Evolution of ocean-island rifts:
The northeast rift zone of Tenerife, Canary Islands

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ABSTRACT

The northeast rift zone of Tenerife presents a superb opportunity to study the entire cycle of activity of an oceanic rift zone. Field geology, isotopic dating, and magnetic stratigraphy provide a reliable temporal and spatial framework for the evolution of the NE rift zone, which includes a period of very fast growth toward instability (between ca. 1.1 and 0.83 Ma) followed by three successive large landslides: the Micheque and Güímar collapses, which occurred approximately contemporaneously at ca. 830 ka and on either side of the rift, and the La Orotava landslide (between 690 ± 10 and 566 ± 13 ka). Our observations suggest that Canarian rift zones show similar patterns of development, which often includes overgrowth, instability, and lateral collapses. Collapses of the rift flanks disrupt established fissural feeding systems, favoring magma ascent and shallow emplacement, which in turn leads to magma differentiation and intermediate to felsic nested eruptions. Rifts and their collapses may therefore act as an important factor in providing architectural and petrological variability to oceanic volcanoes. Conversely, the presence of substantial felsic volcanism in rift settings may indicate the presence of earlier landslide scars, even if concealed by postcollapse volcanism. Comparative analysis of the main rifts in the Canary Islands outlines this general evolutionary pattern: (1) growth of an increasingly high and steep ridge by concentrated basaltic fissure eruptions; (2) flank collapse and catastrophic disruption of the established feeder system of the rift; (3) postcollapse centralized nested volcanism, commonly evolving from initially ultramafic-mafic to terminal felsic compositions (trachytes, phonolites); and (4) progressive decline of nested eruptive activity.

INTRODUCTION

Rifts (known in the Canaries as "dorsales") in ocean-island settings probably represent the surface expression of initial plume-related fracturing (Wyss, 1980; Carracedo, 1994), and/or extensional fissures due to volcano instability that develop once a volcano has grown to a certain height (Walter and Troll, 2003; Walter et al., 2005). They constitute the most relevant and persistent structures in the development of oceanic volcanic islands because they: (1) control the construction of the insular edifices, possibly from the initial stages; (2) form the main relief features (shape and topography); (3) concentrate eruptive activity; (4) are crucial structures in the distribution of volcanic hazards; and (5) condition the distribution of natural resources, such as groundwater (Navarro and Farrujia, 1989).

Although rifts were initially recognized in the Hawaiian Islands (Fiske and Jackson, 1972; Walker, 1986, 1987, 1992; Dieterich, 1988; Swanson et al., 1976), a good part of the progress made in understanding their genesis and structure has been achieved through their study in the Canary Islands (Carracedo, 1975, 1979, 1994, 1996, 1999; Carracedo et al., 1992, 1998, 2001, 2007; Guillou et al., 1996; Walter and Schmincke, 2002; Walter and Troll, 2003; Walter et al., 2005; Hansen, 2009). Compared with those of the Hawaiian Islands, rifts in the Canaries are considerably longer lasting, exert greater overall control on the construction of the islands, and present more conspicuous elements of relief. The lower magmatic activity of the mantle plume or hotspot that has generated the Canaries produces much lower eruptive rates (Geldmacher et al., 2001). This favors higher-aspect-ratio rift zones by accumulation of relatively short flows, producing some very prominent ridges in the relief of these islands. On the other hand, because of the very low drift velocity of the African plate and the apparent lack of significant subsidence of the Canaries, the record of subaerial volcanic history of these islands (at least 24 m.y.) is much longer than that of the Hawaiian Islands (~6 m.y.), where subsidence rates are much higher and the velocity of movement of the Pacific plate is an order of magnitude greater (Carracedo et al.,

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1998). This circumstance creates longer-lasting rifts in the Canaries, along with frequently recurring activity.

The absence of surface water (lakes, rivers) and the great demand for water by the large population of the Canary Islands (almost 2 million inhabitants and 12 million annual visitors) have led to the drilling of numerous water tunnels (2 × 2 m and several kilometers long) for groundwater mining, particularly in the islands of Tenerife, La Palma, and El Hierro (with a combined length of >3000 km). These water tunnels, locally known as *galerías*, allow access to the deep structure of the rift and greatly facilitated our observations and sampling (see also Coello, 1973; Carracedo, 1975, 1994; Carracedo et al., 2007; Guillou et al., 1996, 1998).

GEOLOGICAL FRAMEWORK AND PREVIOUS WORK

Both the characteristic rifts of the early stages of shield development and the later posterosional rejuvenation stages are very well represented in the Canaries. The rifts of El Hierro or the Cumbre Vieja rift, on La Palma, belong to the former group, and the northwest (NW) and northeast (NE) rifts of Tenerife belong to the posterosional stage. The NW rift of Tenerife exemplifies a rift zone that was very active during the Holocene (Carracedo et al., 2007). Consequently, it serves as an example to study the spatial and temporal distribution of volcanism and the associated geochemical and petrological variations (Ablay and Martí, 2000; Carracedo et al., 2006; Carracedo et al., 2007). The NE rift, in contrast, has been inactive for hundreds of thousands of years along most of its length. Historical eruptions (1704–1705 CE) produced small volumes of lava (<3.5 × 10^6 m; Carracedo et al., 2006). The resulting erosion, combined with two massive giant landslide scarps that show only scant subsequent fill-in, allows an in-depth study of the rift's internal structure, including the complex network of dikes exposed.

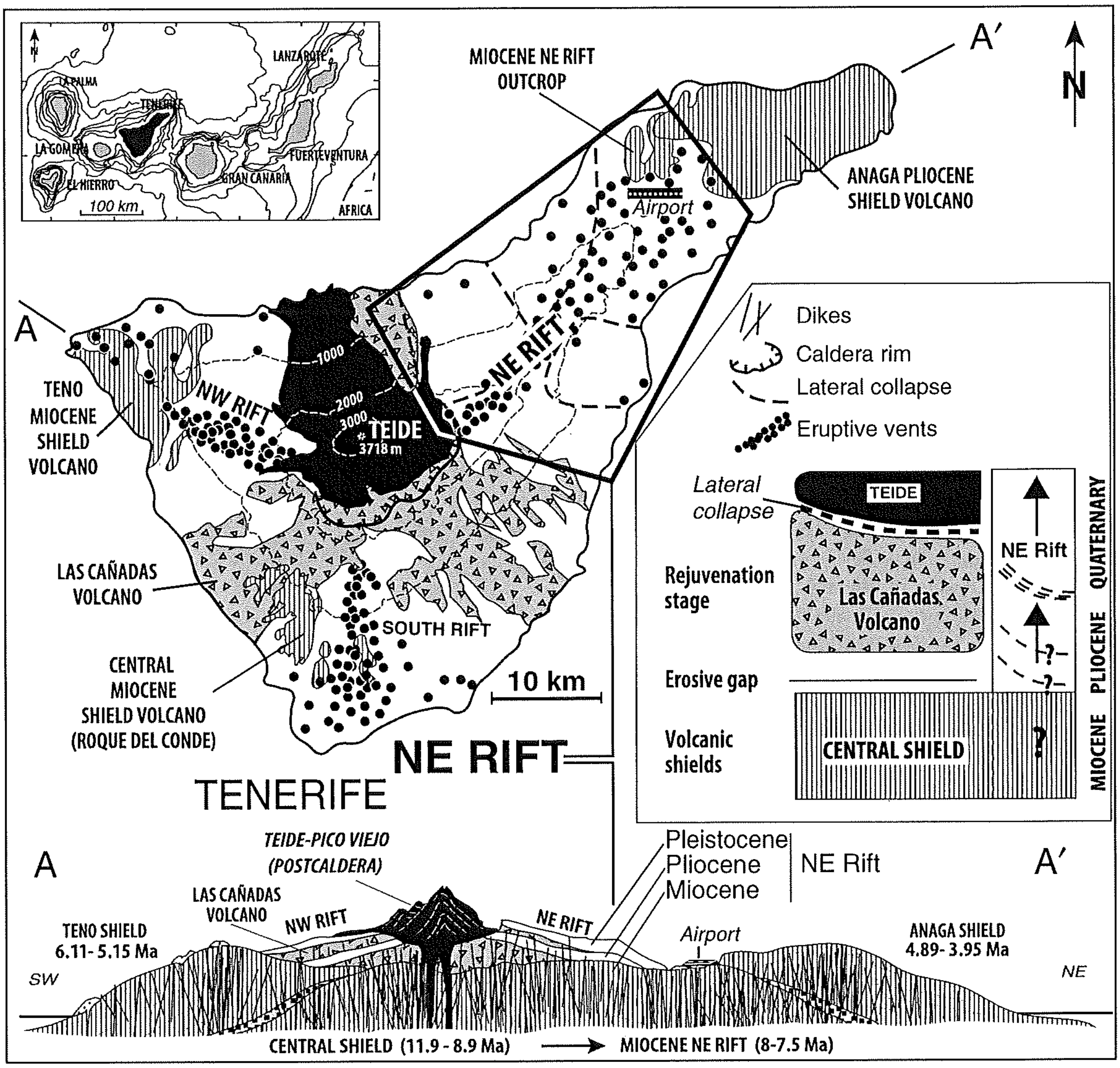

Figure 1. Simplified geological map of Tenerife indicating the location of the NE rift (box). Map and geological cross section show the Miocene shield, forming the central part of the island that according to our observations extended toward the northeast, now overlain by the later Anaga shield (modified from Guillou et al., 2004a and Carracedo et al., 2007).

The 30-km-long NE rift zone connects the central edifice of Las Cañadas, to the SW, with the Anaga massif, to the NE (Figs. 1 and 2). The overall height of the NE rift zone decreases from the volcanic edifice of Las Cañadas, upon which it rests, to the northeast (Izaña, 2386 m above sea level [asl]; Ayosa, 2078 m asl; Joco, 1956 m asl; Gaitero, 1748 m asl).

Although it is one of the most interesting geological features of Tenerife, the challenging complexity of the NE rift zone has prevented intense study so far. Geological knowledge of the rift zone is limited to some general descriptions (Fúster et al., 1968; Ancochea el al., 1990), a basic petrological map (Fúster et al., 1968), and a somewhat more recent version of the Spanish National Geological Map MAGNA (IGME, 1978). Ancochea et al. (1990) were the first authors to consider the NE rift as an independent volcanic feature, naming it the "Cordillera Dorsal."

Many isotopic dates (K/Ar and Ar/Ar) have been published for this rift (Abdel-Monem et al., 1972; Ancochea et al., 1990; Thirlwall et al., 2000; Guillou et al., 2004a; Carracedo et al., 2007), but these dates were carried out within the framework of overview studies of the entire island of Tenerife. In contrast, the present work focuses in detail on the NE rift zone, including many previously undated geological formations.

In contrast to the scant published geological information on the NE rift zone, abundant literature is available on the two conspicuous valleys of La Orotava and Güímar. A number of authors interpreted these depressions as having originated by lateral collapses (Navarro and Coello, 1989; Carracedo, 1994; Watts and Masson, 1995). Navarro and Coello (1989) were the first to describe the systematic presence of a landslide breccia below the volcanic sequences filling both valleys. Abundant detailed geomorphologic analyses of submarine and surface features of huge landslide depressions in the Canaries have been published since (Teide Group, 1997; Martí et al., 1997; Ablay and Hürlimann, 2000; Hürlimann et al., 1999, 2004; Watts and Masson, 1995; Walter and Schmincke, 2002; Carracedo et al., 2007; Manconi et al., 2009).

Several authors have speculated on the presence of a third lateral collapse in the NE rift zone, north of the La Orotava valley. The first mention of this inferred landslide appears in a map of Tenerife outlining the amphitheaters of the major landslides (fig. 12 *in* Schmincke and Sumita, 1998), based, according to these authors, on unpublished data. From analysis of swath bathymetric data from Teide Group (1997), Ablay and Hürlimann (2000) defined a series of lobes and troughs that they assigned to the La Orotava landslide and a younger landslide they named East Dorsal, locating the scar of the latter approximately in the same location as that proposed by Schmincke and Sumita (1998), in the NW flank of the NE rift zone (see fig. 5 *in* Ablay and Hürlimann, 2000). Following this, the East Dorsal landslide scar has been included in several articles, without any additional supporting data, amongst the large volcanic landslides of Tenerife (Hürlimann et al., 2001, their figs. 1, 2, and 3; Hürlimann et al., 2004, their figs. 1–5).

Here, we present a study of the NE rift zone of Tenerife, a volcanic feature that forms the larger part of northeast Tenerife and constitutes one of the best possible examples to provide evidence to clarify the evolution of rift zones on volcanic islands. This work complements the previous study of the NW rift zone of Tenerife and the Teide–Pico Viejo stratocones (Carracedo et al., 2007), and it has been partly previously published in Spanish (Carracedo et al., 2009).

SAMPLING AND ANALYTICAL METHODS

Correlation of the different volcanic formations and the accurate reconstruction of the geological evolution of this rift proved difficult at the beginning of this work, mainly due to the lack of isotopic published ages. Lithological units defined in published maps were not linked to volcanic edifices that formed throughout the development of this complex volcanic structure and, therefore, could not provide evidence of relevant eruptive and structural changes in the rift. For that reason, particular attention has been paid to geochronology in this work, applying paleomagnetic and isotopic dating (geomagnetic inversions and K/Ar dating, respectively). Since the rift evolved rapidly at times, the geomagnetic inversions, once they had been dated and in some cases identified, particularly at the subchron level, allowed the volcanic formations to be correlated with an accuracy that equals and even exceeds in some cases the limits of error of isotopic dating.

The most important volcanic and structural changes in the NE rift zone took place in a relatively short period of time, coinciding with the later part of the Matuyama and early Brunhes chrons. Therefore, the determination of geomagnetic polarities of the volcanic sequences has proven to be a valuable tool, not only for correlation and dating of volcanic sequences,

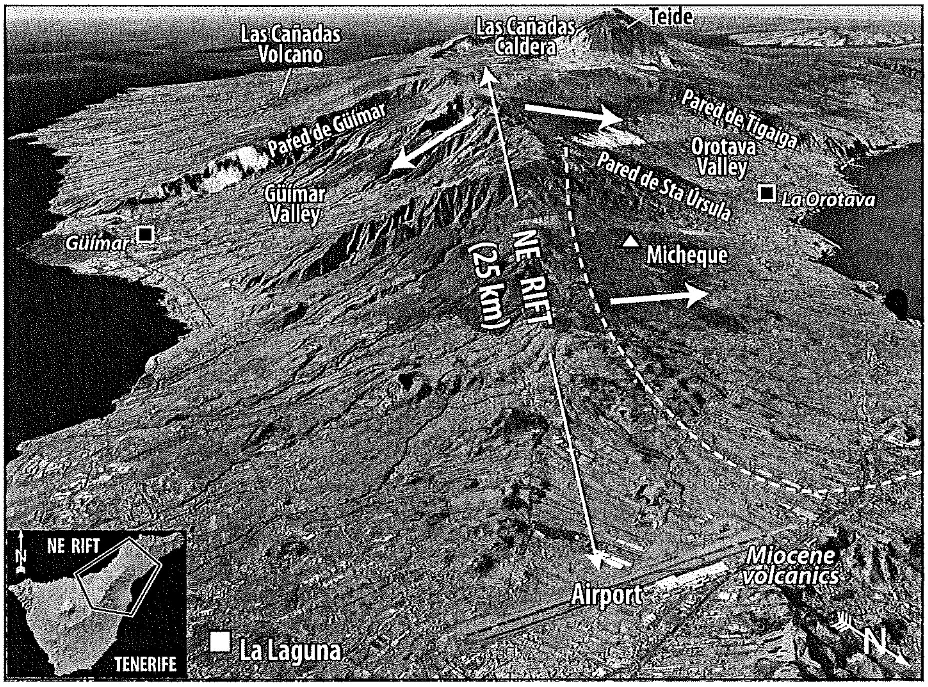

Figure 2. Google Earth image of the NE rift zone of Tenerife (NERZT) viewed from the Anaga massif (oblique view of Tenerife from the NE). The rift extended already in the Miocene from the central edifice of what is now Las Cañadas toward the Miocene-Pliocene Anaga massif. The landslide scars of La Orotava and Güímar are clearly visible, unlike the Micheque one. Micheque is completely filled-in and is thus not readily discernible from topography, except by geological evidence, particularly through the galerías.

but also for establishing constraints in the time of occurrence of the successive lateral collapses.

