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Abstract

The Las Cañadas caldera is one of the best exposed volcanic calderas in the world and one of the few known evolved alkaline volcanoes. It truncates the pre-Teide-Pico Viejo central volcanic edifice, the Las Cañadas edifice, which started to take shape at the end of the formation of a large basaltic shield that forms the main part of island of Tenerife. Historically, the origin of the Las Cañadas caldera has been controversial, as it has been interpreted as the result of either multiple vertical collapses or due to a giant sector collapse. The available stratigraphical, structural, volcanological, geochronological, and geophysical data, as well as its comparison to other well-known collapse calderas should not offer any doubt as to its direct relationship with a long history of phonolitic explosive volcanism. However, the existence of large landslide events on Tenerife, which have significantly modified the flanks of the Las Cañadas volcano, have also been used as a potential explanation for the origin of the Las Cañadas depression. This contribution reviews the available information on the Las Cañadas caldera, the causes of this controversy, and rationalises the most plausible explanation for the origin of Las Cañadas caldera based on the current evidence gathered from all previous studies.

Keywords	Las Cañadas caldera; Tenerife; Canary Islands; volcanological controversy; explosive volcanism; collapse caldera; landslides
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Las Cañadas caldera, Tenerife, Canary Islands: A review, or the end of a long volcanological controversy

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ABSTRACT.

The Las Cañadas caldera is one of the best exposed volcanic calderas in the world and one of the few known evolved alkaline volcanoes. It truncates the pre-Teide-Pico Viejo central volcanic edifice, the Las Cañadas edifice, which started to take shape at the end of the formation of a large basaltic shield that forms the main part of island of Tenerife. Historically, the origin of the Las Cañadas caldera has been controversial, as it has been interpreted as the result of either multiple vertical collapses or due to a giant sector collapse. The available stratigraphical, structural, volcanological, geochronological, and geophysical data, as well as its comparison to other well-known collapse calderas should not offer any doubt as to its direct relationship with a long history of phonolitic explosive volcanism. However, the existence of large landslide events on Tenerife, which have significantly modified the flanks of the Las Cañadas volcano, have also been used as a potential explanation for the origin of the Las Cañadas depression. This contribution reviews the available information on the Las Cañadas caldera, the causes of

this controversy, and rationalises the most plausible explanation for the origin of Las Cañadas caldera based on the current evidence gathered from all previous studies.

Key words: Las Cañadas caldera, Tenerife, volcanological controversy, explosive volcanism, collapse caldera, landslides.

1. Introduction

Named a World Heritage Site by UNESCO in 2007, the Las Cañadas caldera, on the island of Tenerife (Canary Islands), the home of the active volcanic complex Teide-Pico Viejo (TPV), is one of the most beautiful geological landscapes of our planet and one of the best exposed and most interesting volcanic calderas in the world (Fig. 1). Proof of this is the interest that it has always awakened within the international scientific community, having been studied more or less continuously, from the middle of the nineteenth century to the present day (Table 1). All these studies have provided a considerable volume of information (geological, volcanological, geophysical, geomorphological, hydrogeological, petrological, etc.) on the Las Cañadas caldera and have generated various theories about its formation, which over time have been fuelling one of the most surprising and long lasting volcanological controversies, in light of the existing data and the arguments used on some occasions.

The Las Cañadas caldera offers a typical case study in which the available geological and geophysical data have not been properly considered to solve a volcanological controversy of international proportions. At present, the two main ideas that dispute the origin of the Las Cañadas caldera correspond on the one hand to a depression caused by one or several landslides towards the northern side of Tenerife (e.g., Bravo, 1962;

Coello, 1973; Ancochea et al., 1990, 1999; Carracedo, 1994; Cantagrel et al., 1999; Watts et al., 1995, 2001), and on the other hand to a depression resulting from a series of vertical collapses of the volcanic edifice associated with repeated cycles of explosive volcanism (e.g., Fuster et al., 1968; Araña, 1971; Martí et al., 1994, 1997; Martí and Gudmundsson, 2000).

This review focusses on the origin and development of this controversy, the correct interpretation of the available data, and on the direction and approach that future studies of this volcanic structure should take, in order to guarantee a definitive improvement of its knowledge and a significant scientific advance with respect to what is already known. This review shows that the amount and quality of available geological and geophysical data are sufficient to correctly interpret the origin of the Las Cañadas caldera, and addresses why this volcanological controversy has been sustained, in part, due to the misinterpretation and/or ignorance of some of these data.

2. Geological framework

The island of Tenerife in the Canary Islands of Spain, lies in the east-central Atlantic Ocean about 300 km off the coast of Morocco in northwest Africa, and is one of the largest and most complex volcanic systems on Earth. Tenerife rises nearly 8,000 m above the Miocene oceanic crust (Watts et al., 1997) and began to grow very quickly due to the contribution of basaltic lavas through fissural eruptions, which gave rise to a shield volcano that comprises almost 90% of the island (Fig. 3). Remnants of this basaltic shield emerge at the corners of Anaga and Teno and in the Roque del Conde (Fig. 3). These subaerial rocks have ages between 12 and 3.3 Ma according to existing radiometric dates (K-Ar and Ar-Ar) (Ancochea et al., 1990; Thirlwall et al., 2000).

Following this phase of basaltic volcanism, and after a certain period of erosion, the eruptive activity of phonolitic magmas started from much more localized centres. Their products (lavas and pyroclastics) built the Las Cañadas edifice in the centre of the island. This phonolitic volcanism alternated with basaltic volcanism and both continued the construction of the island until Present. The Las Cañadas edifice, with an age of more than 3.5 Ma, covers a large part of the subaerial sectors of the initial basaltic edifice, hence giving the impression of being much more important volumetrically than it actually is. The last part of the construction of the central volcanic complex of Tenerife corresponds to the Teide-Pico Viejo complex, which began to develop about 17-18 Ka years ago in the Las Cañadas caldera, a depression created by several destructive episodes that truncated the top of the Las Cañadas edifice.

The geological evolution of Tenerife has been controlled by regional tectonic fractures already defined in the oceanic basement of the island resulting from the differential movements between the oceanic and continental parts of the African plate (Dash and Bosshard, 1969; Bosshard and Macfarlane, 1970; Mezcua et al., 1992; Verhoef et al., 1991; Roest et al., 1992.; Mezcua et al., 1992; Watts et al., 1997; Canales and Daño-beitia, 1998; Mantovani et al., 2007; Geyer and Martí, 2010). This tectonic configuration has been slightly modified over time due, in part, to the construction of the island itself, which has constantly modified the value of gravitational stresses because of the progressive increase of the island's load on the basement, thus inducing considerable bending of the lithosphere (Watts et al., 1997) and a "spreading" of the base of the volcanic edifice. This basalt shield building volcanism continues to the present day through multiple eruption sites, including the north-eastern (Dorsal Rift) and north-western (Santiago Rift) fissure vent systems (Fig. 3), and from several small scoria-lava cones

located at the heads of major landslide valleys (La Orotava, Güímar, Icod), as well as elsewhere. The most recent basaltic eruptions occurred at Chahorra (1798), on one of the flanks of Pico Viejo stratovolcano, and at Chinyero (1909) in the Santiago del Teide Rift.

Among the most characteristic aspects of the evolution of Tenerife, as it happens on other volcanic ocean islands, is the existence of constructive (accumulation of volcanic materials) and destructive episodes (caldera collapses, sector collapses, and erosion). Caldera collapses and sector collapses involve mass movements of tens to hundreds of cubic kilometres (e.g., Martí et al., 1994; Brown et al., 2003; Martí et al., 2010; Edgar et al., 2007, 2017; Carracedo, 1994; Watts and Masson, 1995, 2001; Ablay and Hurlimann, 2000; Hurlimann et al., 2004; Hunt et al., 2011, 2013a, 2013b). Although the existence of both processes is well demonstrated, the exact causes by which they originate as well as their spatial-temporal relationships, are still unclear.

3. Las Cañadas edifice and caldera

3.1 The Las Cañadas edifice

Morphologically, the Las Cañadas edifice had an elongated structure in a SW-NE direction, a relatively flat top with a maximum height of no more than 3,000 meters, with abrupt slopes on all sides, especially in the south (Araña, 1971). These flanks had been crossed by numerous ravines that controlled the location of the pyroclastic flows coming from the upper part of the edifice. The roof of Las Cañadas edifice is now occupied by the Las Cañadas caldera in which the active volcanic complex of Teide-Pico Viejo resides.

Most of the authors who have studied the Las Cañadas edifice agree on the existence of various volcanic cycles during the construction of this volcanic complex (Furter et al., 1968; Araña, 1971; Ancochea et al., 1990, 1999; Ibarrola et al., 1993; Martí et al., 1994, 2010; Bryan et al., 1998; Huertas et al., 2002; Martí and Gudmundsson, 2000; Zafrilla, 2001; Soriano et al., 2002, 2006; Brown et al., 2003; Edgar et al., 2007). The eruptive activity of the Las Cañadas edifice has been suggested to have begun after an interruption in the construction of the basaltic shield and following an important erosive period (about > 3.5 Ma) (Ancochea et al., 1990; Martí et al., 1994). However, only its uppermost part is visible—mostly along the caldera wall and distal areas close to the southern coast—because a significant part of this volcanic complex is covered by younger basaltic volcanism deposits or due to landslide removal of sectors of the edifice. The presence of fragments of lavas and pyroclastic rocks not exposed in the outcropping part of the Las Cañadas edifice, inside the pyroclastic deposits at the caldera wall, and at more distal locations, suggests that the phonolitic activity could have started much earlier.

