THE CALDERAS OF MACARONESIA

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With 5 figures and 1 table

ABSTRACT

In the archipelagos of Macaronesia, occur a number of calderas, several of which have long been known to scholars and the public at large.
The term 'caldera' is taken from these islands, but there still is considerable confusion in the terminology.
Many workers have presented their opinions as to mode(s) of origin of these features, yet debate still continues. The role of erosion and gravitational mass movements is apparent in all to varying degrees, and some calderas are thought to be primarily of exogenetic origin rather than due to volcanic or volcano-tectonic causes. Descriptions are given of 24 calderas, pertinent statistical data presented, and a discussion of caldera types.

Introduction

The archipelagos in the Atlantic, W of the coasts of Europe and Africa, have been known to Europeans for at least 600 years, and in the case of the Canaries, peoples of the Bronze Age settled there.

Relative closeness to Europe developed intimate associations, for these are Spanish and Portuguese archipelagos (Cape Verde islands now form a republic, but were formerly Portuguese). In a scientific and especially geological sense this applies no less, and for some 200 years, scholars have visited these enchanting islands.

All who knew these archipelagos were impressed by many large, deep depressions scooped out of the earth, to which the names «calderas» (Spanish) or «caldeiras» (Portuguese) were given. Many of these have become known to a large public, especially in these days of tourism, and naturally have attracted the attention of geologists.

In what follows, we shall enumerate and describe these great basins occurring in various islands, statistical data being given in Table I. For general geological information regarding these archipelagos, reference may be made to the author's publication of 1976.

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Confusion of Nomenclature

The words «caldera» and «caldeira» in the respective languages, both refer to a cauldron, kettle, boiler, a receptacle relatively deep

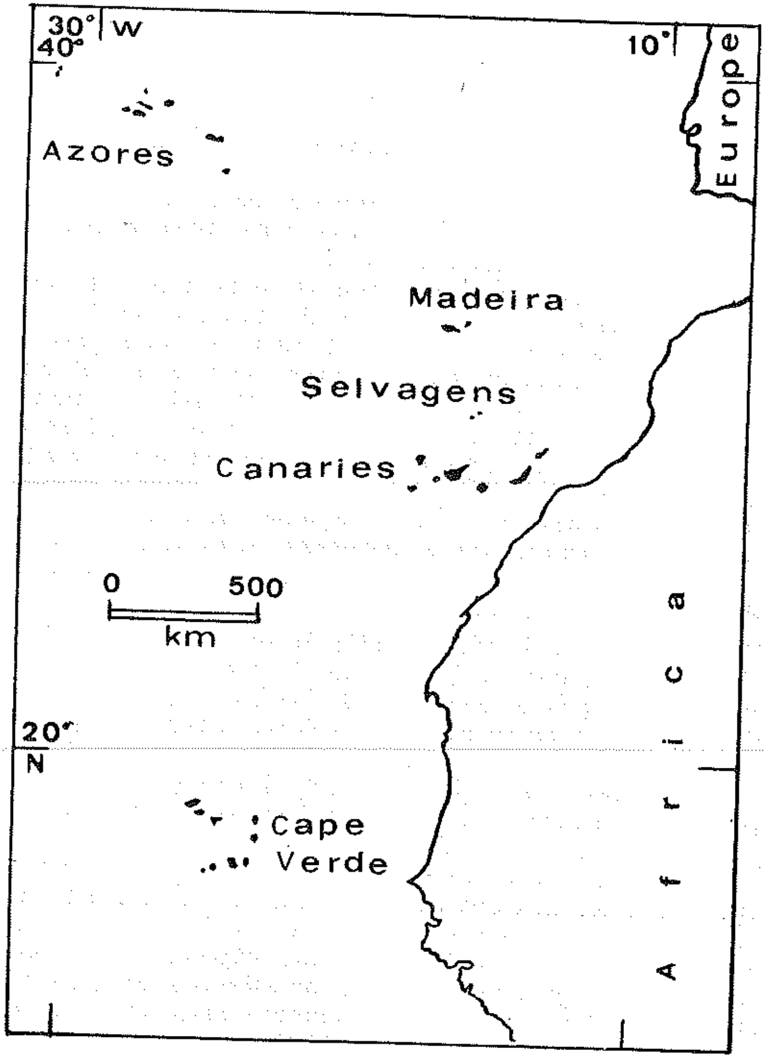

Fig. 1. — Macaronesia.

for its diameter. That the islanders should have seen analogies between these large depressions and the shape of cauldrons or kettles is very understandable. Their early use of «calderas» («calderetas» if small) and «calderas» («caldeirões» if large, «caldeirinhas» if small), naturally enough without any comprehension as to modes of origin, set in motion a confusion which lasts to this day.

In geological parlance, a caldera has a specific meaning, being a large, somewhat rounded or oval volcanic depression, with a diameter very much larger than that of the intruded vent(s), wall and floor characteristics being of secondary importance. It is a structure resulting from volcanic mechanisms, to which are frequently added tectonic mechanisms, and as regards dimensions, is taken to be larger than a crater, in which purely volcanic mechanisms are responsible.

The word «caldera» was adopted into the geological vocabulary by von Buch in 1825. There is some doubt as to whether he took the name from the Caldera de Taburienta in La Palma (which has the dimensions of a caldera) or from Caldera de Bandama, Gran Canaria (which is a crater). In von Buch's time, a dimensional distinction between calderas and craters was not made (today we consider calderas to have a diameter of at least some 1.6 km, craters being smaller) nor was the volcanic nature much stressed — as opposed to erosional, etc. origin — so that early on confusion arose. In the succeeding years, scientists, and geologists no less, have compounded the confusion by indiscriminantly referring to almost any relatively deep depression with precipitous walls of natural occurrence as calderas or caldeiras, paying attention neither to dimensions nor origins. This is particularly true in the Spanish and Portuguese languages as regards these Macaronesian features. That geologists of these nations should be guilty of such loose terminology is all the more surprising in that in both tongues, the word «cratera» is recognized, and most assuredly Spanish and Portuguese geologists are aware of the world-wide distinction, based on dimensions, between craters and calderas.

Thus Spanish and Portuguese literature, maps, sections, etc. repeatedly refer to «calderas» and «caldeiras» which have neither a volcanic origin nor yet the dimensions of such. The English language is considerably more precise than many other languages in its geological nomenclature, but geologists in general throughout the world have recognized the above distinction, but not so the Spaniards and Portuguese.

It follows then that here are mentioned far fewer calderas than the Spanish and Portuguese literature, etc. refers to — the great majority of such are craters, not calderas.

In Macaronesia, quite a few large depressions have been thought to have resulted to a large extent — perhaps even entirely — from erosion and gravitational mass movements. Unfortunately we have no term to refer to great hollows resulting primarily or entirely from exogenetic agencies and processes. Williams (1941, 1968) persisted in the term «Erosional Calderas» for «unusually large depressions formed within summits of volcanoes by erosional widening of original craters», and not the results of subsidence or collapse. The term is scarce appropriate, for it excludes other exogenic agencies than erosion, and most certainly landslides, slumpings, rock falls, etc. can hollow- out depressions by «widening of original craters». Exogenic Calderas seems a more appropriate term to use, though in the case where such alone have been operative, the resulting depression is not strictly a caldera. Thus Exogenic Calderas are to be recognized in Macaronesia.

Again, within some of the islands notable depressions are found linear in plan and relatively narrow, e.g. Valle de Orotava, Valle de Guimar in Tenerife, the Ribeira Grande valley in Sto. Antão, etc. Such features, not of circular or oval shape and bordered by linear rims are to be classed as Volcano-Tectonic Depressions, akin to graben, determined by structural characteristics of sub-volcanic basements. In Macaronesia, most such features have been described as «calderas» or «caldeiras», which again is confusing.

Thus for these islands, we shall limit ourselves to discussing only true volcanic calderas and such great depressions where exogenic processes have most certainly been operative, perhaps to a dominating, even complete, extent.

Caldera Types and Origins

Williams' 1941 classification of caldera types became well known and widely accepted, and is still used by many today. However in 1968, he and McBirney realized some amendments were necessary in the light of later studies. Summarizing their more modern treatment would recognize the following types:

A. *Explosion Calderas*. Large, oval-shaped depressions, caused by collapse of volcano flanks as a result solely of steam-blast eruptions.

B. *Erosion Calderas*. (= Exogenic Calderas). Very large depressions within volcano summits, caused by deepening and widening via erosive agencies.

C. *Engulfment Calderas*. Several subdivisions are possible here:

1. Calderas associated with voluminous explosive eruptions of siliceous magmas:

    a. Krakatoa type. Subsidence due to copious magma eruptions in the form of pumice falls and pumice flows.

    b. Katmai type. Subsidence due to drainage of magma from central vent, perhaps also from some of the deeper chambres through adjacent conduits.

c. V a l l e s t y p e. Subsidence due to discharge of great volumes of pyroclastic flows (ash and pumice) via arcuate fissures unrelated to preexisting volcanoes.

2. Calderas associated with effusive eruptions of basaltic magmas:

a. M a s a y a t y p e. Migration of magma at depth causes repetition of vent collapses, within summits of broad, basaltic shield volcanoes.

b. H a w a i i a n t y p e. Subsidence occurs during later stages of growth of large, basaltic shield volcanoes, the collapse resulting from withdrawal of a summit-block with steeply dipping ring fractures.

c. G a l a p a g o s t y p e. Likewise collapse occurs during late stages of growth of large, basaltic shield volcanoes, but engulfment is principally due to sill injections and lava eruptions through peripheral fractures near summits and from radial fractures far down the flanks.

3. Calderas associated with mixed eruptions from ring fractures:

a. G l e n C o e t y p e. Intermittent eruptions, continuing for a long period, of lavas and pyroclastics from arcuate fractures around a subsiding cauldron.

b. S u s w a t y p e. Engulfments of summits of large volcanic cones and cone-clustres, around ring fractures, causes collapse due to magma withdrawal or gravitational settling. As distinct from the Krakatoa type, eruptions do not precede and instigate subsidence, but rather are consequent upon collapse.

These authors have a final division, Volcano-tectonic Depressions, large collapse features associated with vast eruptions of pyroclastic flows, whose forms are controlled by structures in basement rocks. Such have a graben appearance, lacking the cirquelike appearance of true calderas.

