$^{40}Ar/^{39}Ar$ stratigraphy of pyroclastic units from the Cañadas Volcanic Edifice (Tenerife, Canary Islands) and their bearing on the structural evolution

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Abstract

Many felsic pyroclastic units of various types are exposed in different sectors of Tenerife. New $^{40}Ar/^{39}Ar$ determinations allow them to be placed more precisely in the general volcano-stratigraphic succession. According to geographic distribution, stratigraphic position and isotopic ages, four main pyroclastic phases may be identified. The first, San Juan de la Rambla phase (2.1 Ma), is only known in the north of Tenerife in the Tigaiga massif. The second, Adeje phase (1.8–1.5 Ma), is most completely developed in the southwest of the island, but occasionally occurs in the other sectors. The third, Las Américas phase (1 Ma), is only presently known in the southern region. The fourth, Bandas del Sur phase (0.7–0.15 Ma), is essentially exposed in the southeast sector. The results of this work emphasise the complexity of the pre-1-Ma eruptive history of Tenerife and underline the fact that explosive volcanic activity has taken place for at least the last 2 Ma. Vertical collapse structures have developed as a result of pyroclastic flow activity and these may be as old as 1.6–1.8 Ma, therefore much older than generally considered. The precise location of calderas is difficult to ascertain as a result of the repeated lateral flank collapse during the construction of the Cañadas volcano.

Keywords: ignimbrites; $^{40}Ar/^{39}Ar$ dating; Cañadas volcano; Tenerife; caldera

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1. Introduction

In Tenerife (Fig. 1), numerous pyroclastic eruptions of felsic alkaline magma occurred during the construction of the central Cañadas volcanic edifice (CE). This explosive activity became more frequent through time, and pyroclastic deposits of all types represent a large proportion of the different volcanic series that make up the CE (Ancochea et al., 1990, 1999; Martí et al., 1994). They are especially well exposed on the southeast lower slopes (Bandas del Sur) of the island where they have been extensively studied (Alonso, 1989; Bryan et al., 1998), but are also present in various

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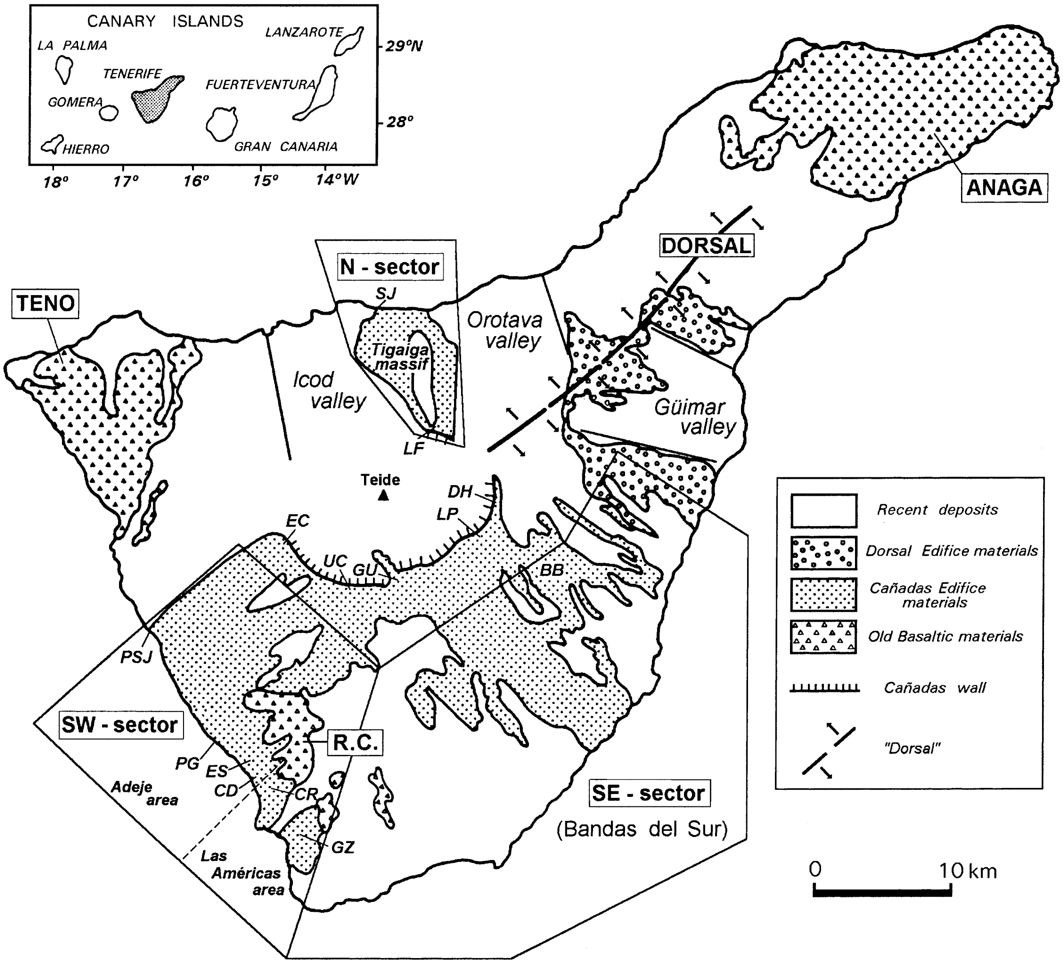

Fig. 1. Geologic sketch map of Tenerife Island: BB, Barranco de la Bentrana; CD, Casa del Duque; CR, Caldera del Rey; DH, Diego Hernández; EC, El Cedro; ES, Ermita San Sebastian; GU, Mta. Guajara; GZ, Mta. Guaza dome; LCC, Las Cañadas Caldera; LF, La Fortaleza; LP, Las Pilas; PG, Punta de las Gaviotas; PSJ, Playa de San Juan; R.C., Roque del Conde massif; SJ, San Juan de la Rambla; UC, Ucanca. Arrows indicate direction of flows.

stratigraphic positions in other sectors of the CE. While the young southeastern pyroclastic units have been extensively described, no detailed stratigraphy and volcanological description have been published on the earlier history of the CE. A first study of the ignimbrites in the southwestern flank of the CE (Adeje area), was published by Fúster et al. (1994). The present paper describes a more comprehensive $^{40}Ar/^{39}Ar$ chronology for the entire Cañadas volcano, with emphasis on previously less described ignimbrites on the northern and southwestern slopes. This revised dataset complements and details the earlier stratigraphy of Martí et al. (1989, 1994), Martí and Araña (1991), Ancochea et al. (1989, 1990), Mitjavila and Villa (1993), Fúster et al. (1994) and Bryan et al. (1998). Age determinations of the main pyroclastic units are significant in deciphering the structural evolution of the volcanic edifice and the formation of interpreted summit caldera(s).

