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11. CHRONOSTRATIGRAPHY OF GRAN CANARIA[1]

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ABSTRACT

A chronostratigraphy of Miocene/Pliocene volcanism on Gran Canaria (Canary Islands) has been established by single-crystal $^{40}Ar/^{39}Ar$ laser dating of feldspar crystals from 58 samples of welded ignimbrites, lava flows, fallout tephra layers, and intrusive rocks. All subaerially exposed volcanic and intrusive rocks of Gran Canaria were emplaced within the last 14.5 Ma, comprising three major magmatic/volcanic cycles. The subaerial Miocene evolution started with the rapid formation (<0.5 Ma) of the exposed, mildly alkalic shield basalts. The basaltic shield phase ended between 14.04 ± 0.10 Ma and 13.95 ± 0.02 Ma and was followed by a 0.6-m.y. magmatism of trachytic to rhyolitic composition (Mogán Group). Single-crystal $^{40}Ar/^{39}Ar$ laser dating shows that the ash flows erupted at intervals of 0.03–0.04 m.y., with peak eruption rates as much as 2000 km^3/m.y. during the initial stages of silicic magma production (Lower Mogán Formation). High-precision ages have been determined for major, widespread lithostratigraphic markers of the Mogán Group, such as ignimbrite P1 (13.95 ± 0.02 Ma), ignimbrite X (13.71 ± 0.02 Ma), ignimbrite D (13.44 ± 0.01 Ma), and ignimbrite E (13.37 ± 0.03 Ma).

After the rhyolitic stage, >500 km^3 of silica-undersaturated nepheline trachyphonolitic ash flows, lava flows, and fallout tephra, as well as rare basanite and nephelinite dikes and lavas were erupted between 13.29 Ma and 13.04 Ma (Montaña Horno Formation) and 12.43 Ma and 9.85 Ma (Fataga Group). This stage was accompanied and followed by intrusive syenites and a large cone sheet swarm in the central caldera complex, lasting until at least 8.28 Ma. Following a major, nearly nonvolcanic hiatus lasting ~4.7 m.y. (Las Palmas Formation), eruptions resumed with the local emplacement of small volumes of nephelinites, basanites, and tholeiites at ~5 to 4.5 Ma, with peak activity and eruptions of highly evolved phonolite magma between 4.15 and 3.78 Ma (Roque Nublo Group).

INTRODUCTION

Gran Canaria has been volcanically active intermittently throughout at least the past 15 m.y. Mafic and evolved magmas generated an extreme compositional spectrum of igneous rocks, as well as frequent explosive rhyolitic, trachytic, and phonolitic fallout ashes and many ash flow deposits that are preserved both on the island and in the islands volcaniclastic sedimentary apron. The excellent recovery and very detailed biostratigraphy and magnetostratigraphy of the 1200-m section drilled at Site 953 (Schmincke, Weaver, Firth, et al., 1995) make this an ideal section to calibrate the Cenozoic biostratigraphic and magnetostratigraphic time scales. In particular, the abundance of many tens of thick tephra units, many of which can be correlated unequivocally with rhyolitic and trachyphonolitic ignimbrites on land, allow the Miocene section between 9 and 14 Ma to be stratigraphically subdivided and temporally quantified. The discussion of the stratigraphy of this section at Sites 953, 955, and 956 (Freundt and Schmincke, Chap. 14; Sumita and Schmincke, Chap. 15; both this volume), as well as the discussion of the emplacement mechanisms of the volcaniclastic units (Schmincke and Sumita, Chap. 16, this volume) very much depend on reliable geochronologic data. Although feldspars from the Miocene tephra layers have not yet been dated radiometrically, the correlation of individual ignimbrites, as well as several formations, to the land record allow us to define chronostratigraphic markers and anchor points in the drill sections, provided that ages for correlated land deposits are available.

We report here many single-crystal $^{40}Ar/^{39}Ar$ ages for the first time, dominantly of ignimbrites and lava flows from the Mogán and Fataga Groups, as well as from many tephra fallout layers from the Roque Nublo Group of Gran Canaria. These age determinations form the backbone for a high-resolution chronostratigraphy of Gran Canaria and also allow us to quantify both magma eruption and sedimentation rates in the volcaniclastic apron around Gran Canaria. The stratigraphic scheme presented here is based on the formalized lithostratigraphic subdivision (groups, formations, members) of the volcanic series of Schmincke (1976; additions and amendments 1987–1994). Results from previous geochronological studies (Abdel-Monem et al., 1971; Lietz and Schmincke, 1975; McDougall and Schmincke, 1977; Féraud et al., 1981; Bogaard et al., 1988) will be discussed in the text.

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

Analytical Procedure

Rock samples were crushed and/or sieved, and anorthoclase feldspar crystals were hand-picked with a vacuum tweezer. Crystal masses ranged from 0.01 to 1.18 mg, with an average of 0.23 mg. Crystal separates were etched in hydrofluoric acid and cleaned ultrasonically. Irradiations were carried out in three separate runs in the 5MW research reactor of the GKSS Research Center (Geesthacht, F.R.G.), with crystals in aluminum trays and cans (no Cd liner).

$^{40}Ar/^{39}Ar$ laser analyses were carried out at the Geomar Tephrochronology Laboratory by applying a 25 W Spectra Physics argon ion laser and a MAP 216 series mass spectrometer, fitted with a Baur-Signer ion source and a Johnston electron multiplier. Raw mass spectrometer peaks were corrected for mass discrimination, background and blank values (determined every five analyses), and interfering neutron reactions on Ca and K using CaF_2 and K_2SO_4 salts that had been irradiated together with the samples. The applied irradiation monitor was hornblende standard MMhb-1 (520.4 Ma; Samson and Alexander, 1987). Significant heterogeneities of the MMhb-1 monitor were not detected in the standard batch applied (Bogaard, 1995).

A total of 58 rock samples from many lithostratigraphic units of the Miocene/Pliocene interval were analyzed. Fifty-six samples are represented by multiple single-crystal analyses. Two age estimates are based on only one single-crystal analysis each. A total of 480 single-crystal analyses was carried out. On the average, ~10 crystals were analyzed per sample.

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Prior Chapter Contents Next Chapter

Data Reduction

Multiple analyses of single crystals were carried out to check the homogeneity of samples, to identify older xenocrysts, and to permit more precise age estimates using error contraction in weighted averages in homogeneous (gaussian distribution), single-crystal age data populations. Single age and error estimates are derived for each sample by calculating the mean apparent age (single-crystal ages weighted by the inverse of their variance; Young, 1962) of each population, assuming an initial "atmospheric" $^{40}Ar/^{36}Ar$ ratio of 295.5 (Table 1). Mean square weighted deviates (MSWD; Wendt and Carl, 1991) were determined for the mean apparent ages to test the scatter of the single-crystal data. The mean square weighted deviates are generally ≤3 (52 of 56 samples). Two Miocene (7250 and 7120) and two Pliocene (7012 and 70177018) unwelded fallout tuff samples give significantly higher MSWD values (>3). Slightly older xenocrysts are most likely present beside juvenile feldspar crystals in these loose ash deposits, thereby introducing a "geological" scatter that is significantly larger than the analytical scatter alone. Two samples from Fataga ignimbrites (Samples 7243 and 6013) and two Mogán samples (Samples 72047205 and 7223) show one significantly older outlier crystal each, beside an otherwise homogeneous single-crystal population. These outliers are also interpreted to represent nonequilibrated older xenocrysts, and they were excluded from the weighted averages and MSWD calculation of these samples. The xenocrysts are of Late Mogán to Early Fataga age in Samples 7243 and 6013 (Middle Fataga) and Middle Mogán to Lower Mogán age in Samples 72047205 and 7223.

The low MSWD values, derived from 52 out of 56 single-crystal apparent age populations, indicate that the basic assumption underlying the calculated mean apparent ages (i.e., atmospheric initial $^{40}Ar/^{36}Ar$ ratios) may be justified. Its validity, however, can be tested more

Table 1. $^{40}Ar/^{39}Ar$ laser dating ages of Miocene/Pliocene ignimbrites, lava flows, phonolite intrusions, and tephra deposits from Gran Canaria.