The above classification, like all classifications of natural features, has a large measure of artificiality, and in reality, the majority of calderas result from a combination of causes. The three principal groupings of engulfment calderas, based upon magma types and relative amounts of lavas and pyroclastics, calderas formed as a result of explosion only and those hybrid features, exogenic calderas, represent more significant distinctions.

Explosion, per se, can create very large hollows in volcanic terrains, later enlarged by erosion, etc. but such appears to be a very rare occurrence. The vast majority of calderas are formed by other mechanisms, usually polygenetic in origin, as distinct from the former which are monogenetic. Drainage of magma away from its reservoir, usually in the form of ash and pumice, leads to copious expulsions through vents and very frequently subterranean oozing into fractured zones. Fluid lavas to a lesser extent may cause eruptions from flank fissures, especially from basaltic shield volcanoes. Concomitant explosive action, so common a feature in caldera formation, may find exits from summit vents of older volcanoes, from arcuate flank fissures, and even perhaps from fissures lacking relationships with earlier-formed volcanoes. The sagging of the magma chamber roof is assumed to result from lack of support, which latter could occur via loss of magma already expelled, increased magma chamber volume resulting from tectonism, magma volume diminution as a result of cooling and volatile losses, or then various combinations thereof.

Circular fractures could be expected to promote gravitational subsidence, perhaps with surficial eruptions taking place at the same time. Once it was thought that the ring fractures of calderas should be either outward-inclined or vertical, but the concept of inward-dipping boundary faults has increasingly gained acceptance. The common feature of the «basining» of beds within the caldera, and such type faults developing during the tumescence which precedes the accompanying and subsequent explosions are arguments in favour of inward-dipping boundary fractures. The sinking cylinder or block may be less dense than the magmatic milieu, in which case relative densities will determine the point of buoyancy. With a higher density sinking block, settlement will continue until prohibited either by higher density material encountered at depth or then by material stoped earlier from the chamber roof. Williams and McBirney remarked that proneness to collapse is increased if the caldera is small compared to the magma reservoir, if said reservoir lies near the surface, if its roof has a gentle inclination and if it is already perforated by innumerable conduits.

Post-collapse movements can occur in the caldera and vicinity. There may be a resurgence or tumescence of magma after initial withdrawal, perhaps even a pulsatory mechanism. The caldera floor can be upheaved, break-throuph to the caldera floor can occur, or then the caldera perimeter.

Caldera formation involves mass movements, and wherever such occur on a grander scale, conditions of unbalance in the Earth are created. Isostatic readjustments aim to restore balances. Vast quantities of material are explosively expelled in calderas, the volume of subsidence almost invariably being much greater. After the initiation of sinking, the chamber roof will undergo isostatic adjustment, during which time the centre settles and the perimetral rims rise in trying to reestablish equilibrium. Along with such there may be significant tiltings of the structure as a whole, resulting in interior step-faulting.

Macaronesian Calderas

The scientific world at large recognizes some two dozen calderas in these archipelagos. Volcano-tectonic depressions would add a further five or six. The majority of the two dozen are subsidence features, a few may be due solely to exogenic processes, and these will be briefly described below.

1. C O R V O . The greater part of this small island comprises the flanks of a caldera located in the NW sector. Basalts, basalts tending in places towards andesites, and intercalated tuffs constitute the form, with numerous basaltic and andesitic dykes, either radial or then orientated NE-SW. Within the caldera are scoria cones and two very small shallow lakes. The western slopes and caldera wall have undergone drastic erosion, principally marine, with consequent undermining instigating landslides, rockfalls, etc. Within a relatively short time geologically, it can be expected that the western caldera rim will be breached and the lakes emptied. Formidable cliffs occur N and E of the caldera at distances of ca. 1 - 1.5 km, from respective coasts and in the geological scale of events, trenchant marine erosion plus lesser so, fluvial erosion, can be expected to largely destroy the entire island.

2. F L O R E S . The caldera of Pico da Sé lies in the NE part of the island, the eastern rim being some 1.5 km distant from the E coast. This is a trachytic and andesitic complex, forming one of the five volcanic complexes of Flores. Within the caldera rises the prominent trachytic cone of Pico da Sé to an elevation of 722 m, the surrounding caldera floor lying on an average 300 m lower. The depression is drained eastwards by the Ribeira da Badanela exiting at an elevation of some 120 m. The eastern rim is the lowest, descending from ca. 400 m to less than 200 m. A well-defined semi-circular crater, 200 m in diameter and also several Péléan-type needles are present in the eastern part of caldera. The southern part of the caldera is drained by the Ribeira d'Além which joins the Badanela near the exit. These streams have eroded the caldera interior into a complex of ravines and prominent interfluvial spines. The Além valley is marked throughout by thick basaltic flows which exit from the caldera and flow down to the coast.

3. F A I A L . The caldera occupies a central and summit position of the main volcanic massif which constituted the primitive island. Within the caldera exposures of trachytes, andesistes and peridotitic andesites occur, pyroclastics (cinders, scoria, pumice, agglomerates mostly) forming much of the interior walls and far down all the flanks. About half the area of the caldera interior shows talus and alluvium deposits. There is also here a lake and small but prominent latite eruptions and a secondary cone having a crater, 125m in diameter and 30 m deep. The caldera floor has an average elevation of 580 m, with several fumaroles in the flat, southern part. Though the N rim has a lower eleva-

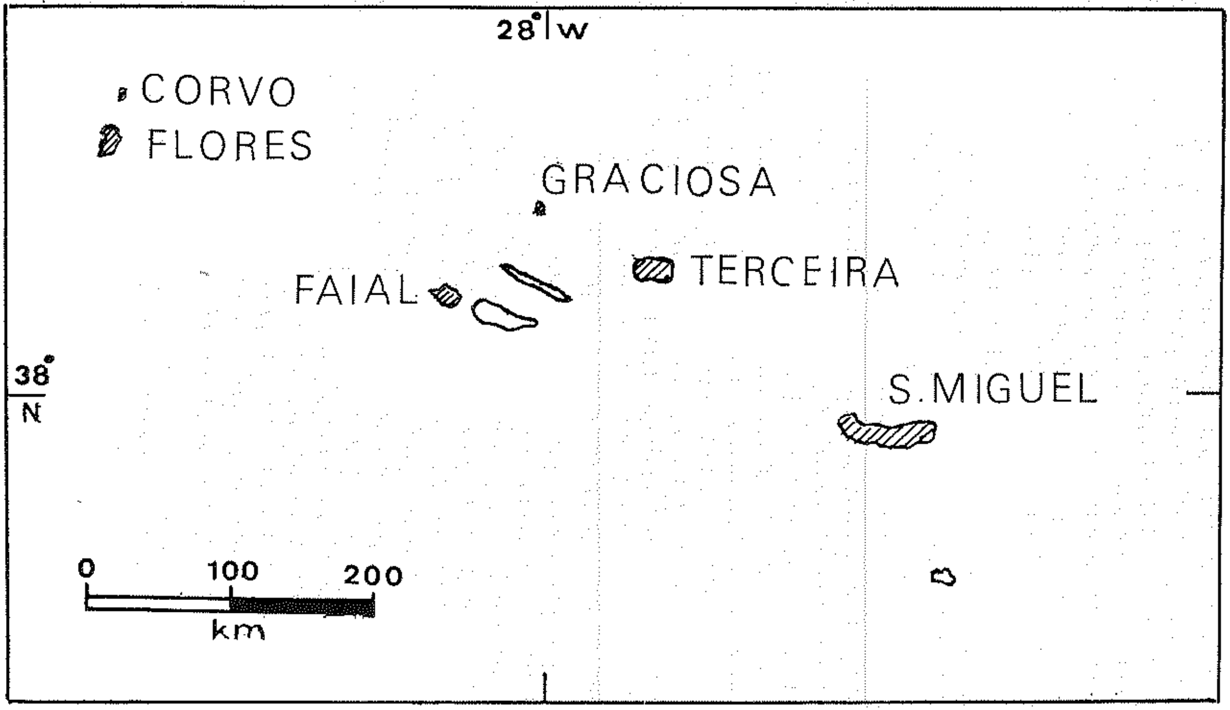

Fig. 2. — Islands with Calderas in the Azores Archipelago.

tion than the southern one, slopes down to the caldera floor are steeper along the former perimeter, the caldera interior being tilted towards the N-NW. Subsidence is thought to have been preceded by powerful explosions of pumice and cinders of trachytic composition. Such tephra is 70 m thick along the borders of the caldera, and 10 km distant is at least one metre thick. This caldera represents one of the rarer instances in which volumes of explosive material and of subsidence are roughly equal, Machado (1965 a) remarking that such are ca. 0.7-0.8 km^3, from which he concluded that the central block occupied the identical space as where the explosive material came from.

4. C A N A L D O F A I A L . Within the strait separating the islands of Faial and Pico, the nature of the bathymetric contours plus faulting in neighbouring Faial, first led Machado (1957) to suggest the presence of a submarine caldera here. Already in 1953 Berthois seemed to imply such a feature in the strait, and further mapping in Faial by Zbyszewski et al (1959) substantiated faults striking eastward, a transform one through Baixo do Norte submarine bank and Ilheus de Madalena to the Pico coast. These faults border a steep basin to the S and a gentler depression to the N. Between Baixa do Norte and Baixa do Sul — another submarine bank — the isobaths show a distinctly rougly circular basin, maximum depth of 195 m. The SW, S and SE borders steepen relatively rapidly from the 70 m isobath downward; the NE and SW edges are outlined by the shallow banks. There is indeed a strong likelihood that here is a submarine caldera. Berthois spoke of downthrows of 120-130m in Faial coastal areas. The 70 m isobath marks the true beginning of crowding of the bathymetric contours, and subtracting this from the maximum depth of the basin gives a figure of 125 m, which could represent the extent of subsidence undergone by the depression. Consideration taken of probable submarine rifting in the area, multiple graben structure in eastern Faial, transcurrent and gravity faulting in the same island, significant vulcanism and seismism extending into historical times in both Faial and Pico, the general gravity pictures determined in these islands by Coelho (1968 a), all combine to lend substantiation to a caldera structure in the 6-7.5 km wide body of water, but further investigations are lacking.

