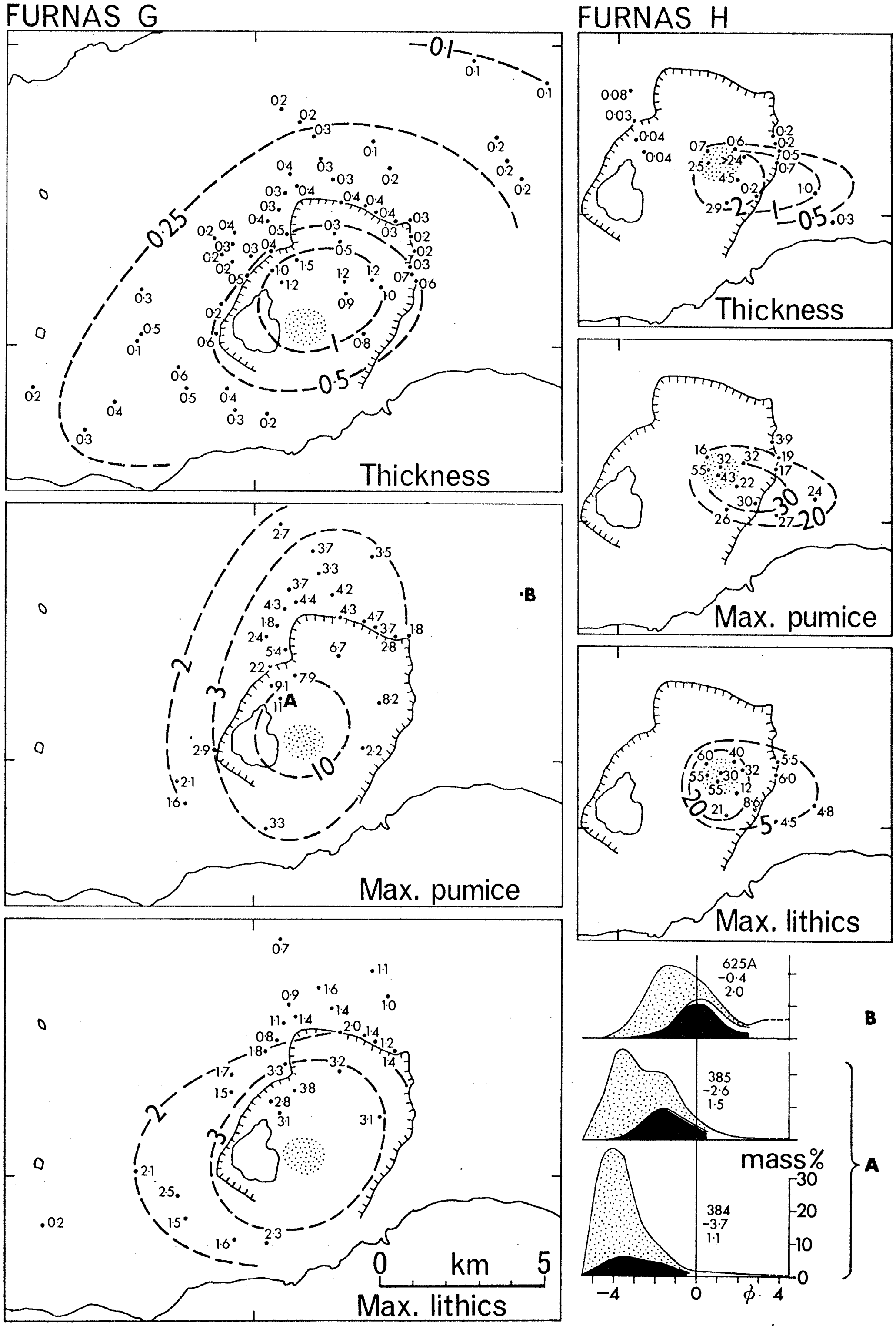

FURNAS G
Thickness
Max. pumice
Max. lithics
0 km 5
FURNAS H
Thickness
Max. pumice
Max. lithics
625A
−0·4
2·0
385
−2·6
1·5
384
−3·7
1·1
mass %
B
A
−4 0 ϕ 4

FIGURE 14

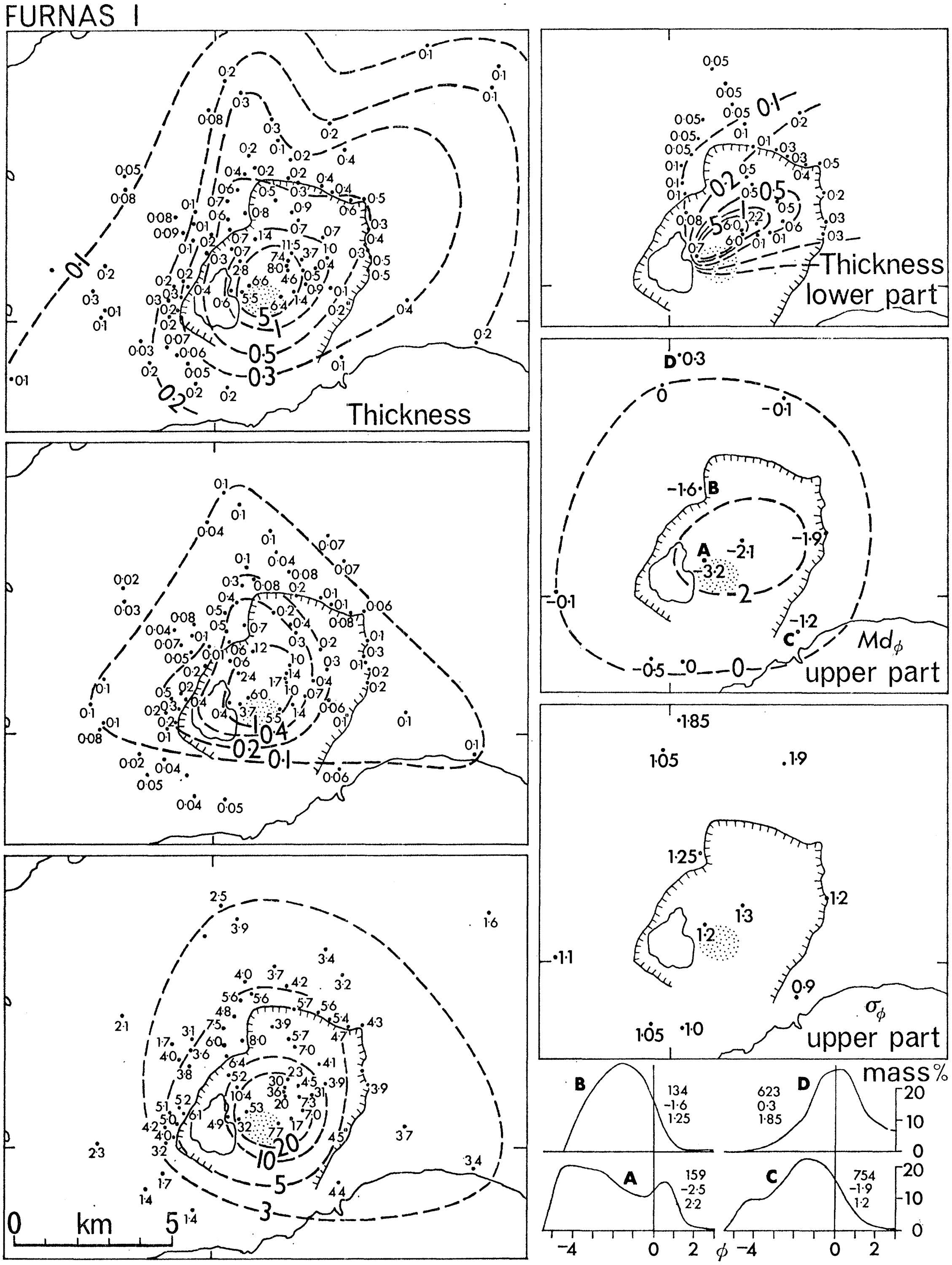


FIGURE 15. Left middle: thickness of the sub-plinian upper part of the Furnas I deposit only. Left bottom: average maximum diameter in centimetres of the three largest pumice clasts. Top right: the thickness of the lower part of the deposit only. The centre and bottom maps (right) give the median diameter (Md_ϕ) and the graphic standard deviation (σ_ϕ) respectively from sieved samples of the sub-plinian upper part of the deposit. The grain size frequency curves relate to this upper part of the deposit.

(*i*) *Furnas* 1640

This is the only Furnas deposit formed in an historic eruption. Over most of its extent and through most of its thickness it is a fine-grained pumiceous ash, and accretionary lapilli are widely distributed. The coarser pumice beds contain a pale-coloured and moderately porphyritic pumice, and have a uniformly low lithic content. The opening explosive phase formed a particularly coarse bed of pumice up to 0.5 m thick over the country 1–3 km south of Lagoa das Furnas, and a thin pumice bed occurs at the base over most of its dispersal area. The deposit tends to become finer grained upwards, indicating a general decline in vigour of the eruption, but towards the end the eruption briefly entered a plinian phase and the resulting very clean, pure, coarse-grained homogeneous pumice bed is dispersed over a narrow belt southeastwards from the source.

The source is the well-defined double ash-ring of Cova da Burra, which has a trachyte dome in the centre of the northern part. Approximately 30 m of well-bedded deposits are seen in exposures on the western and southwestern sides of the ring. The plinian deposit is more than 6 m thick where exposed in a pit on the inner eastern wall. A pumice bomb in it there is 2.7 m long, and both it and the enclosing pumice are dark-coloured due to oxidation while cooling. A similar darkening attributed to the rapid accumulation of hot pumice is locally shown by the Lagoa Congro deposit on the rim of the crater (figure 32, plate 3). The plinian bed is 3 m thick on the hilltop east of Cova da Burra (figure 16, specimen 615) and 1 m thick on the coast at Ribeira Quente (figure 16, specimens 611–613). Not enough data are available to draw a separate isopach map for it.

Ribeira Quente village is in part built on a flat terrace composed largely of mudflows. The plinian deposit described above is intercalated with these mudflows, which probably formed during the 1640 eruption. They are not included on the isopach map. Carbonized wood is common at the base of the 1640 deposit in the steep old sunken track running southwest from Lagoa das Furnas below its intersection with the present main road. A photograph of an exposure near here is reproduced in Walker & Croasdale (1971), pl. 1 (*b*); on this photograph the deposit is labelled 3, while 2 is the Furnas C deposit.

5. Basaltic activity

The basaltic eruptions on land have taken place from several hundreds of separate vents or short fissures and have produced lava flows and pyroclastic deposits. Some took place from monogenetic parasitic vents on the flanks of the stratovolcanoes, and others took place from vents in the 'waist' which cannot be assigned specifically to either the Sete Cidades or Agua de Pau volcanoes. Nearly 200 scoria cones occur in the 'waist' (figure 35, plate 4), and basaltic lavas slope north and south from the fissure zone to the coast at an average of 4°. A few eruptions produced trachybasalts, but these are included here for convenience with the basalts. The post-Fogo A period saw at least 30 separate basaltic eruptions, all from vents in the western half of Sao Miguel and none in the calderas.

The lava flows are almost invariably of aa type, and normally have a thickness of 5–10 m. None is more than 5 km long, although several have flowed into the sea to build lava deltas (e.g. Ponta da Ferraria, Ribeira Seca, and Agua de Pau, figures 1 and 18). The lavas are mostly porphyritic, with phenocrysts of augite, olivine and occasionally feldspar. Coarse-grained

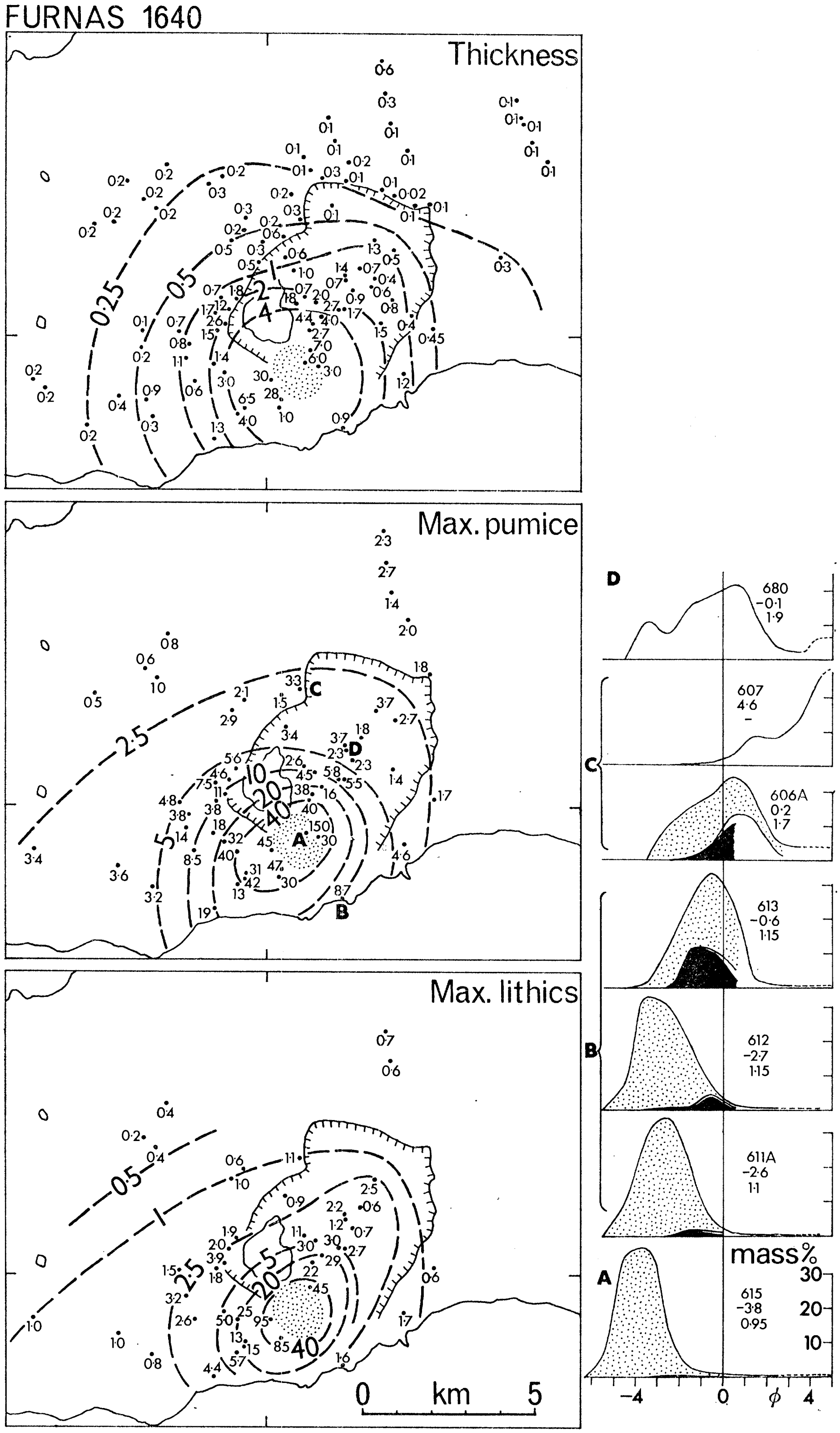

FURNAS 1640
Thickness
Max. pumice
Max. lithics
0 km 5
D
680
−0·1
1·9
C
607
4·6
–
606A
0·2
1·7
B
613
−0·6
1·15
612
−2·7
1·15
611A
−2·6
1·1
A
615
−3·8
0·95
mass%
30
20
10
−4
0
φ
4

FIGURE 16

inclusions of hornblende-plagioclase rock up to 30 cm in size are extremely abundant in one lava, that of Ponta da Ferraria.