Sample	Unit	Locality	Mean ± error (Ma)	MSWD	N	Isochron ± error (Ma)	Initial ± error (Ma)	MSWD (Ma)
7032	RN phonolite lava flow	Artenara (1)	3.78 ± 0.01	1.26	7	3.79 ± 0.02	288 ± 11	1.73
7247	RN pumice breccia	Soria (4)	3.86 ± 0.01	1.07	10	3.85 ± 0.01	312 ± 10	0.95
7022	RN Upper Artenara fallout pumice	Artenara (1)	3.88 ± 0.03	0.98	6	3.75 ± 0.10	340 ± 31	0.60
7210/7211	RN pumice breccia	Soria (4)	3.89 ± 0.05	1.24	9	3.84 ± 0.06	316 ± 16	1.08
6003	RN Risco Blanco phonolite intrusion	Risco Blanco (12)	3.91 ± 0.01	2.63	8	3.92 ± 0.02	286 ± 16	3.16
7025/7028	RN Middle Artenara fallout pumice	Artenara (1)	3.91 ± 0.02	2.48	15	3.85 ± 0.05	315 ± 14	2.54
7001	RN Phonolite lava flow	Artenara (2)	3.92 ± 0.06	1.69	6	3.61 ± 0.23	326 ± 22	1.35
7225	RN phonolite dike	Andres-Mogán (5)	3.95 ± 0.06	1.60	10	3.93 ± 0.08	298 ± 7	1.80
7012	RN Lower Artenara fallout tuff	Artenara (1)	4.00 ± 0.02	3.59	7	4.01 ± 0.03	291 ± 5	4.25
7020	RN Upper Bentaiga fallout Pumice	R. Bentaiga (3)	4.02 ± 0.01	0.86	6	4.02 ± 0.02	285 ± 8	0.81
7017/7018	RN Lower Bentaiga fallout Pumice	R. Bentaiga (3)	4.15 ± 0.01	3.45	12	4.12 ± 0.02	302 ± 2	3.36
7209	Fataga phonolite intrusion	La Plata (6)	8.28 ± 0.02	0.77	4	8.25 ± 0.04	300 ± 5	0.78
7213	Fataga laharic pumice flow	B. Arguineguin (7)	8.84 ± 0.01	0.90	8	8.82 ± 0.03	319 ± 22	0.89
7116	Fataga phonolite lava flow LX	Excusabaraja (24)	9.85 ± 0.03	0.20	3	9.83 ± 0.17	308 ± 111	0.58
6007	Fataga phonolite intrusion	Temisas (19)	9.95 ± 0.02	0.37	10	9.92 ± 0.04	298 ± 3	0.29
7226	Fataga ignimbrite (Arguineguin)	B. Arguineguin (7)	10.19 ± 0.02	3.02	8	10.18 ± 0.03	295 ± 11	3.91
6012	Fataga ignimbrite Las Palmas	Bahia Confital (8)	10.22 ± 0.03	1.46	9	10.31 ± 0.05	190 ± 46	1.12
7243	Fataga ignimbrite (Pozzulane)	B. Arguineguin (7)	10.40 ± 0.01	0.15	6 + 1	10.39 ± 0.03	320 ± 62	0.17
7239	Fataga fallout tuff	Excusabaraja (24)	10.62 ± 0.01	1.49	6	10.64 ± 0.02	274 ± 9	1.06
7208	Fataga fallout tuff (F.d. Don Simon)	Excusabaraja (24)	10.65 ± 0.02	0.28	9	10.68 ± 0.04	259 ± 49	0.26
7227	Fataga fallout tuff	Excusabaraja (24)	10.82 ± 0.01	1.34	7	10.84 ± 0.02	274 ± 17	1.48
7248	Fataga trachyphonolite lava flow	B. Fataga(9)	10.94 ± 0.02	0.75	5	10.94 ± 0.04	296 ± 55	0.18
7250	Fataga tuff (brown)	B. Fataga (9)	10.97 ± 0.02	3.21	9	10.94 ± 0.03	339 ± 25	2.78
7117/7128	Fataga ignimbrite	Excusabaraja (24)	11.36 ± 0.02	0.47	6	11.34 ± 0.06	305 ± 19	0.87
7241	Fataga unwelded flow (Casa blanca)	B. Fataga (9)	11.42 ± 0.02	0.70	6	11.40 ± 0.02	315 ± 34	0.82
7203/7214	Fataga fallout tephra (Casa blanca)	B. Fataga (9)	11.43 ± 0.01	0.66	14	11.39 ± 0.03	341 ± 26	0.54
7231	Fataga ignimbrite (Casa blanca)	B. Fataga (9)	11.52 ± 0.01	1.02	5	11.55 ± 0.03	264 ± 29	1.16
7121	Fataga ignimbrite alpha	B. Fataga (10)	11.68 ± 0.02	1.00	3	13.38 ± 1.86	-1172 ± 1611	0.13
7242/7246	Fataga ignimbrite (xl-rich-b)	B. Arguineguin (7)	11.71 ± 0.01	1.48	13	11.73 ± 0.01	272 ± 9	1.19
7206	Fataga ignimbrite (xl-rich-a)	B. Arguineguin (7)	11.77 ± 0.02	0.93	6	11.73 ± 0.03	321 ± 13	0.31
6013	Fataga ignimbrite P3	B. de Tauro (23)	11.90 ± 0.02	0.10	9+1	11.92 ± 0.05	278 ± 49	0.11
7240	Fataga ignimbrite (brown)	B. Arguineguin (7)	11.95 ± 0.01	1.00	8	11.96 ± 0.03	289 ± 26	1.43
7207	Fataga ignimbrite (xl-poor)	B. Arguineguin (7)	12.07 ± 0.04	2.38	8	12.03 ± 0.05	305 ± 7	2.09
7380	Lower Fataga ignimbrite	Temisas (19)	12.33 ± 0.02		1	n.a.		
7120	Fataga tuff	Fataga B. (11)	12.36 ± 0.05	3.36	3	12.31 ± 0.05	349 ± 23	6.16
7212	Fataga welded tuff	Andres-Mogán (5)	12.36 ± 0.02	0.88	7	12.35 ± 0.02	298 ± 2	0.91
7381	Fataga tuff	Fataga B. (11)	12.40 ± 0.10		1	n.a.		
7249	Fataga tuff	Andres-Mogán (5)	12.43 ± 0.02	2.01	6	12.47 ± 0.04	240 ± 54	2.37
7204/7205	Montaña Horno oxidized ignimbrite	Red Hill (21)	13.04 ± 0.02	1.62	14 + 1	13.05 ± 0.03	289 ± 13	1.98
7129	Montaña Horno ignimbrite	Montaña Horno (22)	13.16 ± 0.04	0.22	3	13.12 ± 0.07	313 ± 22	0.30
7224	Montaña Horno Tuff	Los Azulejos (25)	13.29 ± 0.02	1.05	7	13.33 ± 0.03	264 ± 19	0.83
7104	Mogán ignimbrite F	B. Taurito (13)	13.36 ± 0.01	0.68	10	13.32 ± 0.04	302 ± 4	0.33
7112	Mogán ignimbrite E	B. Taurito (13)	13.37 ± 0.03	1.87	11	13.42 ± 0.07	260 ± 66	3.06
7105	Mogán ignimbrite D	B. Taurito (13)	13.44 ± 0.01	0.29	10	13.44 ± 0.07	295 ± 38	0.43
7106	Mogán ignimbrite A	B. Taurito (13)	13.63 ± 0.04	0.12	4	13.61 ± 0.07	303 ± 17	0.22
7230	Mogán ignimbrite O	B. Arguineguin (7)	13.64 ± 0.01	0.45	8	13.64 ± 0.02	296 ± 4	0.63
7109	Mogán ignimbrite X	Hogarzales (14)	13.71 ± 0.02	0.41	34	13.70 ± 0.05	306 ± 10	0.55
7103	Mogán ignimbrite TL	M. Carboneras (17)	13.85 ± 0.01	0.89	91	3.85 ± 0.04	298 ± 3	1.04
6011	Mogán ignimbrite above P1	B. de Balos (18)	13.87 ± 0.03	0.80	91	3.97 ± 0.08	218 ± 52	0.68
7256/7107	Mogán ignimbrite P2	M. Carboneras (17)	13.89 ± 0.05	0.41	10	13.92 ± 0.08	290 ± 13	0.44
6005/7102	Mogán ignimbrite VI	Teheral (20)	13.90 ± 0.03	0.89	14	13.86 ± 0.05	303 ± 6	0.88
6010/7118	Mogán tuff TVI	B. de Balos (18)	13.91 ± 0.03	1.18	10	13.87 ± 0.06	302 ± 11	1.62
7100	Mogán lava VL	M. Carboneras (17)	13.97 ± 0.02	0.58	11	13.97 ± 0.05	296 ± 4	0.70
7223	Mogán tuff TVL	M. Carboneras (17)	13.93 ± 0.03	1.66	7 + 1	13.92 ± 0.04	299 ± 6	2.00
7127	Mogán ignimbrite U	Anden Verde (15)	13.94 ± 0.05	0.76	3	14.00 ± 0.20	271 ± 68	1.64
7108	Mogán ignimbrite P1	Anden Verde (15)	13.95 ± 0.03	2.10	12	13.95 ± 0.05	295 ± 3	2.49
7101	Mogán Tuff P1-R1	Anden Verde (15)	13.97 ± 0.03	1.00	9	14.05 ± 0.06	293 ± 2	1.17
7245	Hogarzales Basalt	B. Arguineguin (16)	14.04 ± 0.10	0.65	9	13.98 ± 0.16	297 ± 3	0.72

Notes: Locality numbers (1) to (25) refer to Figure 1. MSWD = mean square weighted deviates, N = number of single crystal analyses used to derive mean and isochron age, +1 = one older xenocryst excluded, and initial= initial $^{40}Ar/^{36}Ar$ ratio.

rigorously by isotope correlation, where no assumptions need to be made regarding the composition of the nonradiogenic "initial" argon isotope components.

For 51 single-crystal populations, isochron calculations yield initial $^{40}Ar/^{36}Ar$ ratios that are indistinguishable from an atmospheric ratio of 295.5 within 2-σ error limits (Table 1). Forty-seven of these data sets represent isochrons sensu stricto (MSWD <3), and the isochron ages generally overlap with the mean apparent ages within error limits. Three isochronous data sets (6012, 7239, 70427046) yield erroneously low initial $^{40}Ar/^{36}Ar$ ratios. Two samples (7120 and 70177018; see above) yield slightly elevated initial ratios, but their single-crystal populations are not strictly isochronous (MSWD >3). Thus, with a few exceptions and within the 95% confidence bands, the results of isotope correlation confirm the assumption of atmospheric initial $^{40}Ar/^{36}Ar$ ratios for the Miocene/Pliocene Gran Canaria volcanics.

The Miocene/Pliocene chronostratigraphy of Gran Canaria presented in this paper is based on the mean apparent ages derived from replicate single-crystal laser $^{40}Ar/^{39}Ar$ age determinations. K-Ar ages quoted from previous studies (Lietz and Schmincke, 1975; McDougall and Schmincke, 1977; Féraud et al., 1981) were recalculated to new constants if necessary (Mankinen and Dalrymple, 1979). Errors are quoted at the 1σ level, and include analytical errors of J-value estimates.

RESULTS

Miocene Basalt Group

The oldest rocks of Gran Canaria, a series of shield-forming basalt flows reaching 1000 meters above sea level (masl) were fed from several eruptive centers and crop out mainly in the western and southwestern parts of the island (Fig. 1). The oldest basalts occur in the east. A major erosional unconformity separates the older Guigui Formation in the west from the younger Hogarzales Formation (Schmincke, 1968). Clinopyroxene-olivine-phyric basalts of the Guigui Formation are most common in southwestern and western Gran Canaria. K-Ar age determinations show the lavas at Guigui to be ~13.9 ± 0.2 to 14.3 ± 0.2 Ma old (McDougall and Schmincke, 1977), just slightly older than ignimbrite P1.

The lavas of the Hogarzales Formation unconformably overlay the Guigui Formation in southwestern Gran Canaria. Fine-grained, thick, brecciated hawaiites and mugearites decrease in thickness from several 100 m at Barranco de Guigui to ~100 m farther inland, where the unconformity is less obvious. The Hogarzales lavas are dominated by alternating plagioclase-phyric pahoehoe units and thicker fine-grained, almost aphyric, hawaiites to mugearites. Whole- rock K-Ar ages of Hogarzales basalts range from 13.3 ± 0.2 Ma to 14.1 ± 0.2 Ma (McDougall and Schmincke, 1977). $^{40}Ar/^{39}Ar$ laser dating of plagioclase phenocrysts from plagioclase-clinopyroxene-olivine phyric lavas from Barranco de Arguineguin yields a mean apparent age of 14.04 ± 0.10 Ma (Sample 7245; Fig. 2). The unit dated is exposed ~20 m stratigraphically below P1, and there is no geologic evidence of a major sedimentary or erosional hiatus between the end of the basaltic shield stage and the Miocene felsic series in this area.

Miocene Felsic Rocks

The Miocene basalts are overlain by >500 m (>1000 m in the southeast) of felsic extrusive rocks that form the outflow facies of a large caldera ~20 km in diameter. The caldera is filled with >1000 m of sedimentary, extrusive, and intrusive felsic rocks. The outflow facies has been divided into the lower trachytic to rhyolitic Mogán Group, as much as ~300 m thick, and the trachyphonolitic Fataga Group, locally >1000 m thick.

Mogán Group

The Mogán Formation (about >300 km^3) consists of 15–20 dominantly ignimbritic trachytic to pantelleritic cooling units. The Mogán Group is subdivided into (1) Lower Mogán Formation: Members (cooling units) Pl, R, U, T3 (basalt) VL, VI; (2) Middle Mogán Formation: Members (cooling units) P2, T6 (basalt), TL (locally two cooling units), X, O (locally 2 cooling units), a major compositional break occurs between TL and X; and (3) Upper Mogán Formation: Members (cooling units) T4 (basalt), A, B, C, D, E, and F (compositionally transitional to Fataga rocks).