The stratigraphy of the exposed part of the Las Cañadas edifice can be established from the study of the caldera wall and from examining the remains of deposits that cover the slopes of the central complex (Fig. 4) (Martí et al., 1994). Thus, two stratigraphic groups separated by a first-order unconformity can be identified. The Lower Group has an age ranging from > 3.5 to < 2 Ma and includes several successions of basaltic and/or phonolitic deposits representing several volcanic centres. The Upper Group ranges from 1.57 Ma to 0.17–0.18 Ma (Ancochea et al., 1990, 1999; Mitjavila and Vila, 1993; Martí et al., 1994; Bryan et al., 1998; Huertas et al., 2002; Brown et al., 2003; Edgar et al., 2007; Boulesteix et al., 2012) and includes the Ucanca, Guajara, and Diego

Hernández formations (Fig. 5), each representing a complete phonolitic eruptive cycle several hundred thousand years long (Martí et al., 1994; Martí and Gudmundsson, 2000). The Ucanca and Guajara formations (Figs 5a and 5b) are mainly characterized by phonolitic, welded (up to 100 m thick), and non-welded fallout deposits, in addition to non-welded pyroclastic flows and surge deposits, while the presence of lavas is very scarce. The distal facies of these welded fallout deposits can have very different aspect, more typically as non-welded pumice-fall deposits (Martí et al., 1994; Bryan et al., 1998). The Diego Hernández Formation (Fig. 5c) is only composed of non-welded pyroclastic-fall and flow deposits. The periods that separate these phonolitic formations last between 120 ka to 250 ka and are represented by basaltic or intermediate rocks. Each cycle of phonolitic eruptive activity culminated in the formation of a caldera, affecting different sectors of the Las Cañadas edifice. Thus, the Las Cañadas caldera should not be considered as the result of a single event, but as a multi-cyclical destructive/constructive processes whose formation covers a period of time ranging from 1.07 to 0.17–0.18 Ma (Fig. 4).

One of the main aspects of the evolution of the upper part of the Las Cañadas edifice, corroborated by stratigraphic, geochronological, and structural data, is the SW-NE migration of the location of volcanic activity over time (Ancochea et al., 1990, 1999; Martí et al., 1994; Bryan et al., 1998; Huertas et al., 2002; Brown et al., 2003) (Fig. 4). This spatial and temporal variation can be observed both in the distribution of the deposits of the caldera wall and on the slopes of the Las Cañadas edifice, especially in the south of the island. However, after the last formation episode, volcanic activity (especially that related to phonolitic magmas) migrated towards the NW, giving rise to the formation of the Teide-Pico Viejo complex.

The distal deposits appear on the flanks of the Las Cañadas edifice, generally in areas close to the coast and mainly in the south, forming what it is locally known as the Bandas del Sur (Alonso, 1987; Bryan et al., 1998) (Fig. 3). The lack of continuity, possibly due to erosion, between the proximal and distal areas makes it difficult to establish precise stratigraphic correlations and with this, the identification of the corresponding vents for each eruption. However, for those cases in which identification has been possible, as well as for the construction of isopach maps from several fallout deposits in the distal areas, observations indicate that most of these deposits came from the area currently occupied by the Las Cañadas caldera (Both, 1973; Alonso, 1989; Martí et al., 1994; Bryan et al., 1998, 2000,; Brown et al., 2003; Brown and Branney, 2004; Edgar et al., 2002, 2007, 2017).

3.2. *Las Cañadas caldera*

The Las Cañadas caldera (Figs. 1 and 4) is an elliptical depression measuring 16 x 9 km, with a maximum depth of 600 m below the top of the caldera wall at Guajara (2,717 m.a.s.l). Its morphological boundary comprises several scalloped walls. A large spur (Roques de García) divides the caldera into two parts, the western depression being 150 m deeper than the eastern one. Towards the northwest this spur continues below the Pico Viejo lavas, as is indicated by the prominent southern bulge on the SE side of this volcano (Ablay and Martí, 2000). The caldera depression is currently filled with lavas and pyroclastic deposits mostly coming from the Teide and Pico Viejo stratovolcanoes, but also from several vents located inside the caldera and from the south-eastern sector of the Dorsal Rift. The caldera wall is visible for 27 km along the SW, SE, E, and NE sectors, being partially open in the north, at El Portillo (Fig. 5). This caldera depression

hosts the main aquifer of Tenerife and, consequently, represents the main fresh water resource for the island (Custodio 1988; Marrero-Díaz, 2010)

Los Roques de García spur (Fig. 6) gives one of the clues to understanding the origin of the Las Cañadas caldera, as we will see later in this review. Its stratigraphy is concordant with the rest of the caldera wall and was established by Martí et al. (2010) who identified several formations composed of primary pyroclastic deposits and reworked sediments, which from base to top include: the Los Roques de García Formation and the Los Azulejos Formation, both belonging to the Lower Group, as well as the lower part of the Ucanca Formation. The Los Roques de García Formation occupies the main part of the Los Roques de García spur and includes proximal facies of pyroclastic (Lower Member) and sedimentary (epiclastic) (Upper Member) deposits, predominantly breccias, all of them intruded by a dense network of phonolitic dikes and necks. Pyroclastic deposits mostly correspond to co-ignimbrite lag breccias, lithic-rich ignimbrites, and minor surge and ashfall beds. Epiclastic rocks mainly include poorly to well-stratified, proximal debris flow breccias deposited in an alluvial fan environment, with some interbedded pyroclastic and epiclastic sandstone and conglomerate units. The central sector of the Los Roques de García spur is highly fractured due to the movement of several normal faults, thus conferring a chaotic aspect to that zone. Strong hydrothermal alteration also affects some sectors of this spur, enhancing its chaotic aspect. Magnetotelluric studies (Pous et al., 2002; Coppo et al., 2008, 2010) show that the spur forms a true structural barrier that extends several thousands of meters below the present caldera floor (Fig. 7). Based on this stratigraphic and structural evidence, Martí et al. (2010) interpreted Los Roques de García either as a former Las Cañadas intracaldera sequence or as the apron of an older stratovolcano, in contrast with previous interpretations (An-

cochea et al., 1999; Cantagrel, et al., 1999; Arnaud et al., 2001; Watts and Masson, 2001) suggesting that they correspond to the products of a major debris avalanche event that contributed to the formation of the present caldera.

Several sets of phonolitic radial dykes, cone sheets, and vertical concentric dykes can be identified along the caldera wall and at Los Roques de García (Fig. 8) (Martí et al., 1994, 2010; Galindo et al., 2005; Soriano et al., 2006). Their areal distribution and structural (cross-cutting) characteristics indicate that at least two spatially and temporarily separated phonolitic chambers were responsible for their emplacement (Martí et al., 1994, 2010), as is already inferred from the stratigraphical and petrological characteristics of the Ucanca and Guajara formations (Martí et al., 1994; Zafrilla, 2001). In the case of Diego Hernandez, where phonolitic dykes are lacking, the existence of an associated phonolitic magma chamber is inferred from the presence of a thick sequence of phonolitic deposits of a younger age with slightly different petrological and geochemical characteristics compared to the previous formations (Zafrilla, 2000; Bryan et al., 2002; Edgar et al., 2007, 2017).

The NW-SE and NE-SW structural trends that are visible in many parts of the island are also present in the Las Cañadas caldera, represented by the proper long axis of the caldera, the linear alignment of basaltic vents of the Lower Group, or in the main distributions shown by the phonolitic dykes (Martí et al., 1994; Ablay and Martí, 2000). A graben structure (Los Azulejos Graben, in Galindo et al., 2005), oriented NE-SW and which is the continuation of the Dorsal Rift inside the depression, affects the western margin of the Las Cañadas caldera wall, particularly the southern side of the Los Roques de García spur (Fig. 9). Cross-cutting stratigraphic and structural relations indicate that the graben system was active for at least 0.5 Ma, from the end of the UCCA Forma-

tion to the end of the Guajara Formation; and kinematic indicators on the fault planes at both sides of the graben suggest several up and down displacements (Galindo et al., 2005). However, further reactivation of this set of faults during inflation and deflation of shallow magma chambers and during the formation of the western and central sectors of the caldera is possible (Galindo et al., 2005).

Finally, it is important to mention the position of the Teide-Pico Viejo stratovolcanoes with respect to the orientation of the caldera. They rest in the northern sector of the caldera, where the wall is largely absent (Figs. 1 and 5). Their products extend northwards into the Icod valley, and northeast, through a gap in the wall at El Portillo, into the La Orotava valley. In the west, the TPV complex encompasses flank vents developed on the Santiago del Teide Rift. The products of these vents bury the western flank of the Las Cañadas edifice and obscure the western limit of the caldera (Figs. 1 and 5). In the east, flank vents of TPV occur on the upper Dorsal rift zone and on the eastern flank of the Las Cañadas edifice. Several phonolitic flank-vent complexes are developed around the TPV stratovolcanoes and their products covering much of the central/eastern floor of the caldera and upper Icod valley, as well as parts of the northwest flank of Pico Viejo (Fig. 10).

4. The landslide valleys

The slopes of Tenerife are marked by several huge landslide scars and valleys that confirm the occurrence of significant mass wasting episodes throughout the construction of Tenerife, during both the basaltic shield and the central edifice phases (Bravo, 1962; Carracedo, 1994, Watts and Masson, 1997, 2001; Ablay and Hurlimann, 2000; Masson et al., 2002; Walter and Schmincke, 2002; Walter and Troll, 2003; Walter et al.,

2005; Carracedo et al., 2011; Dávila-Harris et al., 2011; Paris et al., 2017). The most important are Icod and La Oratava in the north, and Güímar in the south (Fig. 3), with total volumes of removed material higher than 100 km³ in each case. The Icod landslide is thought to have occurred between ~ 0.165 – 0.179 Ma (Martí et al., 1994, 1997; Boulesteix et al., 2012; Hunt et al., 2011), and the age of the Güímar landslide is well constrained between 0.86 and 0.83 Ma (Ancochea et al., 1990; Carracedo et al., 2011). However, the age of the La Oratava landslide is less precise, only being constrained between 0.69 and 0.56 Ma (Ibarrola et al., 1993; Carracedo et al., 2011). The comparison of the stratigraphy of their infilling successions deduced from surface geology and the inspection of the stratigraphy in the water galleries (Bravo, 1962; Coello, 1973; Martí et al., 1994; Bryan et al., 1998; Edgar et al., 2002; Brown et al., 2003; Boulesteix et al., 2012; Iribarren, 2014) with the stratigraphy and geochronology of the caldera wall (Martí et al., 1994), helps to better constrain the age of the valleys. In this sense, in addition to other rocks (lavas and pyroclastic deposits) coming from the rift zones and TPV stratovolcanoes, the Güímar valley contains deposits from the Guajara and Diego Hernandez formations, La Orotava valley has only deposits from the whole Diego Hernandez Formation, and the Icod valley only contains lavas and pyroclastic deposits from the TPV complex and from the Santiago del Teide rift.

