Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K-Ar data

Eumenio Ancochea[a], José María Fuster[a], Elisa Ibarrola[b], Antonio Cendrero[c], Juan Coello[d], Francisco Hernan[d], Jean M. Cantagrel[e] and Colette Jamond[e]

[a]Departamento de Petrología y Geoquímica, Facultad de Ciencias Geológicas, Universidad Complutense, Ciudad Universitaria, 28040 Madrid, Spain

[b]U.E.I. de Petrología, Instituto de Geología Económica, CSIC-Universidad Complutense, Facultad de Ciencias Geológicas, Ciudad Universitaria, 28040 Madrid, Spain

[c]DCITTYM (División de Ciencias de la Tierra), Facultad de Ciencias, Universidad de Cantabria, Av.Los Castros s/n, 39005 Santander, Spain

[d]Departamento de Edafología y Geología, Universidad de La Laguna, Tenerife, Spain

[e]Departement de Géologie CNRS, L.A.10 Université Clermont-II, 5, rue Kessler, 63000 Clermont-Ferrand, France

(Received June 21, 1989; revised and accepted May 3, 1990)

ABSTRACT

Ancochea, E., Fuster J.M., Ibarrola, E., Cendrero, A., Coello, J., Hernan, F., Cantagrel, J.M. and Jamond, C., 1990. Volcanic evolution of the island of Tenerife (Canary Island) in the light of new K-Ar data. *J. Volcanol. Geotherm. Res.*, 44: 231–249.

New age determinations from Tenerife, together with those previously published (93 in all), provide a fairly comprehensive picture of the volcanic evolution of the island. The oldest volcanic series, with ages starting in the late Miocene, are formed mainly by basalts with some trachytes and phonolites which appear in Anaga, Teno and Roque del Conde massifs. In Anaga (NE), three volcanic cycles occurred: one older than 6.5 Ma, a second one between 6.5 and 4.5 Ma, with a possible gap between 5.4 and 4.8 Ma, and a late cycle around 3.6 Ma. In Teno (NW), after some undated units, the activity took place between 6.7 and 4.5 Ma, with two main series separated by a possible pause between 6.2 and 5.6 Ma. In the zone of Roque del Conde (S), the ages are scattered between 11.6 and 3.5 Ma. Between 3.3 and 1.9 Ma, the whole island underwent a period of volcanic quiescence and erosion.

The large Cañadas volcano, made up of basalts, trachytes and phonolites, was built essentially between 1.9 and 0.2 Ma. To the NE of this central volcano, linking it with Anaga, is a chain of basaltic emission centers, with a peak of activity around 0.8 Ma. The Cañadas Caldera had several collapse phases, associated with large ignimbrite emissions. There were, at least, an older phase more than 1 Ma old, on the western part of the volcano, and a younger one, less than 0.6 Ma old, in the eastern side. The two large "valleys" of Guimar and la Orotava were formed by large landslides less than 0.8 Ma ago, and probably before 0.6 Ma ago. The present Cañadas caldera was formed by another landslide, less than 0.2 Ma ago. This caldera was later filled by the huge Teide volcano, which has been active even in historic times. During the same period a series of small volcanoes erupted at scattered locations throughout the island.

The average eruptive rate in Tenerife was 0.3 km^3/ka, with relatively small variations for the different eruptive periods. This island and La Gomera represent a model of growth by discontinuous pulses of volcanic activity, separated by gaps often coinciding with episodes of destruction of the edifices and sometimes extended for several million years. The neighbouring Gran Canaria, on the other hand, had an initial, rapid "shield-building phase" during which more than 90% of the island was built, and a series of smaller pulses at a much later period.

A comparison between these three central islands indicates that the previously postulated westward displacement in time of a gap in the volcanic activity is valid only as a first approximation. Several gaps are present on each island, overlapping in time and not clearly supporting either of the models proposed to explain the evolution of the Canaries.

(*) Research funded under Project no 1771, CAICYT, Spain.

General geological features of Tenerife

Tenerife is the largest (2058 km^2) and highest (3718 m) island of the Canaries. It occupies a central position in the Archipelago and is one of the most complex from the volcanological point of view. The oldest visible unit on the island is the "Old Basaltic Series", formed of basaltic lavas and pyroclastics, with some salic differentiates, typically occurring as dykes and domes emplaced at the terminal part of the basaltic emissions. This "series" forms three deeply eroded edifices, not visibly connected, in the NE (Anaga), NW (Teno) and S of the island (Fig. 1). The younger volcanic sequences formed at the central composite volcano of Las Cañadas, with basaltic, trachybasaltic, trachytic and phonolitic materials, and along a SW–NE ridge linking Las Cañadas and Anaga, the Cordillera Dorsal, with predomi-

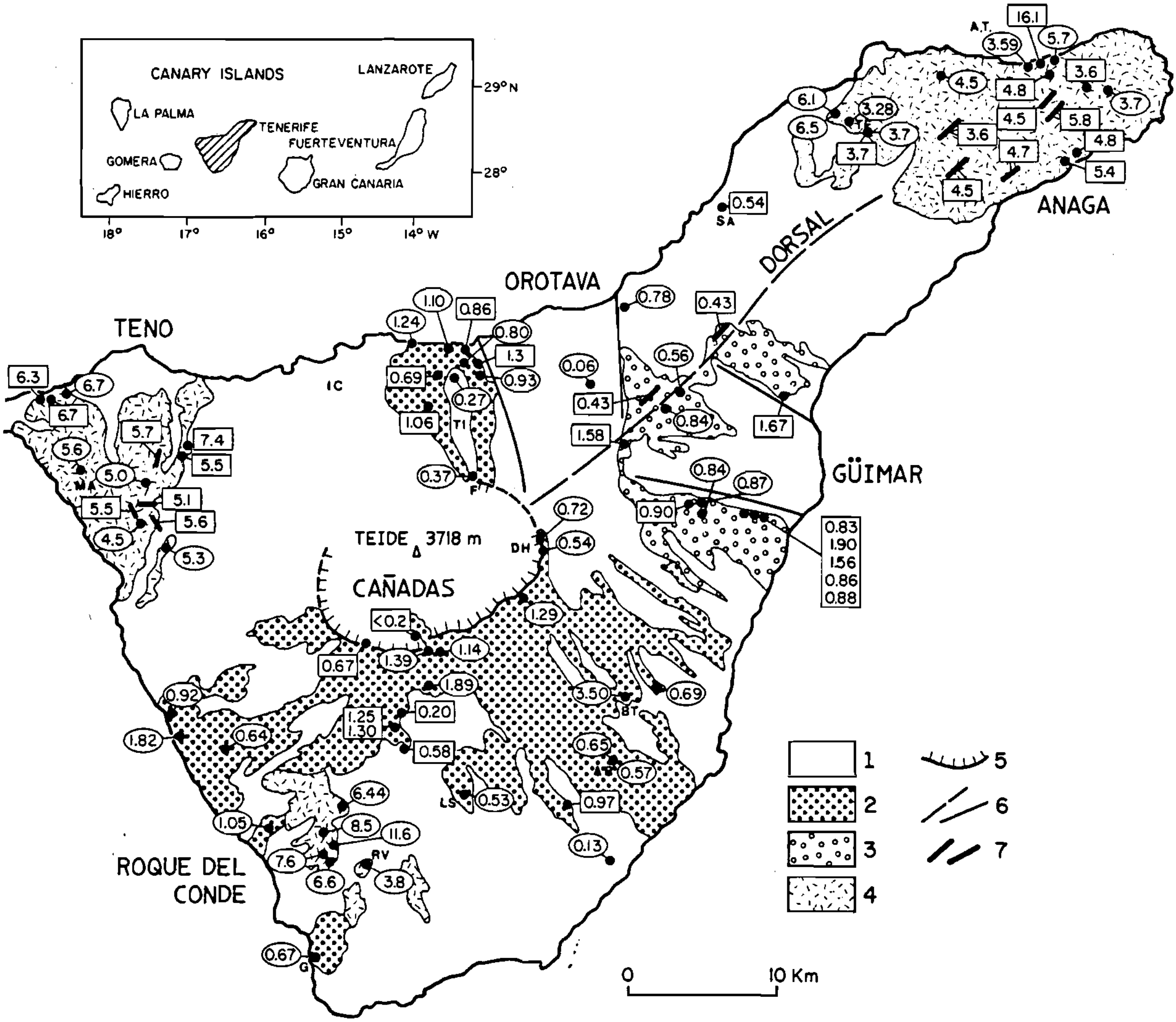

Fig. 1. Simplified geological map of Tenerife. *1* = Recent Series; *2* = "Cañadas" Series; *3* = "Dorsal" Series; *4* = Old Basaltic Series; *5* = Caldera rim; *6* = Main trend of the "Dorsal" and scarps of Güimar and La Orotava; *7* = Dated dykes. Age in Ma: ovals, this work; squares, previous data. *AR* = Arico; *AT* = Arco de Taganana; *BT* = Barranco de Tamadaya; *DH* = Cañada de Diego Hernández; *F* = La Fortaleza; *G* = Guaza; *IC* = Icod; *LS* = Lomo Simón; *MA* = Masca; *RV* = Roque Vento; *SA* = El Sauzal, *TE* = Tejina; *TI* = Tigaiga.

nantly basaltic emissions. The upper part of the Cañadas volcano was destroyed, forming a large caldera filled by the later emissions of the Teide-Pico Viejo complex. On each side of the "Dorsal" large depressions occur, the "valleys" of Güimar and La Orotava.

The most recent volcanic activity is represented, on the one hand, by many, mostly basaltic, volcanoes scattered throughout the island and, on the other hand, by the central Teide-Pico Viejo edifice, with basaltic and salic emissions.

The general character of the magmatic cycles which have been identified, is alkaline to highly alkaline, with an increase in alkalinity from the older to the recent series (Ibarrola, 1969, 1970; Ridley, 1970a; Brandle, 1973).

More details about the geology, volcanology, petrology and geochemistry of Tenerife can be found in Jeremine (1933), Hausen (1956), Fúster et al. (1968, 1980), Ibarrola (1969, 1970), Ridley (1970 a, b, c), Araña (1971), Brandle (1973), Hernández-Pacheco and Ibarrola (1973), Booth (1973), Coello (1973), Borley (1974), Carracedo (1975, 1979), Wolff (1985).

