The Volcanic Geoheritage of El Teide National Park (Tenerife, Canary Islands, Spain)

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Abstract
El Teide National Park on the island of Tenerife (Canary Islands) is home to one of the most spectacular volcanic landscapes in the world. Although the conservation of its geodiversity is not a major problem given that it is governed by strict Spanish laws on geoconservation and is, in addition, a UNESCO World Heritage site, the diffusion of its geological values among the general public is more of a challenge due to the lack of any specific program for scientific knowledge transfer to visitors. The volcanological history of this national park needs to be transmitted in a clear and comprehensible fashion. However, the lack of adequate outreach material and of any coherent and consistent narrative regarding the significance of the island’s geological heritage makes it difficult to incorporate its geological history into the minds of visitors. This engenders a perception of its geoheritage that underestimates its importance. To remedy this misconception, the following tasks need to be carried out: (1) a compilation of all current scientific knowledge of the geology and volcanology of the area; (2) the identification of key geosites that offer the best means of understanding the history and evolution of this volcanic area; (3) the production of outreach and diffusion programs specifically designed to transmit this scientific knowledge to the general public; and (4) the establishment of permanent training programs for park and tourist guides that will guarantee the efficacy of this knowledge transmission. This contribution summarizes the main aspects of the geological history of El Teide National Park, identifies the elements that best exhibit its geological heritage, discusses the main problems observed in transmitting these geological values to visitors, and provides some clues as to how to face up to these challenges.

Keywords El Teide National Park · Tenerife · Volcanic geoheritage · Geodiversity · Conservation

Introduction

Due to their geological richness, volcanic zones are important geoheritage sites. Active volcanic fields are of special interest because they facilitate the observation of the complex and interesting stratigraphic relationships that characterize their products and processes, and, furthermore, often contain landscapes of unusual beauty (Nemeth et al. 2017; Casadevall et al. 2019; Planagumà and Martí 2020). Visitors to these geological sites would be able to appreciate the full complexity of volcanic activity and the need to preserve the geoheritage sites if the scientific information explaining the geologic processes is available, explained in such a way that public in general, particularly tourists, could understand these processes. Like the rest of knowledge-based tourism, it is a very effective interdisciplinary way of ensuring that tourism is compatible with the conservation and interpretation of our geological heritage. Additionally, this type of tourism aids the economic and social development of local communities, especially on volcanic islands whose main income is from tourism (Newsome and Dowling 2010; Sigurdsson, and Lopes-Gautier 2000; Erfurt-Cooper 2011; Dóniz-Páez 2014). Volcanoes and volcanic terrains have a worldwide fascination and many are visited by huge numbers of people every year (e.g., Iceland, Canary Islands, Hawaii, Yellowstone, Etna, and Vesuvius). These visits to both live and extinct volcanic landscapes provide much public recreation, adventure and enjoyment, while also affording opportunities for observing, learning, and appreciating the power and role of volcanism in building our planet’s surface, and for raising awareness of associated risks. Geotourism and, in particular, volcanic tourism may have other significant
benefits including self-esteem, employment, and wealth generation for local and regional communities, above all if it is organized and managed in a sustainable way (Plannagumà and Martí 2018).

El Teide National Park (TNP) was declared on 22 January 1954 and was then one of only three national parks in Spain. Subsequently, the park was reclassified in 1981 as an area with a special legal regime. In 1989, the park was awarded the European Diploma of Protected Areas by the Council of Europe, which was renewed in 1994, 1999, and 2004. Finally, it was classified as a UNESCO World Heritage Site in 2007. Its 18,990 ha embraces Las Cañadas caldera complex and the twin stratovolcanoes of Teide and Pico Viejo, as well as numerous intra- and extra-caldera volcanic vents, some of them related to the active rift systems of Dorsal and Santiago del Teide (Fig. 1). With around 3.5 million visitors annually, it is one of the most visited national parks in the world.

The caldera of Las Cañadas and El Teide-Pico Viejo active volcanic complex is a well-exposed and highly interesting volcanic setting (Fig. 2). Proof of this is the interest that it has always stimulated within the international scientific community, having been studied ever since the early nineteenth century (see Martí 2019). These studies have provided a considerable volume of information (geological, volcanological, geophysical, geomorphological, hydrogeological, petrological, etc.) on Las Cañadas and El Teide-Pico Viejo and various theories about their formation have been advanced, which over time have fuelled one of the most surprising and long-lasting of all data-based volcanological controversies (see Martí 2019).

Among the many visitors that come to the TNP every year, there are always a large number of students and academics from universities and research centers. They are principally attracted by the visibility of most of the park’s geological outcrops and have great interest in training, learning,
and conducting research into the different volcanicological outcrops that are exposed. In this sense, it is not pretentious to say that the TNP constitutes one of the best natural volcanicological schools anywhere in the world, and one in which most textbook volcanic processes and products can be directly observed and studied.

However, despite this richness in geological and volcanicological values, the paucity of the information available to visitors is surprising. For example, the amount of information on the wide geodiversity of this park found on webpages such as Wikipedia, in both its Spanish and English versions (https://es.wikipedia.org/wiki/Parque_nacional_del_Teide, https://en.wikipedia.org/wiki/Teide_National_Park), or on the park’s webpages (http://www.gobiernodecanarias.org/parquesnacionalescanarias/es/Teide/; https://parquesnacionales.cnig.es/teide), is slight or non-existent, or even erroneous if compared to existing scientific information. Likewise, available outreach and dissemination material for visitors is few and far between, and often out-of-date and lacking the scientific rigor to be expected for such a geologically important site. In addition, information on the geoheritage of the park transferred to potential park guides (e.g., https://www.miteco.gob.es/es/red-parques-nacionales/boletin/guias-pn-teide.aspx) is insufficient for them to show and explain to visitors all the geological and volcanological values of the park. Therefore, the role of the TNP in promoting geological and volcanological knowledge is still not as relevant as it should be, despite the potential it possesses.

In order to improve the current understanding of this unique geological scenery and to increase awareness among the general public, this contribution aims to provide an overview of the geoheritage preserved in the TNP, offer a synthesis of the volcanological evolution it reveals, identify its main geosites, and discuss the actions that could be undertaken to enhance communication, outreach, and the preservation of these geological values.

### Geological Setting

The island of Tenerife in the Canary Islands (Spain) lies in the east-central Atlantic Ocean, about 300 km off the coast of Morocco (NW Africa), and is one of the largest and most complex volcanic systems on Earth. Tenerife rises nearly 8000 m above the Miocene oceanic crust (Watts et al. 1997) and began to grow very quickly due to the accumulation of basaltic lavas during fissure eruptions, which gave rise to a shield volcano that comprises almost 90% of the island (Fig. 1). Remnants of this basaltic shield emerge at the corners of Anaga and Teno and in Roque del Conde (Fig. 1). These subaerial rocks date from between 12 and 3.3 Ma according to existing radiometric data (K–Ar and Ar–Ar) (Ancochea et al. 1990; Thirlwall et al. 2000).