The pyroclastic products form cones of scoria and spatter ranging from 20 to 300 m high, together with scoria beds of limited lateral extent around or down-wind from the cones. Many cones are breached on one side, with lava flows issuing from them, although not all have associated lava flows. The cones are typically made of very coarse-grained scoria (figure 36, plate 4), including spatter and scattered sub-spherical or pancake-shaped bombs up to 1 or

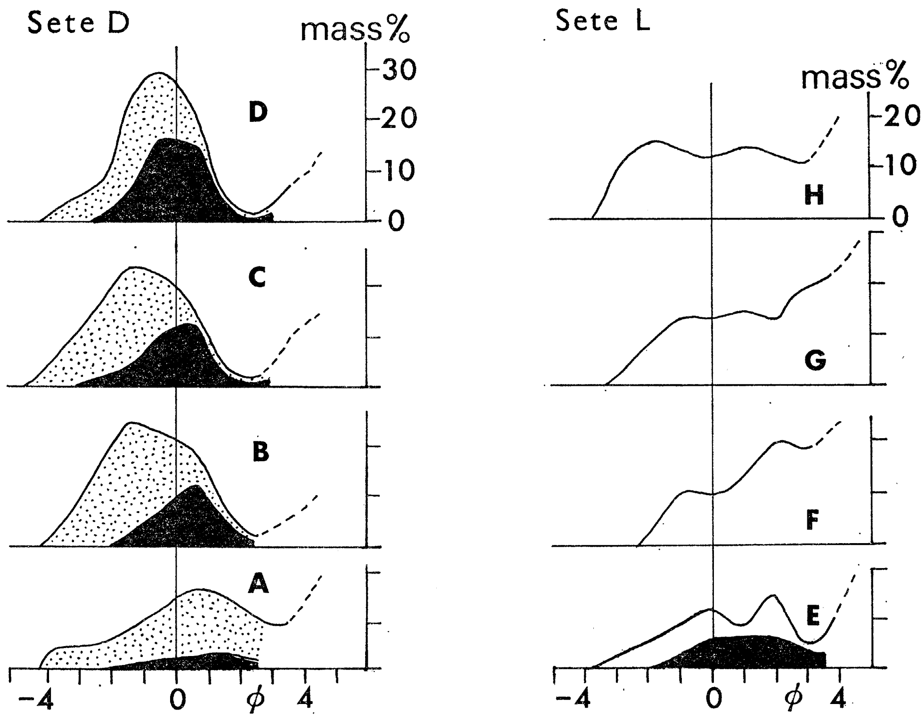


FIGURE 17. Frequency curves for selected samples of Sete D and Sete L pumice fall deposits, showing the generally better sorted character of D. The locations from which the samples came are shown on figures 6 and 9.

2 m in size. Spindle bombs are rare. Achneliths (Walker & Croasdale 1972) are common. Partially fused inclusions of syenite, now more or less pumiceous, are common in several cones. Dispersal maps of the scoria beds associated with some cones are given in figure 19. They are coarse and well sorted, and are typically strombolian in type.

Basaltic eruptions which have taken place in the sea have produced tuff-rings (for example, Vila Franca Island, the promontaries of Capelas and Sao Roque, and some of the islets near Mosteiros). Generally the material is more or less well lithified, but it is usually possible to collect some non-lithified material and many samples have been sieved. They are fine-grained and poorly sorted, lack achneliths, and are typically surtseyan in type. These rings are all older than Fogo A, and are not considered further. The ashes resulting from the off-shore eruptions of 1638, 1682 and 1811 have not been identified on land, but the eruptions were presumably also of surtseyan type and that of 1811 produced a temporary island (Sabrina).

(*a*) *Eruptions in the 'waist'*

Post-Fogo A basaltic activity has been concentrated in the fissure zone of the 'waist'. Dating of events relative to the Fogo A and Sete D deposits is possible over most of the area and on figure 18 the cones are divided into three age groups, namely pre-A, post-A/pre-D, and post-D. Because of a scarcity of good exposures the dating of some cones is uncertain, and in the absence

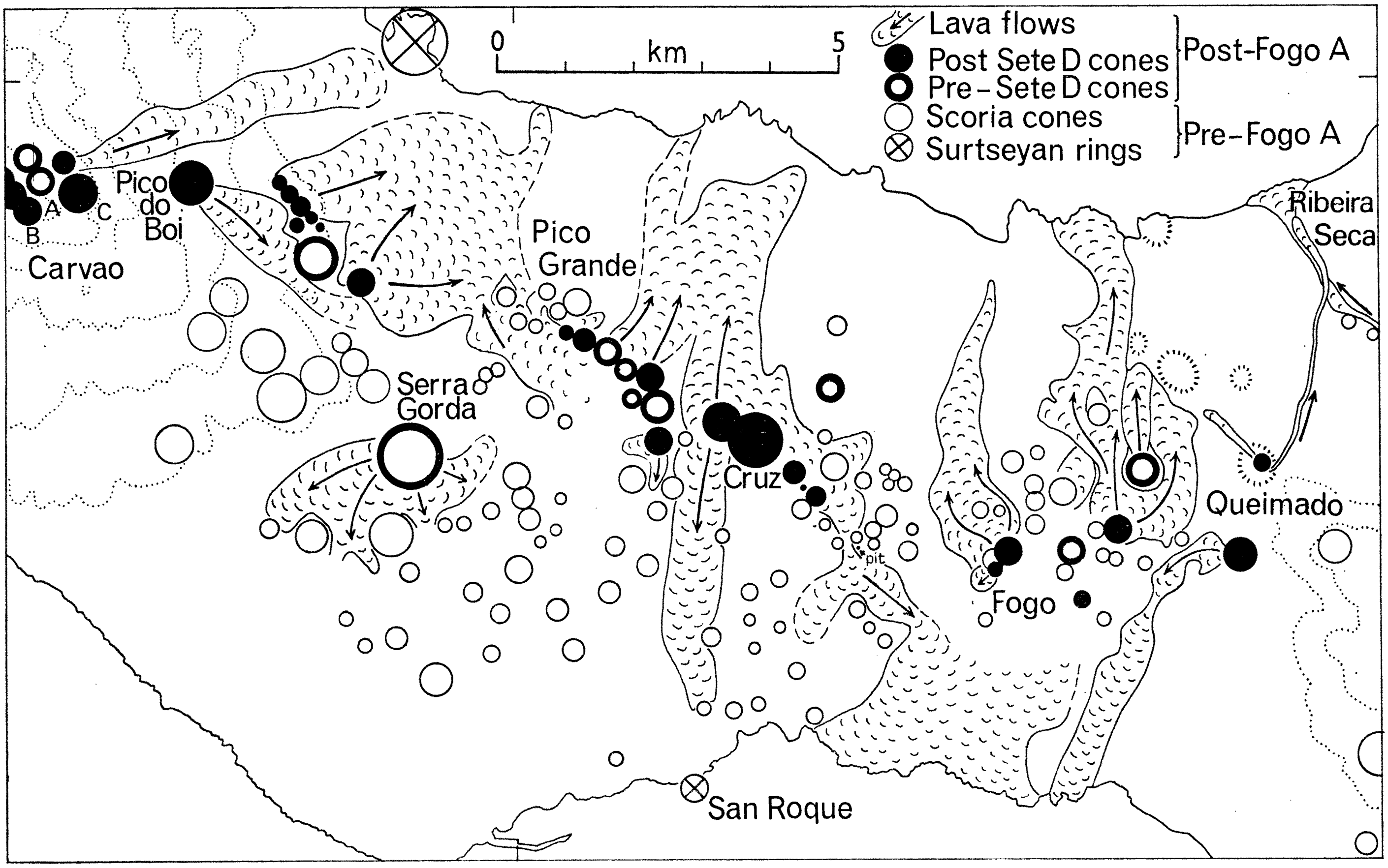


FIGURE 18. Map of the 'waist' region of Sao Miguel and the lower slopes of Sete Cidades volcano showing the distribution of basaltic scoria cones and young basaltic lavas. Three ages of scoria cones are distinguished. The lavas shown are those which post-date Fogo member A pumice fall deposit. Contours 400 m and upwards are shown dotted at 100 m intervals.

of aerial photographs no serious attempt has been made to map in detail the basalt lavas, although their general distribution is shown on figure 18. At least 19 separate post-A eruptions are known, accounting for roughly one third of the total number of scoria cones in the 'waist'.

At least seven of these eruptions date from the post-A/pre-D period, the most noteworthy being those which produced the cone and lava of Serra Gorda, and the cone and lava delta south of Agua de Pau village (figure 1). Other eruptions in this period include those which produced Pico Grande and cones southeast of it (these perhaps lie on the same fissure), the cone west of Queimado, and the cone just west of Fogo, later the scene of the small trachybasalt eruption of 1652 (the Fogo referred to here is the scoria cone of that name, figure 18, and not the Lagoa do Fogo caldera).

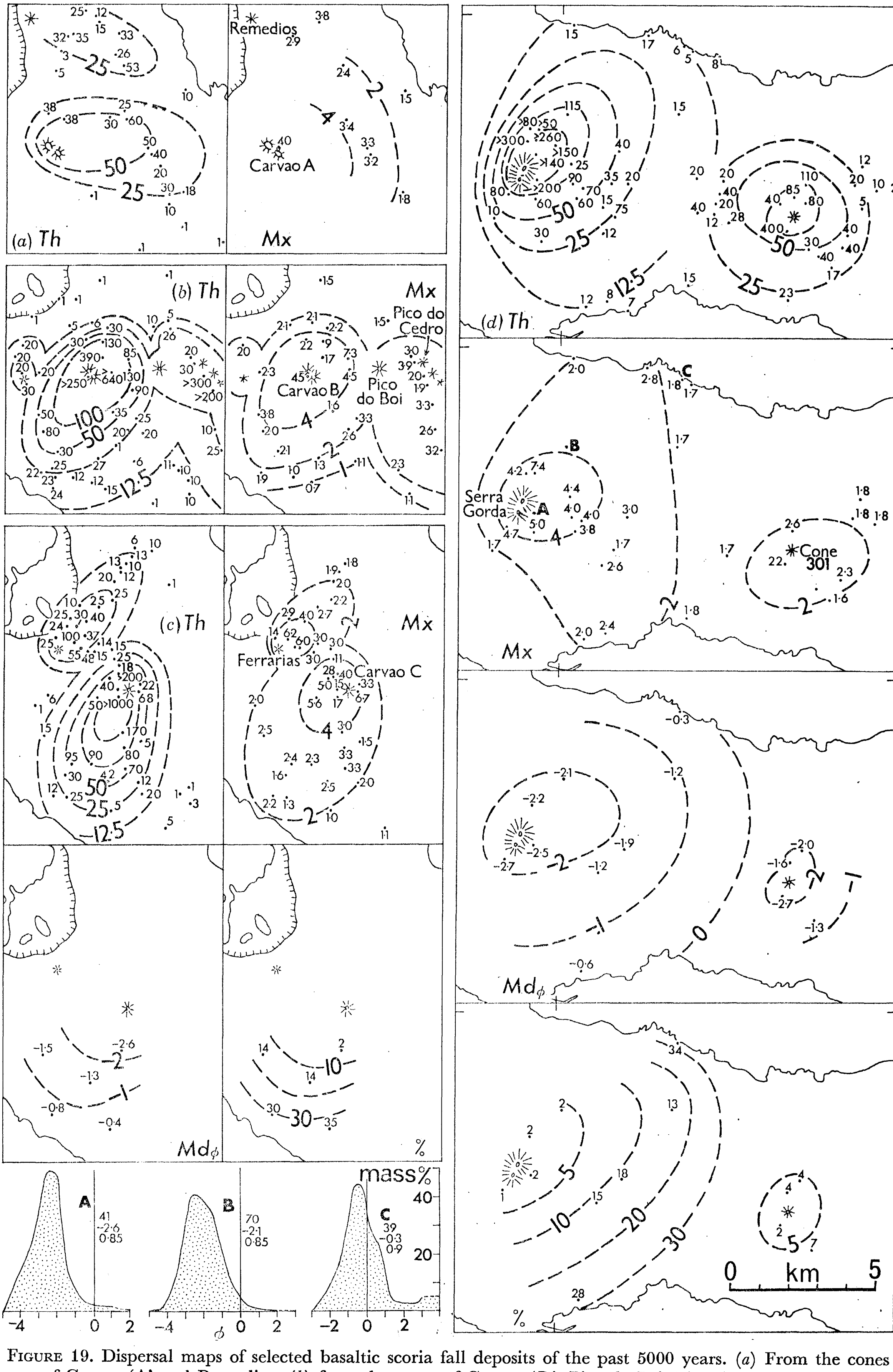


FIGURE 19. Dispersal maps of selected basaltic scoria fall deposits of the past 5000 years. (*a*) From the cones of Carvao 'A' and Remedios; (*b*) from the cones of Carvao 'B', Pico do Boi, Pico do Cedro and an un-named cone west of Carvao; (*c*) from the cones of Carvao 'C' and Ferrarias; (*d*) from the cones of Serra Gorda and un-named cone 301 east of Fogo. The dispersal maps show: *Th*, thickness in centimetres; *Mx*, average maximum diameter of the three largest scoria fragments in centimetres; Md_ϕ, median diameter; %, mass percentage finer than 1 mm. The frequency curves are for specimens collected from the Serra Gorda deposit.

Serra Gorda is one of the largest scoria cones on Sao Miguel. It is a double-peaked structure more than 200 m high. The scoria bed extends as far as the coast where at Rabo de Peixe, 8 km from the source, it is 8 cm thick (figure 19). The associated basalt lava flows cover 3 km^2. Pico da Cova, a prominent scoria cone 1.8 km west of Queimado, has a lava flow on the north side partly concealed by younger lavas from a cone farther south. Of similar age is the vent 1 km east of Fogo which has produced an extensive scoria bed (figure 19). The pair of scoria cones south of Agua de Pau village and the associated lava delta represent the most easterly post-A basaltic activity. They lie outside the 'waist' proper, and are not included on figure 18.

At least 12 separate basaltic eruptions date from the post-Sete D period and have produced some 22 cones. They include Mata do Leal (just N.W. of Cruz), the fissure S.E. of Cruz, Pico Grande, Fogo, and peaks east and southeast of Fogo, as well as the historic vents of 1563 and 1652.

One of the best examples of a fissure eruption known on Sao Miguel is that represented by the line of cones and pits southeast of Cruz. The associated augite-rich lava is one of the largest in the 'waist' and reaches the sea west of Lagoa. Two pits, each 20 m or more deep and believed to be due to a final withdrawal of lava into the fissure, lie on this line and the south-western one is situated beside the main road just south of a quarried scoria cone. Another extensive basalt lava, which flowed both northwards and southwards towards the coast, came from Mata do Leal which lies on the same line though it may not belong to the same eruption. A thick basaltic scoria deposit occurs around a cone 1.5 km north of Fogo and is worked in roadside pits. One of the youngest cones is Fogo, which has a blocky lava extending northwards from the crater. Another cone 1.3 km southeast of Fogo may be of the same age.