Description and K-Ar chronology of the volcanic series

This paper is based on 48 new K-Ar determinations, which together with the 45 previously published by Abdel-Monem et al. (1972), Carracedo (1975, 1979) and Féraud (1981), provide a new and more precise geochronological framework for the understanding of the volcanic evolution of the island.

The analytical methods (with replicate analyses that confirm their accuracy) have been described elsewhere (Cantagrel et al., 1984). Most K-Ar analyses were performed on whole-rock samples, but olivine and clinopyroxene were removed from seven samples. Five analyses were for feldspar crystal separates. The analytical results are presented in Table 1. The location and a brief description of the samples are given in the Appendix.

Old Basaltic Series

This unit was already mentioned by Fritsch and Reiss (1868) as well as by Hausen (1956) and Bravo (1962). According to Hausen (1956) the "basaltic tableland series" included all the basaltic rocks in Anaga, Teno, Roque del Conde, Cordillera Dorsal, scarps of Güimar and La Orotava and the bottom of some deep valleys in the northern and southern parts of the island.

Fúster et al. (1968) pointed out the existence of two Old Basaltic Series, I and II, although they failed to show their distribution in their map. The first K-Ar data, obtained by Abdel Monem et al. (1972), established clearly the large age difference which separates the Anaga and Teno rocks from the ones in Güimar and Tigaiga. The stratigraphic succession proposed by Coello (1973) includes in the Old Basaltic Series I the massifs of Anaga, Teno and Roque del Conde, as well as the bottom of several deep "barrancos". The rest of the "Old Basaltic Series" is considered to form a Series II. This distinction has remained essentially unchanged; however, the new data allow to introduce greater precission in the stratigraphy and interpretation of the different edifices.

Anaga

This massif is formed mainly by a complex sequence of alkali basaltic lava flows, with abundant volcanoclastic layers, intruded by subvolcanic bodies (dykes, domes, laccoliths) of basalts, trachybasalts, trachytes and phonolites. The series dips roughly seawards on all sides, except in the north, and has a total thickness of about 1000 m. Due to the existing structure the oldest unit (Lower Series I) appears in the north, in a large arcuate landform called "Arco de Taganana". This unit is formed by volcanoclastic rocks, some debris-flow deposits and small intrusive bodies (gabbros, syenites) cut by dykes. Abdel Monem et al. (1972)

TABLE 1

K-Ar analytical resutls

Sample no.	Field no.	Rock type	Location	%K	40Ar* (ng/g)	% Ar (atm.)	Age (Ma)
OLD BASALTIC SERIES							
NE: Anaga							
R. 10708	T.15.A	Trachybasaltic flow	Mesa de Tejina	2.22	0.505	61.3	3.28 ± 0.08
R.10711	T.52.F	Basaltic dyke	Taganana	1.98	0.493	62.1	3.59 ± 0.09
R.10709	T.16.A	Basaltic flow	Mesa de Tejina	0.881	0.226	82.1	3.7 ± 0.2
R.11077	T.50.F	Basanitic dyke	Lomo de las Bodegas	0.977	0.249	66.0	3.7 ± 0.1
R.10713	T.53.F	Basaltic flow	Taborno	0.510	0.160	82.4	4.5 ± 0.2
R.11076	T.5.CH	Syenite intrusive	Benijo-Taganana	4.25	1.695	71.9	5.7 ± 0.2
R.11078	T.18.A	Basaltic flow	Mesa de Tejina	1.15	0.488	57.0	6.12 ± 0.15
R.10710	T.17.A	Phonolitic flow	Mesa de Tejina	2.99	1.350	34.5	6.5 ± 0.1
NW: Teno							
R.11075	T.4.CH	Phonolitic plug	Roque Blanco	3.75	1.16	72.5	4.5 ± 0.15
R.10869	T.39.F	Basaltic flow	Montaña de Gala	0.902	0.311	57.6	5.0 ± 0.1
R.10716	T.38.F	Trachytic flow	Arguayo	2.94	1.07	51.7	5.3 ± 0.1
R.10714	T.35.F	Basaltic flow	Los Carrizaies	1.02	0.394	76.5	5.6 ± 0.2
R.10715	T.37.F	Ankaramitic flow	Pista del Faro-Toscón	0.866	0.400	78.6	6.7 ± 0.3
S: Roque del Conde, and E							
R.11079	T.12.CH	Phonotephritic flow	Bco. de Tamadaya	3.11	0.756	46.2	3.50 ± 0.07
R.10706	T.10.F	Trachytic plug	Roque Vento	1.42	0.371	68.3	3.8 ± 0.1
R.10707	T.1.A	Basaltic flow	Bco. del Rey-Imoque	1.09	0.487	51.5	6.44 ± 0.14
R.11292	T.24.A	Trachybasaltic flow	Bco. del Rey	2.05	0.937	36.2	6.6 ± 0.1
R.10864	T.14.F	Trachybasaltic flow	Risco Bisechi	2.16	1.13	57.9	7.5 ± 0.2
R.11291	T.23.A	Trachybasaltic flow	Roque del Conde top	2.52	1.49	28.6	8.5 ± 0.2
R.10863	T.13.F	Basaltic dyke	Barranco del Rey	1.93	1.55	24.3	11.6 ± 0.2
CAÑADAS SERIES							
R. 11297	T.26.A	Sanidine (plumice flow)	Road to S, km 53	5.32	0.047	92.0	0.13 ± 0.02
R.10877	T.44.F	Basaltic flow	Icod el Alto	1.805	0.019	95.4	0.27 ± 0.07
R.11564	T.13.CH	Phonolitic flow	La Fortaleza	4.61	0.116	95.2	0.37 ± 0.07
R.10873	T.23.F	Phonolitic plug	Lomo Simón	4.39	0.161	83.8	0.53 ± 0.04
R.11081	T.2.CH	Basaltic flow	Cañada Diego Hernández	1.30	0.049	91.6	0.54 ± 0.06
F.11091	T.3.A.	Sanidine from phonolite	Old road to S, km 70.8	4.68	0.183	73.6	0.57 ± 0.2
R.10874	T.18.F	Trachybasaltic flow	Taucho	2.66	0.118	91.5	0.64 ± 0.07
F.11295	T.25.A	Sanidine of ignimbrite	Arico	3.79	0.172	77.5	0.65 ± 0.03
R.10725	T.6.F.	Trachytic flow	Guaza	4.12	0.190	77.0	0.67 ± 0.03
R.10876	T.4.A.	Trachybasaltic flow	Bco de la Cueva	2.47	0.119	77.4	0.69 ± 0.03
R.11565	T.14.CH	Basaltic flow	Cañada Diego Hernández	1.39	0.070	94.7	0.72 ± 0.13
R.10871	T.43.F	Trachytic flow	Tigaiga, km 12.850	3.22	0.178	78.1	0.80 ± 0.03
R.10875	T.21.F	Maric trachytic flow	Barranco de Chabugo	2.75	0.176	82.8	0.92 ± 0.05
R.10721	T.42.F	Phonolitic flow	Tigaiga, km 12.300	4.53	0.292	72.0	0.93 ± 0.03
F.11090	T.17.F	Sanidine of ignimbrite	Adeje	3.88	0.283	65.6	1.05 ± 0.03
R.10870	T.46.F	Basaltic flow	El Terreno	2.07	0.158	84.9	1.10 ± 0.07
R.10719	T.12.A	Trachybasaltic flow	Guajara	3.01	0.237	77.7	1.14 ± 0.05
F.11293	T.56.F	Sanidine of ignimbrite	San Juan de la Rambia	2.29	0.197	86.3	1.24 ± 0.08
R.10717	T.1.C.	Phonolitic flow	La Angostura	4.27	0.381	66.1	1.29 ± 0.01
R.10720	T.14.A	Phonolitic flow	Guajara	4.35	0.420	70.6	1.39 ± 0.04

TABLE 1 (continued)

K-Ar analytical resutls

Sample no.	Field no.	Rock type	Location	%K	40Ar* (ng/g)	% Ar (atm.)	Age (Ma)
R.10723	T.20.F	Mafic trachytic flow	Barranco de Erques	3.08	0.388	60.2	1.82 ± 0.04
R.10724	T.25.F	Basaltic flow	Lomo de Topo Negro	2.35	0.308	62.1	1.89 ± 0.05
DORSAL SERIES							
R.10879	T.20.A	Trachybasaltic flow	Fuente del Joco	2.15	0.083	84.1	0.56 ± 0.03
R.10722	T.48.F	Basaltic flow	Mirador de Humbolt	1.53	0.082	95.8	0.78 ± 0.18
R.10872	T.21.A	Basaltic flow	Dorsal road, km 27.8	2.05	0.120	80.3	0.81 ± 0.04
R.10868	T.9.A.	Basaltic flow	Bco. de Badajoz, 1565 m	2.14	0.125	75.9	0.84 ± 0.03
R.10866	T.7.A	Basaltic flow	Bco. de Badajoz, 1270 m	1.81	0.110	79.0	0.87 ± 0.04
RECENT-SERIES							
R.10380	T.22.A	Basaltic flow	La Orotava	1.25	0.005	99.0	0.05 ± 0.06

Constants $\lambda(^{\Delta G}K_{\beta}) = 4.962 \times 10^{-10}a^{-1}$; $\lambda(^{\Delta G}K_{\epsilon}) \cdot \lambda(^{\Delta G}K_{\epsilon}) = 0.681 \times 10^{-10}a^{-1}$; $^{40}K = 0.01167$ atm %

obtained a 16.1 Ma age(*) for an ankaramite from this formation. We have failed to find materials suitable for sampling at the location referred to by Abdel-Monem, or elsewhere in the unit, due to the intense alteration of the rocks. We have only been able to obtain a K-Ar age of 5.7 Ma for a syenite intrusive intensely cut by dykes, at the very base of the unit. This age, younger than the ones for the units above, is very likely due to the heating effect of the dykes. The establishment of an age for this unit must await more detailed data. It seems that the 16.1 Ma age, so much older than the other ages on the island, must, at the moment, be viewed with caution.