Following this phase of basaltic volcanism and after an erosive period, which duration is still not well constrained, the eruption of phonolitic magmas started to occur from much more localized centers. Their products (lavas and pyroclasts) built Las Cañadas Edifice in the center of the island. This phonolitic volcanism alternated with basaltic volcanism, and both have continued up to the present day on the island. Las Cañadas Edifice, aged over >3.5 Ma, covers a large part of the subaerial sectors of the initial basaltic edifice. The construction of Las Cañadas Edifice by basaltic and phonolitic magmas—the latter generating highly explosive eruptions—is a feature that sets Tenerife (as well as Gran Canaria; Fuster et al. 1968a) apart from other large oceanic
volcanic systems such as Hawaii or La Reunion where the volcanism is practically only basaltic. Las Cañadas Edifice (Fuster et al. 1968b; Araña 1971) overlies an erosional unconformity at the top of the lower basaltic shield (Old Basaltic Series, Fuster et al 1968; Ancochea et al. 1990), although the contact zone is not clearly exposed. Las Cañadas Edifice is a large composite stratovolcano consisting of a predominantly mafic-to-intermediate Lower Group (> 3.5–< 2 Ma) and an Upper Group (1.6–0.18 Ma) comprising the products of three basaltic-to-phonolitic volcanic cycles, each one representing a different stratigraphic formation (Ucanda, Guajara, Diego Hernandez), which terminated with caldera collapse events (Martí et al. 1994) (Fig. 3). The phonolitic rocks from each formation are mostly pyroclastic and have petrological and geochemical features that separate them from those of the other formations (Zafirilla 2001). Phonolitic rocks from the Ucanda Formation overlie the Lower Group and range in age from 1.57 to 1.07 Ma, while those of the Guajara Formation were emplaced between 0.85 and 0.57 Ma. The phonolitic pyroclastic rocks of the Diego Hernández Formation range in age from 0.37 to 0.18 Ma. Volumes of several tens of cubic kilometers have been estimated for the largest pyroclastic deposits (Martí et al. 1994; Bryan et al. 2000; Edgar et al. 2002, 2007, 2017), while a minimum volume of 140 km$^3$ has been calculated for the whole pyroclastic sequence of the Upper Group (Martí et al. 1994). A large variety of Las Cañadas Edifice pyroclastic and associated deposits, including welded and non-welded air-fall deposits with different grain sizes, dense (ignimbrites) and dilute (pyroclastic surges) pyroclastic density current (PDC) deposits, lahars, debris avalanche deposits, and secondary volcanioclastic deposits, as well as lava flows of different thickness and a large variety of dykes, can be observed along the magnificently exposed caldera wall.

The final part of the construction of the central volcanic complex of Tenerife corresponds to El Teide-Pico Viejo, which began to develop about 17–18 Ka years ago inside Las Cañadas caldera, a depression created by several caldera collapse episodes that truncated the top of Las Cañadas Edifice (Martí et al. 1994; Martí and Gudmundsson 2000; Martí 2019). Several large episodes of flank collapse also occurred during the construction of Tenerife (Bravo 1962; Coello 1973; Carracedo 1994; Watts and Masson 1995, 2001; Ablay and Hurlimann 2000; Hurlimann et al. 2004; Hunt et al. 2011, 2013a, 2013b). The Icod landslide is thought to have occurred between ~0.165 and ~0.179 Ma (Martí et al. 1994, 1997; Boulesteix et al. 2012; Hunt et al. 2011), while the age of the Güímar landslide is well-constrained between 0.86 and 0.83 Ma (Ancochea et al. 1990). However, the age of La Orotava landslide is less precise and is constrained only between 0.69 and 0.56 Ma (Ibarrola et al. 1993). The Güímar valley contains deposits from the Guajara and Diego

![Fig. 3](image-url)  
**Fig. 3** Left: simplified stratigraphy of Tenerife (after Ablay and Martí 2000). Rest of the figure: schematic illustration of the stratigraphy of Las Cañadas caldera wall, showing the Lower Group and Upper Group formations (modified from Martí et al. 1994). Isotopic ages in boxes are taken from Martí et al. (1994) and Ancochea et al. (1990, 1999, 2000). The shaded relief of the central part of Tenerife, showing the caldera wall sectors and El Teide-Pico Viejo stratovolcanoes, was taken from the same DEM as in Fig. 1
Hernandez formations, while La Orotava valley has deposits from the whole Diego Hernandez Formation, in addition to later basaltic lavas. The Icod valley only contains lavas and pyroclastic deposits from El Teide and Pico Viejo complex and from the Santiago del Teide rift.

Basaltic volcanism continues today at multiple eruption sites, including the north-eastern (Dorsal Rift) and north-western (Santiago Rift) fissure vent systems (Fig. 1), and in several small scoria-lava cones located at the heads of major landslide valleys (La Orotava, Güímar, Icod) and elsewhere. The two active rift systems (Fuster et al. 1968; Carracedo 1994; Carracedo et al. 2011; Geyer and Martí 2010; Delcamp et al. 2010, 2012, 2014) (Fig. 1) have hosted all the Tenerife historical eruptions. The interior of these rift systems has recently been imaged using gravimetric inverse modelling, which has shown that they correspond to shallow structures that facilitate the lateral migration of deep basaltic magmas that rise close to the surface (Sainz-Maza et al. 2019).

The Overall Geological and Volcanological History of El Teide National Park

The most important question that needs to be answered when designing an education plan for the geoheritage of this protected area is what type of history should be taught to visitors to El Teide National Park. We first need to take into account current scientific knowledge, which should provide the basis for any outreach and public-awareness programme. Well-informed tourism is one of the best ways of disseminating scientific knowledge related to geoheritage preservation since what visitors will take back to their respective homes is the essence of the geoheritage message.

In summary, the geological and volcanological history of TNP represents the last phase in the evolution of a large composite volcano, named the Cañadas Edifice. This history embraces a wide diversity of eruption styles, the origin of the Las Cañadas caldera, the formation of the Icod and La Orotava landslide valleys, and the birth and further evolution of El Teide and Pico Viejo stratovolcanoes inside the caldera depression. The origin of Las Cañadas caldera and its relation to the Icod and La Orotava valleys, an interesting example of cascading extreme hazards, could be misunderstood if it is not well presented and transmitted (see Martí 2019). The origin and evolution of El Teide and Pico Viejo is not unanimously agreed upon by the scientific community, which means that differing opinions regarding the significance and current state of volcanic activity in the park is transferred to the visitors, thereby creating confusion if they compare the information they have received. This is why only the direct observation of the exposed geosites throughout the TNP, accompanied by an objective and concise explanation of their meaning and significance can guarantee that visitors receive an unbiased view of the island’s unique geoheritage.

Las Cañadas caldera is a multicycle overlapping collapse caldera that formed over a period of more than one million years. It is the result of different caldera-forming events that occurred at the end of each of the phonolitic cycles identified in the Upper Group (Fig. 4). Although much of the evidence that supports the origin and internal structure of this caldera derives from indirect indications provided by geophysical studies (Ortiz et al. 1986; Camacho et al. 1991; Pous et al. 2002; Coppo et al. 2008, 2010; Gottsmann et al. 2008; Blanco-Montenegro et al. 2011; García-Yeguas et al. 2017), other relevant aspects for interpreting the caldera formation can be directly observed. These include (a) the morphology of the caldera wall, which shows the embayments corresponding to each caldera sector and the degree of erosion of each of them as a consequence of their different age of formation; (b) the presence of faults that controlled the collapse events in some sectors of the caldera; (c) the succession of deposits derived from some of the caldera collapse episodes; and (d) the geometry and cross-cutting relationships of different families of sheet intrusions that were related to the plumbing system of Las Cañadas Edifice.

The roots of Las Cañadas Edifice can be observed today in the form of dykes and other types of phonolitic intrusions, as well as in certain older volcanic deposits that crop out in the interior of the caldera along Los Roques de García spur and various sectors of the caldera wall. All these rocks have been exposed on the surface due to caldera collapse events and the subsequent erosion of the resulting caldera walls (see itineraries 2, 3, and 5). Phonolitic sheet intrusions represent the remnant of the different shallow plumbing systems that were installed when Las Cañadas Edifice was being constructed. Different sets and geometries of sheet intrusions, including radial, concentric, and inclined (cone sheets) dykes, as well as plugs formed at the intersection of dykes, can also be viewed (Martí et al. 1994; Galindo et al. 2005; Soriano et al. 2006). They have different thicknesses, from centimeters to meters, appear as single or multiple intrusions, and exhibit a range of different cross-cutting relationships. This suggests that these sheet intrusions formed at different times and from different pressure sources (magma chambers) during the construction of Las Cañadas Edifice. Moreover, it is worth mentioning that many of these dykes have pyroclastic textures, thereby indicating that they were feeder dykes originating from the phonolitic eruptions that produced the deposits observable along the caldera wall.