2. Analytical techniques

^{40}Ar/^{39}Ar dating of young pyroclastic rocks is difficult even if favourable minerals such as potassium feldspars are used. Erroneous ages usually result from excess argon, post-eruptive alteration or the presence of xenocrysts. The ^{40}Ar/^{39}Ar step-heating method allows for statistical treatments such as the determination of plateau ages or inverse isochrons yielding, in most cases, the probable age of eruption in cases of excess argon or alteration. In this study, the reported ages are derived either from plateaus or isochrons as will be indicated and discussed in each case. However in Tenerife, as in other volcanic centres, xenocrysts, which are not much older than the minerals from the primary magma to be dated, are commonly inherited from the volcanic edifice itself. Xenocrysts are therefore difficult to eliminate and their influence on the result is not easily recognised. New ^{40}Ar/^{39}Ar age determinations of pyroclastic deposits were carried out on anorthoclase concentrates extracted from a single or very few pumice clasts interpreted as representing the primary eruptive magma. Although older potassium feldspars can, in some cases, survive eruption as xenocrysts, this phase is the richest in potassium allowing for precise dating of young rocks. It is also often the only datable mineral in the pumices. Ten to fifteen mg of K-feldspar were irradiated in the Siloe reactor of the CEN Grenoble together with standards (Fish Canyon tuff sanidine, Lanphere and Baadsgaard, 2001). The argon was extracted in 10–12 steps of increasing temperature between 500 and 1400°C and analysed on a VG 3600 mass spectrometer at the laboratory of the University of Clermont-Ferrand. Detailed description of the analytical technique may be found in Arnaud and Kelley (1997). All errors are given at the 1σ level and include the error on the *J*-factor. Only plateau and isochron results are given in Table 1 but the complete dataset is available from the authors upon request.

3. Chronostratigraphy of the pyroclastic deposits

A general chronostratigraphy of the Cañadas edifice was presented by Ancochea et al. (1999) while Bryan et al. (1998 and references therein) suggested another stratigraphy essentially compiled from the successions observed in the Bandas del Sur and Cañadas caldera wall (CW). A schematic comparison is proposed in Fig. 2. It can be seen that these stratigraphies differ in the following way: in Bryan et al. (1998), the Lower Group (3.3–2 Ma) and major erosional unconformity (2–1.56 Ma) corresponds to both Cañadas I (CE-I, 3.5–2.6 Ma) and the lower part of Cañadas II (CE-II, 2.5–1.3 Ma) edifices of Ancochea et al.

Table 1
New ^{40}Ar/^{39}Ar radiometric ages of the ignimbritic units

Sample	Unit	Localitation	Isochron age Ma	Plateau age Ma
San Juan de la Rambla phase:				
T-56-F	San Juan de la Rambla 1	31.41.750//3.38.250	(2.3 ± 0.3)	2.11 ± 0.07
Adeje phase				
T-77-F	San Juan de la Rambla 2	31.41650//3.38.550	no isochron	1.62 ± 0.12
T-197-	Las Gaviotas ignimbrite	31.10.250//3.27.150	1.84 ± 0.07	(2.24 ± 0.04)
T-178-F	El Pris ignimbrite	31.10.780//3.26.400	1.69 ± 0.05	(1.88 ± 0.04)
T-99-F	Adeje ignimbrite	31.11.060//3.26.480	1.50 ± 0.03	1.48 ± 0.05
T-103-F	Taucho ignimbrite	31.09.900//3.31.580	1.51 ± 0.03	(1.61 ± 0.06)
T-187-F	La Bentrana ignimbrite	31.11.000//3.52.700	(1.5 ± 0.17)	1.44 ± 0.12
Las Américas phase				
9.2	Caldera del Rey ignimbrite	31.07.000//3.31.370	1.07 ± 0.04	1.13 ± 0.03
T-2-CO	Guajara peak	31.21.950//3.41.930	(0.89 ± 0.05)	1.00 ± 0.03
Bandas del Sur phase				
T-143-F	Arico ignimbrite	3.11.220//3.52.850	0.61 ± 0.05	0.61 ± 0.09

Parentheses indicate age rejected after comparison of plateau and isochron ages.

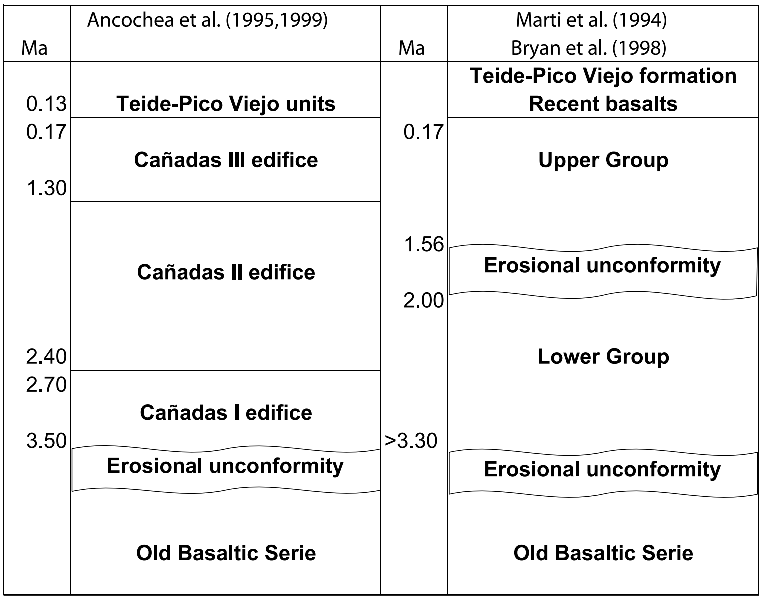

Fig. 2. Schematic stratigraphy proposed by Martí et al. (1994) and Bryan et al. (1998) compared with that of Ancochea et al. (1995, 1999).

(1999); similarly in Bryan et al. (1998) the Upper Group is divided into CE-II and Cañadas III (CE-III, 1.2–0.5 Ma). While the presence of collapse calderas is probable, the stratigraphic position of the interpreted calderas in Bryan et al. (1998) is difficult to reconcile with the Ancochea et al. (1999) stratigraphy. The present study therefore summarises the essential field observations and age data (new and already published) of the pyroclastic units of the CE-II and CE-III edifices in order to constrain their chronological limits and assess the relative importance of pyroclastic eruptive activity in each case.

3.1. Northern sector: Tigaiga massif

According to the succession defined by Ibarrola et al. (1993) and Ancochea et al. (1999), pyroclastic deposits are observed throughout the Tigaiga massif, the only preserved part of the CE in the north of the island. They are best exposed near the northern coast around the San Juan de la Rambla village (SJ, Fig. 1).

San Juan de la Rambla 1 ignimbrite (Fig. 3): overlying 2.26 Ma trachybasaltic lavas (Ancochea et al., 1999), this formation includes several welded flow units with flattened juvenile felsic clasts. A new $^{40}Ar/^{39}Ar$ age measured on the potassium feldspars separated from these scoria clasts yields an age (T56F, Fig. 4) of 2.11 ± 0.07 Ma (Table 1). This age is defined by a weak plateau containing 60% of ^{39}Ar degassed while the isochron is too scattered to be useful. However the latter strongly suggests excess argon in high-temperature steps explaining the unreasonable old ages at the end of the degassing spectrum. This plateau age for the ignimbrite, although older than formerly considered by Ancochea et al., 1990, is consistent with its position in the volcanic succession. Only known in this area, this unit is locally overlain by non-welded tuffs and it is the oldest presently known ignimbrite from the CE.