Two other series have been identified at Anaga. The Middle Series I is separated from the former by an unconformity. It makes up most of the massif and is constituted by basaltic materials, mostly pyroclastics, with subordinate salic plugs and flows. The oldest ages (Fig. 2) within this series correspond to a phonolite (6.50 ± 0.10 Ma) and an underlying basalt (6.12 ± 0.15 Ma) sampled at the base of the Mesa de Tejina, to the west. The basaltic sample is slightly altered, which could account for that small contradiction in age. It seems clear that the base of the "Old Basaltic Series",

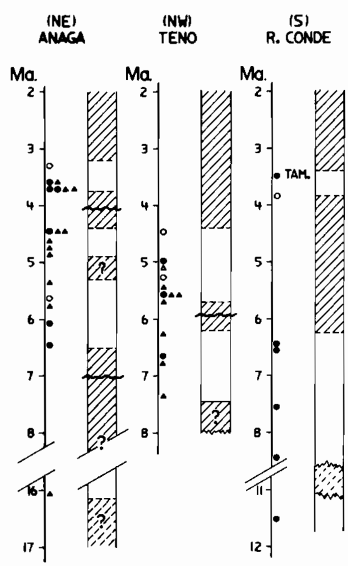

Fig. 2. K-Ar ages for the Old Basaltic Series. Full symbols, basic materials; hollow symbols, salic materials. Triangles, previous data; circles, this work. Shaded, no recorded volcanism. Unconformities are indicated.

(*) All previously published ages were recalculated using the new set of decay constants (Steiger and Jaeger, 1977) on the western side, is older than 6 Ma. Two more Miocene ages are available for this unit: 5.37 Ma for a basaltic flow (Carracedo, 1975) and 5.79 Ma for a basaltic dyke (Féraud, 1981). The six remaining ages in the Middle Series I are grouped between 4.8 and 4.5 Ma. A possible gap exists between 6.2 and 5.6 Ma.

The Upper Series I lies above a very clear unconformity visible in the western part of the massif, at the Mesa the Tejina. It has yielded an age of 3.7 Ma (Carracedo, 1975, and this work) for a basalt at the base and 3.28 Ma for a trachybasalt at the top. Four other existing determinations are grouped around 3.6 Ma; they correspond to salic and basaltic dykes and plugs from different locations within Anaga (Fig. 1).

Therefore, three successive cycles can be identified in Anaga, each one with basalts and salic differentiates, separated by periods of erosion with little, if any, volcanic activity.

Teno

This massif is made up of a lower sequence of basaltic lava flows and pyroclastics, dipping seawards on all sides (Masca-Carrizales edifice of Barrera et al., 1989), covered unconformably by an upper sequence of subhorizontal basaltic flows with some trachytes. The whole massif is cut by dykes (mostly basaltic) and salic plugs. Intercalated towards the middle and the base of the lower sequence are polimictic breccias, interpreted by Barrera et al. (1989) as the result of explosive eruptions. Similar breccias, in an equivalent stratigraphic position, appear on the island of La Gomera (Cendrero, 1970, 1971). The ages of 6.26, 6.71 and 7.37 Ma (Abdel-Monem et al., 1972) and 6.7 Ma (this work), which represent the oldest well dated episode in the massif (Fig. 2) correspond to the top of the lower unit of Teno.

At the unconformity between the upper and the lower sequence, there is a 10 – 15 m thick layer of polimictic breccia of possible laharic origin (Barrera et al., 1989) with an intercalated flow dated as 5.6 Ma. Thus, the destructive episode which separates both units can be placed around this age. The upper unit has a thickness of 600 – 700 m and its top has an age of 5.0 Ma. Seven other determinations, corresponding to dykes and flows, fall within this age interval. The youngest age in this massif corresponds to a phonolitic plug of 4.5 Ma.

Roque del Conde

In the southern part of the island several outcrops of "Old Basaltic Series" appear. The most important of these is the Roque del Conde, where the sequence is about 1000 m thick. Five new determinations carried out in this area from the bottom to the top of the series (Fig. 2) yield ages between 11.6 and 6.4 Ma. Although the data are not totally coherent with the stratigraphy, it is clear that these outcrops, with ages mainly between 8.5 and 6.4 Ma, correspond to the lower parts of the Old Basaltic Series, roughly equivalent, in age, to the lower unit of Teno. The age of 2.4 Ma presented by Carracedo (1975) corresponds to a flow for which we have obtained 7.6 Ma. The latest dated episode in this sector is a salic dome (Roque Vento, 3.8 Ma). To the east, the Old Basaltic Series crops out in several deep "barrancos", where it is separated by clear unconformities from more recent series. A new determination in the "Barranco de Tamadaya", 3.5 Ma, is coherent with the ages of the final salic episode just mentioned (3.8 Ma) and of the upper part of Anaga.

Cañadas series

A period of volcanic quiescence and erosion took place between the building up of the "Old Basaltic Series" and the eruptions which originated the younger volcanic series. No volcanic materials have been found on the surface with ages between 3.3 and 1.9 Ma. However, a phonolite flow sampled by Carracedo (1975, 1979) within the thick fragmental deposits described by Bravo (1962) and Coello (1973), inside a tunnel dug for groundwater extraction, yielded an age of 2.3 Ma. This suggests the possibility of minor activity towards the end of this period.

The composite volcano of Las Cañadas filled the area between the eroded remnants of the "Old Basaltic Series". This volcano was the result of the superposition of several edifices. The oldest materials dated in this sequence are two basaltic lava flows of 1.89 and 1.82 Ma (Figs. 1 and 3). A complex succesion of basalts, trachybasalts, trachytes and phonolites follows, with ages between 1.5 and 0.13 Ma. There are, however, some differences in the volcanic sequence and age of the materials in the N, SW and SE parts of the series.

The N side has a clear stratigraphic sequence: 1.10 Ma for a basalt at the base, 1.24 Ma for an ignimbrite, also at the base but without a clear relationship with the former, and 0.93 and 0.80 Ma, respectively, for a phonolite and a trachybasalt above them. Our results are in good agreement with the stratigraphy, in contrast to data presented by Abdel-Monem et al. (1972) which, though similar in age range, do not correspond so well to the stratigraphy (Fúster et al., 1968; Bellido and Gómez, 1989). Resting unconformably on this sequence are basaltic flows (0.27 Ma) and a phonolite (0.37 Ma) which appears at the top of the Cañadas rim in La Fortaleza.

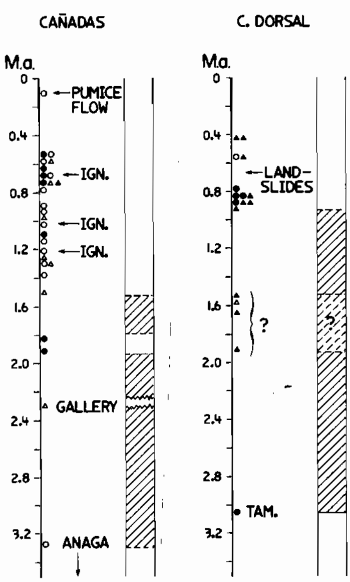

Fig. 3. K-Ar ages for the Cañadas and Dorsal Series. Same symbols as in Fig. 2.

In the S-SW, the basaltic flows of 1.89 – 1.82 Ma, are followed by trachybasalts, basalts, trachytes and phonolites dated between 1.5 and 0.92 Ma, with several ignimbrites, the lower one dated at 1.05 Ma. The caldera wall itself, in this sector, has ages ranging from 1.39 Ma at the base, to 1.14 Ma at the top. (Fig. 1). Three other determinations around 0.6 Ma represent a final phase of minor activity in this sector.

In the eastern part of the caldera wall (Cañada de Diego Hernández) a "palaeovalley" filled by volcanic materials lying unconformably over the rest of the caldera rim occurs. The sequence filling this valley, with a total thickness of 200 m, is made up of interbedded salic pyroclastics with basaltic lavas and lapillis. Two basaltic flows in this sequence yielded ages of 0.54 and 0.72 Ma. Towards the E and SE of this sector of the caldera rim, the Cañadas deposits are formed by a thick succession of salic pyroclastics with some phonolite flows, in which more than 45 individual layers have been identified (Booth, 1973; Wolff and Storey, 1984; Wolff, 1985; Alonso, 1989). These layers are separated by frequent palaeosoils, indicating that the pyroclastic emissions were interrupted by fairly long intervals. The age determined for these deposits ranges from 0.65 Ma, for an ignimbrite in the lower part of the sequence, to 0.13 Ma for a lithic-rich pyroclastic flow, including coarse-grained syenites and gabbros, at the top. A similar pyroclastic flow, also including syenite and gabbro fragments, tops the sequence of the caldera rim at the Cañada de Diego Hernández and it has been dated at 0.17 Ma (Martí et al., 1989).

In the light of these data, the ^{14}C age of 28,500 years presented by Wolff and Storey (1984) for one layer in the middle of this sequence seems to be too recent.

During the last stages of the formation of the Cañdas volcano, there was an episode of salic emissions scattered throughout the island, around 0.6 Ma. This episode included Montaña Guaza (0.67 Ma) and Lomo Simón (0.53 Ma) at the south, and El Sauzal (0.54 Ma) at the NE.

Cordillera dorsal

A total of 16 age determinations are available for the Cordillera Dorsal and the scarps of the valleys of Güimar and La Orotava (Figs. 1 and 3). A group of 8 determinations yielded ages between 0.9 and 0.78 Ma. In particular, we sampled two flows in a sequence more than 800 m thick, at Güimar, in which the 1:25.000 geologic map (Ancochea et al., 1978) indicates the presence of a major unconformity; the ages obtained below and above the unconformity were 0.87 and 0.84 Ma, respectively, showing that it does not represent an important discontinuity. A group of ages between 1.9 and 1.56 Ma, all by Abdel-Monem et al. (1972) are not in accordance with the former. Those authors already pointed out a certain lack of consistency for their data in this sector. We can offer no further explanation for these apparently anomalous results. The data so far available suggest that the thick basaltic sequence on the Cordillera Dorsal accumulated mostly in a span not much longer than 0.1 Ma. It is quite clear that, despite their appearance, the scarps of Güimar and La Orotava are not part of the Old Basaltic Series, as Abdel-Monem et al. (1972) already pointed out.

