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POTASSIUM-ARGON AGES, VOLCANIC STRATIGRAPHY, AND GEOMAGNETIC POLARITY HISTORY OF THE CANARY ISLANDS: TENERIFE, LA PALMA, AND HIERRO†

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ABSTRACT. Thirty-six igneous bodies from the east Atlantic islands of Tenerife, La Palma, and Hierro have been dated using the potassium-argon method. The paleomagnetic polarities of the same bodies have also been determined.

Miocene to Lower Pliocene volcanics occur on the Anaga and Teno peninsulas of Tenerife, but the remaining 80 percent of the subaerial volcanics are of Pleistocene age. Three limited areas on Tenerife, previously mapped as equivalents of the Anaga and Teno peninsula volcanics, are reassigned to the Pleistocene. The present Las Canadas Caldera was initiated approximately 0.2 m.y. ago.

The lavas draping the basement complex centered on the Taburiente Caldera on La Palma are confined to the Pleistocene. Hierro is also Pleistocene in outcrop.

The potassium-argon results and paleomagnetic data for the 29 units on Tenerife, La Palma, and Hierro that are less than 2.0 m.y. old are completely consistent with the established geomagnetic polarity scale: the Jaramillo event is detected three times, and the Gilsa event is detected on Tenerife.

INTRODUCTION

In a previous paper (Abdel-Monem, Watkins, and Gast, 1971) we described the volcanic history and paleomagnetism of Lanzarote, Fuerteventura, Gran Canaria, and La Gomera, in the Canary Island group, straddling the continental-oceanic boundary in the east-central North Atlantic (fig. 1). It was shown that plutonic outcrops as old as Oligocene exist on Fuerteventura, but the other islands were no older than Early Miocene in outcrop. For the time range where a comparison is possible, potassium-argon ages and paleomagnetic polarities of all samples were shown to be consistent with the established geomagnetic polarity history (Cox, 1969).

Previously established within-island stratigraphic correlations were confirmed in most cases, but several unexpected age differences were shown to exist between rock groups on Lanzarote and La Gomera. The time relationships of the diverse igneous rock types found on Gran Canaria were defined. For the first time, a quantitative between-island correlation of volcanism was established. A basaltic "Tableland Series",

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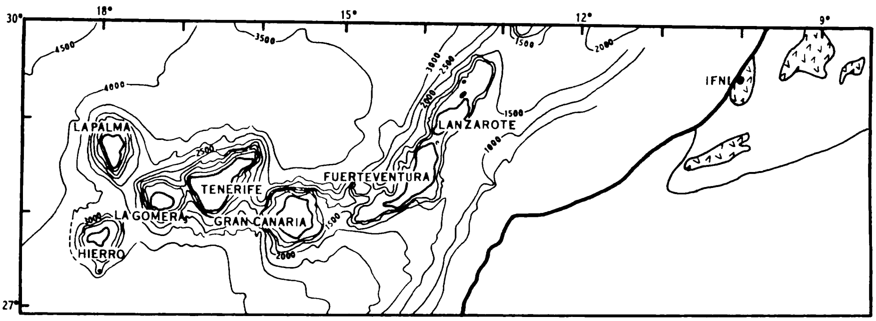


Fig. 1. Map showing location of the Canary Islands, relative to the adjacent African coast, and regional bathymetry (Dash and Bossard, 1969). Precambrian volcanics of Anti-Atlas of Morocco are indicated by check pattern. Bathymetric contours in meters.

previously suspected to be correlative between all islands was shown to be youngest on Lanzarote, with that on La Gomera being younger than the roughly contemporeaneous outcrops on Fuerteventura and Gran Canaria. Late-stage intrusions into the "basement complexes" of Fuerteventura and La Gomera were not found to overlap in age, and the oldest (earliest Miocene) basalts were found in southern Lanzarote and northern Fuerteventura.

In this paper, we extend our study to the remaining three large islands in the Canary Islands group (fig. 1). This will provide the possibility of quantitative correlations across the island chain as well as further definition of the geomagnetic polarity history.

GEOLOGICAL BACKGROUND

The 3000 m bathymetric contour encloses all the Canary Islands except Hierro (fig. 1), clearly demonstrating that the islands are not completely independent volcanic edifices. Dash and Bosshard (1969) have shown that the western Canary Islands are above oceanic crust, and the central islands are underlain by crust transitional between oceanic and continental. Dietz and Sproll (1970) support this suggestion on grounds involving reconstruction of the Atlantic Ocean prior to continental drift. Heirtzler and Hayes (1967) believe that the western boundary of the zone of low amplitude marine magnetic anomalies and eastern boundary of the higher amplitude anomalies characteristic of oceanic crust pass between La Gomera on the east and La Palma and Hierro on the west. The low amplitude anomalies are thought to represent oceanic crust of Permian or Cretaceous age, which, because of the non-varying geomagnetic polarity during most of those periods, would not be expected to possess the contrasting polarities required to produce high amplitude marine magnetic anomalies.

Geological investigations of the Canary Islands date back to the earliest scientific studies of igneous rocks. Hausen (1956) has summarized these early works, which began with Von Buch (1825). The most extensive and best documented studies of Lanzarote, Fuerteventura, Gran Canaria, and La Gomera have been summarized by Abdel-Monem, Watkins, and Gast (1971).

Tenerife has been subject to considerable geological investigation, but La Palma and Hierro have been studied only rarely. We shall include mention of earlier publications in discussion of our K:Ar results.

METHODS OF STUDY

Field.—Samples were taken during three different field seasons: 1965, 1966, and 1968. The site locations are shown in figures 2, 3, and 4 and are described in the appendix.

During 1965, two geographically oriented cores of 2.5 cm diameter were drilled from over eighty separate igneous bodies on Tenerife and Hierro as part of a paleomagnetic survey of five of the Canary Islands. A gasoline-powered portable drill (Doell and Cox, 1964) was used throughout. The results of this paleomagnetic survey have already been reported (Watkins, Richardson, and Mason, 1966). In the following year, the survey was extended by further sampling of the same bodies. An additional forty-five bodies were sampled by taking up to eight separate cores from each unit. Finally, in 1968, Hierro was again visited for repeated and additional sampling, and a further twelve units were sampled on Tenerife.

In all cases, sample sites were located with respect to the currently available stratigraphic maps on 1:25,000 topographic maps. The stratigraphic maps were by Hausen (1956) and later, Fuster and others (1968) for Tenerife; Hausen (personal commun., 1967) for La Palma; and Hausen (1964) for Hierro.

Laboratory (paleomagnetism).—From each core, a specimen 2.2 cm long was cut for paleomagnetic measurement. The direction and intensity of magnetization was determined using astatic and spinner magnetometers. The unstable components were minimized using a two-axis demagnetizing unit. Alternating magnetic fields of 100, 200, and 300 oersteds were applied to each specimen, and final mean directions and Fisher (1953) statistics for each body were computed using a least dispersion criterion (Irving, Stott, and Ward, 1961).

Polished thin sections were manufactured from at least one core in each body, in order to examine the oxidation state of the titanomagnetites, which dominates in the magnetic properties of the specimens.

Laboratory (geochemistry).— Full details of the method use, analytical procedure, and the error computation method have been given in our previous paper (Abdel-Monem, Watkins, and Gast, 1971).

For each specimen analyzed, a thin section was cut for transmitted light petrographic examination. Several authors including Miller and Mussett, (1963), Dalrymple (1963, 1964), McDougall (1964), Cox, Hopkins, and Dalrymple (1966), Baksi, York, and Watkins (1967), and Grey and Kittleman (1967) have discussed the petrographic criteria that should be employed in the evaluation of the suitability of basaltic rocks for potassium-argon dating.