Los Roques de García Formation belongs to the Lower Group (Fig. 3) and forms the morphological and structural barrier that divides Las Cañadas caldera into two morphological depressions, the eastern side being 150 m higher than the western one (Martí et al. 2010). This spur controlled the distribution of El Teide and Pico Viejo lava flows emplaced
in the caldera from the southern flanks of the volcanoes. The rocks forming Los Roques de García consist of several successions of proximal pyroclastic and sedimentary (epiclastic) deposits, predominantly breccias, all of which were intruded by a dense network of phonolitic dikes and necks. The central sector of Los Roques de García spur is highly fractured due to the movement of several normal faults. It has also undergone strong hydrothermal alteration that has conferred on the exposed rocks a large variety of colors (blue, green, yellow, white, etc.), which makes this zone (Los Azulejos) one of the most attractive places in Las Cañadas caldera. In addition to its beauty, Los Roques de García are crucial for understanding and interpreting correctly the formation of Las Cañadas caldera (Martí et al. 2010). This stratigraphic succession is concordant with the rest of Las Cañadas caldera wall and corresponds to the lower part (Lower Group) of Las Cañadas Edifice but has no relation to any of the later explosive episodes that were responsible for the deposition of its upper part (Upper Group). The lithological, sedimentological, and volcanological characteristics of Los Roques de García rocks allow them to be interpreted either as an older Las Cañadas intracaldera sequence or as the apron of a previous stratovolcano, unlike previous interpretations (Ancochea et al. 1999; Cantagrel et al. 1999; Arnaud et al.

Fig. 4 Depiction of the succession of events that led to the formation of Las Cañadas caldera and their relationship with the landslide valleys (modified from Martí, 2019) (see text for explanation)
that suggested that they correspond to the products of a major debris avalanche event that contributed to the formation of the present caldera.

The slopes of Tenerife are affected by several huge landslide scars and valleys (Bravo 1962; Carracedo 1994, Watts and Masson 1995, 2001; Ablay and Hurlimann 2000; Masson et al. 2002; Paris et al. 2017), the most important of which are those of the Icod, La Orotava and Güímar valleys (Fig. 1) whose headwalls are included within the limits of the TNP.

In the debate on the origin of Las Cañadas caldera, some authors (e.g., Bravo 1962; Coello 1973; Carracedo 1994; Watts and Masson 1995, 2001; Boulesteix et al. 2012; Paris et al. 2017) have suggested that it formed as a result of the same landslide process as the Icod valley, which would mean that the whole caldera wall would be the product of a single event and be the headwall of this valley. This idea is explained to visitors and backed up by the TNP (Fig. 5), mainly due to the fact that it was suggested by local geologists (e.g., Bravo 1962; Coello 1973; Carracedo 1994). However, all available geological and geophysical evidence strongly supports the idea of the caldera collapse origin explained above, with a cause/effect relationship operating between the Guajara and Diego-Hernández caldera-forming events and the landslides of the La Orotava and Icod valleys, respectively (see Martí 2019 for a review on this controversy). A visit to the TNP should provide objective information on these processes and on their possible spatial and temporal relationships, and try and avoid the misinterpretations of the geological evidence that exist in the park literature. As an example, the above-mentioned simple observation of the different degrees of erosion affecting the various sectors of the caldera wall is evidence enough to be able to convincingly reject the idea that Las Cañadas caldera was formed as the result of a single destructive event.

Fig. 5 Explanatory panel located at Las Ruleta viewpoint looking toward the Ucanca depression, which explains the origin of Las Cañadas caldera and Icod Valley as the result of the same massive landslide in contradiction with most current scientific evidence

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In fact, vertical collapses occurred several times during the evolution of the Upper Group; the collapses that culminated the phonolitic cycles of the Guajara and Diego Hernández formations were associated with the formation of La Orotava and Icod valleys, respectively. In these two cases, the succession of events that may be deduced from the geological record includes the following (Fig. 4): (a) previous situation (state of equilibrium); (b) an overpressurized phonolitic magma chamber due to the arrival of new magma; (c) increase in seismicity and deformation (unrest episode) caused by magma chamber overpressurization, which could provoke flank instability, thereby triggering a sector collapse to the north originated in the offshore sector of the volcano; (d) large-volume, phonolitic eruption forming a widespread ignimbrite covering part or all of the island, and also emplacing offshore in some directions, and causing caldera collapse; (e) the seismicity associated with the caldera collapse and the gravitational instability generated by these large eruptions triggered a landslide in the onshore sector of the volcano, partially affecting the northern sector of the newly formed caldera and generating the valleys and associated tsunamis; and (f) after the last episode of caldera formation, basaltic magmas rose again to the surface and started to construct El Teide-Pico Viejo complex in the northern sector of the caldera ring fault.

El Teide and Pico Viejo started to grow inside the northern border of the caldera just after the formation of its final eastern sector (Diego Hernández) (Ablay and Martí 2000). The products of these two volcanoes—mainly lava flows and pyroclastic deposits of basaltic-to-phonolitic composition—constructed two large stratovolcanoes rising to altitudes of 3135 and 3715 m a.s.l at Pico Viejo and Teide, respectively. They also filled the caldera depression and the Icod and La Orotava valleys with over 600-m- and 500-m-thick deposits, respectively. Only the deposits from the final eruptions are currently visible, although a large variety of lava flow morphologies (e.g., blocky, aa, pahoehoe, lava tubes, levees, lava fronts, etc.) are all easily observed (Fig. 2). The presence of different craters in both stratovolcanoes is also of interest and gives a clue as to the complexity of their evolution. The current degree of activity in both volcanoes is low; the only evidence being the permanent fumaroles at and around the summit crater on El Teide and frequent low-magnitude seismic swarms (see https://www.ign.es/web/ign/portal/vlc-area-volcanologia). Despite this, neither should be considered as extinct, as they have erupted several times during the Holocene (past 10,000 years), having its last eruption (Lavas Negras) occurred about 1000 years ago. In addition to the Teide-Pico Viejo stratovolcanoes, the most recent volcanic activity inside the TNP has also occurred in relation to the two rift zones.

**Identification and Observation of the Main Geological and Volcanological Values**

Two of the main advantages of the TNP are the excellent state of preservation of most of its outcrops and the lack of vegetation cover over much of its surface area that enable good views to be had of all its geosites. In addition, the excellent network of paths and trails, all well preserved and indicated, allow visitors to reach all observation points on foot (Fig. 6). The following is a description of the main observation points (Table 1) that can provide visitors with a complete overview of the volcanological geoheritage of the TNP. Access to these points is along paths and trails, and occasionally along the main roads that cross the park. This description is based on the itineraries that take visitors to the main observation points and a number of isolated sites, and aims to take in the most relevant geological sites in the TNP.

**Itinerary 1: Pico Viejo Crater and La Fortaleza Viewpoints**

Itinerary 1 (Fig. 7) follows the path along the former crater of Pico Teide (La Ramlbleta) between the Pico Viejo viewpoint to the west and La Fortaleza viewpoint to the east (paths 12 and 11 in Fig. 6, respectively), and provides an aerial view of the whole Las Cañadas caldera. The objective of this itinerary is to visit the caldera wall, identify its main stratigraphic units, and observe the geometry of Los Roques de García spur. It also allows visitors to admire the Pico Viejo crater and the connection of this volcano with the NW rift, the Montaña Blanca complex, the northern sector of the caldera wall at La Fortaleza, and the La Orotava Valley. The itinerary starts at the Mirador de Pico Viejo, which can be reached by cable car and then on foot along paths 12 and 11 (Fig. 6), on foot from the Montaña Blanca trail to the Refugio de Altavista and then Pico Teide (path 7 in Fig. 11), or from Pico Viejo (paths 9 and 23 in Fig. 11). This itinerary includes the following observation points (OP) (Figs. 7 and 8).

**OP 1.1: Pico Viejo Crater Viewpoint**

The general view of the Pico Viejo crater and the northwestern rift (Santiago del Teide rift) is defined by an alignment of scoria cones and basaltic lava flows (Fig. 8a). The Pico Viejo crater is 1500-m wide and 150-m deep, and corresponds to a collapse caldera of a ‘summit crater’-type that truncates the top of the volcano. The bottom of the caldera is relatively flat except for the presence of a funnel-shaped pit crater in the SW part of the caldera, with
an additional depth of 100 m. The caldera wall exposes lava flows that dip out of the caldera at angles between 25° and 35°.