The 1563 basaltic eruption followed closely on the trachytic one in the Lagoa do Fogo caldera and formed a short line of craters on top of the pre-A extrusive trachyte dome of Queimado. One of the two narrow lava streams from it entered Ribeira Seca where a small excavation now reveals an old wash house which was buried by the lava. The lava is distinctive on account of the abundant inclusions in it of partially fused syenite. The young trachybasalt lava which forms a lava delta on the coast north of Ribeira Seca originated from a vent (not shown on figure 18) southeast of Ribeira Seca.

The 1652 eruption ascribed to the basaltic cone called Fogo did not take place from Fogo itself but from a vent on the side of an adjacent cone to the west. This adjacent cone is of post-A and pre-D age and is mantled by basaltic scoria from Fogo. On the south side however there is a flank crater around which is spread a thin and poorly sorted ash containing fragments of trachybasalt and lacking achneliths. This ash, possibly due to a small explosive eruption of vulcanian type, rests on the Fogo basaltic ash and a very thin layer of trachytic ash (possibly Sete L) lies between them. The authors believe that this crater and vulcanian ash and the associated blocky trachybasalt lava are the products of the 1652 activity.

(*b*) *Eruptions on Sete Cidades*

The post Fogo-A basaltic activity on Sete Cidades has been concentrated on the main ridge southeast of the caldera. This ridge includes all the highest ground on the volcano and appears to be largely basaltic. Three parallel post-A eruptive fissures occur 2–3 km from the caldera rim. The earliest, referred to on the maps, figures 18 and 19, as Carvao 'A', consists of several contiguous craters with small lakes and immediately pre-dates Sete D. The second fissure, Carvao 'B', lies southwest of and adjacent to the first and consists of a line of contiguous craters, two of them occupied by small lakes, and is post-Sete D/E and pre-Sete G/H. The third fissure, Carvao 'C', lies northeast of the first and includes the prominent cone of Carvao and a spatter crater northwest of it through which the road passes. A basalt lava flow issued from this spatter crater and almost reached the coast at Capelas. Farther west, the solitary cone of Ferrarias (not shown on figure 19), which appears to be of the same age as Carvao, gave rise to a narrow lava stream which entered the sea below Feteiras. The eruptions of the three fissures and Ferrarias were all of strombolian type and produced a substantial amount of basaltic scoria, the distribution of which is summarized in figure 19.

Three post-Fogo A eruptive vents occur on the eastern flanks of Sete Cidades (figures 18 and 19). The oldest is the cone of Fontainhas. The second is the line of scoria and spatter cones of Pico do Cedro and Pico do Enforcado, one of the best examples of a fissure eruption on Sao Miguel and the source of an extensive lava flow. The third and perhaps the youngest is the prominent cone of Pico do Boi, which has given rise to a lava flow and a thin ash bed, distinctive on account of the abundance in it of small olivine crystals. The above cones can all be closely dated relative to the trachytic pumice deposits of Sete Cidades (figure 2).

Probably the youngest basaltic activity is that represented by the pair of small cones and lava delta of Ponta da Ferraria, now the westernmost point on Sao Miguel which, as mentioned earlier, contains plutonic inclusions. The eruption was possibly an historic one: Weston (1964) mentions an eruption in 1713 said to have taken place at Pico das Camarinhas, one of the above-mentioned cones.

6. Chronology

The chronological succession of the deposits from the three volcanoes is summarized by figure 2. A radiocarbon age of associated plant remains is available for four members, as indicated on the figure, and two others are correlated with historically recorded eruptions. In the absence of datable plant remains, the positions of the remaining deposits relative to these dated ones are based on the thickness of the soils which separate them. Thus Furnas J and Fogo 1563 are separated by a rudimentary soil similar in thickness to that between Fogo 1563 and Furnas 1640, and a period of comparable length is therefore believed to separate them.

The available dates do not permit the cumulative output of the volcanoes to be reliably plotted against time as was done for Oshima by Nakamura (1964), and thus the idea that the magnitude of an eruption is a simple function of the length of the preceding repose period cannot be tested. There is no obvious direct correlation between the activity of the three volcanoes, or any clear sign of a periodicity.

7. Pre-Fogo A events

The 5000 year period under review may not be sufficiently long to reveal the existence of major cycles of activity. A partial record of the pre-A activity of one volcano over a much longer period is given by a measured section in the coastal cliffs east of Ribeira Cha (figure 20

Figure 20. Composite section through the pyroclastic succession, about 60 m thick, exposed in the cliffs east of Ribeira Cha. The section comprises 65 separate trachytic pyroclastic fall deposits, numbered 1–65 in sequence upwards, and includes several of plinian type (P), together with three thin basaltic ashes, one welded ignimbrite, a number of mudflows (m), some of which have been omitted, and a lava flow. The thick and in part very coarse fall deposit number 14 has a local source. The figures to the left of the column give the average maximum diameters in cm respectively of the three largest pumice clasts and the three largest lithic clasts found. Stars indicate radiocarbon dates.

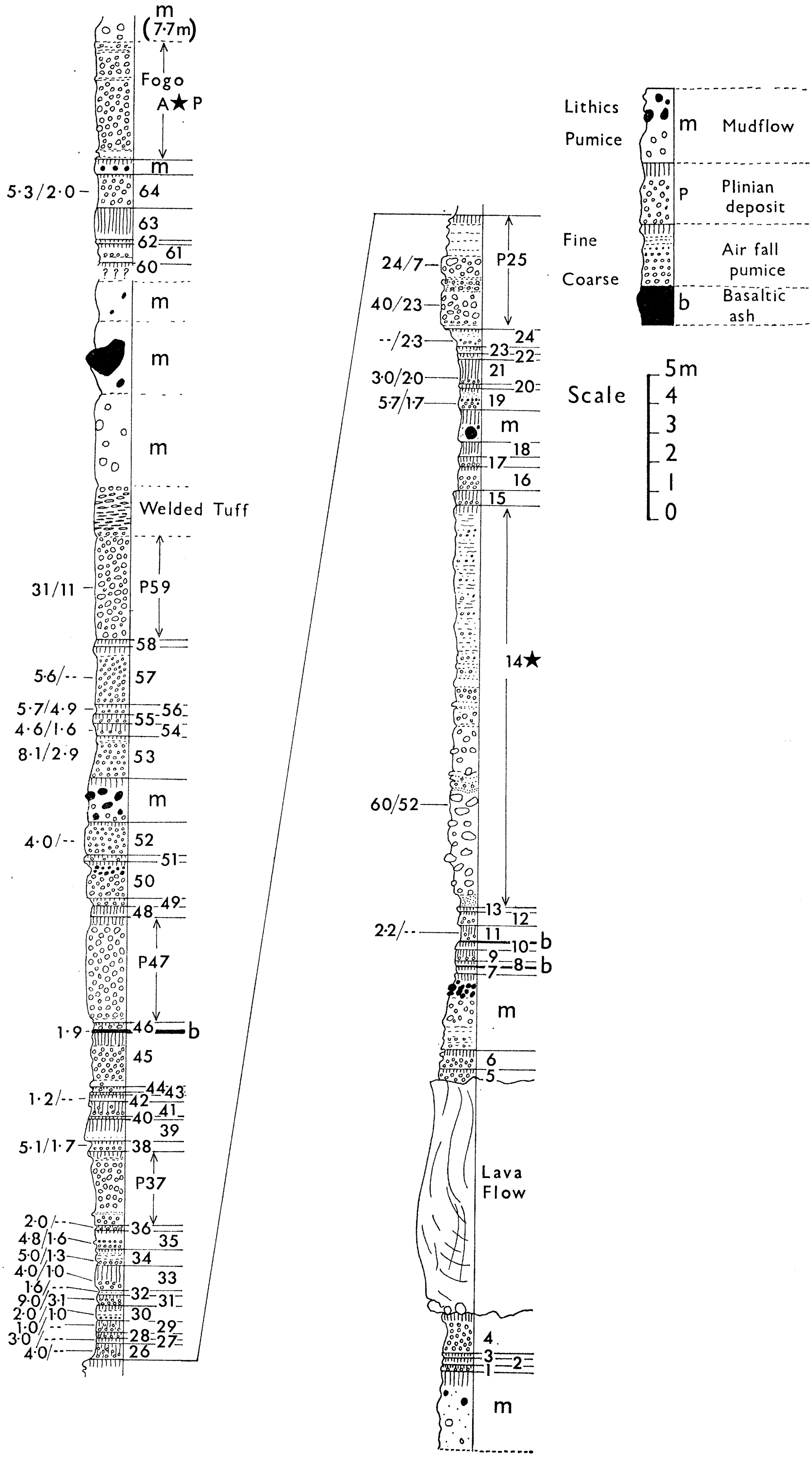


Figure 20. For description see opposite page.

and plate 3, figure 34) on the south side of the Agua de Pau volcano. This section, which is 95 m thick, spans several tens of thousands of years of activity: carbonized wood from a deposit (number 14 on figure 20) near the bottom of the section gives a ^{14}C date of considerably more than 34200 years (Birm-307; Shotton & Williams 1973). The picture given by this section is inevitably incomplete because only the deposits dispersed on the south side of the volcano are seen. For example Fogo B, C, D and 1563 are not represented, and the likelihood is that many earlier ones are likewise not represented or only their thin marginal part is present. There is, moreover, the possibility that some of them may have come from vents in the Furnas area or elsewhere. One coarse-grained deposit near the bottom (number 14 on figure 20) has originated from a vent on the coast east of Ribeira Cha.

The most noteworthy features of the Ribeira Cha section are firstly that it is predominantly made of pumiceous trachytic pyroclastic fall deposits, secondly that it contains at least 65 members, separated by soil horizons, thus recording at least 65 separate explosive eruptions, and thirdly that it includes five particularly thick and fairly uniformly spaced plinian deposits (labelled P on figure 20), the latest being Fogo A. The section includes several mudflows and one welded ignimbrite, the only one known on the volcano. These flows form laterally impersistent lenses of very variable thickness, mostly occupying valleys cut in the pumice deposits, and some of the mudflows are missing from the measured part of the section.

The ignimbrite referred to is worked in a small quarry at Praia, 1.6 km east of Ribeira Cha. It is a brownish-grey welded tuff containing prominent and partly devitrified obsidian fiamme, abundant feldspar crystals, and scattered fragments of syenite, trachyte and other rocks. In nearby road cuttings the welded zone is sandwiched between zones of non-welded ash and is seen to wedge out at the side of the valley which the ignimbrite fills. In a road cutting at Ribeira Cha the ignimbrite, which is partly welded, rests on a plinian pumice (no. 59 on figure 20). There is little doubt that the ignimbrite and underlying pumice are products of the same eruption, and likewise the mudflows which overlie the ignimbrite. Scattered exposures, probably of the same ignimbrite, are seen at various points higher on the volcano.

The Ribeira Cha ignimbrite is not the only one on Sao Miguel. Many exposures of another ignimbrite are seen in and around Povoacao and welded ignimbrite is worked in several quarries near the village. Some of the best exposures are in the coastal cliffs where there are well-defined welded and non-welded zones. The Povoacao ignimbrite is very much older than the Ribeira Cha one, to judge from the large number of trachytic ashes which overlie it, and both come well outside the 5000 year period covered by this paper.

The Ribeira Cha section records a long period of remarkably persistent explosive activity with an average spacing of the order of 500 years between eruptions. The regular spacing of the five plinian deposits suggests the existence of major cycles of activity marked by particularly large eruptions at intervals of the order of 5000 to 10000 years. The relatively deep-seated origin of these plinian eruptions is shown by the abundance of fragments of syenite in them, not seen in the other pumice deposits. Finally the section reveals clearly that the activity pattern of the past 5000 years is typical of that of at least the preceding 30000 years, as far back in time as it is possible to discern at Ribeira Cha.

8. Characteristics of the fall deposits

About half of the eruptive products formed in the past 5000 years are trachytic and the remainder mostly basaltic. The following discussion is concerned mostly with the trachytic members, because the characteristics of the basaltic ones have already been described elsewhere (Walker & Croasdale 1972).

The trachytic eruptions were explosive and produced large volumes of pumice. All the resulting deposits are of air-fall type with the exception of a few fine-grained beds interstratified with some members (notably Fogo A) which are interpreted as pyroclastic flows or pyroclastic surge deposits. The pumice deposits are composed mainly of juvenile material, namely pumice, glass shards and crystals. The crystals, mostly sanidine, vary in amount from 0 % in some deposits to nearly 50 % in others, and are phenocrysts liberated from the magma by the explosive eruptions. Lithics are generally subordinate in amount in all but the finer sieve classes, although they form discrete beds in some deposits. The lithics are mostly fragmented pre-existing basalt and trachyte, although a small proportion may be non-vesiculated juvenile material. Fragments of plutonic type, up to several tens of centimetres in diameter, are common in the Fogo A and Fogo 1563 deposits. They are mostly syenite of chemical composition similar to the trachytes, and studies of them have been made by a number of workers (including Cann 1967, and others cited by him). Similar plutonic rocks are found in several of the older pumice deposits of the same volcano.

(a) *Classification*

The trachytic pyroclastic deposits may be arranged in a continuous series on their field and grain size characteristics. At the one extreme is the type exemplified by Fogo A which is a very coarse-grained, reasonably well sorted, homogeneous and virtually unstratified pumice breccia with a very wide dispersal. At the other extreme is the type exemplified by the Sete A and Sete L (Caldeira Seca) ashes which are fine-grained, virtually unsorted, poorly stratified and much less widely dispersed. The other deposits lie mostly between these two extremes; some (e.g. Furnas B and Sete D) are nearer to Fogo A in character, and others (e.g. Furnas 1640) nearer to Sete L (Caldeira Seca). Most of them are well stratified and have alternating beds of coarse pumice and fine ash. Some show a general upward decrease in grain size.

The Fogo A type is believed to result from an exceptionally powerful continuous gas-blast of plinian type. Through most of its thickness it is remarkably homogeneous in character, and departures from homogeneity are the inclusion of thin nuée ardente deposits within 7 km of the vent and the well-stratified character of the uppermost part of the deposit. This uppermost part consists of a dark-coloured pumice, and shows that towards the end of the eruption the activity became spasmodic and much weaker, and the erupting magma more mafic.

The Caldeira Seca ash is almost as homogeneous as Fogo A, but is very much finer grained, and is unsorted like an ignimbrite or mudflow (figures 17 and 21). The lack of sorting cannot be due to eruption in windless conditions, because the elliptical form of the isopachs (figure 9) shows that there was some wind blowing, and the deposit is in any case so completely different in character from Fogo A which likewise formed when there was little wind. The problem seems really to be one of accounting for the much greater degree of comminution of the juvenile material in the Caldeira Seca ash.