San Juan de la Rambla 2 pyroclastic deposits: after an erosion period followed by deposition of debris flow deposits several metres thick, other ash and pumice flow deposits were laid down (Fig. 3). One of these pumice flows is dated at 1.62 ± 0.12 Ma (Table 1) corresponding to a good plateau (T77F, Fig. 4) again showing excess argon in the high-temperature extraction steps. Thus a 500 ka local gap in the volcanic succession is documented. This second pyroclastic episode is

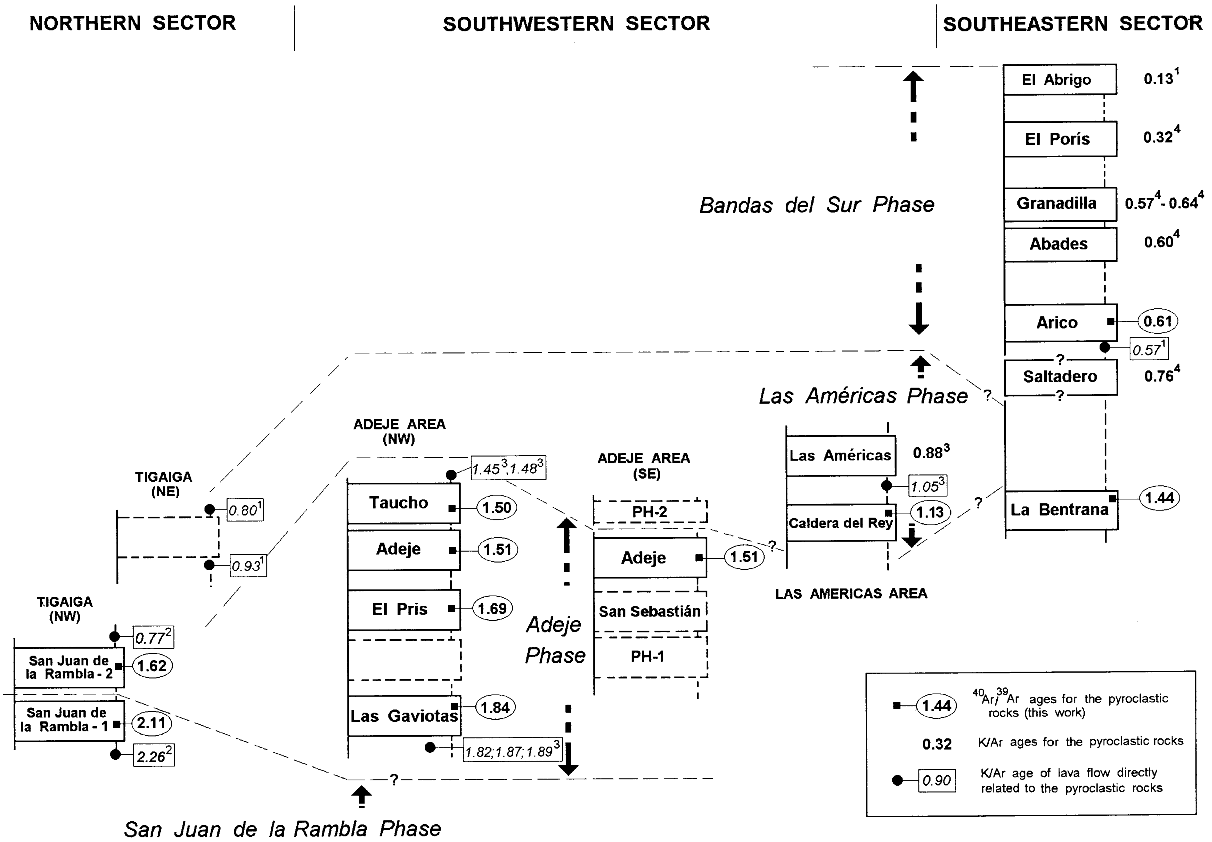

Fig. 3. Schematic stratigraphic columns of the main pyroclastic deposits showing possible correlations. The pyroclastic series which have not yet been isotopically dated are shown in their inferred stratigraphic position with stipple borders. Ages (in Ma) already published were obtained from the following references: 1, Ancochea et al. (1990); 2, Ibarrola et al. (1993); 3, Fúster et al. (1994); 4, Bryan et al. (1998). PH1 are the hydromagmatic layers at the base of the Ermita de San Sebastian (ES) section, PH2 are those from the CD section (see text for details).

contemporaneous with deposits observed in the SW sector (see below). The San Juan de la Rambla 2 ignimbrite is covered by much younger (0.77 Ma, Ibarrola et al., 1993) phonolitic lavas.

In the NE part of the Tigaiga massif the succession is different: a few pumice fall deposits are interbedded between 0.93 and 0.8 Ma phonolitic lavas. Martí et al. (1995) gave a similar age (828 ± 16 ka) for one layer below the uppermost (0.37 Ma) phonolitic La Fortaleza unit.

3.2. Southwestern sector

This sector may be divided into two distinct areas according to their geological and volcanological characteristics (Figs. 1 and 3): the 'Adeje area' in the northwest with excellent exposures along the coast and the 'Playa de Las Américas' area further to the SE.

3.2.1. Adeje area

No detailed geological map of this region is presently available and precise correlations between exposures are difficult. Pyroclastic units are widespread along the lower coastal slopes, and individual ignimbrites are divided in several channelled and divergent lobes showing abrupt lateral variations in thickness. Toward the interior of the island, they appear in the most deeply eroded ravines covered by younger basaltic lavas.