5. G R A C I O S A . An ideally elliptical small caldera lies in the SE part of the island. Basalts occur within the structure and as a single external flow, whilst andesites occur lower down the exterior flanks. Within the caldera are two well-preserved semi-circular craters, some volcanic blisters or intumescences (Quellkuppen), rising as much as 50 m above the surrounding terrain, solfataras and fumaroles. Vertical fractures within the caldera walls are common. Agostinho (1937) ascribed the caldera to subsidence due to relaxation of pressure within the magma «chimney», the flatter floor forming as a result of gas explosions within the deeper accumulating magma. The well known Furna do Enxofre is

at times highly active, with sulphurous and carbonic gas exhalations. This solfatara hollow measures 180 x 150 m, is more than 40 m in height, contains a small lake almost hidden by a basaltic roof. The temperature of the fumarole is almost always lower than 30° C. Saucier (1965), the only one to study the caldera in more detail, thought that sinking took place along a complex set of both radial and concentric fractures, the latter being best observed along the inner eastern sides. Solfataras, fumarloes and Quellkuppen have interested also several foreign workers, e.g. Hartung (1860), Friedländer (1929), Berthoois (1953) and Krejci-Graf (1961), the last-mentioned establishing a genetic relation between solfataras-fumaroles and Quellkuppen.

6. TERCEIRA.

(A) Santa Barbara caldera lies in the W of the island. In reality, there are two calderas here, an older, larger one, whose, western rim is less well developed, and a nested smaller, younger one, with well developed walls all around. (In Table I, data are quoted for the older caldera.) Here we have a large, truncated, strato-volcanic cone, with a diameter of some 8-9 km, rising to a height of 1021 m, and forming one-third of the island. Andesites occupy the lowest stratigraphic position, followed by trachytes, both being intercalated with pyroclastics, especially pumice. Radially outward extend andesitic, thin lava flows, and thicker more extensive trachytic flows. External western slopes are regular, with deeply incised valleys, many adventive cones and trachytic domes. Other external slopes are more interrupted by eruptive centres, with thick, overlapping basaltic, trachytic and andesitic flows and a profusion of scoria cones and domes, including the mushroom-domes of the 1761 eruption. Two very small lakes lie within the younger caldera, each showing centripetal drainage, in small enclosed corridors which appear to be small graben, with N-S inward-facing fault scarps. Within the caldera rise several trachytic domes, to a maximum height of 982 m or some 60 m above the general surroundings. Mottet (1972) mentioned, for the old caldera, small circular faults with downthrows not greater than 5 m, only well developed on the SW side. The younger caldera likely subsided more, resulting in «capturing» of headwater streams, blocking their exits and so creating marshy conditions and also the two lakes. This second subsidence appears to have stabilized somewhat the major volcanic structure. The calderas here represent but a very small fraction of the strato-volcano, but infilling has been extensive. It is to be noted that of the three calderas in Terceira, both the Faye anomalies (max. + 205 mgls) and the Bouguer anomalies (min. + 91 mgls) show the clearest distinct closed patterns for Santa Barbara. (Coelho, 1968 a).

(B) Guilherme Moniz caldera has a well-marked rim to the W, SW, S and SE, sinuous and interrupted by faults perpendicular to the walls. There is also a SW-NE longer fracture paralleling the Serra do

Morião at the SE side of the caldera. Post-caldera trachytic and basaltic flows and pyroclastics moving to the S and SW have obliterated the walls to the N and NE. The floor is occupied by basalts, the lower inner walls showing outcrops of trachytes and trachy-andesites, the latter usually intercalated with pyroclastics. Prominent scoria cones (Strombolian) are found bordering the caldera to the N and NE as well as one peak within the caldera. The caldera rims in the S and SE are offset by N-S orientated faults, faulting likewise having affected the Serra and tilted the latter into a complex pattern. The southern part of the caldera floor is remarkably level, dotted throughout by small shallow lakes and ponds, which often become dry in summer. On the southern exterior flank, trachytic flows occur, whilst to W and E, basaltic flows of aa type, course down to the sea. Faulting is held responsible for the somewhat rectangular shape of the caldera and general linear perimeters. The reason for the degree of flatness of the caldera floor is not clearly vident — perhaps aeolian action?

(C) Cinco Picos, largest of the three calderas, almost coalesces with Guilherme Moniz to the W. It is the opinion of Zbyszewski et al (1971) that this is an old caldera of a primitive volcanic massif which has been largely dismantled. To the NE is the prominently curved rim of Serra do Cume, rising to 545 m, with steep interior slopes, gentle exterior ones. To the SW lies the more or less linear Serra da Ribeirinha, with less steep interior slopes, more steep exterior slopes than Cume, and rising to a height of 410 m. Elsewhere the caldera walls are not clearly outlined structurally, but a topographic boundary can be observed. The interior floor, large enough to be termed a plain, comprises wellcultivated extents of gently rolling landscape. Recent basaltic flows and several prominent Strombolian cones rising about 180 m above the surroundings — the Cinco Picos — where there also occurs a small lake, which is neither a crater lake nor a maar, but rather a small damed lake blocked by a small puy, as per Mottet (1972). The floor is formed of basalts and overlying pyroclastics, the former emerging to the surface in the southern sector. The lower interior slopes of Cume show trachytes which also have smaller outcrops in the eastern floor. The Cume curved escarpment is a fault scarp, and within the caldera, scoria cones and craters align themselves along NW-SE directed fractures.

7. S Ã O M I G U E L . Four calderas occur here, of which two are well known.

(A) Sete Cidades, in the extreme NW of the island, though not the largest or most spectacular of calderas, is surely one of the most scenically attractive calderas of the world, with its two beautiful green and blue lakes, the smiling, neat, green landscape, sunshine, blue skies and blue sea. Along the northern inner walls of the caldera, andesites and peridotitic andesites occur, the latter only along the western walls, towards the S and E, peridotitic andesites, trachytes and basalts. This explosion-collapse feature shows present volcanic activity only in the form of mineral springs, chlorinated sodic waters issuing at a temperature of 62.5° C. Within the caldera are several secondary forms, scoria cones and perfect craters, and also five lakes. The two largest lakes, Azul and Verde, are thought to be subsidence features post-dating the volcanic eruptions of the cones W of here, as no tephra from these cones occurs in these two lakes. The evolution of the caldera site is as follows: (a) formation of large volcano of Sete Cidades, constituting an independent island, formed of peridotitic andesites and similar-type pyroclastics. (b) formations of caldera by explosion followed by collapse. (c) appearance of secondary eruptive centres in following sequence: (i) trachyte flows S of Lagoa Verde and E thereof, (ii) emplacement of smaller cone NW of Lagoa Azul, (iii) formation of two larger cones W and SW of Azul. (d) renewed sinking forming present sites of Azul and Verde. (Zbyszewski, 1961). The last eruptivity at Sete Cidades is thought to have occurred between 1432 and 1444, resulting in pumice explosions. Dykes and fractures around the caldera have a general NW-SE trend, and to the SE, fractures as long as some 9 km are the loci of many cones and crater summits.

(B) Água de Pau caldera lies within a trachytic volcano, with basaltic and andesitic flows lower down the exterior flanks. Emissions of trachytes first formed a large composite cone, followed somewhat later by peridotitic andesites along with trachytes. Following these events basalts and peridotitic andesites erupted more or less simultaneously, the sequence forming the volcanic structure. Then occurred many acidic eruptions of highly explosive nature, forming thick layers of trachytic pumice, and it is presumed this was followed by subsidence to form the caldera. Present vulcanicity is restricted to fumaroles and mineral springs. Lagoa do Fogo lies in the central part of the caldera, the latter having better preserved walls along the western and eastern sides. NW-SE larger fractures predominante over smaller NE-SW ones. Machado (1955) remarked upon the many basaltic cinder cones eccentric to the caldera which appear to outline a distinct radial pattern of fissures, concentric pattern less well developed. Such alignments extend N and S to the respective coasts and up to 9 km latitudinally. Of all the S. Miguel calderas, Água de Pau is most clearly demarcated by Bouguer gravity anomalies, an elliptical closed pattern showing a minimum of + 103 mgls at Barrosa, 945 m, just W of the lake. (Coelho, 1968 a).

(C) The caldera of Furnas is known chiefly for its many mineral springs and fumaroles. The caldera opens southward, and to the E, coalesces with the Povoação caldera, sharing a common rim for part of their perimeters. Within the walls, trachytes, latites, andesites, alternating with pyroclastics, are to be seen, with trachytes occurring in the central, southern and eastern parts of the caldera, basalts in eastern part, and exterior flows to the N and S. Within the caldera, trachyte, andesite, peridotitic andesite and basalt dykes are common. Here also occur three modern structures of trachytic composition, two of which were erupted in 1630 displacing lakes. At present, vulcanicity is limited to fumaroles and active mineral and thermal springs. The mineral waters are extremely varied and include: (a) hyperthermal alkaine, (b) hyperthermal slightly acidic, (c) cold acidic, (d) hyperthermal acidic, (e) cold neutral, (f) mesothermal neutral, (g) strongly hyperthermal acidic. Chemical composition no less shows wide variation. (Lepierre, 1917, Zbyszewski, 1970) Lagoa das Furnas appears to occupy the base of an old crater, the S-SW edges of the lake suggesting this. E of the lake are two large coalesced craters, with a smaller crater within. Fumaroles and mineral springs are chiefly concentrated to the NE of the lake, and here also, as well as by the lake side, mineral spring deposits occur, siliceous or ferruginous, often with sulphur efflorescences. Fracturing and dyke formation are not common in the caldera area.