Four age determinations are available for the upper part of the series. A trachytic flow dated by Abdel Monem et al. (1972) at 0.54 Ma; a trachybasaltic flow at the top, from a group covering the morphological scarp of the valley of La Orotava, with a 0.56 Ma age that enables to establish a minimum age for the valley, and two dykes dated by Féraud (1981) at 0.43 Ma.

More recent series

The post-caldera activity is represented essentially by the Teide-Pico Viejo complex, formed by basalts, trachytes and phonolites, which fills the caldera, and by many small scattered individual basaltic volcanoes, mainly on the Dorsal. Six of such volcanoes have erupted in historical times and the Teide-Pico Viejo complex has also experienced historical activity (Cabrera and Hernández-Pacheco, 1987). A basaltic flow at the bottom of the valley of La Orotava has been dated at 0.06 Ma. Two ^{14}C ages of 2,470 a B.P. (J.M. Navarro, pers. commun., 1900) and 1,910 a B.P. (Soler and Carracedo, 1986) have been obtained for charcoal fragments from lavas in the Teide-Pico Viejo complex. Palaeomagnetic data from the latter authors have established two other eruptions in 1150 and 1400 A.D.

Discussion

Volcanic evolution of Tenerife

The three old massifs located at the three corners of the island represent independent edifices, each one with its own volcanic history. This is particularly so for Anaga and Teno, although the differences between the latter and Roque del Conde are not so clear (Figs. 2, 4 and 6). These massifs are accumulations of predominantly basaltic rocks with thicknesses greater than 1000 m, culminated by salic materials. Important units made up of volcanic breccias of uncertain origin appear at the lower part of the sequences, with the exception of Roque del Conde. The age of the oldest formations (Lower Series I of Anaga and lower unit of Teno) is not wel defined, due to their intense alteration, although the 16.1 Ma determination by Abdel Monem et al. (1972) indicates that they might go back to the lower Miocene.

There are, however, important differences.

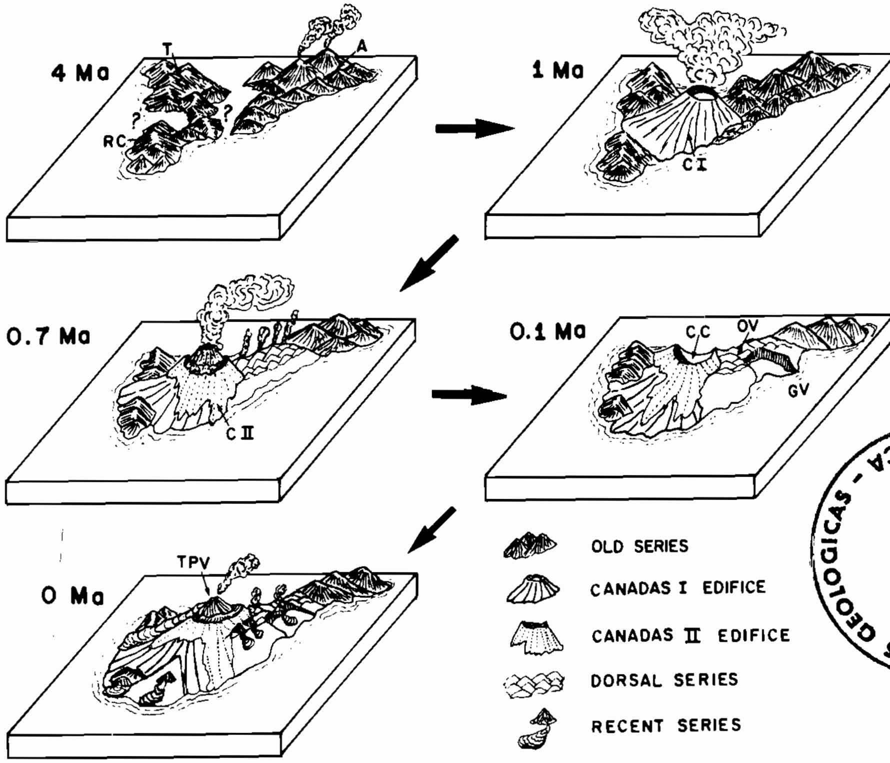

Fig. 4. Time-spatial evolution of the volcanic activity in Tenerife. *A* = Anaga massif; *T* = Teno massif; *RC* = Roque del Conde massif; *CI* = Cañadas I edifice; *CII* = Cañadas II edifice; *CC* = Cañadas caldera; *OV* = Orotava valley; *GV* = Güimar valley; *TPV* = Teide-Pico Viejo edifice.

Whereas the salic rocks occur only at the top of the sequences of Teno and Roque del Conde, in Anaga they are present throughout the succession (Fig. 2). The periods of volcanic activity were also different. In Anaga at least three periods of activity occurred, separated by gaps represented by unconformities. In Teno only two periods, clearly separated by an unconformity, have been identified. In Roque del Conde no unconformity is visible, but the age determinations obtained are concentrated in two separate periods (Figs. 2, 5 and 6).

In summary, although the growth of the older volcanic formations in what is now the island of Tenerife took place mainly in the upper Miocene and lower Pliocene, this growth was irregular in time and quite different in each edifice.

The evolution of the two edifices, Cañadas and Dorsal, which grew between the remnants of the Old Basaltic Series was quite different. The Cañadas volcano started with basaltic emissions, about 2.0 Ma ago, followed by a complex evolution, with the eruption of trachytes, phonolites and basalts in several cycles which extended practically to the present time. The Teide-Pico Viejo volcano would be the latest stage in the evolution of this edifice. The eruptions in the Cordillera Dorsal started around 1.0 Ma ago, and they also continued to the present time, but in this case practically only with basalts, with some trachytic and phonolitic emissions in the upper part of the sequence, from about 0.5 Ma.

The central Cañadas volcano was built in several episodes, during which there was a displacement of the emission centers from the SW to the NE. During the initial episode (ap-

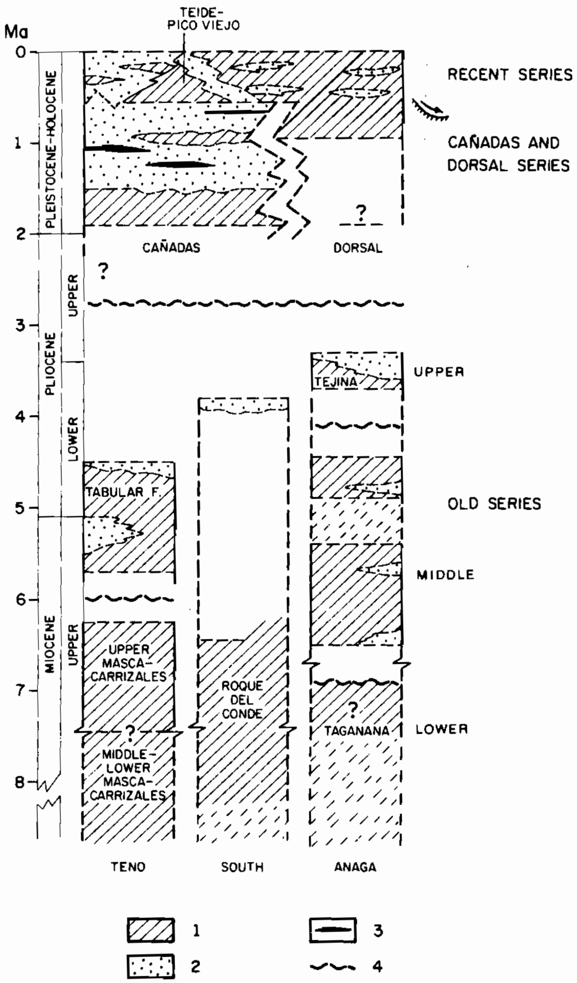

Fig. 5. Synthetic volcano-stratigraphic sequence and chronology of Tenerife. *1* = basic rocks; *2* = salic and intermediate rocks; *3* = ignimbrites; *4* = unconformity.

proximately 2.0 to 1.0 Ma) a Cañadas I edifice was formed, whose emissions appear mainly in the S, SW and N flanks of the island. The abundant deposits of pyroclastic flows and ignimbrites, two of them dated at 1.24 and 1.05 Ma, could be related to collapse events in the western part of the caldera. In a second episode, from 1.0 Ma onwards, the eruptions which formed the Cañadas II edifice took place, covering mostly the E-SE and N sectors, and also parts of the S-SW. The succession visible in the Cañada de Diego Hernández (approximately 0.6 to 0.2 Ma) and the pyroclastic layers at the SE, with similar ages, are representative of this episode.

The unconformity overlain by the sequence at the Cañada de Diego Hernández shows that a partial destruction of this edifice occurred prior to 0.6 Ma. The numerous pyroclastic layers erupted after 0.6 Ma might have been related with collapse events in the Cañadas II edifice.

During this period, at the Cordillera Dorsal two large morphological features formed, the "valleys" of Güimar and La Orotava. Both valleys formed in a short time span, between 0.83 and 0.78 Ma, which are the most recent ages obtained for the flows in the scarps of Güimar and La Orotava, respectively, and 0.56 Ma, age of the flows that cover the scarp of La Orotava. These structures have been interpreted as depressions between two volcanic massifs (Fristch and Reiss, 1868), graben (Hausen, 1956), landslides (Bravo, 1962; Coello, 1973) and collapse due to a "trap door type of mechanism" (Ridley, 1971). Recently, Navarro and Coello (1989) have revised the existing evidence, especially the one obtained through observations underground in the numerous tunnels for water extraction which penetrate accross and below the fill material in both "valleys". There is a systematic presence of a chaotic landslide breccia, with a clayey-sandy matrix and more than 100 m thick, covered by a volcanic filling between 150 and 600 m thick. The chaotic deposit follows an inclined surface, with a slope slightly gentler than the present topographic surface. Navarro and Coello (1989) interpret this evidence as indicative of a landslide origin, in which the volumes displaced were greater than 100 km^3. This seems to be confirmed by the presence of a "hump" in the bathimetric curves in front of both valleys. According to those authors, the valley of Güimar was formed first and then the one of La Orotava. The existing geochronological data are coherent with their interpretation.

The "palaeovalley" at the Cañada de Diego

Hernández has an age and a position which indicate a possible relationship with the landslip that originated the "valley" of La Orotava. If the minor pyroclastic flow deposits which appear here at the top of the caldera sequence, cut by the caldera scarp, constitute, as it seems logical, the last materials erupted by the Cañadas II volcano, the present caldera must have formed after 0.17 – 0.13 Ma.