The limitations of the available geological maps prompted us to compile a completely new geological map of the rift (at the 1:10,000 scale and in geographic information systems [GIS]), taking advantage of detailed and highly accurate topographic maps and images (GRAFCAN, Google Earth, etc.) that did not exist when the previous geological maps were compiled and published. Field work, of a duration of several months, was carried out to analyze the numerous geomagnetic polarity determinations of lavas and dikes, as well as to perform the corresponding sample collecting and geological mapping of the entire NE rift zone (see the geological map in the GSA Data Repository appendix[1]).

Paleomagnetism

Paleomagnetic determinations in this work focus on the identification of the geo-magnetic polarity of flows and dikes. More specific determinations and analyses of the direction, inclination, paleointensity, etc., of the magnetic remanence, particularly in relation to the analysis of short-lived geomagnetic excursions (Jaramillo, Mono Lake) present in the NE rift zone, have been published elsewhere (Guillou et al., 2010). In this study, we use geomagnetic polarities as a correlation tool. The determination of the geomagnetic polarity of volcanic formations, and the comparison of the ages and polarities with the established geomagnetic and astronomical polarity time scale (GPTS and APTS) have been shown to be very powerful in defining the magnetic stratigraphy of volcanoes in the Canary Islands (Carracedo, 1975, 1979; Guillou et al., 1996, 1998, 2004a, 2004b; Carracedo et al., 2001; Paris et al., 2005a). For more details on this method, see Carracedo (1975), Carracedo and Soler (1995), and Guillou et al. (1996).

The determination of geomagnetic polarities in volcanic sequences was carried out in the field using portable fluxgate magnetometers (for details of the method, see Guillou et al., 1996). Samples were also analyzed using standard paleomagnetic laboratory methods (thermal demagnetization and spinner magnetometer measurements) as part of a forthcoming study. Those results have, in all cases, confirmed the polarity results that we determined in the field and report here.

Isotopic Dating

Once the units that have the same geomagnetic polarity were determined, the next step was to date them by isotopic means. Previously published ages were concentrated in specific areas (for example, the Pared de Güímar and Tigaiga scarps), whereas the greater part of the rift remained undated. In order to fill this gap, 14 new ages were obtained by K/Ar, following the method described in Guillou et al. (1996). Groundmass splits from fresh samples were prepared following methods of Guillou et al. (1998). Phenocrysts and xenocrysts, which are potential carriers of extraneous ^{40}Ar (including excess and inherited components), were eliminated using magnetic, gravimetric, and handpicking separation. Replicate unspiked K-Ar age determinations were done on the microcrystalline groundmass because the groundmass is assumed to have formed shortly after eruption and should not contain any significant excess argon.

The unspiked K-Ar technique described by Charbit et al. (1998) is perfectly adapted to accurate and precise dating of young Quaternary lavas (Cassignol and Gillot, 1982; Yurtmen et al., 2002; Guillou et al., 2004a, 2004b). When compared with the ^{40}Ar/^{39}Ar method, conventional K-Ar dating has proven successful in dating very young subaerial volcanic rocks (Ackert et al., 2003; Guillou et al., 2004a, 2004b; Singer et al., 2002, 2004a, 2004b, 2009).

The rapid development of the rift required a great degree of accuracy in dating the volcanic sequences. Once key units were reliably dated by isotopic methods, the presence of short-lived geomagnetic events (some thousands or a few tens of thousands of years) facilitated correlation of these various sequences with the established time scale of geomagnetic reversals (GPTS).

RESULTS

Geomagnetic Stratigraphy and Correlation of Volcanic Sequences

Three main units (A, B, and C in Fig. 3) were identified from the geomagnetic polarities of flows and dikes defined in the NE rift zone. The lowest unit (A) corresponds to reverse polarity lavas that are crossed by dikes of both normal and reverse polarity. The intermediate unit (B) is made up of normal polarity lavas intruded by dikes of both normal and reverse polarity. The uppermost unit (C) is formed by normal polarity lavas cut only by dikes of normal polarity. The fact that dikes with reverse polarity have not been observed in unit C seems to indicate, even before dating the units by isotopic methods, that it corresponds to the Brunhes chron, implying that unit A would belong to the Matuyama chron and unit B would belong to one of the Matuyama subchrons.

Two subunits—A_1 and A_2—are distinguishable in unit A, separated by a marked discordance, which is observed in galerías as a thick (50–100 m) layer of debris avalanche deposits (Fig. 4). The lower unit (A_1), is made up of pyroclasts and weathered basaltic lavas of reverse polarity, crossed by a dense swarm of dikes of predominantly reverse polarity, and it does not crop out on the northwest flank of the rift, even inside the galerías. It does, however, form almost the entire southeast flank of the rift, except in the collapsed areas (see Fig. 3). The upper unit (A_2), composed also of basaltic flows with reverse polarity, generally shows a lesser degree of alteration than those of unit A_1 and has a larger proportion of normal polarity dikes. This unit also crops out in the NE flank of the rift and in its central part, as well as at the top of the lower part of the Pared de Güímar (see Fig. 3). Unit A_2 is also observed in the galerías situated in the north flank of the rift (Fig. 4), although subunit A_1 has not been located in these galerías, and the avalanche breccia passes directly into a formation much older than A_1.

In the El Loro galería (Fig. 4), initially described by Carracedo (1979), unit B was correctly interpreted as a Matuyama event, but the debris avalanche breccia that appears in the final stretch of the galería was mistaken for sedimentary deposits associated with an erosive discordance, relating the volcanism that occurred prior to the breccia to a pre-Gilbert (Miocene) formation. The sequence is repeated in the Los Dornajos galería (above in Fig. 4), situated at a higher altitude, where the samples that gave K/Ar ages crucial for dating the described units were collected.

The breccia crossed by both galerías is a thick (50–100 m) layer very similar to that studied in the galería Salto del Fronton, in the northern flank of the Teide volcanic complex (see fig. 4 *in* Carracedo et al., 2007). This polymict breccia is composed of heterogeneous angular fragments of volcanic rocks in a clay-rich matrix, similar to the "fanglomerado," a plastic formation underlying the sequence of lava flows from Teide volcano, reported by Bravo (1962) as derived from explosive volcanism and subsequent alteration and partial transformation to clay. This "fanglomerado" was later described by Navarro and Coello (1989) as showing characteristic features of a debris avalanche deposit, which these authors

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[1] GSA Data Repository item 2011011, Geological Map of the Northeast rift zone (NERZT) of Tenerife, Canary Islands, is available at http://www.geosociety.org/pubs/ft2010.htm or by request to editing@geosociety.org.

related to a lateral collapse forming the Las Cañadas and Icod–La Guancha depressions. The main difference observed between the NE rift zone breccia in Los Dornajos galería and the breccia underlying Teide volcano is that the former is hard rock, allowing the galería to cross the entire breccia layer to reach the underlying formation. In contrast, in the soft and ductile, hydrothermally altered breccia underlying Teide volcano, the galerías never cross the breccia because tunnel wall collapse makes further excavation simply unfeasible.

K/Ar Ages

The ages obtained are given in Table 1 and Figure 5, where previously reported ages are summarized also. The age of 7.27 ± 0.16 Ma of sample TF-801, a basaltic lava flow in the Valley of Tegueste, suggests a Miocene age for this phase of volcanism. Sample GLD-20, at the end of the Los Dornajos galería (3070 m), is from a fresh rock (loss on ignition [LOI] 1.89) within a weathered unit and gave an age of 2.71 ± 0.06 Ma, implying that the nucleus of the rift may be considerably older than the exposed formations (see Fig. 4).

The latest stage of development of the NE rift zone is reflected by the ages of samples JCD-550 (1008 ± 22 ka) and JCD-576 (929 ± 20 ka) from the base of the northern and southern scarps of the Güímar Valley, respectively. The ages of KAR-42 (860 ± 18 ka) and JCD-501 (806 ± 18 ka) date the top of these scarps (see Fig. 5). The period of formation of the north scarp of the Güímar Valley defined by these ages is in agreement with the uniformity of the

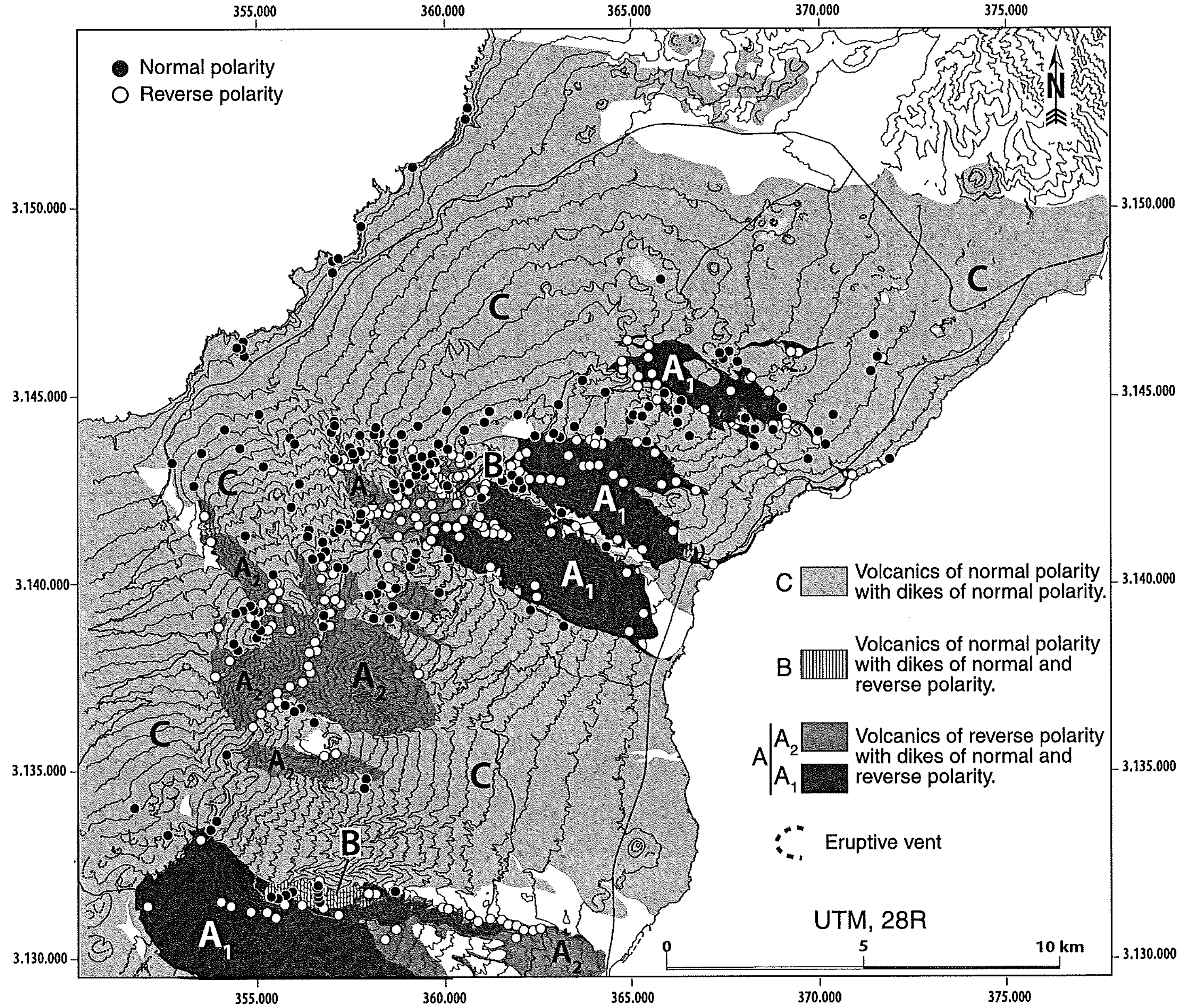

Figure 3. Main magnetostratigraphic units defined as a function of the polarity of 415 oriented cores of lavas and dikes in the NE rift zone. These units have proven to be extremely useful to correlate and reconstruct the successive eruptions that have formed the rift. See text for details. Open symbols indicate reversed polarity, and closed symbols indicate normal polarity. Contour interval is 100 m.

sequence, the lavas of which are consistently of reverse polarity and lack any discordances in this scarp. In this sequence, no lavas of normal polarity corresponding to the Jaramillo event have been detected, but they are present in the south scarp of the Güímar Valley (the Pared de Güímar). These data suggest that the post–Güímar-collapse stage of development of the rift occurred in the post-Jaramillo portion of the Matuyama chron. The age of 1560 ± 110 ka of Abdel Monem et al. (1972) appears to be considerably too old, possibly due to excess argon, as also seen in the similar ages given by these authors for the south scarp of Güímar Valley (see Fig. 5).

The polarity of the 500-m-thick lava sequence of the Pared de Güímar shifts from normal polarity at the lower part of the scarp (samples JCD-550 of 1008 ± 22 ka and KAR-41 of 992 ± 21 ka) to reverse polarity at the top of the sequence (samples JCD-533 of 963 ± 21 ka and KAR-42 of 860 ± 18 ka). Our new ages confirm that the part of the sequence with normal polarity corresponds to the Jaramillo event (988–1072 ka; Horng et al., 2002), and the upper part to the top of the Matuyama chron. In turn, the ages of 830 ± 19 ka (GLD-14) and 808 ± 18 ka (GLD-04), of the Los Dornajos galería, date from base to top a sequence of lavas of reverse polarity that have an intercalated 400–500-m-thick sequence of normal polarity. The normal polarity lavas may, consequently, correspond to the Matuyama-Brunhes precursor subchron (M-B precursor), dated by several authors from 780 ka to 819 ka (Coe et al., 2004; Brown et al., 2004; Singer et al., 2005; Petronille et al., 2005; Dreyfus et al., 2008).

The importance of the presence of these events lies in the fact that they constitute short-lived benchmarks that are highly relevant and accurate in the correlation of volcanic formations and are crucial elements to constrain the age of the successive lateral collapses that occurred in the NE rift. The ages of KAR-40 (831 ± 18 ka) and JCD-520 (818 ± 18 ka) belong to early fill-in lavas of the Güímar collapse valley, while JCD-324 (566 ± 13 ka) corresponds to the first lavas that cascaded over the east scarp of the Valley of La Orotava (Pared de Santa Úrsula) (see Fig. 5).