(D) Povoção, in the eastern end of the island, is the largest caldera. As remarked above, in the W it partially coalesces with Furnas, and like the latter, is also open towards the S. The walls are more circular in shape, obliterated in the NE where more recent basalt flows have spilt over into the caldera. There is a well-developed dendritic drainage pattern, but the narrow, deep valleys do not show good volcanic exposures but are eroded into pyroclastics, especially pumice beds. In these valleys occur torrential conglomerates, of Late Pliocene or Old Quaternary age. The oldest volcanics, basalts, are exposed in the eastern part, part of the NE Basaltic Complex. There usually follow trachytes and latites, with peridotitic andesites on top. Several superb Péléan type «needles» occur within the caldera. In the southern sector, andesite and basalt dykes and small faults are numerous, the former having a radial pattern. To date, only natural gas exhalations are known in the caldera. Zbyszewski (1961) listed the following sequence of events: (a) formation of old basalts, (b) trachytic eruptions, (c) peridotitic andesite eruptions, (d) explosion followed by collapse of caldera, (e) trachyte eruptions within caldera and trachytic dyke formation, (f) emplacement of modern basalts. On the N and NW sides of the caldera, dykes tend to have a NW-SE trend, whilst on the E-SE sides, there is a diagonal pattern. The trends of Faye and Bouguer anomalies would suggest a WSW-ENE fracture extending across the caldera, abruptly terminated at the extreme eastern end of the island by a N-S fracture. (Coelho 1968a). S. Miguel is the most seismic of all the Azores — and the Azores the most seismic of Macaronesian archipelagos — and historic earthquakes have occurred in or near all four calderas mentioned here, along with rejuvenation of volcanic activity, so that relatively speaking, S. Miguel is highly unstable.

8. MADEIRA. Two large and spectacular depressions occur in the South-Central part of the island, those of Serra de Ãgua to the W and Curral das Freiras to the E. The latter, a truly stupendous hollow, variously described as «a scene conjured up by Walt Disney» and «an earthly representation of Dante's Inferno», is, without doubt, the premier attraction to tourist and scientist alike. The higher walls of each caldera comprise mostly trachytes, trachy-andesites and trachy-basalts. In the lower interiors, basalts intercalated with pyroclastics are commoner. Both coarse- and fine-grained tephra occupy most of the interiors. Though scoria cones are not lacking, craters are scarce ever preserved in the general region. One the exterior flanks, to NW and SE, with one or two small exposures within Serra de Ãgua, are plutonics, comprising gabbros, essexites, and more rarely, diabases and teschenites. Prominent towards the exteriors of both depressions are extensive developments of dyke networks, being chiefly of basaltic and trachytic composition. In Serra de Ãgua, dykes more generally have a W-E orientation, but in Curral das Freiras, a crude radial pattern is evident. The common junction of the two calderas is transected by a maze of dykes. In Serra de Ãgua, the Ribeira Brava and its tributaries display a centripetal pattern, likewise the Ribeira Socorridos and its tributaries in Curral das Freiras. Both streams exit southward in deep, narrow gorges. These calderas of Madeira, and even more so those of the Canarias, have given rise to wide speculation as to their modes of origin, this being probably due to the fact that more scholars, especially foreign, have visited the calderas of these two archipelagoes than those of the Azores and Cape Verde Islands. Stübel (1910), Gagel (1913, 1915), Morais (1945), and partially so, Ribeiro (1949) for example claimed that here we have true volcanic calderas, with explosivity followed or not followed by internal collapse — typical Azorean mechanisms. On the other hand, Lyell (1854), Hartung (1864), Grabham (1948), Lautensach (1949), Blumenthal (1961), Machado (1965 a), Montaggioni (1968) and Zbyszewski (1971) all believed that these great depressions resulted solely from erosive processes. Further comments on these calderas as regards mode(s) of origin will be given later. Faye anomalies show a maximum of + 386 mgls centred on Pico do Arieiro on the eastern rim of Curral das Freiras, and Bouguer anomalies, a minimum value of + 183 mgls at the same place. Though both anomalies show closed patterns, these do not clearly coincide with the calderas, but in a broad way, maximum Faye and minimum Bouguer occur in the Serra de Ãgua - Curral das Freiras area. (Coelho, 1968 b).

9. LA PALMA. The Caldera de Taburiente and Las Cañadas in Tenerife are the best known calderas in Macaronesia, and certainly have attracted most scientific interest. The great amphitheatre of Taburiente is open towards the SW, drained by the Barranco de Las Angustias and its tributaries. The W-NW rim forms a most impressive

feature, the El Time escarpment, whilst the northern walls attain heights over 2300 m, culminating in Roque de los Muchachos, 2426 m. Within the deepest parts of the caldera, the Basal Complex outcrops, comprising gabbros, basalts and salic trachy-syenites, completely metamorphosed, submarine emissions of oceanites, doleritic basalts and subaerial polygenetic agglomerates, with dense dunitic breccia dyke networks, the breccias having groundmasses ranging from basaltic to

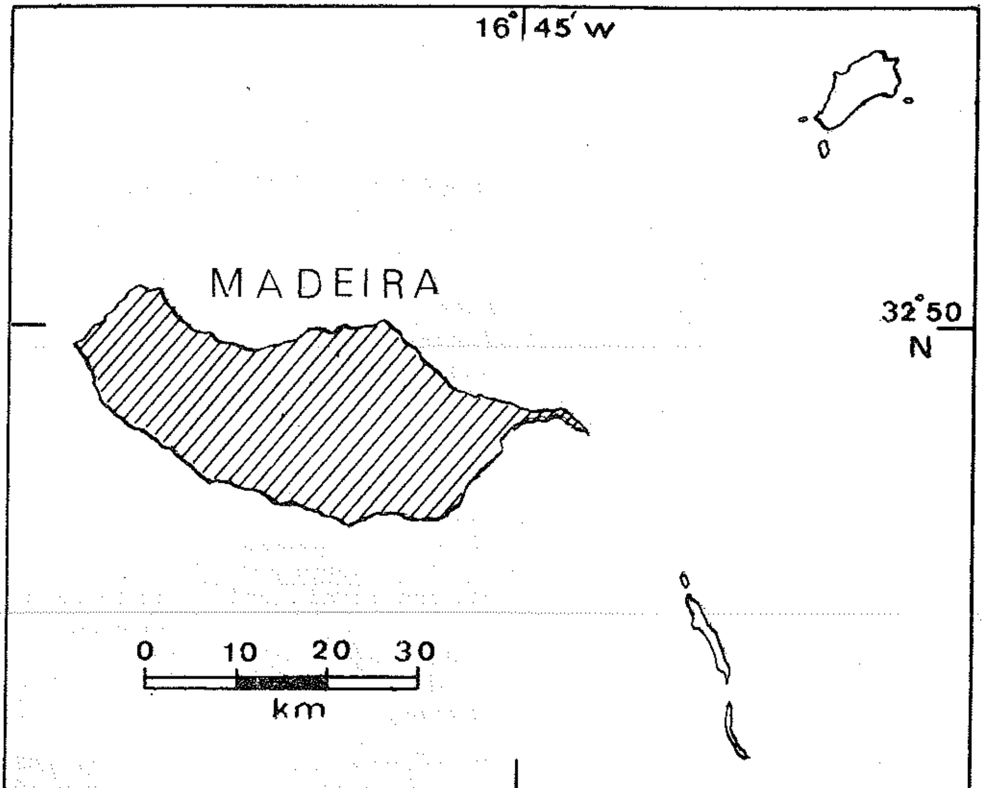

Fig. 3. — Islands with Calderas in the Madeira Archipelago.

gabbroidal. Higher up the interior slopes occur basalts and pyroclastics with gentle outward dips, forming remarkably steep walls, up to 1000 m in height on the NW side. Towards the lower SW end of the caldera, talus deposits, gravel fans, fanglomerates, breccias, rockfalls and alluvium in valley bottoms occur. The reporting of sandstones, gravels and conglomerates containing Miocene (Helvetian?) fossils by von Fritsch (in Gagel, 1908) has never been confirmed in later times.

Since the days of von Humboldt and von Buch, the question as to the origin(s) of this immense depression has aroused a great deal of discussion. Three modes of origin have been proposed: (a) »craters of elevations», (b) collapse cauldron, (c) erosion plus mass gravitational movements. The adherents to these various schools of thought are as follows:

a. Craters of Elevation or Risen Craters.

- von Buch (1825)
- von Knebel (1906)

b. Collapsed Cauldron.

- Reck (1928)
- Ridley (1971)
- Middlemost (1972) — partly

c. Erosion, with/without Mass Gravitational Movements.

- Lyell (1855)
- Hartung (1862)
- von Fritsch (1867)
- Gagel (1908)
- von Wolff (1931)
- Bravo (1954) — explosion + erosion
- Blumenthal (1961)
- Machado (1965 a, 1965 b)
- Gastesi, Hernandez-Pacheco & Munoz (1966)
- Hausen (1961, 1969) — tectonics + erosion
- Dingman & Nunez (1969)
- Middlemost (1970, 1972) — partly
- Hernandez-Pacheco (1971, 1975)

The old idea of craters or calderas being upraised by gas pressure (von Buch) or magmatic pressure (von Knebel), either of which eventually shattered the structure by innumerable fissures which later were widened, deepened by erosion, is not considered in favour today, and since pre-Lyell days, only von Knebel has upheld the view. But it must be admitted that the adherents of the other two views have not presented convincing evidences for their opinions. Further comments will be made later.