Resting against the southern edge of the wall, there is an isolated block that represents a succession of massive, horizontally arranged phonolitic lava flows that exhibit a clear unconformity with the previous lavas. At the top of this block, there is a dilute PDC deposit (pyroclastic surge) of basaltic composition and the products of a phreatic explosion. This explosion generated a widely dispersed grey deposit, and is very rich in lithic fragments of different lithologies, including significant amounts of nepheline syenites and gabbros. This block of lavas represents the remnants of a lava lake that formed a thick succession of phonolitic lavas in the interior of the crater. This same succession can be observed at the pit wall, today displaced 150 m below its original position, which is evidence for the existence of a caldera collapse episode in the upper part of Pico Viejo volcano.

**OP 1.2: Ucanca Depression Viewpoint**

A general view of the western sector of the caldera (Ucanca depression) from which the morphology and stratigraphy of this sector of the caldera wall, the morphology of the felling lavas from El Teide-Pico Viejo complex, and the geometry of Roques de García can be observed (Fig. 8b). Among the deposits of the Ucanca and Guajara successions, it is worth highlighting the presence of thick (up to 120 m) welded rock units (proximal pumice fall deposits) that make up the most abrupt scarps of the wall. These deposits are examined in detail at observation points OPs 4.2 and 4.3 on itinerary 4.

**OP 1.3: Guajara Depression**

A general view of the central sector of the caldera (Guajara), from where the succession of deposits of the Guajara Formation and El Teide lavas that infilled the caldera depression can be observed (Fig. 8c). The Guajara Formation is
characterized by large scarps of welded rocks. From this observation point, the centers of Montaña Blanca, Montaña Rajada, and the scoriaceous lava of Tabonal Negro, all products of the Montaña Blanca eruption (2020 BP), can be observed.

**OP 1.4: La Fortaleza Viewpoint**

This observation point offers a general view of the eastern and northern sectors of the caldera, from where visitors can appreciate the head of La Orotava Valley, as well as the intersection of this area of the caldera and the northeastern rift (Dorsal de La Esperanza rift), the Icod valley to the west, and the Tigaiga massif in the middle separating the two valleys (Fig. 8d). La Orotava valley is infilled by phonolitic pyroclastic deposits corresponding to the Diego Hernández Formation and lava flows from El Teide. The southern end of the Tigaiga massif was intersected by the formation of the caldera and forms part of its northern wall, which is hidden on both sides below lavas from El Teide emplaced toward La Orotava and Icod valleys. The upper part of the southern end of the Tigaiga massif corresponds to La Fortaleza phonolitic welded rock unit, over 100 m thick, corresponding to the Diego Hernández Formation.

**Itinerary 2: Ucanca Caldera Wall**

This itinerary runs along roads from La Ruleta observation point at Los Roques de García to the Las Narices del Teide viewpoint (Figs. 7 and 9). Visitors can examine the western sector (Ucanca) in more detail and also gain a general view of Los Roques de García and Azulejos, and the 1798 Chahorra eruption craters and lavas. Specific aspects to be examined include the stratigraphy of the caldera wall and...
its morphological evolution, the general stratigraphy of Los Roques de García, the hydrothermal alteration of Los Azulejos, Los Azulejos graben, different sets of phonolitic dikes, the Boca de Tauce edifice, and the Narices del Teide eruption (1798) and its relationship with the Santiago del Teide rift. Likewise, El Teide-Pico Viejo complex and the head of La Orotava valley can also be appreciated.

**OP 2.1: General View of the Ucanca Depression and Caldera Wall**

This viewpoint offers a general view of the Ucanca depression and the western caldera wall, as well as part of Los Roques de García and recent lavas from Pico Viejo (Fig. 9a).

**OP 2.2: Los Roques de García Viewpoint**

As indicated above, Los Roques de García (Fig. 9b) is key to understanding the origin of the caldera. Various authors (Ancochea et al. 1999; Cantagrel et al. 1999; Arnaud et al. 2001) who favor the hypothesis of lateral collapse as the origin of Las Cañadas caldera have proposed that Los Roques de García represent part of the avalanche deposits of this collapse and interpret its components as being blocks and megablocks from that avalanche. Conversely, others authors postulate a hypothesis of vertical collapse (Arana 1971; Martinez et al. 1994; Martí and Gudmundson 2000; Galindo et al. 2005; Martí et al. 2010), while current geophysical data (Pous et al. 2002; Coppo et al. 2008) suggest that Los Roques de García represent the eroded remnants of the wall resulting from the intersection between two caldera depressions (Ucanca and Guajara) and a true structural barrier up to several kilometers deep. Nevertheless, the stratigraphy and volcanology of Los Roques de García (Martí et al. 2010) reveals that this succession of deposits, together with the adjacent sequence of Los Azulejos toward the south, correspond to a set of pyroclastic (ignimbrites, ash breccias, pyroclastic surge deposits) and epiclastic materials (breccias and conglomerates) of proximal character belonging to the Lower Group. They have a concordant stratigraphic position within the whole Las Cañadas Edifice and form part of its Lower Group. This succession of old deposits is intruded by a dense network of phonolitic dikes and necks, and corresponds to a caldera fill sequence formed prior to the formation of the current caldera (Upper Group).

**OP 2.3: Boca de Tauce Viewpoint**

From this point and looking toward the southeast, the geometrical relationship and relative age of various sets of phonolitic dykes (inclined, radial, and concentric) can be observed (Fig. 9c). The presence of these intrusions reveals the existence of shallow magma chambers that controlled their location during different phases of magma rising. A structural analysis based on the statistical study of the distribution and geometry of these sheet intrusions allows us to reconstruct the position of the magma chambers from which they originated, and to infer the existence of several such centres in the western and central zones.
during the construction of the upper part of Las Cañadas Edifice (Martí et al. 1994; Galindo 2005).

From here and looking toward de southwest, we can also appreciate the presence of the Boca de Tauce Edifice, a remnant of the basaltic shield on which Las Cañadas Edifice was constructed. It is formed of dense plagioclase basalts, mostly autobrecciated lava flows, which produce a positive gravimetric anomaly throughout the entire western area of the caldera, extending northwards below Pico Viejo (Ablay and Kearey 2000; Gottsmann et al. 2008). The continuity of the Boca de Tauce Edifice below Las Cañadas suggests the presence of a continuous basaltic shield that links the remnants of this shield that emerges in Teno, Anaga, and Roque del Conde. This idea differs from the model positng the existence of isolated edifices forming the initial subaerial phase of Tenerife (Ancochea et al. 1990), which visitors to the TNP see on some information panels.

**OP 2.4: Chahorra or Narices del Teide Viewpoint**

The Chahorra or Narices del Teide eruption (1798) is the only one to have occurred inside the caldera in historical times. This eruption is associated with a magma of tephritic composition and occurred along an eruptive fissure forming an angle of about 30° with the main axis of extension of the Santiago del Teide rift on the western flank of Pico Viejo (Fig. 9d). This eruption was Strombolian-to-violent-Strombolian in type and generated spatter and ash deposits, as well as a broad lava flow field. It seems to have also been the cause of the phreatic explosion that originated the Pico Viejo pit crater (Ablay and Martí 2000).
Itinerary 3: Eastern and Central Sectors of the Caldera Wall

This itinerary runs along the entire route of the Siete Cañadas track (path 4 in Fig. 6) at the base of the caldera wall in its eastern and central sectors, from El Portillo to the Parador. Along this itinerary, different aspects of the geology and volcanology of Las Cañadas Edifice and caldera, all well-exposed along the caldera wall, can be observed. The most relevant features are the presence of basaltic volcanism at the intersection between the NE rift (Dorsal de la Esperanza) and the central complex, the pyroclastic sequence of the Diego Hernández Formation, the Risco Verde scarp corresponding to the headwall of La Orotava valley, different sequences of the Lower Group (Angostura, Montón de Trigo, Capricho), and the presence of numerous dikes and phonolitic necks. In addition, the morphology of the fronts of the lavas flows from El Teide volcano is also visible.