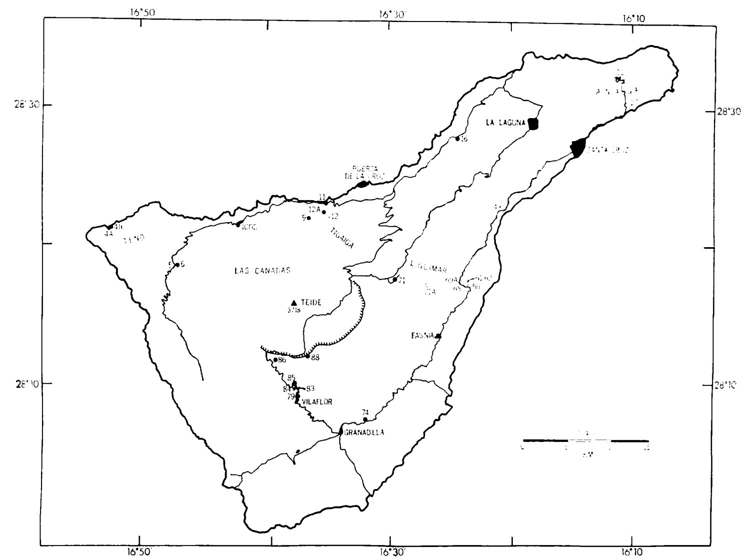


Fig. 2A. Location and numbers of samples sites on Tenerife. Major roads and towns or villages are shown. Southern edge of the Las Canadas Caldera, location and height (in meters) of the Teide Peak, and significant geographic divisions (Teno, Tigaiga, Anaga, Ladera de Guimar, and Vilaflor) are also indicated. Paleomagnetic polarities of the sampled bodies (table 2) are indicated as follows: solid circles are normal polarity; open circles, reversed polarity; split circles (sites 22 and 84), intermediate polarities (with the virtual geomagnetic pole equatorward of 30° lat).

RESULTS

The potassium-argon data are given in table 1 and in figure 2B, 3, and 4B. The petrographic description of each specimen is not given here but is available from the authors on request.

The paleomagnetic data are given in table 2. Paleomagnetic polarities are indicated on figures 2A, 2B, 3, 4A, and 4B. The potassium-argon ages of table 1 are also added to table 2, for ease of comparison.

The oxidation state of the titanomagnetites in each body sampled has already been published elsewhere (Ade-Hall and Watkins, 1970), as part of a study of titanomagnetite oxidation state and magnetic polarity in volcanic rocks. The titanomagnetites are generally of a low oxidation state.

DISCUSSION

In the following discussions of the results, all stratigraphic terms used are due to Fuster and others (1968) and Hausen (1964, 1969). Unit numbers refer to locations in figures 2A, 3 ,and 4A. Geographic terms are on the same diagrams.

Tenerife

The volcanic cone of Teide (3718 m), the highest point in the Atlantic, dominates Tenerife. It was recognized early as a great phono-

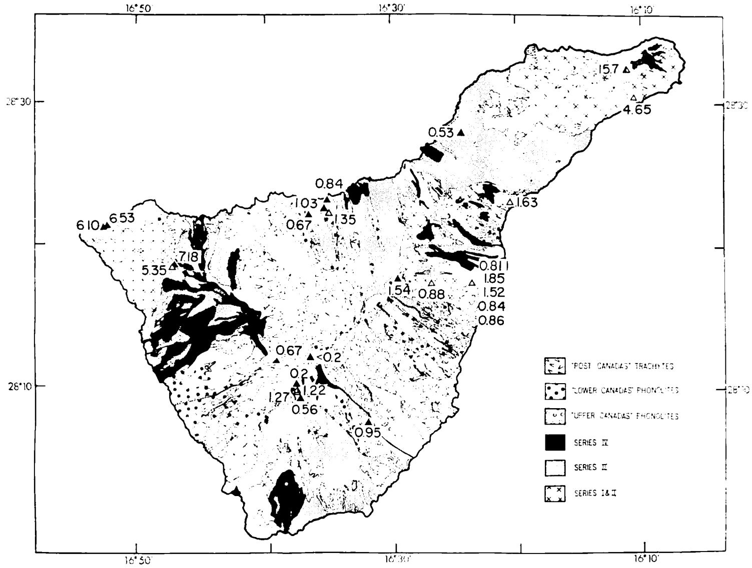


Fig. 2B. Potassium–argon age (in millions of years) and paleomagnetic polarity of each dated body, superimposed on a surface geological sketch map, after Fuster and others (1968). Sites (fig. 2A) shown as triangles. Ages from table 1, polarities as in table 2: black solid triangles are normal polarity; open triangles, reversed polarity; split triangles, intermediate polarities (see caption to fig. 2A for definition). Note that the five dates at the site on the east-central coast are in stratigraphic order; see text for the preferred explanation of the anomalously old dates for the second and third lavas.

lite body. Jeremine (1933) published a petrographic and petrological study of some Tenerife rocks, which stressed their highly alkalic nature. She included the first attempt at stratigraphic subdivisions of the island. Hausen (1956) made the first major and detailed description of the geology and geochemistry of Tenerife, and this has since been superseded by the more detailed work of Fuster and others (1968), from which the geological map shown in figure 2B is taken. Geographic terminology is included in figure 2A. The deeply dissected eastern peninsula of Anaga is thought of as equivalent in age to the Teno peninsula of the northwest (Fuster and others, 1968). These are the "Old Basalts" (Series I and II, fig. 2B) which are also thought to outcrop southwest of Teide and in the Ladera de Guimar. Phonolitic dikes and plugs cut these basalts. Far less dissected basic lavas (Series III and IV) surround the relatively young outpourings of the Teide phonolites, tephrites, and basanites. We discuss our results in stratigraphic order, beginning with the oldest unit (fig. 2B).

Basalt Series I and II.—The peninsulas of Teno and Anaga (fig. 2A) are dominantly basaltic and ankaramatic flows dipping toward the coast. They are divided into lower Series I, which is mainly pyroclastic, and a younger Series II, which is composed mainly of lava flows. They

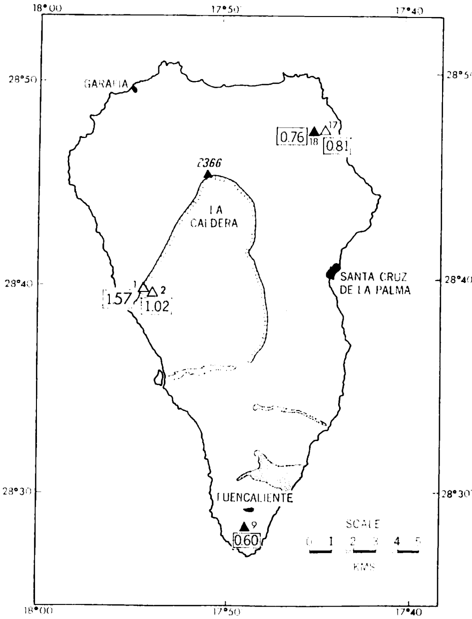


Fig. 3. Map of the island of La Palma, showing location and limits of the Taburiente Caldera. Major towns (black), elevation (in meters) of the highest point above the caldera, and areas of very recent volcanic eruptions (dotted) shown. Potassium–argon ages (table 2) in millions of years shown in rectangles at the sample sites (triangles), which are numbered 1, 2, 9, 17, and 18. Paleomagnetic polarities of the sampled units are indicated at the sites: black triangle is normal polarity; open triangle is reversed polarity.