10. HIERRO. In this, the smallest, least known and least studied of the Canarian islands, there occurs a most impressive, large, scalloped embayment on the N coast known as El Golfo. The very steep

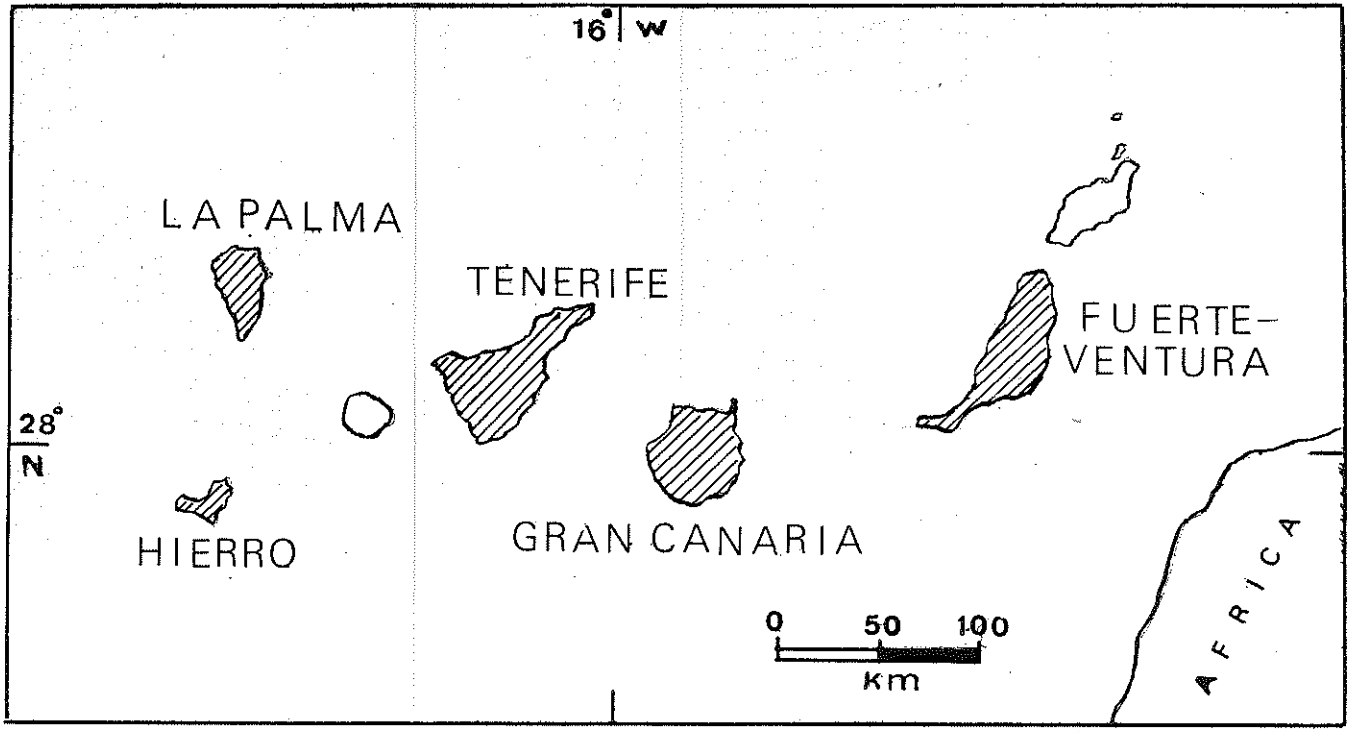

Fig. 4. — Islands with Calderas in the Canaries Archipelago.

N-facing walls afford an insight into the geological constitution of the island. The upper slopes here comprise alkali basalts and pyroclastics. Lower down within the embayment, basalts, trachy-basalts, trachytes and tephrites are exposed, along with cinder cones, tuffs and lapilli. Three principal volcanic series occur. The oldest forms the higher parts of the interior wall, whilst within the embayment and on the gentler exterior slopes to S, E and W, lavas and pyroclastics are present. Youngest material is sporadically outcropping throughout the island. Within the embayment and on the exterior slopes, cinder cones and craters are numerous. The rim area shows many fractures which roughly parallel the curvilinear form, whilst in hte NE part of Hierro, within some 2-3 km of the eastern walls, more pronounced and lengthy fractures strike NE-SW. Von Knebel (1906), Fernandes (1908), Blumenthal (1961), Ridelly (1971) and Coelho (1971) all favoured a subsidence origin for this feature, though some also recognized explosive activity and tectonism as playing roles in the mechanism. On the other hand, Hausen (1973) and Pellicer (1977) favoured an exogenic origin, both recognizing that faulting has aided in the process. The first «school» would argue El Golfo is all that remains of a central caldera of which half has subsided beneath the sea. Admittedly some 30 km N of the island there is an abrupt shallowing of the sea, forming a domical, small area less than 2000 m deep, but such is not thought to have any relation to a submerged caldera. Isotopic age determinations by Abdel-Monem et al (1972) gave values of ca. 0.20 MY for the upper basalts (Tableland Basalt Series of Hausen) and for one sample at the base of El Golfo. They concluded the island was not older than ca. 3.30 MY (hence the youngest in the archipelago), and that the El Golfo scarp dates from some 0.2 MY.

11. TENERIFE. Pico Teide, 3718 m, highest peak in all the Atlantic islands, and the imposing southern wall of the caldera Las Cañadas, are well known sights to all who have visited this beautiful island. A predominantly basaltic shield was the first vulcanic episode, now exposed in the NW and NE peninsulas, and thereafter vulcanism was restricted to the island centre, as witnessed by the intermediate and salic flows, lapilli and volcano-clastites comprising the Cañadas Series. Series rocks include trachytes, mafic phonolites, basalts, trachy-basalts, welded tuffs, etc. After this episode, the twin volcanos of Teide and Viejo were formed. The culmination of the Cañadas vulcanism was the formation of the caldera, from within which the twin volcanos arose. SW from Pico Viejo, basaltic and trachy-basaltic flows of the 1798 eruption form the flank here. Scattered within the caldera and around the rims are many scoria cones. From the two large interior volcanos, lava flows poured forth in all directions, almost to the base of the interior walls, but descent down to sea level on the N, presumably smothering the northern caldera wall.

As with Taburiente in La Palma, many ideas have been presented as to the origin(s) of this large depression. These may be classified thus:

a. Craters of Elevation or Risen Craters.
   - von Buch (1825)
   - Saint-Claire Deville (1846)

b. Explosion.
   - von Fritsch & Reiss (1868)
   - Gagel (1910)
   - Hausen (1955, 1961) — + collapse + erosion.

c. Erosion with/without Gravitational Mass Movements.
   - Lyell (1855)
   - Hartung (1862)
   - Benitez (1946) — marine erosion.
   - Bravo (1962)
   - Macfarlane & Ridley (1968)

d. Collapse.
   - Webb & Berthelot (1839)
   - Friedländer (1915 - 1916)
   - Fernandez (1916, 1917)
   - Blumenthal (1961)
   - Macau (1963)
   - Mingaro (1963)
   - Machado (1964)
   - Schmincke (1967, 1976)
   - Borley (1966, 1974)
   - Ridley (1970, 1971, 1972)
   - Arana (1971)
   - Fuster, Arana, Brandle, Navarro Alonso & Aparicio (1968) — collapse?

A recent view of volcano events here may be quoted from Ridley (1972) thus: (a) Period of activity of Las Cañadas Series, culminating in all the northern part collapsing and some of the southern part of the Series. (b) Collapse of summit along a ring fracture, amount of subsidence unknown. (c) Outpouring of pahoehoe flows into caldera floor. (d) Infilling of caldera with thin flows. (e) Second collapse along same fractures, but in SW area, thin flows adhere to the walls, forming a remnant block. (f) Emission of aa flow from limiting fracture on E side, partly filling floor. (g) Violent explosive activity in W part of caldera. Naturally such a sequence of events is not agreed upon by all, nor do all subscribe to a collapse origin. It should be noted, as Hausen (1971) remarked, that there actually are two depressions within Las Cañadas, the eastern one being somewhat higher and much more filled with lavas emanating from Pico Teide. No less are there two distinct scarps along the southern edge, the eastern one (Portillo) being distinctly scalloped and better defined than the western or Tauce scarp which shows a more simple curve. (Ridley, 1971.

12. GRAN CANARIA. Two well-known large depressions have long been known, and in recent times, the possibility of a gigantic caldera has been proposed.

(A) Tirajana caldera lies in the SE sector of the island, drained by the Barranco de Tirajana and its tributaries. The eastern side of the caldera comprises post-Miocene basalts; in the southern extremity trachytic-phonolitic-syenitic ignimbrites, trachytes and andesites occur within the major valley, and in the S, tephrites, basalts and younger olivine-basalts. To the N, tephrites, basalts and agglomerates predominate. Southern and northern rock occurrences are all considered older than the post-Miocene eastern basalts and are judged to be Miocene in age. Much of the central, lower part of the caldera interior are occupied by alluvium, talus deposits, rockfalls, etc. Some, e. g. Bourcart (1935) postulated a great fault running NW-SE across the island, the Tirajana stream making use of this weakness zone to carve out its channel, the fault pasing through the caldera with the same trend, downfaulting being to the E. As will be shown later, there is no such major fault in the island.

For this depression also, various scholars have put forth their views as to its origin(s), and can be summarized thus:

a. Craters of Elevation
or Risen Craters.
von Buch (1825)
von Knebel (1907)

b. Explosion.
Fernandez (1925)

c. Explosion plus
Collapse.
von Wolff (1931)

d. Collapse.
Benitez (1946, 1963)
Macau (1957, 1959)
Schmincke (1968, 1976)

e. Erosion.

von Fritsch-Reiss (1868)
Bourcart-Jérémine (1937)
Bravo (1954)
Blumenthal (1961)
Hausen (1961, 1962) + tectonism
Machado (1965 a)

f. Gravitational Sliding.

Fuster, Hernandez-Pacheco, Munoz, Rodriguez, Garcia (1968)

Each protagonist argues on behalf of his own views, criticizes the contentions of others, but all are open to questioning.

(B) The SE extremity of Tejeda caldera almost impinges on the NW edge of Tirajana. The former region has been given considerably more geological attention in recent times, such stemming from the work of Hausen (1962). Tejeda extends westwards from the high watershed of Cruz de Tejeda, the Barranco of the same name flowing to the W along the low axis of the caldera. A similar sequence of rocks outcrop here as in Tirajana, only the trachytic-syenitic complex outcrops in the extreme NW corner of Tejeda, whilst alluvium, talus deposits and chaotic landslide material are but sparingly developed. The inner, lower parts of the caldera show syenites, multiple trachyte and phonolite dykes, these latter constituting a cone-sheet complex of inverted cone structure. Hausen (1962) claimed the feature had not the slightest similarity to a true volcanic caldera the so-called «caldera» having a considerably smaller area than that of the Tejeda drainage basin. The feature he described as a broad valley, with wild gorges, steep mountain walls around, with a narrow exit in the W where the stream formed a water gap. Yet in 1970 he did mention a volcanic caldera with erosion and slumpings subsequently active after formation, and in 1971 was uncertain whether this was a collapse feature or one created by exogenic agencies or both.

Varying origin(s) have been proposed:

a. Erosion.

von Fritsch (1867)
Bourcart-Jérémine (1937)
Bravo (1954)
Blumenthal (1961)
Hausen (1962)
Machado (1965 a)

b. Exogenic Agencies.