**OP 3.1: North end of the Diego Hernández Wall**

At this point, there is a magnificent exposure of basaltic volcanism originating from the Dorsal rift. It is represented by a set of dykes, sills, scoria cones, and lava flows (dark colors), which in this sector are interbedded in or intersect the pyroclastic products (light colors) from Las Cañadas Edifice (Diego Hernández Formation) (Fig. 10a). The whole complex was affected by the formation of the caldera, thereby

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**Fig. 9** The main geological and volcanological features observable along itinerary 2. a OP 2.1: view of the Ucanca depression and western caldera wall from La Ruleta observation point. La Catedral phonolitic plug (Roques de García) and lava flows from Pico Viejo are also observable from this point. b OP 2.2: panorama of Los Roques de García and Los Azulejos (Lower Group) in concordant contact with the Ucanca Formation (Upper Group) from Los Roques de García viewpoint. The line of the northern fault of Los Azulejos graben is indicated (Galindo et al. 2005). c OP 2.3: cross-cutting relationship between phonolitic sheet intrusions (concentric, radial and cone sheet dykes) in the western wall of the caldera. d OP 2.4: view of the western flank of Pico Viejo showing the orientation of the Santiago del Teide rift and the eruptive fissure of the Chahorra eruption (1798).
intrusions and plugs of phonolitic composition overlying non-welded deposits. 

where at least four thick, strongly-welded units can be recognised 

radial distribution of some dikes with respect to the cylindrical cen-

tral intrusion.

an intrusive body (plug) of phonolitic composition that corresponds 

to one of the feeder conduits of the Guajara Formation. Note the 

the complex stratigraphic relationship between the successions from 

Hernández deposits (left) and those of Las Pilas Formation (right) is 

clearly visible. 

d OP3.4: view of La Angostura Formation in which 

the type of alteration of the deposits, demon-

ance of lithic clasts, some of them hydrothermally altered, 

explosive character of the materials in the Diego Hernández 

Formation is reflected in the nature of the deposits: the abun-

dance of lithic clasts, some of them hydrothermally altered, 

together with the type of alteration of the deposits, demonstra-

the presence of banded pumice in some deposits suggests that 

some eruptions may have occurred as a consequence of the 

intrusion of hotter and more fluid basaltic magma into the 

phonolitic chamber.

OP 3.3: Risco Verde Cliff

The Risco Verde cliff represents the eastern end of the Diego Hernández caldera wall and corresponds to the succession of lavas and welded pyroclastic deposits of phonolitic composition of Las Pilas Formation belonging to the Lower Group (Fig. 3). This sector of Las Cañadas Edifice was par-

tially destroyed by the formation of La Orotava valley, and was later infilled with pyroclastic deposits from the Diego Hernández Formation (Fig. 10c).

OP 3.4: Las Angosturas Volcanic Edifice from the Lower Group

Unlike the Upper Group, whose materials are distributed homogeneously and sub-horizontally along most of the wall, the Lower Group sequences are clearly associated with localized centres, and always have unconformities with the materials from adjacent centers (Fig. 10d). In the case of Las Angosturas Formation, the phonolitic PDC deposits (igni-

mbrites and pyroclastic surges) are limited in extent and 

are interbedded with very localized basaltic materials and 

epiclastic deposits.

OP 3.5: Montón de Trigo Formation

In this area, in addition to observing another of the sequences of the Lower Group (Montón de Trigo Formation, Martí et al. 1994), numerous phonolitic intrusive bodies (dikes and necks) can be observed. These were emplaced into the rocks of the Lower Group and Ucanca Formation, and correspond to feeding conduits for the eruptions of the Guajara Formation (Fig. 10e).

OP 3.6: Montaña Guajara Viewpoint

From this point, the full succession of the Guajara For-

mation is visible, separated from the Ucanca Formation

demonstrating the synchronicity of the basaltic activity 

along the Dorsal rifts and the explosive volcanism in the 

central edifice.

OP 3.2: Central Sector of the Diego Hernández Wall

Both in its proximal (caldera wall) and distal sectors (Ban-

das del Sur), the Diego Hernández Formation (Fig. 10b) is 

the most-studied sector of Las Cañadas Edifice and the site 

for which the greatest amount of stratigraphic, petrologi-

cal, volcanological, and geochronological data exists (e.g., 

Martí et al. 1994; Edgar et al. 2002, 2007, 2017; Brown 

et al. 2003; Brown and Branney 2004; Pittari 2004; Pittari 

et al. 2008). This formation is made up almost entirely of 

non-welded, dense phonolitic PDC deposits (ignimbrites) 

with some associated pyroclastic surge deposits, along with 

air fall-deposits rich in lithic fragments from the substrate. 

Occasionally, the presence of banded pumice becomes evident, the result of the mixing of basaltic and phonolitic magmas. The directions of flow observed in the PDC depos-

its, as well as their geometry, indicate that these materials 

originate from a vent area located in the easternmost sec-

tor of Las Cañadas Edifice, which later collapsed to form 

that sector of the caldera (Martí et al. 1994). The products 

erupted from that vent area were mainly emplaced within a 

paleovalley excavated out of older materials on the eastern 

flank of Las Cañadas Edifice, corresponding to the head of 

La Orotava valley, formed by gravitational sliding (Bravo 

and Hurlimann et al. 2004). Interbedded with the Diego Hernández phonolitic materials, there are also a number of 

different basaltic deposits (lavas and pyroclasts) derived 

from activity at the Dorsal rift. These basaltic vents corre-

spond to monogenetic cones located at the northern end 

of the wall and form one of the borders of the paleovalley 

(Fig. 2). It is difficult to determine the time elapsed between
by discontinuous basaltic scorias and lavas and intruded at its base by several dykes and plugs (Fig. 10f). The Guajara Formation has a maximum thickness of 250 m at Montaña Guajara and becomes progressively thinner toward the east (La Angostura and Las Pilas Cañadas). The phonolitic pyroclastic deposits of the Guajara Formation display a wide range of lithofacies with both welded and non-welded components. Most of the deposits dip gently (4–7°) southwards. The non-welded deposits include several horizons of well-stratified pumice lapilli beds, pumice breccia beds of fallout origin, pumice-rich ignimbrites with associated pyroclastic surge deposits, and some breccias. Welded rocks have a well-developed eutaxitic texture, defined by large, 1–20 cm in length, dark glassy or pale green devitrified fiamme. Most of the welded rocks resemble proximal welded fallout deposits (Martí et al. 1994), the exception being the uppermost unit, which is a classic welded ignimbrite consisting of a welded matrix with fiammes and lithic fragments. At this point, path 5 starts (Fig. 6) and climbs up to Montaña Guajara.

Fig. 11 The main geological and volcanological features observable along itinerary 4. a OP 4.1: general view of El Capricho pumice cone from the path to the Degollada de Ucanca. Note the stratification of the pumice layers in opposite directions. b OP 4.2: example of welded rock, with a non-welded base (for explanation, see text). c OP 4.3: view of alternating welded and non-welded pyroclastic deposits from the Guajara Formation at the Barranco del Rio. d OP 4.4: view of the Ucanca fault forming the southern boundary of Los Azulejos graben from the edge of the caldera wall in the Ucanca sector. Equivalent units on both sides of the fault plane are indicated by the same letter. The fault plane line and its relative movement are also indicated.
**OP 3.7: Phonolitic Dykes and Plugs**

This sector of the itinerary displays a large variety of sheet intrusions and plugs, which form dense arrangements and sometimes even conceal the host rocks (Fig. 10g). They are radial, concentric, and mostly single and multiple cone-sheets. They range in thickness from one to tens of meters, and their textures change from aphyric to porphyric with large plagioclase phenocrysts. Contacts with the host rocks or between different intrusions are marked by chilled margins. Most of these intrusions are massive, although some pyroclastic intrusions are also present. Some plugs appear at the intersection of several families of dykes, forming a much thicker intrusion with roughly circular morphology.

