

# Repeated debris avalanches on Tenerife and genesis of Las Cañadas caldera wall (Canary Islands)

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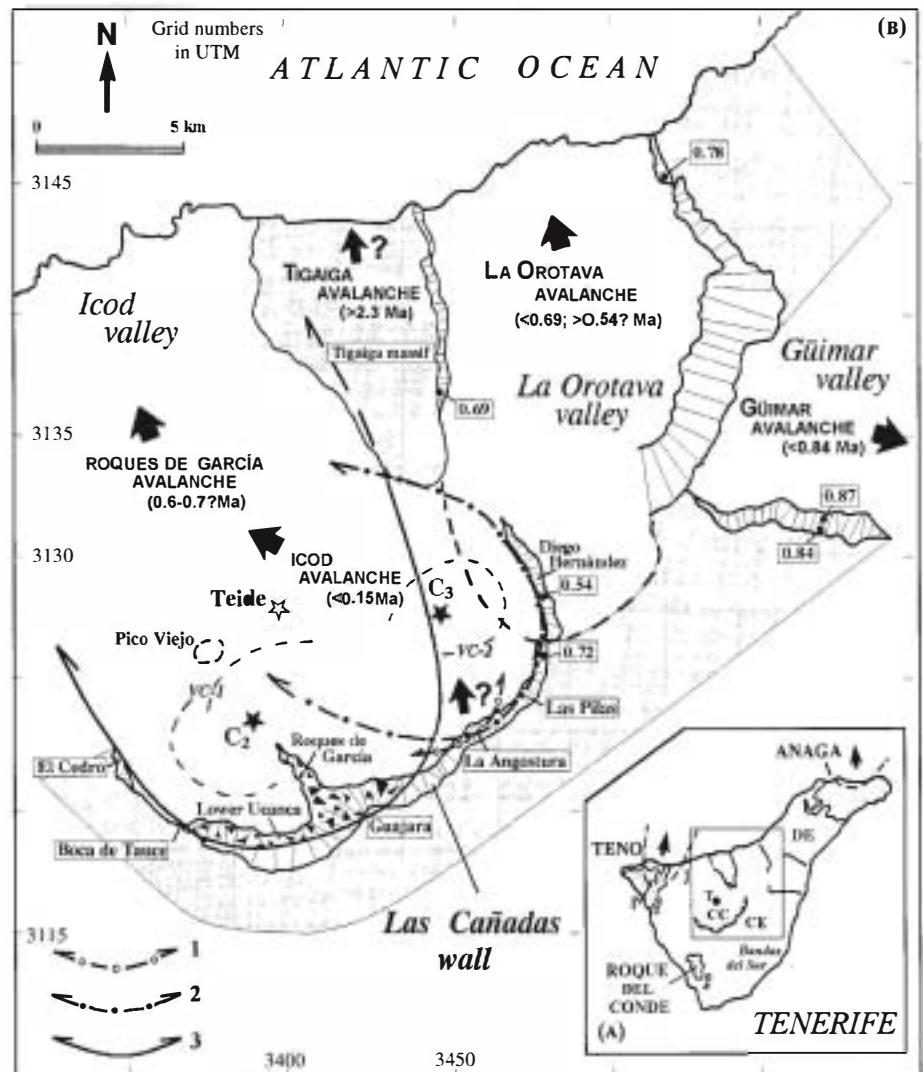
## ABSTRACT

Geologic evidence on Tenerife, Canary Islands, indicates six successive north-directed debris avalanche events, including: the Anaga and Teno (ca. 6 Ma) events that affected the old basaltic series, and the Tigaiga (>2.3 Ma), Roques de García (possibly 0.6–0.7 Ma), Orotava (ca. 0.6 Ma), and Icod (<0.15 Ma) avalanche events that affected the Cañadas and Dorsal volcanic edifices. The approximate total volume (>1000 km<sup>3</sup>) inferred for these events can account for the volume of previous estimates of offshore volcanic debris. These repeated flank failures can also account for the present morphology of Las Cañadas caldera wall, which partly bounds a multiepisodic lateral-collapse structure 25 km wide.