When these new ages are analyzed within the overall framework of earlier published works and correlated with the geomagnetic polarity time scale (GPTS), we observe that the greater part of the ages agree with the general geological framework defined in this study (Fig. 6). However, a few previously published ages must necessarily be corrected. These are in disagreement with their respective stratigraphic positions presented herein and/or correlation with the geomagnetic polarity time scale, probably due to loss or excess of Ar. This limitation was put forward by the authors themselves (Abdel Monem et al., 1972; Ancochea et al., 1990) but can now be resolved. The age of 870 ± 40 ka of Ancochea et al. (1990) is younger than that of the sequence to which it belongs, which corresponds to the Jaramillo subchron (Fig. 6), probably a case of Ar loss. The ages of 1560 ± 150 and 1900 ± 370 ka of the lowest part of the Pared de Güímar (Abdel Monem et al., 1972) are above lavas dated by these authors at the top of the sequence at 860 ± 50 and 880 ± 220 ka, all of which have reverse polarity. The authors pointed out this inconsistency and expressed their preference for the younger ages, explaining the older ages as a consequence of excess Ar, an interpretation coherent with the data in this work. A similar explanation would account for their age of 1580 ± 170 ka, of normal polarity, which is stratigraphically overlying sample JCD-550 (1008 ± 22 ka) of this work.

A very interesting age is that of sample KAR-40 (831 ± 18 ka), from a fresh basaltic flow at the bottom of a lava sequence forming the north wall of the Barranco de Badajoz (see Figs. 2 and 7). This lava, with reverse polarity, corresponds to the initial eruptions flowing inside the collapse of Güímar Valley and gives an approximate minimum age for this lateral collapse. The Pared de Güímar section consists of a sequence of some 500 m of basaltic lava flows that accumulated in a very short period of time of around 150 ka (see Fig. 7).

Several eruptive vents at the top of the Pared de Güímar scarp seemingly erupted after the Güímar lateral collapse. At the top of the scarp lies a group of basaltic eruptive centers

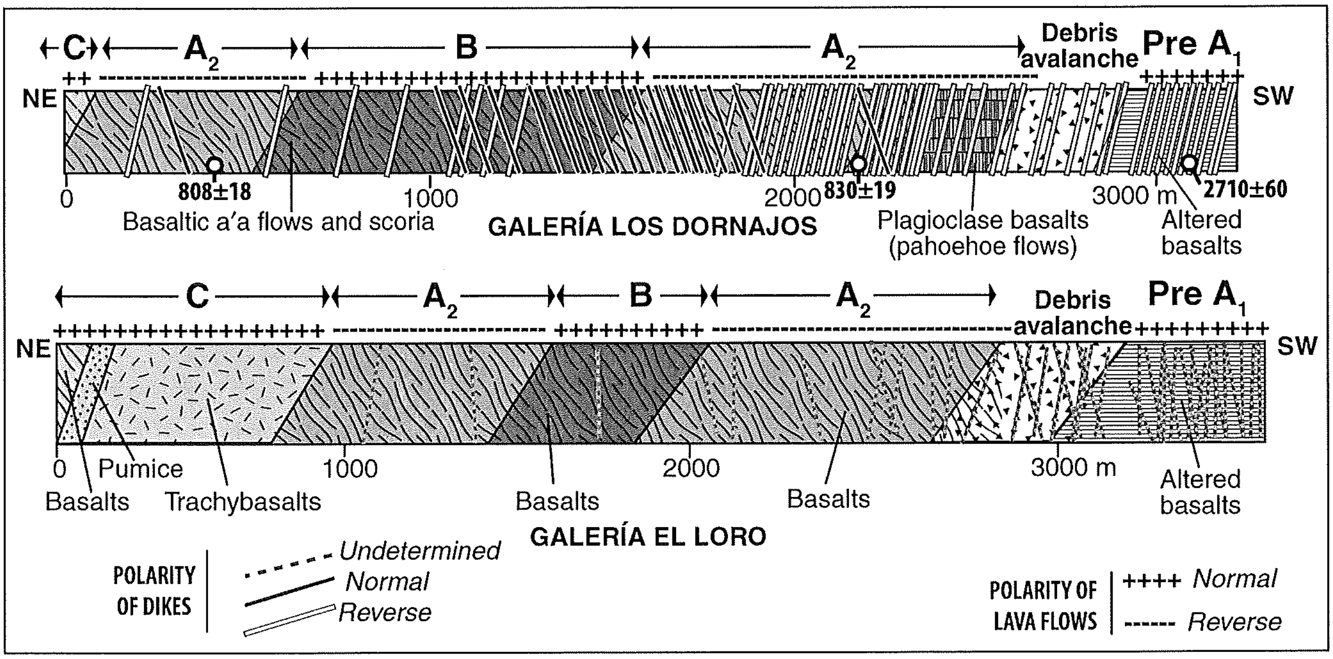

Figure 4. Geomagnetic polarity of the volcanic formations found in the Los Dornajos and El Loro galerías, both on the north flank of the NE rift. A similar pattern is retained in both examples, including a debris avalanche deposit.

TABLE 1. K-Ar AGES OF SAMPLES FROM NE RIFT (TENERIFE)

Sample ID	Location (UTM)	Polarity	Weight molten (g)	K* (wt%)	^{40}Ar* (%)	^{40}Ar* (10^{-13} mol/g)	^{40}Ar* weighted mean ([10^{-13} mol/g] ±1σ)	Age (±2σ ka)
JCD-499	Orotava Valley (1950 m)	N	0.46559	4.441 ± 0.044	9.516	17.724 ± 0.261		
JCD-499	351.548/3.133.758		0.97990	–	9.191	17.008 ± 0.137	17.163 ± 0.121	223 ± 6
KAR-46	Top of the western wall of Orotava Valley	N	1.24023	1.943 ± 0.019	16.562	17.032 ± 0.114		
KAR-46	343.932/3.136.340		0.96426	–	18.611	17.218 ± 0.117	17.123 ± 0.082	508 ± 11
JCD-324	Lavas cascading the eastern wall of Orotava Valley		1.30467	2.084 ± 0.021	15.685	20.441 ± 0.135		
JCD-324	353.854/3.141.594	N	1.68574	–	24.925	20.636 ± 0.137	20.537 ± 0.096	566 ± 13
JCD-500	Pista Orticosa		1.13947	1.752 ± 0.018	15.482	24.297 ± 0.144		
JCD-500	359.444/3.141.213	R	2.02545	–	37.970	24.312 ± 0.127	24.305 ± 0.095	800 ± 17
JCD-501	Pista Orticosa		1.98748	1.096 ± 0.011	15.591	15.597 ± 0.090		
JCD-501	361.230/3.141.330	R	1.00541	–	14.760	14.749 ± 0.130	15.323 ± 0.073	806 ± 18
GLD-04	Galería Los Dornajos (320 m)		1.12005	1.287 ± 0.13	23.335	17.937 ± 0.139		
GLD-04	357.920/3.144.100	R	2.50433	–	18.642	18.069 ± 0.094	18.028 ± 0.078	808 ± 18
JCD-520	Cho Marcial volcano		1.07593	2.241 ± 0.024	17.391	32.130 ± 0.186		
JCD-520	355.425/3.137,116	R	1.51367	–	27.323	31.533 ± 0.164	31.795 ± 0.123	818 ± 18
GLD-14	Galería Los Dornajos (2200 m)		1.00058	1.187 ± 0.012	9.671	17.120 ± 0.125		
GLD-14	357.920/3.144.100	R	2.02854	–	8.255	17.046 ± 0.115	17.080 ± 0.085	830 ± 19
KAR-40	Barranco de Badajoz, 1218 masl		1.84107	2.341 ± 0.023	26.796	33.546 ± 0.182		
KAR-40	356.650/3.131.820	R	2.03898	–	32.538	33.939 ± 0.177	33.748 ± 0.127	831 ± 18
KAR-42	Pared de Güímar sequence, upper part (1595 m)		1.59131	2.042 ± 0.020	34.939	29.866 ± 0.161		
KAR-42	356.410/3.131.155	R	1.96904	–	23.578	31.076 ± 0.164	30.463 ± 0.115	860 ± 18
JCD-576	Northern wall of Güímar Valley		1.57350	2.100 ± 0.021	28.355	33.456 ± 0.177		
JCD-576	361.153/3.140.396	R	1.49589	–	12.441	34.399 ± 0.221	33.824 ± 0.137	929 ± 20
JCD-533	Upper part of the Pared de Güímar scarp		1.25272	1.428 ± 0.014	23.888	23.993 ± 0.141		
JCD-533	355.893/3.131.436	R	2.59277	–	31.536	23.744 ± 0.121	23.849 ± 0.092	963 ± 21
KAR-41	Pared de Güímar scarp, lower part (1326 m)		1.56192	1.843 ± 0.018	29.250	31.985 ± 0.177		
KAR-41	356.516/3.131.542	N	1.47186	–	34.887	31.468 ± 0.174	31.722 ± 0.124	992 ± 21
JCD-550	Foot of the Pared de Güímar sequence		2.22261	1.254 ± 0.013	21.660	22.077 ± 0.117		
JCD-550	355.189/3.131.365	N	2.02602	–	29.307	21.750 ± 0.120	21.917 ± 0.083	1008 ± 22
GLD-20	Galería Los Dornajos (3070 m)		0.98937	1.610 ± 0.016	21.196	76.373 ± 0.395		
GLD-20	357.920/3.144.100	N	1.00059	–	28.091	75.097 ± 0.387	75.722 ± 0.276	2710 ± 60
TF-801	Valle de Tegueste, road TF-1213, km 3.1		0.65988	0.448 ± 0.005	21.912	55.558 ± 0.314		
TF-801	366.350/3.153.115	N	0.99405	–	12.852	57.590 ± 0.316	56.567 ± 0.220	7270 ± 160

Note: Age calculations are based on the decay and abundance constants from Steiger and Jäger (1977).

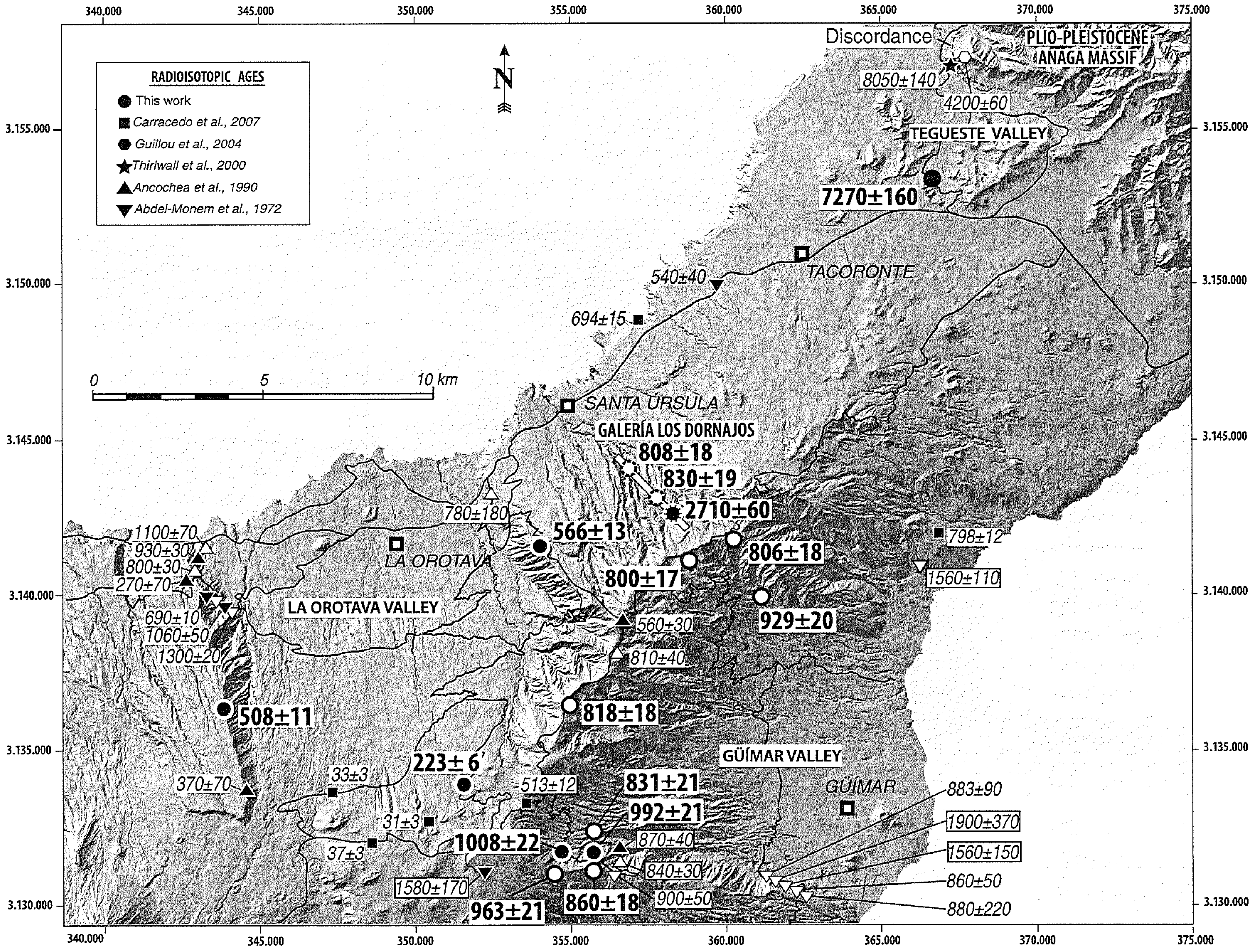

Figure 5. K/Ar ages from this work and earlier studies on rocks of the NE rift zone (ages in ka). The ages in boxes are inconsistent with the new information that is presented in our study. Bold indicates data from this study. Open symbols indicate reversed polarity, and closed symbols indicate normal polarity.

where lavas of reverse polarity cascaded down the scarp, now cropping out at the base of the scarp. There, they can be misinterpreted as scree deposits upon cursory inspection (Fig. 8). The cascading parts of these flows are easily removed by erosion and are, therefore, very ephemeral features. The remaining part of these flows may crop out concordantly on top of the collapse scarps, and thus yield erroneous (younger) ages for lateral collapses. This is probably the case with samples JCD-500 (800 ± 17 ka) and JCD-501 (806 ± 18 ka), both from the top of the northern scarp of the Güímar Valley, and two ages (370 ± 70 ka and 270 ± 70 ka) from the top of the western wall of the La Orotava collapse valley (Pared de Tigaiga) (see Fig. 5). These lavas have been dated younger than sequences filling these landslide scars and are, hence, postcollapse features.

A group of basaltic eruptive centers, weathered and dismantled by erosion, crops out north of the Güímar Valley and near the coast (see Fig. 5). Their lava flows, of normal polarity, have given an age of 798 ± 12 ka (Carracedo et al., 2007), compatible with the M-B precursor event.