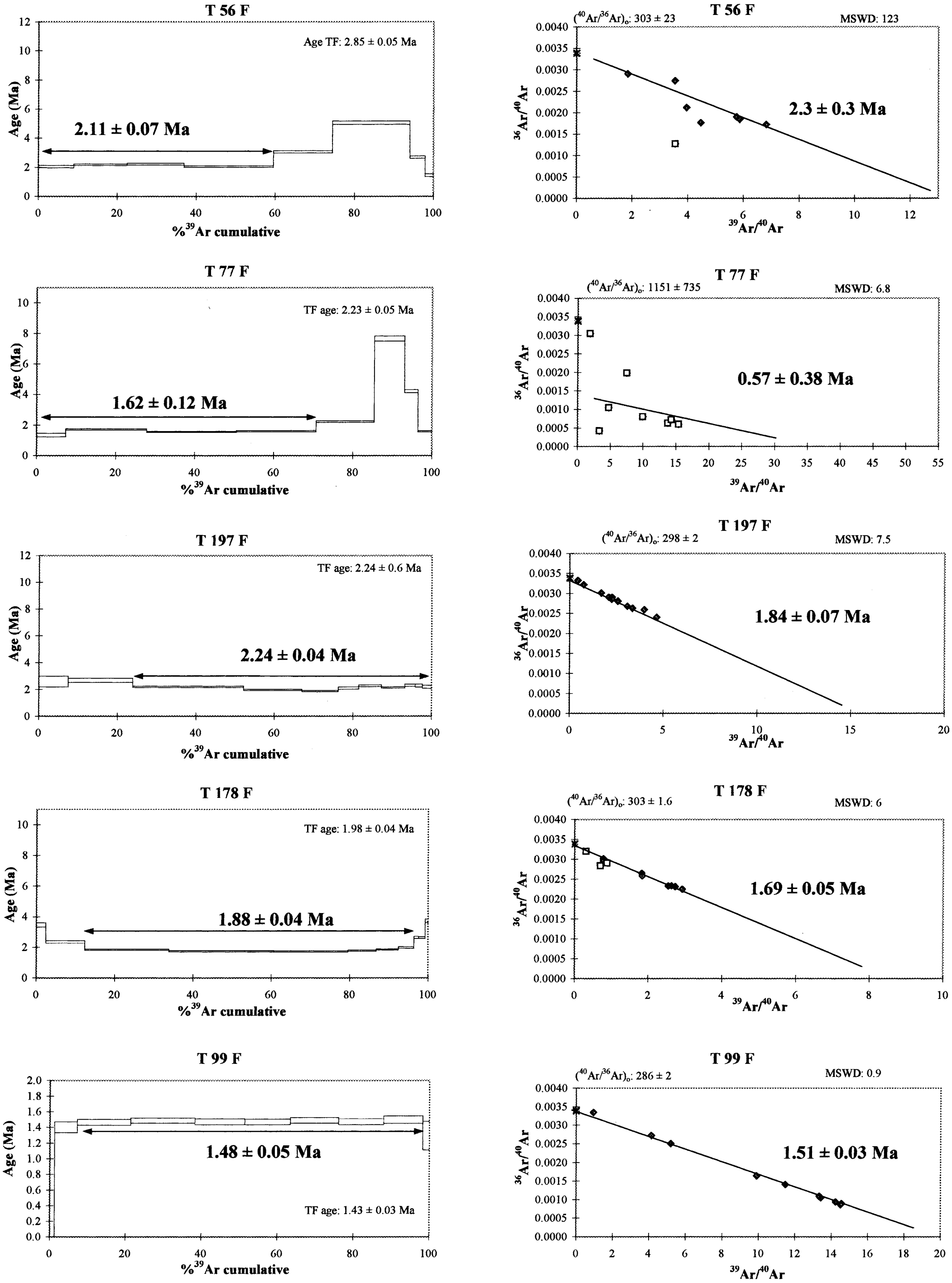

Fig. 4. ^{40}Ar/^{39}Ar age spectra and isochron. The plateau age is shown below steps used in the calculation along with total fusion age (TF age). The isochron age is shown along with ^{40}Ar/^{36}Ar intercept and MSWD of fit. The white squares are the points rejected from the fit. The star on the ^{36}Ar/^{40}Ar axis corresponds to the atmospheric composition. All errors are shown at 1σ and include the error on the *J* factor. Sample numbers are those used in the text.

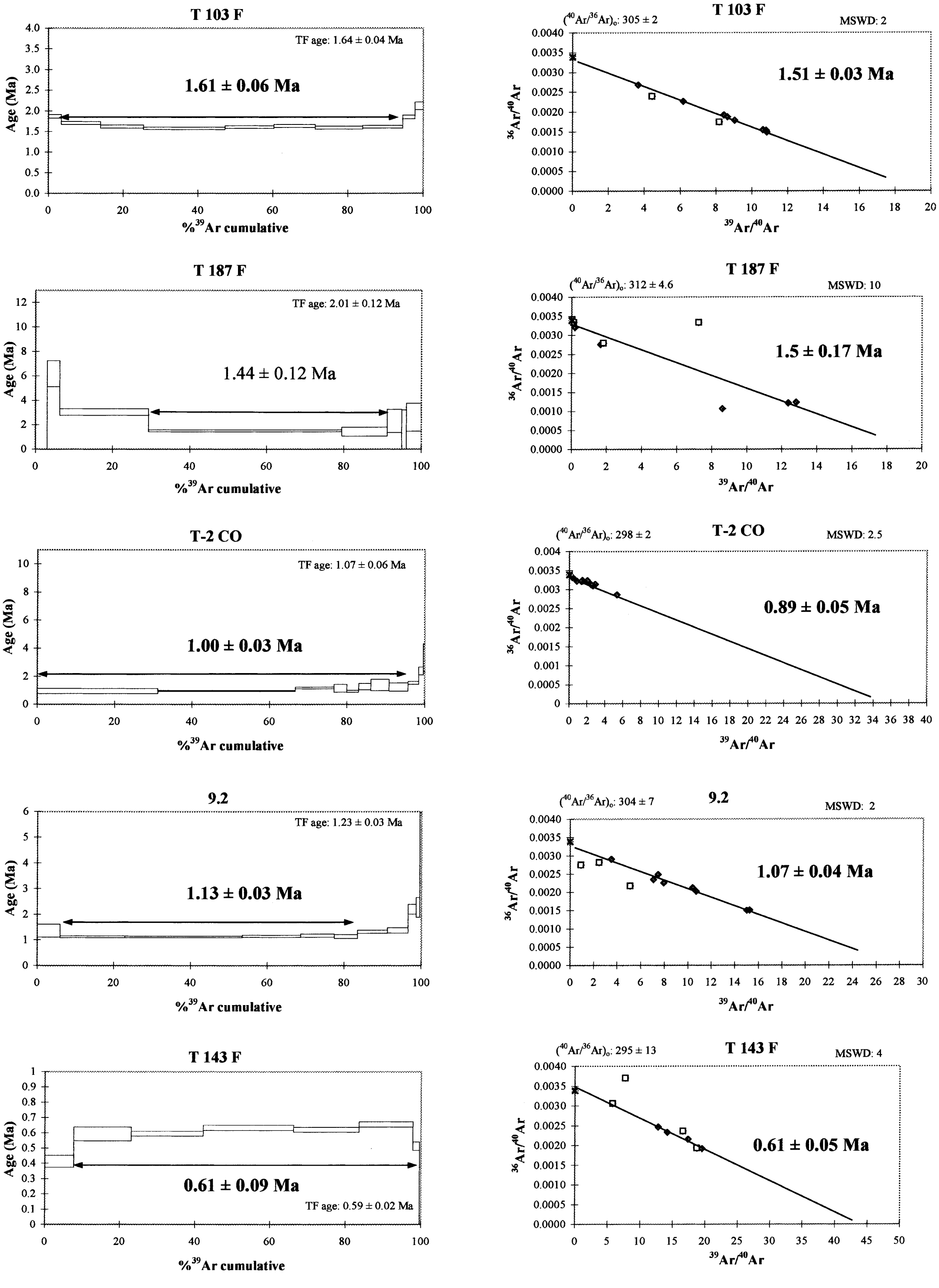

Fig. 4. (*Continued*).