In each of these landslide valleys the infilling succession rests on a thick (> 100 m) avalanche deposit, locally known as “Mortalon” (Bravo, 1962; Coello, 1973), with very similar lithological characteristics in all cases, composed of blocks from old Las Cañadas and basaltic shield rocks immersed in an abundant clay-rich matrix (Fig. 10). This material has a high plasticity and has been interpreted as an old stratigraphic unit derived from a previous dismantling episode now forming the slipping surface on which

the landslides occurred (Bravo, 1962; Coello, 1973; Carracedo, 1994), but also as the avalanche breccia, which result from each landslide (Carracedo et al., 2011).

Offshore, the landslides and resulting debris avalanche deposits have been imaged on the deep-sea floor surrounding Tenerife (Watts and Masson, 1995, 2001; Ablay and Hurlimann, 2000; Masson et al., 2002; Carracedo et al., 2011; Hunt et al., 2011, 2013a, 2013b). The study of these submarine deposits—and occasionally of their associated tsunami deposits—reveals that the formation of these landslides was a multistage retrogressive failure, with the stages being separated by several days, starting on the submarine flanks and retrograding on land and affecting the subaerial edifice (Hunt et al., 2011; Paris et al., 2017). The triggers for these landslides have been attributed either to lateral overpressure caused by multiple dyke intrusions along the rift zones (Carracedo 1994; Carracedo et al, 2011), to gravitational spreading of the Tenerife volcanic edifice (Walter, 2003), to a combination of both (Walter et al., 2005), or to seismic shocks associated with caldera collapse (Martí et al., 1997; Hurlimann et al., 1999, 2001). Additionally, it has been proposed that the occurrence of these landslides caused decompression of the shallow Tenerife magmatic systems triggering large explosive eruptions that immediately followed the landslide events (Carracedo, 2011; Hunt et al., 2011; Boulesteix et al., 2012; Paris et al., 2017).

5. The controversial origin of the Las Cañadas caldera

As has been shown, the evolution of the Las Cañadas edifice is characterised by the existence of various destructive episodes. These episodes led to the formation of the Güimar, La Orotava, and Icod valleys, and to the formation of the Las Cañadas caldera (Fig. 11). One of the main issues that arises when trying to interpret the origin of these

structures lies in how we use the existing volcanological, geological, and geophysical evidence, which may support or deny each of the different hypotheses we can propose if they are not considered as a whole. In the case of the Las Cañadas caldera, the impossibility of observing its interior, as it is a relatively young structure, only slightly eroded and covered by the post-caldera products from TPV, may represent a certain difficulty to interpret its origin. However, the important volume of geophysical and geological data, both from surface and subsoil, that currently exists on this volcanic structure, and its comparison with other similar structures whose origin is *not* in doubt, should be sufficient to definitively close the controversy over the origin of this caldera.

Traditionally, two hypotheses have been considered to explain the genesis of the Las Cañadas caldera (Fig. 2) (Table 1). On the one hand its origin has been suggested to have occurred through one or several vertical collapses of the volcanic edifice over the course of one or several explosive eruptions, so forming a succession of collapse calderas (Araña, 1971; Booth, 1973; Martí et al., 1994; 1997, 2010; Martí and Gudmundsson, 2000; Bryan et al., 2000; Hurlimann et al., 2000; Brown et al., 2003; Brown and Branney, 2004; Edgar et al., 2002, 2007, 2017; Galindo et al., 2005; Pittari et al., 2008; Coppo et al., 2008, 2010; Iribarren, 2014; Piña-Varas et al., 2015). On the other hand, it has been proposed that the Las Cañadas caldera had originated due to a lateral collapse of the volcanic edifice because of the gravitational instability of one of its flanks—a fact that would have occurred during the formation of the Icod valley, such that the caldera of Las Cañadas would be its head wall (Bravo, 1962; Coello, 1973; Ancochea et al., 1990, 1999; Carracedo, 1994; Carracedo et al., 2007; Cantagrel et al., 1999; Watts and Masson, 1995, 2001; Masson et al., 2002; Marquez et al., 2008; Boulesteix et al., 2012; Paris et al., 2017).

The stratigraphic and volcanological data strongly support the existence of significantly large explosive eruptions of phonolitic magmas during the evolution of the Las Cañadas edifice. Likewise, revision of the geology of the water galleries that perforate the slopes of the volcanic edifice (Bravo, 1962; Coello, 1973; Marrero-Díaz, 2010; Carracedo et al., 2011; Boulesteix et al., 2012; Iribarren, 2014), together with the bathymetry of the submarine flanks of the island (Watts and Masson, 1995, 2001; Ablay and Hurlimann, 2000; Masson et al., 2002), demonstrate the existence of large landslides, valleys, and mass wasting products generated during the formation of the Cañadas edifice, as in the case of the Güimar, La Orotava, and Icod valleys among others that are less visible (see Walter and Schmincke, 2002; Walter et al., 2005; Carracedo et al., 2011; Dávil-Harris et al., 2011). However, this last information is not enough to determine the position and layout of the head of the Icod Valley, the only one that could really explain the genesis of the depression of the Cañadas by a sector collapse. So, any attempt to justify the prolongation of the Icod Valley to the interior of the Las Cañadas depression needs to be fully supported by the geological and geophysical evidence that is currently available. Otherwise, it may be simply an over-interpretation of some of the existing data or even a misunderstanding of them.

The apparent contradiction between these two hypotheses can, however, be solved in a simple way: by admitting the existence of both processes, which could have been temporally and even mechanically related (i.e., one may be the cause of the other) (see Martí et al., 1997; Hurlimann et al., 2000). Admittedly, each process could have affected a different portion of the Las Cañadas edifice, or that they were not strictly coincident in time—but neither should imply mutual exclusion. In any case, it should be agreed, according to the existing data, that the Las Cañadas caldera is not the result of a

single event, but of a multi-cyclic process, which makes it impossible to be explained only as the result of the formation of the Icod Valley. The existence of eruptions such as Adeje, Granadilla, Fasnia, Poris, or El Abrigo (Booth, 1973; Bryan et al., 2000; Brown et al., 2003; Brown and Branney, 2004; Edgar et al., 2002, 2007, 2017; Pittari et al., 2008) during the construction of the Las Cañadas edifice, with individual volumes of extruded material greater than 10–20 km³, and a characteristic eruptive sequence compatible with a caldera-forming process, would be considered for other volcanoes (see Geyer and Martí, 2008; Sobradelo et al., 2010, for a data-base on collapse calderas) as irrefutable evidence for the existence of collapse calderas. Likewise, it must be accepted that the valleys of Güímar, La Orotava, and Icod are the result of several episodes of large-scale lateral or sector collapses (Bravo, 1962; Hurlimann et al., 2004; Carracedo et al., 2011), and that Icod could be responsible for the disappearance of a sector of the northern caldera wall, but this does not mean that such a process affected the totality of the Las Cañadas depression.

So, in the case of the Las Cañadas caldera, as in most geological studies, we must take into account the existence of abundant published data and analyse in detail the content of such information before supporting or excluding a particular hypothesis. The following text introduces the most significant information currently available on the Las Cañadas caldera, which will guide the discussion on its origin from an objective background.

5.1 Stratigraphy

One of the most important aspects of the existing information on the Las Cañadas caldera is its wall stratigraphy, which offers a unique opportunity to study the top of

the Cañadas edifice and its proximal deposits (Martí et al., 1994, 2010; Bryan et al., 1998, 2000; Soriano et al., 2002, 2006). The stratigraphy of the caldera wall (Fig. 4) clearly shows the existence of products from different eruptive centres, with different locations, and of varying eruption dynamics and ages, as well as with changing composition over time (Zafrilla, 2001). The division into a Lower and Upper Group is based on this observation. This stratigraphy also indicates that during the Upper Group there was a migration of loci of volcanic activity with time from SW to NE. Stratigraphic unconformities and levels of erosion and alteration horizons reveal the existence of more or less important interruptions of phonolitic eruptive activity in some parts of the stratigraphic sequence.

As indicated before, the stratigraphic data also reveal whether or not phonolitic deposits from the Upper Group are within the valleys of Güímar, La Orotava, and Icod, thus providing their relative age according to the evolution of the caldera and its chronostratigraphy. The Güímar Valley contains deposits from the Guajara and Diego Hernandez Formations. The La Orotava Valley shows in its interior a full succession of deposits from the Diego Hernandez Formation but none from the Guajara Formation (Martí et al., 1994; Iribarren, 2014). And the Icod valley does not contain Las Cañadas deposits at all (Bravo, 1962; Coello, 1973; Iribarren, 2014), indicating that it formed when all the eruptions at the Las Cañadas edifice ceased.

5.2. *Geochronology*

Radiometric methods (K-Ar, Ar-Ar) have been extensively used to date the rocks from the Las Cañadas edifice (Martí et al., 1990, 1994; Ancochea et al., 1990, 1999; Ibarrola et al., 1993; Mitjavila and Villa, 1993; Bryan et al., 1998; van den Bogaard,

1998; Huertas et al., 1999; Arnaud et al., 2001; Brown et al., 2003; Edgar et al., 2007; Hunt et al., 2011; Boulesteix et al., 2012). Despite the different methods and laboratories used there is good consistency among all existing data, well within the range of the errors provided in each particular case. The existing geochronological data from both the caldera wall deposits and their distal equivalents confirm the depositional hiatus between the Lower and Upper Las Cañadas groups, the migration of eruptive centers from west to east with time, the existence of different eruptive cycles of phonolitic volcanism (and the duration of each of them), and different ages for the Güímar, La Orotava, and Icod valleys. In this regard, it should be noted that the relative age established for the formation of La Orotava (0.56–69 Ma, Carracedo et al., 2011) and Icod (0.165–0.175 Ma, Hunt et al., 2011; Boulesteix et al., 2012) valleys roughly coincides with the end of two major eruptive phases corresponding to the Guajara (The Granadilla eruption, 0.56 Ma, Bryan et al., 2000) and Diego Hernández (El Abrigo eruption, 0.169–179 Ma Martí et al., 1990, 1994; Mitjavila and Villa, 1993; Brown et al., 2003) formations, respectively. In addition, the age of the offshore landslide deposits corresponding to the Icod valley have also been estimated to be between 0.165–0.175 Ma (Watts and Masson, 1995; Hunt et al., 2011; Paris et al., 2017).