The origin of Las Cañadas has been widely discussed and several mechanisms have been proposed for the formation of the present caldera (Humboldt, 1814; Von Buch, 1825; Lyell, 1855; Fristch and Reiss, 1868; Gagel, 1910; Fernández Navarro, 1917; and, more recently, Hausen, 1956; Blumenthal, 1961;

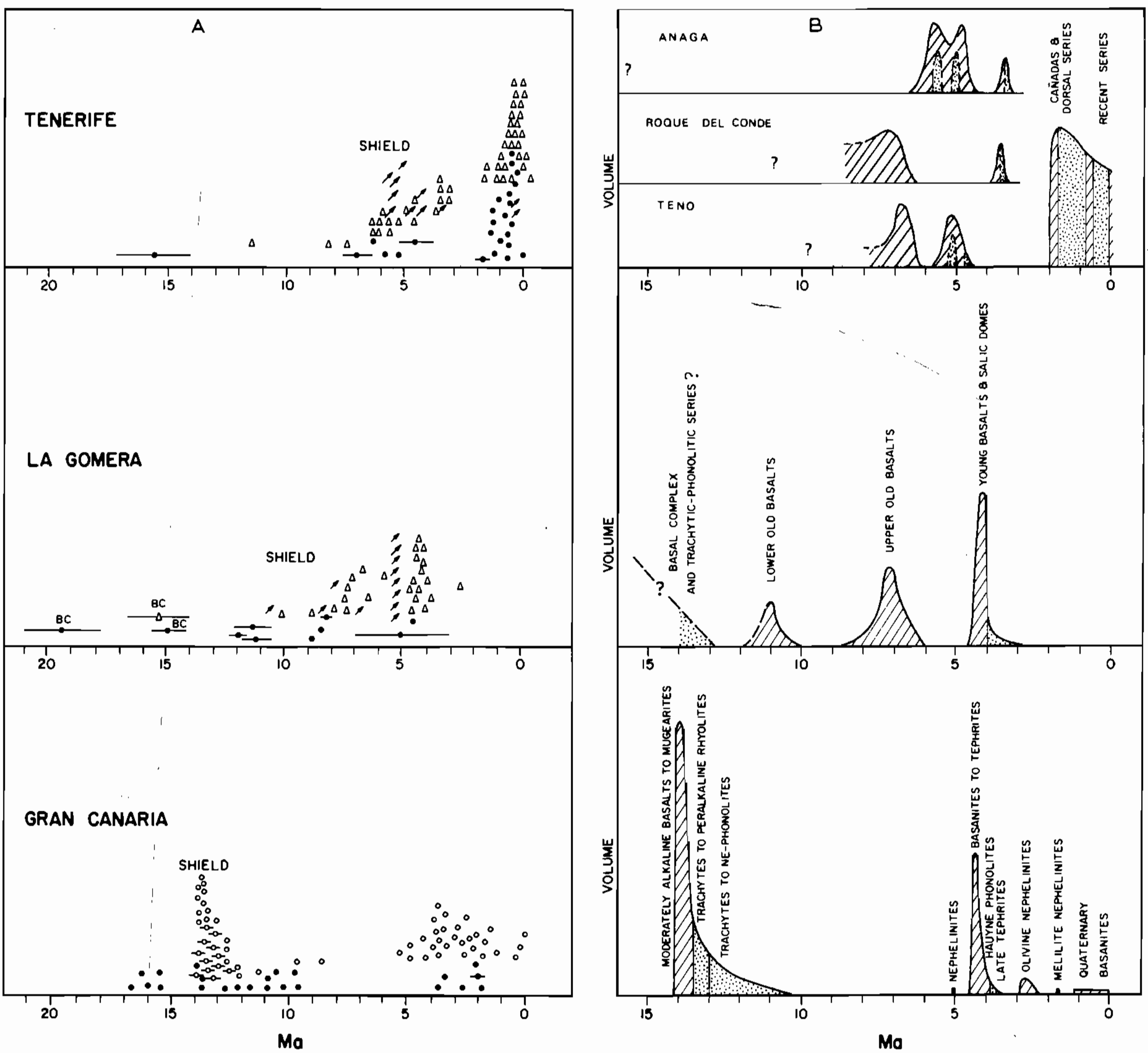

Fig. 6. (A). Comparison of K-Ar data on Tenerife, La Gomera and Gran Canaria. Full circles: Abdel-Monem et al. (1971, 1972). Hollow circles: McDougall and Schmincke (1976). Crosses: Carracedo (1979). Arrows: Féraud (1981). Triangles: this work and Cantagrell et al. (1984). B.C.: Basal Complex. (B). Distribution and approximate volume (not to scale) of the volcanic cycles. Data on Gran Canaria redrawn from Schmincke (1981). Dotted: salic and intermediate materials; hatched: basic materials.

Bravo, 1962; Fúster et al., 1968; Macfarlane and Ridley, 1968; Ridley, 1971; Araña, 1971; Coello, 1973; Booth, 1973; Borley, 1974).

Recent observations by Navarro and Coello (1989) on the the sequences that can be observed underground, in the many water tunnels (amounting to more than 150 km) which penetrate through the Teide-Pico Viejo complex and below the presumed hidden caldera rim, have shown that below the Teide-Pico Viejo edifice a chaotic deposit similar to the ones in Güimar and La Orotava occurs and that no caldera rim can be found in the NW side of Las Cañadas. The chaotic breccia, more than 100 m thick and covered by 500 to 900 m of Teide-Pico Viejo lavas, also follows a surface gently inclined towards the N-NW. These materials fill a "valley" similar to the ones described above, the "palaeovalley" of Icod.

These data strongly support the interpretation (Navarro and Coello, 1989) of the present Cañadas caldera as the result of a landslide. If so, the landslide must have occurred after the 0.17 – 0.13 Ma event already mentioned. Similar morphostructures have been described in Réunion (Chevalier and Bachelery, 1981; Duffield et al., 1982), Hawaii (Moore, 1964; Duffield et al., 1982), Mount Pelée (Vincent et al., 1989), Volcán Colima, Mexico (Luhr and Prestgaard, 1988) and Socompa volcano, Chile (Francis et al., 1985).

The activity leading to the formation of the Teide-Pico Viejo complex started afterwards, with the emission of trachybasalts, followed by 500 m of basalts (Navarro and Coello, 1989) and later by trachytes and phonolites (Fúster et al., 1968; Ridley, 1970; Brandle, 1973; Borley, 1974; Quesada, 1988).

Figure 5 summarizes the volcano-stratigraphic sequence of the island in the light of new K-Ar data.

Eruptive rates

An attempt can be made to estimate the process of building of these oceanic islands. The total volume of the Tenerife edifice, from the sea floor at 3000 m to the Teide (3718 m) is about 15,000 km^3. This would be 23,600 km^3 if the base of the edifice is considered to be at the 3500-m isobath (Schmincke, 1981). About 2000 km^3 correspond to the subaerial part of the edifice. As there is no information about the constitution and age of the edifice below sea level, the following calculations are centered on the emerged part of the island.

The volume erupted during the building of the Old Basaltic Series must have been between 2000 and 1000 km^3. The first estimate was made considering the area presently covered by the island and an average thickness of 1000 m, which is the present height of the three existing massifs. The second one considers that the three massifs were never connected above sea level, occupying approximately half that surface. These materials were erupted essentially in the 8 – 4 Ma interval, with an average construction rate of 0.5 – 0.25 km^3/ka.

The Cañadas I volcano, with about 20 km radius and 2500 m altitude over the Old Basaltic Series, had an approximate volume of 350 – 400 km^3. The edifice was formed in slightly less than 1.0 Ma, giving an average construction rate of 0.4 km^3/ka. The Cañadas II volcano, with dimensions probably somewhat smaller than Cañadas I, had an approximate volume of 150 – 200 km^3. This takes into account the materials accumulated on the flanks and the possible filling of a caldera 14 km wide and 600 m deep. If this volcano was built in about 0.8 Ma, the average construction rate was 0.2 – 0.25 km^3/ka.

The Cordillera Dorsal is 25 km long, 18 km wide at the base and 1.6 km high, of which 1/3 – 1/4 is occupied by components assigned to the Old Basaltic Series. This gives a total volume of 250 – 300 km^3, erupted in a 0.2-Ma interval, with an average rate of 1.25 – 1.5 km^3/ka.

The Teide-Pico Viejo edifice, including the filling of the caldera and of the "palaeovalley" of Icod, has a total volume around 150 km^3

(Coello, 1973). As, according to the age data presented above, this volcano formed in less than 0.2 Ma, the average construction rate was at least 0.75 km^3/ka. The rest of the recent series amounts to about 100 km^3, with an average construction rate of 0.5 km^3/ka.

After the data presented by Cabrera and Hernández-Pacheco (1987), an eruptive rate of 0.3 km^3/ka can be calculated for the eruptions during the last 500 years.

Thus, it can be seen that the average construction rates in the different periods of activity have varied between 0.2 and 1.75 km^3/ka. The average eruptive rate for the 8 Ma period of well documented activity was 0.2–0.4 km^3/ka. It is worth pointing out that the present rate, in this island considered to be of reduced activity, is equivalent to the one throughout its volcanic history. These construction rates are clearly smaller than the ones for most of the volcanoes analysed by Wadge (1982), although comparable to those described by Booth et al. (1978) in Sao Miguel, Azores.

As the bulk of the emissions in each epoch probably took place in periods shorter than the total intervals considered, the actual eruptive rates must have been higher during the main volcano-building episodes. This is confirmed by the rates obtained for sequences in which the initial and final moments of activity are precisely known (Dorsal, Teide-Pico Viejo and recent series).

Assuming that the eruptive behaviour of Tenerife since it started to grow from the sea floor was similar to the average so far known, the island edifice would have been built in about 50 Ma. If the submerged part was erupted at a rate equivalent to the highest one determined, the island edifice would have taken less than 20 Ma to form.

Comparison of the three Central Islands

Sufficient data exist for the island of Gran Canaria (Mac Dougall and Schmincke, 1976) and La Gomera (Cantagrel et al., 1984) to attempt a brief comparison between the subaerial volcanic activity of the three central islands of the archipelago. This comparison provides interesting clues with respect to the growth of this type of oceanic islands.