**Itinerary 4: Deposits from the Ucanca and Guajara Formations**

This itinerary (Fig. 7) (path 31 in Fig. 6) includes the ascent to the Ucanca caldera rim (Degollada de Ucanca) and then turns west along the caldera border for several kilometers toward Boca de Tauce. Midway along the route, Los Azulejos graben is perfectly visible. Observations to be made during this itinerary include, in addition to this first-order tectonic accident, the pumice cone of Capricho (Lower Group), the welded rock sequences of the Ucanca Formation, and the alternation of welded and non-welded pyroclastic materials from the Guajara Formation.

**OP 4.1: El Capricho**

El Capricho consists of the remnants of a pumice cone that has been eroded into uniquely capricious forms (hence its name), in which the internal stratification with opposite-facing dips to the north and south can still be observed (Fig. 11a). This structure was once a pumice cone formed by the accumulation of fallout pumice fragments around an emission centre during an eruption on the southeast flank of El Teide that was similar to that of Montaña Blanca (2020 bp). This unit belongs to the Lower Group and is located stratigraphically above Los Azulejos and below the Ucanca Formation.

**OP 4.2: Ucanca and Guajara Welded Rocks**

These thick units of welded rocks corresponding to proximal fall deposits constitute the most significant lithological feature of the Ucanca and Guajara formations (Martí et al. 1994; Soriano et al. 2002), and are one of the most characteristic features along the central and western sectors of the caldera wall. In general, the base of these units is well-stratified and non-welded, but there are also some spatter agglutinate beds, non-welded pumice fragments, beds rich in lithic fragments, and alternations of non-welded and welded deposits blending upwards into an up-to-120-m thick, densely welded, lava-like unit (Fig. 11b). In the transitional zone from non-welded to welded, there are highly vesiculated pumice fragments, highly flattened obsidian fiammes, obsidian spatter, and lithic fragments. The fiammes and spatters are thought to have been deposited from a low fountain-like eruption column, while the non-collapsed, vesiculated fragments are believed to have been transported high into the column where they cooled before deposition. The welded units are characterized by a well-developed eutaxitic texture defined by large (2–24 cm in length), flattened obsidian or pale green devitrified glass fragments. They lack a fine-grained matrix and often grade up from coarse, pumice-rich, non-welded fall deposits. These welded fall deposits formed by the accumulation of large fragments of magma that were still very hot during emplacement, and were able to sinter and weld when reaching the ground, thereby giving rise to a compact deposit that even had the ability to flow (rheomorphic) down the slope to generate a lava-like rock. Although confusion between phonolitic lavas and rheomorphic welded fall deposits is common, there are certain characteristics of welded fall deposits that separate them from phonolitic lavas: welded fall deposits grade laterally and vertically into non-welded deposits, have mantle topography, contain lithic clasts and do not have autobreccias at their margins unless they have become rheomorphic, in which case autobrecciation can occur and form deposits that are meters-to-tens of meters thick.

The gradual transition from non-welded to strongly welded shown by most of these units reflects a change in the physical conditions of the eruptive magma (fall in gas content, increase in temperature, fall in viscosity, etc.) within a zoned magma chamber. This creates a progressive change in the eruption style, from a typically Plinian phase (gas-rich magma) to a less explosive phase characterized by a much lower pyroclastic fountain (gas-poor magma) (Fig. 11b) (Soriano et al. 2002; Martí et al. 2020). Occasionally, these deposits may pass laterally into unwelded Plinian fall deposits, when more distant from the vent. In proximal areas, where these deposits behave rheomorphically, they may flow down the slope for several kilometers. In extreme cases, the front of the rheomorphic flow can detach itself from the rest of the deposits and slide down the slope for a few kilometers (Fig. 11b).

**OP 4.3: Barranco del Río**

Looking east from this observation point at the top of Degollada de Ucanca, a north–south cross-section of the entire sequence of the Guajara Formation and part of that of Ucanca can be seen (Fig. 11c). It is worth noting here the above-mentioned alternation of non-welded pyroclastic...
The main geological and volcanological features observable along itinerary 5. a OP 5.1: Roque Cinchado succession, forming part of Los Roques de García Upper Member and containing different units of proximal epiclastic deposits (breccia, cross-bedded sandstones, and conglomerates, intruded on top by an inclined sheet of phonolithic composition). b OP 5.1: cone-sheet, with pyroclastic texture and chilled margins. c OP 5.2: close-up view of Pico Viejo phonolithic lava flows. d OP 5.3: detail of a set of phonolithic intrusions showing columnar jointing. e OP 5.4: detail of the Lower Member pyroclastic rocks from Los Roques de García Formation, consisting of altered primary lithic and pumice rich ignimbrites. f OP 5.4: co-ignimbrite lag breccia deposits consisting of coarse lithic breccias with a high content of large lithic fragments embedded in an ignimbritic matrix. g OP 5.5: overview of a multiple phonolithic intrusion with well-developed columnar jointing. b OP 5.6: La Catedral plug, characterized by well-developed columnar jointing arranged in different directions. i OP 5.7: detail of Los Azulejos fault, which corresponds to the northern border of Los Azulejos graben (Galindo et al. 2005) as seen from the observation point OP 4.4. j OP 5.8: succession of strongly hydrothermally altered phonolitic pyroclastic deposits in Los Azulejos Formation.

deposits (pumice fall, ignimbrites, and pyroclastic surges) with welded rock units.

**OP 4.4: Los Azulejos Graben**

Los Azulejos graben in the western sector of Las Cañadas caldera wall is 1 km wide and is limited by two important NE-SW oriented normal faults: Los Azulejos and Ucanca (Fig. 11d) (Galindo et al. 2005). This graben was active for at least 0.5 Ma, from the end of the Ucanca Formation to the end of the Guajara Formation, clearly before the collapse of Las Cañadas Edifice. The main geological and volcanological features of this part of Las Cañadas caldera. A transtensional tectonic regime acted on the graben as demonstrated by kinematic indicators. The extension of the Dorsal rift zone toward Las Cañadas Edifice is the most probable volcano-tectonic origin of this graben, which facilitated the formation of the eastern sector and central sectors of the caldera. In this context, the inflation of the associated shallow phonolitic magma chambers could have caused the inverse reactivation of the normal faults. The main hydrothermal alteration of Los Azulejos occurred before the formation of this graben, while a secondary hydrothermal alteration associated with these normal faults occurred during and after its formation (Galindo et al. 2005).

**Itinerary 5: Los Roques de García and Azulejos Formations**

This itinerary (Fig. 7) corresponds to path 3 in Fig. 6 and takes visitors around the main part of Los Roques de García spur. Several observation points allow visitors to appreciate the main geological features of this part of Las Cañadas caldera. The succession mainly consists of polygenetic breccias of volcanic (lithic-rich ignimbrites and co-ignimbrite lag breccias) and sedimentary (debris flows and alluvial fan deposits) origin, rich in fragments of basaltic and phonolitic lavas, all intruded by a dense network of phonolitic dykes and plugs. Martí et al. (2010) distinguish two main members in Los Roques de García Formation. The Lower Member is continuous along most of the exposure of Los Roques de García spur and mainly comprises proximal lithic-rich pyroclastic deposits. Although the lower contact of the Lower Member is not visible, the upper contact corresponds to an erosive contact with the Upper Member, which is mostly composed of different types of well-stratified, proximal, epiclastic breccias derived from the reworking of volcanic material, with some interbedded pyroclastic deposits and epiclastic sandstone and conglomerate units.

In the southeastern part of the spur, Los Roques de García sequence is in contact through a normal fault (Los Azulejos fault, Galindo et al. 2005) with the younger volcanic sequence of Los Azulejos (OP 4.4), which is conformably overlain by El Capricho eroded pumice cone (OP 4.1).  