5.3. *Structural Geology*

The structural geology of Tenerife is still poorly studied, but there is relevant information on the central part of Tenerife and in particular on the Las Cañadas caldera that may contribute to clarifying this controversy (see Galindo et al., 2005; Soriano et al., 2006; Martí et al., 2010). For example, the existence of normal faults with vertical displacement of several tens to hundreds of meters in the Ucanca sector of the caldera

wall while crossing the Las Roques de Garcia, is an important fact (Figs. 6 and 9); even more so when it is observed that some of these faults have been subjected to several vertical movements, both up and down (Galindo et al., 2005; Soriano et al., 2006; Martí et al, 2010). The verticality of the northern sector of the caldera wall exposed at La Fortaleza (Fig. 12) containing vertical striations also suggests the presence of a normal fault.

The existence of different families of phonolitic dykes with different orientation and cross cutting relationships (Fig. 8) indicates the occurrence of several intrusive episodes related to different pressure sources (i.e., magma chambers) affecting the western and central sectors of the caldera.

Moreover, the influence of regional tectonics in the central part of the island is also indicated by certain structures. Inside the caldera, cone alignments clearly define the major structural trends of the Dorsal and Santiago del Teide rifts, the former also highlighted by the presence of a graben that affects the central and western sectors of the caldera (see Galindo et al., 2005). The caldera itself is aligned parallel to this graben and the NE-SW Dorsal Rift.

5.4. Geomorphology

From the geomorphological point of view there are several aspects to highlight. In the first place, the different degree of morphological evolution (i.e., erosion) of the different sectors of the wall, with the western sector (Ucanca) being the most affected by erosion, and the eastern sector (Diego Hernández-La Fortaleza), the one that shows a major verticality of the caldera wall (Fig. 13). This suggest a different exposure time for each sector of the caldera wall and agrees with the age migration of the focus of volca-

nic activity over time from W to E. It is also worth noting the prominent bulge defined by the Pico Viejo lavas when covering the northern sector of the Las Roques de García spur, which suggests that this rock formation continues for a certain distance below that stratovolcano (Fig. 13).

The opening of the caldera wall in its northern sector, through both the Icod and La Orotava valleys, is another notable morphological aspect. The fact that these two sites are now covered by lavas from the TPV complex does not allow us to define what is the true extent of both valleys into the caldera depression, nor to determine how deep the caldera wall is missing. However, there are two water galleries that penetrate a certain distance into the caldera depression from the north, but they are located topographically too high to really provide a clear constraint on how deep the caldera wall was eroded (Coello, 1973; Iribarren, 2014) (Fig. 14).

Another morphological aspect that is relevant to the purpose of identifying the origin of the caldera is the shape of the Icod valley, since the whole caldera wall has been interpreted as corresponding to its head wall (e.g., Carracedo, 1994; Watts and Masson, 1995, 2001, among many others). This contrasts with the morphology shown by other valleys of similar origin, including those of Güímar and La Orotava, in which the headwall tends to be equal to or narrower than the exit (Siebert, 1984).

5.5. *Physical volcanology*

The spatial distribution and exposed volumes of the pyroclastic deposits from the Las Cañadas edifice gives an idea of the magnitude of the explosive eruptions associated with this volcanic complex. A minimum volume of approximately 150 km³ of phonolitic magma has been calculated for all the pyroclastic deposits that appear at the

caldera wall and in nearby areas, together with more distal deposits (Martí et al., 1994). However, this volume should be much greater if the amount of on-land phonolitic deposits were eroded out and the volume of these materials were deposited off-shore, from which there is evidence of thick successions at the channel between Tenerife and Gran Canaria (Rodehorst et al., 1998; Van den Bogaard and Schmincke, 1998); abundant ash deposits at the north (Hunt et al., 2011), could also be taken into account. On an individual level, the volume of magma emitted by these explosive phonolitic eruptions varies between 1 and $> 20 \text{ km}^3$ (Bryan et al., 1998, 2000; Brown et al., 2003; Edgar et al., 2007, 2017). Eruptions exceeding 10 km^3 of phonolitic magma were common during the Upper Group (Booth, 1973; Martí et al., 1994; Bryan et al., 1998, 2000; Edgar et al., 2002, 2007, 2017; Brown et al., 2003) and probably also during the Lower Group (Martí et al., 2010). This explosive activity was mainly characterized by plinian and ignimbritic eruptions, representing in some cases typical eruptive sequences associated with the formation of collapse calderas (e.g., high eruption rates during the ignimbritic phases, presence of widespread and thick lag-breccia co-ignimbrite deposits, areal distribution and volume of the ignimbritic deposits, etc.) (Bryan et al., 2000; Brown and Branney, 2004; Edgar et al., 2002, 2007; Pittari et al., 2008).

5.6. *Petrology*

The petrology and geochemistry of the rocks from the Las Cañadas edifice is one of the aspects that requires further attention. Still, existing data (Wolff, 1984, 1985; Wolff et al., 2000; Zafrilla, 2001; Bryan et al., 2002; Edgar et al., 2007) are significant enough to assist in the interpretation of the Las Cañadas caldera. The petrology of phonolitic deposits reveals, despite the apparent compositional homogeneity, the existence

of significant differences between the rocks of the different constructive episodes identified through volcanic stratigraphy. These differences in the composition of the mineral assemblages that characterise each formation, not to mention differences between their groundmass compositions, reveal differences in the thermodynamic conditions that controlled the evolution of phonolite magmas in each case, thus suggesting the existence of several shallow magma chambers during the construction of the upper part of the Las Cañadas edifice (Zafrilla, 2001; Bryan et al, 2002). This is in good agreement with the stratigraphy of the deposits, the migration in the position of the eruptive vents, and the cross-cutting relationships among the phonolitic dyke complexes. Moreover, experimental petrology data (Andujar et al., 2008) indicate that for the El Abrigo eruption, the caldera-forming episode that culminated with the generation of Las Cañadas caldera, the corresponding magma chamber was located at 130 ± 50 MPa (corresponding to ca. 4–5 km below the surface), 825 ± 25 °C, with 3 ± 1 wt.% dissolved H₂O and fO_2 at the Ni–NiO buffer ± 1 log unit. This shows that the magma that produced the largest ignimbrite on Tenerife was stored at relatively shallow depths but was water-undersaturated, and its eruption was probably triggered by input of fresh mafic magma (Andujar et al., 2008). Comparison with the previous caldera episodes (Zafrilla, 2001; Bryan et al., 1998, 2002) suggests similar conditions for their corresponding magma chambers.

Therefore, the existing petrological data also confirm the existence of several cycles of phonolitic activity during the construction of the upper part of Las Cañadas edifice. Each cycle was separated from the next one by the massive occurrence of basaltic volcanism on the flanks of Tenerife (Martí et al., 1994; Bryan et al., 1998), the separation time between each cycle being 0.15–0.25 Ma. In this sense, it is important to remark that this is the time scale for phonolite melt generation and differentiation in-

ferred from U-series isotope variations in the TPV stratovolcanoes (Hawkesworth et al., 2000, 2001, 2004).

5.7. *On-land geophysics*

Geophysical studies constitute another singular aspect in the dispute over the origin of the caldera. As it was mentioned for the existing physical volcanology data, geophysical data have not been considered in any of the works that support an origin of the caldera by sector collapse. However, geophysical studies, including magnetism, gravimetry, magnetotellurics, audio-magnetotellurics, seismic tomography, and self-potential studies, provide structural data on the interior of Tenerife that are crucial to interpret the internal structure of the Las Cañadas caldera and consequently, its origin (see MacFarlane and Ridley, 1968; Vieira et al., 1986; Ortiz et al., 1986; Camacho et al., 1991, 2011; García et al., 1997; Aubert and Kieffer, 1998; Ablay and Kearey, 2000; Araña et al., 2000; Almendros et al., 2000, 2007; Pous et al., 2002; Gottsmann et al., 2008; Coppo et al., 2008, 2010; Garcia-Yeguas, 2010; Blanco-Montenegro et al., 2011; De Barros et al., 2012; García-Yeguas et al., 2012, 2017; Prudencio et al., 2013, 2015; Piña-Varas et al., 2014, 2015; Villasante et al., 2014). Summarising the main findings among all these studies, the following observations arise (Fig. 15): 1) the existence of important negative gravimetric anomalies in the interior of Las Cañadas caldera; 2) the presence of low magnetic materials infilling the caldera depression and high magnetic anomalies along the rift systems; 3) the existence of a conductive level below the post-caldera infill, the topographic surface of which reveals the presence of several depressions, corresponding to the western (Ucanca), central (Guajara), and eastern (Diego Hernández) zones, outlined by Martí et al. (1994); 4) the presence of hydrothermal al-

teration along the entire boundary of the caldera, even below the TPV complex; 5) the presence of the structural wall of the Las Roques de García rooted at depth separating the depressions of Ucanca and Guajara; and 6) the existence of a structural discontinuity between the interior of the caldera and the Icod valley, marked by a sharp contrast in electrical conductivity, density, and with strong seismic wave refractions (Almendros et al., 2007).

5.8. Boreholes

Several boreholes drilled at different times and for different purposes (MOP-PNUD, 1975; Farrujia et al., 2001; Ablay and Martí, 2000) penetrated into the caldera fill succession at different depths (Fig. 16), so the minimum excavation or vertical displacement necessary to form the current depression may be estimated for different sectors of the caldera (Fig. 16). In the western sector (Ucanca depression), three boreholes were drilled during the UNESCO SPA 15 Project (MOP-PNUD, 1975). These boreholes, named C1, C2, C3, started at 2,053, 2,067, and 2,014 m a.s.l. and stopped at a depth of 1,777, 1,847, and 1,847, m a.s.l., respectively. All these boreholes intersected Las Cañadas pre-caldera rocks at a depth of 1,848, 1,892, 1,898 m a.s.l., respectively (Ablay and Martí, 2000; Marrero, 2010). Two more boreholes were drilled in the central and eastern sectors. The first of them, labeled S-1 or "Montaña Majúa", is located in the centre of Las Cañadas at an altitude of 2,264 m a.s.l., having a total depth of 505 m and reaching the water table at 1819 m a.s.l.. The second one, called S-2 or "El Portillo", was drilled 7 km away from the previous one, at 2,133 m a.s.l., in the eastern sector of Las Cañadas (Farrujia et al., 2001). In the year 1995, the latter, with a depth of 404 m,

also reached the water table at, 1780 m a.s.l. Both boreholes encountered only post-caldera infill rocks from the TPV complex.