Lower Mogán Formation

P1 (Rhyolite-Basalt Ignimbrite: 13.95 ± 0.02 Ma)

The Lower Mogán Formation begins with the most widespread (>400 km^2) cooling unit on the entire island, an ignimbrite zoned from rhyolite with admixed trachyte in the lower part to basalt at the top, representing a bulk volume of ~45 km^3 (Freundt and Schmincke, 1995). The eruption of Pl was accompanied by the onset of the collapse of the Tejeda Caldera and local faulting of the lower part of Pl, indicating the synchroneity of ash flow eruption and caldera subsidence.

At Anden Verde (5 km west-northwest of San Nicolas), P1 begins with a thin, fine-grained, crudely layered tuff (P1-R1), whose vitric components are largely altered to clay but contain pockets of remnant-fresh anorthoclase crystals 3–5 mm in diameter. Laser $^{40}Ar/^{39}Ar$ dating of feldspars from P1-R1 (Sample 7101; Fig. 3) indicate an eruption at 13.97 ± 0.03 Ma. Feldspar phenocrysts from the overlying welded ignimbrite, dated using Sample 7108 also from Anden Verde, yield an age of 13.95 ± 0.03 Ma, which is identical (within error limits) to P1-R1. The weighted mean age of both (P1 and P1-R1) anorthoclase populations yields an eruption age of 13.95 ± 0.02 Ma (N=21 and MSWD = 1.57) for ignimbrite P1.

U (Subalkalic Rhyolite Ignimbrite: 13.94 ± 0.05 Ma; Sample 7127; Fig. 3)

A 10-m-thick trachyrhyolitic, very strongly welded ignimbrite, so far definitely known only from Anden Verde and in the Hogarzales-Cedro area, contains a basal vitrophyre with well-developed fiamme. It contains sparse oligoclase, clinopyroxene, hypersthene, and Fe/Ti-oxide phenocrysts.

VL (Subalkalic Rhyolite Lavas: 13.97 ± 0.02 Ma; Sample 7100)

Low-silica rhyolite lava flows (VL) locally dominate the lower Mogán Formation. The phenocryst content of these rocks is always <3%. The thick viscous flows formed hilly morphology, with a rough surface against which several of the overlying ignimbrites pinched out. Two rhyolite dikes (8 and 2 m thick) of similar composition, located southeast of Montaña Horno outside the caldera wall, may indicate that VL magmas were erupted also outside the caldera (Schmincke and Swanson, 1966). The VL are underlain in the Montaña Carboneras area by several decimeters of bedded crystal-vitric tuff (TVL; Sample 7223) dated as 13.93 ± 0.03 Ma.

VI (Subalkalic-Comenditic Rhyolitic Ignimbrite: 13.90 ± 0.03 Ma; Sample 7100)

A widespread 5- to 15-m-thick ignimbrite cooling unit overlies lava flow VL, which it resembles in color, mineral amount, and composition. Its thickness is highly dependent on the irregular morphology of VL, over which it drapes as a viscous veneer. Ignimbrite VI is underlain throughout southern Gran Canaria by widespread fallout

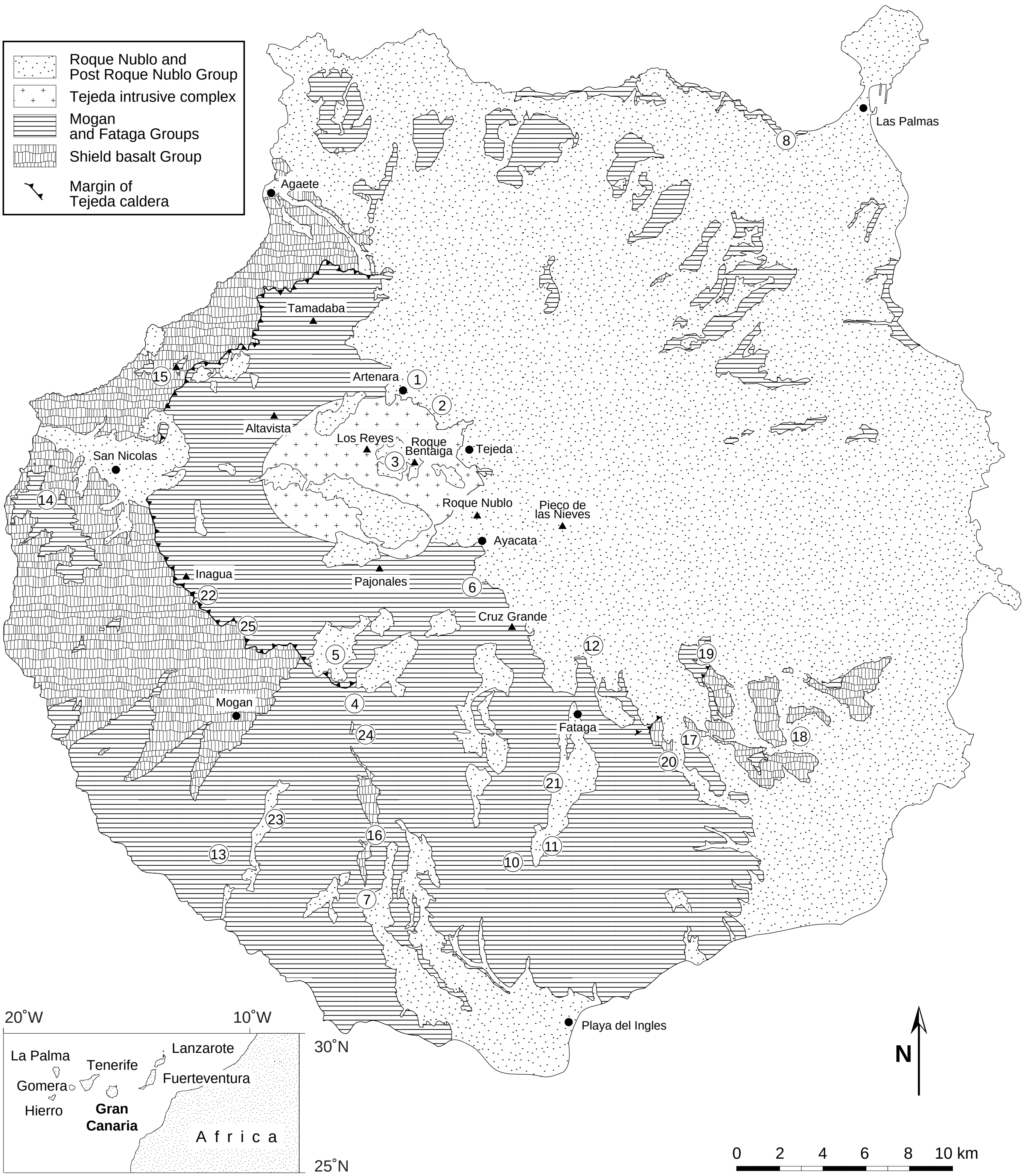

Figure 1. Simplified geological map of Gran Canaria showing the main Miocene/Pliocene lithostratigraphic units and the locations of sections and samples studied. Circled numbers correspond with sample locality numbers given in Table 1.

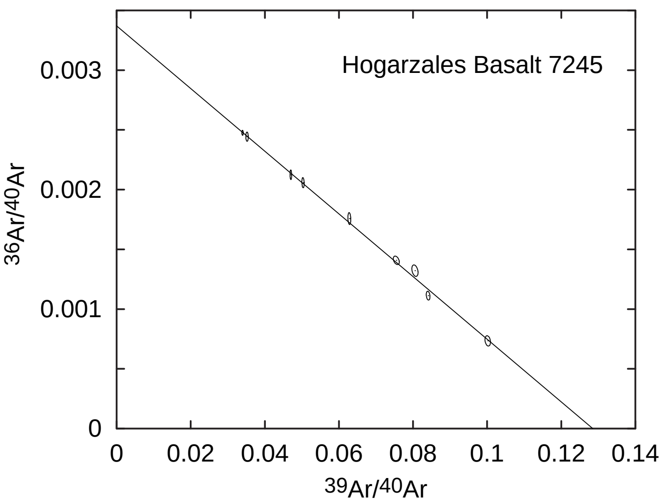

Figure 2. Isotope correlation diagram of plagioclase microphenocrysts from Miocene shield basalt Sample 7245 (Hogarzales Formation). Isochron calculation (York, 1969) yields an isochrone age of 13.98 ± 0.16 Ma and an initial $^{40}Ar/^{36}Ar$ ratio of 297 ± 3 (MSWD = 0.72). Single-crystal $^{40}Ar/^{39}Ar$ argon isotope ratios are shown with 1-σ error ellipses. All data are normalized to a common J-value of 1E-3.

tuffs (TVI), locally >5 m thick in southwestern Gran Canaria. $^{40}Ar/^{39}Ar$ dating of anorthoclase phenocrysts from tephra TVI (Sample 60107118) gives an age of 13.91 ± 0.03 Ma.

Middle Mogán Formation

P2 (Trachyte Ignimbrite: 13.89 ± 0.05 Ma; Sample 72567107; Fig. 3)

Ignimbrite P2, like Pl, is an extremely phyric cooling unit, but rather thin (2–3 m) and highly indurated from welding and vapor phase crystallization. P2 contains abundant oligoclase, amphibole, and large green clinopyroxene phenocrysts. P2 is chemically and mineralogically transitional between the Lower and Middle Mogán, as shown by the presence of orthopyroxene and zircon, both characteristic of the Lower Mogán, as well as sodic feldspars. A tuff as much as 1 m thick locally separates P2 and succeeding lava flow TL. It is crystal poor and fused as much as 30 cm at the contact with TL. A thin conglomerate/fanglomerate and local tuff underlie, and are mixed with, P2 in the Montaña Carboneras area.

TL (Comendite-Trachyte Ignimbrite-Lava Flow: 13.85 ± 0.01 Ma; Sample 7103)

TL, a dark gray-brown cooling unit, locally with a highly irregular, lava-like surface morphology, is exceedingly complex; it consists of comendite (anorthoclase, amphibole) and trachyte (oligoclase, clinopyroxene, rare hypersthene), as well as ignimbrite and lava components. An ignimbrite overlying P1 at Barranco de Balos, tentatively correlated with TL, yields an $^{40}Ar/^{39}Ar$ age of 13.87 ± 0.03 Ma (Sample 6011), which largely overlaps, within error limits, with the ages of ignimbrites TL and P2.

X (Comendite Ignimbrite: 13.71 ± 0.02 Ma; Sample 7109)

An extremely crystal-rich cooling unit, X forms a striking contrast to TL. X locally levels out the surface morphology, whereas TL is characterized by a top breccia and is overlain locally by paleosol, indicating a longer hiatus between TL and X. X contains anorthoclase (Or 32–34), amphibole (characteristically with chevkinite inclusions), and sphene.

O (Comendite-Pantellerite Ignimbrite: 13.64 ± 0.01 Ma; Sample 7230)

Moderately crystal-rich pantelleritic ignimbrite O (10–20 m thick) is locally represented by more than one cooling unit (Tasarte, Carboneras). Anorthoclase (Or 27–34) and richteritic amphibole are the main phenocrysts.

