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RESEARCH ARTICLE

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Conduit-vent structures and related proximal deposits in the Las Cañadas caldera, Tenerife, Canary Islands

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Abstract The Las Cañadas caldera wall and the outer slopes of the caldera provide three-dimensional exposures of numerous proximal-welded fallout deposits and have been mapped in detail. As a result, some parts of the Ucanca and Guajara Formations of the stratigraphy of Martí et al. (1994) have been divided into members that correspond to individual eruptions. Mapping has also revealed the occurrence of conduit-vent structures associated with proximal-welded fallout deposits. Conduit-vent structures consist of an upper flaring area and a lower narrow conduit. Conduit-vent geometry and dimensions include cylindrical plugs and eruptive fissures steeply dipping towards the caldera depression and elongated vents. The flaring area can be rather asymmetric and is usually filled by down-vent rheomorphic flow of the proximal fallout deposit. The lower conduits are filled by lava plug, agglutination of juveniles onto conduit walls and dyke intrusion with eventual dome extrusion. The eruption dynamics of welded fallout deposits and magma fragmentation within the conduit are consistent with an evolution from explosive to effusive. In this context conduit flow regimes evolve from turbulent to annular flow in which the conduit is progressively choked, and laminar flow leading to the final conduit closure.

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Introduction

Volcanic systems can be envisaged as having three parts: magma reservoirs, conduits connecting reservoirs to the Earth's surface and volcanic deposits. Ancient, deeply eroded volcanoes provide good exposures of their plutonic roots and crystallized former magma reservoirs. In young and active volcanoes, the deeper levels are typically buried by lavas and tephras, which likewise have been extensively studied. In contrast, exposures of volcanic conduit-vent structures are relatively rare and only some field investigations have been published (Almond 1971; Koronovsky 1971; Ekren and Byers 1976; Reedman et al. 1987; Wolff et al. 1989; Stasiuk et al. 1996; Kano et al. 1997). Due to limitations of exposure, fewer still of these studies have been able to link vent structures and their filling processes with proximal deposits produced during the same eruptions (Almond 1971; Koronovsky 1971; Ekren and Byers 1976). These authors described ignimbrite vents; we know of no published descriptions linking conduit-vent structures to proximal fallout deposits. The Las Cañadas caldera wall in Tenerife is a natural scarp that truncates the Las Cañadas edifice (Fig. 1) and provides superb three-dimensional exposures through the uppermost part of the edifice. The scarp itself affords near-vertical sections, while the proximal dip-slopes around the caldera provide exposures in plan view. Gullies in both the caldera wall and the proximal dip-slopes provide vertical sections radial to the caldera. However, most previous volcanological studies of the explosive phonolitic Las Cañadas eruption products have focussed on distal deposits many kilometres from the caldera rim (Edgar et al. 2002; Huertas et al. 2002; Brown et al. 2003).

During mapping of the caldera wall at a scale of 1:5,000, several proximal deposits connected to their respective conduit-vent structures have been studied in detail. Conduit-vent geometry and dimensions have been recon-