It has been shown (Walker & Croasdale 1972) that basaltic ashes of surtseyan type are in general much finer grained and poorer sorted than those of strombolian type. This is attributed to a much higher degree of fragmentation and the generation of a great amount of very fine dust in a surtseyan eruption, resulting from thermal shock when lava is squirted into water which pours into the vent. A similar relationship may apply also to trachytic eruptions, and it is

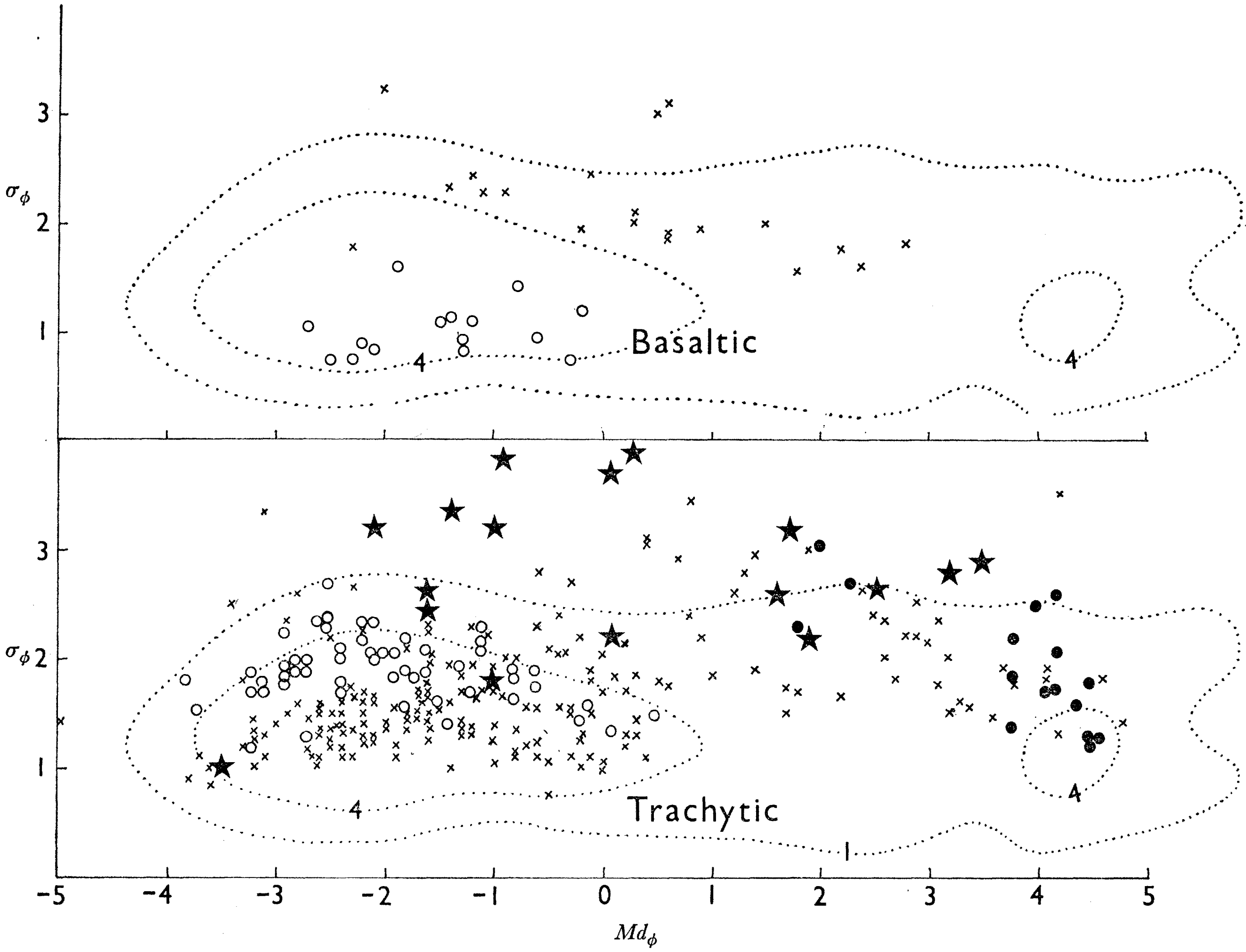


FIGURE 21. Plot of graphic standard deviation (σ_ϕ) against median diameter (Md_ϕ) for sieved samples of the Sao Miguel pyroclastic deposits. Top: basaltic; bottom: trachytic. The dotted lines are the 1% and 4% contours for the pyroclastic fall field from Walker (1971). For the lower part of the figure: ★, Sete A and L; ●, rain flush beds; ○, Fogo A; ×, other trachytic fall deposits. For the upper part of the figure: ○, strombolian ashes; ×, surtseyan ashes.

postulated that the Caldeira Seca and Sete A eruptions took place within a caldera lake as the trachytic analogues of surtseyan eruptions. The ash-ring of Caldeira Seca stands on low flat ground very near the present lake. The present bottom of the crater is not much higher than the present lake surface which is now lower than the natural level because of drainage through an artificial tunnel. The Sete A ash, which is very similar in characteristics, may well have originated from a submerged vent in Lagoa Azul. The beds of coarse pumice found near the base of the deposit are thought to represent phases when the eruption became sub-plinian in character, perhaps when lake water was temporarily denied access to the vent by a crater wall.

A further point should be made. When a steam-rich eruption takes place the finer ash may flocculate in the ash cloud and fall as snowflake-like clumps, as was observed by one of the authors (G.P.L.W.) during the 1971 eruption of Etna (Booth & Walker 1973), and result in the premature descent of much fine ash. Accretionary lapilli, usually regarded as an indicator of rain, have not however been found.

A classification scheme for the explosive eruptions which produce pyroclastic fall deposits (proposed by Walker 1973) is based on the area of dispersal and degree of fragmentation of the deposits. An empirical measure of the dispersal, denoted D, is given by the area enclosed by the 0.01 T_{max} isopach (where T_{max} is the maximum thickness of the deposit), and ranges in known

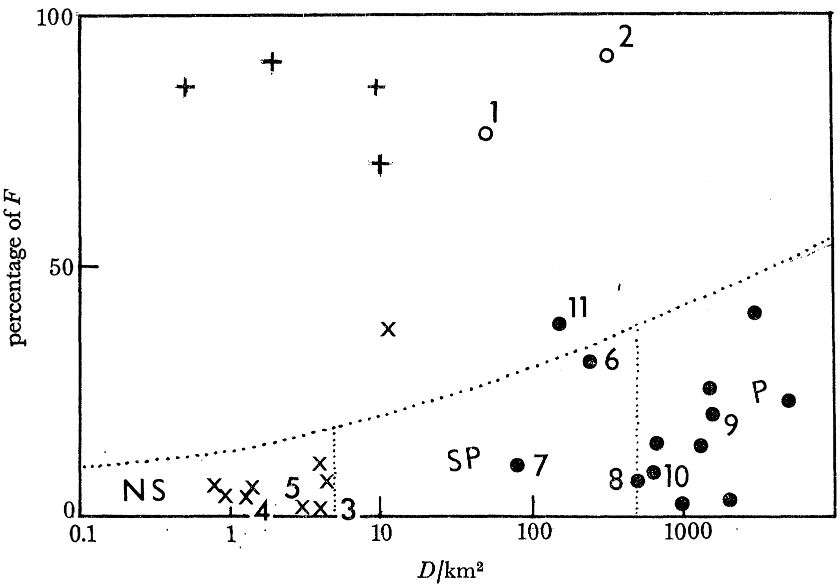


FIGURE 22. Plot of F (the mass percentage finer than 1 mm on the dispersal axis at the 0.1 T_{max} isopach) against D (area enclosed by the 0.01 T_{max} isopach) for various pyroclastic fall deposits. Sao Miguel deposits are numbered: 1, Sete L (main part of deposit); 2, Sete A; 3, Carvao; 4, cone east of Fogo; 5, Serra Gorda; 6, Sete C; 7, Furnas I (sub-plinian part); 8, Fogo 1563; 9, Fogo A; 10, Sete D; 11, Sete L (coarse pumice bed near base). The fields outlined by dotted lines are for normal strombolian (NS), sub-plinian (SP) and plinian (P) types. +, ×, Basaltic; ○, ●, salic types; +, surtseyan; ○, salic equivalent of surtseyan.

examples from less than 1 to more than 1000 km². An empirical measure of the degree of fragmentation, denoted F, is given by the mass percentage of material finer than 1 mm in the deposit at the point where the 0.1 T_{max} isopach intersects the dispersal axis. Plinian deposits give a high D and a low to moderate F, strombolian give low D and low F, and surtseyan give low to moderate D and very high F. The Caldeira Secca type is simlar to the surtseyan type although with a higher D value (see figure 22).

The Sete A and L ashes both give high F values and are similar to surtseyan ashes except in having D values at least an order of magnitude higher. One of the Sete pumice deposits, D, is, like Fogo A and 1563, of plinian type giving a D value of 650 km², and an F value of 8 %. Several pumice deposits are of sub-plinian type, having D values lower than the 500 km² proposed for the sub-plinian/plinian boundary. They include Sete C and Furnas I and the coarse parts of several other deposits (for example, the coarse base of Sete L). As shown by Walker (1973) the Serra Gorda basaltic scoria deposit is a typically strombolian one, and the other basaltic deposits shown on figures 19 and 22 are also strombolian.

(*b*) *Grain-size as a function of distance from the source*

At the time when the present work was commenced, very few studies had been made of the variation in grain-size of pyroclastic fall deposits with distance from the source, and little was known of the range capabilities of volcanic explosions. A large number of grain size measurements were therefore made, and the new data greatly increases that available. Two methods were employed. One was to measure the average maximum diameter of the three largest

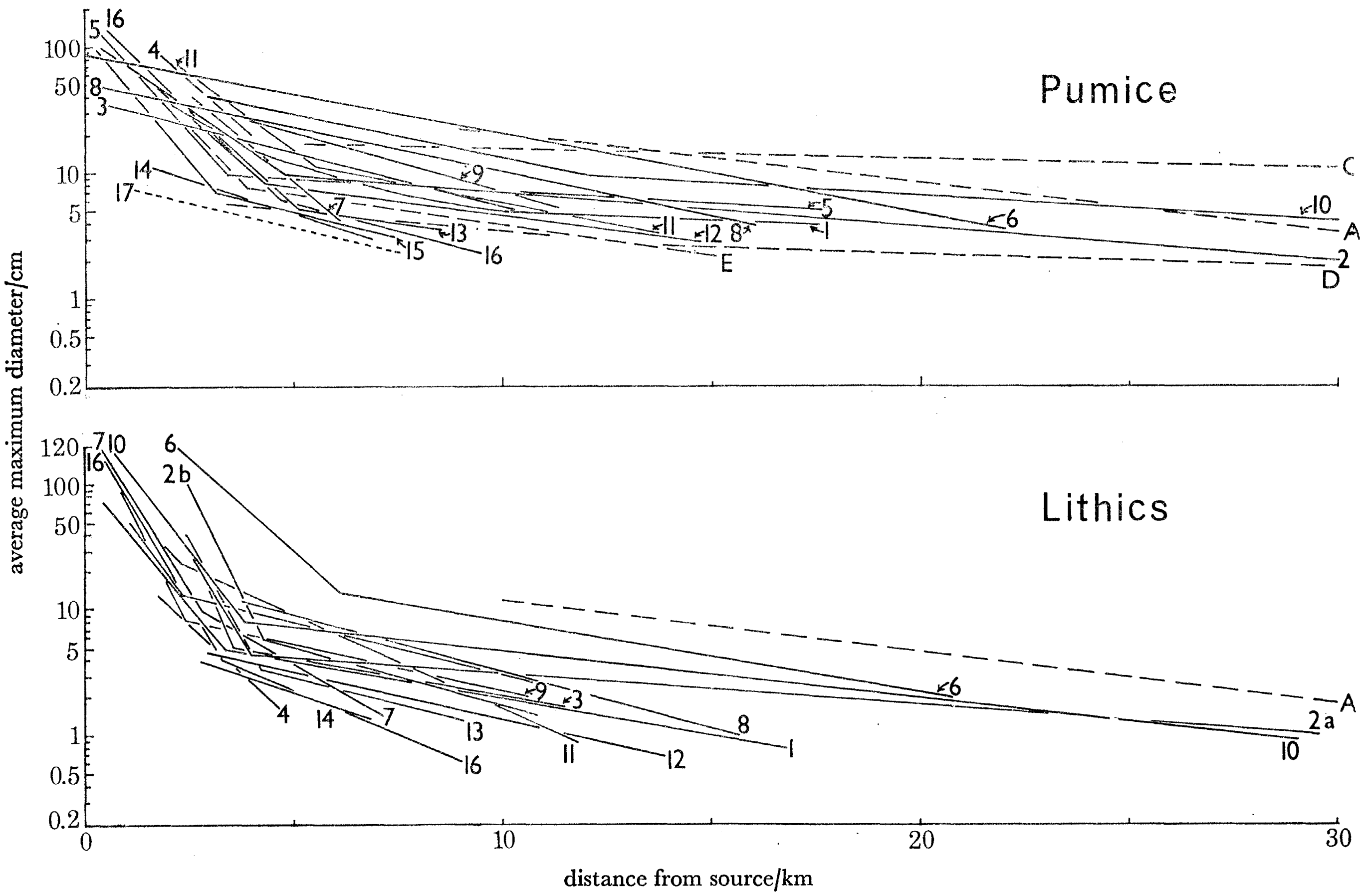


FIGURE 23. Above: plot of the average maximum diameter of the three largest pumice clasts against distance from the source for a selection of trachytic (solid lines) and basaltic (dotted lines) fall deposits of São Miguel. Data from the literature on pyroclastic fall deposits elsewhere are given by dashed lines. Below: similar plot for lithic clasts. 1–5, Sete Cidades (1, Sete C; 2a, Sete D; 2b, Sete I; 3, Sete J; 4, Sete K; 5, Sete L). 6, Fogo A. 7, Congro. 8–10. Fogo (8, Fogo B; 9, Fogo D; 10, Fogo 1563). 11–16, Furnas (11, Furnas C; 12, Furnas E; 13, Furnas F; 14, Furnas G; 15, Furnas I; 16, Furnas 1640). 17, A basaltic fall deposit (Serra Gorda). A–E, Fall deposits of other areas (A, Vesuvius A.D. 79; C, Ontake; D, Hekla 1947; E, Montana Blanca, Tenerife).

fragments found at each locality, separately for pumice and lithics, and contoured maps of these are given for each deposit (figures 4–16). The other was to collect samples for sieving, and study the variation in median diameter as done elsewhere for Fogo A (Walker & Croasdale 1971). This has been done (figure 15) for another pumice deposit and (figure 19) for two basaltic scoria deposits.

When all the available maximum pumice or lithic size data for a deposit are plotted against distance from the vent, a line drawn along the top of the resulting scatter of points gives the maximum range of fragments of a given size. Maximum range lines have been drawn for all the deposits of the present study and are plotted on figure 23, separately for pumice and lithics. Most of the scanty data available in the literature are also plotted on figure 23.

For the Fogo A and 1563 deposits it was earlier shown that the maximum range of lithic fragments can be expressed by a line with an inflexion a few kilometres from the source, the near-vent part being steeper. Partly on this basis two categories of lithic fragments were distinguished: large ones which pursued a ballistic trajectory more or less unaffected by the wind, corresponding with the steep line near the vent, and smaller wind-drifted lithics corresponding with the other line farther away. Most of the present deposits for which adequate size data are available give a similar pattern (figure 23), which confirms earlier findings. The point of inflexion varies between 2 and 6 km from the source, at a diameter mostly between 4 and 15 cm.

For some deposits the maximum range of pumice can be expressed by a single line, straight or slightly concave upwards on figure 23. For others it can be expressed by a line with an inflexion, although the difference in slope of the two parts is small and the inflexion is much less clear than for lithic fragments. One reason is that large pumice clasts are mechanically weak and tend to break when they land so that really large ballistic blocks, those exceeding about 50 cm in diameter, have seldom survived unbroken. Examples of such blocks which have broken on impact are often seen, and we observed extensive breakage of scoria falling during the Heimaey eruption (Iceland) in 1973. Another reason is that the difference between ballistic and wind-drifted fragments is blurred because of the relatively low density of the pumice; all pumice, whatever its size, has a distribution pattern significantly affected by the wind, whereas in comparison, the effect of wind on large lithic blocks is insignificant.