In the Adeje area, toward the north, they locally overlie 1.80–1.90 Ma basaltic and trachybasaltic lava flows from the Erques unit (Fúster et al., 1994; Ancochea et al., 1999). A simplified succession from the oldest to the youngest is described below (Fig. 3).

Las Gaviotas ignimbrite: the lowest unit observed in this section at the Punta de Las Gaviotas (PG, Fig. 1) is a pink ignimbrite rich in lithic fragments (basaltic, phonolitic or syenitic in composition, up to 20 cm in size) with no visible grading. The juvenile clasts are black trachyphonolitic glassy scorias with abundant anorthoclase phenocrysts, which give an isochron age of 1.84 ± 0.07 Ma (T197F, Fig. 4, Table 1). The slight saddle-shape age spectra suggests that the plateau age is somewhat affected by excess argon (Zeitler, 1987), or that two populations of grains of different age have been analysed (Feraud et al., 1990).

Overlying an erosion surface on the Las Gaviotas ignimbrite is a complex sequence of lithic-rich layers containing syenitic and rather few pumice fragments. This sequence is tentatively interpreted as laharic deposits with some intercalations of reworked pyroclastic beds.

El Pris ignimbrites: above a disconformity marked by sedimentary deposits is a 20–30-m-thick and complex succession of (four or five) white to cream-coloured pumice-bearing ignimbrites (Fig. 3) containing plant moulds and some intercalations of stratified pyroclastic beds of fall and surge origin. The K-feldspars from a pumice fragment taken in an ignimbrite of the upper level give a good isochron age (T178F, Fig. 4) of 1.69 ± 0.05 Ma while the saddle-shape age spectra implies either the presence of excess argon (Fig. 2, Table 1) or mixed grains.

Adeje ignimbrites (Fúster et al., 1994): this sequence is characterised by two or three poorly welded deposits generally forming a single cooling unit with a variable brown to cream ('siena tostada') colour. Accidental lithics are abundant and this unit is characterised by 1 to 2-m-thick concentration zones of pebble- to cobble-sized (up to 50 cm in diameter) black obsidian clasts in basal or middle positions. These juvenile obsidian blocks were probably still plastic during deposition because they appear to have been deformed while in contact with one another. No directly linked fall deposit has been observed. Former K–Ar determinations on different K-feldspar samples from different exposures of the ignimbrite (Fúster et al., 1994) produced a variety of ages from 1.32 to 1.64 Ma. This spectrum of ages may be due to either the variable presence of xenocrysts, or occurrence of small glass inclusions within, or glass adhering to, the crystals. New careful hand-picking of crystal separates aimed at avoiding glass or glass-surrounded feldspars produced a ^{40}Ar/^{39}Ar plateau age (T99F Fig. 4, Table 1) of 1.48 ± 0.05 (95% argon released, with no evidence of argon loss or argon in excess) and a concordant isochron age of 1.51 ± 0.03 Ma.

Taucho-Playa de San Juan ignimbrites: situated above the Adeje ignimbrite and a localised erosion surface is the Taucho ignimbrite which represents the youngest pyroclastic unit at this sector (Fig. 3). The ignimbrite is grey to brown in colour and near Playa de San Juan (PSJ, Fig. 1) it is 4–5 m thick and locally exhibits a columnar jointing. The juvenile phonolithic clasts are porphyritic scoria with anorthoclase and biotite phenocrysts. Immediately below (Fig. 3) is a thin, 50-cm-thick, green densely welded ignimbrite unit: the Playa de San Juan ignimbrite (Fúster et al., 1968; Coello-Bravo and Izquierdo, 1992) with a well-developed eutaxitic texture. In some places a thin, 1-cm-thick, layer of a similar green welded facies is interbedded within the brown Taucho ignimbrite. This is either a demonstration that these two units were erupted at the same time, or an artefact associated with a very peculiar hydrothermal alteration of the Taucho unit. No material suitable for dating was found in the Playa de San Juan ignimbrite which is extensively hydrothermally altered. Fúster et al. (1994) gave rather imprecise K–Ar ages (1.40 ± 0.12 and 1.68 ± 0.10 Ma) for the Taucho ignimbrite. Our K-feldspar sample from a juvenile clast yielded an ^{40}Ar/^{39}Ar isochron age (T103F, Fig. 4) of 1.50 ± 0.03 Ma, while the age spectrum suggests a small amount of excess argon. This result is identical, within analytical error, to the age of the underlying Adeje ignimbrite and is in good agreement with K–Ar ages of approximately 1.50 Ma measured in this region on immediately overlying basaltic and trachyphonolitic lava flows (Fúster, et al., 1994).

In the southeast of the Adeje sector, a different succession may be described (Fig. 3) near Ermita de San Sebastian (ES, Fig. 1). Overlying epiclastic deposits, but separated by an erosion surface, are well-stratified, white, phreatomagmatic deposits. They include several ash beds rich in accretionary lapilli. This phreatomagmatic sequence (PH1, Fig. 3) was formerly interpreted as coming from the neighbouring Caldera del Rey (CR) maar structure (Fig. 1) (Fúster et al., 1994). This attribution may now be questioned and will be discussed later.

Above the phreatomagmatic deposits, several thick, yellow, ash and pumice ignimbrites crop out, and are informally named the San Sebastián ignimbrite (Fig. 3). They exhibit extreme vapour-phase alteration and have large pumice concentration zones. Intercalated in the upper part of the series are minor surges and fallout layers and finally, two or three, grey to brown ash and felsic scoria flow deposits. According to their stratigraphic position, these deposits might be similar in age to the El Pris ignimbrites.

In this sector the most recently deposited ignimbrites are the Adeje ignimbrites. At Casa del Duque (CD, Fig. 1), a new road-cutting exposes a 50-cm-thick ash bed and phreatomagmatic surge deposits on top of this ignimbrite (PH2, Fig. 3), both overlying a palaeosoil. These phreatomagmatic deposits, could be correlated to volcanic material erupted from the CR craters.

3.2.2. Las Américas area

In this area the pyroclastic deposits on the coastal plain are separated from more inland Cañadas formations by the topographic barrier of the Roque del Conde massif, an isolated outcrop of the Old Basaltic Series (Fúster et al., 1968). Near Las Américas occur two felsic eruptive centres: the CR (Fig. 1) phreatomagmatic structure (Paradas and Fernández-Santín, 1984) and the dome/flow complex of Montaña de Guaza (GZ, Fig. 1), which complicate the stratigraphy.