Upper Mogán Formation

T4 (Basalt Lava Flows and Local Scoria Cones: 13.7 ± 0.1 Ma; Féraud et al., 1981)

T4 consists of very widespread hawaiite-mugearite lava flows (microphenocrysts of clinopyroxene, plagioclase, and magnetite), associated with local scoria cones and lapilli fallout beds. In Barranco Taurito and Montaña Carboneras areas, the top of T4 lava flows is generally strongly eroded and overlain by conglomerates.

A (Comendite-Trachyte Ignimbrite: 13.63 ± 0.04 Ma; Sample 7106; Fig. 4)

Ignimbrite A, a thin (<l0 m) cooling unit with characteristic trachytic (with resorbed plagioclase phenoscrysts) and white felsic (comenditic pumice) fiamme is trachytic in its bulk composition. It contains low-K anorthoclase (<10 vol%), amphibole (<0.2 vol%), phlogopite, and oxides.

D (Pantellerite- Trachyte Ignimbrite: 13.44 ± 0.01 Ma; Sample 7105)

D and overlying E are the most widespread ignimbrites of the Upper Mogán Formation. Pantelleritic to trachytic cooling unit D (>400 km^2, >15 km^3) is zoned from almost aphyric and xenolith-rich pantellerite in its lower part to phyric trachyte (~18% phenocrysts, mainly anorthoclase, amphibole and plagioclase) in its upper part.

E (Comendite-Trachyte Ignimbrite: 13.37 ± 0.03 Ma; Sample 7112)

Distinctive ignimbrite E is generally 15–30 m thick. The trachytic part of the ignimbrite (ET) was emplaced in at least five flow units. The comendite and trachyte components contain 5–15 vol% phenocrysts (the comendite being the more phyric), dominantly anorthoclase, edenite, and Fe/Ti oxides, with clinopyroxene, hypersthene, and more sodic feldspar in ET.

F (Trachyte Ignimbrite: 13.36 ± 0.01 Ma; Sample 7104)

Ignimbrite F contains phlogopite and clinopyroxene, apart from anorthoclase (Or 23–30). Chemically, it is a trachyte that is compositionally transitional to Fataga compositions. At the type locality Barranco de Taurito, F is separated from E by as much as 30 cm of tuffs and epiclastic sandstone to fanglomerate in local depressions.

Montaña Horno Formation (~13.3–13.0 Ma)

The Montaña Horno Formation (Fig. 4) comprises the outer intracaldera series of ignimbrites between Montaña Viso and Barranco de Arguineguin (Azulejos Member), and the uppermost, oxidized extracaldera cooling units in the Lower Barranco de Fataga (Red Hill Member).

The Azulejos Member is composed largely of distinctive green, mildly hydrothermally altered, slightly welded to unwelded pumice deposits, with the $^{40}Ar/^{39}Ar$ age of anorthoclase feldspars from Los Azulejos type locality indicating an eruption at 13.29 ± 0.02 Ma

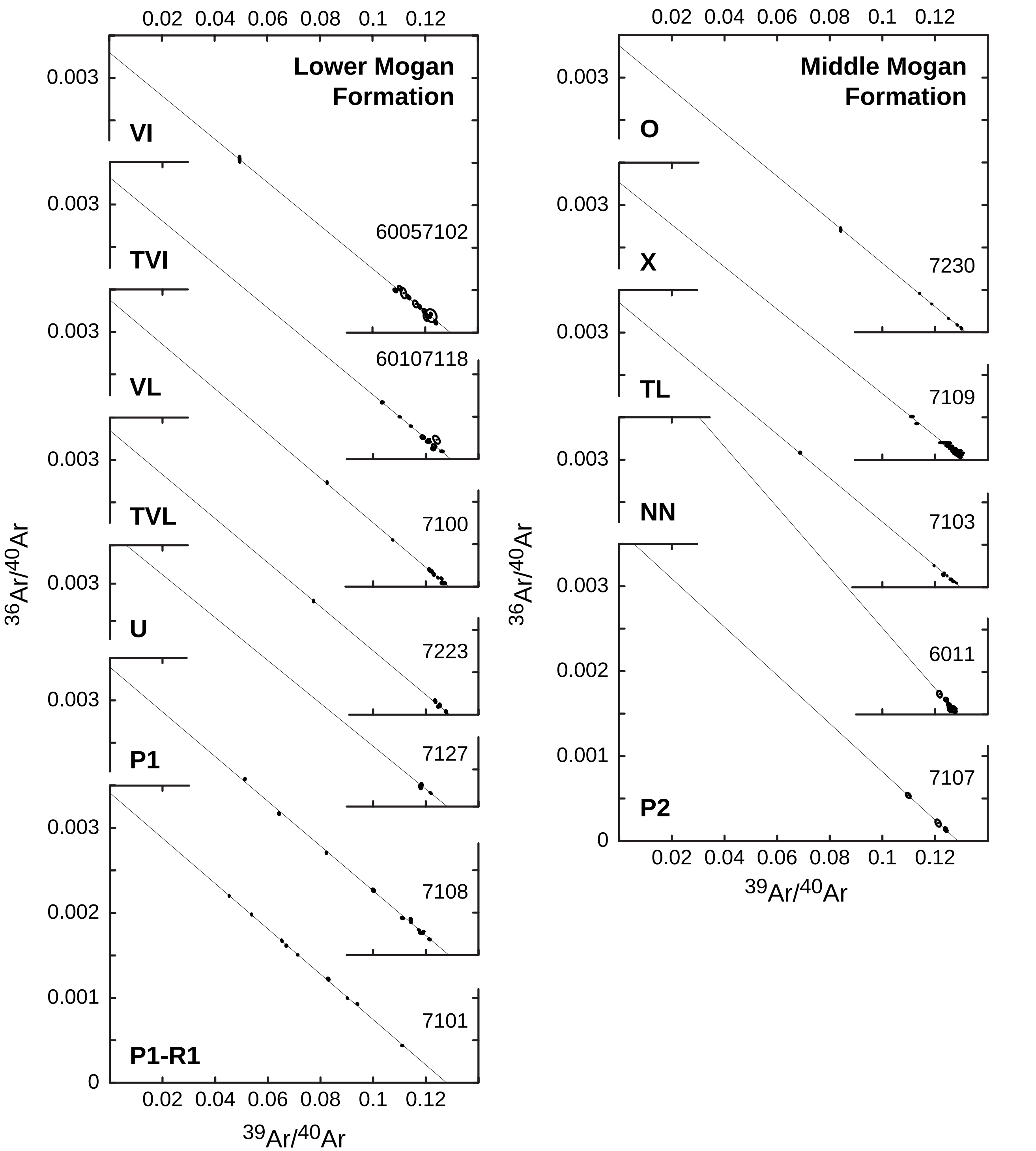

Figure 3. Isotope correlation diagrams of the argon isotope composition of single anorthoclase phenocrysts (shown with slightly enlarged 1-σ error ellipses) from cooling units of the Lower and Middle Mogán Formations. Numerical results of isochron calculations and error-weighted averages are compiled in Table 1. All data are normalized to a common J-value of 1E-3 and are ordered with decreasing age from bottom to top and from left to right.

(Sample 7224). It is locally interbedded with, and overlain by, widespread sheets of strongly welded ignimbrites and local intrusions that form the bulk of the Montaña Horno Formation. Magma compositions are mostly pantelleritic and comenditic and are thus correlative to the Upper (extracaldera) Mogán Formation. An ignimbrite from the middle Montaña Horno Formation at the type locality below Montaña Horno is here dated as 13.16 ± 0.04 Ma (Sample 7129). These unwelded pumice deposits are overlain by slightly altered ignimbrite units that are transitional in composition between Mogán and Fataga and unaltered, trachyphonolitic ignimbrites and pumice tuffs, the youngest of which probably correlate with the lowermost Fataga Formation. Ignimbrites and lava flows of Fataga chemistry and mineralogy are common inside the caldera. They form the topmost cooling units at Montaña Horno and form a series >500 m thick between

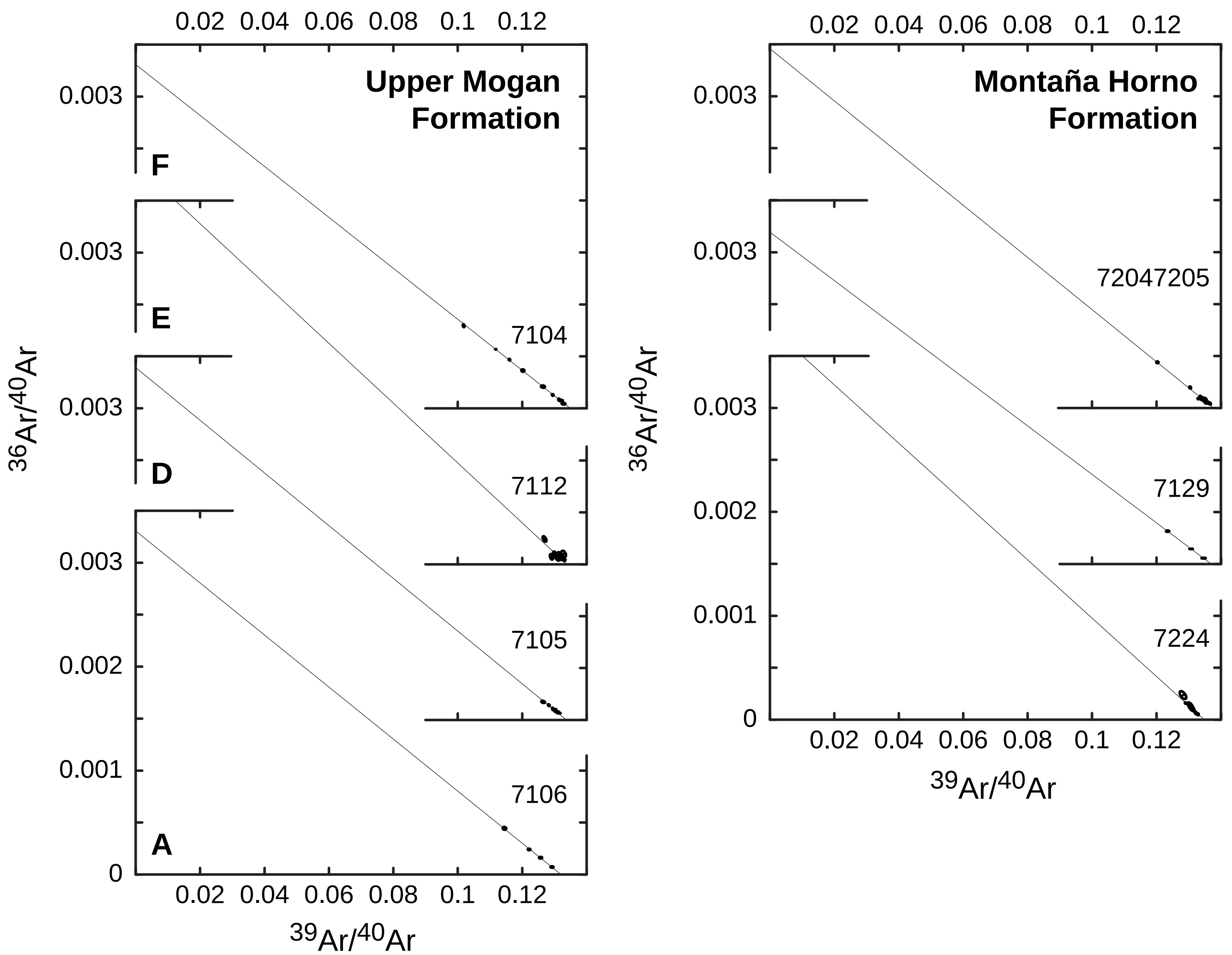

Figure 4. Isotope correlation diagrams of the argon isotope composition of single anorthoclase phenocrysts (shown with slightly enlarged 1-σ error ellipses) from cooling units of the Upper Mogán Formation and Montaña Horno Formation. Numerical results of isochron calculations and error-weighted averages are compiled in Table 1. All data are normalized to a common J-value of 1E-3.