Hausen (1970) + collapse

c. Gravitation Mass Movements.

Fuster, Hernandez-Pacheco, Munoz, Rodriguez & Garcia (1968)

d. Collapse.

Benitez (1946, 1959, 1963)
Macau (1957, 1959)
Schmincke (1966, 1967, 1976)
Hausen (1971)
Hernan (1976)

It should be added that in personal correspondence, Professor Schmincke has stated that his Tejeda caldera mentioned in his 1967 publication is in no way related to the erosional velleys of other authors — vd. below.

(C) Schmincke & Swanson (1966) first proposed «Eine alte Caldera» in central Gran Canaria, marked by a very steep contact some 25-30km in length and having a semi-circular shape. This contact had been interpreted by Bourcart & Jérémine (1937) as a great NW-SE fault crossing the island, passing through Tejeda and Tirajana calderas. The above authors (plus Schmincke, 1968) argued correctly that such a fault is non-existent, that rather we have a feature of «synvolcanic» origin, sharply delimiting basalts outside the curving trend from trachytic welded ash flows within. Hernan (1976) has elaborated further regarding the general geology and petrology of the area in question and the effusives within and without this feature, discussing the erosive discordancy concept of junction proposed by Fuster et al (1968) and the tectonic idea of Schminke & Swanson, agreeing with the latter authors. Schmincke has continued to illustrate in his maps and his descriptions of the region a partial curvilinear caldera wall, but in his more recent joint paper of 1976-77 and in personal correspondence, would now continue eastwards this caldera wall as far as Temisas, just E of the eastern rim of the Tirajana caldera. In this publication, the extension eastwards of the wall is referred to as the «Miocene Caldera Perimeter Fault». Thus the total length of the partial caldera wall is now some 55 km, and encloses both the Tejeda and Tirajana calderas. McDougall & Schmincke (1976-77) outline the history of events of this old caldera thus: (a) formation of a large, dominantly basaltic shield volcano, including all or almost all of the present island. (b) emission of trachytic, rhyolitic and trachy-phonolitic flows and welded ash flow deposits, accompanied by collapse of the caldera which was ca. 15 km in diameter. (c) infilling of the caldera and later intrusion of trachyte cone sheet swarm, syenite masses and phonolite dykes. (d) period of erosion. (e) second cycle of vulcanicity, involving basanites, ankaramites, tephrites, phonolites, essexites, with pronounced breccia sheets of similar composition. (f) second erosional period. (g) third magmatic cycle, first of olivine-nephelinite flows, succeeded by melilite-nepheline and basanite flows from innumerable foci. This last phase has continued to the Present. We thus have a first magmatic cycle of Middle Miocene age, a second phase of Pliocene age, and a third of Late Pliocene-Quaternary age, with major erosional unconformities between these volcanic phases.

This concept of one huge central caldera has the support of Schmincke, Swanson, McDougall and Hernan, but to date the topic is not mentioned in other literature. As remarked above, Tejada and Tirajana calderas would merely form parts of this huge central caldera, the former then perhaps being phreatomagmatic phenomena.

Gravity studies by Bosshard and Macfarlane (1970) showed a crowding together of Bouguer anomalies trending SW-NE about 15 km off the NW coast of the island, where a particularly steep gravity gradient — change of 138 mgls within 23 km — occurs, which is interpreted as a major fracture. The curving shoreline in the NW part of the island, with land exceeding 1250 m in height fronting the coastal area, reminds one of similar conditions in Hierro and Jandia, Fuerteventura, and isobaths here off Gran Canaria also are worth noting in pattern and range. Whether or not there is a sunken caldera in this marine area is unknown, but further investigation is warranted.

13. FUERTEVENTURA. In the extreme SW of the island the curving shore and arcuate paralleling mountain range have been suggested as remains of a caldera. The Jandia range is highly asymmetrical, with steep northern slopes, gentle ones to the S, the range and peninsula being separated from similar outcropping rocks to the E-NE by a low area — the Istmo de la Pared — of loose and consolidated calcareous agglomerates, tuffs and scoria, at times alternating, also with basaltic-type dykes. The curvilinear shore and asymmetric range were thought by Hartung (1857) to represent the remains of a caldera, almost all of which is now beneath the sea. von Fritsch (1867) seemed to incline towards this view also. Though neither of them actually say so, their views agree with a collapse mechanism. Bourcart (1938) believed that the N coast trend could only be explained by faulting parallel to the present coast, that part N of the scarp being downfaulted. Hausen (1956, 1958, 1961, 1971) also believed in downfaulting, the region being modified by subsequent marine erosion and gravitational mass movements, but almost no fluvial erosion. He thought the original flows emanated from centres to the N now below sea level. Lopez (1969) has shown that the Jandia dykes have three chief trends, parallel to the coast, NE-SW and NW-SE, which appears to lend some substantiation to fracturing. Benitez (1946) thought there was a sunken caldera here, further destruction being accomplished by

powerful marine erosion. Fuster et al (1968), like Hausen, also believed that eruptive centres must now lie below sea level to the N. They further thought that pre-Quaternary tilting of the island as a whole and differential rising of the western sector accelerated fluvial erosion, and marine erosion no less was operative, as testified by the high northern cliffs.

Thus of the origins proposed, caldera subsidence, downfaulting and erosion (chiefly marine), we have our choice, but in no instance is there convincing proof. Seismic reflexion studies by Arana & Palomo (1973) in the marine area somewhat NE of Jandia and within some 12 km of the coast, show an abrupt tectonic trench and scarp — a graben-like feature — heading SW towards the Jandia embayment. Whether this feature is in any way related to a possible sunken caldera here is unknown, and thus at this time, we have no clear ideas if there really is a caldera here or how it was formed.

14. S A N T O A N T Ã O . Here in the northernmost Cape Verde island there is a deep depression on the southern slopes in the western part of the island, known as Chão de Morte, Floor of Death, said to refer to the wiping out of the inhabitants during one of the many economic crises caused by drought which have affected the archipelago. Almost the entire inner slopes and floor are occupied by basalts and basalt flows alternating with lapilli and tuffs. A small part of the western wall shows phonolites, nephelinites and leucitites, whilst the outer western slopes show scoria, lapilli and tuffs. The western rim is the most pronounced, also parts of the northern wall, but to the E, maximum heights and inner slopes are considerably less. Dykes are common on the NW slopes, generally parallel to the present fault scarp, and such dykes may very well partake of the nature of ring structures. Within the caldera dykes also are numerous, but of no distinct orientation. The depression is drained by the Ribeira Patas and tributaries. It is believed that a NW-SE fracture zone crossing the feature, marked the loci of fissural basaltic eruptions, this weakened zone being taken advantage of by the main stream in seeking its route and exit towards the SE. A rapid release of magma here undermined the volcanic structure, followed by internal collapse due to magma withdrawal, in which case we have a collapse structure here. On the other hand, Bebiano (1932) favoured erosion as responsible for the large excavation, but whilst such no doubt has enlarged the depression, the latter is thought to be initially due to collapse. Mendes-Victor (1970) showed a strong Bouguer anomaly centre in the approximate location of the caldera, the many dykes and thermal sources in the depression suggesting to him that the volcanic focus must be near the surface. Both gravimetrically and geomorphologically, this depression is clearly outlined. Unfortunately the evolution of volcanic events here has not been studied — there are suggestions, for example, that dyke formation is

post-caldera in age, in places at least, and until this is done, we cannot be certain whether this caldera is of subsidence or exogenic origin.

15. SÃO VICENTE. Extending SE and well towards the southern and eastern coasts, is a large gently basinal area, surrounded in interrupted fashion by heights up to nearly 800 m. Within the basin both volcanics — basalts, basanitoids, analcitites, phonolites, limburgites, ankaratrites, nephelinites — and plutonics — syenites, gabbros, ijolites, teschenites, dolerites, etc. — occur as outcrops. To the E and

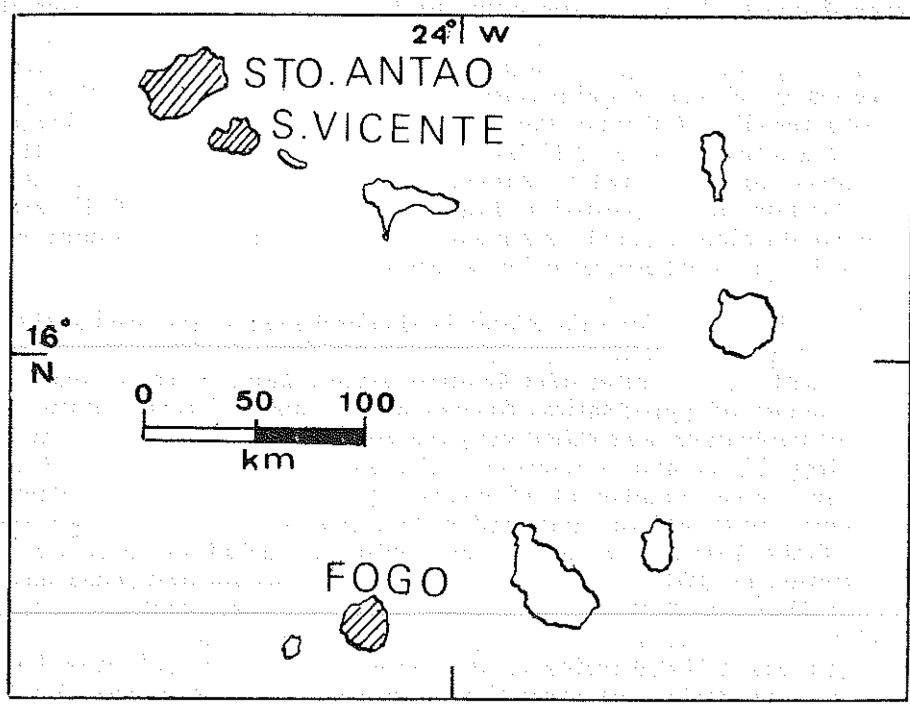

Fig. 5. — Islands with Calderas in the Cape Verde Archipelago.