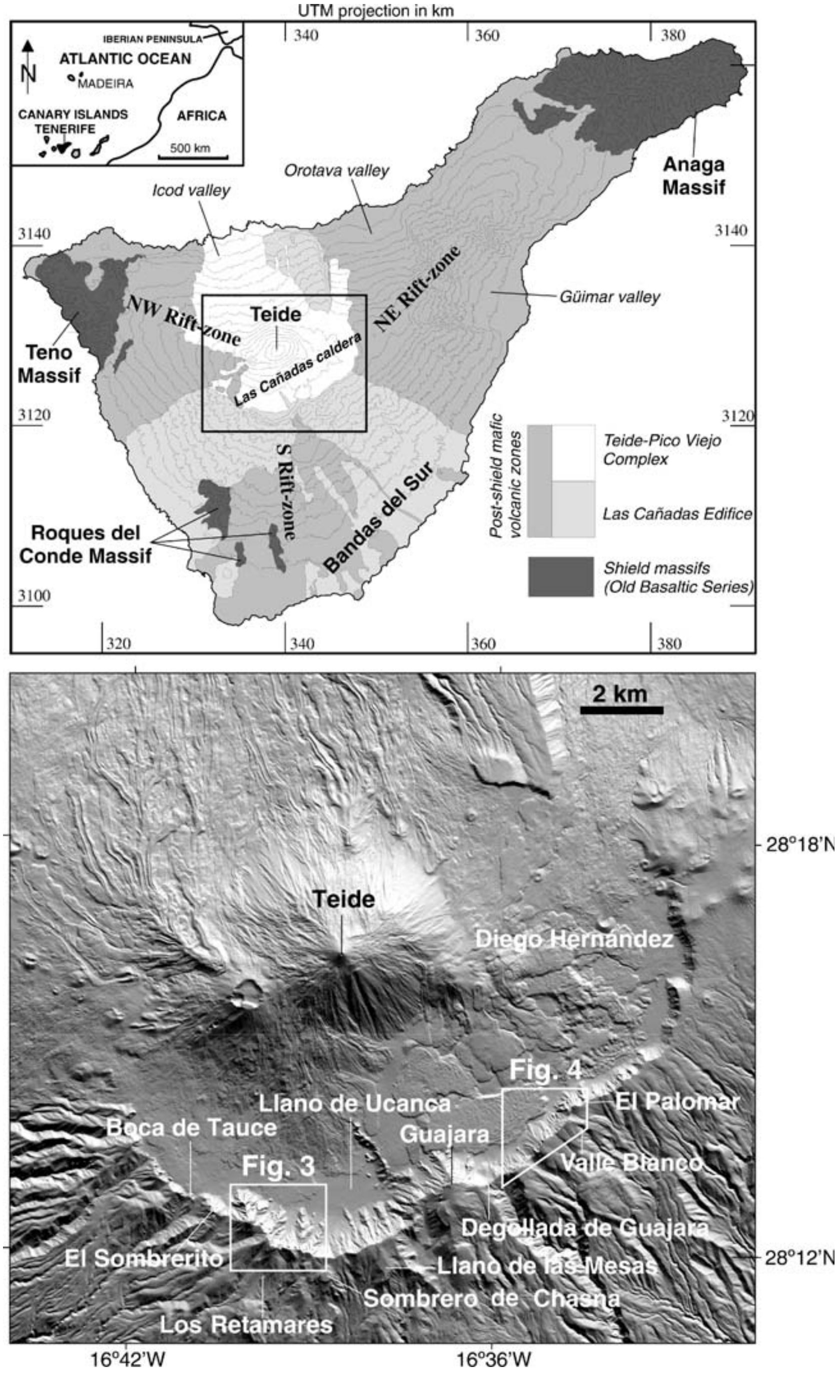

Fig. 1 Simplified geological map of Tenerife showing the main volcanic units (contour interval is 200 m) and *shaded relief* digital elevation model of the central part of Tenerife showing the location of Figs. 3 and 4

structed, and relationships with proximal deposits in terms of conduit-vent filling processes and eruption dynamics have been established. In this paper we describe and interpret several conduit-vent structures and related proximal deposits distributed along the caldera wall and rim. To show the best examples of conduit-vent structures and related welded fallout deposits, we focus on two areas, one in the western sector of the caldera and the other in the eastern sector. Unlike previous geological studies of explosive vents, all the proximal deposits demonstrably associated with the conduit-vent structures are fallout. Detailed maps, cross-sections and stratigraphic sections are shown, and the implications for conduit processes such as magma fragmentation, conduit filling and eruption dynamics of explosive phonolitic eruptions in proximal settings are discussed.

Summary of the geology of Tenerife

Tenerife, the largest of the Canary Islands, is built on oceanic crust close to the northwest African passive margin. The subaerial basaltic shield of the island (3.3–12 Ma) is exposed in the Teno, Anaga and Roque del

Conde massifs (Fig. 1). The central part of the island consists of a volcanic complex which includes the Las Cañadas edifice and the late Teide-Pico Viejo Complex (3.5 Ma to present), dominated by differentiated magmas. Basaltic lavas erupted contemporaneously with this central complex from NW, NE and S rift zones (Fig. 1). The southern slopes (Bandas del Sur) and part of the northern slopes of the island are covered by a pyroclastic apron erupted from the Las Cañadas edifice during the Pleistocene. In the central part of the island, the Las Cañadas caldera is an elliptical depression, measuring 16×19 km, which truncates the Las Cañadas edifice. It is defined to the southwest, south, southeast and east by a scalloped wall up to 500 m high (Fig. 1). The Teide and Pico Viejo stratovolcanoes and associated satellite vents lie within the caldera, and their products partially fill the caldera depression. Large sector collapses have modified the northern and southern slopes of the island producing the Icod, Orotava and Güímar valleys (Fig. 1).