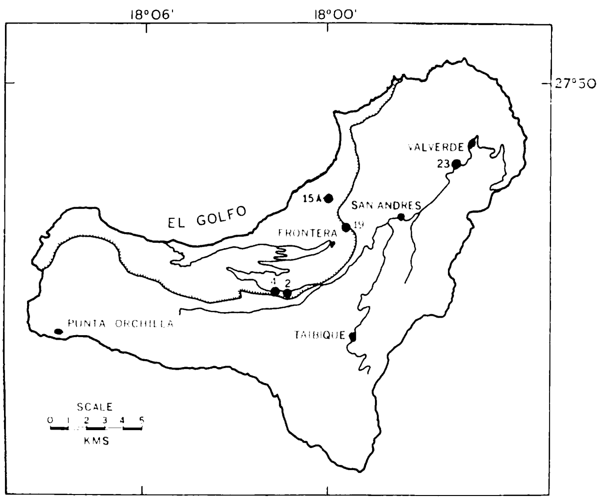


Fig. 4A. Location and numbers (2, 4, 15A, 19, and 23) of sample sites (solid black dots) on Hierro. Major villages or towns and main roads or tracks are indicated. The edge of the El Golfo scarp is indicated by a hashered line.

are mapped as one unit (fig. 2B) because of the lack of a readily recognizable unconformity between the two units. Six lava flows and dikes in the Teno and Anaga peninsulas have been dated (figs. 2A and 2B, table 1). The results show that the rocks exposed on the northern slope of Anaga (unit 22, t = 15.7 m.y.) are significantly older than those on the southern slopes (unit 27, t = 4.65 m.y.), suggesting the presence of a large hiatus in the Anaga volcanics. Three of the results from the Teno peninsula provide closely-grouped ages: unit 4A (t = 6.10 m.y.), unit 4B (t = 6.53 m.y.), and unit 6 (t = 7.18 m.y.). The age of unit 5 (t = 5.35 m.y.) is consistent with field relationships: it is a trachyte dike cutting unit 6. These limited results suggest that volcanism on Teno and Anaga took place intermittently over an extended period of time, between at least 16 and 4.5 m.y. ago. Comparison of these data with results from the upper part of the titled Old Basalts on the island of La Gomera and the Farmara section and Los Ajaches Mountains of Lanzarote (Abdel-Monem, Watkins, and Gast, 1971) suggest that they overlap in age with the Anaga and Teno volcanism on Tenerife. Similarly, the unit from the north side of the Anaga peninsula is equivalent in age to the upper part of Basaltic Series I on Gran Canaria and the basalts of the Jandia peninsula of Fuerteventura (Abdel-Monem, Watkins, and Gast, 1971). The horizontal basalts of La Gomera and some of the earlier shield volcanoes of Fuerteventura are of similar age to the units from the southern slopes of the Anaga peninsula. These several age overlaps are therefore partly consistent with Hausen's (1956, 1958, 1962) concept of a "Tableland Series", which is equivalent in age, on Fuerteventura, Lanzarote, Gran Canaria, Tenerife, and La Gomera. No

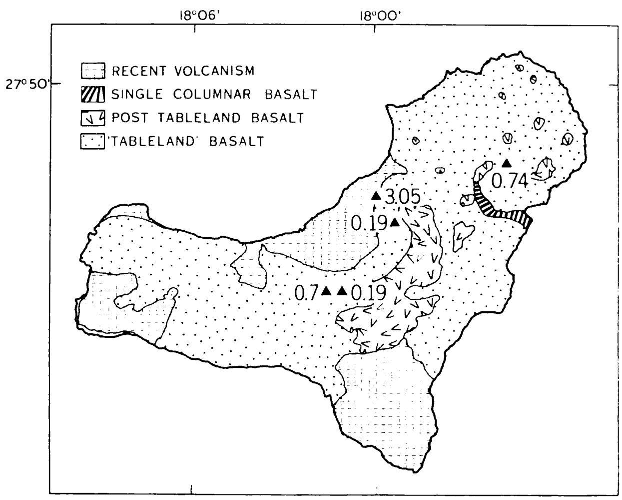


Fig. 4B. Potassium–argon ages (table 1) in millions of years and paleomagnetic polarity of each dated body at the sample sites (fig. 4B) superimposed on a surface geological map (Hausen, 1964) of Hierro. All bodies are normal polarity (solid black site-location triangles).

TABLE 1

Potassium-argon ages for Tenerife, La Palma, Hierro, Canary Islands

Diagram no.	Original field no.	Rock type	%K	Ar*/g × 10^{-6} Scc	Ar*/Ar_t	Calculated age (m.y.) and error
		Tenerife				
22	TF-58	Olivine–augite basalt	0.41	0.255	0.10	15.68 ± 1.60
6	TF-87	Olivine basalt	1.10	0.315	2.23	7.18 ± 0.57
4B	TF-132	Olivine–augite basalt	0.80	0.209	0.41	6.53 ± 0.26
4A	TF-131	Olivine basalt	0.58	0.141	0.51	6.10 ± 0.18
5	TF-86	Trachyte	2.61	0.557	0.62	5.35 ± 0.11
27	TF-18	Augite basalt	1.50	0.304	0.12	4.65 ± 0.70
62	TF-38	Augite basalt	0.80	0.072	0.13	
				0.062	0.10	
				0.049	0.07	
				0.052	0.05	
				Avg. 0.059		1.85 ± 0.37
49	TF-93	Augite olivine basalt	0.87	0.057	0.22	1.63 ± 0.11
71	TF-70	Trachyte	2.10	0.129	0.16	1.54 ± 0.17
61	TF-90	Augite olivine basalt	1.09	0.067	0.18	1.52 ± 0.15
12	TF-96	Phonolite	4.63	0.250	0.71	1.35 ± 0.02
83	TF-113	Phonolite	4.12	0.207	0.46	1.27 ± 0.04
84	TF-3	Phonolite	4.54	0.219	0.06	
				0.221	0.02	
				Avg. 0.220		1.22 ± 0.04
12A	TF-128	Trachybasalt	0.65	0.030	0.39	
				0.023	0.24	
				Avg. 0.027		1.03 ± 0.05
74	TF-12	Phonolite	3.83	0.143	0.26	0.95 ± 0.06
71A	TF-127	Plagioclase–augite basalt	1.32	0.049	0.30	
				0.043	0.28	
				Avg. 0.046		0.88 ± 0.05
69A	TF-46	Plagioclase basalt	1.65	0.061	0.15	
				0.048	0.06	
				0.061	0.04	
				Avg. 0.057		0.86 ± 0.22

evidence exists to support Hausen's belief that the series was continuous and later separated into the present islands by normal faulting.

The basaltic scarps of Ladera de Guimar and Hondo Canyon are mapped by Hausen (1956) and Fuster and others (1968) as equivalent in age to the Series I and II rocks of the Anaga and Teno peninsulas. This older material is also thought to outcrop as an inlier on the northern coast, west of Puerta de la Cruz and north of the Tigaiga block (fig. 5). We have dated several extrusives from these three areas: units 50, 61, 62, 68, 69A, 71A, and 71 from the Ladera de Guimar, unit 49 from Hondo Canyon, and unit 11 from the outcrop on the northern coast (fig. 5). The results are shown in figures 2B and 5.

The outcrop on the Ladera de Guimar scarp is such that no difficulty occurs in placing five of the units in stratigraphic order. The ages of these are illustrated, in stratigraphic order, in figure 2B. It can be seen that the second and third units at t = 1.85 and 1.52 m.y. provide radiometric ages older than those lavas above (t = 0.81 m.y.) *and* below (t = 0.84 and 0.86 m.y.). The Hondo Canyon sample is dated as t = 1.63 m.y., and the north coast outcrop is t = 0.84 m.y. The lack of

TABLE 1
(data arranged in order of decreasing age)

Diagram no.	Original field no.	Rock type	%K	Ar*/g × 10^{-6} Scc	Ar*/Ar_t	Calculated age (m.y.) and error
11	TF-73	Plagioclase basalt	1.69	0.052	0.24	
				0.059	0.31	
				Avg. 0.056		0.84 ± 0.05
68	TF-44	Plagioclase basalt	0.73	0.024	0.06	0.84 ± 0.28
50	TF-27	Augite basalt	0.70	0.023	0.17	0.81 ± 0.09
86	TF-112	Phonolite	3.47	0.092	0.58	0.67 ± 0.01
9	TF-88	Phonolite	3.68	0.098	0.62	0.67 ± 0.01
79	TF-10	Alkali trachyte	2.81	0.064	0.23	0.56 ± 0.04
16	TF-67	Alkali trachyte	2.49	0.052	0.26	0.53 ± 0.03
85	TF-114	Alkali trachyte	2.04	0.015	0.05	0.20 ± 0.08
88	TF-104	Phonolite	4.55	zero	0.00	<0.20
		La Palma				
2	LP-2	Olivine basalt	0.85	0.053	0.28	1.57 ± 0.09
1	LP-3	Plagioclase basalt	2.08	0.083	0.47	1.02 ± 0.03
17	LP-26	Olivine basalt	0.70	0.023	0.17	0.81 ± 0.09
18	LP-27	Olivine basalt	0.83	0.025	0.15	0.76 ± 0.09
9	LP-15	Phonolite	3.86	0.089	0.04	0.60 ± 0.30
		Hierro				
15A	H-43	Olivine–augite basalt	1.04	0.137	0.02	
				0.115	0.02	
				Avg. 0.126		3.05 ± 3.00
23	H-16	Plagioclase basalt	1.53	0.048	0.32	
				0.043	0.22	
				Avg. 0.045		0.74 ± 0.04
4	H-9	Plagioclase basalt	0.82	0.26	0.17	
				0.23	0.20	
				0.20		0.70 ± 0.07
2	H-7	Alkali olivine basalt	1.27	0.009	0.12	0.19 ± 0.03
19	H-4	Alkali olivine basalt	1.47	0.011	0.04	0.19 ± 0.01