## INTRODUCTION

The Cañadas volcanic edifice of Tenerife, Canary Islands, grew upon the 8–3.2 Ma old basaltic series comprising the Teno, Anaga, and Roque del Conde massifs (Fig. 1A). It is currently indented by the Las Cañadas caldera, a semielliptical depression having a northeast-trending axis 16 km long and a southeastern wall as high as 500 m. The origin of the Cañadas caldera has long been debated. In the recent years the debate has focused on the alternatives of vertical collapse versus lateral collapse, or a combination of both. We recognize that deposits of both ignimbrites and debris avalanches exist both on land and offshore of Tenerife. In this paper we focus on the avalanches, differentiating several successive events that we interpret as repeated lateral collapses of the Cañadas edifice and that can explain the scalloped horseshoe trace of the caldera wall. The hypothesis of lateral collapse was first expressed by Navarro and Coello (1989), and the recent discovery of more than

Figure 1. A: Main volcanic structures of Tenerife Island. CE, Las Cañadas edifice; CC, Las Cañadas caldera; T, Teide; DE, Dorsal edifice; I-I', cross section of Figure 3. B: Sketch map of Las Cañadas lateral-collapse structure; contours drawn from satellite Spot image; ages in Ma. VC-1 and VC-2, inferred position of vertical-collapse calderas; C<sub>2</sub> and C<sub>3</sub>, inferred centers for Cañadas II and Cañadas III phase edifices. Curves 1, 2, and 3 are traces of successive avalanche rim faults: Tigaiga, Icod, and Roques de García respectively; arrows indicate directions of the avalanches.



1000 km<sup>3</sup> of volcanic debris spread widely across the sea floor north of Tenerife is a strong argument in favor of the hypothesis (Watts and Masson, 1995). Subaerial evidence also supports this origin for the Las Cañadas caldera.

## VOLCANIC STRATIGRAPHY AND CHRONOLOGY OF LAS CAÑADAS EDIFICE

Las Cañadas edifice was built by a long complex series of eruptions during the past 3.5 m.y. Figure 2 presents a simplified sequence based on geologic mapping, radiometric dating, and other observations (Ancochea et al., 1999). Las Cañadas grew in three main phases. The Cañadas I phase (C-I phase), between 3.5 and 2.6 Ma, was essentially basaltic but included a few late salic eruptions. Basaltic flows dated as 3 Ma crop out low in the caldera wall at Boca de Tauce and La Angostura (Fig. 1B) and in the deepest ravines along the southern flank of the Cañadas edifice. To the north flank, at the base of the Tigaiga massif (Fig. 1B), is the Tigaiga breccia described by Bravo (1962) and interpreted as a landslide deposit by Navarro and Coello (1989). This breccia is 200–300 m thick but is visible only in water tunnels. It consists of fragmented volcanic material within a clay-rich matrix; it is overlain by 2.3 Ma trachybasaltic flows (Ibarrola et al., 1993). The Tigaiga breccia is inferred to mark the end of the C-I phase of growth.

The Cañadas II phase (C-II phase), produced a lower (2.3–2.0 Ma) sequence of trachybasalt flows and an upper sequence of southwest-dipping phonolites that crop out in the caldera wall at El Centro (Fig. 1B). On the upper south flank of the Cañadas edifice are intermediate to salic flows