**OP 5.1: Epiclastic Upper Member and Pyroclastic Cone-Sheet**

The Upper Member of Los Roques de García Formation consists of an up-to-200-m-thick sequence of proximal epiclastic deposits and minor primary volcanic deposits. It constitutes the thickest accumulation of reworked volcanic material in the whole Las Cañadas caldera. Although the base of the Upper Member is characterized by a sharp contact that cuts into the deposits of the Lower Member, the upper stratigraphic contact is nowhere exposed. The Upper Member is mainly composed of thick sequences of highly indurated epiclastic breccias (up to 25 m thick), alternating with minor cross-bedded sandstones, conglomerates, lavas, and pyroclastic units. All of them have crude internal bedding that is consistent with the northeast-dipping bedding displayed by the remaining units in Los Roques de García spur. Epiclastic breccias are heterolithic and contain fragments from up to 2 m in diameter to centimeter-to-millimeter-sized fragments in the matrix, with erosive-to-planar bases. Minor lenses of pebbles and coarse sands also occur, which occasionally display cross-bedding (Fig. 12a). The lithological and sedimentological characteristics of the Upper Member deposits indicate that they correspond to a proximal sedimentary sequence derived from the erosion and alluvial reworking of primary volcanic material, including the Lower Member rocks.

Looking westwards from the same observation point, there is an interesting visible example of a cone-sheet, inclined northwards and turning vertically upwards in its upper part. Its main characteristic is its pyroclastic texture, very similar to some of the welded ignimbrites that outcrop along the caldera wall (Fig. 12b). This intrusion has chilled
margins at its borders, which were formed by the rapid cooling of magma during emplacement, and contains abundant lithic fragments and fragments of glassy pumices elongated parallel to the flow direction. This pyroclastic texture and the fact that the dyke turns vertically upwards in its uppermost part suggest that it was a feeder that reached the surface during the eruption.

**OP 5.2: Pico Viejo Lava Flows**

At this point, it is possible also to observe several recent phonolitic lava flows from Pico Viejo that were superimposed in the interior of the caldera, all with different morphologies and textures. The lobes formed by some of these lavas are clearly visible, as are the levees that originated on both sides of some of them, forming a channel along the lava flow that controlled its emplacement. Lava morphologies observable from this point include the classical pahoehoe roped surface in some areas, as well as aa-to-blocky morphology in others. Another curiosity of some of these lavas is the presence of plagioclase feldspar megacrysts that measure one or more centimeters across (Fig. 12c).

**OP 5.3: Phonolitic Multiple Dykes**

One of the main characteristics of Los Roques de García is the large number of phonolitic intrusions that in some places make it difficult to distinguish the host rock, which can be massive or pyroclastic, single or multiple, vertical or inclined, with plagioclase phenocrysts or nearly aphyric, from a few decimeters to several meters thick. In most cases these intrusions exhibit well-developed columnar jointing perpendicular to the intrusion surfaces. Here, it is also possible to study one of these multiple intrusions, where several dykes have intruded along the same discontinuity to form what appears at distance to be a very thick single intrusion (Fig. 12d). The presence of these sheet intrusions, as in many other parts of the caldera wall, is evidence for the presence of a number of shallow magma chambers that underwent several inflation episodes, thereby causing the rupture of the chamber walls and the intrusion of magma into this sector of the original Las Cañadas Edifice.

**OP 5.4: Pyroclastic Lower Member**

The Lower Member of Los Roques de García Formation is better exposed in the northern sector of the spur. However, it continues toward the central and southern sectors, despite the fact that intra-formational and later faulting, hydrothermal alteration, and erosion all mask its presence in these other zones. It contains a well stratified, up to 150-m-thick succession of proximal primary pyroclastic deposits (Fig. 12e), which include massive, lithic, and pumice-rich deposits (i.e., ignimbrites), as well as pyroclastic breccias and fine-grained, thinly bedded deposits. The ignimbrites range from one to several metres in thickness and tend to have planar lower and upper contacts, which are sometimes associated with thin, fine grained (ash) layers with unidirectional sedimentary depositional structures. No paleosoils, erosion surfaces, or intraformational unconformities have been observed in this sequence, which suggests that the whole sequence corresponds to a single eruptive event consisting of several phases (see Martí et al. 2010 for more details).

All the deposits have been diagenetically and probably also hydrothermally altered, and all primary glass has been transformed into clay minerals and zeolites, giving rise to a strong induration of the rocks. However, some original, non-reworked pumice (vesiculated) textures have been preserved and it is possible to recognise the primary character of the pyroclastic deposits. All the deposits have a high content of angular-to-subrounded lithic fragments, mainly massive porphyritic phonolites, with subordinate fragments of basaltic and intermediate massive volcanic rock.

Some units correspond to coarse lithic breccias (Fig. 12f) that resemble ignimbrites; however, they can be distinguished by their greater content of larger lithic fragments, some several metres in diameter. Most of the lithic clasts are subrounded and consist of massive porphyritic phonolites. Some of these clasts have chilled margins and occasionally internal fractures, which in some cases also reflect a jigsaw-like texture. The matrix also contains ash fragments, but much less abundantly. Each individual coarse lithic breccia unit is several metres thick and has planar contacts. These breccias can be interpreted as co-ignimbrite lag breccias, which sometimes appear associated with ignimbritic deposits in proximal areas (see Walker 1985). The presence of co-ignimbrite lag breccias has also been noted in Las Cañadas Edifice Upper Group (Martí et al. 1994; Bryan et al. 1998; Pittari 2004; Pittari et al. 2008) and suggests evidence of caldera collapse events.

**OP 5.5: Overview of Multiple Phonolitic Dykes (La Escalerita)**

Here, visitors can enjoy an aerial view of an impressive multiple phonolitic intrusion with well-developed columnar jointing, whose discontinuity throughout the whole unit reveals the presence of several parallel sheet intrusions in the same structural plane (Fig. 12g).

**OP 5.6: La Catedral**

La Catedral is the most representative plug structure in Las Cañadas. This 120-m-diameter structure formed at the
intersection of several families of dykes. It is characterized by well-defined columnar jointing, with pristine subhorizontal prisms in a radial arrangement, which form a rim around the inner part of the intrusion where the columns are vertical (Fig. 12h).

**OP 5.7: Los Azulejos Graben Fault**

Los Azulejos Formation is separated from Los Roques de García by the fault that marks the northern limit of Los Azulejos graben (Galindo et al. 2005), and can be viewed from observation point OP 4.4. The repeated movement of this fault during the evolution of Las Cañadas caldera is responsible for the chaotic distribution of the rocks on both sides of the fault plane (Fig. 12i). Additionally, minor normal faults with vertical displacements up to 40 m are present to the north and south of Los Azulejos Fault; they cause further disruption to the stratigraphy of Los Roques de García and Los Azulejos sequences and intensify the chaotic aspect of the central sector of Los Roques de García spur.

**OP 5.8: Los Azulejos Formation**

Los Azulejos Formation is unconformably underlain by the Ucanca Formation and consists of a succession of 220-m-thick phonolitic pyroclastic breccias, interbedded with pumice-rich ignimbrites, and surge and air-fall deposits (Fig. 12). They exhibit well-preserved bedding that dips gently to the south-west. These breccias correspond to proximal facies and include intra-formational breccia deposits and epiclastic breccias. The lithic fragments are of the same composition as those found in Los Roques de García Formation. These rocks have been strongly altered by hydrothermal processes that occurred before the intrusion of the dyke systems related to the deposition of the Upper Group. This suggests that Los Roques de García and Los Azulejos formations represent an important volcanic edifice, constructed during the early stages of the upper part of Las Cañadas Edifice, which had no relation to the later caldera-forming eruptions (Martí et al. 2010). This is confirmed by the fact that both formations are intruded by the same dyke systems as those that affected other sectors of Las Cañadas caldera wall. The hydrothermal alteration gave rise to the characteristic bluish, greenish and yellowish colors of this formation, caused by the transformation of the original glass components into zeolites and clay minerals.

**Additional Viewpoints**

**OP 6.1: La Orotava Vantage Point**

This observation point (Fig. 7) affords the best view over La Orotava valley. It allows visitors to distinguish the alignment of Strombolian cones along the uppermost part of the valley, the infill by a succession of lavas from El Teide and the Dorsal rift, and the phonolitic pyroclastic deposits of Las Cañadas that underlie them. It is also interesting to view from here the stratification of the rocks that form the Tigaiga massif on the western wall of the valley, as well as the presence of various younger monogenetic cones inside the valley (Fig. 13a).