The decay constants used in the age calculations are $\lambda_e = 0.585 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.72 \times 10^{-10}$ yr^{-1}; $K^{40}/K = 0.0119$ atomic %. Ar* = radiogenic argon. Avg. = average content, when duplicate analyses made. Ar_t = total argon. See text for discussion of possible excess radiogenic argon content in two Tenerife basalts. See Abdel-Monem, Watkins, and Gast (1971) for method of calculation of error limits.

internal consistency of the stratigraphically controlled sequence on the Ladera de Guimar scarp makes analysis of the results difficult. Figure 5 shows the stratigraphic relationships of the north coast Tigaiga block Series I and II basalt outcrop with the younger phonolite and trachyte units, according to Fuster and others (1968). Internal inconsistency of stratigraphic order and age is again apparent.

These data can be interpreted in several ways. The apparently older two lavas of the Ladera de Guimar scarp sequence may possess excess radiogenic argon. If this *is* so, the age and stratigraphic positions of the remaining three lavas in the sequence are internally consistent. Although we do not know the exact stratigraphic relationship of unit number 71A with this sequence, it is of the same approximate age. The age of t = 0.88 m.y. would therefore, if correct, be consistent with the presence of excess argon in the two older lavas of the coastal sequence. Unfortunately the paleomagnetic polarities (which are all reversed) of the coastal and inland Ladera de Guimar lavas cannot assist in resolution of the am-

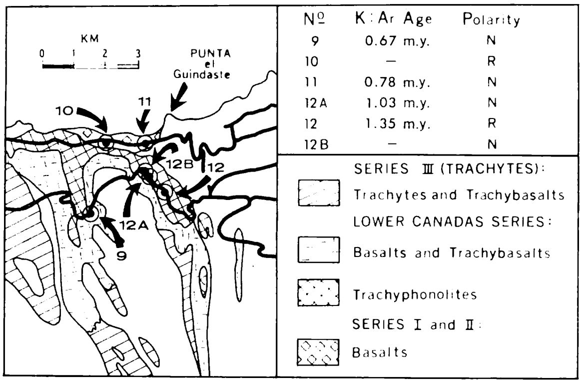


Fig. 5. Details of sample site locations and numbers, potassium argon ages, and paleomagnetic polarities on the north-central coast of Tenerife in the area of the Tigiaga block (fig. 2A). Major roads shown as solid black lines; geological map and stratigraphy after Fuster and others (1968); sample sites shown as circled dots; numbers as in figure 2A. Sites include two bodies sampled for paleomagnetic study but not potassium–argon analyses. Site numbers, potassium–argon ages (table 2), and polarities (table 2, N = normal polarity, R = reversed polarity) are given in the inset for all sampled bodies. See text for the preferred explanation of the inconsistency between the potassium–argon age and assigned stratigraphic identification (Fuster and others, 1968) of unit 11.

biguities, since the lavas would appear to be all confined to the Matuyama reversed polarity epoch, whether as the true age or one resulting from excess argon. The alternative explanation for the inconsistencies in the age of the Ladera de Guimar coastal sequence would be argon loss in the youngest lava, the two older lavas, and the lava inland from the section, and furthermore the loss would have to be systematically greater with decreasing stratigraphic age in the coastal section. We believe that the former explanation is the most preferable of the two possibilities. The problem of the discordantly young age of the Series I and II basalt inlier on the north coast (fig. 5) cannot be explained in a similar way: the possibilities here are either that the outcrop is not mapped correctly, and is in fact a younger basalt which flowed around this northern edge of the Tigaiga block, or argon loss has taken place. The normal polarity of this unit is consistent with a Brunhes (less than 0.7 m.y.) age, suggesting that no argon loss has occurred, but it could conceivably be of Olduvai ($t = 1.9$ m.y.) or Gilsa (1.6 m.y.) normal polarity event age, if argon loss in fact occurred. We favor interpretation of this north coast data to be consistent with an error in field mapping but must await further details of field mapping prior to making conclusive statements.

Even though doubts exist about the exact ages of the Ladera de Guimar section, the Hondo Canyon lava sample, and the north coast Series I and II outcrop, these outcrops are without doubt very much younger than the Teno and Anaga lavas, which are mapped as time equivalent units by Fuster and others (1968), as shown in figure 2B. If our preferred interpretation of the data is correct, the units are all just less than 1 m.y. old. This would produce an even greater conflict with the established stratigraphy of the island: the Ladera de Guimar scarp lavas would have to have been extruded after the Lower Canadas Series basalts and trachybasalts (see below, and fig. 4). We stress the final resolution of these stratigraphic and radiometric age inconsistencies requires further study.

Upper and Lower Canadas Series.—The Vilaflor Complex is named after the village south of the Teide Caldera (figs. 2A and 2B) but includes exposures on the north coast, as the Tigaiga block (figs. 2B and 5). The complex is divided into two groups by Hausen (1956), Fuster and others (1968), and Ridley (1972). The Lower Canadas Series consists mainly of trachybasalts, trachytes, mafic and plagioclase phonolites, and related pyroclastics, where as the Upper Canadas Series are mainly phonolites and peralkaline rocks and related pyroclastics.

The stratigraphic sequence in the Lower Canadas outcrop in figure 5 is consistent with the three potassium-argon ages obtained (fig. 5). Furthermore the ages and polarities are consistent with the established geomagnetic polarity history. We therefore believe that these data are reliable.

Unit 71 (fig. 2A), a trachyte from Montaña Izana, provided a potassium-argon age of 1.54 m.y. This would place it in the lower part of the Lower Canadas Series, which is not inconsistent with the field mapping. The normal magnetic polarity of this body has special significance: the Gilsa event (McDougall and Wensink 1966) is detected. Although doubt existed about the reality of the event following its initial discovery, subsequent analyses have not only confirmed its existence (Watkins and Goodell, 1967; Cox, 1969; Emilia and Heinrichs, 1969; Watkins and Abdel-Monem, 1971) but show that it is the major normal polarity event within the Matuyama reversed epoch, although Grommé and Hay (1971) have recently questioned this point. It may be significant that the Gilsa event has now been detected in as many geographic sites (Iceland, Alaska, Madeira, and Tenerife) as the Olduvai (detected in East Africa, Alaska, Cocos Islands, and Australia), using conventional paleomagnetic and K:Ar methods (summary by Watkins, 1972).

The major outcrop area of the Vilaflor Complex is on the southern slopes of Teide (fig. 2). The samples from the Canadas Series Phonolites provide ages of 1.27 m.y. (unit 83), 1.22 m.y. (unit 84), 0.95 m.y. (unit 74), and 0.67 m.y. (unit 86). The strong overlap with the ages of the Tigaiga block results (fig. 5) strengthens the validity of the results. We believe that the igneous rocks of the Vilaflor Complex were emplaced between $t = 2.0$ m.y. and $t = 0.6$ m.y. This sequence of volcanics is therefore well suited for study of the geomagnetic polarity history within the Matuyama reversed epoch. The ages so far obtained, when combined with the paleomagnetic data (table 2), are all consistent with the established geomagnetic polarity history: the Brunhes normal epoch (unit 86), the Matuyama reversed epoch (units 83 and 84), and the Jaramillo event (unit 74) are represented by our limited collection.