Caldera del Rey: CR is a well preserved edifice with a double crater which erupted phreatomagmatic surge and fall deposits with abundant accretionary lapilli beds, plinian ash fall layers and a few minor, lithic-rich ignimbrites. Feldspar concentrates taken from one of the associated ignimbrites produced a rather imprecise K/Ar age of 1.54 ± 0.28 Ma (Fúster et al., 1994). A new ^{40}Ar/^{39}Ar analysis (sample 9.2, Table 1) on carefully selected anorthoclase from the same sample gave a plateau age of 1.13 ± 0.03 Ma (with 80% of the ^{39}Ar released) concordant within errors with the isochron age (sample 9.2 Fig. 4). The CR deposits are locally overlain (Fig. 3) by a basaltic lava flow dated at 1.05 ± 0.10 (K–Ar age, Fúster et al., 1994). This is in turn overlain by sediments and a palaeosoil, above which the 0.88 Ma Las Américas ignimbrite (Fig. 3), described below, is exposed. In this context the age of the CR deposits appears to be rather well established, but is in conflict with previous estimations. Martí et al. (1995), Bryan et al. (1998) and Bryan (1995) proposed much younger ages: younger than 0.57 Ma or even younger than 0.3 Ma for these deposits. These studies correlate pyroclastic deposits mantling recent strombolian cones near Aldea Blanca above the Granadilla ignimbrite (0.57 Ma, Bryan et al., 1998) with the CR eruption. However this interpretation has several problems. First, it is difficult to imagine that pyroclastic surges would travel 10 km away from the eruption craters and over a significant relief (the Old Basaltic series). Second if indeed the CR deposit is younger than 0.57 Ma one could expect this deposit to be found above the Las Americas ignimbrites (0.88 Ma) or the Guaza dome (0.67 Ma, K/Ar age, Ancochea et al., 1990) 1–3 km away from the CR craters. In fact they are well-exposed below the Las Américas ignimbrites along the southern highway. On the other hand, if the 1.13 Ma age is retained for the CR, the freshness of the volcanic morphology is remarkable and perhaps linked to the extremely dry climate during that period.

This result is compatible with the age of the phreatomagmatic deposits observed above the Adeje ignimbrite at CD (PH2, Fig. 3). In contrast, the PH1 deposits at the Ermita de San Sebastián cannot in any sense be interpreted as coming from the CR eruption.

This succession underlines the difficulty of making correlations at face value. It is even plausible that, taking the present position of the coast as having remained more or less constant, some of the accretionary lapilli rich beds closest to the shore (for example PH1 deposits) could result from pyroclastic flows entering the sea as suggested by Martí et al. (1995) rather than phreatomagmatic eruptions from maar craters.

Las Américas ignimbrite: this unit includes at least four 3–4-m-thick ignimbrite beds with small basaltic, syenitic and gabbroic lithics, palm-tree moulds and large (up to 20 cm in size) inversely graded porphyritic pumices (Fig. 3) in the upper levels. One of these ignimbrites gave a K–Ar age of 0.88 ± 0.06 Ma (Fúster et al., 1994) on K-feldspar. These units are only known locally and outcrop over a restricted area. They may have been derived from eruptions in the upper regions of the CE having been channeled down barrancos. Their summit equivalents have not yet been identified. At intermediate altitudes in the barrancos cut into the Old Basaltic Series, other ignimbrites are recorded but their stratigraphic position is unknown and their distal equivalents have not been clearly identified in the coastal region.

To the east of the Playa de Las Américas area, several recent pyroclastic units overlie the CR deposits and Montaña Guaza dome (Fúster et al., 1994; Fernández Santín and Nafria, 1979). The most important is the informally named Tosca ignimbrite. This has been strongly indurated by vapour-phase alteration and all the pumice fragments have been altered and weathered out from exposures. The Tosca ignimbrite is overlain by a palaeosoil and several other pyroclastic flow deposits. The upper most of these (1–2 m thick) is the distinctive El Abrigo ignimbrite (0.17 Ma, see Alonso, 1989; Bryan et al., 1998; Martí et al., 1994; Ancochea et al., 1990, 1999) containing brecciated syenitic lithics. Therefore, the recent Bandas del Sur pyroclastites are also represented in the Las Américas sector.

3.3. Southeastern sector: Bandas del Sur

On the SE flank of the Cañadas edifice between the coast and a mean altitude of about 1200 m, large areas are covered by a complex succession of phonolitic pyroclastic units. They have been extensively studied and described by Booth (1973), Wolff (1985) and Alonso (1989). More recently, Bryan et al. (1998) identified three pyroclastic cycles in Tenerife: cycles 2 and 3, the most recent, exposed in the Bandas del Sur and cycle 1, the oldest, exposed along the northern and western part of the island. Several tens of pyroclastic units have been identified but their lateral extent is limited. This precludes documentation of a single stratigraphic column for the entire Bandas del Sur. The southeast stratigraphic column of Fig. 3 is a highly simplified representation of the volcanic succession (see Bryan et al., 1998, for detail) where we have only retained the units presently dated between 0.76 Ma for the lowest Saltadero ignimbrite and 0.17 Ma (or 0.13 Ma, Ancochea et al., 1990) for the upper most El Abrigo ignimbrite (Bryan et al., 1998).

The K/Ar age of the Arico ignimbrite (0.65 ± 0.03 Ma, Ancochea et al., 1990), one of the good markers in the stratigraphy because it is the only welded unit, has been redated using K-feldspars at 0.61 ± 0.09 Ma (^{40}Ar/^{39}Ar plateau age (T143F, Fig. 4) concordant with the isochron age of 0.61 ± 0.05 Ma). In the Barranco de la Bentrana (BB, Fig. 1), one of the deepest and most comprehensive cross-sections through the volcanic pile (Alonso, 1989) below the Arico ignimbrite, are several pyroclastic units interbedded with debris flow deposits and palaeosoils. Near the base of this section, one ignimbrite (level 2, Alonso, 1989), here informally named La Bentrana ignimbrite, has been dated using K-feldspars from a pumice concentration zone. However, the saddle-shape age spectra (T187F, Fig. 4) suggests that the age is imprecise, due to the likely presence of excess argon. The minimum of the spectrum gives a probable maximum age of 1.44 ± 0.12 Ma. This is close to a very imprecisely defined isochron age obtained from very scattered points at 1.50 ± 0.17 Ma. Nevertheless, such an old age was not expected in this region and indicates that pyroclastic material with an age similar to the most recent units in the Adeje sector are also present in the Bandas del Sur.

4. Comparison of flank pyroclastic units with units from the Cañadas CW sector

In the upper part of the CE is a semi-elliptic depression that measures up to 16 km in its longest axis, the 'Caldera de Las Cañadas' (LCC, Fig. 1). This depression is partially surrounded by a wall, Las Cañadas CW, more than 25 km in length but absent from the northern and northwestern sides of the caldera. There is no lateral continuity between the pyroclastic units described on the lower slopes (below 1000–1200 m in elevation) and those occurring in the summit region and the CW (above 2000 m). Erosion or non-deposition of the ignimbrite during eruption may explain the lack of outcrops at intermediate levels. Whatever the reason this renders correlations difficult. Facies variations in single units over long distances also complicate correlations between the summit and coastal areas.