Tamadaba and Montaña Horno. Correlation of individual ignimbrites with the extracaldera Fataga Group is, however, uncertain.

The Red Hill Member comprises a group of 4–6 extracaldera ignimbrites, transitional between Mogán and Fataga in composition and degree of oxidization, that are unconformably overlain by gray, unoxidized ignimbrites of the Lower Fataga Formation in the Lower Barranco de Fataga. Possibly, these cooling units were erupted between the end of Mogán volcanism (~13.35 Ma) and the earliest Fataga cooling units at Taurito (~13 Ma). The top ignimbrite from the Red Hill section in Barranco de Fataga has an age of 13.04 ± 0.02 Ma (Sample 72047205).

Inside Tejeda Caldera, which had formed during the eruption of Lower Mogán ignimbrite P1, the eruption and deposition of extracaldera ignimbrites and lava flows was accompanied by the formation of a large intrusive complex. Six major stages of intrusion comprising peralkaline rhyolite dikes; biotite and hornblende syenites stocks; trachytic and trachyphonolitic cone sheet dikes; and phonolitic to tephritic dikes, with magma compositions ranging from transitional Upper Mogán to Roque Nublo (Ferriz and Schmincke, 1989). McDougall and Schmincke (1977) reported K-Ar ages from 12.2 ± 0.3 Ma to 12.1 ± 0.3 Ma for syenite dikes, and an age of 8.9 ± 0.1 Ma for a trachyphonolite dike of the Tejeda Member. Two intrusive dikes of trachyphonolitic Fataga composition dated here yielded ages of 9.95 ± 0.02 Ma (Sample 6007) and 8.28 ± 0.02 Ma (Sample 7209).

Fataga Group

The Fataga Group, generally ~500 m thick, consists of moderately silica-undersaturated trachyphonolitic ignimbrites, lava flows, fallout tephra, debris avalanche, and epiclastic deposits with variable amounts of phenocrysts of anorthoclase, Fe/Ti oxides, phlogopite (mainly in ignimbrites), amphibole and green clinopyroxene (in ignimbrites and lava flows), sphene, groundmass sanidine, aegirine, alkali feldspar, alkali amphibole, nepheline (generally altered to analcime), and magnetite. The major differences in the phenocryst mineralogy to the Mogán ignimbrites are the more potassic composition of the feldspar and the common occurrence of phlogopite found in the Fataga ignimbrites and lavas. Many of the lava flows are practically aphyric. In the main outcrop area between Tirajana and Arguineguin, four formations are tentatively distinguished from one another based on field relationships and $^{40}Ar/^{39}Ar$ laser dating.

Lower Fataga Formation (~12.4–12.3 Ma)

The Lower Fataga Formation (Fig. 5) consisting dominantly of ignimbrites and phonolite lava flows, is ~200 m thick in Upper Barranco de Fataga. Two to four grayish ignimbrites with interlayered conglomerate, locally and unconformably overlying the oxidized transitional ignimbrites of the Montaña Horno Formation, are covered by several phonolite lava flows.

The ages of tuff deposits interlayered with Lower Fataga ignimbrites and lava flows at Presa de Fataga, Andres, and Temisas range from 12.43 ± 0.02 Ma to 12.36 ± 0.02 Ma (Samples 7249, 7381, 7212, and 7120), whereas the uppermost ignimbrite in the Temisas section erupted at 12.33 ± 0.02 Ma (Sample 7380).

Middle Fataga Formation (~12.1–11.4 Ma)

A prominent group of about five ignimbrites can be traced continuously from Barranco de Fataga to the Monte Leon area to the west and are well exposed at Degollada Ancha, the type locality (Fig. 5). The two lower, thin, green ignimbrites (labeled I and II) are variably thick because they level out the irregular surface of the prominent underlying phonolite lava flow. Ignimbrite III ("P3 ignimbrite") is a 10- to 20-m thick ignimbrite that is rich in small, light gray lithics. Ignimbrite IV, a "spatter-rich" ignimbrite that is ~10–20 m thick and rich in phonolitic lava inclusions, is strongly welded and is separated from III by a thin conglomerate and, locally, by paleosol. Ignimbrite V ("Ayagaures ignimbrite"), is a widespread, thick, crystal-rich ignimbrite. However, the middle Fataga Formation comprises at least seven ignimbrite cooling units.

In the Lower Barranco Arguineguin, only part of the Middle Fataga Formation is exposed, starting with a lower ignimbrite dated 12.07 ± 0.04 Ma (Sample 7207), overlain by brown ignimbrite (11.95 ± 0.01 Ma; Sample 7240), and two crystal-rich ignimbrites (11.77 ± 0.02 Ma and 11.71 ± 0.01 Ma; Samples 7206 and 72427246), unconformably overlain by Upper Fataga ignimbrites (Pozzulane-Ig, Arguineguin-Ig; see below).

At Barranco de Tauro, xenolith-rich ignimbrite III has been dated as 11.90 ± 0.02 Ma (Sample 6013). Ignimbrite IV (Lower Barranco Fataga) gives an age of 11.68 ± 0.02 Ma (Sample 7121), which is identical, within error limits, to the younger, crystal-rich ignimbrite at Lower Barranco Arguineguin. The overlying Ayagaures ignimbrite (V) is also exposed in the Casa Blanca section above the town of Fataga, where it represents the uppermost ignimbrite cooling unit, and has been dated as 11.52 ± 0.01 Ma (Sample 7231). It is overlain by >20 m of cream-colored tephra deposits dominated by laharic deposits derived from reworked unwelded ignimbrites, reflecting a major phase of highly explosive eruptive activity before major lava flow extrusion. Two samples from these deposits at Casa Blanca were dated as 11.43 ± 0.03 Ma and 11.42 ± 0.01 Ma (Samples 72037214 and 7241).

At Embalse de Escusabaraja, the Ayagaures ignimbrite is overlain by minor pumice-rich pyroclastic flow deposits (possibly equivalent to the cream-colored tuff) and the uppermost ignimbrite of the Middle Fataga Formation ("Excusabaraja ignimbrite"), which erupted at 11.36 ± 0.02 Ma (Sample 71177128).

Upper Fataga Formation (~11.0–9.9 Ma)

The Upper Fataga Formation (Fig. 6) consists dominantly of thick phonolite lava flows, some exceeding 100 m in thickness. The formation is at least 800 m thick near Moya and ~500 m above Fataga. Reconnaissance data suggest that pyroclastic and epiclastic deposits become more abundant at this stage west of Barranco de Fataga.

Tuff deposits at the base of the Upper Fataga Formation, exposed at Barranco Fataga (road Maspalomas-Fataga), give an eruption age of 10.97 ± 0.02 Ma (Sample 7250) and are overlain by phonolite lava flows dated as 10.94 ± 0.02 Ma (Sample 7248). A sequence of fallout tephra deposits at Escusabaraja erupted at 10.82 ± 0.01 Ma, 10.65 ± 0.02 Ma, and 10.62 ± 0.01 Ma (Samples 7227, 7208, and 7239).

Upper Fataga lava flows occur abundantly north of Agaete and at several places in the northern part of the island, such as at Moya, but they have not been dated yet. The Las Palmas Terrace west and east of Las Palmas rests on widespread phonolite lava flows, which form the base to the sedimentary Las Palmas fan. Some of these lava flows at Punta de Palo have been dated by K-Ar and yielded ages of 10.0 ± 0.2 and 10.1 ± 0.2 Ma (Abdel-Monem et al., 1971; McDougall and Schmincke, 1977). At Bahia Confital and farther south, the phonolitic lava flows are overlain by at least two ignimbrite cooling units. The basal welded ignimbrite from the coastal section of Bahia Confital, 2 km west of Las Palmas, is dated here as 10.22 ± 0.03 Ma (Sample 6012) and is thus identical, within error limits, in age to the thick, unwelded Arguineguin ignimbrite (10.19 ± 0.02 Ma; Sample 7266), which overlies a prominent, cream-colored, unwelded friable pumice flow deposit ("Pozzulan ignimbrite"; 10.40 ± 0.01 Ma; Sample 7243) in Lower Barranco Arguineguin.

The Upper Fataga Formation terminates with phonolite intrusions, exposed, for example, at Temisas and there dated as 9.95 ± 0.02 Ma (Sample 6007), and a third sequence of phonolite lava flows comprising phonolite flow LX at Excusabaraja (9.85 ± 0.03 Ma; Sample 7116).

Las Palmas Formation (~8.8–4.5 Ma)

In the Las Palmas Formation (Fig. 6), many phonolite intrusions cut the Miocene trachytic/phonolitic cone sheet swarm between Cruz Grande, Ayacata, and Pinar de Pajonales that chemically resemble Roque Nublo phonolites in their low silica, high Al_2O_3, high alkali concentrations, and generally very highly differentiated, silica-undersaturated character. Most likely, therefore, the mafic parent magmas had become more nephelinitic near the end of Fataga volcanism. One intrusive phonolite from 3 km east of Artenara has been dated as 8.28 ± 0.02 Ma (Sample 7209). Rare laharic pumice flows (8.84 ± 0.01 Ma; Sample 7213), interbedded with thick epiclastic sediments in the Arguineguin area, represent the youngest volcanic rocks presently dated from the Fataga Formation. They are still overlain, however, by one, as yet undated, welded ignimbrite east of the westernmost freeway tunnel, located 1 km east of Arguineguin.

After the end of the Miocene phonolitic volcanic stage at 8.84 Ma and until the beginning of the Roque Nublo Formation (4.15 Ma), the evolution of Gran Canaria is dominated by a period of most intense erosion. Canyons have not been appreciably deepened since then (Schmincke 1968). During this period, only minor olivine nephelinite and basanite lavas and pyroclastics were erupted in southern Gran Canaria around El Tablero and occur as intracanyon flow remnants near the mouth of Barranco de Tazartico and in other places scattered around the island. The composition ranges from basanite to nephelinite, and K-Ar ages range from 5.0 ± 0.2 Ma to 5.6 ± 0.1 Ma (Lietz and Schmincke, 1975; McDougall and Schmincke, 1977).

Roque Nublo Group

The very thick Roque Nublo group is made up of lava flows in its basal part, crudely bedded tuffaceous rocks and breccia sheets interbedded with lava flows in its lower middle part, thick massive breccia sheets in its upper middle part, and strongly hauyne-phyric intrusives and a few trachyte and hauyne-rich lava flows in its upper part. Lava compositions range from transitional tholeiites and alkali basalts to trachytes and from basanites through phonolites, as well as nephelinites.