Trachyte–Trachybasalt Series and Basaltic Series III.—The Vilaflor Complex is overlain by a series of trachytes, trachybasalts, and basalts, as well as basanitic and tephritic lavas. Hausen (1956) called this whole unit the post-Caldera basic lava sheets, but Fuster and others (1968) divide it into a lower Trachyte and Trachbasaltic Series and an upper Basaltic Series III. We have dated three alkali trachytes from this series. Two lavas from the Vilaflor Valley (units 79 and 85, fig. 2A) provide ages of 0.56 m.y. and 0.2 m.y., respectively. The third body (unit 16, fig. 2A) is from the eastern area of Series III outcrop and is dated at $t = 0.53$ m.y. In all cases, the bodies are of normal polarity and were therefore extruded during the Brunhes geomagnetic polarity epoch. These results suggest that the extrusion of the trachytic lavas followed the Vilaflor phonolites, with relatively little break (or conceivably overlapped very slightly in time) and continued until 0.2 m.y. ago, which is the probable approximate time of the formation of the Las Canadas Caldera.

Very late stages of the Trachyte–Trachybasalt Series are found on the southern rim of the Las Canada Caldera. Unit 88, which is a thick phonolite flow, provides an age of less than 0.2 m.y. The small amount of radiogenic argon present approaches the sensitivity limits of the mass spectrometer: we are unable to date the unit more accurately. Even with a generous error margin (table 2) it is less than 0.2 m.y. old. It is not surprising that the flow is of normal polarity.

La Palma

The area of La Palma is 730 km². It rises 6500 m above the sea floor. The island (fig. 3) is dominated by a northern dome centered on the 1600 m deep Caldera de Taburiente, which is open to the sea on the southwest through the Barranco de las Angustias. Hausen (1961) considers the ridge south from the Caldera as a volcano-tectonic feature because several recent eruptions have taken place along it, the most recent being in 1949 and 1967. Lyell (1874), Gagel (1908), Reck (1928), Bravo (1954), and Blumenthal (1961) have speculated on the origin of the caldera, which is floored by a basement complex. This basement complex has been variously interpreted as altered diabases intruded by dikes (Hartung, 1857; Gagel, 1908) or spilitic lavas and tuffs and breccias intruded by lamprophyre dikes (Jeremine, 1933; Blumenthal, 1961). Most recently, Gastesi, Hernandez-Pacheco, and Munoz (1966) suggest that the caldera features plutonic series ranging from dunites and pyroxenites to syenitic gabbros with common dikes.

A major unconformity separates the basement complex from a series of basalts draped around the caldera. These are intruded by small alkalic domes, especially to the south. Blumenthal (1961) and Gastesi and others (1966) have discussed this volcanic series. In contrast with Tenerife, phonolitic lavas and salic rocks are very rare.

Our collection from La Palma (fig. 3) is restricted to the lavas that drape the major unconformity above the basement complex of the Caldera de Taburiente, and a phonolitic dome. Hausen (1969) published a description of the geology of La Palma after our field work was completed. Our samples are from his Adventive Basaltic Volcanoes of Quaternary age, and phonolitic necks.

The oldest samples (1 and 2, fig. 3) were collected from the northern wall of the Barranco de las Angustias. The highest flow (unit 2) provides t = 1.02 m.y., and the lowest flow (unit) t = 1.57 m.y. Both flows are reversely magnetized, consistent with their extrusion during the Matuyama epoch.

Units 17 and 18, on the northeast shore of the island, are from the latest adventive alkali basalt volcanism. Their ages, although very close, straddle a polarity change. We believe that unit 18 (t = 0.76 m.y.), which is normal polarity, is of Brunhes epoch age. Unit 17, which is 50 m stratigraphically below unit 18, is of reversed polarity and Matuyama epoch age, at t = 0.81 m.y.

Unit 9 is a hauyne–phonolite intrusive at the southern end of the island. The age of 0.6 m.y. is consistent with its normal polarity and its field relationship with the older lavas.

It appears that the lavas that drape the basement complex of La Palma date from at least 1.6 m.y. ago: this provides a minimum age for the caldera.

Hierro

This is the smallest (227 km^2) and westernmost island in the Canary group. It rises more than 5500 m from the sea floor. The physiography is dominated by many small recent adventive cones and the large and steep scarp of El Golfo (fig. 4A) which is suspected to be the remains of an explosive caldera (Knebel, 1906; Navarro, 1908), although Hausen (1964) rejects this idea because of the lack of ejecta on the surrounding highlands.

Navarro (1908, 1926) published the first geological study of the island. Jeremine (1933) reported on the petrography. It is entirely volcanic without any exposed basement complex and, like La Palma, is distinguished from Tenerife by the lack of phonolitic volcanism. Basalts, tephrites, and some trachytes are succeeded by adventive volcanic cones which have ejected substantial amounts of tuff over the island. At the bottom of the El Golfo scarp and in the west and south (fig. 4B) irregular recent pahoehoe lavas are common. Alkalic volcanism characterizes the island. On geomorphological grounds, Navarro (1908) favored a recent origin for the island, whereas Hausen (1964) suggests that the El Golfo scarp is a relatively old feature.

We have dated five samples from Hierro (fig. 4A). These are all from the Tableland Basalt Series of Hausen (1964). Unit 15A is from the base of the El Golfo scarp, immediately below a prominent reddish soil zone. The preferred interpretation of the age of t = 3.05 ± 3.0 m.y. and normal magnetic polarity is that the lava was extruded during the Brunhes epoch, but a Gauss age is not impossible. The reason for this young age preference is the Brunhes epoch results for the other dated units: there is no evidence of a hiatus of the order of 1 to 2 m.y. between this and younger lavas.

Three of the other four units are part of the uppermost rim of the El Golfo scarp. Unit 19 yields a 0.19 m.y. age, as does unit 2. Ages of 0.7 m.y. and 0.74 m.y. were obtained from the other two bodies (4 and 23, fig. 4A), which are from a series of lavas beneath the rim, and a thick sequence of horizontal lavas near Valverde, respectively.

Our data suggest that the El Golfo scarp came into existence about 0.2 m.y. ago, which is the same time we favor for initiation of the present Las Canadas Caldera on Tenerife. Hierro, like La Palma, is very clearly composed mainly of Pleistocene basalts in outcrop.

All the paleomagnetic data are consistent with the ages, in that they are all normal polarity with a mean virtual geomagnetic pole close to the present geographic pole. Over forty additional lavas have been sampled on Hierro. So far no reversed polarity lava has been found.

It is clear that the "Tableland Series" of Hierro (Hausen, 1964) is not correlative with the Tableland Series of Lanzarote, Fuerteventura, Gran Canaria, Tenerife, or La Gomera.

THE GEOMAGNETIC POLARITY TIME SCALE

We have shown that the paleomagnetic polarities have provided verification of the validity of much of the potassium–argon data, when comparison of both parameters is made with the independently defined geomagnetic polarity scale (fig. 6).

Of the total of 29 units for which both a potassium–argon date and paleomagnetic measurement are available, it is gratifying to observe (fig. 6) that all the data agree with the geomagnetic polarity scale. As we have stressed, two of the Ladera de Guimar ages result from the possible presence of excess radiogenic argon, increasing the age from late Matuyama to an apparently early Matuyama age. Nevertheless, the great similarity of the independently-defined polarity scale and that resulting from our data is a powerful verification of the validity of the potassium–argon results.

Inspection of figure 6 and table 2 shows that the Jaramillo event was detected three times on Tenerife, and the Gilsa event once on Tenerife.

CONCLUSIONS

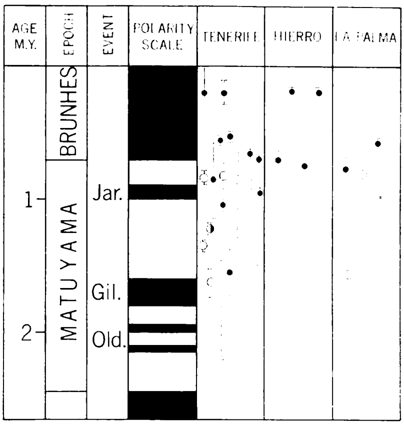
Our study of selected igneous bodies from Tenerife, La Palma, and Hierro provides us with the following conclusions:

1. The Teno and Anaga peninsulas on Tenerife are areas where volcanism occurred intermittently from at least 16 to 4.5 m.y. ago. The northern slope of the Anaga peninsula may be the oldest of these Miocene to Pliocene peninsulas. Hausen's (1956, 1958, 1962) Tableland Series concept, where an older basaltic series is envisaged as common to several of the Canary Islands, is valid only in part: lavas from La Gomera, Lanzarote (The Farmara Section and Los Ajaches Mountains), Gran

Canaria (the upper part of the Basaltic Series I), and Fuerteventura (the Jandia peninsula) overlap in age with those of the Anaga and Teno peninsulas, but lavas from Hierro, La Palma, and east-central Fuerteventura are all outside the age ranges involved. His concept of an originally continuous and closely contemporaneous series, later separated by faulting into the present islands, is not favored.