The different stratigraphy shown by these boreholes at both sides of the Los Roques de García spur indicates the different structure of the caldera depression at both sides of this structural barrier. In addition, the stratigraphic correlations that were established between equivalent units along the boreholes show that TPV lavas were deposited on a fairly flat bottom, on both sides of the caldera (Ablay and Martí, 2000).

5.9. Water galleries

A total of nearly 1,500 km in the form of water tunnels have been excavated subhorizontally on the flanks of Tenerife (Bravo, 1962; Coello, 1973; Iribarren, 2014). The stratigraphic successions recorded inside these subhorizontal galleries have permitted three main observations: 1) the Icod Valley lacks any Las Cañadas deposit; 2) the presence of a thick layer of avalanche deposits, composed of old Las Cañadas and basaltic shield blocks surrounded by a clayish matrix of high plasticity; this breccia deposit is common in all the landslide valleys at the base of their infilling sequences, but also in other sectors of the island (e.g., at the Tigaiga Massif) at the contact between the basaltic shield and Las Cañadas deposits; and 3) some galleries drilled in the northern sector of Tenerife penetrated into the Las Cañadas depression without encountering the supposed caldera wall.

A recent revision of the stratigraphy of the water galleries (Iribarren, 2014) has permitted us to constrain these observations a little better. Most of these subhorizontal tunnels drilled in the Icod Valley do not cross the base of the Teide-Pico Viejo lavas, except for those very close to the Tigaiga Massif that reach the avalanche deposits.

Moreover, the galleries that enter the caldera depression are located topographically too high to confirm that the caldera wall in that sector does not exist (Fig. 14). In fact, a comparison with the adjacent sectors of the visible caldera wall at La Fortaleza and Mt. Chazogo (Fig. 5) shows how the original Las Cañadas edifice was already much shorter in the northern sector. So, from the information provided by the water galleries it is not possible to infer the exact location of the Icod Valley headwall. Also, based on this new review of the stratigraphy the Tenerife subsoil (Iribarren, 2014), it has been possible to deduce a very similar inclination of the roof of the avalanche deposits (“Mortalon”) on the northern flank of the island. This inclination is 9.42° for Icod, 10.11° for Tigaiga and 8.31° for La Orotava, which suggests a common plane for the base of the two landslides and for the base of the Tigaiga Massif. This observation is in good agreement with the idea of Bravo (1962), who interpreted this breccia as an old deposit generated by a previous dismantling episode that was later used as the decollement layer for both landslides.

5.10 Bathymetry and marine geophysics

Several bathymetric and marine geophysical surveys have been conducted in the last decades around Tenerife (Watts and Masson, 1995, 2001; Masson et al., 2002; Hunt et al., 2011, 2013a, 2013b), which have provided relevant information to characterise the offshore sector of the landslides and their resulting debris avalanche deposits. These studies have revealed the extent of the landslide deposits and the submarine morphology of the the landslide valleys and, as it has been mentioned before, they have contributed to understand the formation of such large slope failure events. Despite these studies do not offer any clue to infer the origin of the Las Cañadas caldera, some authors (e.g.,

Watts and Masson, 1995, 2001; Masson et al., 2002) have supported a particular origin only based on the evidence provided by these bathymetric studies, without considering the evidence shown by the on-land geology.

6. Discussion

The fundamental problem in understanding the complete geologic history on the Las Cañadas caldera is that the floor of this volcanic depression is covered by young lavas from Teide-Pico Viejo complex (TPV), and the rocks that were formed during caldera collapse or landslides are not exposed. Hence, the crucial observations needed to resolve the controversy cannot be made through conventional surface geological observations. In volcanic areas with a long history of eruptions, such as Tenerife, calderas are identified either on the basis of their topographic expression and relationship to associated pyroclastic rocks, or on the basis of a distinctive “caldera fill” association of deposits. In Tenerife, the topography of Las Cañadas is equivocal, as this has been the subject of the controversy. However, other calderas with a very similar morphology (e.g., Soma Vesuvius, Santorini, or Campi Flegrei) have not suffered such a strong insistence to debate their origin.

Regardless of the origin preferred, there are certain facts that should be accepted according to the evidence and data presented in this manuscript. The most relevant are:

- 1) Las Cañadas caldera is the result of a multi-cycle process and not the result of a single event;
- 2) there is an ageing of the caldera wall from east to west;
- 3) large volume and intensity eruptions of phonolitic magmas occurred during the construction of the Las Cañadas edifice;
- 4) the construction of the Las Cañadas edifice involved the development of different magma chambers, from West to East parallel to the migration of the volcanic activity focus;
- 5) the presence of several normal faults affecting the caldera

wall and the Los Roques de García spur, with kinematic indicators showing vertical displacements; 6) Los Roques de García is a structural barrier that divides the caldera into two sectors, which in their northern extreme are buried by the lavas from Pico Viejo—although their continuation inside the stratovolcano is unknown; 7) part of the northern caldera border is buried by TPV lavas and part is missing, but the maximum depth to which it has been eroded out is not known; 8) the caldera depression contains the main aquifer of Tenerife; 9) the morphology of the interior of the caldera is defined by three depressions, two closed (Ucanca and Guajara), and one partially open to the north (Diego Hernandez); 10) there are clear geophysical (i.e., mechanical) contrasts between the northern border of the Las Cañadas caldera and the Icod Valley, so the transition between these two structures is not continuous; 11) the identification of alteration zones at depth all around the caldera border, including the northern side and the “missing” caldera wall sector; and 12) the TPV complex is located precisely on this discontinuity.

All these observations are compatible with the existence of both, collapse calderas and large sector collapses, these being two processes that are not mutually exclusive. However, if both processes occurred, then what was the temporal sequence that they followed, and, more interestingly, was there any cause/effect relationship between them? To answer this question, it is first necessary to identify the options that are not feasible or that have been misinterpreted in previous studies.

The stratigraphic data reveal the existence or absence of phonolitic Upper Group deposits within the valleys of Güímar, La Orotava, and Icod, thus providing their relative ages according to the evolution of the caldera. This information reveals that the Güímar and La Orotava valleys originated much earlier than the completion of the caldera formation. Therefore, if the caldera had originated by a landslide, this must be the

one corresponding to Icod Valley. Accordingly, this would imply that the caldera would have been formed by a single event, at around 0.17 Ma, which would be in clear contradiction to several of the observations made previously in this section. In addition, this origin would be required to satisfactorily explain the unusual geometry that such a landslide could need, with its headwall much wider than its mouth. But even more difficult explain would be how the western sector of the landslide overshot the Los Roques de Garcia on its way north. Some authors (Cantagrel et al., 1999; Ancochea et al., 1999; Arnaud et al., 2001; Masson et al., 2002) have suggested that the Los Roques de Garcia is an avalanche deposit detached from the caldera wall at Guajara. However, this is in contradiction with the robust geological and geophysical evidence summarised here (Pous et al., 2002; Galindo et al., 2005; Coppo et al., 2008; 2010; Martí et al., 2010), showing that this part of the caldera is an “in situ” succession of the Lower Group deposits, intruded by several families of phonolitic dykes that in some cases show their continuation in the western and central sectors of the caldera. Moreover, and perhaps the most striking evidence that the Los Roques de García did not form as a landslide from the Guajara sector, is to explain how is it possible that these supposed avalanche deposits do not contain clasts from the Guajara Formation (Martí et al., 2010)?

It is crucial to know the characteristics of the pyroclastic deposits associated with the evolution of the Las Cañadas edifice in order to determine the origin of the Las Cañadas caldera. For instance, what type of collapse was it?. All the previous studies that have promoted an origin by a sector collapse (e.g., Bravo, 1962, Coello, 1973, Ancochea et al., 1990, 1999, Carracedo, 1994, 1999; Carracedo et al., 2007, Cantagrel et al., 1999, Watts and Masson, 1995, 2001, Masson et al., 2002; Boulesteix et al., 2012) have ignored characterising the pyroclastic deposits. They have consistently omitted any

reference to the relationship between the pyroclastic deposits of the Cañadas edifice and the formation of the caldera, despite the existence of a more reasonable explanation involving the stratigraphy, distribution, and geochronology of the pyroclastic deposits. From the volcanological point of view, the Las Cañadas caldera does not differ from many other intermediate size calderas originated by vertical collapse processes and which have closed morphologies (e.g., Crater Lake, USA; Bolsena, Italy), or are open in some sectors (Santorini, Greece; Soma Vesuvius, or Campis Flegrei, Italy) (see the collapse calderas database in Geyer and Martí, 2018; Sobradelo et al., 2010). The eruption sequences deduced from the successions of deposits generated by several eruptions from the Las Cañadas edifice, as well as the extension and volume of these deposits, strongly support caldera-forming eruptions (e.g., *El Abrigo*, 0.17 Ma: Martí et al., 1994; Pittari, 2004; Pittari et al., 2008; *Granadilla*, 0.56 Ma: Booth, 1973; Bryan et al., 2000; *Poris*: Edgar et al., 2002; Brown et al., 2003; Brown and Branney, 2004; *La Caleta*: Brown et al., 2003; *Fasnia*: Edgar et al., 2017; *Adeje*, 1.5 Ma: Dávila-Harris et al., 2013).