S, the exterior parts of the basin comprise analcitites and basanitoids of the strato-cone structure; in the western and more central parts, basalts, with much pyroclastics, sometimes alternating occur. Along the central NW-SE axis, plutonics are exposed in the lowest areas. Dykes within the caldera show predominant NW-SE and W-E trends. (Mitchell-Thomé, 1960, Serralheiro, 1966). Bebiano (1932) referred to a main central eruptive locus just S of the port of Mindelo, where a 2 km radius would delineate a crater rim. He also spoke of a large «crater», presumably the present large basin, which has the dimensions of a caldera. The intermittent streams with broad, open valleys and mature appearance are outlined by alluvium and finer talus deposits, whilst alluvium extends 2 - 3 km inland from the bay of Porto Grande.

The writer (1960), Machado (1965 a), Serralheiro (1966), Assunção (1968) and Mendes-Victor (1970) have all considered this large basinal feature to be a caldera, though some seem to prefer a subsidence origin whilst others emphasize rather exogenic processes, chiefly erosion, both fluvial and marine (in part). At the NW end, marine erosion has broken through the caldera rim and carved out the semicircular embayment of Porto Grande, the best harbour in all the archipelago. Isobaths here — especially the 50 m one — would suggest the former extension of the rim seawards, the tiny Ilhéu dos Pássaros representing an emerged fragment. Mendes-Victor showed Bouguer anomalies of closed, roughly circular shape (maximum, + 310 mgls), the axis trending NW-SE, like that of the caldera. Stronger Bouguer anomaly gradients on the NE, SW and SE sides of the anomaly pattern he believed to be related to subsidence. From the residual anomalies closed pattern he suggested a fault at depth of general W-E trend, which would thus coincide approximately with the S-SE caldera rim. To him, this is a caldera of collapse origin.

16. F O G O . In this island is the best-known and best-preserved caldera in the archipelago, known as Caldera da Cha. Pre-caldera lavas, mostly nephelinites and kindred suites, along with a relatively small amount of pyroclastics, formed an original conal structure, cut by many nephelinite and other granular-rock dykes, well exposed in the inner steep N, W and S walls. On the outer slopes, to N, W, S and SE occur a great number of adventive cinder cones. The floor comprises chiefly post-caldera limburgites and basanites, and similar type flows of the 18th., 19th. and 20th. centuries, including those of the last eruption in 1951. The following sequence of events have been postulated by Machado & Assunção (1965) and Assunção, Machado & Silva (1967): (a) formation of volcanic cone, more or less symmetric. (b) slippage along a N-S directed fault, wherely the eastern side was down-dropped some 1000m. (c) formation of asymmetric cone of pyroclastics, exceeding 3500 m in elevation. (d) subsidence as per a circular fracture (= ring structure) of central part of cone which sank at least 1000 m. (e) period of lava effusions and formation of tephra, covering lower caldera floor and eastern scarp and overflowing out of the caldera. The eastern steep exterior slopes of post-caldera flows, overbrimming the caldera, reach down to the sea, and all those of historic times still present a chaotic mass of broken lava fields devoid of all vegetation. Assunção (1968) spoke of two great eruptive phases, a pre-caldera «Somma» phase, and a post-caldera «Vesbio» phase, adopting such terms from Vesuvius. Machado (1965 c) did not think explosion occurred here, as the volume of ejectamenta is inconsistent with such a concept, but probably isostatic adjustments occurred over the central volcanic

mass, the structure subsiding along a circular fault, now evident as the fault scarp of the perimeter. He estimated that the withdrawn magma chamber now lies some 8 km below the surface. Mendes-Victor (1970) remarked that Bouguer anomalies (maximum of + 304 mgls) in the caldera floor, do not clearly outline the caldera, except to the N and E, as do the residual anomalies, again only clear to the N and E. He thought that the configuration of the negative residual anomalies was an argument in favour of postulating a NNW-SSE fracture, coinciding more or less with the NW sector of the rim, such being responsible for the present geomorphologic aspect of the island. To date, Machado and Mendes-Victor are the only two to give more than passing attention to this most imposing caldera.

It is to be noted that some commanding depressions, of roughly circular or linear shape, occur in other islands, e. g. where Ribeira Brava, capital of São Nicolau lies, valley of the Ribeira Garças in Santo Antão, valleys of the Ribeiras Orgãos and Picos in Santiago. However, to date, neither the writer, nor seemingly others, have had time to study these areas in more detail, though the writer is inclined to see in these depressions a dominant role of exogenic agencies.

Types of Macaronesian Calderas.

The Azorean calderas have usually been placed in the Krakatoa type of Williams (1941), i.e. collapse subsequent to explosions of pumice and ash, amended 1968 to read pumice falls and flows. The formation of the majority of the Azorean calderas involved violent explosions followed by pyroclastic emissions largely of trachytic type. In Flores, Faial, Sta. Bárbara, Ãgua de Pau and Povoação, we have trachytic-antesitic flows and pyroclastics; in Graciosa, Guilherme Moniz, Cinco Picos, Sete Cidades and Furnas there occur material of basaltic-trachytic-andesitic materials, and in Corvo are basalts, some tending towards andesites.

We would amend the opinions of Machado (1965 a) as follow:

At Ãgua de Pau, drainage away from the caldera of trachytic and andesitic flows occurs a considerable distance away to the N, W and S, towards the N coast and lesser so towards the S coast. Further, a large fracture extending from near the N coast in a SE trend to SW of Lagoa do Fogo is outlined by trachytic domes, also suggesting drainage away from the sub-caldera magma chamber. Such features then suggest that magma withdrawal took place at considerable distances away from the site of the caldera, that this withdrawal caused the foundering and formation of the caldera. Phenonema such as these are more in keeping with a Katmai type of caldera. Williams & McBirney (1968) remarkel that apart from the Katmai-Valley of Ten Thousand Smokes in Alaska, no other calderas of this type had then been recognized, but saw no reason why such should not be found. (It is worth noting that not a single caldera in Macaronesia is mentioned by these authors.)

According to Machado (1957), Corvo, along with the other Azorean calderas, are transitional between Williams (1941) Krakatoan and Glen Coe types, confessing that the Azorean calderas do not correspond exactly to the Willianms classification. For Corvo, we would question Machado's remark. At Caldeirão, the lavas involved are almost entirely basaltic in nature, not mixed as in Glen Coe types, where, at the type locality at Glen Coe in Scotland, basaltic trachytic and andesitic lavas occur. Then ring fracture stoping is implicit in Glen Coe types — or at least discharge of magma via arcuate vents parallel and close to the border of the sinking block. Neither ring fractures nor arcuate vents are evident in Corvo. Radial dykes and smaller fractures occur down the caldera flanks, as well as fissural eruptions, all of which seem to pre-date the collapse — in other words, subsidence is presumed to have occurred at a later stage in the growth of the small volcanic island.

We are thus inclined to consider Caldeirão in Corvo as a Galapagos type of caldera.

Guilherme Moniz caldera appears to show intermittent eruptivity along the edges. The SW and S rims are taken to represent more linear-type ring fractures, and in these sectors of the caldera intermittent subsidence appears to have continued for a long time. The extremely flat floor could represent very gradual infilling and sinking whereby exogenic agencies did not have time to carve out irregularities, such smoothing as did occur being very superficial, perhaps of aeolian origin. Such features may be more indicative of a Glen Coe type of caldera, or at least transitional Krakatoa-Glen Coe.

The two calderas in Madeira have generally been considered as due to collapse or then erosion, as remarked above. Curral das Freiras especially, lesser so in Serra de Água, shows a very dense dyke network. The Ribeiras dos Socorridos and Brava, which exit from these depressions, are both controlled by fissures which have allowed gorges to be excavated. Extensive fracturing then is to be recognized within peripheral areas of the calderas, with large fractures extending from the calderas down to the S coast. The steep thalwegs of these drainage networks promoted powerful headward erosion, stream erosion and transportation leaving many rock masses in unstable positions, with consequent undermining leading to rockfalls and landslides. Thus the role of exogenic agencies in widening, deepening these depressions, is paramountly obvious. However the steep slopes, particularly in the northern parts of the calderas, along with other evidences of fracturing and fissuring, are taken to indicate subsidence, and copious pyroclastic development is suggstive of powerful explosive activity. They are classed as Krakatoa type.

Hausen (1961) in his summation, classified the Canarian calderas here mentioned as follows:

1. Erosion-landslide calderas, formed in fault-dissected parts of these islands.	Tejeda, Tirajana, Taburiente.
2. Semi-caldera produced by semi-circular faults on an island slope.	El Golfo.
3. Volcanic caldera in the true meaning, formed by explosions and subsequent collapse.	Las Cañadas.

Thus only Las Cañadas caldera is a volcanic feature, an opinion shared by Machado (1965 a).

As with Madeira calderas, extensive dyke development is present in Taburiente caldera. The El Time scarp and the valley of the Barranco de Las Angustias mark the sites of fractures. Dyke development took place in three phases (Hernandez-Pacheco, 1971), of which the last indicates conduits whereby the fissured series forming the walls escaped into the floor of the caldera, intimately transecting the Basement Complex. Immediately S of the caldera lies the El Paso tectonic basin (Middlemost, 1972), a collapsed block of 100 km2 area. The eastward-bounding fault of this graben region is continued southward through the island as a spine, Cumbre Vieja, with a great number of volcanic cones, craters, smaller volcanic pits, not to mention extensive faulting in adjoining vents. It is also to be noted that there appears to be no specific focus of central eruptivity in the caldera but rather a dense network of fissures through which magma oozed upward forming dykes. Such features, along with the very thick occurrences of tephra, inclines one to see here a feature resulting from explosive activity plus collapse. The caldera shows effusives chiefly of basaltic character, and this, along with the down-settling of the El Paso basin, plus the more distant extensive effusive activity of the Cumbre Vieja spine, appear to be suggestive of a caldera of Galapagos type. Undeniably exogenic processes have had powerful effects, on first acquaintance they dominate one's thinking, tectonism no less has been operative, but it is believed that initially we have a collapse structure here.