(2.3–2.2 Ma), overlain by a thick basaltic succession (1.9 Ma) and then south-dipping phonolites (upper Ucanca unit, 1.5–1.4 Ma). Several welded and nonwelded pyroclastic flows of the C-II phase (Fúster et al., 1994) that have Ar/Ar ages between 1.8 and 1.5 Ma (Fig. 2) are well exposed in the southwest slopes of the island. Some of these pyroclastic episodes represent rapid eruptions of several square kilometers or ten of cubic kilometers and therefore probably represent a multi-episodic vertical collapse caldera (VC-1, Fig. 1B) much older than previously recognized (Martí et al., 1994, 1997) on top of the C-II phase edifice. Dikes attributed to the C-II phase edifice radiate from a locus (C2, Fig. 1B) that we infer to approximate the center of the C-II phase edifice. Morphologic reconstruction (Ancochea et al., 1999) suggests that the C-II phase central edifice could have had a basal radius of about 20 km and reached an elevation of 3200 m. A vertical-collapse caldera related to the ignimbrites must have been located in the vicinity of C2 (VC-1, Fig. 1B), but its size, shape, and exact location are uncertain.

The Cañadas III phase (C-IIIa phase) began ca. 1.1 Ma with basaltic lava flows followed by thick phonolic flows that are now exposed in the Tigaiga massif and also compose the Las Pilas unit in the caldera wall (Fig. 1B). The Dorsal edifice (Ancochea et al., 1999), a northeast-trending volcanic ridge, the westernmost flows of which are interbedded with salic rocks from the C-III phase central edifice, was built during the same time. Additional pyroclastic flows (Las Américas ignimbrites, Fig. 2) exposed near the south coast are dated as 0.9–1.0 Ma (Fúster et al., 1994). The upper level of the caldera wall is characterized by several 10-m-thick welded and nonwelded near-

vent phonolitic fall deposits that erupted ca. 0.9 and 0.6 Ma (e.g., at Guajara peak). The final activity of the C-III phase (C-IIIb) edifice (Fig. 2) was dominated by a complex succession of phonolitic pyroclastic eruptions that were studied by Martí et al. (1990) in the easternmost Diego Hernández section of the caldera wall and by Wolff (1985), Alonso (1989), and Bryan et al. (1998) in the Bandas del Sur (Fig. 1B). K/Ar and Ar/Ar ages for this late pyroclastic series are between 0.6 Ma (Arico welded ignimbrite) and 0.13 or 0.17 Ma (El Abrigo ignimbrite) and are from rocks exposed on top of the Diego Hernández segment of the caldera wall (Ancochea et al., 1990; Mitjavila and Villa, 1993). Here those pyroclastic deposits are sufficiently voluminous (Bryan et al., 1998) that their eruption probably produced a new complex, vertical-collapse caldera of uncertain size and shape, centered in the vicinity of C3 (VC-2, Fig. 1B).

## DEBRIS-AVALANCHE EPISODES

### Teno and Anaga Avalanches of the Old Basaltic Edifices

Watts and Masson (1995) used sonar backscatter to differentiate four debris units on the sea floor north of Tenerife. The oldest units probably correlate with flank failures in the old basaltic massif of Teno and Anaga. Age information is currently not available for the Anaga avalanche, which is likely a pre-Cañadas event. In Teno, however, between an older (6.3–6.7 Ma) west-dipping pile and a younger (5.6–5.0 Ma) horizontal pile (Ancochea et al., 1990), is a breccia overlain by volcanic debris flows, each 1–2 m thick. This sequence probably represents the subaerial remains of the Teno avalanche, which therefore must have an age of ca. 6 Ma (Fig. 3).