El Tablero Formation (4.5–4.3 Ma)

In this formation (Fig. 7), a marine horizon transgressively overlies the phonolitic gravels at Las Palmas between 40 and 130 masl, depending on the location of the sediments. These sediments are overlain by widespread olivine-clinopyroxene-plagioclase-phyric basanitic pillow lavas grading upward into pahoehoe lavas. The lavas are K-Ar dated as ~4.36 ± 0.09 to 4.49 ± 0.09 Ma (Lietz and Schmincke, 1975) and thus date the main fossiliferous bed as early Pliocene. The

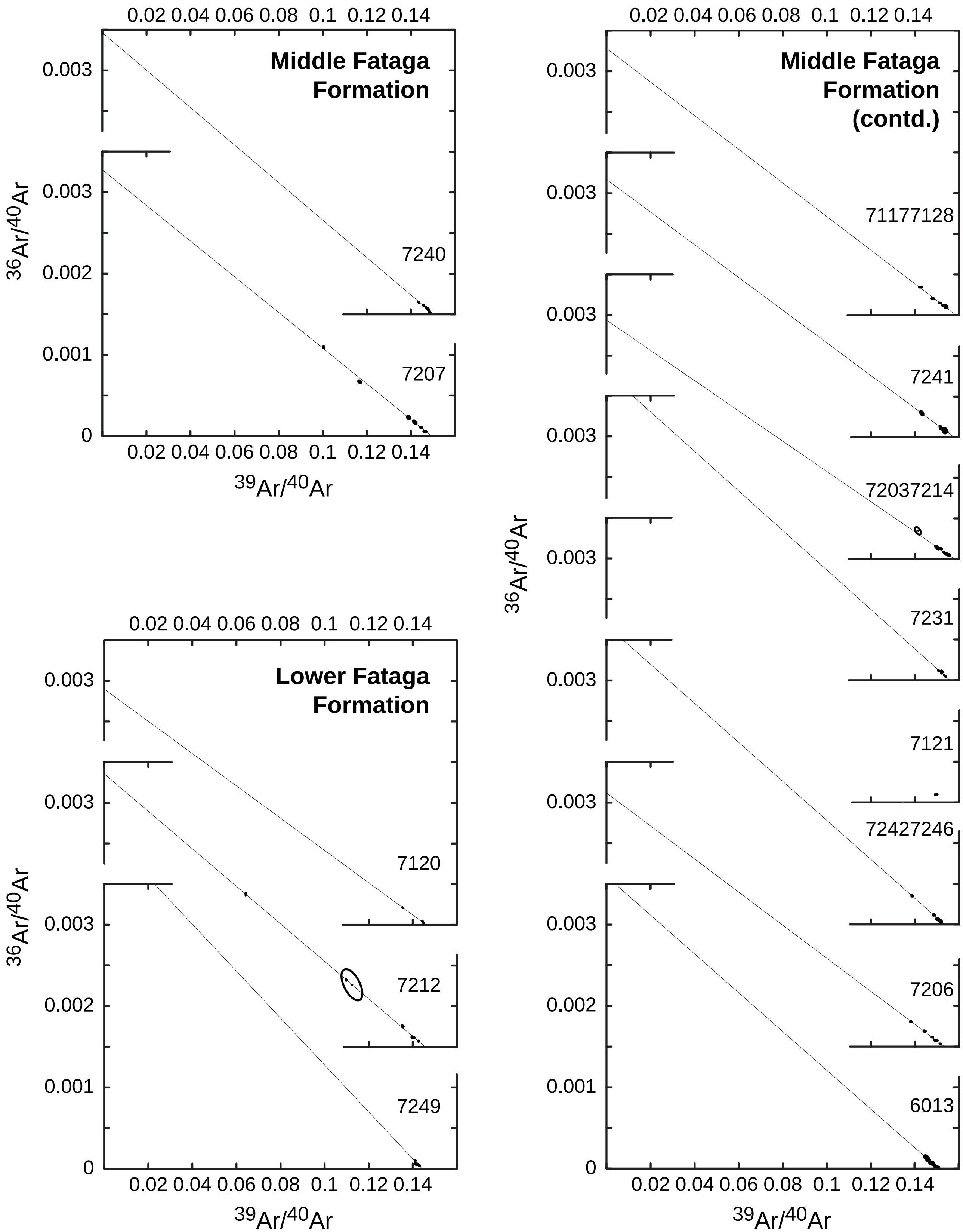

Figure 5. Isotope correlation diagrams of the argon isotope composition of single anorthoclase phenocrysts (shown with slightly enlarged 1-σ error ellipses) from cooling units of the Lower and Middle Fataga Formations. Numerical results of isochron calculations and error-weighted averages are compiled in Table 1. Note highly radiogenic argon composition of more potassium-rich K-feldspars from Fataga, compared with those from Mogán.

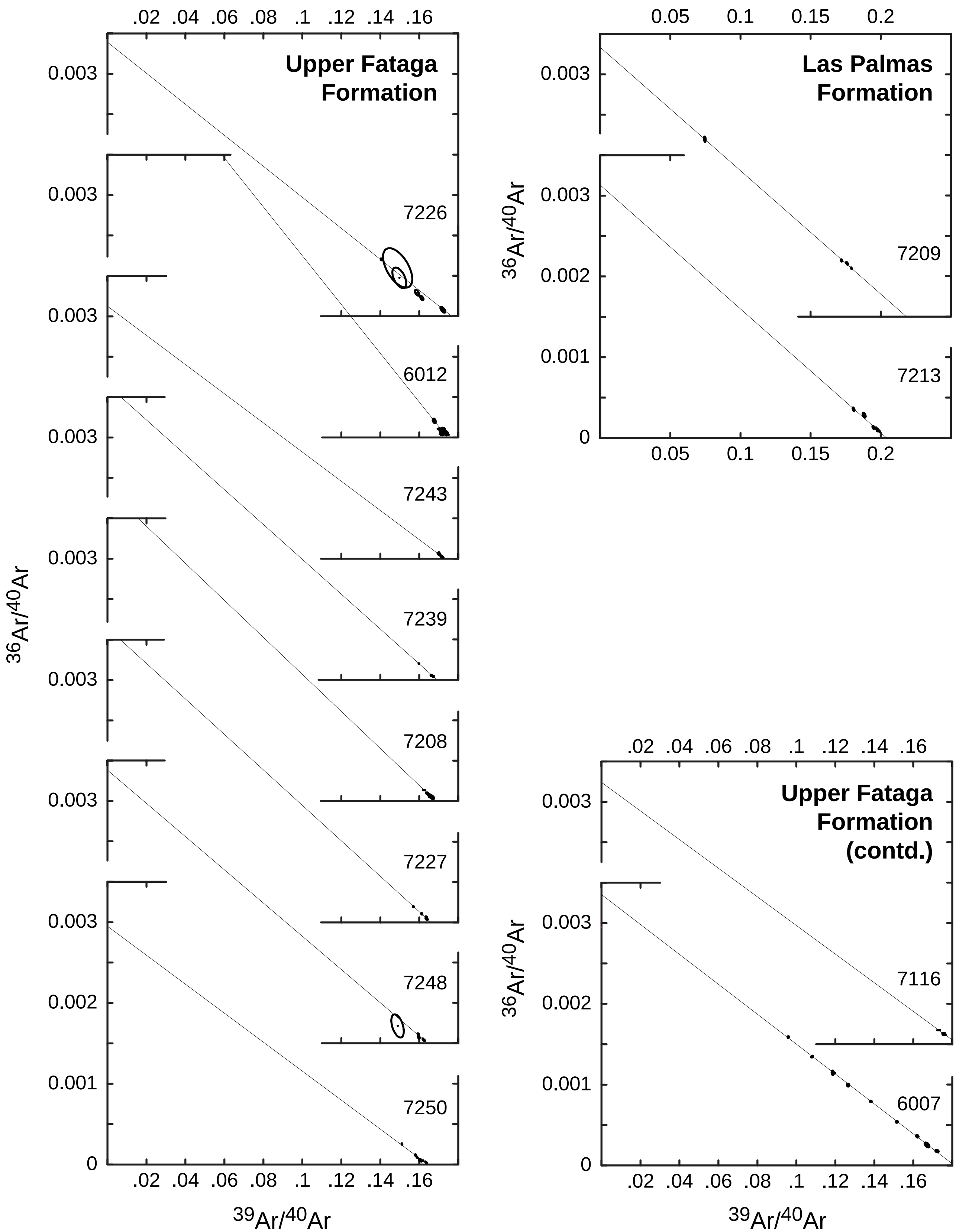

Figure 6. Isotope correlation diagrams of the argon isotope composition of single anorthoclase phenocrysts (shown with slightly enlarged 1-σ error ellipses) from cooling units of the Upper Fataga and Las Palmas Formations. Numerical results of isochron calculations and error-weighted averages are compiled in Table 1. All data are normalized to a common J-value of 1E-3.

lavas locally overlie a major phonolitic fallout tephra sequence as much as ~1 m thick.

Mesa de Junquillo and Los Listos Formation (4.15–3.5 Ma)

The Mesa de Junquillo and the overlapping, but slightly younger, Los Listos Formations (Fig. 7) consist of a series of lavas and breccias as much as 700 m thick filling many of the deep barrancos carved previously, particularly in the western and eastern center of the island and in northern Gran Canaria. Olivine tholeiites, olivine-phyric basanites, strongly clinopyroxene- and Fe/Ti-oxide-phyric ankaramites are dominant in the lower part of the sequence, and tephrites to phonolites are dominant in the upper part. The lava flows of the Mesa de Junquillo Formation may, in part, precede the Los Listos Formation (Lietz and Schmincke, 1975).

The Los Listos Formation, underlying the eastern central highland of Gran Canaria at the head of Barranco de Tirajana and extending into lower Barranco de Tirajana, is made up of alternating lava flows (mostly ankaramites and tephrites), pyroclastic breccias, and epiclastic bedded and massive sediments. It exceeds 500 m in thickness. It is correlated with the >500-m-thick section of lava flows and, toward the top of the section, increasing amounts of breccia sheets with intercalated phonolite pumice fallout deposits between Artenara and El Rinco. It is traversed in its lower part by the road Artenara-Tejeda and has a sequence of lava flows, breccia beds, and fallout tephra deposits exposed at Roque Bentaiga. Ages of phonolite pumice fallout beds in the Roque Bentaiga sequence range from 4.15 ± 0.01 Ma (Lower Bentaiga Pumice; Sample 70177018) to 4.02 ± 0.01 Ma (Upper Bentaiga Pumice; Sample 7020), partly overlapping with, or immediately succeeded by, the Artenara section. The ages of three phonolitic pumice layers bracketing and subdividing the Artenara section (Lower Artenara Pumice: 4.00 ± 0.02 Ma; Middle Artenara Pumice: 3.91 ± 0.02 Ma; and Upper Artenara Pumice: 3.88 ± 0.03 Ma [Samples 7012, 70257028, and 7022, respectively]) also constrain the age of the most spectacular and characteristic rocks of the Roque Nublo Formation: massive, layered breccia sheets several tens of meters thick, derived from pyroclastic flows, lahars, and debris avalanches, which are interlayered with lava flows (3.92 ± 0.06 Ma; Sample 7001) and the fallout tephra layers in the Artenara section.