2. A lava sequence at Ladera de Guimar, Tenerife, and a single lava on the north coast of Henerife were assigned by previous workers (Hausen, 1956; Fuster and others, 1968) to the older stratigraphic units, equivalent in age to outcrops in the Teno and Anaga peninsulas.

The sequence at Ladera de Guimar contains two lavas with discordantly old potassium–argon ages *or* three lavas with systematically discordant young ages. We prefer, but cannot be absolutely certain of, the former explanation. In any case, these lavas are clearly younger than the outcrops of the Teno and Anaga peninsulas and, if our preferred interpretation is correct, may be younger than the phonolites of the north-coast Tigaiga block and part of the Las Canadas Series Phonolites in the Vilaflor area. The single lava on the north coast also provides an age very much younger than those units that are mapped as age equivalents on Anaga and Teno. It is also younger than a phonolite sequence forming cliffs above the outcrop.



Jar. = Jaramillo, Gil. = Gilsa, Old. = Olduvai.

Fig. 6. Comparison of the age and paleomagnetic polarity of each sample of less than 2.5 m.y. age from Tenerife, Hierro, and La Palma, with the established geomagnetic polarity time scale. Results, from tables 1 and 2, are solid black dots = normal polarity; open circles = reversed polarity: split circle = intermediate polarity (see caption to fig. 2A for definition), as a function of potassium argon age, in millions of years (left). Error bars for the potassium-argon ages are included. Geomagnetic polarity time scale after Cox (1969): black = normal polarity; clear = reversed polarity. Note that two of the older reversed polarity data from Tenerife may not reflect the real geological age but perhaps a function of excess radiogenic argon (see text). The data point with large one-sign error bar in the upper Brunhes epoch on Tenerife is plotted at the maximum age: the radiogenic argon content was insufficient for exact age determination (see text and table 1).

TABLE 2
Paleomagnetic results

Diagram no.	Original field no.	N	D	I	J	R	K_{max}	θ'	ϕ'	Polarity	Age
88	TF-104	4	019.5	+21.0	0.01	3.773	13.2	+65.0	116.6	N*	<0.20
85	TF-114	2	9.0	+23.1	1.36	1.995	—	+71.9	137.5	N	0.20 ± 0.08
16	TF-67	6	10.8	+59.0	0.72	5.950	99.9	+75.2	021.8	N	0.53 ± 0.03
79	TF-10	3	6.1	+28.6	0.08	2.985	133.3	+75.8	142.5	N	0.56 ± 0.04
9	TF-88	5	343.1	+37.3	0.30	4.991	423.9	+73.0	236.0	N	0.67 ± 0.01
86	TF-112	5	339.0	+31.4	0.15	4.861	28.8	+67.7	232.0	N	0.67 ± 0.01
50	TF-27	2	187.8	—31.1	4.50	1.986	—	—76.4	309.7	R	0.81 ± 0.09
11	TF-73	6	021.5	—45.2	0.27	5.372	8.0	+31.5	144.6	N*	0.84 ± 0.28
68	TF-44	2	289.3	—73.3	3.00	1.905	—	—32.8	194.2	R†	0.84 ± 0.05
69A	TF-46	2	207.0	—63.4	1.76	1.999	—	—62.7	211.7	R†	0.86 ± 0.22
71A	TF-127	3	173.4	—26.6	0.66	2.991	229.4	—74.8	012.2	R	0.88 ± 0.05
74	TF-12	3	016.3	+33.1	0.24	2.999	2402.1	+72.0	107.3	N	0.95 ± 0.06
12A	TF-128	5	335.7	+38.9	0.08	4.477	173.4	+67.2	247.3	N	1.03 ± 0.05
84	TF-3	2	072.1	—82.1	2.00	1.890	—	—22.5	147.6	I	1.22 ± 0.04
83	TF-113	3	184.7	—59.2	0.37	2.999	2533.1	—77.4	183.9	R	1.27 ± 0.04
12	TF-96	8	165.3	—37.6	0.02	7.530	14.9	—74.9	052.9	R*	1.35 ± 0.02
61	TF-90	4	191.6	—41.9	1.54	3.977	132.0	—78.9	275.0	R†	1.52 ± 0.15
71	TF-70	6	353.4	+43.8	0.29	5.963	134.8	+83.6	236.5	N†	1.54 ± 0.17
49	TF-93	7	137.0	—41.4	1.02	6.617	15.7	—51.3	081.0	R*	1.63 ± 0.11
62	TF-38	2	166.5	—51.4	1.83	1.999	—	—77.6	099.4	R†	1.85 ± 0.37
27	TF-18	3	196.3	—26.4	0.12	2.778	9.0	—69.3	296.6	R*†	4.65 ± 0.70
5	TF-86	6	146.5	—39.2	0.42	5.918	60.8	—59.2	073.9	R	5.35 ± 0.11
4A	TF-131	4	022.1	+43.6	0.23	3.893	28.1	+70.1	079.4	N	6.10 ± 0.18
4B	TF-132	4	005.1	+42.7	1.62	3.999	2417.3	+84.4	111.6	N	6.53 ± 0.26
6	TF-87	4	033.5	+13.2	0.60	3.917	36.2	+51.8	104.8	N†	7.18 ± 0.57
22	TF-58	3	086.5	+67.9	0.04	2.792	9.6	+23.7	30.6	I*†	15.68 ± 1.6
9	LP-15	6	000.5	+29.9	1.19	5.902	51.0	+77.3	163.4	N†	0.60 ± 0.30
18	LP-27	6	003.1	+50.4	1.26	5.823	28.2	+86.4	031.9	N	0.76 ± 0.09
17	LP-26	4	166.3	—46.4	2.48	3.997	1092.6	—77.9	074.3	R	0.81 ± 0.09
1	LP-3	4	165.6	—10.4	1.06	3.352	4.6	—62.9	018.7	R*	1.02 ± 0.03
2	LP-2	5	021.5	+47.1	4.03	4.983	234.1	+71.1	071.9	R	1.57 ± 0.09
19	H-4	2	020.3	+18.9	0.38	1.999	—	+63.7	111.2	N	0.19 ± 0.01
2	H-7	2	356.2	+10.1	0.86	1.983	—	+67.1	171.8	N	0.19 ± 0.03
4	H-9	2	015.7	+54.8	0.92	1.999	—	+70.2	036.4	N	0.70 ± 0.07
23	H-16	6	342.8	+45.7	0.71	5.949	97.8	+74.8	253.8	N	0.74 ± 0.04
15A	H-43	8	011.2	+43.8	1.35	7.915	82.8	+79.8	081.1	N†	3.05 ± 3.00

Diagram no. refers to figures 2, 3, 4, and 5. Original field no.: TF = Tenerife; LP = La Palma; H= Hierro. N = number of separate samples from the given body. D and I = declination and inclination of remanent magnetism, in degrees east of geographic north and with respect to horizontal (+ = downward; — = upward) respectively. J = intensity of magnetization in emu/g × 10^{-3}. R = resultant vector length, applying unit vector per sample. K_{max} = precision parameter = (N-1)/(N-R) (Fisher, 1953). θ' and ϕ' = latitude and longitude of virtual geomagnetic pole (the surface expression of the geocentric dipole will create the observed D and I): latitude is positive for northern hemisphere; negative for southern hemisphere; longitude is in degrees east. Polarity is N (normal), R (reversed), or I (intermediate, or equatorward of the 30° lat.). D, I, J, R, K_{max}, θ', and ϕ' are all based on the remanent magnetism direction after treatment in three different alternating magnetic field values (100, 200, and 300 oersteds) and computation for maximum K, using one demagnetized D and I result per sample (Watkins and Richardson, 1968). Age from table 1.