It is interesting to compare the age of the scarps of the Güímar and La Orotava valleys (see Fig. 5). The basal formations of the western scarp of the Valley of La Orotava (Pared de Tigaiga) and those of the Pared de Güímar, with similar ages, were formed much earlier than the basal sequence of the opposite wall of the Orotava Valley (Pared de Santa Úrsula). The Jaramillo event, present in the former formations, is absent in the eastern wall of the Orotava Valley. Lava sequences forming the cliffs of the north coast, between Santa Úrsula and Tacoronte, gave much younger ages, 694 ± 15 ka (Carracedo et al., 2007) and 540 ± 40 ka (Abdel Monem et al., 1972), both of which have normal (Brunhes) polarity.

The more dispersed and less frequent basaltic eruptions of the final stage of activity of the NE rift, which spread along the entire NE rift zone, partially filling the Güímar and La Orotava Valleys, display ages ranging from 513 ± 12 ka, on the crest of the rift at La Cumbrecita (Carracedo et al., 2007), to the historic eruptions of the volcanoes of Fasnia and Arafo, both in 1705. A good part of the basaltic cones of the rift are, however, partially covered by a layer of pumice fall (see geological map in the GSA Data Repository [see footnote 1]), which may correspond to that described and dated by Edgar et al. (2002) at 270 ka. It appears therefore that the eruptive activity of the NE rift zone gradually

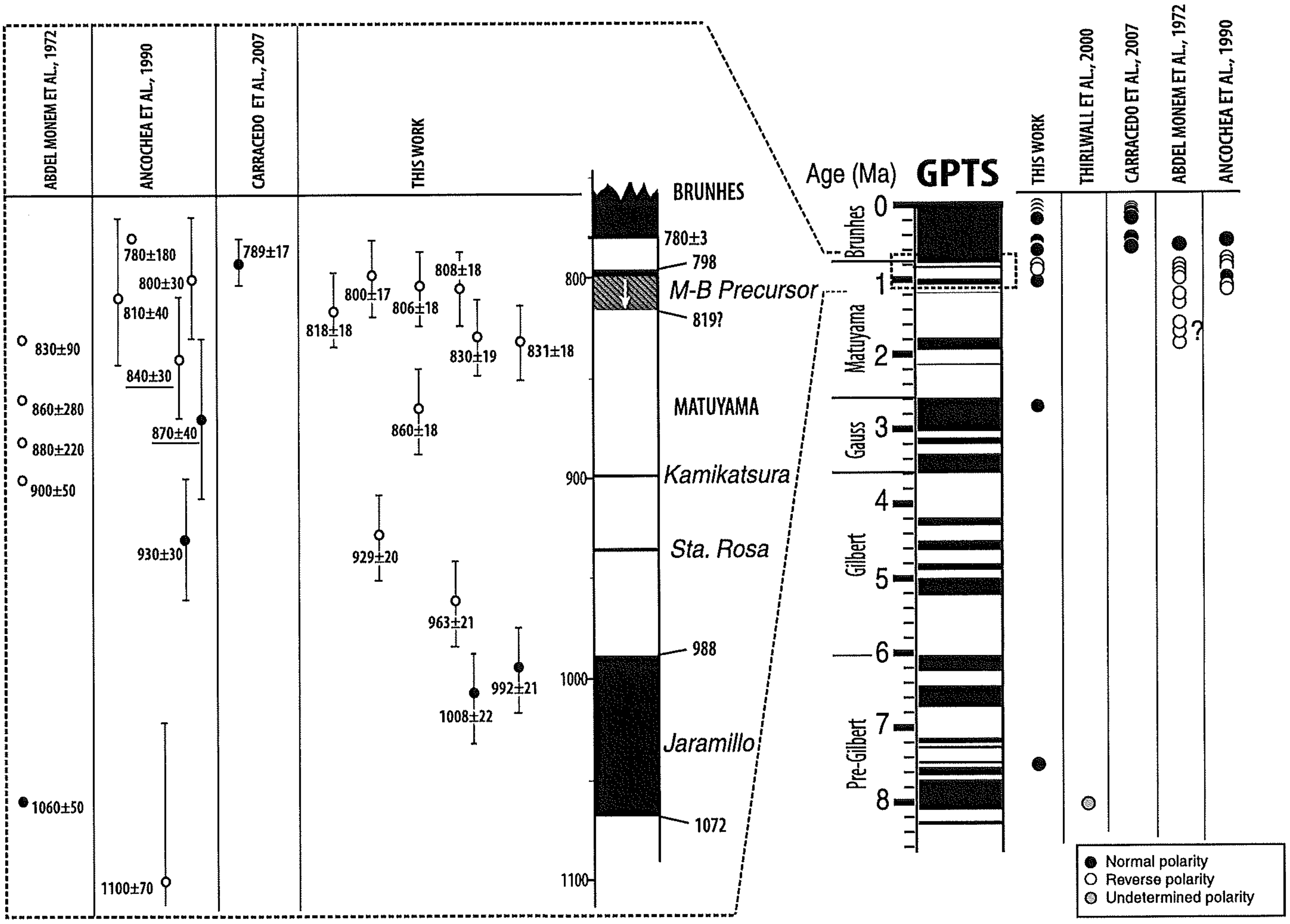

Figure 6. Comparison of published K/Ar ages from the NE rift zone and those obtained in this study with the geomagnetic polarity time scale indicated (GPTS). Note the rift displays three stages of activity: (1) Miocene, (2) Pliocene, and (3) Pleistocene. On the left, we focus on the GPTS stage that includes the rift's most recent and extensive stage of development. Underlined ages are from Ancochea et al. (1990) that are too young, possibly due to Ar loss.

declined from the stage of maximum activity during the period 1010–800 ka. However, a recent reactivation appears to have taken place at the southern end of the rift, close to the rim of the Caldera de Las Cañadas, where there is a large number of basaltic eruptive centers, dated from 31 to 37 ka (Carracedo et al., 2007).

Intrusive Facies of the NE Rift Zone

Samples of 462 dikes from the NE rift were collected and information compiled, including their physical parameters (strike and dip, thickness, composition, etc.), in addition to their geomagnetic polarity. The detailed magnetic, structural, and petrological analysis of the minor intrusions of this rift is being undertaken in a tandem study (Delcamp et al., 2008). Only a broad overview will be given here.

The directions of the analyzed dikes (Fig. 9) show a strong grouping in two main trends: (1) 0°–10° (almost N-S), prevalent in the dikes that crop out in the Pared de Güímar; and (2) 20°–40°, predominating in the dikes of normal polarity and reverse polarity elsewhere in the NE rift zone. The former cut the Jaramillo-aged lavas but are earlier than those of the Brunhes epoch. This suggests a major change in direction of the dikes in this part of the NE rift, possibly passing from the general NE-SW trend to a new N-S trend in the upper Matuyama.

Our observations concur with those of Hürlimann et al. (2004). These authors measured the orientation of 217 dikes at the head of the La Orotava amphitheater and observed a clear NE-SW strike trend (see their Fig. 4). Most of the dikes had a subvertical dip.

DISCUSSION

Stages in the Construction of the NE Rift

Mapping, dating, and correlation of the volcanic sequences allow the reconstruction of the eruptive and structural history of the rift, defining its main stages of growth and successive flank failures.

A Previous Miocene-Pliocene Cycle of the NE Rift Zone?

Data compiled from observations in many galerías of the NE rift zone by the Consejo Insular de Aguas de Tenerife show the presence of volcanic sequences intensely altered and densely intruded by dikes forming the deep internal part of the rift. These rocks were interpreted as pertaining to the Old Basaltic

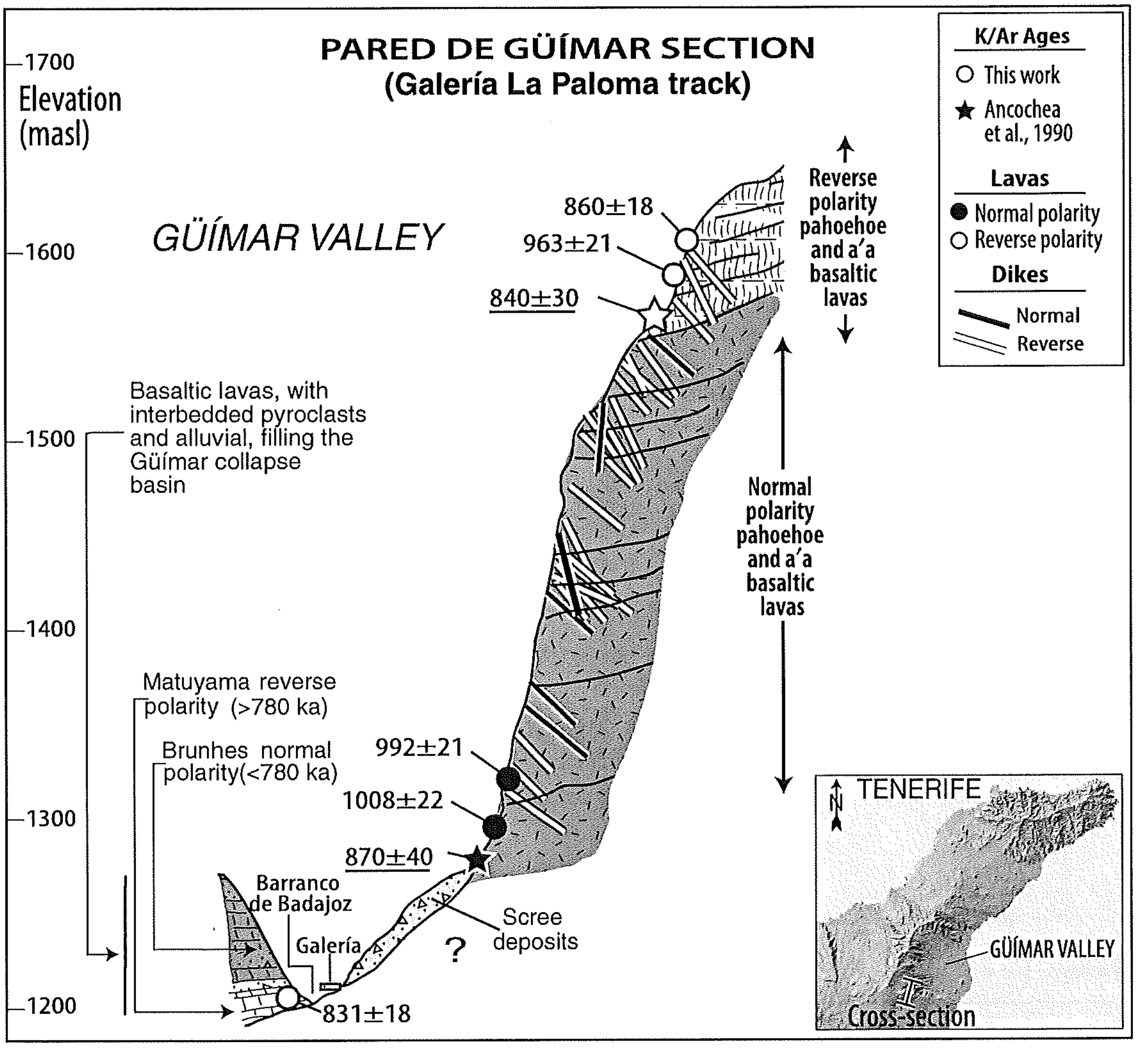

Figure 7. Stratigraphy and magnetostratigraphy of the Pared de Güímar, the southern scarp of the lateral collapse valley of Güímar (compare with Fig. 2). The ages underlined, like in Figure 6, are too young, possibly due to Ar loss.

Series I of Fúster et al. (1968), but were not dated previously, and the issue remained open.

Guillou et al. (2004a) proposed, on the basis of observations from galerías and stratigraphic, isotopic, and paleomagnetic data, that a large Miocene shield occupies the central part of Tenerife, albeit intensely eroded and subsequently covered. Conversely, Ancochea et al. (1990) postulated an extension of the Anaga massif toward the center of the island during Miocene and Pliocene time. These authors pointed out, when assessing the eruptive rates of the Cordillera Dorsal (the NE rift), that 25%–33% of this volcano is formed by the Old Basaltic Series (Fúster et al., 1968), thus implying the presence of a Miocene volcano base at perhaps 400–500 m asl. The issue is, therefore, not the existence of a Miocene-Pliocene core to the NE rift zone, but whether this core is associated with the Anaga massif or with the Central shield.

In this work, we obtained a Miocene age (7.27 Ma) from lavas of the south wall of the Valle de Tegueste (see Figs. 5 and 10A),

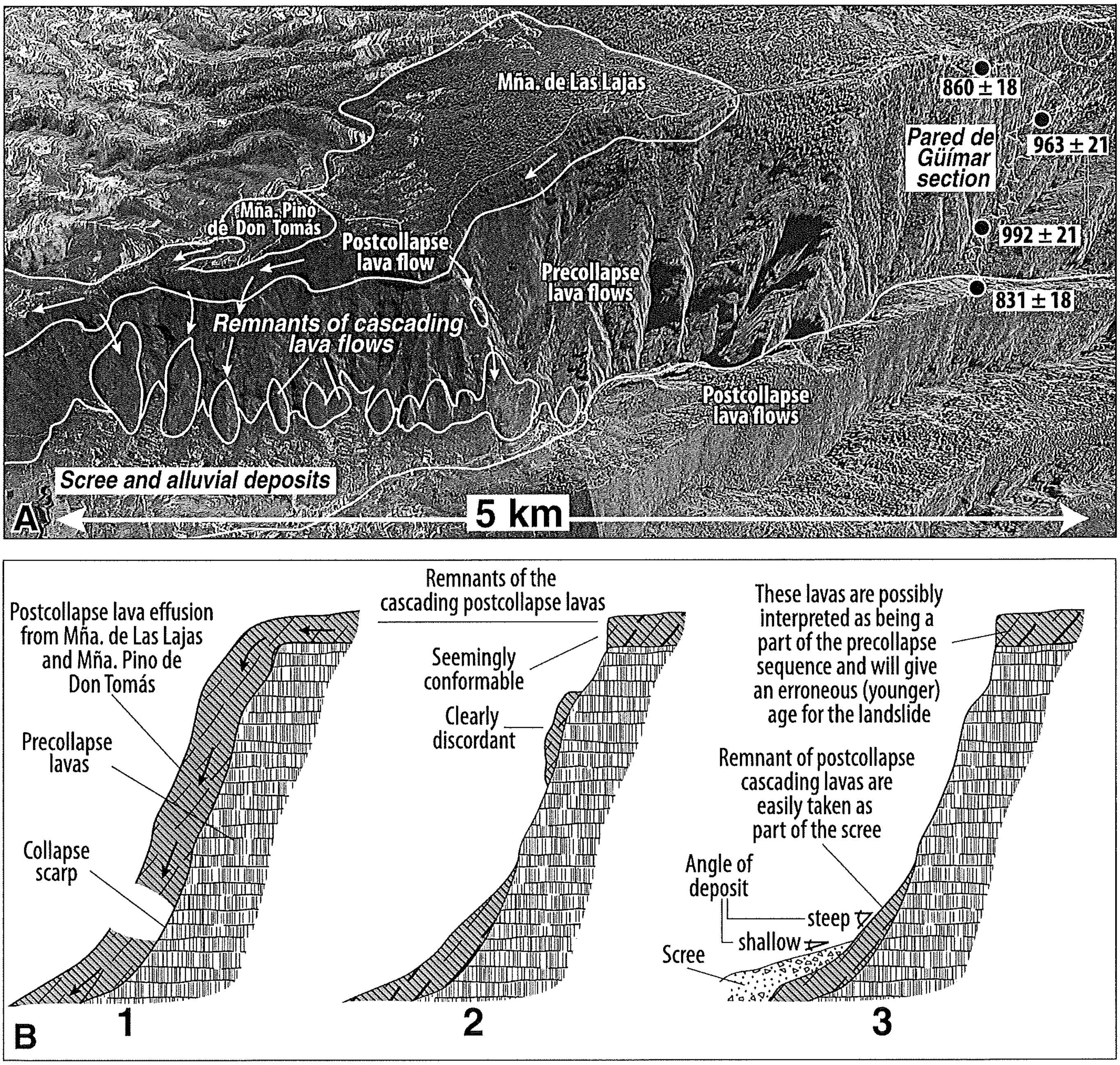

Figure 8. Oblique view (Google Earth) from the north of the southern wall of the Güímar giant landslide scar (the Pared de Güímar). (A) Ages dating the pre- and postcollapse formation are shown in the right-hand side of the figure. In the left-hand side, two eruptive centers (Mña. de Las Lajas and Mña Pino de Don Tomás) are shown with their lavas cascading down the scarp, and thus postdating the collapse. (B) Sketch illustrating how erosive remnants of the postcollapse lavas can be misinterpreted as a part of the precollapse sequence, or mistaken as scree deposits at the foot of the scarp.

confirming that a Miocene root underlies the NE rift zone in this area. This sequence is mainly made up of basaltic pyroclasts that are densely intruded by dikes and felsic domes. The age is similar to that obtained by Thirlwall et al. (2000) in the discordant sequence at the base of the Anaga massif. Therefore, although supported by a single date and thus remaining tentative, we favor the hypothesis of Guillou et al. (2004a) of an extension of the Central Miocene shield of Tenerife toward the Anaga massif forming the initial stage of the NE rift zone (see cross section in Figure 1 here and figure 1 *in* Guillou et al., 2004a).