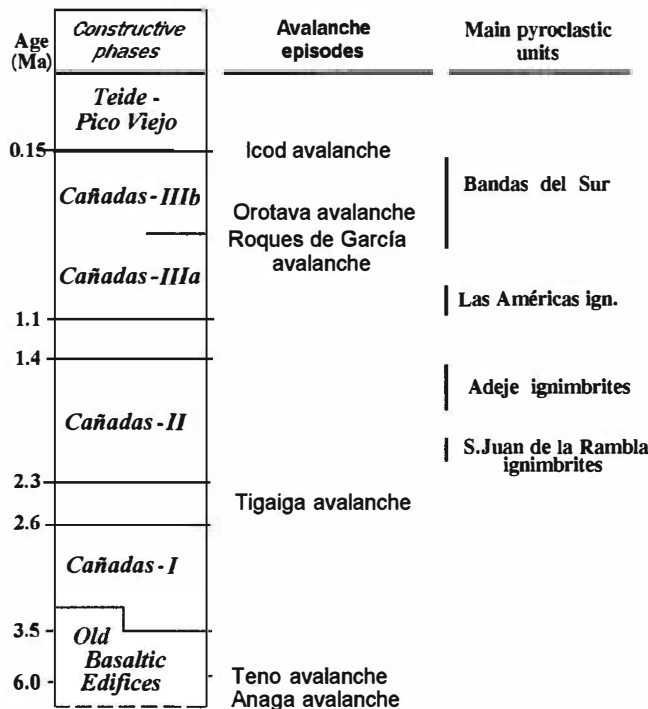


Figure 2. Simplified volcanic stratigraphy, avalanche episodes, and main pyroclastic units of Las Cañadas edifice.

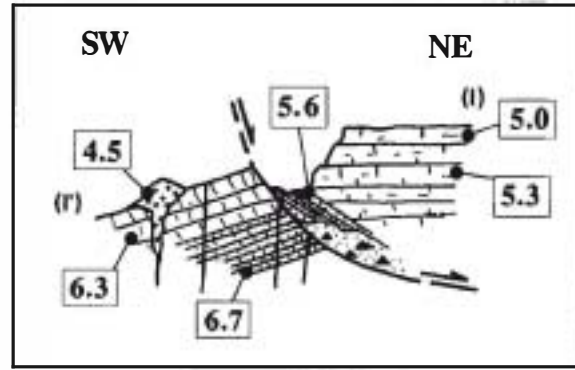
### Tigaiga Avalanche

Few clues exist for reconstructing the shape of the C-I phase volcano. Assuming that it was a more or less circular basaltic shield, it could have had a radius of ~19 km and height of ~3000 m (Ancochea et al., 1999). Alternatively, assuming that it was built along a two- or three-armed rift system (Carracedo, 1994), it might have resembled the Canary Island of El Hierro (Fúster et al., 1993), which has an avalanche caldera (El Golfo) 15 km in diameter (Masson, 1996). In this latter case, the C-I phase volcano could have had an old (ca. 2.5 Ma) wide depression open to the north and related to the formation of the Tigaiga breccia overlain by 2.3 Ma trachybasalt flows. The trace of a headwall fault may exist along the present caldera wall at La Angostura (Fig. 1B), separating brecciated younger trachyte (2.6–2.7 Ma) at a lower elevation from older (3 Ma) basalt flows in the cliff above (Ancochea et al., 1999).

### Roques de García Avalanche

In the caldera wall, the lower Ucanca unit (Fig. 1B) is a complex of lava flows, intrusions,

**Figure 3. Schematic cross section of Teno massif showing stratigraphic position of Teno avalanche deposit. Ages in Ma. Cross section location in Figure 1A.**



and pyroclastic or polygenic breccias jumbled together with no clear stratigraphy because of the intense fracturing without a preferred trend. It is cut by many dikes having various orientations. The lower Ucanca unit grades across the Cañadas caldera into the Roques de García unit (Fig. 1B). The Roques de García unit is deeply eroded, and its lower levels have a chaotic structure in which blocks of various lithologies and sizes appear to be broken into clasts that can be fit together locally. These shattered blocks are embedded within a more intensively crushed matrix and injected by clastic dikes a few centimeters thick and composed of variously crushed rocks. The lower part of the Roques de García unit has characteristics of a landslide deposit; we interpret it as the proximal facies of a debris-avalanche deposit. In contrast, the upper levels of the Roques de García unit consist of stratified volcanoclastic sediments that are cut locally by later dikes (Fig. 4B). At the foot of the present caldera wall, deep hydrothermal alteration of breccias indicates that the deep interior of the volcanic edifice was involved in an avalanche of great size, not a local rockfall from a preexisting caldera wall.