One purpose of figure 23 is to summarize all that is currently known on the range capabilities of volcanoes. It is not claimed that the maximum range possible is yet known, and it is doubtful if any conscious effort has yet been made to determine it. Knowledge of the range of volcanoes is of some social significance, since a 10 cm pumice or 5 cm lithic fragment falling from a great height can damage buildings and injure people and livestock. This diagram therefore gives an indication of the range of possible destruction of property and life by impact.

Wilson (1976) has developed a model for plinian-type eruption columns based in part on data from Fogo A and Fogo 1563, and has calculated muzzle velocities of 520 and 415 m s^{-1} respectively for these two eruptions.

9. The distribution of eruptive centres

During the 5000 year period under review, trachytic magmas have been erupted from at least 14 different vents, of which 12 are located within the calderas, one is just outside the Fogo caldera, and one is at Lagoa do Congro (figure 24*b*). During the same period, basaltic eruptions constructed at least 45 scoria cones which mostly occupy a narrow belt of country trending west northwest from Furnas and Lagoa do Fogo across the 'waist' and extending out to sea in the direction of the island of Terceira or Sao Jorge. The Fogo and Furnas calderas, the Congro crater and the basaltic vents all lie in the same belt, indicated by a dotted line on figure 24*c*. The Sete Cidades caldera is a short distance north of this belt, although the highest point on the volcano lies on it.

The locations of known vents of the period immediately prior to the Fogo A eruption are shown in figure 24*a*. Trachytic vents must exist in or near the areas now occupied by the three calderas. Basaltic activity during the same period produced many cones lying between Fogo and Furnas and low down on the flanks of these volcanoes, as well as in the 'waist' and on Sete Cidades. The distribution of still older trachytic and basaltic vents is broadly similar.

When the two maps, figure 24*a* and *b*, are compared, one significant difference can be seen, namely the more restricted distribution of basaltic vents which erupted in the post-A period

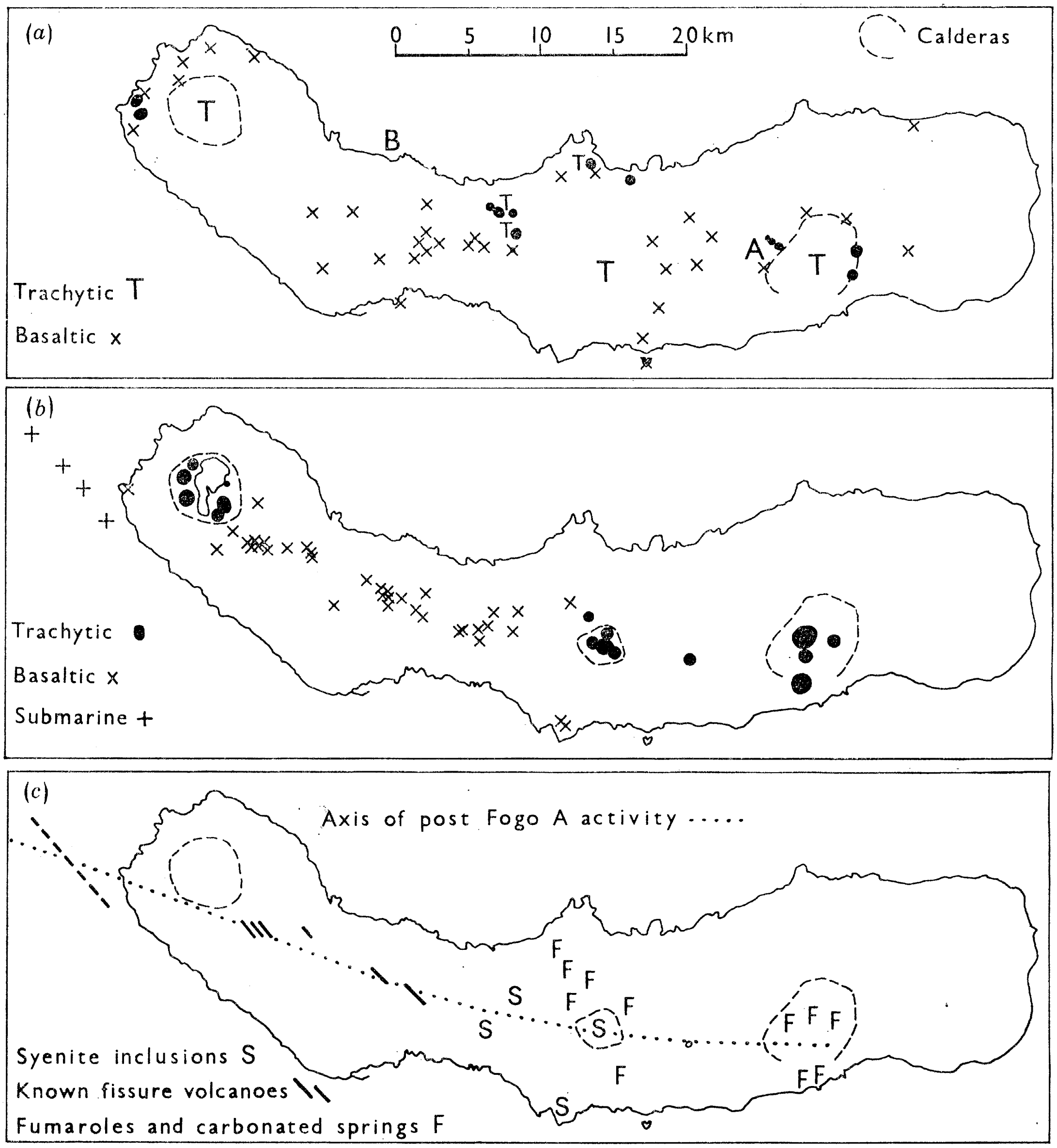


FIGURE 24. Maps of Sao Miguel showing: (*a*) The location of known trachytic and basaltic vents which erupted in the few millennia before the 5000 year period under review. Trachytic vents are known to occur in the areas indicated by T although their precise positions are uncertain. (*b*) The location of trachytic and basaltic vents (some of them submarine) which erupted during the past 5000 years. (*c*) Distribution of vents (S) from which syenite has been erupted during the past 5000 years; fumaroles, hot springs and carbonated cold springs (F); and known basaltic fissures which erupted during the same period. These fissures, and two of the calderas, delineate the axis of post Fogo A activity. The dashed lines indicate the present extent of the calderas.

compared with the earlier period. These younger basaltic vents not only occupy a narrower belt of country, but also they are confined to the western half of the island. It is believed that the 5000 year period is sufficiently long for this reduction of the area of basaltic activity to be a real one. The following are two possible explanations.

First, this reduction may reflect a general westward migration of activity, and this is supported by the fact that the oldest part of the island is at the eastern end; several other islands in the Azores, notably Faial, show a similar younging on the side which is nearer to the actively spreading mid-oceanic ridge. A similar relation is known from various other oceanic areas. However the intensity of trachytic activity at Furnas, the easternmost active volcano on Sao Miguel, was maintained during this 5000 year period and it is only the area of basaltic activity which has become reduced. Also 5000 years seems on general grounds to be too short for a regional migration of this magnitude (of the order of 20 km) to be accomplished, and the cause may therefore be a more local one.

Secondly, a possible local cause which could account for the reduction is the establishment by lateral spreading of a wide trachytic magma chamber beneath the Fogo/Furnas area at about the time of the Fogo A eruption. The subsequent reduction of the area of basaltic volcanism might then be due to the inability of basaltic magma to penetrate this trachytic magma; from the point of view of basaltic volcanism, the eastern half of the island can be regarded as a form of 'shadow-zone' above this postulated magma sheet. The existence of a laterally extensive chamber below this area has been postulated by Machado (1966, 1973) from seismic evidence. Slight support for it might be given by the wide distribution of furmaroles, hot springs and carbonated cold springs, shown on figure 24*c*.

The existence of a broad trachytic magma sheet could also account for the narrowness of the post-A belt of basaltic volcanism. Such a sheet, by preventing the uprise of basaltic magma into high levels in these volcanoes, would also prevent the localized uplift of the type which produces radial fissures. Basaltic magma, unable to come out from radial fissures low on the flanks of the volcanoes, is then constrained to rise along regionally controlled fissures.

Fragments of syenite have been ejected by eruptions from vents distributed over quite a large area of Sao Miguel, which suggests the existence of laterally extensive syenite intrusions such as might have been produced by an earlier period of lateral spreading of trachytic magma of the type postulated to accompany Fogo A. In the 5000 year period, syenite was ejected in three of the Fogo ashes (A, B and 1563), and partially fused syenite at several basaltic vents including that at the village of Agua de Pau.

Syenite fragments also occur in some deposits, much older than the 5000 year period under review, which may have come from other eruptive centres. Blocks of syenite up to 25 cm in size occur in a coarse pumice bed exposed in a pit 2 km northwest of Lagoa das Furnas (at A, figure 24*a*). This bed which is 2.7 m thick must have originated from an unidentified vent fairly near at hand, possibly concealed on the flat ground between Lagoa do Fogo and Furnas. It is separated from Fogo A by two soils and is probably 8000 to 10000 years old. Two conspicuous pumice fall deposits of plinian type, one of which contains syenite, are exposed at two points 4.5 km apart on the north coast of the 'waist' (B, figure 24*a*). These deposits are too thick (each has a thickness of 2–4 m) and too coarse-grained (pumice sizes up to 40 cm, and lithic sizes up to 10 cm have been measured) to have come from either the Sete Cidades or Lagoa do Fogo calderas, the former about 15 km to the west and the latter about 10 km to the southeast. They are thought to have originated from the 'waist' region, from vents or a caldera now concealed below basaltic rocks, and conceivably a volcano once existed here which has since been destroyed. The lower deposit contains syenite fragments up to 10 cm in size which indicate the existence of a buried intrusion transected by the explosive vent. These pumice deposits underlie a basalt flow, and twigs carbonized by this flow give a ^{14}C age of 5992 years B.P. (Birm-91; Shotton *et al.* 1969). The upper pumice bed is separated from this lava by several soils and is probably 8000 to 10000 years old.

Finally, attention is drawn to the prevalent northwest trend of individual eruptive fissures on the volcanoes. Examples are given by the alignment of old trachyte domes northwest of Lagoa do Fogo and northwest of Furnas (figure 24*a*) and the alignment of basaltic vents at the village of Agua de Pau, on Queimado, in the 'waist', and in the area of Carvao on Sete Cidades. These fissure directions cross the main volcanic belt obliquely. The explanation is believed to be that the Sao Miguel volcanic belt overlies a fracture zone along which right lateral transcurrent movement is taking place, generating fissures arranged on echelon in the zone.

10. Volume relations

The volume of each trachytic pumice fall deposit on land has been determined by measurement of its isopach map, and is recorded in column 3 of table 2. The total volume of each, including the part which fell at sea, has been estimated by first plotting a graph of the area enclosed by each isopach against the thickness, then extrapolating the resulting curve (by drawing it parallel to curves plotted for other fall deposits described in the literature), and finally calculating the area lying below the extrapolated curve. These volumes are given in column 4 of table 2. In column 5 they are reduced to the equivalent volume of dense rock (d.r.e.) with $\rho = 2.5\ g\ cm^{-3}$.

This pyroclastic material is largely juvenile, but it includes lithic (pre-existing dense rock) debris, and the estimated lithic contents based on separations made on samples are given in column 6, while column 7 gives the volume of juvenile ejecta (d.r.e.). Column 7 does not give the entire output of trachyte from the three volcanoes on São Miguel during the 5000 year period, because trachyte domes were also extruded in each caldera and also in the Lagoa do Congro crater; their estimated volumes are given in column 8, although it is not in every case certain to which eruption a particular trachyte extrusion belongs. The final column gives the magnitude of each eruption on the scale of Tsuya (1955), and is based on the sum of the volumes in columns 5 and 8.

The volume of basalt is more difficult to assess. Not only are the age, thickness and extent of some of the lavas uncertain but also the volumes of the scoria cones are difficult to determine. Where cross sections through a cone are not available, the position of the true base may not coincide with the lower limit of the steep part, particularly where lava flows have issued from it. The value of 0.6 km^3 for the post-A scoria cones which is taken here is if anything likely to be an under-estimate.

The basaltic scoria sheets outside the limit of the cones contain an additional 0.2 km^3, giving a total of 0.8 km^3 for post-A basaltic pyroclastics, or 0.5 km^3 d.r.e. ($\rho = 3.0\ g\ cm^{-3}$). Post-A lavas cover 90 km^2, and assuming an average thickness of 10 m (allowing for some overlapping of one flow on another) this gives a total of 0.9 km^3. Basaltic eruptions in the post-A period have therefore produced 1.4 km^3 (d.r.e.) of basalt.

The explosivity index, defined as the percentage of pyroclastics in the total material erupted, exceeds 90 for the trachytes and is about 33 for the basalts. The overall explosivity index for the past 5000 years of activity is 65, and a similar figure seems to apply also to earlier activity of the three volcanoes.

The volcanic rocks formed in the past 5000 years can be divided chemically into two broad groups (figure 25). The first group consists mainly of alkali basalt with 45–51 % SiO_2 and 2.5–5.8 % $K_2O + Na_2O$, some of the rocks having a composition of hawaiite or trachybasalt. The second group consists mainly of trachyte, with 61–65 % SiO_2 and 11.5–14.5 % $K_2O + Na_2O$. Between these two groups there is a scatter of points of intermediate composition closely approximating to tristanite.

TABLE 1. ESTIMATED VOLUMES OF SELECTED POST-FOGO A BASALTIC ERUPTIONS

	vol. of pyroclastics/10^6 m^3				area of lavas km^2	vol. of lavas 10^6 m^3	total vol. d.r.e. 10^6 m^3	magnitude on Tsyua's scale
	cone	scoria fall	total	total d.r.e.				
Sete Cidades								
Ponta da Ferraria	1	—	1	0.5	2.0	60	60	5
Ferrarias	1	6	7	3	13.5	70	73	5
Carvao ('Carvao C')	11	20	31	15	3.0	15	30	5
Pico do Boi	10	5	15	7	1.5	8	15	5
Pico do Enforcado	4	—	4	2	7.2	36	38	5
'Waist'								
Serra Gorda	30	60	90	40	3.0	15	55	5
Muta do Leal	10	?	10	5	7.2	72	77	5
S.W. of Muta do Leal	2	?	2	1	0.2	2	3	4
Fissure S.E. of Cruz	10	?	10	5	5.6	56	61	5
1652 vent S.W. of Fogo	—	—	1	0.5	0.2	5	5.5	4
Fogo	5	?	5	3	2.5	25	28	5
Cone E. of Fogo	5	20	25	12	—	—	12	5
Pico 290 m	5	?	5	3	4.8	48	51	5
Pico da Cova	10	?	10	5	0.5	5	10	4–5
S. of Queimado	10	?	10	5	2.0	15	20	5
1563, Queimado	5	—	5	2	0.4	2	4	4
Others								
Agua de Pau	30	10	40	20	6.0	300	320	6
S.E. of Ribeira Seca	0.5	—	0.5	0.2	1.1	11	11	5

An important factor in petrogenesis is the proportion of basalt to more salic types, a quantity which has rarely been rigorously determined. For the past 5000 years on Sao Miguel 55 % of the new rock (d.r.e.) actually present on the island is basaltic. However, this figure is not realistic because half of the trachyte formed in the same period fell at sea, and when this 'lost' trachyte is included (as it must be for any petrogenetic interpretation), the percentage of basalt falls to less than 30. On the other hand no allowance has been made for basaltic outpourings on the neighbouring sea-floor. The three submarine eruptions which are known to have taken place just west of Sao Miguel during the 500 year historic period were probably basaltic, and such activity might well bring the percentage of basalt to around 50.