Pleistocene Evolution of the NE Rift Zone

In this study, we focus on the Pleistocene stage of activity of the NE rift zone (see Figs. 10 and 11), in which successive constructive episodes and lateral collapses, which in turn were filled again with nested volcanism, define different episodes that lead up to the latest (Quaternary) period of development of the NE rift zone.

Initial Development. The initial Pliocene episode (Figs. 10A and 11A) was apparently characterized by the development of a volcano that may have reached an altitude of 2000 m asl. From this volcano, centered in the area between the present-day Montaña Gaitero and Montaña de Joco, only a part of the NE flank crops out at present. This takes the form of two triangular areas situated to each side of the Güímar Valley (Fig. 10A). The remainder of this formation has been dismantled by successive flank failures or appears covered by subsequent eruptions.

The polarity of the lavas and dikes of this formation (Units A_1 and B of the Pared de Güímar; see Fig. 3) and the isotopic ages described confirm that this volcano was formed in the upper Matuyama chron, in the period comprising the base of the Jaramillo subchron to some 830 ka, when the formation must have reached an unstable configuration. The critical stage of construction was most strongly developed between ca. 1100 and 860 ka, as reflected in the sequence of the Pared de Güímar. There, the growth rate may have reached 3.5 m/k.y., indicating an intense episode of intrusive activity and the progressive instability of the volcano. A consequence of this instability may be the change in dike direction (see, e.g., Walter and Troll, 2003) in the reverse polarity dikes of the upper Matuyama chron that change from 20°–40° to 0°–10° (see Fig. 9).

Micheque Lateral Collapse. Schmincke and Sumita (1998) postulated the existence of a major landslide on the NW flank of the NE rift zone north of the La Orotava Valley, unfortunately with reference to unpublished data only. Ablay and Hürlimann (2000) inferred a similar feature, their East Dorsal landslide, albeit on debatable and inconclusive evidence. We have considered the name East Dorsal to be inappropriate because dorsal is the term for all ridge-like features in the Canaries. We prefer to name the sector collapse we have identified in the NE rift zone, east of the La Orotava Valley, with a toponym (similar to La Orotava and Güímar landslides), and we choose the name of Montaña Micheque, a trachytic vent, the youngest and most prominent topographic feature inside the collapse scar (i.e., Micheque lateral collapse).

The main constraint for the time of occurrence of the Micheque lateral collapse (estimated volume assessed from analysis of digital elevation model based on topographic data by GRAFCAN is ~60 km^3) is primarily based on the ages obtained in the galería Los Dornajos (see Figs. 4 and 5). Accordingly, the collapse must have occurred ca. 830 ka, which is the age of the first nested lavas above the avalanche breccia crossed at the end of Los Dornajos galería and, consequently, a minimum age bracket for the collapse (see Figs. 4 and 11). The 830 ± 19 ka age is from a lava flow that is stratigraphically very close to the collapse breccias, and it is plausible that this age closely dates the collapse itself.

The landslide generated a basin in the north flank of the rift that would enclose the areas from Tacoronte in the NE to the interior of the present-day valley of La Orotava in the SW (Figs. 10B and 11C). Subsequent volcanism filled large parts of this basin, extending beyond the coastline to conceal the scar and the avalanche breccia. An age of 694 ± 15 ka (Carracedo et al., 2007), obtained from a

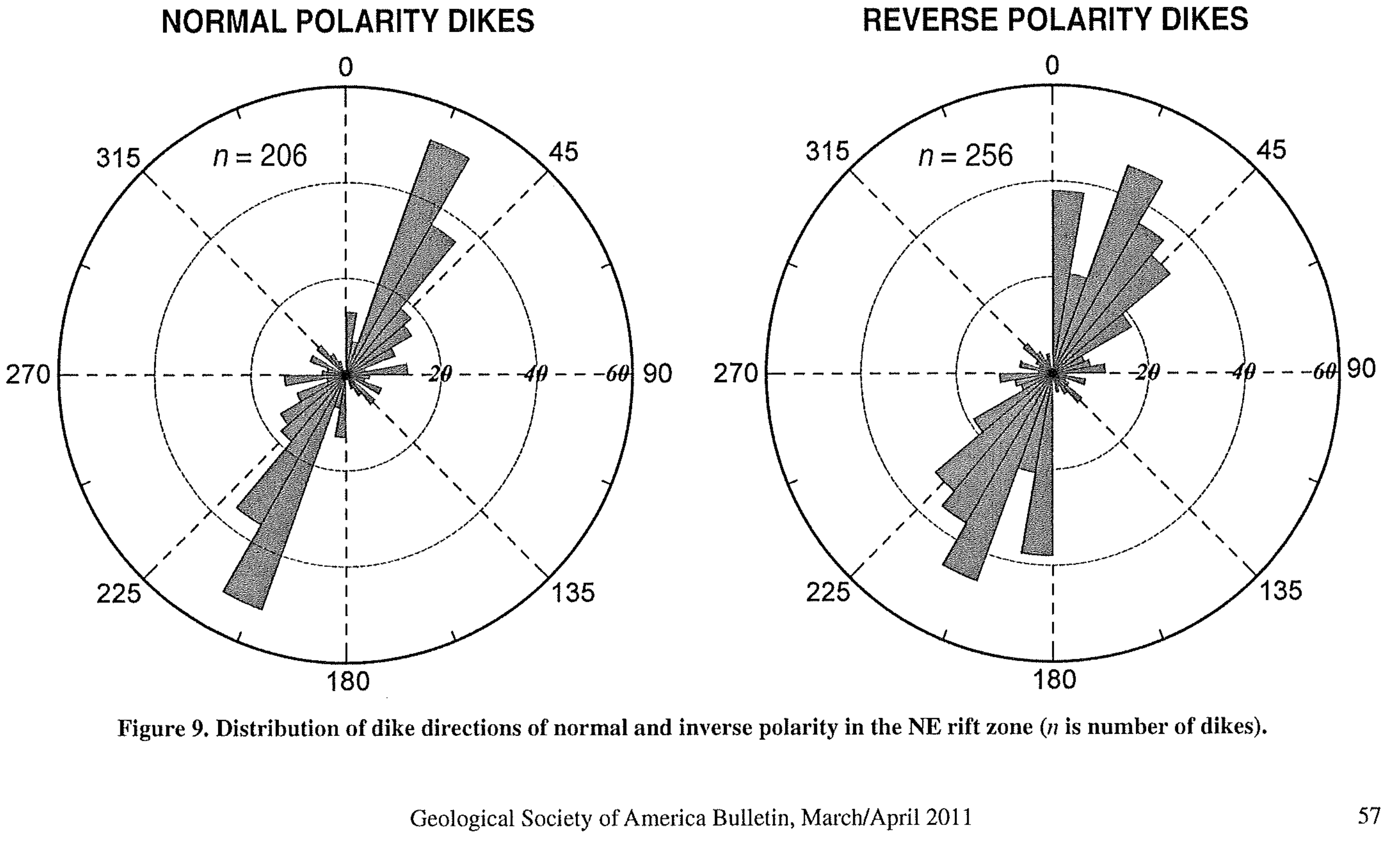

Figure 9. Distribution of dike directions of normal and inverse polarity in the NE rift zone (*n* is number of dikes).

lava flow at the base of the coastal cliff in the Micheque landslide basin (see Figs. 5 and 10D), confirms that the entire cliff is formed by the sequence that filled this collapse depression and thus concealed the collapse scar completely. Postcollapse volcanism (unit A_2 in Fig. 3) was therefore limited to eruptions nested inside the Micheque landslide basin and its flanks and headwall (Fig. 10B).

A breccia formation, with angular clasts of varied composition (basalt to trachyte), exposed at the base of the Pared de Santa Úrsula, near Pino Alto (Fig. 12), may correspond to the Micheque landslide debris avalanche underlying the Micheque fill-in sequence (Fig. 11C). This apparent avalanche formation is cut at a similar altitude in the El Loro and Los Dornajos galerìas (see Fig. 4). The breccia crops out at this level because the La Orotava collapse carved more deeply into the edifice than the earlier Micheque landslide, thus leaving the fill-in sequence of the Micheque collapse basin overhanging in the present La Orotava collapse eastern wall. The thick and continuous scree deposits covering the base of this scarp and volcanism postdating the collapse hinder more detailed observations of the debris avalanche deposit (Fig. 12).

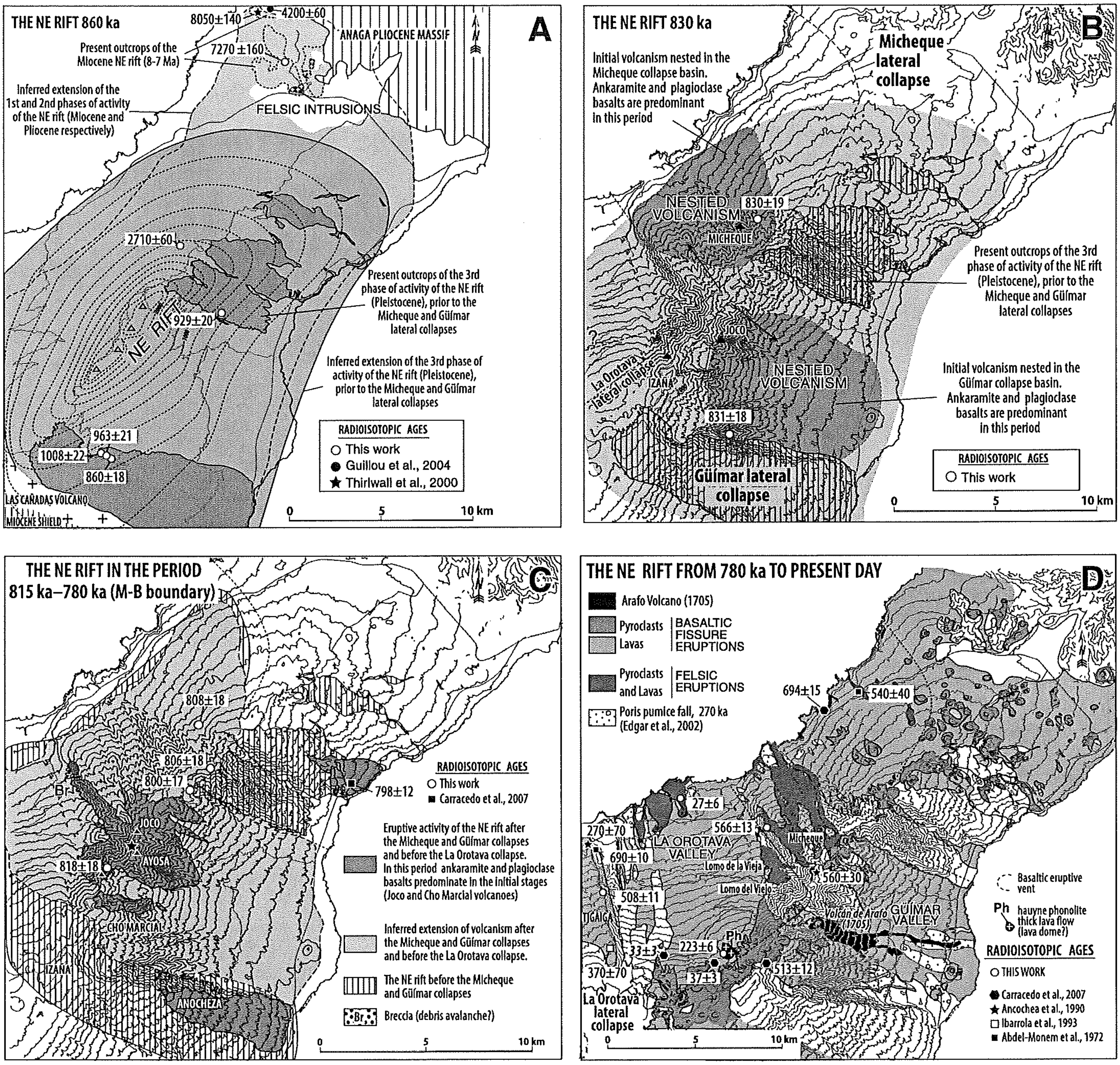

Figure 10. Different stages of development of the NE rift zone (all ages in ka except Arafo volcano, in D, which is 1705 A.D.). In C, "Br" indicates an outcrop of breccias at the base of the Micheque fill that may belong to the landslide breccia of the lateral collapse (see also Figs. 5 and 12).