* These polarity:age data cannot be applied to definition of the polarity time scale because of an insufficiently well-defined direction of remanent magnetism (K_{max} >25), according to the criterion of McDougall and Chamaulaun (1966).

† These polarity:age data cannot be applied to definition of the polarity time scale because the K:Ar data do not satisfy the criteria of Cox and Dalrymple (1967).

3. The Lower Canada Series and Upper Canadas Series of the Vilaflor complex extend in age from about 2.0 to 0.6 m.y. With very little time break, extrusion of the Trachyte and Trachybasalt Series and Basaltic Series III began and lasted until approximately 0.2 m.y. ago at about which time the present La Canadas Caldera was initiated.

4. The lavas that drape the major unconformity above the basement complex on La Palma and those lavas above a prominent soil zone at the base of the large El Golfo scarp section on Hierro are confined to the Pleistocene.

5. The data are consistent with established geomagnetic polarity time scale.

In summary, we have demonstrated that the volcanics outcropping in Tenerife, La Palma, and Hierro are overwhelmingly Pleistocene in age.

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APPENDIX

Location of each specimen. First number is unit number (figs. 2 to 5 and tables 1 and 2). Second number is original field number. In many cases, the locations are referred to the common km posts used on the islands.

Tenerife

4A (TF-131)
Thick amygdaloidal olivine basalt on new cut of the Buenavista-Teno coast road, between most westerly and next tunnel directly below thick sequence of thin flow units. The rock is dark gray, fine grained, and porphyritic.

4B (TF-132)
Thin olivine–augite basalt, stratigraphically immediately below unit 4A. The rock is dark gray, fine grained, and porphyritic.

5 (TF-86)
Trachyte, Teno Peninsula, dike striking at 70° east, close to the 80 km post on the south-north road. The rock is light gray, fine grained, and slightly porphyritic.

6 (TF-87)
Olivine basalt, Teno peninsula, on the main south-north road at the 80 km post. The rock is dark gray, very fine grained, and slightly porphyritic.

9 (TF-88)
Plagioclase phonolite, head of Barranco Rambler, east side of road, 200 m southwest of 16 km post. The rock is light gray in color, fine grained, and slightly porphyritic.

11 (TF-73)
Plagioclase basalt, 550 m west of 56 km post on south side of highway above Playa del Socorro. The rock is dark gray, very fine grained, and aphyric.

12 (TF-96)
Phonolite (hauyne-bearing), cliff above Los Realejos, west side of the road between 300 m north of 12 km post. The rock is greenish gray, fine grained, and slightly porphyritic.

12A (TF-128)
Thick trachybasalt, west side of road, above Tigaiga, 100 m south of 13 km post, above prominent yellowish pyroclastic layer, which is in turn above unit 12. The rock is reddish gray, very fine grained, and partly altered.

16 (TF-67)
Alkali trachyte, near Suazal, small quarry at 21 km post. The rock is light gray, fine grained, and massive.

22 (TF-58)
Augite–olivine ankaramite, on road above the village of Taganana, Anaga peninsula. The unit is dark black, coarse grained, and porphyritic.

27 (TF 18)
Augite basalt, San Andres Valley, Anaga peninsula, on west side of main highway, 200 m south of the 19 km post. The rock is dark gray, very fine grained, and slightly porphyritic.

49 (TF-93)
Augite–olivine basalt, on the road along the Las Tablas scarp, north of Candeleria, at 20 km post. The rock is dark gray, medium to coarse grained, slightly vesicular, and porphyritic.

50 (TF-27)
Augite basalt (olivine poor), highest lava on roadcut at east end of Ladera de Guimar Scarp. This is a dark grayish, fine to medium grained, porphyrite rock.

61 (TF-90)
Augite–olivine basalt, Ladera de Guimar scarp, eight lavas above base of roadcut lava sequence. The rock is grayish, fine to medium grained, slightly vesicular, and porphyritic.

62 (TF-38)
Augite basalt (olivine poor), Ladera de Guimar scarp, twelfth lava below top of road cut. The rock is light reddish gray in color, fine to medium grained, porphyritic, with a few amygdales.

68 (TF-44)
Plagioclase basalt (olivine poor), Ladera de Guimar scarp, six lavas below unit 62. The rock is light gray, medium grained, and porphyritic with a few amygdales.

69A (TF-46)
Trachy–plagioclase basalt, Ladera de Guimar scarp, lowest lava in road cut. The rock is light reddish gray in color, fine grained, and vesicular.

71 (TF-70)
Plagioclase–augite basalt (olivine poor), Montaña Izana, about 0.9 km along the road to the Meteorological Observatory. The rock is dark gray, fine to medium grained, slightly vesicular, and porphyritic.

71A (TF-127)
Plagioclase–augite basalt, western part of Ladera de Guimar scarp, on cut in track from Hoya del Mal Abrigo to Chamusco, 800 m below head of Barranco Teguigo. The rock is very dark gray, fine grained, vesicular, and slightly porphyritic.

74 (TF-12)
Trachy–phonolite, on the road between Arico and Granadilla de Aboña 350 m east of the 79 km post. The rock is light colored, fine grained, and slightly porphyritic.

79 (TF-10)
Alkali Trachyte, Montaña de las Coloradas, on the road north from Granadilla de Aboña, 220 m north of the 72 km post. The rock is dark gray, slightly vesicular, and slightly porphyritic.

83 (TF-113)
Trachy–phonolite (nepheline bearing), on the road north from Vilaflor, 200 m south of unit 84. The rock is a greenish gray, very fine grained, and slightly porphyritic.

84 (TF-3)
Trachy–phonolite, on the road north from Vilaflor, 200 m south of the 65 km post. The rock is dark gray and very fine grained with trachytic structure.

85 (TF-114)
Alkali trachyte, on the road north from Vilaflor, at 64 km post. The rock is light grayish, fine to medium grained, and porphyritic.

86 (TF-112)
Blue phonolite, Los Rogues de Ucanca, roadcut at 55 km post, west of La Lachucha. The rock is light gray, very fine grained, and slightly porphyritic.

88 (TF-104)
Phonolite, Los Azulejos, southern rim of Las Canada caldera on the road at the 45 km post. The rock is light gray, fine grained, and porphyritic.

La Palma

1 (LP-3)
Plagioclase basalt (olivine poor), roadcut on Barranco Angustias, above pumping station before bridge. The rock is dark grayish, very fine grained, and aphyric.

2 (LP-2)
Olivine augite basalt, Barranco Angustias, cut on north side of road facing K-62 post. The rock is dark gray and porphyritic.

9 (LP-15)
Hauyne phonolite from the side of Montaña San Antonio, south of Fuencaliente. Locally called El Campanario ("The Bell Tower") according to Hausen (1969, p. 57). The rock is light colored and porphyritic.

17 (LP-26)
Olivine–augite ankaramite, Barranco de las Lomados, roadcut about 50 m south of the bridge, at 26 km post. Light greenish-gray, coarse grained, porphyritic rock.

18 (LP-27)
Olivine–augite basalt, Barranco de las Lomados, roadcut at the 25 km post: a grayish and fine grained porphyritic rock.

Hierro

2 (H-7)
Alkali olivine basalt, cut on south side of road going from the rim into the El Golfo scarp, immediately below Mt. Tabaño. The rock is gray, fine grained, vesicular, and porphyritic.

4 (H-9)
Thick plagioclase (olivine poor), 200 m west of unit 2, on south side of road, at base of high road cut. The rock is grayish, fine grained, and porphyritic.

15A (H-43)
Olivine–augite basalt, the oldest lava in the wall of the El Golfo scarp, immediately above the village of Frontera. The rock is grayish, fine grained, and porphyritic.

19 (H-4)
Alkali–olivine basalt, fourth flow from top of El Golfo scarp, immediately below outlook plaza. The rock is dark grayish, very fine grained, vesicular, and porphyritic.

23 (H-16)
Plagioclase basalt (olivine poor), at 14 km post, on northwest side of the road from San Andres to Valverde. The rock is grayish, very fine grained, slightly vesicular, and porphyritic.

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, Fuerteventure, Gran Canaria, and La Gomera: Am. Jour. Sci., v. 271, p. 490-521.