While there is thus some doubt about the exact proportions of basalt and trachyte, there is no doubt that they were formed in closely comparable amounts, and basalt certainly does not occupy a predominant position. Moreover, there is also no doubt that rocks intermediate between basalts and trachytes constitute only a very small percentage of the total volume. The products of the past 5000 years seem to be in no way different from those in the older parts of the same volcanoes. In the circumstances, any hypothesis of the derivation of the trachytic magmas from a basaltic parent by crystal fractionation should perhaps be questioned. The combined output is, in terms of the actual volume increment to the island, about 7 km^3 in 5000 years. The total volume of the above-sea level parts of the three volcanoes is about 200 km^3, and these volcanoes could therefore have been built up from sea level in 150000 years.

Table 2

	1	2	3	4	5	6	7	8†	9
volcano	deposit	area on land/km^2	vol. on land/km^3	total vol./km^3	vol./km^3 d.r.e.	volume lithics	volume juvenile d.r.e.	dome vol./km^3	magnitude
Sete Cidades	L	160	0.11	0.27	0.06	0.01	0.05	—	5
	K	55	0.08	0.26	0.08	0.02	0.06	—	5
	J	150	0.14	0.39	0.10	0.02	0.08	—	5–6
	I	230	0.21	0.56	0.16	0.05	0.11	—	6
	G, H	130	0.07	0.21	0.08	0.01	0.07	—	5, 4
	E, F	120	0.09	0.24	0.06	0.01	0.05	—	5, 4
	D	350	0.23	0.68	0.16	0.03	0.13	0.25	6
	C	320	0.21	0.40	0.14	0.03	0.11	—	6
	B	100	0.10	0.24	0.07	0.01	0.06	—	5
	A	190	0.28	0.53	0.13	0.02	0.11	—	6
total	—	—	1.52	3.78	1.04	0.21	0.83	0.25	—
Fogo	1562	360	0.33	1.00	0.20	0.06	0.14	—	6
	C, D	180	0.13	0.18	0.07	0.02	0.05	—	5
	B	330	0.25	0.63	0.20	0.06	0.14	—	6
	A	440	1.40‡	3.20	0.64	0.09	0.55	—	6
Congro	—	130	0.05	0.08	0.02	0.01	0.01	< 0.01	5
total	—	—	2.16	5.09	1.13	0.24	0.89	< 0.01	—
Furnas	1640	230	0.25	0.25	0.09	0.01	0.08	0.04	5
	I	220	0.09	(0.10)	0.02	—	0.02	—	5
	H	80	0.02	0.02	< 0.01	—	< 0.01	—	4
	G	260	0.07	0.18	0.05	0.01	0.04	—	5
	F	160	0.10	0.20	0.08	0.01	0.07	0.03	5
	E	200	0.11	0.24	0.11	0.05	0.06	—	6
	D	40	< 0.01	0.01	—	—	—	—	4
	C	330	0.66	1.54	0.37	0.07	0.30	—	6
	A, B	200	0.09	0.10	0.03	< 0.01	0.02	—	5, 4
total	—	—	1.40	2.64	0.76	0.16	0.60	0.07	—
overall total	—	—	5.08	11.51	2.93	0.61	2.32	0.33	—

† It is not certain in every case to which explosive eruption a particular extrusive dome belongs.
‡ Including pyroclastic flows and mudflows.

Regarding the relative levels of land and sea which obviously affects these figures to some extent, there is evidence of a sinking of the land relative to the sea during this period, since many fall deposits extend down to present sea level and occur in a situation in which a pumice fall deposited today would not survive wave action. This is borne out by underwater investigations on some lava deltas (Mapstone, Rood & Jackson 1975). More striking evidence of subsidence, estimated to average 1 mm a^{-1} over the past 690000 years, is given by the borehole put down at Ribeira Grande (Muecke *et al.* 1974).

Few studies have been made of the output of volcanoes in general, and good data are currently available for only nine volcanoes, namely Etna (Cumin 1954; Wadge, Walker & Guest 1975), Kilauea and Mauna Loa (Macdonald 1955), Vesuvius (Imbo & Luongo 1968), Oshima (Nakamura 1964), Kaimon-dake (Nakamura 1967), Hekla (Thorarinsson 1967), and volcanoes on Terceira (Self 1976). Of these, Kilauea and Mauna Loa top the list with a combined output of 4.6 km^3 per century. Of the others, Hekla has an output per century of about 0.9 km^3, Etna 0.75 km^3, and Oshima 0.2 km^3.

To this list must now be added the three volcanoes on Sao Miguel which, unlike the others outside the Azores and Etna, belong to the alkali basalt/trachyte suite. Their combined output is 0.09 km^3 d.r.e. per century. The volcanoes on Terceira yield a somewhat lower figure still. The significance of this low output must await the accumulation of further data on the output of volcanoes elsewhere.

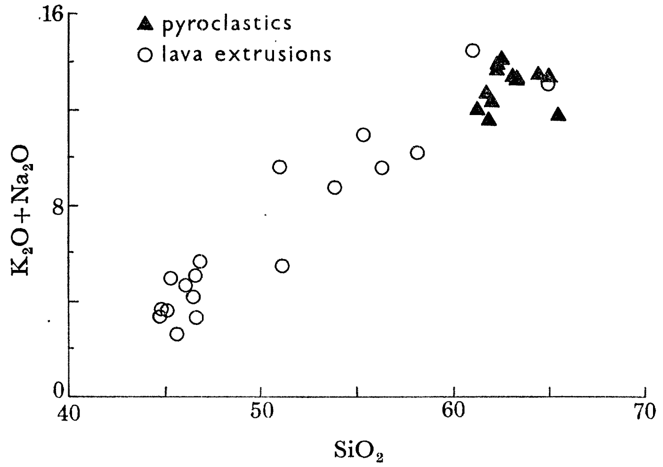


FIGURE 25. Plot of Na_2O+K_2O against SiO_2 for analysed recent volcanic rocks from the Agua de Pau and Furnas volcanoes and the waist region of São Miguel.

(a) *Origin of the Calderas*

The question now arises whether the volume of the post-Fogo A pyroclastic deposits is comparable with that of the calderas from which they came. Both the Sete Cidades and Furnas calderas were in existence before Fogo A times. The estimated volume of each is 5 km^3, but the post-A pyroclastics around each caldera have a total volume of only 0.76–1.0 km^3 (d.r.e.) and it is concluded that the post-A events have changed the size and form of the caldera little beyond creating pyroclastic-rings and lava domes inside them.

The situation is different for the much smaller Fogo caldera. The missing part of the volcano is estimated to amount to about 1.1 km^3 (Walker & Croasdale 1971), and the five Fogo eruptions of the past 5000 years produced the same total volume of material (d.r.e.). Only 20 % of this material is lithic debris, and the caldera is therefore attributed largely to collapse following the eruption of magma from an underlying chamber. Each eruption may have contributed to the collapse, although Fogo A was largely responsible.

One implication is that the Fogo caldera is by far the youngest on Sao Miguel and did not exist before the Fogo A eruption. A problem which now arises is that great thicknesses of pre-Fogo A pumice deposits are exposed on the Agua de Pau volcano. These deposits are particularly well exposed on the coast near Ribeira Cha (figure 20) where the succession includes several which must be comparable in size to Fogo A and the eruption of any one of them may well have been accompanied by caldera formation.

This raises the possibility that the present Fogo caldera may be merely the latest of a series of which the earlier ones have been obliterated by subsequent activity. One may have been located in the Lombadas area, about 1 km northeast of Lagoa do Fogo, where the pumice deposits are particularly thick. Another may possibly have existed on the high ground between Lagoa do Fogo and Furnas. There are many thick trachyte extrusions exposed on the north and south slopes of the Agua de Pau volcano, and it is possible that some of the postulated earlier calderas became infilled with lava in much the same way that the present calderas of Santa Barbara and Pico Alto, on the island of Terceira, have been largely infilled with lava (Self 1976).

It is worth noting that no single large pyroclastic deposit has been found around Sete Cidades which has been identified with a caldera-forming eruption. The same may be true of Furnas; the Povoacao ignimbrite may have come from this volcano but its relationship to the formation of the caldera is conjectural.

(*b*) *Eruption magnitudes*

The magnitudes of the eruptions during the past 5000 years on Tsuya's scale are given in the final columns of tables 1 and 2, and are based on the total volumes (d.r.e.) of material erupted. Of the 28 trachytic and 29 basaltic eruptions known to have occurred during this period, ten were of magnitude 6, twenty-six of magnitude 5, and at least nine of magnitude 4. Regarding eruptions of magnitude 4 or less, the products of some may not have been detected and the actual number may therefore be much greater than four. Although no eruptions of magnitude 7 have occurred during this period, such eruptions are no doubt possible on the island.

An eruption of magnitude 6 thus takes place on average once every 500 years on Sao Miguel, one of magnitude 5 every 200 years, and at least one of magnitude 4 every 600 years. The past 500 years since the island was settled have seen one eruption of magnitude 6, one of magnitude 5, and probably three of magnitude 4, while three other eruptions of unknown magnitude have taken place off the west coast of the island during the same period.

There are very few volcanoes for which data are available with which these figures can at present be compared.

11. Palaeowind directions

The trend of the dispersal axis of a pyroclastic fall deposit gives the wind direction at the time of the eruption. This is plotted on figure 26 for each deposit which has a well-defined axis to give a picture of the prevalent wind directions over the 5000 year period.

An elongated dispersal fan could be produced by a non-vertical directed blast, but the effect is unlikely to extend far from the vent. The clearest evidence for a directed blast is a marked departure from circularity of the maximum size isopleths for ballistic lithics, the distribution of which is little affected by the wind. Such a departure indicates a southwestward blast for the Fogo A eruption (during which the wind was from the west) and a southward one for the Sete G and H eruptions when the wind was northwesterly.

Some deposits, notably Fogo 1563 (Walker & Croasdale 1971), Furnas C (figure 12) and

Sete D (figure 6), have a clearly marked axis of dispersal. Others, notably Furnas 1640 (figure 16), do not. The absence of a well-defined axis can be due to eruption under windless, or near-windless conditions, and the upper part of Furnas I (figure 15) must come into this category; alternatively, it can be due to a frequent change in the wind direction during the course of the eruption, especially if the eruption lasted a long time. This is considered to be the main cause for the lack of a well-defined axis in, for instance, Sete J (figure 7), Fogo C and D (figure 10), and Furnas 1640 (figure 16). If the dispersal pattern of a part of the deposit could be mapped

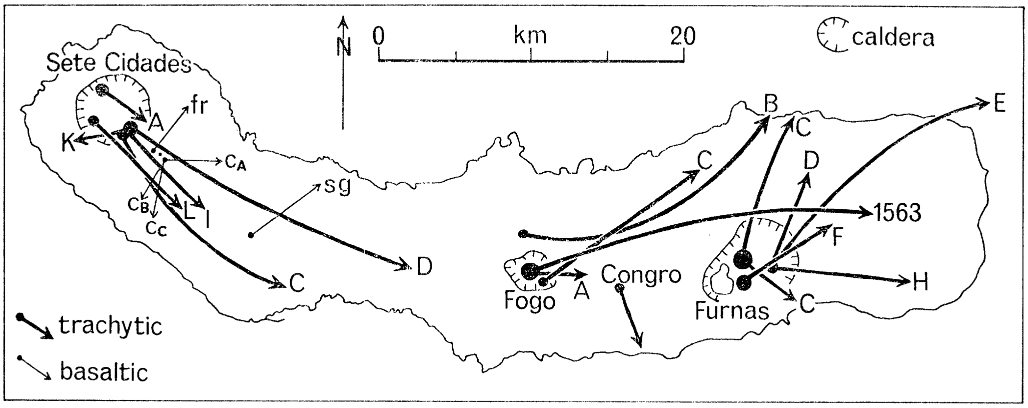


FIGURE 26. Map of Sao Miguel showing palaeowind directions deduced from the dispersal axes of trachytic (thick arrows) and basaltic (thin arrows) fall deposits. The length of the arrow is roughly proportional to the wind strength as deduced from the isopach maps. c, Carvao; fr, Ferrarias; sg, Serra Gorda.

separately, that part might sometimes be found to have a well-defined axis: pumice from the final plinian phase of the Furnas 1640 eruption, dispersed over a narrow fan southeast of the source, is a good example.

Several comments may be made about the wind directions. First they are mostly between northwest and southwest. Secondly there appears to have been no systematic change in the direction with time during the 5000 year period under review. Thirdly the fall-out from the Sete Cidades volcano appears to have taken place mostly towards the southeast, whereas from the other two volcanoes it was mostly towards the east or northeast. However, because the caldera of Sete Cidades lies so close to the western and northern seaboard it is very difficult to detect a principal axis of dispersal in those directions, so the difference may be apparent rather than real.

12. Summary and conclusions

The main purpose of this paper is to document the rate and style of volcanic activity on Sao Miguel over the past 5000 years, as determined by a tephrochronological study of the volcanic products.

The total rate of output of new magma by the three active volcanoes and the associated fissure zone on the island averages 0.09 km^3 per century of dense rock equivalent. Of this, approximately half is basaltic and half trachytic. Rocks intermediate in composition between basalt and trachyte are scarce. This rate is believed to be typical of at least the past 50000 years, the time period for which the record is well preserved, and at this rate the three volcanoes, which are equally active, could have built up from sea level in approximately 150000 years.

The style of activity from the three trachytic volcanoes has been predominantly explosive, and of plinian to sub-plinian type except where water gained access to a vent in large volumes to give rise to the salic equivalent of a surtseyan eruption. Basaltic eruptions have been of strombolian type, producing both scoria cones and lava flows. Other eruptions, presumably basaltic, have taken place at sea.

In its broader geological setting, Sao Miguel is situated some 300 km east of the Mid-Atlantic Ridge. It overlies a WNW–ESE fracture zone, the Terceira Rift, which probably controls its present position. This zone has been interpreted by Krause & Watkins (1970) as a secondary spreading axis. However, the en-echelon arrangement of some of the eruptive fissures suggests that the fracture zone may in fact be a buried transform fault.

The oldest rocks on Sao Miguel occur at the eastern end of the island where volcanism appears to have ceased. Basaltic activity over the past 5000 years has been largely confined to the western half of the island, a smaller area than that of the immediately preceding period. This suggests that a westerly migration of the volcanically active zone may have taken place due, for example, to the island moving eastwards over a fixed 'hot spot'. However, there is an alternative and purely local explanation, based on the postulated existence of a laterally extensive trachytic magma sheet below the central part of the island which restricted the ability of basaltic magma to attain the surface there.

This study has shown that large explosive eruptions of trachytic magmas take place at the rate of one every few hundred years, and the period of 300 years since the latest one is comparable to the average repose interval. The volcanoes on Sao Miguel must be regarded as being no less active today than they have been in the past. This paper therefore provides a basis for the general prediction of future volcanic activity.