In summary, strong evidence for the Micheque landslide can be drawn from the stratigraphic and geochronological differences in the eastern and western flanks of the central part of the NE rift zone. As shown in the cross sections of Figures 11A and 11C, lavas forming the eastern flank are consistently older (between ca. 1008 and 860 ka) than those erupted at the western flank (<830 ka). The basal formation of the western lava sequence is a polymict breccia, similar to the debris avalanche underlying the sequence of flows from Teide volcano (Bravo, 1962; Navarro and Coello, 1989; Carracedo et al., 2007; Márquez et al., 2008). This chaotic breccia, indicative of a landslide origin, has been observed in galerías in the western flank of the NE rift zone and in the La Orotava and Güímar Valleys (Navarro and Coello, 1989; Ancochea et al., 1990; this work). Lavas directly below the breccia are densely intruded (see Fig. 4) and have been dated as Pliocene (2.7 Ma). The significant contrast in the ages of lavas above and below the breccia (0.83 ± 0.02 and 2.71 ± 0.06 Ma, respectively) imply a minimum gap

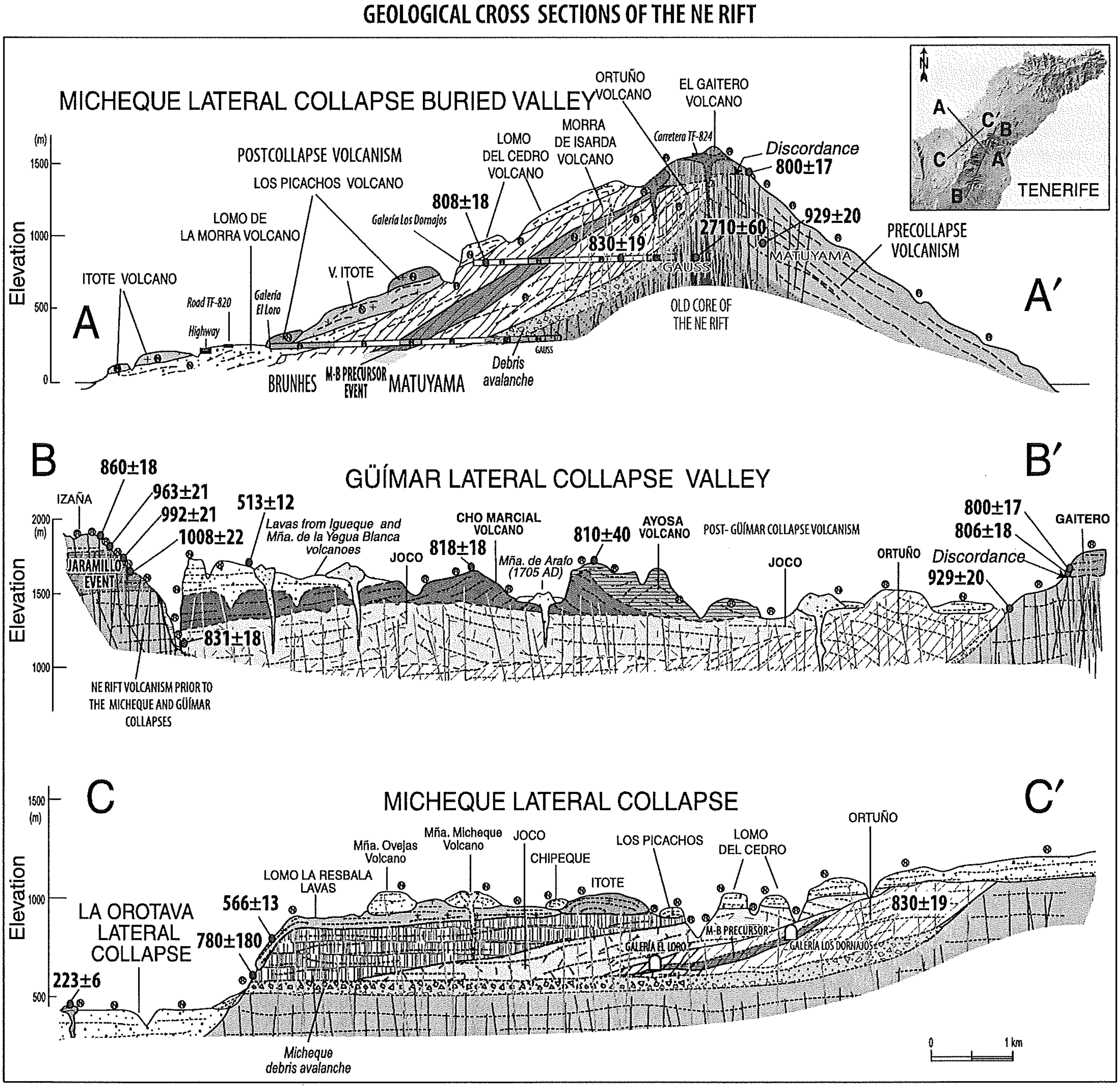

Figure 11. Geological cross sections of the NE rift zone (ages in ka). The polarity of the stratigraphic units and volcanic edifices is indicated with R (reverse polarity) and N (normal) polarity. Section lines in inset in right-hand corner. A copy of these cross sections in color is included in the geological map of the GSA Data Repository (see text footnote 1).

of 1.84 m.y. that is difficult to explain through differential erosion of the western flank. Instead of the paleosol that would be expected if an erosional gap of 1.84 m.y. existed, a landslide breccia claims this stratigraphic position. As shown in the cross section (Fig. 11C), the sequence of lavas forming the western flank of the NE rift zone are incised by, and therefore predate, the La Orotava landslide.

In our view, the most sensible explanation for these observations is a landslide occurring at ca. 830 ka at the NE flank of the NE rift zone that entirely removed the volcanic formations of the latest Pleistocene stage at this part of the rift, exposing the older Pliocene formations, and the subsequent fill of the landslide depression.

However, this lateral collapse cannot be the East Dorsal landslide described by Ablay and Hürlimann (2000). These authors carried out a complicated morphological analysis of lobes in the debris apron of the north flank of Tenerife, using swath bathymetric data from a previous publication (Teide Group, 1997), but without providing hard age constraints or on-land observations. Ablay and Hürlimann (2000) concluded that the East Dorsal landslide overlaps the La Orotava slide and is, therefore, younger than 560 ka. This was at the time the inferred minimum age of the La Orotava Valley, based on dates obtained from the oldest valley-filling lavas by Ancochea et al. (1990). This is in conflict with the geochronological and structural data presented in this work, since our Micheque landslide predates the La Orotava landslide (Figs. 11C and 12A). Therefore, either the interpretation of the relative ages of the different lobes defined by Ablay and Hürlimann (2000) is incorrect, or they are referring to a young landslide scar north of the La Orotava Valley for which we have not found evidence.

Lateral Collapse of Güímar. This lateral collapse (estimated volume: 47 km^3) of the southern part of the east flank of the NE rift zone formed a pronounced 10 × 10 km, U-shaped, straight-sided depression (Figs. 10B and 11B). The timing of this collapse is constrained by the age of 860 ± 18 ka obtained from reverse polarity lava flows topping the Pared de Güímar, and that of the first nested volcanism, dated at 831 ± 18 ka. Lavas erupted from vents located close to the rim of the depression (Montaña de Arguazo and Montaña Anocheza volcanoes) cascaded down the escarpment of the Pared de Güímar (Figs. 8 and 13A) and therefore postdate the collapse. Both of these lava flows and the first flows that are nested in the collapse depression and crop out along the bed of the Barranco de Badajoz, have reverse polarity, and correspond therefore to the Matuyama post-Jaramillo period (see Fig. 8).

The Güímar scar is well preserved, and little in-fill has accumulated. The eruptive rate and volume of the Micheque fill-in formations seem much greater than those of the Güímar event. Our interpretation is that, although roughly contemporaneous, the Micheque collapse may have been the first to take place, coinciding with a stage of intense volcanic and intrusive activity. This may point to a fundamental difference in the mechanism that caused the two flank failures: distensive stresses associated with intense eruptive and intrusive activity in the former (Micheque), and gravitational instability increased by the response to the earlier collapse in the latter (Güímar). This would explain the observation that, by far, the greater part of rift volcanism continued to be concentrated in the interior of the first collapse (Micheque), even after the Güímar and La Orotava landslides took place, causing the total fill of the former depression and the evolution of significant volumes of magma (0.5–1.0 km^3) toward highly differentiated compositions in this sector only.

Lateral Collapse of La Orotava.

The relatively accurate dating of the Micheque and Güímar collapses has not been achieved for the third collapse that formed the Valle de La Orotava (estimated volume: 57 km^3). Normal polarity lavas (Unit A in Fig. 3), with ages of 690 ± 10 ka (Ibarrola et al., 1993) and 370 ± 70 and 270 ± 70 ka (Ancochea et al., 1990), top the western escarpment (Pared

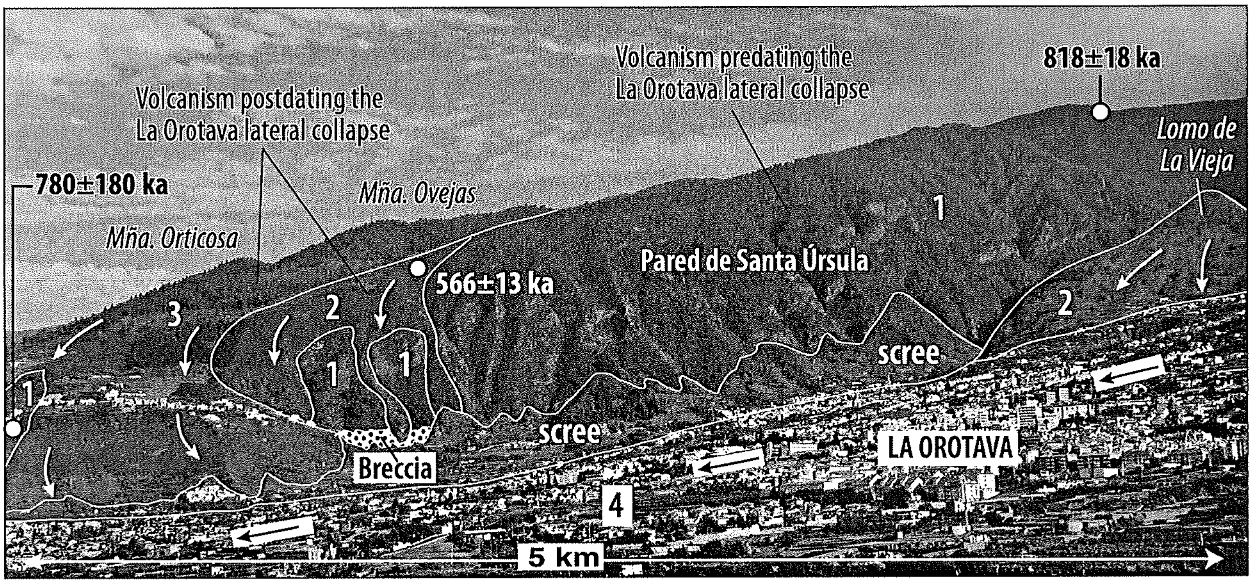

Figure 12. Oblique view from the west of the eastern wall of the Valle de La Orotava: (1) precollapse sequence, (2) postcollapse differentiated eruptions, (3) postcollapse basaltic vents and lava flows from inside the Micheque scar, and (4) postcollapse basaltic flows from the NE rift. A polymict breccia underlying the precollapse unit (1) crops out in a small area and is concealed elsewhere by the postcollapse eruptions and extensive scree deposits at the base of the scarp. The pre-Orotava collapse sequence (1), with two ages of 780 ± 180 ka (Ancochea et al., 1990) and 818 ± 18 ka (this work), is the sequence filling the Micheque collapse. The subsequent La Orotava collapse carved more deeply and left the entire sequence filling the Micheque collapse, apparently including the debris avalanche deposit, exposed at the foot of the collapse scarp.

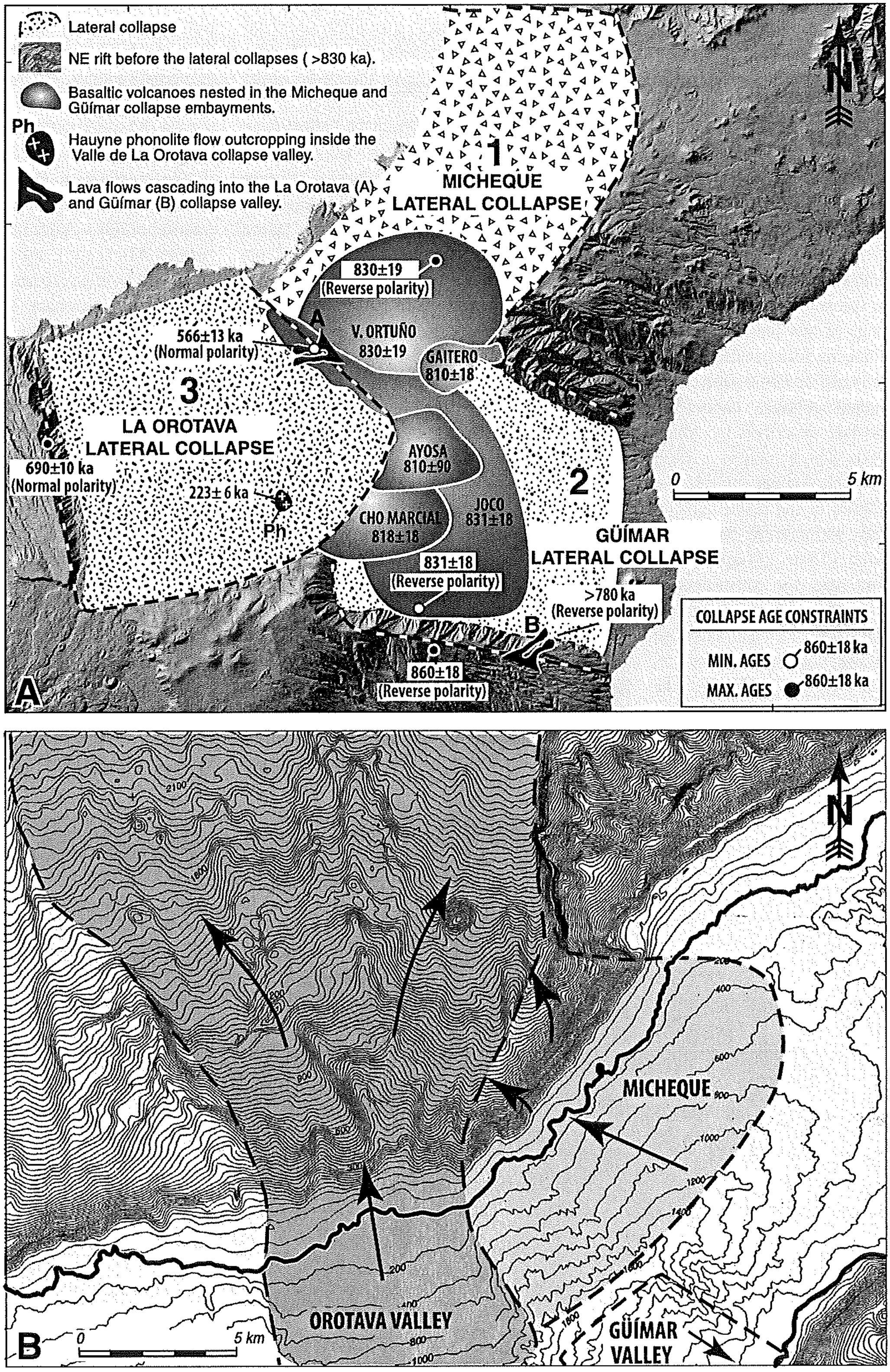

Figure 13. (A) Scheme that synthesizes the successive stages of growth and collapse in the NE rift zone as a function of the age of the volcanism nested in the different landslide basins. (B) Bathymetry of the zone (Palomo et al., 1998) showing the scars of the successive collapses. It is evident that the La Orotava collapse postdates the Micheque collapse, cutting the sequences filling the Micheque basin, which extended into the present-day Valley of La Orotava.

de Tigaiga) of this collapse valley. The lavas of felsic compositions of the Micheque nested volcanism that cascaded into the Orotava Valley at the eastern wall (Pared de Santa Úrsula) have been dated here at 566 ± 13 ka (Figs. 11C and 12A), establishing a minimum age for this collapse. However, attempts to define a reliable and accurate maximum age were not successful. Ibarrola et al. (1993) discussed the possibility that the La Orotava collapse may postdate the age of 270 ka. The ages of 370 ± 70 and 270 ± 70 ka (Ancochea et al., 1990) very possibly correspond to eruptions that took place after the collapse (as described in the Pared de Güímar), and that have later been redeposited by the numerous slumps in this area of the scarp (see Fig. 5). We dated a flow of normal polarity at the top of the western scarp (the Pared de Tigaiga) obtaining an age of 508 ± 11 ka, which is younger than the collapse. Abdel Monem et al. (1972) dated a flow with normal polarity and lower in this sequence at 690 ± 10 ka. It seems therefore plausible to constrain the Orotava collapse between 690 ± 10 and 566 ± 13 ka, which places it significantly after the Micheque and Güímar landslides (see Fig. 13A).