Bryan et al. (1998) correlated their three pyroclastic cycles with the Ucanca formation (cycle 1, 1.56–1.07 Ma), Guajara formation (cycle 2, 0.85–0.65 Ma) and Diego Hernández formation (cycle 3, 0.37–0.17 Ma) as defined in the stratigraphy of the 'upper group' of Martí et al. (1994). A different and more comprehensive general stratigraphy of the Cañadas edifice was proposed by Ancochea et al. (1995, 1999) and Cantagrel et al. (1999) and is presented here including all age results (Fig. 5). In Fig. 5 are included destructive episodes (Cantagrel et al., 1999) and the newly dated ignimbritic units, and thus this figure sums up the most recent and comprehensive description of the chronostratigraphy of the CE.

The old San Juan de la Rambla 1 ignimbrite from the Tigaiga massif, has not been identified so far in the CW. Similar in age to the El Cedro phonolitic unit (2.3–2 Ma, Figs. 1 and 5), it was emplaced during the formation of the CE-II edifice.

In the section of the CW which is the closest to the Adeje pyroclastic deposits, the volcanic units exposed are older than 2 Ma and therefore no Adeje equivalent deposits can be identified. However, the Upper Ucanca unit (Martí et al., 1994; Ancochea et al., 1995, 1999) comprises 1.4–1.5 Ma phonolitic lava flows and pyroclastic rocks similar in age to the uppermost pyroclastic deposits and overlying lava of the Adeje sector. Products equivalent to the oldest units of the Adeje ignimbrites (1.6–1.9 Ma) could be looked for in the lower Ucanca unit of the CW (Fig. 1), which is strongly altered (Los Azulejos) and involved in a debris avalanche event (Ancochea et al., 1999; Cantagrel et al., 1999). Fragments of ignimbritic rocks are indeed found in the resulting debris avalanche deposit (Roques de Garcia unit), but no age information is available on these fragments.

In the central part of the CW is the Guajara unit (GU, Fig. 1) with numerous pyroclastic beds with ages which remain controversial. Martí et al. (1994), Bryan et al. (1998) and Alonso (1989) recognise possible equivalents of both the Arico ignimbrite and the Granadilla Member (thus associating Guajara with cycle 2 of Martí et al. (1994)) on the base of similar phenocryst mineralogy, isopach constraints on vent locations, and "an overlap in available age data". Ancochea et al. (1995, 1999) provided new K/Ar age data indicating that some parts of the GU may also be of older age, around 0.9 ± 0.2 Ma. This age is confirmed by a new and more precise ^{40}Ar/^{39}Ar plateau age (T2CO, Fig. 4, see Ancochea et al. (1995) for the precise location of this sample) of 1.00 ± 0.03 Ma which is almost identical to the isochron age. In this case, those older parts could correspond to the Las Américas pyroclastic phase.

The uppermost levels of the central CW mainly comprise thick, near-vent, welded and non-welded phonolitic fall deposits and rheomorphic lava-like welded falls and ignimbrites. Some of them are undoubtedly associated with pyroclastic deposits of south Tenerife, but more age determinations and facies studies are needed before a comprehensive correlation may be completed.

Further to the east, the Las Pilas unit (LP, Fig. 1, 1.0–0.7 Ma, Ancochea et al., 1995, 1999) has been repeatedly and consistently dated. Felsic pyroclastic deposits are interbedded with basaltic flows from the Dorsal ridge: a SW–NE volcanic ridge linking CE and Anaga massif (Fig. 1). In the upper part of LP, ages (0.8–0.7 Ma) are similar to the oldest formations of the cycle 2 (Bryan et al., 1998). They could thus be correlated with the old-

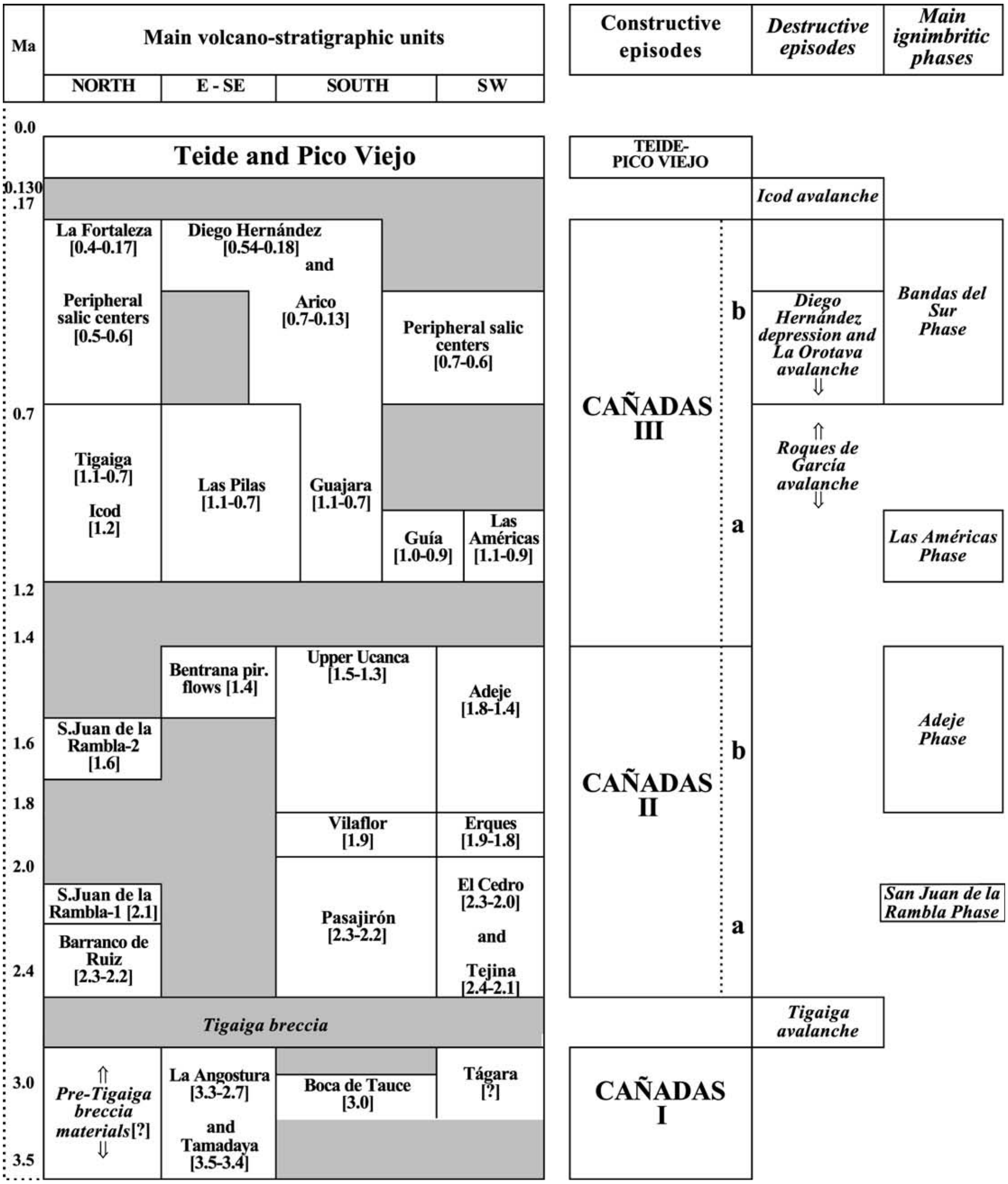

Fig. 5. General time scale for the main volcano-stratigraphic units of the Cañadas edifice (modified from Ancochea et al., 1999). Ages of each unit are shown in brackets. Shaded zones represent a lack of exposure or sampling or measurement, and not necessarily a gap in the volcanic activity at the scale of the entire island. Due to lack of exposures and ongoing work some of the correlations proposed are probably provisional.

est products exposed in the Bandas del Sur, for example in the BB.