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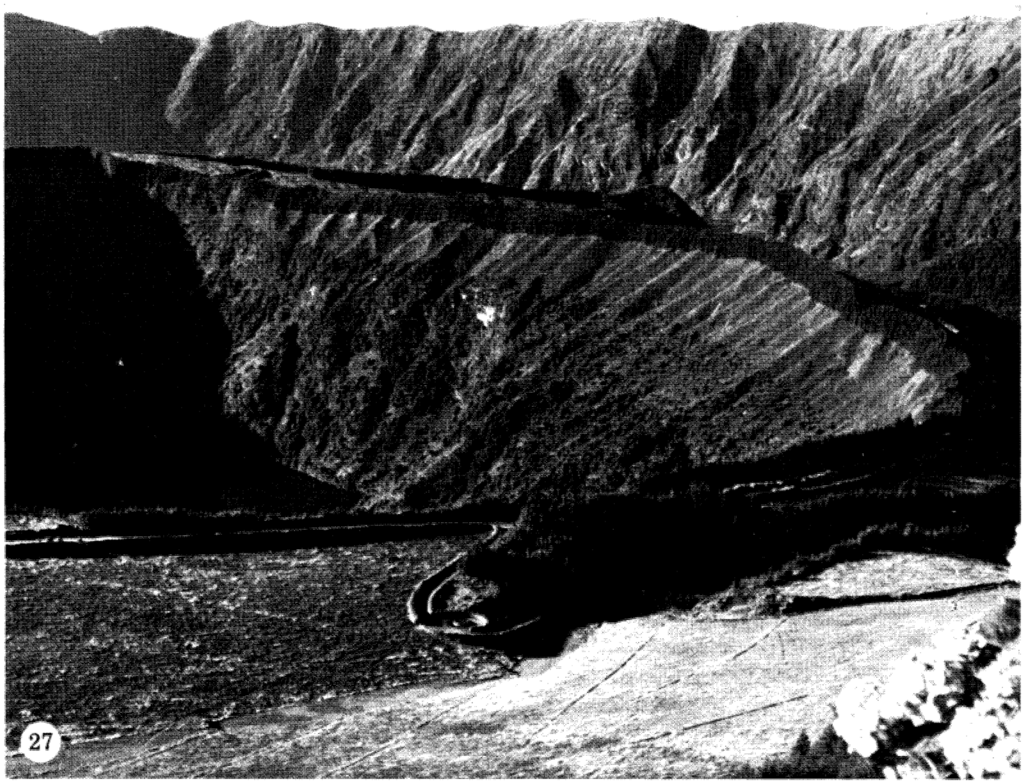

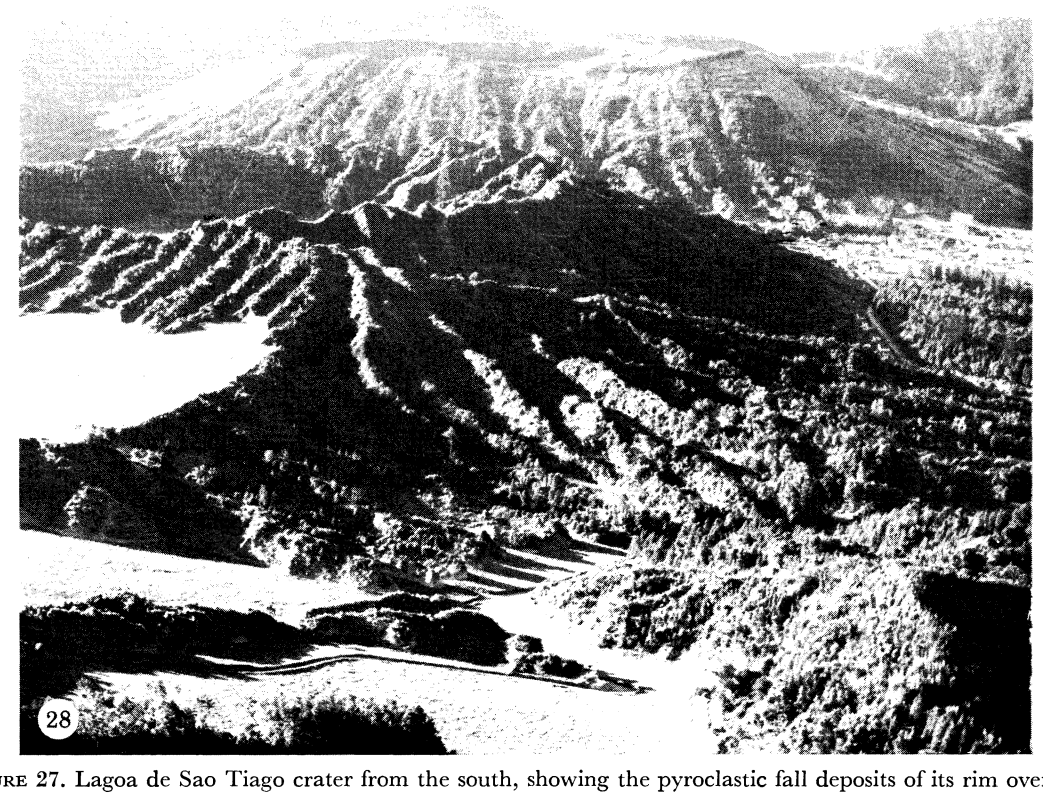

FIGURE 27. Lagoa de Sao Tiago crater from the south, showing the pyroclastic fall deposits of its rim overlying wooded lava extrusion. The northwestern wall of the Sete Cidades caldera appears behind.

FIGURE 28. Deeply dissected ash-ring of Caldeira Seca in the foreground, with the Caldeira do Alferes cratered cone and the northwestern rim of the Sete Cidades caldera behind.

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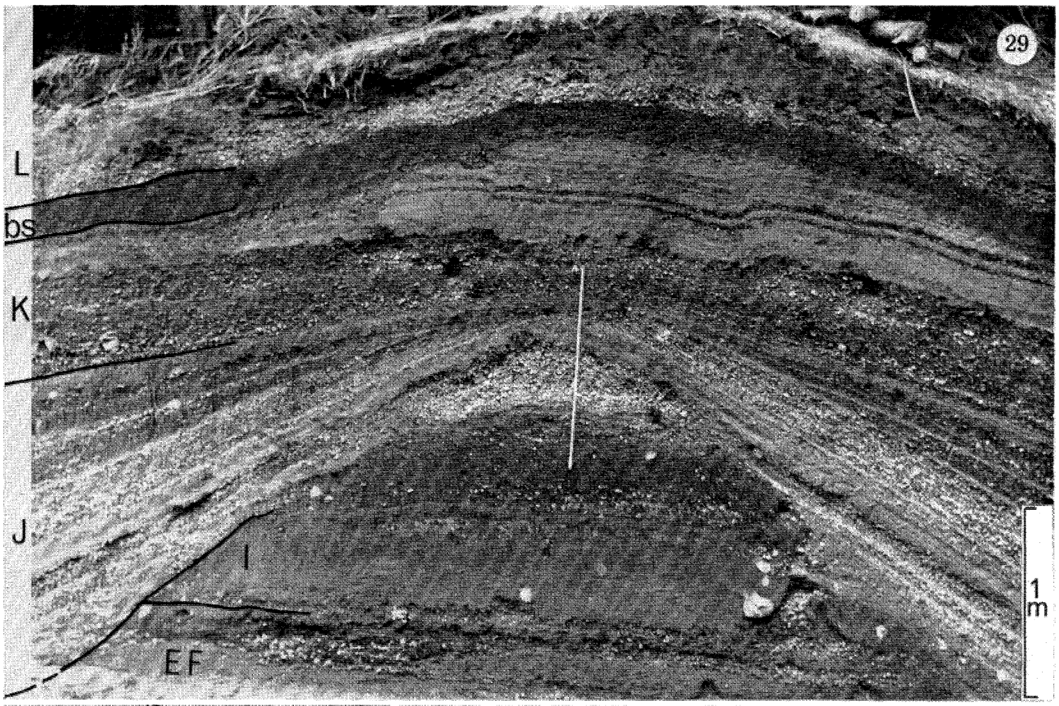


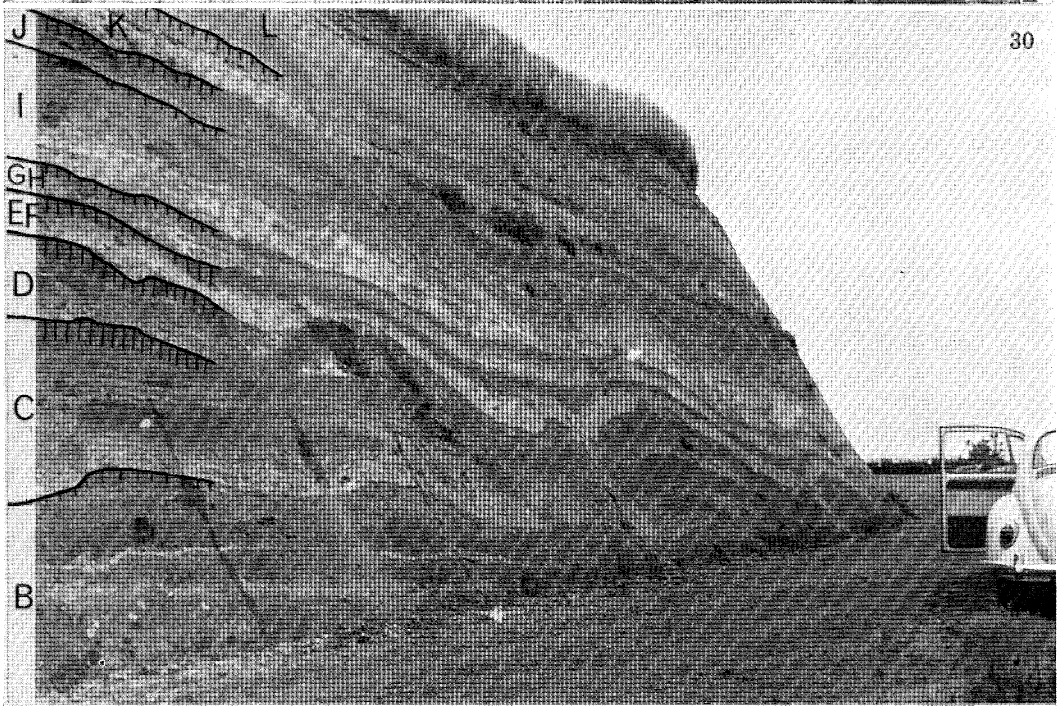
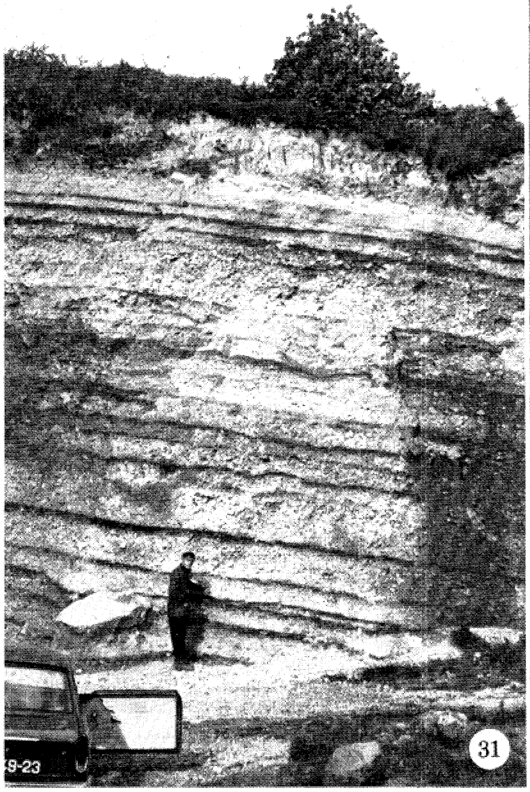


FIGURE 29. Road cutting at Lagoa do Canario showing Sete Cidades fall deposits, as labelled. There is a pronounced erosional break in the middle. See text figure 3, stratigraphic column C.

FIGURE 30. Road cutting on the southwestern rim of the Sete Cidades caldera showing fall deposits, as labelled.



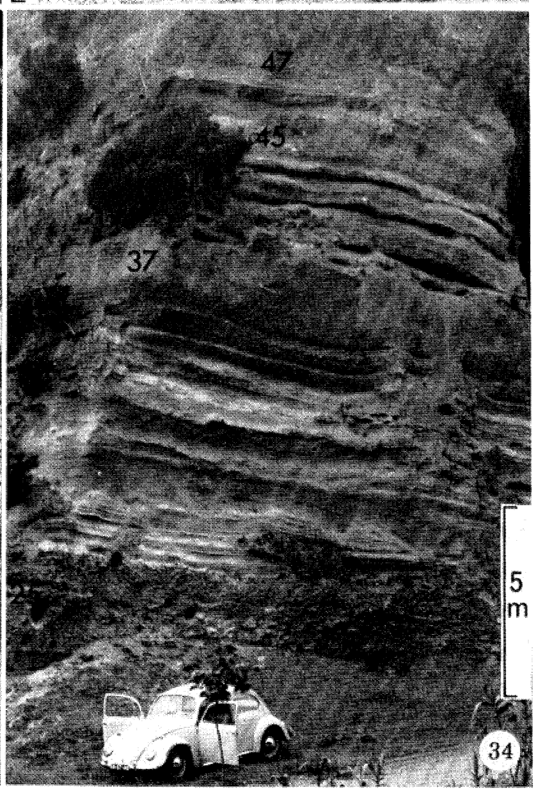


FIGURE 31. The Congro pumice deposit exposed in a pit a short distance southeast of Lagoa do Congro, showing the alternation of coarse pumice and fine ash beds, and a large ballistic lithic block.

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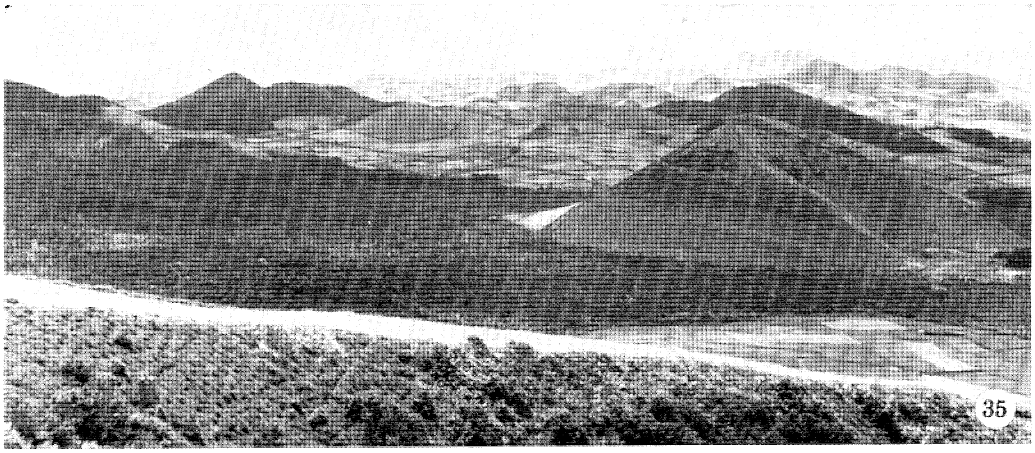
FIGURE 33. The Furnas C pumice fall deposit, exposed in a pit on the northern rim of the Furnas caldera at a point 2.2 km north of the source vent, showing the well-stratified nature of the deposit.