There is a remarcable parallelism between the relative succession of events, the nature of these and even their known chronology in La Gomera (Cantagrel et al., 1984) and Teno, despite the fact that they are clearly independent edifices with sea depths of 2000 m between them. This parallelism does not exist in the case of Anaga, but there is a similar general pattern of growth. Both La Gomera and Tenerife were built by pulses of volcanic activity separated by gaps, which correspond to intervals of destruction of the volcanic reliefs. These periods of destruction are often related to the presence of volcanoclastic formations which have been interpreted by different authors as explosion breccias, Laharic, debris flow or landslide deposits (Bravo, 1964; Cendrero, 1970, 1971; Carracedo, 1975; Schmincke, 1981; Barrera et al., 1989). It seems that during the evolution the these islands episodes of instability of the growing edifices, with or without the direct intervention of volcanic activity, occurred at several periods, resulting in their partial destruction. Fairly similar patterns of construction-destruction have been described in other islands (Moore, 1964; Chevalier and Bachelery, 1981; Duffield et al., 1982; Vincent et al., 1989).

In the case of Gran Canaria (McDougall and Schmincke, 1976; Schmincke, 1981) there was a single, short and intense "shield-building phase" (14.1 to 13.9 Ma ago) during which about 1,000 km^3 of basaltic materials accumulated. This phase would have been considerably longer if the 16.12 to 10.20 Ma ages obtained by Abdel Monem et al. (1971) were correct.

Figure 6 is a cartoon showing the available age determinations and an approximate representation of the duration, volume and composition of the different cycles in the three islands.

During the "shield-building phase" of Gran Canaria there was no or very little activity in

Tenerife, with the possible exception of the Lower Series I of Anaga. In La Gomera, the activity is represented by the alkaline intrusions in the Basal Complex and perhaps by the trachytic-phonolitic series (Cantagrel et al., 1984).

The "Old Basaltic Series" of Tenerife (about 2000 km^3) and the "Old and Younger Basalts" of La Gomera (about 400 km^3), which are roughly equivalent in character to the initial cycle of Gran Canaria, were formed mainly during the gap of activity in the latter island. They were emplaced roughly from 12 to 4 Ma, in several cycles, often culminating by salic emissions and separated by gaps, which overlap in time in the different edifices (Fig. 6). The final episodes of this series in Tenerife ended about 3.5 Ma ago (Anaga and South). In La Gomera, there is an important cycle from 4.6 to 4 Ma, during which about 200 km^3 of basaltic, and to a lesser extend salic materials accumulated. This final episode on La Gomera coincided with the second cycle of activity in Gran Canaria, during which 100 km^3 erupted (McDougall and Schmincke, 1976). However, in this case the nature of the volcanism is completely different, consisting of basanites, tephrites and phonolites, with thick breccia layers (Roque Nublo formation).

Finally, the intense activity of the last cycle in Tenerife (Cañadas volcano, Dorsal, Teide-Pico Viejo, and recent series) took place when in Gran Canaria there was only minor activity and in La Gomera there was no activity at all.

The construction rates on Gran Canaria (McDougall and Schmincke, 1976) and La Gomera show differences, for the different eruptive periods, much greater than the ones on Tenerife. During the "shield-building phase" 5 km^3/ka were erupted in Gran Canaria, whereas the rate in the second cycle of activity was only 0.2 km^3/ka. In La Gomera the rate was 0.05 km^3/ka for the Old Basalts and 0.3 km^3/ka for the Younger Basalts.

It is obvious that the trends in the evolution of the activity for the three islands are very different, both with regards to the periods and rates of construction and to the type of volcanic phenomena and composition of the materials erupted. In other words, each island had its own volcanic history, independent from the other two. The only exception to this general rule is the rough similarity between La Gomera and the "Old Basaltic Series" of Tenerife, particularly at Teno.

Thus, the models of growth were quite different. During the accumulation of the initial subaerial sequences the Tenerife model corresponded to a growth extended for at least 5 Ma, with discontinuous activity and episodes of relief destruction. The Gran Canaria model (McDougall and Schmincke, 1976; Schmincke, 1981) represents a single phase of very rapid growth with no significant destructive episodes. No shield-building, "stricto sensu" took place in Tenerife, as the "Old Basaltic Series" on this island is made up to a grear extent of different types of volcanoclastic rocks, forming rather roof-like, multi-vent edifices.

The model of growth of La Gomera was in a way intermediate between the other two. This island is a shield similar to, although smaller than Gran Canaria, but it was built in several pulses, separated by gaps and destructive phases.

The differences in the patterns of growth of Tenerife and Gran Canaria also exist in the more recent episodes, but with a somewhat inverted character. On Tenerife basalts and salic differentiates were erupted during a single phase, whereas on Gran Canaria several short pulses occurred.

The destruction of part of the edifices through catastrophic events, with or without the direct intervention of volcanic activity, seems to be a characteristic feature of the evolution of these oceanic islands, both at the submarine and seamount-island transition (Schmincke, 1981; Staudigel and Schmincke, 1984) and subaerial (Navarro and Coello, 1989) stages.

The new data show that the different gaps in the volcanic activity of each island, overlap in time, without following any regular pattern that could be clearly explained by the models previously proposed to explain the evolution of the archipelago. Nevertheless, the main gap between the "Old Basaltic Series" and the younger volcanic emissions, migrating in time towards the west, fits better with the propagating fracture model of Anguita and Hernán (1975).

Acknowledgements

Critical review and comments from Drs. Jaupart, Snelling, Vincent and two anonymous referees helped the authors to improve the original manuscript. Financial support from the CICYT, Spain is also acknowledged.

References

Abdel-Monem, A., Watkins, N.D. and Gast, P.W., 1971. Potassium-Argon ages, volcanic stratigraphy and geomagnetic polarity history of the Canary Islands: Lanzarote, Fuerteventura, Gran Canaria and La Gomera. Am. J. Sci., 271: 490 – 521.

Abdel-Monem, A., Watkins, N.D. and Gast, P.W., 1972. Potassium-Argon ages, volcanic stratigraphy and geomagnetic polarity history of the Canary Islands: Tenerife, La Palma and Hierro. Am. J. Sci., 272: 805 – 825.

Alonso, J.J., 1989. Estudio volcano-estratigráfico y volcanológico de los piroclastos sálicos del sur de Tenerife. Col. Investigación, Univ. de La Laguna, 257 pp.

Ancochea, E., Anguita, F., Fúster, J.M., Hernán, F. and Coello, J., 1978. Mapa geológico de España, E. 1:25,000, Güimar, IGME, Madrid.

Anguita, F. and Hernán, F., 1975. A propagating fracture model versus a hot spot origin for the Canary Islands. Earth Planet. Sci. Lett., 27(1): 11 – 19.

Araña, V., 1971. Litología y estructura del edificio Cañadas, Tenerife (Islas Canarias). Est. Geol., 27: 95 – 137.

Barrera, J.L., Gómez, J.A. and Bellido, F., 1989. Mapa geológico de España, E. 1:25,000. Santiago de Teide. IGME, Madrid.

Bellido, F. and Gómez, J.A., 1989. Mapa geológico de España, E. 1:25,000. Puerto de la Cruz. IGME, Madrid.

Blumenthal, M.M., 1961. Rasgos principales de la geología de las Islas Canarias con datos sobre Madeira. Bol. Inst. Geol. Min. Esp., 77: 1 – 30.

Booth, B., 1973. The Granadilla pumice deposit of southern Tenerife, Canary Islands. Proc. Geol. Assoc., 84: 353 – 369.

Booth, B., Croasdale, R. and Walker, G.P.L., 1978. A quantitative study of five thousand years of volcanism on Sao Miguel, Azores. Philos. Trans. R. Soc. London, Ser. A, 288: 271 – 319.

Borley, G.A., 1974. Aspects of the volcanic history and petrology of the island of Tenerife, Canary Islands. Proc. Geol. Assoc., 85: 259 – 279.

Brandle, J.L., 1973. Evolución geoquímica de los materiales sálicos alcalinos de la isla de Tenerife. Est. Geol., 29: 5 – 51.

Bravo, T., 1962. El circo de Las Cañadas y sus dependencias. Bol. R. Soc. Esp. Hist. Nat., 60: 93 – 108.

Bravo, T., 1964. Estudio geológico y petrológico de la isla de La Gomera. Est. Geol., 20: 1 – 56.

Buch, L. von, 1825. Physikalische Beschreibung der Canarischen Inseln. Gedruckt in der Druckerei der K. Akademie der Wissenschaften, Berlin, 407 pp.

Cabrera, M.P. and Hernández-Pacheco, A., 1987. Las erupciones históricas de Tenerife (Canarias) en sus aspectos volcanológico, petrológico y geoguímico. Rev. Mat. Proc. Geol., 5: 143 – 182.

Cantagrel, J.M., Cendrero, A., Fúster, J.M., Ibarrola, E. and Jamond, C., 1984. K-Ar chronology of the volcanic eruptions in the Canarian Archipelago: Island of La Gomera. Bull. Volcanol., 47(3): 597 – 609.

Carracedo, J.C., 1975. Estudio paleomagnético de la isla de Tenerife. Ph.D. Thesis, Univ. Complutensis Madrid.

Carracedo, J.C., 1979. Paleomagnetismo e historia volcánica de Tenerife. Aula de Cultura de Tenerife, 82 pp.

Cendrero, A., 1970. The volcano-plutonic complex of La Gomera, Canary Islands. Bull. Volcanol., 34(2): 537 – 561.

Cendrero, A., 1971. Estudio geológico y petrológico del complejo basal de la isla de La Gomera, Canarias. Est. Geol., 27: 3 – 73.

Chevallier, L. and Bachelery, P., 1981. Evolution structurale du volcan actif du Piton de la Fournaise, Ile de la Réunion, Océan Indien Occidental. Bull. Volcanol., 44(4): 723 – 741.

Coello, J., 1973. Las series volcánicas de los subsuelos de Tenerife. Est. Geol., 29(6): 491 – 512.

Duffield, W.A., Stieltjes, L. and Varet, J., 1982. Huge landslide blocks in the growth of Piton de la Fournaise, La Reunion, and Kilauea Volcano, Hawaii, J. Volcanol. Geotherm. Res., 12: 147 – 160.