During geological mapping, an outcrop of hauyne phonolite was observed at the head of the La Orotava Valley (Ph in Figs. 10D and 13A). The state of erosion and weath0ering of this dome-like formation and its composition, which differs fundamentally from that of the dikes and lavas of the NE rift, appear to indicate an erosive remnant of the Las Cañadas edifice that remained uncovered. However, this flow, dated here at 223 ± 6 ka, seems to correspond to a phonolitic lava dome eruption nested in the Orotava collapse valley.

Final Decline and Dispersed Activity of the NE Rift.

Following the three collapses, the rift entered into a stage of stabilization and progressively decreasing eruptive activity. Simultaneously, the dispersion of the eruptive centers, previously grouped preferentially at the crest of the rift, increased, particularly at the distal NE end (see Fig. 10D). These eruptions, all of normal polarity, have given ages of 513 ± 12 ka (Carracedo et al., 2007), 540 ± 40 ka (Abdel-Monem et al., 1972), and 560 ± 30 ka (Ancochea et al., 1990). The eruptive activity, although attenuated, has continued until recent times, particularly in the proximal (SW) area of the rift, as underlined by ages of 37 ± 3 ka, 33 ± 3 ka, and 33 ± 1 ka (Carracedo et al., 2007), and even to historic times (e.g., Fasnia and Arafo eruptions in 1705 A.D.). The Taoro eruptive alignment, in the interior of the La Orotava Valley, has been dated by ^{40}Ar/^{39}Ar at 27.0 ± 5.9 ka (Carracedo et al., 2008) and therefore belongs to this recent stage as well.

Significance of the Successive Lateral Collapses and Subsequent Nested Volcanism

The Micheque and Güímar lateral collapses preceded the La Orotava one, on the basis of the isotopic ages from lavas at the top of the collapse scarp and those filling the collapse embayment (see Figs. 11C and 12). Furthermore, the volcanoes that developed and nested in the Micheque collapse scar are dissected by the La Orotava landslide (Fig. 13A). Finally, the avalanche deposits of the La Orotava collapse apparently postdate those of the Micheque collapse in the bathymetry north of the La Orotava Valley, as shown in Figure 13B (Palomo et al., 1998).

The order in which the Micheque and Güímar landslides occurred is more difficult to assess. Based on the obtained ages of the oldest nested Micheque (830 ± 19 ka) and Güímar (831 ± 18 ka) volcanism, both landslides apparently occurred geologically at nearly the same time, although there may have been a gap of hundreds to thousands of years between them. We therefore have been unable to find sufficient evidence to put these collapse events in the correct order, but we hypothesize that the Micheque collapse was the first to take place. The reason to assume that the Micheque collapse was the first is the much greater eruptive rates and volumes of postcollapse volcanism nested in the Micheque basin as opposed to the Güímar collapse valley. This may point to the first collapse (Micheque) being triggered by a climactic phase of intrusive and eruptive activity at the rift, followed by equally intense nested activity in and around the collapse embayment. In stark contrast, the Güímar collapse may have been predominantly gravitational in origin. We speculate that the rift instability may have reached a critical stage in response to the first lateral collapse, which might account for the geologically immediate occurrence of a second collapse. This may also explain the much lesser volumes of nested volcanism in the Güímar collapse and would be consistent with Micheque being instantaneous and Güímar and La Orotava being potentially slower at the outset. These later collapses may have been the result of gravitational rearrangements following the Micheque collapse, possibly implying many individual slides over a period of years, instead of requiring one single instantaneous catastrophe. However, this conjecture needs to be tested with further dates and detailed structural analyses of the collapse architecture.

The eruptive activity nested in the landslide basins appears to have declined with each successive collapse. While the scar of the initial (Micheque) collapse was quickly and completely filled, the second landslide basin (Güímar) was only partially covered by postcollapse eruptions. No volumetrically significant nested volcanism seems to have taken place in the youngest collapse of the rift, the La Orotava depression. This basin is in the process of being filled by the later external lavas that originate predominantly from the crest of the rift, and several small cinder cones and phonolite plugs nested in the collapse valley.

In contrast, this behavior of nested volcanism in landslide basins may provide information about the eruptive and intrusive activity prior to the collapse. If the first collapse was preceded by very intense and focused intrusive activity, with rapid rift spreading to accommodate dikes, it seems plausible that the eruptive activity continued or even accelerated immediately after the landslide (Longpré et al., 2008, 2009; Manconi et al., 2009). This would imply intense nested volcanism in the collapse basin, which would rapidly fill up. If, on the other hand, the process that caused the lateral collapse was fundamentally a gravitational instability (i.e., Güímar and La Orotava), nested eruptive activity may have been considerably more limited or may even be absent.

Moreover, if the nested volcanic activity is intense and prolonged, magmatic differentiation processes may occur. The pattern of evolution of nested postcollapse eruptions is typically from mafic basalts (ankaramites and plagioclase phyric basanites) toward differentiated compositions, such as phonolites and trachytes. Probably, after initial eruptions of dense basaltic rocks and progressively increasing edifice load (Pinel and Jaupart, 2000), magma would be stored in shallow chambers, and crystal fractionation plus crustal assimilation would drive later magmas toward more highly differentiated compositions. The early dense magmas may well be a key player in creating a density trap for subsequent magma within the shallow edifice to allow for storage, cooling, and differentiation to take place.

Ankaramitic and plagioclase basalts, generally having pahoehoe morphologies, predominate in the initial stages of the nested volcanism in both the Micheque and Güímar collapses. The ultramafic and mafic nature of the initial postcollapse eruptions has been observed in other landslides such as Cumbre Nueva and Bejenado volcanoes in La Palma (Carracedo et al., 2001), El Golfo in El Hierro (Manconi et al., 2009), Teide (Carracedo et al., 2007) and Teno (Longpré et al., 2008, 2009) in Tenerife.

Magma differentiation at the NE rift zone gave rise to eruptions of intermediate and evolved lavas (mugearites, benmoreites, and trachytes), predominantly nested in the Micheque scar (see Fig. 11 and the geological map in the data repository [see footnote 1]). Some of these eruptions, such as Los Lomos del Viejo and La Vieja (in the center of Fig. 10D), are located directly on the eastern wall of the La Orotava Valley and clearly postdate the collapse, although these eruptions may still have been associated with the Micheque felsic volcanism. The phonolitic eruption in La Orotava valley dated at 223 ka (see Fig. 10D) indicates that some late felsic volcanism occurred inside the Orotava collapse basin too.

Eruptive Rates and Growth Patterns of the NE Rift

The NE rift zone currently represents a volume of ~510 km^3 and reached a maximum volume of ~615 km^3 ca. 840 ka (before the collapses; estimated from GIS digital geologic maps and analysis of DEM based on topographic data by GRAFCAN) and is therefore the largest rift in the Canary Islands (Paris, 2002; Paris et al., 2005b). It developed in the posterosive rejuvenation stage of Tenerife Island. Volumes and eruptive growth rates during the developmental stage of the rift in the Miocene and Pliocene epochs have not been estimated because of a general lack of outcrops and geochronological data. However, the information provided through galerías and the outcrops of the area bordering the Anaga massif suggest that the volume of the rift may have reached ~200 km^3 prior to the onset of the last major stage of growth (Pleistocene).

Ancochea et al. (1990) carried out an initial assessment of the eruptive rates of the "Cordillera Dorsal" (the NE Rift), estimating a volcanic edifice of 25 × 18 × 1.6 km (360 km^3). Of this, 25%–30% was assumed to correspond to the "Old Basaltic Series" (the Miocene shield). For a formation period that Ancochea et al. (1990) limited to 200 k.y., an eruptive rate of 1.25–1.50 km^3/k.y. was projected. We estimate the volume erupted in the NE rift zone during the last one million years at ~415 km^3, with an average eruptive rate of 0.41 km^3/k.y. for this interval (Fig. 14). Eruptive rates were high and apparently continuous between 1 Ma and 840 ka (2.5 km^3/k.y.). These are considerably higher than those estimated for the shield stage of development of El Hierro and La Palma (<1.5 km^3/k.y.; Carracedo et al., 2001), and La Gomera (0.5 km^3/k.y.; Paris et al., 2005a), but in the range of that inferred for the shield stage of the island of Gran Canaria (2 km^3/k.y.; Schmincke, 1994).

Together, the three lateral collapses (Micheque, Güímar, and La Orotava) have involved a loss of ~170 km^3 of rock material, reducing the volume of the rift to some 445 km^3. The concentration of three massive collapses in a short time interval (150–250 k.y.) appears to require much greater rift growth rates than those generally characteristic of rejuvenation stages in the Canary Islands, which average 0.5–0.8 km^3/k.y. After the La Orotava collapse, the eruptive rate declined to ~0.25 km^3/k.y, which may account for the absence of further landslides off the rift. It seems the rift has presently attained a semistable configuration. In this latest stage, the vent distribution relaxed, spreading beyond the crest of the rift. Erosion in this period is limited to the incision of barrancos and recession of coastal cliffs and collapse scarps.

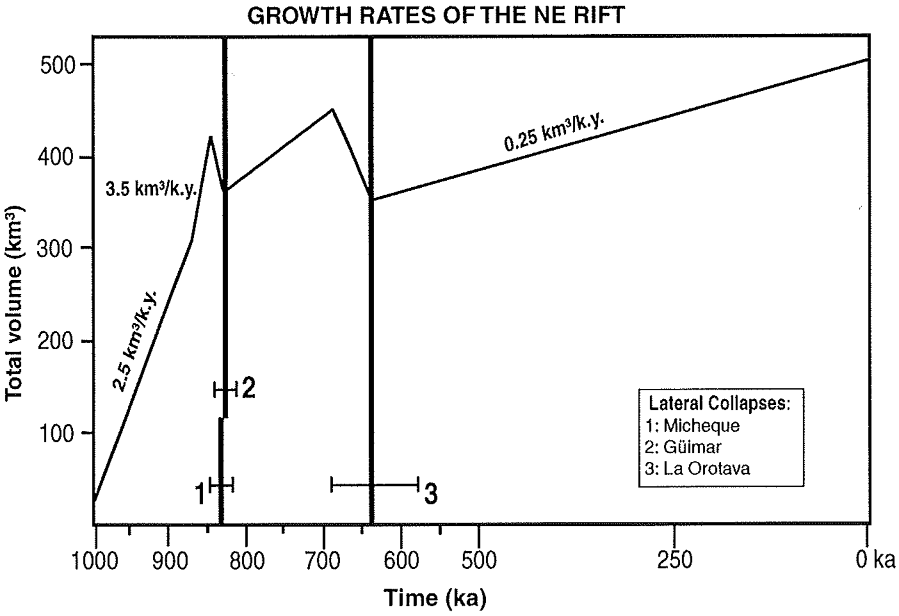

Figure 14. Temporal evolution of eruptive rates and volumes of the NE rift zone showing sharp increases in eruptive rate prior to the successive giant landslides.

These estimates can be refined locally when growth rates are calculated in m/k.y., taking advantage of the accurately dated lava sequences in both the Pared de Güímar and the Los Dornajos galería. In the Pared de Güímar, the section of some 500 m thickness appears to have formed between the base of the Jaramillo event (1072 ka) to the Matuyama-Brunhes boundary (780 ka), which would give the minimum value of rift growth at 1.7 m/k.y. However, if the ages of 1008 ± 20 ka and 860 ± 18 for the base and top of the sequence of the Pared de Güímar are taken into account (see Figs. 5 and 7), the average eruptive rate in this period may be as high as 3.3 m/k.y. The sequence of the north scarp of the Güímar Valley includes 500 m of lava flows with an age of 929 ± 20 ka at the base and discordant Micheque landslide fill lavas at the top, dated in that area at 806 ± 18 ka. These ages result in a calculated growth rate over 4 m/k.y. The highest eruptive rates, however, are those of the initial fill-in of the basin of the first (Micheque) lateral collapse. The Los Dornajos galería tunnels some 2800 m through the fill-in sequence until it reaches the avalanche breccia. Assuming a flow dip of 5°–10°, and a fill-in duration of some 20 k.y., as deduced from the ages obtained at the beginning and end of the initial fill-in sequence of the landslide basin (see Fig. 4), the growth rate exceeds 12 m/k.y. This is the highest observed in the Canaries so far, but it is comparable in magnitude to those reported for other nested volcanoes, such as Bejenado in La Palma, which grew up to 600 m in ~50 k.y. (Carracedo et al., 2001), or major shield stages (Schmincke, 1994).

A Model of the Evolution of Rifts in the Canary Islands

A general model for the evolution of volcanic rifts in the Canaries has to be based not only on our study of the NE rift of Tenerife but also on observations on rift zones of other islands in the Canaries, such as on El Hierro (Guillou et al., 1996; Carracedo et al., 2001), La Palma (Carracedo et al., 1999a, 1999b, 2001; Walter and Troll, 2003), Gran Canaria (Guillou et al., 2004b; Hansen, 2009), and Tenerife (Ancochea et al., 1999; Walter et al., 2005; Guillou et al., 2004a; Carracedo, 1994; Carracedo et al., 2007).