In the eastern part of CW the Diego Hernández (Martí et al., 1989, 1994) formation crops out. Here basaltic lava flows and phonolitic pyroclastic deposits are interbedded in four distinct sequences. Numerous age determinations have been published and discussed by Martí et al. (1989, 1994), Mitjavila (1990), Ancochea et al. (1990, 1999) and Mitjavila and Villa (1993), but the actual age of the base of the Diego Hernández unit and the beginning of cycle 3 are still under discussion: 0.37 Ma (Martí et al., 1989; Bryan et al., 1998) or >0.54 Ma (Ancochea et al., 1995). However, it is clear that these formations correlate with the upper levels of the Bandas del Sur on the external slopes.

5. Discussion and conclusions

5.1. A complex history in Tenerife prior to 1.0 Ma

Detailed stratigraphy on Tenerife has recently been focussed on the most recent period of activity (upper group: Martí et al., 1994; CE-III: Ancochea et al., 1999 and Fig. 2). However, Ibarrola et al. (1993), Fúster et al. (1994) and Ancochea et al. (1995) suggested that the early activity was in fact very complex and could be accounted for by several eruptive cycles corresponding to different stages of CE construction. The present work emphasises the importance of the pre-1.0 Ma volcanic activity in Tenerife and demonstrates the existence of explosive activity during most of the upper part of that period (2.0–1.0 Ma), which could in part be associated with vertical collapse calderas.

5.2. Repeated pyroclastic eruption phases in the formation of the CE

The present geochronological dataset allows characterisation and definition of four main pyroclastic phases in the Cañadas edifice during the last 2 Ma (Fig. 5).

The San Juan de la Rambla phase (~ 2 Ma) is represented by outcrops which are presently restricted to the north of Tenerife. This phase reflects the first period of construction of the CE-II edifice (Ancochea et al., 1999).

The second Adeje phase (1.5–1.8 Ma) produced successive distinct pyroclastic events. A precise volume estimation of the products of each individual eruption is presently impossible. Widespread in the southwest, the pyroclastic deposits of this phase have also been recognised in the Tigaiga massif in the north, and in the deepest levels of the BB in the SE (Bandas del Sur). It occurred during the second part of construction of the CE-II edifice.

The third, Las Américas phase (1.1–0.9 Ma) is presently recognised in the extreme south and in the Tigaiga massif in the north. However, some pyroclastic units stratigraphically located between the La Bentrana and Arico ignimbrites may also belong to this phase (Fig. 3).

The fourth Bandas del Sur phase (0.7–0.15 Ma) is by far the best exposed but also appears the most important in volume. Deposits of this phase are widespread on the southeastern slopes and in the north at the top of the Tigaiga massif but have not been identified in the southwest.

In general, the pyroclastic deposits from south Tenerife are progressively younger from the southwest to the southeast in agreement with the same variation in the ages recorded in the summit region and the Las Cañadas wall (Martí et al., 1994; Ancochea et al., 1995, 1999). This implicates an eastward migration of the successive eruptive centres through time. In parallel, the pyroclastic volcanic activity of the CE becomes more and more important: presently unrecognised during the CE-I phase, it is dominant during the final CE-III phase.

5.3. Pyroclastic deposits, caldera-forming events and the formation of the Cañadas depression

The existence of numerous potentially large volume pyroclastic units, each erupted in a short time, suggests that several vertical collapse calderas may have formed during the construction of the CE. The present Cañadas depression may thus have resulted from vertical collapse(s) of the roof of shallow level magmatic chamber(s) (Booth, 1973; Martí and Araña, 1991; Martí et al., 1994; Bryan et al., 1998) the bordering faults of which would be more or less represented today by the CW. Martí et al. (1994) considered that the Cañadas depression was formed by three overlapping vertical collapse calderas. Bryan et al. (1998) estimated that most of the Bandas del Sur pyroclastic units erupted volumes in the order of 1–10 km^3 and that there were at least two large eruptions (Granadilla and El Abrigo) for which the minimum volumes were “sufficiently large to trigger caldera collapse of dimensions 7–10 km in diameter”. However, the volume of these pyroclastic deposits is not well-determined and published calculations (Booth, 1973; Alonso, 1989; Bryan et al., 1998) are in disagreement. For example, estimations of the DRE volume of the El Abrigo ignimbrite ranges from 0.4 km^3 (Alonso, 1989) to 5–10 km^3 (Bryan et al., 1998).

Navarro and Coello (1989); Ancochea et al. (1990, 1998a, 1998b, 1999), Carracedo (1994), Watts and Masson (1995) and Cantagrel et al. (1999) have proposed that the present Cañadas depression was formed by one or several, large, north-directed lateral collapses and debris avalanches, not necessarily related to pyroclastic eruptions. Although the triggering of flank collapse by large pyroclastic eruptions has been envisaged by Martí et al. (1997) for the formation of the Icod, Orotava and Güimar valleys, the reverse scenario seems more probable if one takes into account historical examples (e.g. Mount St. Helens 1980 eruption). Recent studies (Ancochea et al., 1999; Schmincke et al., 1999) indeed suggest the existence of a large blast deposit possibly associated with the formation of the Icod valley. This deposit now covers most of the eastern summit region of the CE and makes up the top of the Diego Hernandez part of CW. However, the correlation of this blast deposit with the El Abrigo ignimbrite is not uniquely accepted by all workers. However, neither lateral collapse(s) and large debris avalanches nor the actual shape of the Cañadas depression are inconsistent with the existence of vertical collapse caldera(s). Both these kind of structures might have existed at different stages of CE evolution. Within the pyroclastic series the determination of caldera-forming events remains speculative. One can imagine at least a first multi-episodic vertical collapse associated with varied pyroclastic eruptions during the old Adeje phase (1.8–1.5 Ma) and another one associated with varied pyroclastic eruptions during the Bandas del Sur phase (0.7–0.15 Ma).

The reconstruction of successive Cañadas edifices (Ancochea et al., 1999) suggests possible locations in the summit regions, progressively shifting toward the east. The precise ages, sizes, geometries and locations of these calderas are not well-determined yet. However, if such structures existed, they have done so for the last 1.5–1.8 Ma, a period much greater than has previously been considered.

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