**OP 6.2: Güímar Valley and Caldera de Pedro Gil**

This observation point (Fig. 1) offers excellent views of two structural features that developed in relation to the Dorsal rift: the Güímar valley and Caldera de Pedro Gil (Fig. 13b). The Güímar Valley was the result of a catastrophic flank failure that affected the southern slopes of Tenerife several hundred thousand years before the formation of La Orotava valley on the northern side of the island (Ancochea et al. 1990). The Güímar valley has no obvious relationships with any caldera-forming episode. The walls of the valley clearly show the succession of lavas and pyroclastic deposits from the basaltic edifices due to the activity of the NE rift, as well as numerous sheet intrusions of basaltic composition associated with the rift activity. In the valley itself, the Arafo volcano, a cinder cone and its associated lava flow, formed in the historical eruption of 1705, is visible. This cone is related to the Fasnia-Siete Fuentes eruptions that took place along the same SW-NE trending fissure.

Part of the Güímar valley headwall visible from this observation point was affected by another collapse event that formed Caldera de Pedro Gil. This depression is approximately 3 km wide and 540 m deep. However, assuming vertical collapse, its true diameter is probably only 1.5 km and its depth 700 m (Galindo 2005). A paleomorphologic analysis suggests that it formed about 0.81 Ma (Ancochea et al. 1990) after the vertical collapse of the Pedro Gil Edifice (Galindo 2005). The observed cross-cutting relationships suggest that the Güímar valley occurred before Caldera de Pedro Gil, and that this latter structure affected the location of the headwall of the former (Galindo 2005).

**OP 6.3: Mirador del Tabonal Negro: Eastern part of El Teide-Pico Viejo Complex**

From the Mirador del Tabonal Negro (Fig. 7), there is a panorama of the central and eastern sectors of the caldera (Fig. 13c). The relatively flat caldera floor comprises lavas from Montaña Blanca and isolated vents not obviously associated with the stratovolcanoes. Beneath these felsic rocks, there are 560 m of intermediate Teide products infilling the uppermost part of the caldera depression (see Martí 2019). Thick lobate lava flows from the caldera-floor vents of Montaña de la Cruz and Montaña Majua lie to the west.
and south. These trachyphonolite flows are less silica-under-saturated than the phonolites of Montaña Blanca or Pico Viejo, and both have petrological affinities with El Teide products (Ablay et al. 1998). Montaña Majua is a strombolian pumice cone breached by lobate lava flows. To the east, the foreground is occupied by phonolitic lavas from the Arenas Blancas member. Further south and east run mafic lava flows and scoriae erupted from vents close to the eastern caldera wall. These alkali basalts are the most primitive magmas to have erupted within the Las Cañadas caldera, and are believed to represent the parental magmas that feed El Teide-Pico Viejo system (Ablay et al. 1997). In the foreground, El Tabonal Negro is a thick vitric phonolitic lava flow that appears dark due to its relative youth. Beneath El Tabonal, there are more thick, lobate phonolitic lava flows that were emplaced during the early development of Montaña Blanca from a linear array of vents (Ablay et al. 1995).

Montaña Blanca represents the products of a significant explosive eruption that occurred about 2020 years ago (Ablay et al. 1995). Its visible products, from base to top, include (i) the El Tabonal flow, which represents an initial phase of effusive activity; (ii) a thick pumice fall deposit that forms most of the cone, composed of angular, well-sorted unwelded phonolitic pumice lapilli, corresponding to the explosive subplinian phase of the eruption; (iii) a distinctive unit of densely welded obsidian with a strong rheomorphic fabric, which grades laterally into a spatter-fed obsidian lava flow; and (iv) several small domes and stubby lava flows that erupted during a late effusive phase, some from the Montaña Blanca eruptive fissure.

**Discussion and Conclusions**

The previous sections offer a summary of the geological and volcanological history of TNP, as well as a description of the main geosites from which this history can be discerned. Knowledge of these elements is crucial for understanding the
evolution of one of the most impressive and beautiful volcanic landscapes in the world. Unfortunately, a considerable amount of work still remains to be done on how this knowledge can be transmitted to visitors, starting with the precise transfer of current scientific knowledge to the professionals (e.g., park and tourist guides) whose task is to explain to visitors the park’s geological and volcanological riches, and to those in charge of the preservation of this important and unique geoheritage (e.g., park managers).

One of the greatest problems facing the Canary Islands—and Tenerife in particular—is the result of the decision taken in the 1960s and 1970s to promote mass tourism. Despite the wealth it creates and the fact that it is still the region’s main source of income, it is not clear whether the millions of tourists who visit the Canary Islands every year are particularly interested in the natural world. In the case of the TNP, the number of tourists that arrive every year is so great that not all can benefit from a measured explanation of the park’s geological treasures. This situation is an obstacle to the establishment of awareness of the importance of preserving this geoheritage.

A further issue shared by local geologists is that there has been little or no political interest in analyzing this question and drawing appropriate conclusions. Local scientists are trusted but this is not sufficient to make up for the lack of political or collective structures, with rational and open mentalities, that could define which concepts should be presented to visitors.

The communication and preservation of the park’s geological heritage needs to be based on high quality, objective scientific research, untainted by popular knowledge lacking any scientific basis. Today, in many regions, geotourism is becoming a new way of generating income and so it is important to foster it and ensure that it is as sustainable as possible. Examples of how to make geotourism sustainable and a valuable element in the development of a particular area or region have been documented elsewhere (e.g., Plana-gumà and Martí 2020). However, these examples also reveal how demanding this type of tourism is. For this reason, it requires information based on rigorous scientific knowledge and properly trained communicators who can transmit natural values to visitors. In the case of the TNP, it is vital to seriously consider implementing this type of tourism to ensure the correct diffusion and preservation of the park’s geoheritage.

A number of initiatives needs to be undertaken if all the necessary information on the geoheritage of the TNP is to be gathered together and transmitted to visitors in an appropriate fashion. The amount of scientific knowledge, that today exists regarding this particular geological and volcanological site, is sufficient to provide visitors with a clear and well-defined picture of what they are seeing. The managers of the national park should make more efforts to extract information from objective researches and avoid relying on the opinion of local advisors. Currently, political rather than knowledge-based reasons seem to hold sway, which works against the interests of visitors. The information centers that exist in the park should be better prepared and offer objective scientific knowledge rather than the highly limited and often very biased information that is currently provided. Additionally, a complete network of information panels, with representations and descriptions based on the scientific knowledge described here, and illustrations and texts capable of explaining the observable volcanic features at each viewpoint, as well as field guides and mobile and tablets apps, is essential for reaching freelance tourists. The professionals in charge of transmitting the geological values of the park to visitors should have more opportunities for training and for learning and documenting new ideas. Excellent scientific knowledge is not enough if it cannot be adequately communicated to the general public; this is the responsibility of scientists, as well as park managers and other professionals, whose task it is to transfer this knowledge. All should work together to improve the knowledge, communication and outreach of the park’s geoheritage.

This contribution aims to synthesize the current scientific knowledge of one of the most impressive and instructive volcanological sites anywhere in the world, which is, nonetheless, still poorly understood by visitors and by those whose role it is to portray and preserve it. The set of geological elements that can be observed in the park are pieces of a puzzle that explain the evolution of Las Cañadas caldera and El Teide-Pico Viejo stratovolcanoes, a unique and complex central volcanic system. Its importance makes it imperative that visitors interested in knowing and understanding how such a volcanic system works are provided with precise information based on objective scientific knowledge. Otherwise, the knowledge acquired by visitors will not be transmitted adequately, which could lead to a progressive loss of interest in visiting this area. This could have important cultural and socio-economic consequences in the long term and lead to an underestimation of the magnitude and characteristics of the geohazards that have occurred on the island in the past and may occur in the future.

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**Declarations**

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