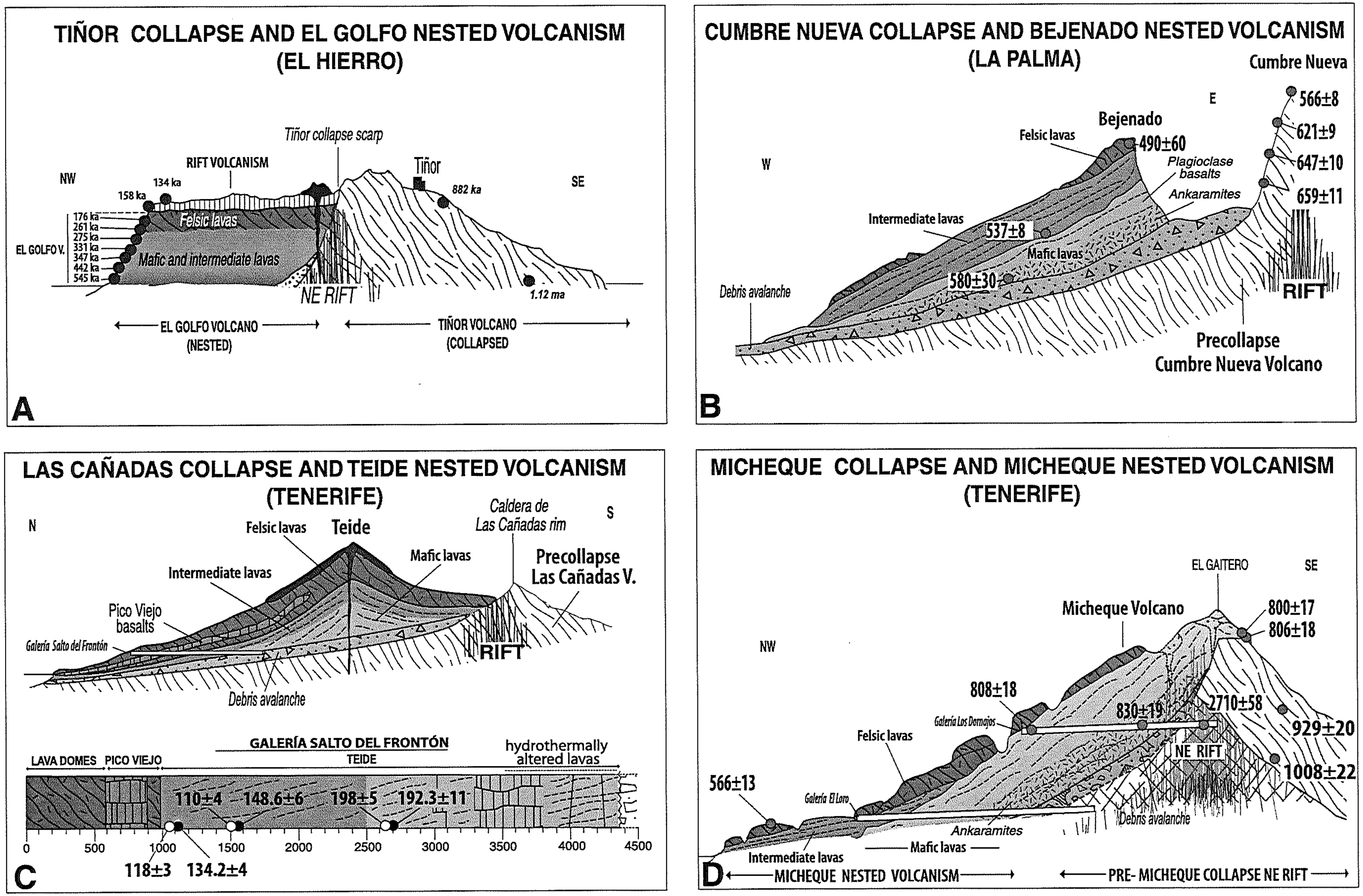

Figure 15. Examples in the Canary Islands of rifts and associated landslides with subsequent nested volcanism. Note the progressive magmatic differentiation in the sequences filling the landslide scars. In C: open circles are K/Ar ages from Carracedo et al. (2007), and closed circles are new ^{40}Ar/^{39}Ar step-heating ages by B. Singer and B. Jicha, Rare Gas Laboratory, University of Wisconsin–Madison, USA (personal commun.).

A comparative analysis of the evolution of different Canarian rifts (Fig. 15) outlines notable common characteristics. Rifts are recurrent features that show cyclic behavior with a broad sequence of events: (1) growth, (2) instability, (3) flank collapse, (4) nested volcanism, and (5) eruptive decline and dispersion. The duration of these cycles is typically on the order of 500 k.y., whereas nested volcanism generally lasts for 150–300 k.y. (see Fig. 15).

Rifts may stop growing and erode. However, commonly they surpass the stability limit and restore their equilibrium by massive flank collapses. We propose a model for the evolution of mature Canarian rifts consisting of four key stages (Fig. 16)

(1) Rifts are formed by the accumulation of eruptions fed by magma supplied through fissures (dikes). As the rifts evolve, the plumbing system becomes progressively fixed in the form of feeder dikes, eventually giving rise to predominantly basaltic fissure eruptions parallel to the main direction of the rift, forming a swarm of dikes of increasing anisotropy. In evolved rifts, this regime persists as a well-established plumbing system until volcanic activity ceases or the rift grows to instability and collapses.

(2) Flank collapses at the rift catastrophically disrupt the established fissure plumbing system. Initial collapses are likely to coincide with climactic phases of eruptive and intrusive activity. Unloading and decompression give rise to violent explosions, fracturing, and the opening of eruptive vents. The fissure plumbing system may change to a central one as eruptions concentrate inside the collapse embayment and around the collapse scar. Simultaneously, eruptive activity at the rifts may decline.

(3) Collapse unloading (i.e., decompression, gas expansion, and possibly isostatic rebound) facilitates the ascent and eruption of mafic, high-density, and crystal-rich fractions of magma that resided in the lower part of the magmatic conduits prior to the collapse (upper mantle). These dense, crystal-rich magmas—ankaramites and plagioclase basalts—often dominate the initial postcollapse stages of nested volcanism (e.g., Taburiente volcano in La Palma, Teno in Tenerife, or El Golfo in El Hierro).

(4) Plumbing disruption and fracturing assist emplacement and residence of magmas at increasingly shallower depths and facilitate magmatic differentiation, leading to a progressive shift toward intermediate and felsic nested eruptions. If volcanism continues, a

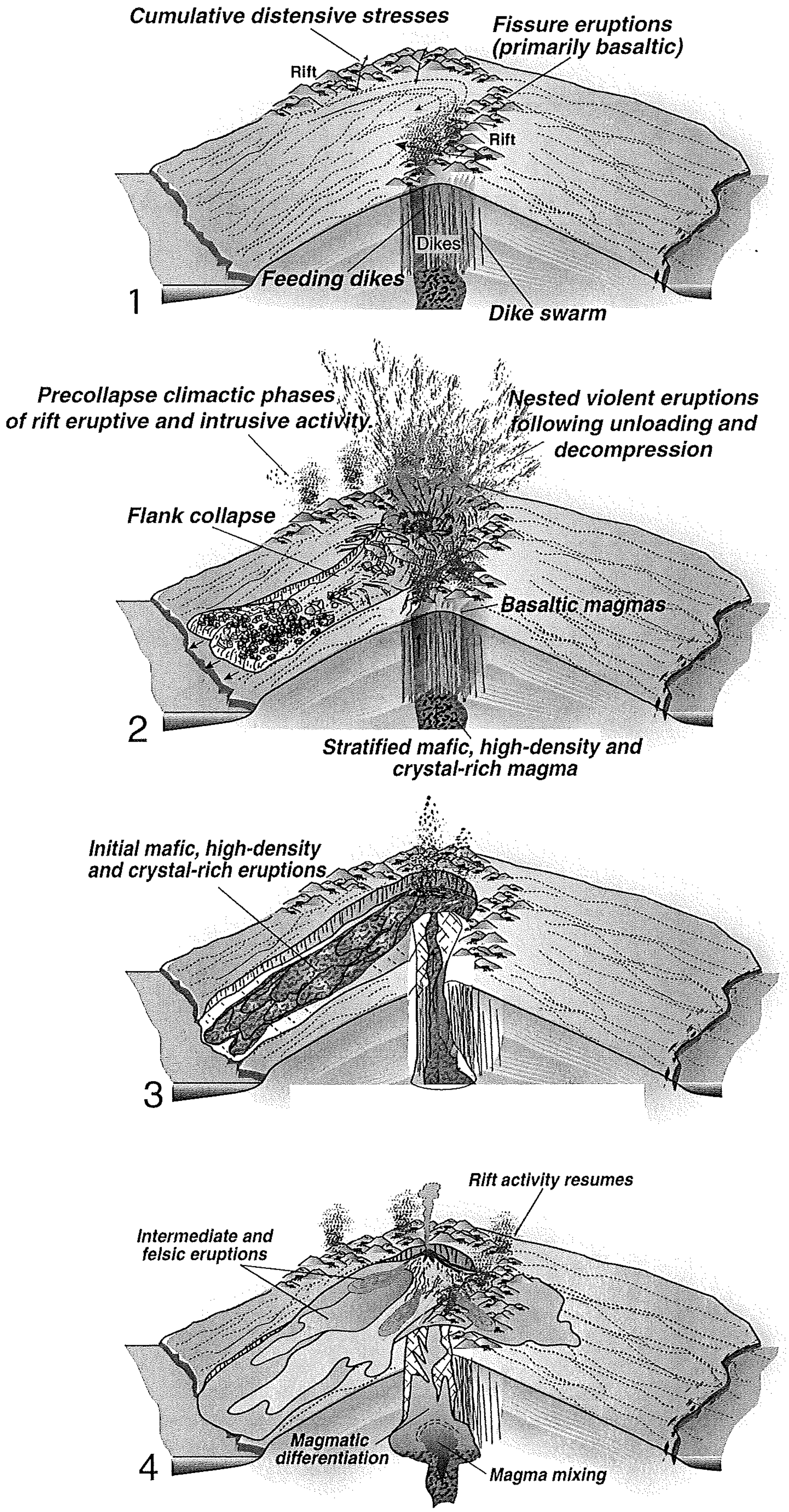

Figure 16. Simplified model of the evolution of Canarian rifts. See text for explanation.

central volcano may develop (e.g., Teide and Micheque volcanoes in Tenerife; Bejenado volcano in La Palma; Vallehermoso volcano in La Gomera). Increasing size and height of the stratocone will further filter the ascent of dense mafic lavas (Davidson and De Silva, 2000; Pinel and Jaupart, 2000), and subsequent subaerial growth will be predominantly by intermediate and felsic eruptions. Finally, the edifice reaches a critical height and a physical limit for summit eruptions, and nested volcanism is modified to felsic lava dome eruptions around the base of the evolving stratovolcano (e.g., Teide). Nested volcanism progressively declines, rift activity resumes, and a new cycle may begin.

The behavior of these rifts, some of which have completed their cycle of activity, suggests that Teide volcano may have reached a terminal stage in the Holocene epoch, and summit eruptions are likely to be few and far between. The 190 k.y. period of relatively scant eruptive activity at the rifts, but with eruptions focused inside the Las Cañadas basin, changed significantly ~12 k.y. ago, when the Teide–Pico Viejo stratocones seem to have completed their main phase of development (Carracedo et al., 2007). Since that time, ~60%–80% were basaltic fissure eruptions on the rifts, whereas only 20%–40% were felsic eruptions related to the stratovolcanoes nested in the Las Cañadas collapse basin. Only one Holocene summit eruption (phonolitic) of the Teide stratocone has occurred, whereas 10–12 phonolitic lava domes and coulees erupted at the basal perimeter of this volcano. We consider this to be the signature of the final stages of a "rift–collapse–fill-in" evolutionary cycle.

CONCLUSIONS

The latest cycle of activity of the NE rift zone took place in the Pleistocene epoch, between ca. 1.1 Ma and the present. During the final stage of development, a period of intense eruptive and intrusive activity occurred between 1.1 Ma and 0.83 Ma. The volcano increased in height at rates of at least 1.7 m/k.y. (possibly in excess of 3.3 m/k.y. occasionally, especially between 1008 and 860 ka). Consequently, the volcanic structure may have reached a highly unstable configuration.

From ca. 830 ka on, three lateral collapses mass wasted the NE rift zone: The roughly contemporaneous Micheque and Güímar landslides (at ca. 830 ka), and the subsequent La Orotava landslide (between 690 and 566 ka). Proof of the existence of the Micheque landslide scar at the NW flank of the NE rift zone and north of La Orotava Valley is based on stratigraphic and geochronological differences between the eastern and western flanks of the central part of the NE rift zone and the presence of a landslide breccia resting upon a much older (Pliocene, 2.7 Ma) formation in several galerías (Los Dornajos, El Loro). The breccia forms the substrate to a fill-in sequence that conceals the landslide scar and spans from 830 ka up to 530 ka. The eruptive rates of these initial stages of the filling process exceeded 12 m/k.y., and perhaps occasionally reached up to 24 m/k.y.

With the available data, it is difficult to affirm which of the two initial landslides occurred first. However, we infer that the Micheque collapse was the first to take place because of the much greater eruptive rates and volume of the postcollapse volcanism nested in the Micheque basin than in the Güímar Valley. We hypothesize that the first landslide to occur was triggered coinciding with a climactic phase of eruptive and intrusive activity at the rift, followed by equally intense nested activity at the landslide scar. In contrast, the subsequent landslide was probably predominantly gravitational in origin, in response to increased instability of the NE rift zone following the occurrence of the first lateral landslide, thus explaining the much lesser nested volcanism.

Volcanic sequences filling the basin of the Micheque landslide record a change in composition, evolving from dense, crystal-rich, mafic basalts and ankaramites to lavas of intermediate composition and, finally, to felsic lavas (trachytes and phonolites).

The sequences filling the Micheque collapse basin and forming the Güímar collapse escarpment have recorded normal polarity events within the Matuyama reverse polarity epoch. K/Ar dating points to the presence in these sequences of the M-B precursor subchron (819–788 ka) and the Jaramillo subchron (1072–988 ka).

Our study of the NE rift zone supports the idea that volcanic rift structures can be long-lasting and have recurring activity, possibly controlling the formation of oceanic islands from their initial stages, although considerable variation in dike orientation through time can be observed. A characteristic feature of rifts is that they can grow excessively until they collapse catastrophically. They generally reach this critical stage of instability coinciding with climactic phases of intrusive and eruptive activity. In these stages, the gravitational tensions imposed by the overgrown and steep rift zones add to the progressive expansion of the structure necessary to accommodate the continued injection of dikes and other shallow intrusions.

Comparative analysis of the evolution of rifts in the Canaries generally shows cycles of growth–instability–flank collapse–nested volcanism–eruptive decline and dispersion. The duration of these cycles is on the order of 500 k.y., and that of nested volcanism 150–300 k.y. According to these observations, Teide volcano may be in a terminal stage in which summit eruptive activity will likely be progressively scant and sporadic, and volcanism will concentrate in the rifts (mainly in the NW rift as basaltic fissure eruptions) and as parasitic felsic lava domes at the foot of the central volcano.

In response to several lateral collapses in the Canaries, variations in magma composition appear to occur, both in the NE rift zone and in other landslides on Tenerife and on other islands of the archipelago. A collapse implies breaching of the established feeding system of the rift, which provides mafic magmas by way of basaltic fissure eruptions. The response is the concentration of progressively centralized eruptions focusing in the interior of the landslide basin, thus progressively filling up the collapse scar. The emplacement of magma at increasingly shallower depth within this nested volcanic edifice will allow for extensive modification of magma and will lead to progressively more differentiated eruptions, commonly reaching felsic compositions (trachytes, phonolites) that become more and more dominant due to the progressive increase in height of the volcanoes nested inside the landslide embayments.

Although felsic volcanic complexes in the Canaries may originate from a variety of processes, a considerable volume of differentiated volcanism in the Canaries appears to be associated with rift flank collapses that are followed by abundant and prolonged nested volcanism. Occasionally, nested eruptions evolve from initially mafic to terminally felsic compositions. Lateral collapses may consequently be considered to represent a major cause for structural and petrological variability in ocean-island settings. On the other hand, the existence of significant felsic volcanism in rift-dominated ridges may be a first-order indicator for a potential earlier "high volcanicity" lateral collapse.

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