FIGURE 34. Part of the sub-Fogo A pyroclastic succession exposed beside the coastal road southeast of Ribeira Cha showing three of the large plinian pumice fall deposits (25, 37 and 47 on figure 20).



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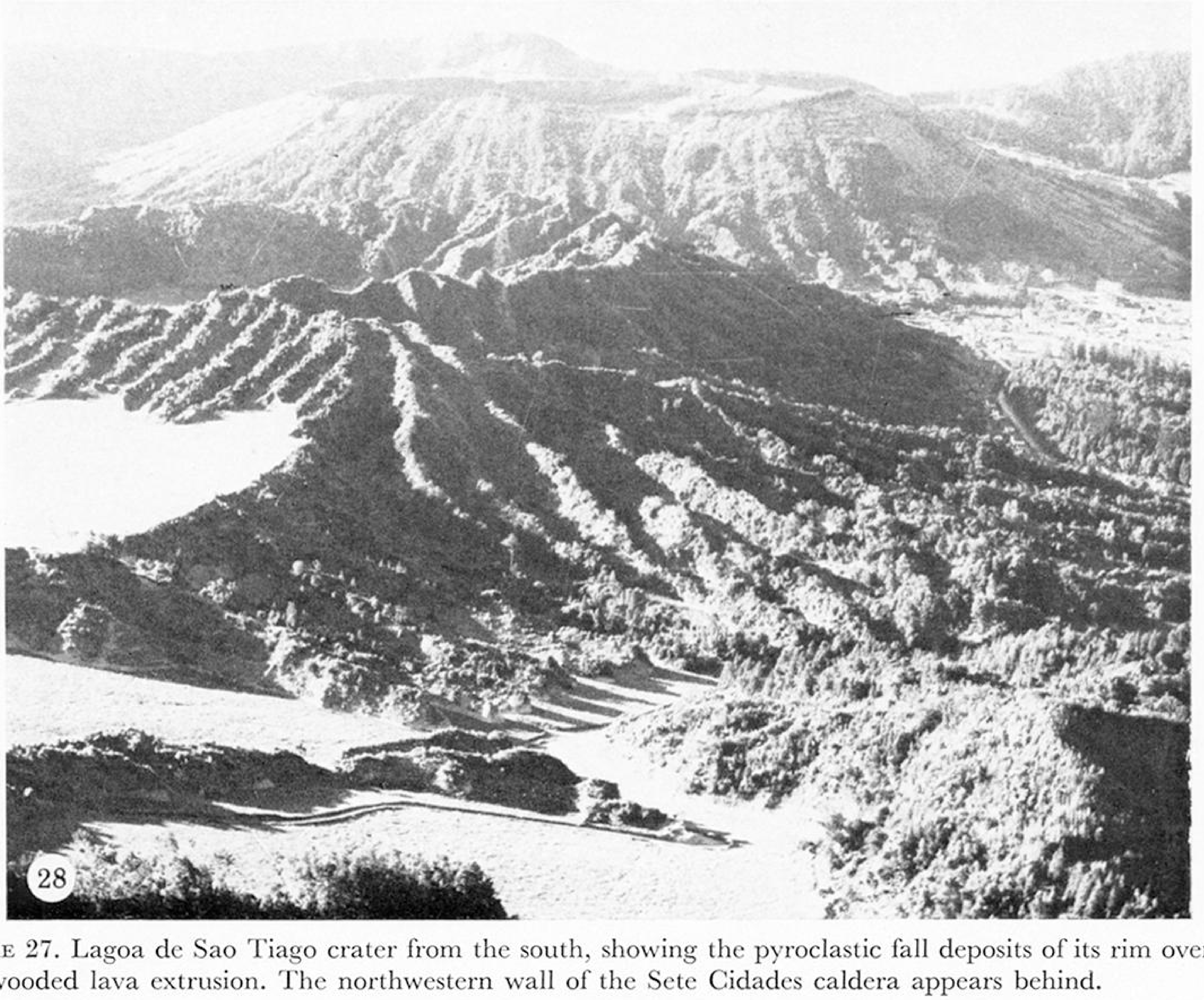

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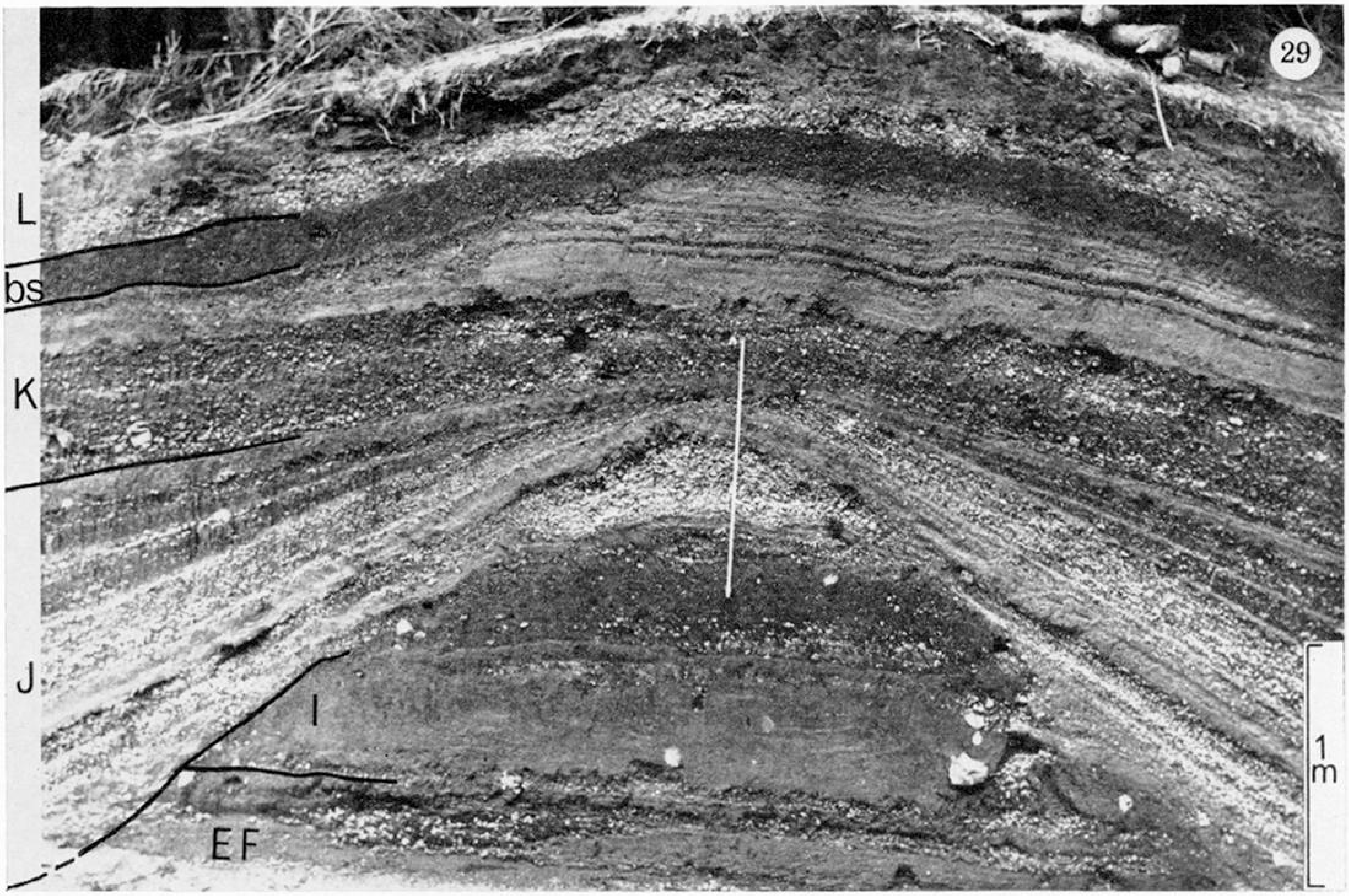

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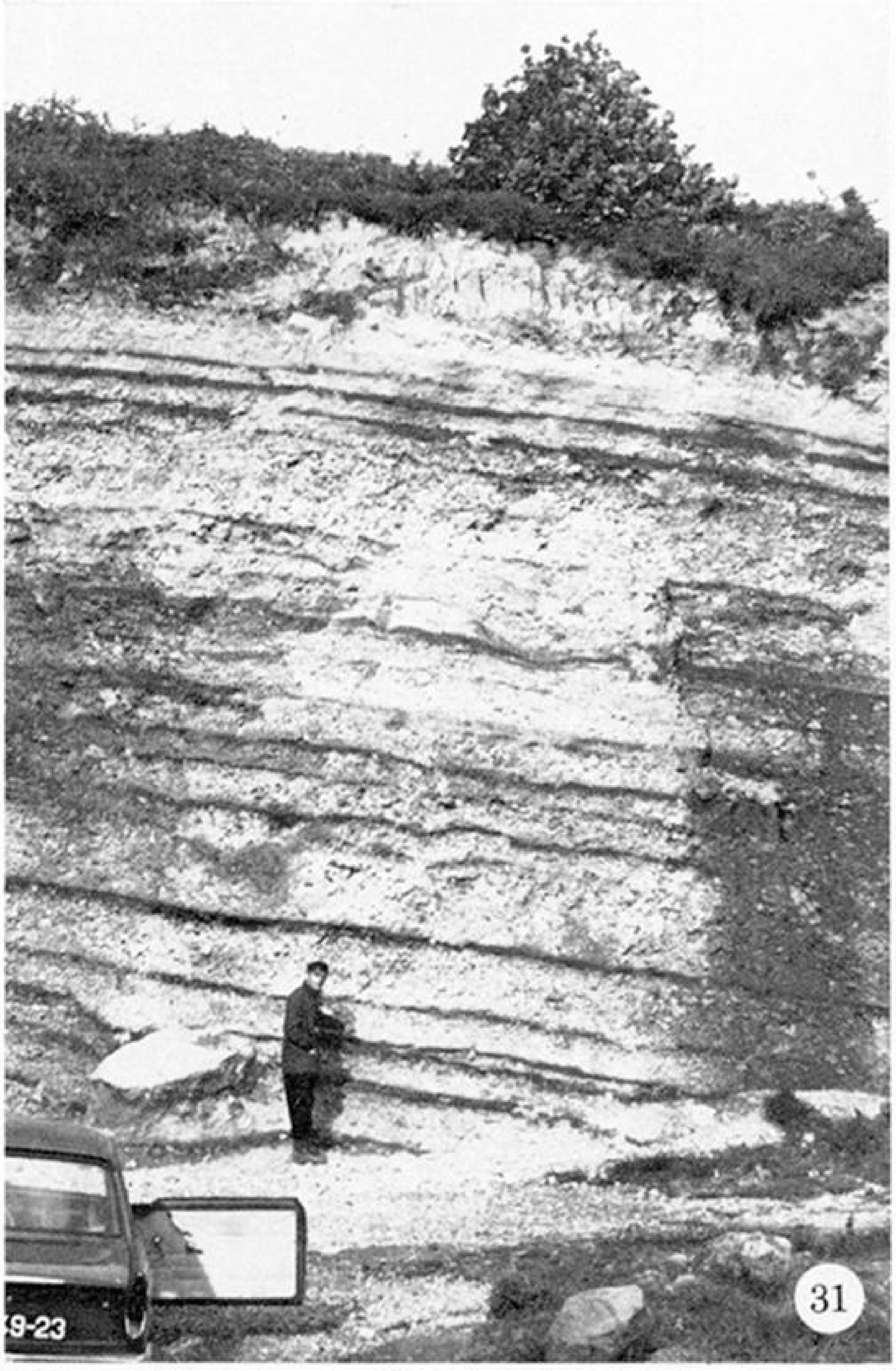

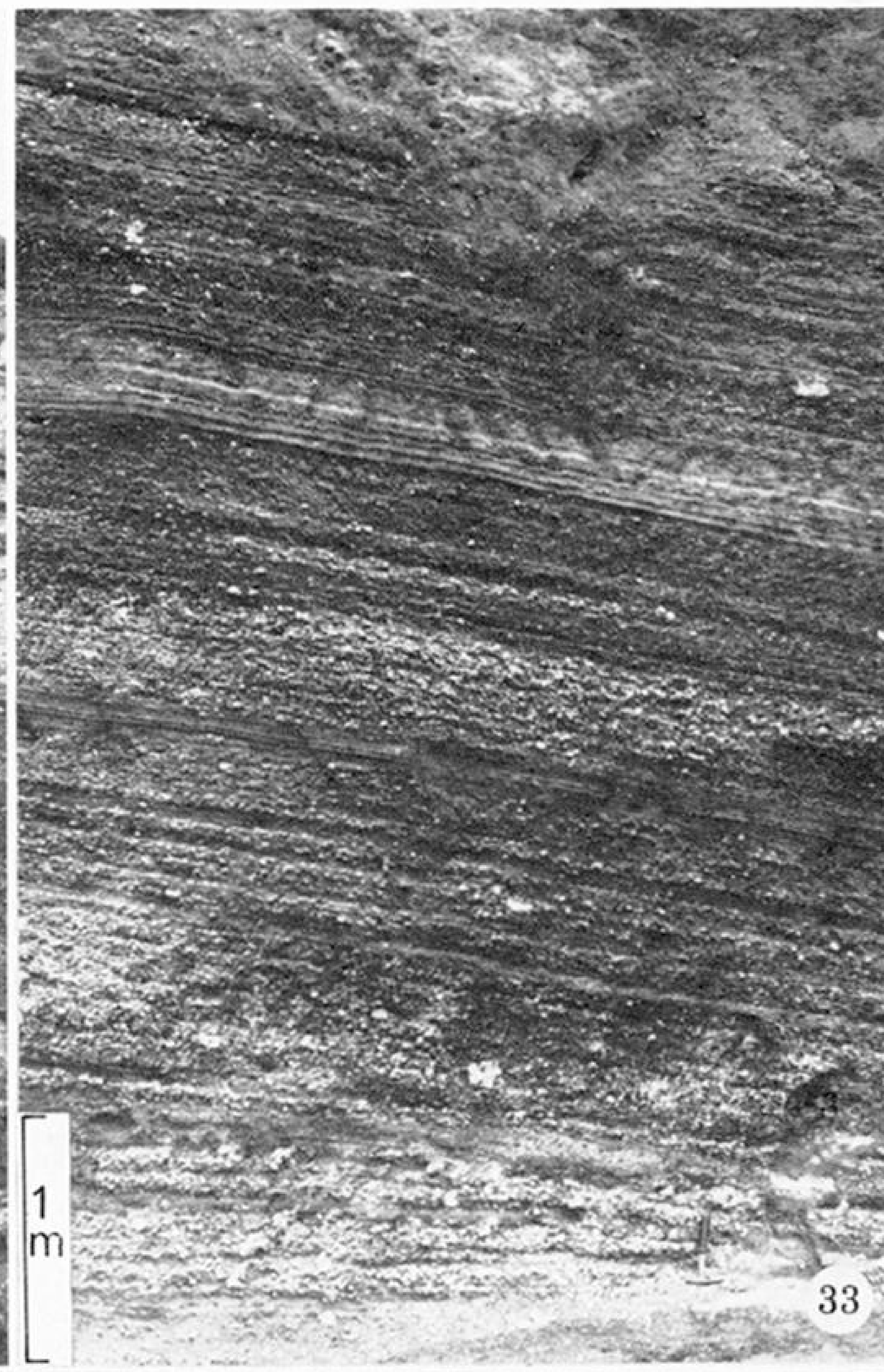

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