The presence of normal faults with vertical displacements of several tens or even more than one hundred metres, which affect the western and central sectors of the caldera wall, in addition to Los Roques de García, is another interesting feature to be considered when trying to elucidate the origin of the caldera. As explained previously, the presence of the northern major fault of the graben (the Azulejos Fault, in Galindo et al., 2005), defines the contact between the Los Roques de García and Los Azulejos formations, causing a chaotic distribution of rocks on both sides of the fault plane. Moreover, minor normal faults with vertical displacements of up to 40 m are present to the north and south of the Los Azulejos Fault, causing additional disruption of the stratigraphy of

the Los Roques de García and Los Azulejos sequences and enhancing the chaotic aspect of the central sector of the Los Roques de García spur. Finally, the formation of the caldera has also implied superimposed fracturing, erosion and re-sedimentation of the Los Roques de García rocks, which have increased the chaotic appearance of some parts of the sequence. However, the presence on some of these fault planes of striations that indicate vertical displacements of the same blocks (Galindo et al, 2005), is not compatible with an origin by landslide attributed to the caldera or in particular to Los Roques de García. On the contrary, it suggests a relationship to a succession of inflation and deflation episodes, such as the ones that should be expected at the intersection of two overlapping collapse calderas (see Martí and Gudmundsson, 2000; Geyer and Martí, 2009),

As mentioned before, one of the most important aspects of Tenerife's geology is the existence of a series of subhorizontal galleries and wells that penetrate to the interior of the island from different points. This permits visualising its subsurface geology, not possible for many other young volcanic terrains. This has provided significant observations in order to understand the structure and evolution of the island (Bravo, 1962; Coello, 1973; Iribarren, 2014). In fact, some of these observations have been the seed that has fed the controversy on the origin of the Las Cañadas caldera. However, these observations can only confirm the on-land existence of the landslide valleys, and that they are infilled with successions of rocks of different ages. The postulated total absence of the northern sector of the caldera is not correct, as the observation made from the water galleries that penetrate into the interior of the caldera would only intersect its uppermost part, such that the caldera wall might actually continue below these galleries. Besides, none of the existing galleries penetrate sufficiently into the caldera or at the appropriate depths to confirm or deny the absence of intracaldera deposits, as they only

penetrate to the depth of the TPV succession. However, the boreholes drilled in the western sector of the caldera during the execution of the SPA-15 project (MOP-PNUD, 1975) did encounter Las Cañadas rocks there.

Another observation that comes from the water galleries is the presence of the “Mortalón” avalanche breccia at the ends of many of them. This material constitutes an impermeable layer with high plasticity on which water slips away from Las Cañadas and other aquifers. This breccia was interpreted by Bravo (1962) and Coello (1973) as an old breccia deposit generated by mass wasting processes that affected the basaltic shield and the beginning of the construction of the Las Cañadas edifice, and which acted as the decollement surface for the La Orotava and Icod landslides. They only found this breccia deposit at the northern side of Tenerife, but recognised the presence of similar deposits in the Güímar Valley and other sectors of the island, attributing them the same cause. However, other authors (Carracedo et al., 2011) have interpreted these breccias as the products of landslides, hence assuming a much younger age for all them. The fact that the same breccia deposits appear in the La Orotava and Icod valleys, but also at the base of the whole Las Cañadas succession at the Tigaiga Massif (Bravo, 1962; Coello, 1973) (Fig.17), implies that they cannot be the avalanche deposits resulting from the formation of these two landslide valleys. This has another important implication that refers to the way in which both valleys (and probably the Güímar Valley too) formed, because the absence of coeval avalanche deposits in these valleys suggests a landslide mechanism rather than a debris avalanche process—at least concerning on-land observations. However, the exact mechanisms that controlled these sector collapses is out of the scope of this review.

There is agreement on the age of formation of the Icod Valley at about 0.17 Ma, coinciding with the last eruption (El Abrigo eruption) from the Las Cañadas caldera (Martí et al., 1994, 1997; Hunt et al., 2011; Boulesteix et al., 2012; Paris et al., 2017), and the existence of a cause/effect relationship between the two processes has also been proposed. However, the disagreement comes when considering which is the cause and which the effect. Martí et al. (1997), based on stratigraphic relationships, suggested that the caldera eruption started before the occurrence of the landslide. Furthermore, they proposed that it was in fact the seismicity caused by the caldera collapse along the ring fault that triggered the landslide. Later, a mechanical model was proposed justifying this hypothesis (Hurlimann et al., 1999, 2000). However, this idea has been challenged by Hunt et al. (2011), Boulesteix et al. (2012), and Paris et al. (2017), based on the stratigraphic succession observed in the off-shore deposits or on tsunami-related deposits, respectively. These authors coincided in proposing that the landslide was first and the decompression it caused on the El Abrigo magma chamber provoked the subsequent eruption. However, the lack of El Abrigo deposits in the Icod Valley, while being present everywhere outside it (Pittari, 2004; Pittari et al., 2008), demonstrates that the eruption preceded the landslide, otherwise El Abrigo deposits must appear inside the valley. Hunt et al. (2011) and Paris et al. (2017) identify the Icod landslide as a multistage process that started off-shore and retrograded on-land. The reason why the off-shore part of the landslide began may also be related to the instability (increase of seismicity, ground deformation) associated with the build-up to the El Abrigo eruption, which affected a relatively shallow and large magma chamber (Andujar et al., 2008). The fact that pumice and ash fragments from that eruption may appear mixed with the uppermost turbidite sediments and with the tsunami deposits caused by the entrance of the landslide into

the sea (Hunt et al., 2011; Paris et al., 2017), does not invalidate this observation. These two processes occurred in a very short time, so it is plausible that while the landslide was occurring, fragments derived from the emplacement of the El Abrigo ignimbrite into the sea (and falling from its co-ignimbrite ash cloud) could be incorporated into the turbidites and tsunamis, hence depositing together. However, on land the El Abrigo ignimbrite uniformly covered most of the island and is now recognised mostly to the south, forming a continuous layer up to 20 m thick—but also in the La Orotava Valley and at the bottom of many ravines, even in the oldest parts of the island (Edgar et al., 2007; Pittari et al., 2008). A similar sequence of events was proposed by Martí et al. (1997) for the formation of the La Orotava Valley in relation to the caldera-forming eruption of Granadilla, about 0.56 Ma, as it follows a very similar stratigraphic relationship.

Catastrophic landslides that destroy large sectors of a volcano do not produce closed depressions, but rather, horseshoe-shaped scars that are open in the downslope direction (Siebert, 1984), hence are inherently incapable of trapping large thicknesses of pyroclastic flow deposits, and furthermore are unlikely sites for lake development. This contrasts with two of the evidences presented in this review: the observation of marked gravimetric and magnetotelluric anomalies at the interior of the caldera depression, indicating that it is infilled with low density and poorly conductive materials, and the presence there of the main aquifer of Tenerife. The explanation given to justify the retention of water in an open depression (in the case of the caldera originated by a landslide) is that this is carried out by the numerous dykes that feed the TPV complex, which would block the exit of water through the north. However, for these dykes to be effective as water dams, they should be oriented parallel to the continuation of the caldera wall

in that sector. Here an important question arises: why should the feeding dykes of TPV have this precise orientation in the middle of a supposed landslide valley, without having any previous structural control? In the face of this unknown, it is much more plausible to assume that the Las Cañadas aquifer is there because the Las Cañadas caldera is a closed depression, as is indicated by most of the geophysical studies conducted on Tenerife. This also explains why TPV is located there, because this position would be controlled by part of the ring fault system, as happens in many other calderas that host stratovolcanoes in their interiors (see Geyer and Martí, 2008)

It is worth mentioning the role of geophysical studies in this controversy. As with physical volcanology, the geophysical data have not been considered in any of the studies that support a landslide origin of the caldera. However, the results from the geophysical surveys conducted in the Las Cañadas caldera and around it, provide data that clearly support the multiple collapse calderas origin. They define three depressions forming the internal structure of the caldera and provide evidence for the existence of the northern caldera border below TPV, thus suggesting the existence of a true ring fault system that limited the caldera and controlled its formation. According to different experimental and theoretical models on the formation of collapse calderas (see Martí et al., 2008 for a review), it is widely accepted that the dimension of the resulting collapse caldera is of the same order than the maximum horizontal section of its magma chamber. In these sense, the diameter of the depression outlined by the geophysical studies would correspond to that of the corresponding magma chambers (5-7 km), which together with the estimated minimum vertical displacements (618-964 m, see Fig. 16) provide the minimum volumes of the available phonolitic magma at the moment the caldera eruptions, which are perfectly coincident with the extruded volumes calculated from the

caldera-forming deposits. Bathymetric data, along with the characterisation of the off-shore deposits, demonstrate that the north flank of Tenerife has been affected by landslide events, but not at their on-shore extent. In this sense, the arguments used are very weak and sometimes contradictory. The existence of large landslides does not demonstrate that the caldera originated by that process. On the contrary, a vertical collapse origin of the caldera is much more consistent with the volcanological, and geophysical evidence presented here, which does not exclude the presence of large landslides in Tenerife. In fact, both processes may coexist and may even be mechanically related (Martí et al., 1997; Hurlimann et al., 1999, 2000). The exact location of the on-land extension of the Icod landslide, based only on morphological and topographical data, is rather speculative and may be misinterpreted. This is a subject that requires putting together all the evidence presented before, which needs to be examined in an objective way without being influenced by any specific train of thought. “This may help to end this debate, based on scientifically based arguments.

In summary, the apparent contradiction between these two hypotheses can be solved in a simple way by admitting the existence of both processes, being possibly related temporally and/or even mechanically (one being the cause of the other), yet accepting that both proposed mechanisms affected different portions of the Las Cañadas edifice. Therefore, the Las Cañadas caldera can be defined as a multi-cyclic, overlapping collapse caldera, whose formation included several caldera-forming eruptions, from which probably two of them (Granadilla and El Abrigo) triggered the coeval landslides responsible for the formation of the La Orotava and Icod valleys, respectively (Fig. 18). The current caldera is today defined by three overlapping depressions, two closed (Ucanca and Guajara) and one (Diego Hernández) partially open to the north. These de-

pressions are now infilled with caldera products and lavas, as well as pyroclastics from the TPV complex and satellite vents located inside the caldera. The depth of each depression increases from west to east, with a total vertical displacement of 750 m in Ucanca, at least 1,100 m in Guajara, and an undetermined amount in Diego Hernández. This could reflect the relative age of each depression, since Ucanca would have been filled with deposits from Guajara and Diego Hernández, Guajara would have been filled with those from Diego Hernández, and Diego Hernandez with only Teide lavas. The head wall of the Icod Valley would be located below the TVP and would have removed the uppermost part of the caldera wall in that sector, the rest of it remaining intact, as revealed by the geophysical data. How many caldera eruptions contributed to the formation of the present caldera is still unknown, but the existing morphology and internal structure seem to be related to the last caldera-forming episodes that ended each of the three phonolitic cycles of the Las Cañadas edifice's Upper Group. The structural evidence for any other intra-formational caldera episode was erased by these three other major events.