Ade-Hall, J. M., and Watkins, N. D., 1970, Absence of correlations between opaque petrology and natural remanence polarity in Canary Island lavas: Royal Astron. Soc. Geophys. Jour., v. 19, p. 351-360.

Baksi, A. K., York, D., and Watkins, N. D., 1967, The age of the Steens Mountain geomagnetic polarity transition: Jour. Geophys. Research, v. 72, p. 6299-6308.

Blumenthal, M. M., 1961, Rasgos principales de la geologia de las Islas Canarias, con datos Sobre Madeira: Inst. geol. min España Bol., v. 77, p. 1-130.

Bravo, T., 1954, Geografia general de Canarias: Santa Cruz de Tenerife, I Goya Ediciones, 1964.

Buch, L. von, 1825, Physikalische Beschreibung der Canarischen Inseln: Berlin, 201 p.

Cox, Allan, 1969, Geomagnetic reversals: Science, v. 163, p. 237-245.

Cox, Allan, Hopkins, D. M., and Dalrymple, G. B., 1966, Geomagnetic polarity epochs, Pribilof Islands, Alaska: Geol. Soc. America Bull., v. 77, p. 883-910.

Dalrymple, G. B., 1963, K:Ar dates of some Cenozoic volcanic rocks of the Sierra Nevada, California: Geol. Soc. America Bull., v. 74, p. 379-390.

——— 1964, K:Ar dates of three Pleistocene interglacial basalt flows from the Sierra Nevada, California: Geol. America Bull., v. 75, p. 753-758.

Dash, B. P., and Bosshard, E., 1969, Seismic and gravity investigations around the western Canary Islands: Earth and Planetary Sci. Letters, v. 7, p. 169-177.

Dietz, R. S., and Sproll, W., 1970, East Canary Islands as a microcontinent within the Africa-North America continental drift fit: Nature, v. 226, p. 1043-1045.

Doell, B. R., and Cox, Allan, 1964, Measurement of the remanent magnetization of igneous rocks: U.S. Geol. Survey Bull., v. 1203A, 32 p.

Emilia, D. A., Heinrichs, D. F., 1969, Ocean floor spreading: Olduvai vs. Gilsa event in the Matuyama epoch: Science, v. 166, p. 1267-1270.

Fisher, R., 1953, Dispersion on a sphere: Royal. Soc. London Proc., v. 217A, p. 295-305.

Fuster, J. M., Arana, V., Brandle, J. L., Navarro, M., Alonso, U., and Aparicio, A., 1968, Geology and volcanology of the Canary Islands, Tenerife: Inst. "Lucas Mallada", Madrid, Internat. Symposium Volcanology, Tenerife, Sept., 1968, Spec. Pub., 218 p.

Gagel, C., 1908, Die Caldera von La Palma: Gesell. fur Erdkunde Zeitschr. (Berlin), p. 168-186.

——— 1910, Die Mittelatlantischen Vulcaninseln: Handbuch der Regionalen Geologie (Heidelberg), v. 7, p. 1-32.

Gastesi, P., Hernandez-Pacheco, A., and Munoz, M., 1966, Las rocas holocristalinas de la Caldera de Taburiente, Isla de la Palma (Canarias): Inst. "Lucas Mallada", Estudios Geol., v. 22, p. 113-134.

Grey, Jane, and Kittleman, L. R., 1967, Geochronology of the Columbia River Basalt and associated floras of Eastern Washington and Western Idaho: Am. Jour. Sci., v. 265, p. 257-291.

Grommé, C. S., and Hay, R. L., 1971, Geomagnetic polarity epochs: age and duration of the Olduvai normal polarity event: Earth and Planetary Sci. Letters, v. 10, p. 179-185.

Hartung, G., 1857, Die Geologischen Verhaltnisse der Inseln Lanzarote und Fuerteventura: Allgem. Schweizer. Gesell. Naturwiss. (Zurich), Neue Denkschr. 15.

Hausen, Hans, 1956, Contributions to the geology of Tenerife (Canary Islands): Soc. Sci. Fennicae, Comm. Phys.-Mat., v. 18, 254 p.

——— 1958, On the geology of Fuerteventura, (Canary Islands): Soc. Sci. Fennicae, Comm. Phys.-Mat., v. 22, 211 p.

——— 1961, Canarian calderas—a short review based on personal impression 1947-1957: Geol. Soc. Finland, 75th Ann. Jubilee, Pub. 196, p. 179-213.

——— 1962, New contributions to the geology of Grand Canary (Gran Canaria, Canary Islands): Soc. Sci. Fennicae, Comm. Phys.-Mat., v. 27, p. 418-622.

——— 1964, Rasgos geologicos generals de la Isla del Hierro: Anuario de Estudios Atlanticos (Madrid), v. 10, p. 45-58.

——— 1965, Some comments on the structural geology of Gomera (Canary Islands): Acta Geog., v. 18, p. 15-25.

——— 1969, Some contributions to the geology of La Palma: Soc. Sci. Fennicae, Comm. Phys.-Mat., v. 35, p. 1-140.

Heirtzler, J. R., and Hayes, D .E., 1967, Magnetic boundaries in the North Atlantic: Science, v. 157, p. 185-187.

Irving, E., Stott, P. M., and Ward, M. A., 1961, Demagnetization of igneous rocks by alternating magnetic fields: Philos. Mag., v. 6, p. 225-241.

Jeremine, E., 1933, Contribution a l'etude petrographique des trois iles de l'archipel Canarien; Tenerife, La Palma, et Gran Canaria: Soc. Mineralogie et Cristalographie France Bull., v. 56, p. 189-260.

Knebel, W. von, 1906, Studien zur Oberflachengestaltung der Insel La Palma und Hierro: Globus, v. 90.

Lyell, Charles, 1874, Elements of Geology, 7th ed., v. 2: Paris, Garnier, 638 p.

McDougall, Ian, 1964, Potassium-argon ages from lavas of the Hawaiian Islands: Geol. Soc. America Bull., v. 75, p. 107-128.

McDougall, I., and Chamalaun, F. H., 1966, Geomagnetic polarity scale of time: Nature, v. 212, p. 1415-1418.

McDougall, I., and Wensink, H., 1966, Paleomagnetism and geochronology of Pliocene-Pleistocene lavas in Iceland: Earth Planetary Sci. Letters, v. 1, p. 232-236.

Miller, J. A., and Mussett, A. E., 1963, Dating basic rocks by the potassium–argon method—the Whin sill: Royal. Astron. Soc. Geophys. Jour., v. 7, p. 547-553.

Navarro, F. L., 1908, Observation geologie en la isla de Hierro: Mem. Nat. Hist. Soc. Espana (Madrid), No. 5.

———— 1926, Fieldguide, Excursion A7, (Islas Canarias): Internat. Geol. Cong., 14th, Madrid.

Reck, H., 1928, Zur Deutung der Vulkanischen Geschichte und der Caldera-bildung auf der Insel La Palma: Zeitschr. fur Vulkanologie (Berlin), v. 11, p. 217-243.

Ridley, W. I., 1972, The geology of the Las Canadas Volcanoes, Tenerife, Canary Islands. I. Field Relations: Bull volcanol., in press.

Watkins, N. D., 1972. Review of the development of the geomagnetic polarity time scale and discussion of prospects for its finer definition: Geol. Soc. America Bull., v. 83, p. 551-574.

Watkins, N. D., and Abdel-Monem, A., 1971, Detection of the Gilsa geomagnetic polarity event on the Island of Madeira: Geol. Soc. America Bull., v. 82, p. 191-198.

Watkins, N. D., and Goodell, H. G., 1967, Confirmation of the reality of the Gilsa geomagnetic polarity event: Earth and Planetary Sci. Letters, 2, p. 123-129.

Watkins, N. D., and Richardson, A., 1968, Palaeomagnetism of the Lisbon Volcanics: Royal Astron. Soc. Geophys. Jour., v. 15, p. 287-304.

Watkins, N. D., Richardson, A., and Mason, R. G., 1966, Paleomagnetism of the Macaronesian Insular Region: Canary Islands: Earth and Planetary Sci. Letters, v. 1, p. 225-231.