Féraud, G., 1981. Datations des réseaux de dykes et de roches volcaniques sous-marines par les méthodes K-Ar et ^{40}Ar-^{39}Ar. Utilisation des dykes comme marqueurs de paleocontraintes. Thèse, Univ. Nice, 146 pp.

Fernández Navarro, L., 1917. Le Pic du Teide et le Cirque de Las Cañadas á Tenerife. C.R. Acad. Sci. Paris, 165: 561 – 563.

Francis, P.W., Gardeweg, M., Ramírez, C.F. and Rothery, D.A., 1985. Catastrophic avalanche deposit of Socompa Volcano, northern Chile. Geology, 13: 600 – 603.

Fúster, J.M., Araña, V., Brandle, J.L., Navarro, J.M., Alonso, U. and Aparicio, A., 1968. Geology and volcanology of the Canary Islands: Tenerife. Inst. Lucas Mallada, CSIC, Madrid, 218 pp.

Fúster, J.M., Muñoz, M., Sagredo, J., Yébenes, A., Bravo, T. and Hernández-Pacheco, A., 1980. Excursion 121 A + C, Islas Canarias. Bol. Geol. Min., 91(2): 351 – 390.

Gagel, C., 1910. Die Mittelatlantischen Vulkaninseln. Handbuch der Regionales Geologie, V-7 (10): 1 – 32.

Hausen, H., 1956. Contributions to the geology of Tenerife (Canary Islands). Soc. Sci. Fennicae, Comm. Phys.-Mat., 18, 254 pp.

Hernández-Pacheco, A. and Ibarrola, E., 1973. Geochemical variation trends between the different Canary islands in relation to their geological position. Lithos, 6: 389 – 402.

Humboldt, A. von, 1814. Voyages aux régions equinoxiales du nouveau continent, 1799-1804. Dufour et Cie, Paris. Vol. 1, 200 pp.

Ibarrola, E., 1969. Variation trends in basaltic rocks of the Canary Islands. Bull. Volcanol., 33: 729 – 777.

Ibarrola, E., 1970. Variabilidad de los magmas basálticos en las Canarias oerientales y centrales. Est. Geol., 26: 337 – 399.

Jéremine, E., 1933. Contribution a l'étude petrographique de trois îles de l'archipel canarien: Tenerife, La Palma et Gran Canaria. Soc. Mineral. Cristallogr. Fr. Bull., 56: 189 – 260.

Luhr, J.F. and Prestgaard, K.L., 1988. Caldera formation at Vocán Colima, Mexico, by a large Holocene debris avalanche. J. Volcanol. Geotherm. Res., 35: 335 – 348.

Lyell, C.H., 1855. A manual of elementary geology. Murray, London, 655 pp.

Martí, J., Mitjavila, J. and Araña, V., 1989. Field trip to Tenerife (Cañadas Caldera). ESF Meeting on Canarian Volcanism, pp. 1 – 42.

McDougall, I. and Schmincke, H.U., 1976-77. Geochronology of Gran Canaria. Canary Islands: Age of shield building volcanism and other magmatic phases. Bull. Volcanol., 40: 1 – 21.

McFarlane, D.I. and Ridley, W.I., 1968. An interpretation of gravity data for Tenerife, Canary Islands. Earth Planet. Sci. Lett., 4: 481 – 486.

Moore, J.G., 1964. Giant submarine landslides on the Hawaiian ridge. U.S. Geol. Surv., Prof. Pap. 501-D: 95 – 98.

Navarro, J.M. and Coello, J., 1989. Depressions originated by landslide processes in Tenerife. ESF Meeting on Canarian Volcanism, pp. 150 – 152.

Quesada, M.L., 1988. Geoquímica de lineamientos volcánicos en las Cañadas del Teide. Ph.D. Thesis, Univ. of La Laguna, Tenerife.

Ridley, W.I., 1970a. The petrology of Las Cañadas volcanoes, Tenerife, Canary Islands. Contrib. Mineral. Petrol., 26: 124 – 160.

Ridley, W.I., 1970b. The abundance of rock types on Tenerife, Canary Islands, and its petrogenetic significance. Bull. Volcanol., 34: 196 – 204.

Ridley, W.I., 1970c. The origin of some collapse structures in the Canary Islands. Geol. Mag., 108: 477 – 484.

Schmincke, H.U., 1981. Volcanic and chemical evolution of the Canary Islands. In: V. Rad te al. (Editors), Evolution of the Passive Margin of NW Africa. Springer Verlag, Heidelberg, pp. 273 – 306.

Soler, V. and Carracedo, J.C., 1986. Aplicación de técnicas paleomagnéticas de corto periodo a la datación del volcanismo sub-histórico de la isla de Tenerife. Geogaceta, 1: 33 – 35.

Staudigel, H. and Schmincke, H.U., 1984. The Pliocene seamont series of La Palma, Canary Islands. J. Geophys. Res., 83: 11195 – 11215.

Steiger, R.H. and Jaeger, E., 1977. Sub-commission on geochronology: convention on the use of decay constants in geo- and cosmo-chronology. Earth Planet. Sci. Lett., 36: 359 – 362.

Vincent, P.M., Bourdier, J.L. and Boudon, G., 1989. The primitive volcano of Mout Pelée: its construction and partial destruction by flank collapse. J. Volcanol. Geotherm. Res., 38: 1 – 15.

Wadge, G., 1982. Steady state volcanism. Evidence from eruption histories of polygenetic volcanoes. J. Geophys. Res., 87(B5): 4035 – 4049.

Wolff, J.A., 1985. Zonation mixing and eruptions of silica-undersaturated alkaline magma: a case study from Tenerife, Canary Islands. Geol. Mag., 122: 623 – 640.

Wolff, J.A. and Storey, M., 1984. Zoning in highly alkaline magma bodies. Geol. Mag., 121: 563 – 575.

Appendix: sample site locations and rock descriptions

OLD BASALTIC SERIES

Anaga

R. 10708-T.15.A. Mesa de Tejina, near the top. 28° 31′ 53′′ N, 16° 20′ 28′′ W, 610 m height.
Trachybasaltic flow. Phenocrysts of greenish augite and groundmass of plagioclase, clinopyroxene and opaques. Interstitial feldspatholds.

R.10711-T.52.F. Taganana, 28° 33′ 38′′ N, 16° 12′ 47′′ W, 130 m height.
Basaltic laccolithic dyke. Aphanitic with some phenocrysts of augite, oxidized amphibole and very scarce plagioclase. Very fine groundmass of clinopyroxene, plagioclase, opaques and nepheline (?).

R.10709-T.16.A. Mesa de Tejina. 28° 31′ 40′′ N, 16° 20′ 03′′ W, 500 m height.
Basaltic flow. Scarce small phenocrysts of augite and olivine. Groundmass of augite, plagioclase with fluidal disposition and opaques.

R.11077-T.50.F. Lomo de las Bodegas, 28° 33′ 43′′ N, 16° 09′20′′ W, 500 m height.
Basanitic laccolithic dyke. Small phenocrysts of olivine and augite. Groundmass with very abundant augite, scarce plagioclase, opaques, biotite and nepheline.

R.10713-T.53.F. Taborno, 28° 33′ 10′′ N, 16° 15′ 48′′ W, 660 m height.
Basaltic flow. Phenocrysts of augite and oxidized olivine. Groundmass of plagioclase, augite, oxidized olivine and opaques.
(olivine and augite were separated for the analytical work).

R. 11076-T.5.CH. Benijo (Taganana). 28° 34′ 20′′ N, 16° 11′ 20′′ W, 20 m height.
Nepheline-syenitic intrusion. K-feldspar slightly altered and nepheline. Aegirine and aegirinic-augite, some amphibole, sphene, apatite and opaques. Secondary carbonate.

R.11078-T.18.A. Mesa de Tejina. 28° 32′ 05′′ N, 16° 21′ 18′′ W, 220 m height.
Basaltic flow. Small phenocrysts of clinopyroxene, Microdoleritic groundmass of plagioclase, oxidized olivine, clinopyroxene and opaques. Small irregular cavities with a film of zeolites (?).

R.10710-T.17.A. Mesa de Tejina. 28° 32′ 03′′ N, 16° 21′ 10′′ W, 310 m height.
Tephrophonolitic flow. Phenocrysts of plagioclase, sphene and greenish pyroxene. Trachytoidic groundmass with feldspar and opaques.

Teno

R.11075-T.4.CH. Roque Blanco. 28° 16′ 58′′ N, 16° 49′ 40′′ W, 860 m height.
Phonolitic plug. Big tabular crystals of feldspar (essentially sanidine) with fluidal disposition. Microphenocrysts of aegirine. hauyne and opaques. Groundmass with similar composition.

R.10869-T.39.F. Montaña de Gala (La Mesa). 28° 18′ 40′′ N, 16° 49′ 08′′ W, 1260 m height.
Basaltic flow. Phenocrysts of olivine. Doleritic groundmass of plagioclase, clinopyroxene and opaques.

R.10716-T.38.F. Arguayo. Loma del Bicho. 28° 16′ 12′′ N, 16° 48′ 25′′ W, 1025 m height.
Trachytic flow. Scarce phenocrysts of anorthoclase and small phenocrysts of aegirinic-augite and sphene. Trachytic groundmass with the same minerals and opaques.

R.10714-T.35.F. Los Carrizales, on the road to Buenavista. 28° 19′ 10′′ N, 16° 51′ 17′′ W, 680 m height.
Basaltic flow. Very abundant big phenocrysts of augite and fresh olivine. Groundmass of plagioclase, clinopyroxene and opaques.
(olivine and augite were separated for the analytical work).

R.10715-T.37.F. On the north coast, at the base of Roque del Toscón. 28° 21′ 45′′ N, 16° 52′ 30′′ W, 120 m height.
Ankaramitic flow. Small phenocrysts of olivine and augite. Groundmass of plagioclase. clinopyroxene and opaques.
(olivine and augite were separated for the analytical work).

Roque del Conde and East

R.11079-T.12.CH. Barranco de Tamadaya. 28° 11′ 30′′ N, 16° 30′ 18′′ W, 600 m height.
Phonotephritic flow. Scarce phenocrysts of feldspar, amphibole, augite, hauyne and opaques, in afluidal matrix with similar composition.