7. Final remarks

The controversy over the origin of caldera of Las Cañadas is largely due to a misinterpretation or to overinterpretation of existing data—mainly indirect data whose correct interpretation is therefore not always possible. Obviously, there are still several complementary actions that could be undertaken to unambiguously decipher the origin of the Las Cañadas caldera, such as a deep borehole inside the depression and a joint inversion of all available geophysical data. However, an objective and detailed examination of the abundant information published until present should be sufficient to ques-

tion or at least re-examine some of the arguments that have traditionally been used to support one or the other hypothesis, always taking into account that whichever the hypothesis is, it should accommodate most of the existing data.

It is evident that deciphering the origin of the Las Cañadas caldera is important not only from a volcanological point of view but also at a socio-economic level, since the development of the island depends in part on it. The hydrogeological model of Tenerife, which has considerable economic implications, depends greatly on the adopted genetic model of the caldera, and this is currently the landslide model (Consejo Insular de Aguas de Tenerife, 1991). Adopting the caldera collapse model requires rethinking the hydrogeological system of Tenerife and re-estimating its fresh water resources.

In a similar way, the origin of the caldera has a strong implication for risk assessment on the island. Whether or not the TPV complex is being constructed on a structural border of a collapse caldera or on a landslide surface (Fig. 2), is crucial to determining the stability of this new volcanic edifice (e.g., del Potro et al., 2009, 2013). The two resulting scenarios are completely different. The weight of the current TPV complex growing on a inclined surface has the potential to reactivate the landslide detachment surface. This poses a potentially major disaster with the entire Teide massif being incorporated into a catastrophic landslide towards the north, which would threaten the lives of people living on the north coast, and generate huge tsunamis endangering much of the eastern Atlantic seaboard. In contrast, if the head of the Icod landslide is buried further north, probably under the TPV, this implies a lesser (but probably still significant) landslide hazard, because only part of the weight of Teide will be borne by the detachment surface.

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Figures and Tables

Figure 1. Aerial image of the Las Cañadas caldera, Tenerife (view from the north) (Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image © 2019 GRAFCAN, obtained from Google Earth)

Figure 2. Simplified sketch illustrating the two main hypotheses on the origin of the Las Cañadas caldera, as they were proposed in the former studies: a) Vertical collapse (e.g., Fuster et al., 1968; Araña et al., 1971); b) Sector collapse (e.g., Bravo, 1962; Coello, 1973). In these initial studies supporting the vertical collapse hypothesis, the origin of the Icod Valley and its potential extension towards the interior of the caldera depression were not considered.

Figure 3. a) Simplified geological map (modified from Ablay and Martí, 2000), b) stratigraphy of Tenerife, and c) schematic cross section of the island. Las Cañadas caldera (LCC) wall localities: EC—El Cedro; BT—Boca Tauce; U—Ucanca; RG—Roques de García; G—Guajara; LA—Las Angosturas; LP—Las Pilas; DH—Diego Hernández; EP—El Portillo; LF—La Fortaleza. Main vent systems of the Teide–Pico Viejo formation: PT—Teide volcano; PV—Pico Viejo volcano; MB—Montaña Blanca. Postshield mafic volcanic zones: SRZ—Santiago rift zone; DRZ—Dorsal rift zone; SVZ—Southern volcanic zone (locally known as Bandas del Sur). Names and locations of landslide valleys are also shown. Contour interval is 200 m. Isotopic ages are from Ancochea et al. (1990) and Martí et al. (1994). Inset map shows the location and distribution of the Canary Islands. Main islands: LP—La Palma; EH—El Hierro; G—La

Gomera; T—Tenerife; GC—Gran Canaria; F—Fuertaventura; L—Lanzarote. White lines indicate the trace of the cross section of part c) of this figure.

Figure 4. Schematic representation of the stratigraphy of the Las Cañadas wall (Martí et al., 1994) with shaded relieve of the caldera. Shaded relief digital elevation model (DEM) of Tenerife (the 25 m DEM is geocoded to the UTM grid system, sector 28N, GCS_WGS_1984, datum: D_WGS_1984), showing the main morphological, volcanological, and structural features of Tenerife. White squares indicate the zone represented in pictures Fig. 5.

Figure 5. General views of different sectors of the Las Cañadas caldera wall. a) Western sector (Ucanca). b) Central sector (Guajara). c) Eastern sector (Diego Hernández) (Credits: Joan Martí).

Figure 6. Panorama of the Los Roques de García spur (Photo taken from the Mirador de Ucanca). The normal fault of the Los Azulejos graben is indicated, as is the contact between the Lower and Upper (Ucanca Fm) groups, and the position of some phonolitic dykes. Details of deposits and structures that can be observed in the Los Roques de García: a) Co-ignimbrite lag breccias. Largest boulders are up to 3 m across. b) Proximal debris flow deposits. Largest boulders are 1.5 m across. c) Intersection of different families of phonolitic dykes that give rise to this plug shaped structure, known as La Catedral (about 100 m high) (Credits: Joan Martí).

Figure 7. Resistivity models for several magnetotelluric profiles (MY and AMT) conducted inside the Las Cañadas caldera (modified from Pous et al., 2002). The models show the presence of a high conductive layer (between 5 and 40 Ω m) for almost the entire caldera underlying a high resistive unit (500-1000 Ω m) at the surface. This conductor is interrupted by the Los Roques de García spur (profile Parador), which divides it into two parts corresponding to the western (Ucanca) and central (Guajara) sectors of the caldera.

Figure 8. Phonolitic dyke intrusions in the Ucanca depression of the Las Cañadas caldera. Three sets of dykes (radial and vertical concentric dykes at the front, and cone-sheets at the back) are distinguished from this observation point. Radial dykes and cone-sheets are intersected by vertical concentric dykes (Credit: Joan Martí).

Figure 9. View of the Ucanca Fault showing downthrown of the northern block. This fault forms the southern limit of the Los Azulejos graben (see Galindo et al 2005, and Fig. 6). The equivalent units on both sides of the fault plane (welded fallout deposits, brown colour; non-welded pyroclastic deposits, light colour) are indicated by the same letter (Credit: Joan Martí).

Figure 10. Details of the “Motalon”, inside the a) Hoya del Ebro (Icod Valley), b) Fuente de las Mesas (Tigaiga Massif), water galleries. Centimetre to decimetre sized angular clasts of phonolitic and basaltic lavas are common in these breccia deposits (Credits: Juan Coello).

Figure 11. Main morphological features of Tenerife (see text for more explanation).

Figure 12. Welded fallout unit of La Fortaleza (Diego Hernández Formation), at 120 m above from the caldera floor, which constitutes the only visible vestige of the northern sector of the caldera wall (Credit: Joan Martí).

Figure 13. Slopes map of the Las Cañadas caldera area. Note the slope of the caldera wall is gentler in the western sector (Ucanca) and much steeper at the eastern side (Diego Hernández), thus suggesting a progressive younging in that sense, in good agreement with the stratigraphy and geochronology of the caldera wall deposits.

Figure 14. Scaled representation of the position of the conductor levels inside the depression of the Cañadas and the Icod Valley. Topographic profile made from the MDE of GRAFCAN SA (25 m DEM geocoded to the UTM grid system, sector 28N, GCS_WGS_1984, datum: D_WGS_1984); Audio-magnetotelluric profiles, according to data from Coppo et al. (2008); Majua borehole, according to data from Farrujia et al. (2001); Galleries, according to data from Coello (1973) and Consejo insular de Aguas (1991).

Figure 15. Examples of some recent geophysical results that provide significant information on the internal structure of Tenerife and, in particular, on that corresponding to the Las Cañadas caldera. a) Gravimetric model of Gottsmann et al. (2008) at a depth of 500 m a.s.l. showing how the caldera depression is infilled by low-density materials (blue and yellow colours) and how the head of the Icod Valley, which is marked by high

density materials (red colours), since they should correspond to the shield structure, is located north of the caldera. b) Interpolated altitude of the top conductive layer as revealed by the 185 AMT soundings conducted by Coppo et al. (2008). Isolines 1,600 and 1,800 m. a.s.l. are drawn in black. Black points are AMT sites. Inferred locations of the three depression (dotted white ellipses) at the origin of the current LCC. c) Example of the 3D joint interpretation of magnetotelluric and seismic tomographic models, at 1,500 m a.s.l., carried out by García Yeguas et al. (2017) using data from Piña Varas et al. (2014) and García Yeguas et al. (2012), respectively; A2, resistivity model; B2, Seismic tomography model in absolute P-wave seismic velocity; C2, Cluster distribution. Legend: Blue: ρ high and V_p (P-wave velocity) medium ($R_h V_m$); Light blue: ρ medium and V_p low ($R_m V_l$); Yellow: ρ low and V_p low-medium ($R_l V_{lm}$); Pink: ρ medium and V_p high ($R_m V_h$); Green: ρ medium and V_p medium ($R_m V_m$). These results show how Las Cañadas is essentially a closed depression, partially opened to the north in the La Orotava and Icod valleys. d) Two different perspectives of the magnetization distribution obtained through linear inversion of the magnetic anomaly map of Tenerife (Blanco Montenegro et al., 2011): (a) polygons represent the areas characterized by a surface paleomagnetic reverse polarity; (b) dashed lines show the location of the headwalls of the Icod (IC), La Orotava (OR), Güímar (G), Teno (T) and Anaga (A) landslides; the small black triangles show the location of the Pico Viejo (PV) and Teide (T) craters. e) 3-D resistivity model at 320 m a.s.l. showing the distribution of the low-resistivity structure ($< 10 \Omega m$) interpreted by Piña-Varas et al. (2014) as the seal (clay cap) of the Tenerife geothermal system (Piña Varas et al., 2015). The distribution of this body has continuity northward but shows a marked discontinuity in the central area, below the Las Cañadas caldera, thus suggesting the presence of the northern wall of the caldera.