The age of this avalanche is not well constrained. One phonolitic fragment and one intrusion (or megablock) within the breccia are dated

as 1.7 and 1.4 Ma (Fig. 4B), respectively, and one inward-dipping dike (cone sheet or tilted and slided fragment of dike) has been dated as 1.3 Ma. Thus the materials involved in the avalanche are similar in age to the youngest intact rocks of the C-II phase edifice. One dike cutting the undeformed volcanoclastic sedimentary rocks is dated as 0.43 Ma, and one radial dike cutting the lower Ucanca unit is dated as 0.6 Ma. These two sets of ages constrain the age of the Roques de García collapse. Moreover, if the uppermost part of the section at Guajara (Fig. 1B) is cut by the headwall fault of the avalanche caldera, the collapse could have occurred more recently than 0.90 Ma (Ancochea et al., 1995) or even 0.60 Ma (Martí et al., 1997). However, if the uppermost Guajara was not cut by the avalanche, but only later by retreat of the caldera wall, the Roques de García event must have occurred ca. 1.4–1.0 Ma. No more precision is available for this avalanche event because datable synfailure magmatic material has not been identified.

#### Orotava and Güimar Avalanches

The Orotava valley is broad (10–12 km wide, opening northward) and steep-walled; a lateral collapse origin is generally accepted. It cuts sharply across the basaltic Dorsal Edifice on its

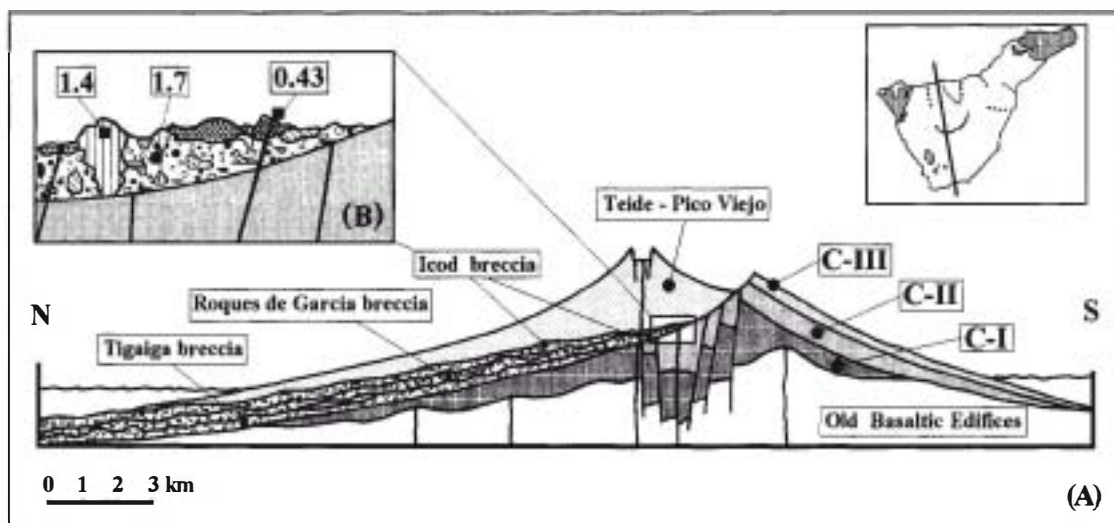
east side and the C-III phase Tigaiga massif on its west side and is floored by a breccia (Coello, 1973). It formed later than 0.69 Ma, the youngest age measured in the C-III phase rocks of the west wall (Tigaiga) and headwall (cutting the Las Pilas unit), but before the oldest fill now exposed (0.54 Ma; Ancochea et al., 1995) in the younger Diego Hernández escarpment (Fig. 1B). The southeast flank of the Dorsal edifice was also marked by another, but south-directed, large landslide that formed the Güimar valley later than 0.84 Ma, as measured on the upper lava flows of its western wall (Ancochea et al., 1990).