Strongly phyric (hauyne, clinopyroxene, sphene, apatite, amphibole, Fe/Ti-oxide, biotite, alkali feldspar) to almost aphyric, strongly alkalic, peraluminous domes make up several prominent monoliths in the eastern highlands of Gran Canaria (e.g., at Tenteniguada). Lava flows of similar composition are associated with these intrusions above Risco Blanco in Barranco de Tirajana and Artenara. Risco Blanco, one of the most prominent of these rock bodies, intruded at 3.91 ± 0.01 Ma, and is overlain by younger post–Roque Nublo lavas and breccias. Other phonolite intrusions occur west of Artenara (K-Ar age 3.96 ± 0.03 Ma; McDougall and Schmincke, 1977), at Andres (3.95 ± 0.06 Ma; Sample 7225), and northeast of Artenara (3.78 ± 0.01 Ma; Sample 7032). The Roque Nublo Formation terminates with the eruption of tephritic lava flows (La Fortaleza, Barranco de Tirajana), K-Ar dated as 3.49 ± 0.04 Ma and 3.58 ± 0.04 Ma (McDougall and Schmincke, 1977).

Post-Roque Nublo Group

Following an erosional interval that lasted from ~3.5 Ma to 3.0 Ma, eruptive activity resumed on Gran Canaria with a major phase of nephelinite volcanism (Llanos de la Pez Formation; K-Ar age: 3.0–2.2 Ma), followed by melilite nephelinite scoria cones and dikes (Los Pechos Formation; ~1.8–1.5 Ma), middle Quaternary basanite and nephelinite lavas (~1.8–0.01 Ma), and basanite scoria cones and lavas erupted during the Holocene (La Calderilla Formation; < 0.01 Ma; Nogales and Schmincke, 1969). The eruption age estimates for the post–Roque Nublo Group are exclusively based on K-Ar age determinations (Lietz and Schmincke, 1975; McDougall and Schmincke, 1977).

DISCUSSION

Single-crystal $^{40}Ar/^{39}Ar$ dating of feldspar crystals from ignimbrites, lava flows, fallout tephra layers, and phonolite intrusions yields an internally consistent, high-resolution chronostratigraphy of the Miocene/Pliocene volcanic activity of Gran Canaria (Fig. 8). Bulk rock and feldspar K-Ar ages from previous studies (Lietz and Schmincke, 1975; McDougall and Schmincke, 1977; Féraud et al., 1981) generally either seamlessly integrate into the chronostratigraphic scheme presented here, or overlap with the $^{40}Ar/^{39}Ar$ dating results within their generally larger analytical uncertainties (i.e., in the Mogán interval) after recalculation to modern constants.

A lava flow of the Hogarzales Formation of the basaltic shield cycle immediately underlying the Miocene felsic series (ignimbrite P1) is here dated as 14.04 ± 0.10 Ma, based on $^{40}Ar/^{39}Ar$ dating of its plagioclase microphenocrysts. The ages of the Hogarzales lava flow and ignimbrite P1 constrain the age of the underlying shield basalt formations to older than 13.95 Ma. However, the age range of the subaerially exposed basalt flows of the shield-forming Guigui and Hogarzales Formations is still poorly constrained. K-Ar ages of Hogarzales and Guigui shield basalts range from 13.3 ± 0.2 and 14.3 ± 0.2 Ma (McDougall and Schmincke, 1977), indicating that some of the apparently younger whole-rock K-Ar ages (chiefly Hogarzales) are affected by argon loss caused by alteration. Nevertheless, the range of available K-Ar and $^{40}Ar/^{39}Ar$ ages (~14.0–14.5 Ma) suggests a rapid formation of the shield basalts followed in western and southern Gran Canaria without a major hiatus between the eruption of the shield basalts and the eruption of ignimbrite P1. More strongly dissected Miocene basalts east of Gran Canaria (Aguimes Formation) may be significantly older than the western basalts, but they remain to be studied.

All cooling units of the Mogán Formation (ignimbrites Pl–PE) were erupted between 13.95 ± 0.02 Ma and 13.36 ± 0.0l Ma. The eruption of the basal ash flow Pl coincided with the main phase of caldera collapse (15- to 20-km diameter Tejeda Caldera). The new dating results are fully compatible with $^{40}Ar/^{39}Ar$ laser dating ages previously determined on a much smaller population of crystals (N = 4) on some samples from identical units (Mogán ignimbrites P1: 14.07 ± 0.09 Ma; X: 13.83 ± 0.09 Ma; E: 13.42 ± 0.09 Ma) at the Geochronology Laboratory at the University of Toronto (Bogaard et al., 1988). The $^{40}Ar/^{39}Ar$ ages presented here are identical within 2-σ error limits (P1, X) or 1-σ error limits (E), and all single-crystal ages are within the range of those determined here.

With analytical uncertainties ideally as low as ± 0.01 Ma and significantly below or at least approaching the average time interval (i.e., Mogán interval) between individual eruptions in all Miocene/Pliocene eruptive stages of Gran Canaria, the $^{40}Ar/^{39}Ar$ ages (and error limits) can be evaluated with respect to eruption frequencies and repose intervals between individual eruptions, thereby integrating evidence from field geological constraints.

The $^{40}Ar/^{39}Ar$ ages of Lower Mogán Formation ignimbrites P1 to VI are basically identical, even within their narrow (0.15%–0.2%) analytical uncertainties, indicating an extremely rapid succession of eruptions and the lack of major pauses during the initial Miocene felsic stage. The minimum effusion rate, or the final stages of the shield-building basaltic episode (Guigui, Hogarzales), has been estimated as ~2000 km^3/m.y., contrasting with an average effusion rate of evolved Mogán magmas of 300–600 km^3/m.y. (Bogaard et al., 1988). Confirming the average Mogán estimate, the more precise ages of the Lower Mogán cooling units (13.95 ± 0.02 Ma to 13.90 ± 0.03 Ma) leave only a narrow corridor for the P1–VI eruptive sequence (~50,000 a), indicate effusions rates on the order of 2000 km^3/m.y.

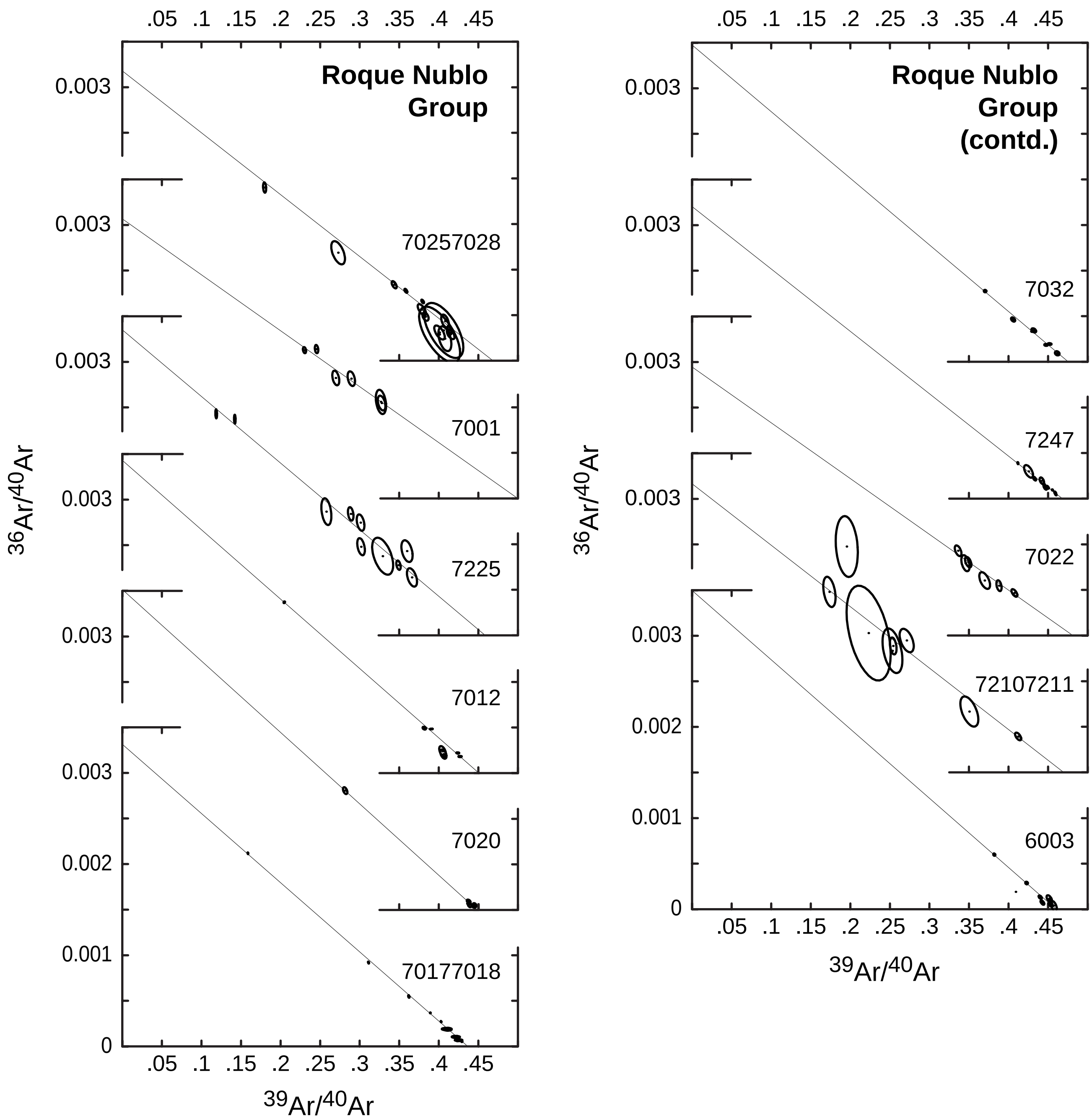

Figure 7. Isotope correlation diagrams of the argon isotope composition of single anorthoclase phenocrysts (shown with slightly enlarged 1-σ error ellipses) phonolite lava flows, dikes, and fallout pumice layers of the Roque Nublo Group. Numerical results of isochron calculations and error-weighted averages are compiled in Table 1. All data are normalized to a common J-value of 1E-3.

also during the early evolution of Miocene felsic magmas, and significantly reduced production rates during later stages of the Mogán interval.

The Middle Mogán Formation comprises a significantly larger time interval (~200–300 Ka) but probably smaller (?) magma volumes, resulting in a significant reduction in the magma production rate following a brief pause in the eruptive activity, which is also reflected by reworked sediments and conglomerates at the base of ignimbrite P2. P2 also heralds new magma compositions, although it is transitional between rocks of the Lower and Middle Mogán.

The mean apparent ages of ignimbrite VI (the latest from the Lower Mogán Formation) and ignimbrite P2 are very similar, but their 1-σ error limits allow for a significant pause or gap of as much as 90,000 yr between V-group ignimbrites and P2.