The relatively few geologists who have worked in Hierro have found El Golfo a puzzling feature. Hausen's (1973) concept of faulting triggering gravitational mass movements is appealing. Off the N coast lies the Canary Deep, with strong submarine slopes. The transfer of vast volumes of rock material via landslides, etc. into the sea would readily be distributed by waves, currents, perhaps turbidity currents, thus obliterating submarine evidences of such enormous mass movements. Somewhat arcuate faults do parallel the embayment, and such could have acted as surfaces of sliding. Ridley (1971) frankly admitted that the mechanism of formation of El Golfo remained unknown and Hausen (op. cit.) described the feature as unique in the whole archipelago — but see Gran Canaria and Fuerteventura. *If* El Golfo is a collapse feature, it would be of category C-2, but further refinement is not possible.

Las Cañadas is a collapse structure, and those in favour of such an origin seem to consider it of Krakatoan type, but Ridley (1971) has pointed out some features which would imply that caution should be exercised in so cataloguing the caldera. We would also add two comments. At this caldera site, salic flows and pyroclastics are present but also mafelsic products occur, hence we have mixed eruptions. Then it is to be noted that collapse likely occurred during the late stage in growth of vulcanism. Hence it appears that here we have features associated with engulfment calderas, but it would be hazardous to specify further.

In Tirajana and Tejeda calderas tectonism has played its part. In the former, large, generally N-S directed fractures, have been utilized by the Tirajana and Fatega streams to carve out deep valleys, headwater erosion by multiple tributaries being made easier by the abundance of less resistant tephra and chaotic masses of slumped material. In Tejeda we have originally a feature of volcano-tectonic origin, again widened and deepened by erosive action. In both these depressions, tectonic and volcano-tectonic preparations were made to facilitate the role of erosion, and the unequal resistance to weathering shown by flows and tephra caused drastic undermining and the consequent importance of rockfalls, landslides, etc. These calderas would be classed as Erosion Calderas by Williams and McBirney but the writer prefers to call them Exogenic Calderas, where both erosion and mass gravitational movements have been chiefly responsible for the features we see today. It is to be stressed that in all Macaronesia, to appreciate fully the role of exogenic agencies versus volcanio-tectonic processes in moulding the landscape, one should visit these islands, not when there is brilliant sunshine and blue skies, but rather in the wet season, when lowered clouds brush over the islands, strong winds blow, torrents come cascading down steep slopes, sheet erosion is actively scraping away the surface, ledges are being loosened and detached blocks thundering downslope. The warm, gentle, clear days of summer, with innocent dry stream beds, represents but only part of the picture; wild, wet days show Nature in a very different mood.

For the «Old Caldera» of Gran Canaria, we have a large, basaltic shield volcano, with more siliceous effusions accompanying the caldera collapse and subsequent thereto, further effusions of firstly siliceous, then basaltic type. Here one can see analogies with both Masaya and

Suswa caldera types, but at this time, such can only be considered as tentative. On the other hand, this large, old feature is accepted as due to subsidence.

Most of what we have said regarding El Golfo would also apply to Jandia. Information available at this time allow of no dogmatism as to mode(s) of origin of the caldera-like feature.

In Chão de Morte caldera, large positive Bouguer anomalies and residual anomalies clearly outline the feature, but the gravity picture, either positive or negative, cannot be relied upon too much in postulating subsidence — e.g. whilst Krakatoan and Valles caldera types often show negative anomalies, this is not always so. In this Sto. Antão caldera, extensive dyke formation and fissuring has taken place, the former suggesting ring structures. The writer is inclined to see a collapse structure here of likely Galapagos type.

The cvaldera of S. Vicente, with the second largest perimeter of any Macaronesian caldera, is considered a collapse feature. Geologic and geomorphologic evidences indicate that this is one of the older Cape Verde islands, and the caldera no less in not a young feature. The large strato-cone structure with initial broad asymmetric shape has shown three principal eruptive phases, during which subsidence was activated along peripheral fractures. Indications are that here we have a caldera of Masaya type.

Lastly, Caldeira de Chá; Fogo, is surely a collapse feature. Machado (1965 a) concluded that explosion had not occurred here but only sinking of a cylindrical block, the present walls being circular faults around which subsidence took palce. He (1965 c) thought the caldera was of Glen Coe type, and (1965 a) also remarked that it showed certain analogies to Guilherme Moniz caldera Terceira, which we have catalogued as of Glen Coe. However, as per the more recent descriptions of calderas given by Williams and McBirney (1968) we are inclined to consider this Fogo caldera as transitional between the Glen Coe and Suswa types.

Conclusion

The majority of the Macaronesian calderas are of explosive-collapse origin. Of the 24 discussed here, 11 are such, 3 represent basaltic effusions, 2 are mixed eruptions associated with ring fractures, 2 are collapse features, 2 of exogenic origin, 2 of either exogenic or collapse type, 1 appears of volcanic hybrid origin and for a submarine feature, we have no knowledge. With the exception of the presumed caldera in the Faial-Pico channel, and those of Corvo and Guilherme Moniz (which are often treated as of Krakatoa type), the remaining nine features conform to what is usually referred to as Azorean type of calderas.

The western Azorean islands lie astride the Mid-Atlantic Ridge, where, as per modern ocean floor spreading concepts, magmatic upwelling produces new crust, the ocean floor spreads laterally on either side, with islands nearer the critical surgence of magmas being younger than those further removed. In this connexion, it is pertinent to note that the Azores — the archipelago nearest the oceanic crestal ridge — shows, within historical times, the highest degree of seismicity and vulcanicity (for the latter, with the exception of Fogo) of all the Macaronesian archipelagos. The prevalence then of caldera formation in the Azores, involving violent explosive activity, foundering, seismicity and repeated vulcanism right down to this decade, all testify to livelier volcano-tectonism here where the Eurasian, African and American plates meet. The further removed these Macaronesian islands are from the oceanic ridge, explosive activity seems to die out, and as regards those islands furthest removed, true volcanic calderas are lacking — that of Jandia, Fuerteventura may in reality be only a feature developed by exogenic processes.

It is obvious that our gleanings of these Macaronesian calderas leave a great many unanswered questions. Vulcanological experts have scarce visited these islands within more modern times, geological investigations have not concentrated on problems specifically associated with calderas, and today we must candidly admit to a very imperfect knowledge of these imposing depressions.

Addendum

Since the completion of the MS, a letter from Professor McBirney of Oregon University, states that since his joint publication of 1968, Williams and he have further simplified their caldera classification system. They do not use the term Erosion Caldera now, and prefer to adopt only two broad categories, viz. calderas associated with basic lavas and those associated with large outpourings of explosive siliceous magmas. Within these categories, several sub-types are recognized, characterized by distinctive structure and mode of eruption. The term cauldron is maintained for depressions formed by passive subsidence, eruption more the consequence than the cause of subsidence. Their newer ideas will be presented in a forthcoming book.

Archipelago	Island	Island Area (km^2)	Max. Island Alt. (m)	Name of Caldera	Max. Rim-Rim Extent (km)	Max.Alt. Caldera Rim (m)	Lowest Elev. in Caldera Floor (m)	Caldera Perimeter (km)	Chief Igneous Rocks--exclusive of Pyroclastics	Caldera Type
Azores	Corvo	17	718	Caldeirao	2.3	718	400	7.0	Basalts	Galapagos
	Flores	143	913	Pico da Sé	4.0	750	120	13.0	Trachytes, Andesites, Basalts	Krakatoa
	Faial	173	1043	Caldeira	2.3	1025	573	7.0	Trachytes, Andesites	Krakatoa
	Faial-Pico	---	---	'Canal do Faial'	3.8	-70	-195	10.0 (Part)	?	?
	Graciosa	61	402	Caldeira	1.6	402	132	4.0	Basalts, Andesites	Krakatoa
	Terceira	401	1021	Santa Barbara	4.4	1000	823	10.0 (Part)	Andesites, Trachytes	Krakatoa
				Guilherme Moniz	4.5	632	458	7.5 (Part)	Trachytes, Trachy-Andesites, Basalts	Glen Coe
				Cinco Picos	7.3	545	250	22.0	Basalts, Trachytes	Krakatoa
	Sao Miguel	757	1103	Sete Cidades	5.4	830	265	16.5	Trachytes, Andesites, Latites, Basalts	Krakatoa
				Agua de Pau	3.8	949	620	10.5	Trachytes, Andesites, Basalts	Katmai
				Furnas	7.5	805	208	16.0 (Part)	Andesites, Trachytes, Basalts	Krakatoa
				Povoçao	6.8	960	100	17.5 (Part)	Trachytes, Andesites, Basalts	Krakatoa
Madeira	Madeira	728	1862	Curral das Freiras	6.5	1862	340	20.0	Trachytes, Basalts, Mugearites	Krakatoa
				Serra de Agua	6.5	1692	275	19.0	Trachytes, Basalts, Mugearites	Krakatoa
Canaries	La Palma	730	2426	Taburiente	11.3	2426	150	28.0	Plutonics, Basalts, Met. Trachy-Syenites	Galapagos
	Hierro	278	1501	El Golfo	16.0	1500	Below SL?	26.0 (Part)	Basalts, Basanites, Tephrites	Exogenic? Collapse?
	Tenerife	2058	3718	Las Canadas	16.0	2717	2024	26.0 (Part)	Trachytes, Phonolites, Basalts, Trachy-Basalts	Collapse
	Gran Canaria	1532	1950	Tirajana	11.3	1950	520	30.0	Basalts, Trachytes, Agglomerates, Andesites	Exogenic
				Tejeda	13.8	1750	250	36.0	Trachytes, Andesites, Basalts, Agglomerates	Exogenic
				'Old Caldera'	28.0	1200	230	55.0 (Part)	Trachytes, Rhyolites, Basalts, Phonolites, Syenites, Essexites	Masaya? Suswa?
	Fuerteventura	1725	807	Jandia	?	807	Below SL	30.0 (Part)	Basalts and kindred rocks	Exogenic? Collapse?
Cape Verde	Santo Antao	779	1979	Cha de Norte	6.6	1750	525	20.0	Basalts, Phonolites, Nephelinites	Collapse
	S.Vicente	227	774	Porto Grande	15.5	774	Below SL	41.0	Basalts, Phonolites, Nephelinites, Gabbros, Syenites	Masaya
	Fogo	476	2829	Cha	9.4	2700	1625	30.0	Nephelinites, Basanites, Limburgites	Glen Coe-Suswa

TABLE I. Data regarding Macaronesian Calderas.

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