Stratigraphy of the Las Cañadas caldera wall

The stratigraphy of the Las Cañadas caldera wall records nearly 3 Ma of volcanic activity and construction of the Las Cañadas edifice. During this time, a wide variety of products erupted from numerous vents has accumulated, yielding a complex stratigraphy with rapid vertical and lateral facies changes. Most of the deposits exposed in the caldera wall are proximal. Hence, different portions of the wall require specific stratigraphic treatment, which commonly cannot be extended to other parts of the wall. In this paper, we use the stratigraphy of the caldera wall proposed by Martí et al. (1994), based on measured sections and correlation along the caldera wall (Fig. 2). This stratigraphy distinguishes the Las Cañadas Lower and Upper Groups, separated by a major unconformity, and three units within the Upper Group: the Ucanca, Guajara and Diego Hernández Formations. In those parts of Martí et al. (1994) stratigraphic framework that we have studied in greater detail, we have distinguished new stratigraphic units. The Ucanca Formation in a portion of the southwestern caldera wall, and the Guajara Formation in a portion of the southeastern wall, have been divided into members to facilitate mapping of the fallout deposits and related conduit-vent structures described in this paper (Fig. 2).

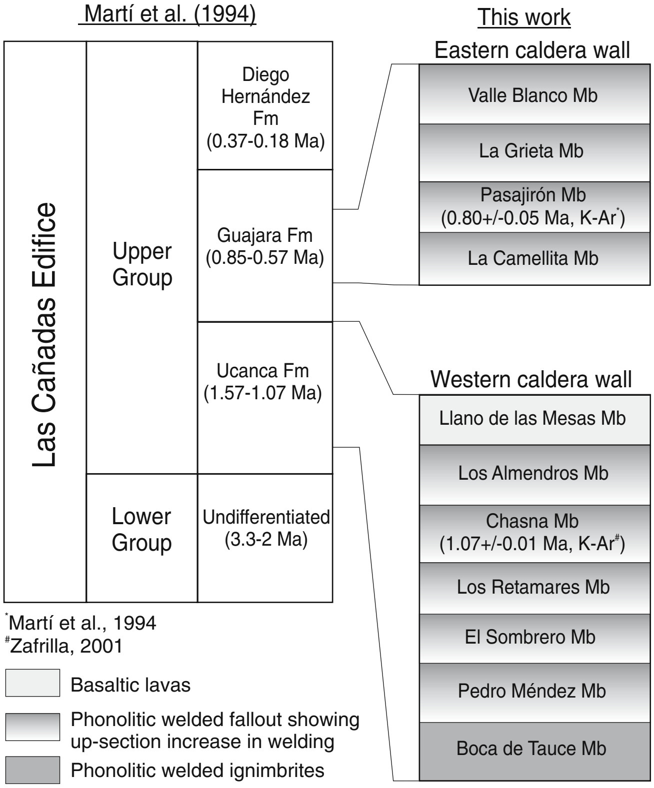

Fig. 2 Stratigraphy of the Las Cañadas caldera wall (adapted from Martí et al. 1994), showing the stratigraphic units distinguished in this work in the eastern and western caldera wall

These members correspond to deposits that occupy different positions in the stratigraphic sequence of the caldera wall, and do not show internal evidences of interruption in the volcanic activity such as palaeosoils, disconformities, and partings. Most of them show a continuous facies transition from non-welded to lava-like. They are thought to correspond to individual eruptions and have been defined according to the following criteria: deposits vented from a known structure and showing lithological differences (clast size, clast composition, sorting) with adjacent deposits; deposits separated from other deposits by erosive surfaces and sedimentary layers; cooling units as defined by Soriano et al. (2002); and radiometric dating. The lack of palaeosoils between units can possibly be explained due to the extreme climate conditions at the altitude of the eruptions (~2,500 m) and the short time elapsed between eruptions. Most of these units are welded fallout deposits (Fig. 2) and, following deposition, the upper densely welded part flowed down the outer slopes away from the caldera. During rheomorphic flowage, this upper densely welded part may have been detached from the lower non-welded part. As a result, recognition of these units as piled in the caldera wall and rim is usually difficult in more distal parts of the outer slopes of the caldera.