#### Icod Avalanche

Another north-directed landslide produced the Icod valley (Fig. 1B) ca. 0.15 Ma (Navarro and Coello, 1989; Ancochea et al., 1990; Watts and Masson, 1995). A subaerial deposit of this landslide is unknown (except in some water tunnels), but can be seen on the sea floor north of Tenerife (Watts and Masson, 1995). For this avalanche, the principal uncertainty is the location of its headwall. Martí et al. (1997) suggested a mechanical connection between a vertical collapse (their Diego Hernández caldera) and the Icod flank collapse, the former triggering the latter. In their interpretation the Icod collapse was limited to the northern flank of the Cañadas edifice. That interpretation has been challenged by Ancochea et al. (1998), and Watts and Masson (1998), who argued that the Icod slide extended southward to the present caldera wall, as proposed by Navarro and Coello (1989) and Watts and Masson (1995). We accept this interpretation, but apply it only to the eastern segment of the caldera wall because we believe that the western segment was formed by the older Roques de García avalanche.

#### Volume of Avalanche Deposits

The existence of more than 1000 km<sup>3</sup> of debris-avalanche and debris-flow deposits on the sea floor north of Tenerife has been demonstrated



**Figure 4. A: Schematic cross section of Tenerife Island; Cañadas I, Cañadas II, and Cañadas III phases are main volcanic units. B: Roques de García debris-avalanche deposit overlain by volcanoclastic sediments cut by dikes. New ages in Ma.**

through marine geophysical studies (Watts and Masson, 1995; Teide Group, 1997). These deposits were formerly attributed to the Icod and Orotava avalanches, but the volume of only these valleys is too small to account for all of the submarine deposits. The volumes of the successive C-I, C-II, and C-III phase edifices can be estimated as about 1000–1200 km<sup>3</sup> each. If 20%–25% of each edifice (typical of examples elsewhere; Holcomb and Searle, 1991) was lost in lateral collapses, the total volume lost is about 700–850 km<sup>3</sup>. However, this does not include material that was lost in forming the Orotava valley, or the unknown volume of the Anaga and Teno landslides; if these are included, and taking into account of volume increase during transport, there is better agreement between the volume of submarine debris and total subaerial volume lost in the avalanches.

## CONCLUSIONS

The Cañadas edifice was built in three eruptive periods, each ending in large-scale flank collapse. The duration of eruptive periods was nearly 1 m.y. each, enough time to build volcanic cones large enough (Ancochea et al., 1999) to become gravitationally unstable. Several potential caldera-forming pyroclastic eruptions occurred, but the resulting structures are no longer visible. There is geologic evidence on land of six north-directed flank-failure events: the Anaga and Teno (ca. 6 Ma) events affecting the old basaltic series, followed by the Tigaiga (>2.3 Ma), Roques de García (possibly 0.6–0.7 Ma), Orotava (ca. 0.6 Ma), and the Icod (<0.15 Ma) avalanches affecting the Cañadas and Dorsal edifices. It is possible that other collapses occurred during submarine growth of the Tenerife volcanic complex. This repetition of flank collapse is consistent with what is now known about many other oceanic islands. Canarian examples have been described for El Hierro (Holcomb and Searle, 1991; Fúster et al., 1993) and La Palma Islands (Ancochea et al., 1994). The total volume lost in the avalanches can account roughly for the volume of volcanic debris observed on the sea floor north of Tenerife. Three distinct collapses produced different segments of the Las Cañadas caldera wall, and a fourth produced the Orotava valley. Together they compose a multiproduct lateral-collapse structure roughly 25 km wide (Fig. 1B). Since the first of these lateral collapses, the Cañadas edifice probably was very asymmetric (Fig. 4A), the old, clay-rich Tigaiga breccia possibly acting as a weak detachment surface for successive later landslides. In this interpretation, the present shape of the Las Cañadas caldera wall is not related to ignimbritic eruptions and vertical collapse, but is instead a product of repeated flank failures. The western segment of the caldera wall is the legacy of the Roques de García avalanche, and the eastern segment is the result of the younger Icod event.

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