P2 and TL are similar not only in age but in composition; however, TL contains a large proportion of comendite, one of the two common compositions in the Middle and Upper Mogán. The major age difference between TL and X is also geologically evident because the only significant soil in the entire Mogán Group is between these two units, and the compositional contrast is also significant. The TL

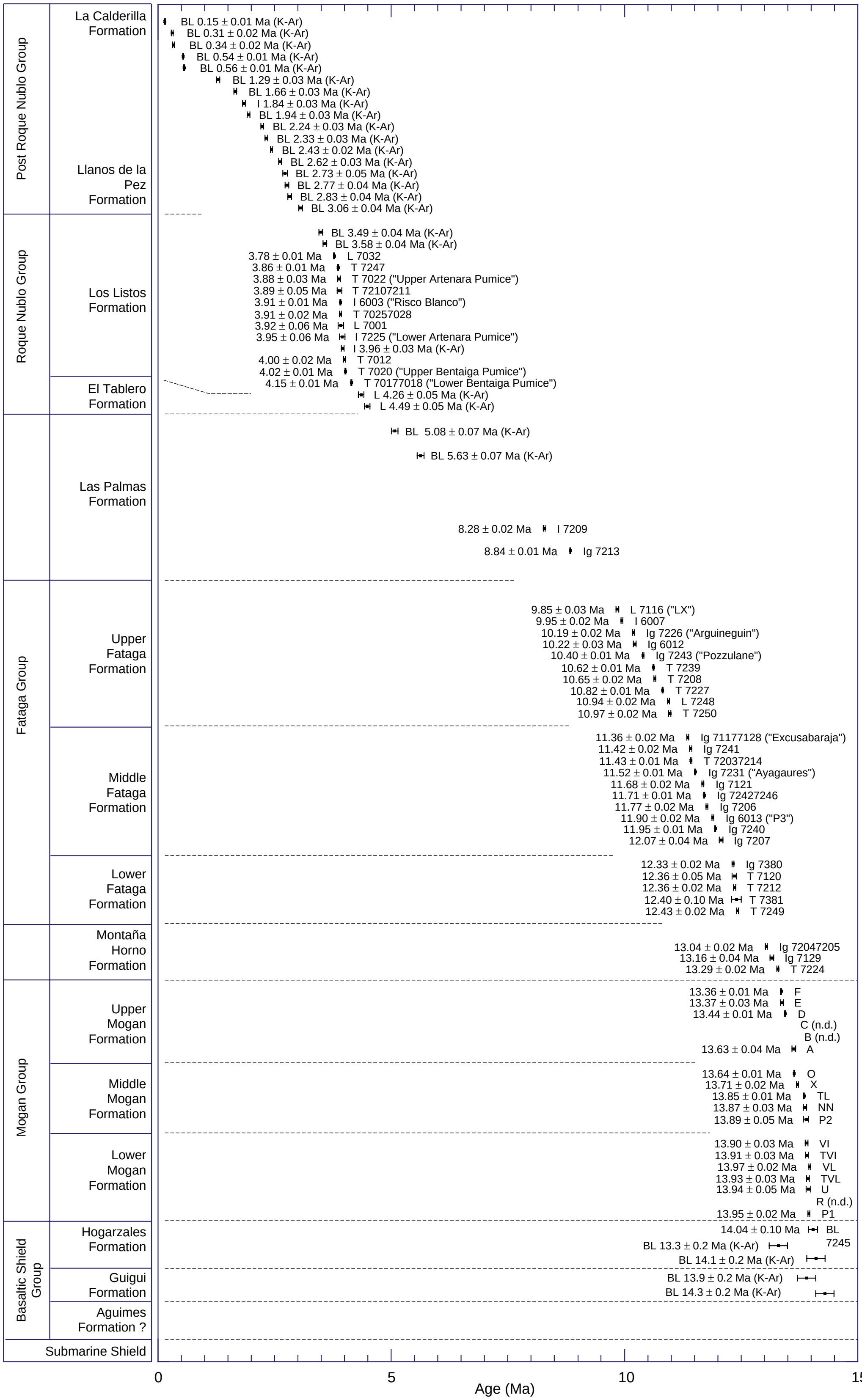

Figure 8. Chronostratigraphy of the Miocene/Pliocene volcanic evolution of Gran Canaria, based on single-crystal $^{40}Ar/^{39}Ar$ laser dating (this study) and selected K-Ar ages (Lietz and Schmincke, 1975; McDougall and Schmincke, 1977; Féraud et al., 1981). Apparent ages (K-Ar) and mean apparent ages ($^{40}Ar/^{39}Ar$) are shown with 1-σ error bars. Except for Mogán Group cooling units P1–F, individual lithologic units are identified by a prefix (Ig = ignimbrite, T = fall-out tephra, L = phonolite lava flow, BL = basalt lava flow, and I = phonolite intrusion or dike), followed by their sample number (Table 1) and local names, where applicable.

–X gap is estimated at 140,000 yr (1 σ). Ignimbrite X and O are compositionaly similar, and there is no geological evidence for a major time break. The pause between X and O could be as brief as 40,000 yr (1 σ), which would represent about Mogán average.

Even though the mean apparent ages of ignimbrites O and A are very similar, there is strong geological evidence for a major break between these two eruptions: magma compositions are significantly different, and widespread basaltic lava flows (T4) erupted between O and A, with erosional unconformities and conglomerates on top of T4, but below A. Analytical 1-σ errors allow for ~40,000 yr of pause between A and O, long enough for many basalt eruptions and significant erosion and reworking, however. Minor pauses on the order of 30,000 to 40,000 yr may also separate the eruptions of ignimbrites D, E, and F, although there is only geological evidence, such as erosion and epiclastic sediments, for a break between Upper Mogán ignimbrites E and F.

Temporal evolution and stratigraphy of the Mogán/Fataga transitional stage (Montaña Horno Formation) and chronology of intrusion inside Tejada Caldera are still poorly constrained. K-Ar (McDougall and Schmincke, 1977) and $^{40}Ar/^{39}Ar$ age determinations indicate intrusion ages from 12.2 to 8.28 Ma, significantly younger than the intra- and extra-caldera cooling units of the Montaña Horno Formation (13.29–13.04 Ma). For comparison, the ages for extracaldera Fataga lavas and ignimbrites reported below range from 12.43 to 8.84 Ma. These data suggest that the development of the intrusive complex started in early Fataga time, but persisted well beyond the peak of extrusive activity.

The time period during which Fataga pyroclastic and lava flows were erupted (~3.6 Ma) is long compared to the 0.6 Ma of the Mogán Group and ~0.3 Ma of the Montaña Horno transitional stage. However, based on currently available ages, the succession of ignimbrites, fallout tephra layers, and lava flows on Gran Canaria indicates that volcanic activity during Fataga time was not continuous. Significant pauses in explosive activity occurred at 12.33–12.07 Ma (~0.20–0.32 Ma), 11.36–10.97 Ma (~0.35–0.43 Ma), and 9.85–8.84 Ma (~0.95–1.05 Ma), the latter interval being dominated by phonolite intrusions and minor basaltic lava flows. During noneruptive intervals, abundant epiclastic sediments (sandstones, fanglomerate, rockfall deposits, and conglomerates) were deposited, with intracanyon flows commonly carving and filling small barrancos. Miocene phonolitic eruptive activity continued until at least 8.8 Ma, confining the largely nonvolcanic and erosional interval between the end of Miocene phonolitic and the beginning of evolved Roque Nublo volcanism, for a total of ~4.7 m.y. Based on the present range of $^{40}Ar/^{39}Ar$ ages obtained from fallout tephra, lava flows, and domes, the phonolite eruptions of the Roque Nublo Group appear to be generally younger than 4.15 ± 0.01 Ma. This may indicate either that the K-Ar ages of pillow lavas of the El Tablero Formation reported by Lietz and Schmincke (1975) may be slightly too high, or that the generation and eruption of evolved magmas during the Roque Nublo interval started as early as ~4.5 Ma.

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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.

Bogaard, P., Schmincke, H.-U., Freundt, A., Hall, C., and York, D., 1988. Eruption ages and magma supply rates during the Miocene evolution of Gran Canaria: single crystal $^{40}Ar/^{39}Ar$ laser ages. *Naturwissenschaften,* 75:616–617.

Bogaard, P.V.D., 1995. $^{40}Ar/^{39}Ar$ ages of sanidine phenocrysts from Laacher See tephra (12.900 yr BP): chronostratigraphic and petrological significance. *Earth Planet. Sci. Lett.,* 133:163–174.

Féraud, G., Schmincke, H.-U., Lietz, J., Gastaud, J., Pritchard, G., and Bleil, U., 1981. New K/Ar ages, chemical analyses and magnetic data of rocks from the islands of Santa Maria (Azores), Porto Santo and Madeira (Madeira Archipelago) and Gran Canaria (Canary Islands). *Bull. Volcanol.,* 44:359–375.

Ferriz, H., and Schmincke, H.-U., 1989. The Miocene cone sheet dike swarm of Gran Canaria, Canary Islands, Spain. *Eur. Sci. Found. Meet. on Canaria Volcanism, Lanzarote, Spain:* 142–144.

Freundt, A., and Schmincke, H.-U., 1995. Petrogenesis of rhyolite-trachyte-basalt composite ignimbrite P1, Gran Canaria, Canary Islands. *J. Geophys. Res.,* 100:455–474.

Lietz, J., and Schmincke, H.-U., 1975. Miocene-Pliocene sea-level changes and volcanic phases on Gran Canaria (Canary Islands) in the light of new K-Ar ages. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 18:213–239.

Mankinen, E.A., and Dalrymple, G.B., 1979. Revised geomagnetic polarity time scale for the interval 0–5 m.y.B.P. *J. Geophys. Res.,* 84:615–626.

McDougall, I., and Schmincke, H.-U., 1977. Geochronology of Gran Canaria, Canary Islands: age of shield-building volcanism and other magmatic phases. *Bull. Volcanol.,* 40:1–21.

Nogales, J., and Schmincke, H.-U., 1969. El pino entarrado de la Cañada de las Arenas (Gran Canaria). *Cuad. Bot. Canar.,* 5:23–25.

Samson, S.D., and Alexander, E.C., Jr., 1987. Calibration of the interlaboratory $^{40}Ar/^{39}Ar$ dating standard, MMhb-1. *Chem. Geol.,* 66:27–34.

Schmincke, H.-U., 1968. Faulting versus erosion and the reconstruction of the Mid-Miocene shield volcano of Gran Canaria. *Geol. Mitt.,* 8:23–50.

————, 1976. The geology of the Canary Islands. *In* Kunkel, G. (Ed.), *Biogeography and Ecology in the Canary Islands:* The Hague (W. Junk), 67–184.

Schmincke, H.-U., and Swanson, D.A., 1966. Eine alte Caldera auf Gran Canaria. *Neues. Jahrb. Geol. Palaeontol. Monatsh.,* 4:260–269.

Schmincke, H.-U., Weaver, P.P.E., Firth, J.V., et al., 1995. *Proc. ODP, Init. Repts.,* 157: College Station, TX (Ocean Drilling Program).

Wendt, I., and Carl, C., 1991. The statistical distribution of the mean squared weighted deviation. *Chem. Geol.,* 86:275–285.

York, D., 1969. Least-squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett.,* 5:320–324.

Young, H.D., 1962. *Statistical Treatment of Experimental Data:* New York (McGraw-Hill).

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