R.10706-T.10.F. Roque Vento 28° 05′ 10′′ N, 16° 40′ 20′′ W, 500 m height.
Trachytic plug. Plagioclase phenocrysts. Groundmass of anorthoclase, aegirine-augite and opaques.

R.10707-T.1.A. At the bottom of the Barranco del Rey-Imoque. 28′ 07′ 05′′ N, 16° 40′ 58′′ W, 860 m height.
Basaltic flow. Aphyric. Microphenocrysts of oxidixed olivine and opaques. Groundmass of plagioclase, opaques and augite.

R.11292-T.24.A. Barranco del Rey, at the base of Risco Bisechi. 28° 05′ 05′′ N, 16° 41′ 54′′ W, 200 m height.
Trachybasaltic flow. Microcystalline without

phenocrysts. Microliths of oriented plagioclase, augite, olivine and opaques.

R.10864-T.14.F. Risco Bisechi, S of Roque del Conde, 28° 05′ 15′′ N, 16° 41′ 50′′ W, 460 m height.
Trachybasaltic flow. Scarce microphenocrysts of plagioclase. Trachytic groundmass of plagioclase, opaques and augite.

R.11291-T.23.A. Near the top of Roque del Conde. 28° 06′ 00′′ N, 16° 41′ 46′′ W, 900 m height.
Trachybasaltic flow. Phenocrysts of titan-augite, amphibole, opaques and apatite. Holocrystalline groundmass of plagioclase, augite and opaques. Very few vacuoles.

R.10863-T.13.F. Barranco del Rey. 28° 05′ 25′′ N, 16° 41′ 30′′ W, 460 m height.
Basaltic dyke. Microphenocrysts of olivine, sometimes skeietal, opaques, plagioclase and augite. Brownish glas very abundant.

CANADAS SERIES

F.11297-T.26.A. Km 53 on the main road to the South. 28° 04′ 40′′ N, 16° 31′ 24′′ W, 110 m height.
Sanidine from the upper dark pumice flow.

R.10877-T.44.F. Icod el Alto. Km 14.100 on the road to La Guancha, 28° 22′ 55′′ N, 16° 36′ 25′′ W, 570 m height.
Basaltic flow. Abundant phenocrysts of olivine with oxidized rim, some phenocrysts of augite. Groundmass of plagioclase, augite and opaques.
(olivine and pyroxene were separated for the analytical work).

R.11564-T.13.CH. La Fortaleza, on the south wall. 28° 18′ 47′′ N, 16° 35′ 35′′ W, 2140 m height.
Trachyphonolithic flow. Phenocrysts of feldspar, biotite and sphene. Groundmass of feldspar, aegirine and glass. Probable feldspathoids altered.

R.10873-T.23.F Lomo Simón. Km 78.2 on the road to Vilaflor. 28° 07′ 50′′ N, 16° 36′ 10′′ W, 910 m height.
Hauynic phonolitic plug. Small phenocrysts of anorthoclase, hauyne, sphene and aegirine-augite. Trachytic groundmass with the same composition.

R.11081-T.2.CH. In the lower part of the caldera rim at the Cañada de Diego Hernández. 28° 16′ 32′′ N, 16° 32′ 55′′ W, 2150 m height.
Basaltic flow. Big phenocryts of olivine, titan-augite and less abundant of plagioclase partially corroded. The size of the components grades to the matrix where the plagiociase has a fluidal disposition.

F.11091-T.3.A. Km 70.8 on the old road to the South. 28° 09′ 17′′ N, 16° 30′ 30′′ W, 500 m height.
Sanidine (anorthoclase-sanidine) from a phonolitic ignimbrite.

R.10874-T.18.F. Taucho. Barranco de la Finca. 28° 09′ 00′′ N, 16° 43′ 28′′ W, 900 m height.
Trachybasaltic flow. Phenocrysts of feldspar, some big phenocrysts of amphibole with oxidized rim. Trachytic groundmass of feldspar, opaques and slightly oxidized aegirine-augite.

F.11295-T.25.A. Arico. Km 70.85 on the old road to the South. 28° 09′ 15′′ N, 16° 30′ 35′′ W, 500 m height.
Sanidine from the obsidian in the Arico's ignimbrite.

R.10725-T.6.F. SW of Guaza. 28° 01′ 45′′ N, 16° 42′ 12′′ W, 60 m height.
Trachytic flow. Abundant phenocrysts of anorthoclase. Groundmass of feldspar, aegirine-augite, opaques and small nephelines.

R.10876-T.4.A. Km 61.5 on the old road to the South, at the bottom of Barranco de la Cueva. 28° 11′ 10′′ N, 16° 28′ 45′′ W, 380 m height.
Trachybasaltic flow. Scarce phenocrysts of plagioclase and some of aegirine-augite. Trachytic groundmass of plagioclase, opaques and augite.

R.11565-T.14.CH. In the wall of Cañada de Diego Hernandez, below the pyroclastic layers. 28° 16′ 37′′ N, 16° 32′ 55′′ W, 2260 m height.
Basaltic flow. Phenocrysts of olivine and augite. Groundmass of olivine, augite, opaques and microliths of plagioclase.

R.10871-T.43.F. Tigaiga. Km 12.850 on the road to La Guancha. 28° 22′ 57′′ N, 16° 36′ 05′′ W, 520 m height.
Trachytic flow. Small phenocrysts of plagioclase, aegirine-augite and someones of oxidized amphibole. Trachytic groundmass of feldspar, opaques and pyroxene.

R.10875-T.21.F. Barranco de Chabugo, near the road. 28° 10′ 17′′ N, 16° 47′ 40′′ W, 100 m height.
Mafic trachytic flow. Scarce small phenocrysts of plagioclase. Trachytic groundmass of plagioclase, opaques, augite and oxidized olivine.

R.10721-T.42.F. Tigaiga. Km. 12.300 on the road to La Guancha. 28° 22′ 45′′ N, 16° 35′ 55′′ W, 500 m height.
Nepheline-phonolitic flow. Phenocrysts of anorthoclase and someones of aegirine augite. Trachytic groundmass of anorthoclase, fresh nepheline and aegirine.

F.11090-T.17.F. At the starting point of the road to Adeje. 28° 06′ 47′′ N, 16° 43′ 55′′ W, 200 m height.
Sanidine from the obsidian in the ignimbrite.

R.10870-T.46.F. El Terreno, Km 46.800 on the road from Santa Cruz to Icod. 28° 23′ 30′′ N. 16° 36′ 23′′ W, 100 m height.
Basaltic flow. Aphyric with plagioclase, pyroxene, opaques and altered olivine.

R.10719-T.12.A. Guajara, Gañadas wall at the Km 48. 28° 12′ 18′′ N, 16° 37′ 20′′ W, 2410 m height.
Trachybasaltic flow. Big phenocrysts of plagioclase,

Ti-pyroxene and oxidized amphibole, someones of olivine. Microcrystalline groundmass of feldspar, pyroxene and opaques.

R.11293-T.56.F. San Juan de la Rambla. 28° 23′ 30′′ N, 16° 38′ 55′′ W, 60 m height.
Sanidine from the ignimbrite.

R.10717-T.1.C.Cañadas wall at La Angostura. 28° 14′ 48′′ N, 16° 33′ 15′′ W, 2300 m height.
Hauynic-phonolitic flow. Some phenocrysts of biotite, feldspar, aegirine-augite, and very fresh hauyne. Trachytic groundmass of nepheline and aegirine.

R.10720-T.14.A. Guajara. Cañadas wall at the Km. 48. 28° 12′ 23′′ N, 16° 37′ 35′′ W, 2240 m height.
Nepheline-phonolitic flow. Sanidine phenocrysts. Microphenocrysts of nepheline and aegirine-augite with sheaf-like disposition. Microliths of feldspar and interstitial glass.

R.10723-T.20.F.Barranco de Erques. 28° 09′ 30′′ N, 16° 47′ 30′′ W, 80 m height.
Mafic trachytic flow. Phenocrysts of plagioclase and scarce of amphibole. Trachytic groundmass with feldspar and opaques. Some secondary carbonate.

R.10724-T.25.F. Lomo de Topo Negro, on the forest road to Vilaflor. 28°10′07′′ N, 16°37′40′′ W, 1650 m height.
Basaltic flow. Phenocrysts of plagioclase and augite. Groundmass of plagioclase, augite and opaques.

DORSAL SERIES

R.10879-T.20.A. Dorsal road, Fuente de Joco. 28° 22′ 00′′ N, 16° 27′ 42′′ W, 1970 m height.
Trachybasaltic flow. Aphyric. Plagioclase and scarce aegirine-augite and sphene. Groundmass of plagioclase, pyroxene and opaques.

R.10722-T.48.F. Mirador de Humbolt. 28° 24′ 20′′ N, 16° 30′ 20′′ W, 320 m height.
Basaltic flow. Aphyric. Slightly altered olivine.

R.10872-T.21.A. Km 27.800 on the Dorsal road, near La Ayosa. 28° 21′ 30′′ N, 16° 27′ 55′′ W, 2000 m height.
Basaltic flow. Phenocrysts of augite and opaques. Almost microdoleritic groundmass of augite, plagioclase and opaques.

R.10868-T.9.A. Barranco de Badajoz. 28° 17′ 40′′ N, 16° 27′ 50′′ W, 1565 m height.
Basaltic flow. Plagioclase phenocrysts. Groundmass of plagioclase, opaques and augite.

R.10866-T.7.A. Barranco de Badajoz. 28° 18′ 00′′ N, 16° 27′ 35′′ W, 1270 m height.
Bassaltic flow. Very abundant phenocrysts of augite, plagioclase and some amphibole. Small phenocrysts of fresh olivine. Trachytic groundmass of plagioclase, opaques and olivine.
(olivine and augite were separated for the analytical work).

RECENT SERIES

R.10880-T.22.A. La Orotava. Km 21.800 on the road to Las Cañadas. 28° 20′ 40′′ N, 16° 31′ 05′′ W, 1420 m height.
Basaltic flow. Abundant phenocrysts of olivine. Groundmass of pyroxene, opaques, scarce plagioclase and some glass.
(olivine was separated for the analytical work).