The main features of these members are summarized in Table 1. Those units that are physically connected to conduit-vent structures, or that have been interpreted as being related to a specific conduit-vent structure, are described in further detail in the text. The members are generally well exposed in the caldera wall and rim, although the contacts between units are currently covered by talus debris. In some cases, however, upper and lower contacts have been observed; otherwise they have been inferred from the general mapping. For example, if a unit overlies two or more different units, the lower contact has been inferred as unconformable, despite the fact that the bedding along most of the caldera wall is parallel to the unit below or above. Further details at map scale such as outcrop extent along the caldera wall and rim and in the external slopes of the caldera, can be directly obtained from the maps in Figs. 3 and 4. The caldera wall and rim is an uninhabited area and place-names are scarce. Hence, the names of the members have been taken after names of the nearest topographic features, some of them in the caldera depression and in the outer slopes of the caldera.

Stratigraphy of the western sector of the caldera wall

The area of the western sector of the caldera showing the best examples of vents and related proximal fallout deposits is located between Boca de Tauce and the Llano de Ucanca (Fig. 1). The overall stratigraphy of this area consists of the Ucanca Formation of the Upper Group overlying the "Boca de Tauce Sequence" of the Lower Group (Martí et al. 1994). The Boca de Tauce Sequence consists of distinctive coarsely plagioclase-phyric basalts, which have been dated by K-Ar at 3.00±0.10 Ma (Ancochea et al. 1999). In this area, the lower part of the Ucanca Formation consists of a succession of phonolitic non-welded pyroclastic rocks up to 300 m thick unconformably overlain by the Boca de Tauce Sequence. The pyroclastic succession includes ignimbrite, surge and fallout deposits and minor sedimentary beds, with a 70-m-thick package of phonolitic lavas (or lava-like welded rocks) near the top. Parts of this succession have been dated by K-Ar at 1.48±0.04 Ma and 1.31±0.04 Ma (Martí et al. 1994). The succession is intensively intruded, by multiple inclined phonolite sheets parallel to the caldera rim and vertical sheets normal to the caldera rim (Fig. 3). All the stratigraphic units distinguished within the Ucanca For-