Figure 16. a) Location of the boreholes drilled inside Las Cañadas for water research purposes (C1, C2, C3, and C5 from the SPA 15 research project, MOP–PNUD, 1975; S1 and S2 from the Tenerife Hydrological Plan, Farrujia et al., 2001), and traces of the sections represented in Fig.16b (red line), and Fig. 16c and Fig. 16d (white lines). b) Topographic profile (red lines in Fig. 16a) along the hydrological boreholes indicating their position, depth, and stratigraphic logs. c) Section of the caldera wall at the Ucanca sector indicating the minimum vertical displacement of the Las Cañadas edifice required to form that depression. Note that this displacement may be much larger if the possible replenishment by the Guajara and Diego formation deposits is considered. d) Section of the caldera wall at the Guajara sector indicating the minimum vertical displacement of the Las Cañadas edifice required to form that depression. Note that this displacement may be much larger if the possible replenishment by the Diego Formation deposits is considered.

Figure 17. Schematic illustration of the stratigraphy and geochronology of the Tigaiga Massif and the infill successions of the La Orotava and Icod valleys. All these three units have at the base and their stratigraphic sequences the breccia deposits locally known as “Mortalón”, which lies on basaltic shield rocks.

Figure 18.- Cartoon representing the succession of events that lead to the formation of the eastern sector of the Las Cañadas caldera and the Icod Valley. a) Previous situation (equilibrium state). b) The El Abrigo magma chamber is overpressurised due to the arrival of new magma and probably to oversaturation of volatiles during magma mixing

(Pittari, 2004; Andujar et al., 2008). c) The unrest (increase in seismicity and deformation) caused by magma chamber overpressurisation may have produced flank instability, thus triggering a sector collapse towards the north, which would have started on the off-shore sector of the volcano (Hunt et al., 2011; Paris et al., 2017). d) The El Abrigo eruption started, extracting a large amount of phonolitic magma in the form of a widespread ignimbrite that covered all the island, also emplacing off-shore in all directions. At the same time, due to the decompression of the magma chamber, the caldera collapse started. e) The seismicity associated with the caldera collapse and the proper gravitational instability generated by this large eruption and the occurrence of partial sector collapses affecting the offshore area triggered the landslide of the on-shore sector of the volcano, partially affecting the northern sector of the newly formed caldera and generating the Icod Valley and tsunamis, the deposits of which are now found on land mixed with El Abrigo pumices (Paris et al., 2017). f) After the caldera formation basaltic magmas could rise again to the surface start to construct the Teide-Pico Viejo complex on the northern sector of the caldera ring fault.

Table 1. Summary of the main studies directly or indirectly related to Las Cañadas caldera, indicating the proposed origin and the main observations they made.

UTM projection in km

cone sheet

radial dyke

concentric dyke

a)

b)

c)

d)

e)

a)

b)

c)

d)

a)

Table 1.- Summary of the main studies directly or indirectly related to Las Cañadas caldera, indicating the proposed origin and their main observations.

Reference	Proposed origin	Observations
von Buch (1825)	collapse of a crater of elevation	
Webb and Berthelot (1839)	structure similar to the Kilawea crater	
Lyell (1855)	ruins of an older cone, chiefly formed by eruptions from a summit which has disappeared	Compares with the Caldera de Taburiente in La Palma Island, formed by erosion, and proposes a different origin
Fritsch and Reiss (1868)	erosion and explosion	
Gagel (1910)	explosion similar to Krakatau	
Friedlander (1915)	vertical collapse	Similar to that of Soma-Vesuvius
Fernandez-Navarro (1917)	remains of a crater similar to those of Santorini and Vesuvius	
Hausen (1955, 1961)	explosion	
Macau (1959)	vertical collapse	
Blumenthal (1961)	vertical collapse	
Bravo (1962)	sector collapse	Observes that the Las Cañadas succession is missing in the Icod Valley
Mingarro (1963)	successive vertical collapses	Defines the caldera as a tectonic depression
Machado (1964)	double vertical collapse	Remarks the role of erosion on defining the final morphology of the caldera
Fuster et al (1968)	vertical collapse	Provide stratigraphical and structural arguments to support the vertical collapse origin
Araña (1971)	vertical collapse	Makes the first comprehensive study of Las Cañadas edifice and caldera

Reference	Proposed origin	Observations
Ridley (1971)	vertical collapse	Uses geophysical data to support his interpretation
Coello (1973)	sector collapse	Provides the first complete stratigraphy of the interior water galleries
Booth (1973)	vertical collapse	Interpretes the Granadilla eruption as a caldera-forming eruption
Vieira et al (1986)	vertical collapse	Gravimetric study of the caldera and identification of two main depression filled with low density rocks
Ortiz et al (1986)	vertical collapse	First magnetotellury study of the caldera, and identifies it as forming for two main depressions
Alonso (1989)	vertical collapse	First stratigraphy of the Bandas del Sur pyroclastics (distal facies of Las Cañadas edifice)
Ancochea et al (1990)	sector collapse	Provide a general geochronology of Tenerife and interpreted the Las Cañadas caldera as the result of the Icod landslide
Martí et al (1994)	vertical collapse	Establish the stratigraphy, geochonology, and physical volcanology of the caldera deposits and interpreted it as a multicyle overlapping collapse caldera
Carracedo (1994)	sector collapse	Compares Las Cañadas caldera morphology with other similar depressions in the Canary Islands and interpret all them as originated by giant landslides
Watts and Masson (1995, 2001)	sector collapse	Identify the offshore deposits at the north of Tenerifeas generated by the Icod and La Orotova landslides, thus supporting the sector collapse origin of the caldera
Martí et al (1997)	vertical collapse	Propose a cause/effect relationship between the Las Cañadas caldera and the Icod and La Orotava valleys, suggesting that calderas collapses triggered the landslides.

Reference	Proposed origin	Observations
Bryan et al (1998, 2000)	vertical collapse	Characterise the physical volcanology of the Bandas del Sur phonolitic deposits, establishing their correlation with the proximal deposits at the caldera wall, and confirm the Granadilla eruption as a caldera-forming eruption.
Aubert and Kieffer (1998)	sector collapse	Confirm the existence of three depressions at the interior of Las Cañadas caldera, two closed (Ucanca and Guajara) and one opened towards the north (Diego Hernandez)
Cantagrel et al (1999)	sector collapse	Interpret Los Roques de García as the deposits from a sector collapse
Carracedo 1999	sector collapse	
Ancochea et al (1999)	sector collapse	Provide a new geochronology for the Las Cañadas edifice and insisted on the sector collapse origin for the caldera
Hurlimann et al (1999, 2000, 2004)	vertical collapse	Model the cause/effect relationship proposed by Martí et al 1997, and identified the headwall of La Orotava Valley.
Martí and Gudmundsson (2000)	vertical collapse	Model Las Cañadas caldera as a multicycle overlapping caldera
Arnau et al (2001)	sector collapse	
Zafrilla (2001)	vertical collapse	Characterises the petrological and geochemical evolution of the Las Cañadas Upper Group, and confirmed the existence of different phonolitic cycles.
Edgar et al (2002, 2007, 2017)	vertical collapse	Characterise the physical volcanology of the Diego Hernandez Formation and identified several caldera collapse episodes
Masson et al (2002)	sector collapse	Continue interpreting from the study of the offshore deposits that the Icod landslide was responsible for the formation of Las Cañadas caldera.

Reference	Proposed origin	Observations
Pous et al (2002)	vertical collapse	Identify two main aquifer zones separated by the Roques de García spur, coinciding with the western and central depressions, and supported the multiple vertical collapse origin for the caldera depression.
Brown et al (2003)	vertical collapse	Review the physical volcanology and geochronology of the Bandas del Sur phonolitic deposits, and proposed the existence of several caldera-forming eruptions.
Pittari (2004)	vertical collapse	Confirms that the physical volcanology of El Abrigo ignimbrite corresponds to a caldera-forming eruption
Galindo et al (2005)	vertical collapse	identified Los Azulejos graben and other normal faults affecting the central and western sector of the Las Cañadas caldera
Soriano et al (2006)	vertical collapse	Identify the occurrence of conduit-vent structures associated with proximal-welded fallout deposits along the caldera wall.
Carracedo et al 2007	sector collapse	Insists on the idea that the Icod lateral collapse formed the Las Cañadas Caldera
Pittari et al., 2008	vertical collapse	Establish the dynamics of the El Abrigo ring fault.
Marquez et al (2008)	sector collapse	Based on the stratigraphy of several water galleries, they propose that Icod Valley extends inside Las Cañadas Caldera directly below Teide volcano
Gottsmann et al (2008)	vertical collapse	Modelled (gravimetry) the sub-surface structure of the caldera and mapped the headwall of the Icod landslide below Teide-Pico Viejo, supporting the vertical collapse origin

Reference	Proposed origin	Observations
Coppo et al (2008 a and b)	vertical collapse	Using magnetotelluric data confirm the existence of three depressions forming the caldera and identify the head of the Icod Valley below the Pico Teide – Pico Viejo Complex.
Martí et al (2010)	vertical collapse	Established the stratigraphy of Los Roques de García and contradicted Cantagrel et al (1999), indicating that this succession corresponds to a former Las Cañadas intracaldera sequence
Blanco Montenegro et al (2011)	vertical collapse	With magnetic data they infer the location of the headwall of the Icod landslide beneath the Teide-Pico Viejo complex
Hunt et al (2011)	???	Established the stratigraphy of the Icod offshore deposits and suggested that the landslide triggered the El Abrigo eruption.
Boulesteix et al (2012)	sector collapse	Date the internal stratigraphy of Teide and suggest that the Icod landslide triggered El Abrigo eruption
Iribarren (2014)	vertical collapse	Full revision of the stratigraphy of the water galleries and identification of the areal extent of the breccia deposits inside the valleys and Tigaiga massif.
Prudencio et al (2015)	vertical collapse	Identify several attenuation zones that suggests that the headwall of the Icod valley does not affect the interior of caldera
Piña-Varas et al (2015)	vertical collapse	With magnetotellurics, identify the buried northern wall of the caldera and the handwall for the Icod Valley under the Teide
Paris et al (2017)	???	Identified on Tenerife tsunami deposits as a consequence of the Icond landslide and suggested it triggered the El Abrigo eruption.