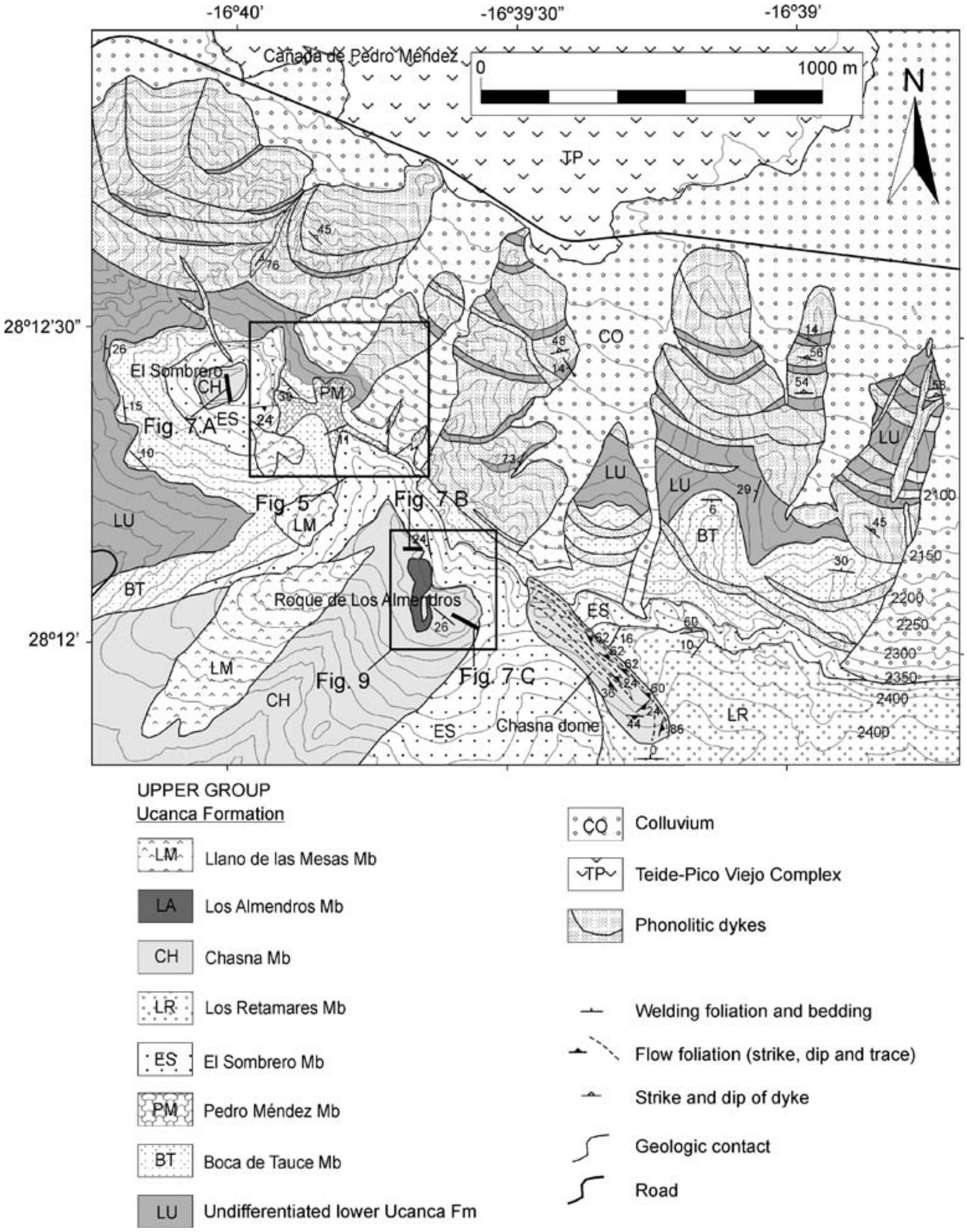

Fig. 3 Geological map of part of the western sector of the caldera wall

Table 1 Summary of the stratigraphic units distinguished in this paper in the western and eastern caldera wall. Those units related to specific conduit-vent structures are described in the text in detail

Stratigraphy of the western caldera wall							
Unit	Lithology	Type locality	Thickness (m)	Lower/upper contact	Underlying unit/lithology	Overlying unit/ lithology	Others
Llano de las Mesas Mb	Basaltic lavas and minor spatter fallout	600 m NE of El Sombrero de Chasna (Fig. 1): 16°38′34″W, 28°11′55′′N	70	Unconformable/–	Several of the units below	–	
Los Almendros Mb	Welded fallout	Roque de los Almendros (Fig. 3): 16°39′39″W, 28°12′6″N	15	Unconformable/–	Welded fallout of Chasna Mb	–	
Chasna Mb	Welded and non-welded pumice fallout	Roque de Los Almendros (Fig. 3): 16°39′35″W, 28°12′3″N	45	Erosive/unconformable	Sedimentary layers and welded fallout of Los Retamares Mb and El Sombrero Mb	Welded fallout of Los Almendros Mb	
Los Retamares Mb	Welded and non-welded spatter fallout	350 m E of the Chasna dome in the caldera wall and rim (Fig. 3): 16°39′11″W, 28°12′2″N	35	Inferred unconformable/ inferred unconformable	Welded fallout of El Sombrero Mb	Intruded by Chasna dome	Small portion dips (60°) and thickens to the caldera depression
El Sombrero Mb	Welded and non-welded pumice fallout	200 m SE of El Sombrero in the caldera wall and rim (Fig. 3): 16°39′57″W, 28°12′23″N	100	Inferred unconformable/ inferred unconformable	Welded fallout of Pedro Méndez Mb and Boca de Tauce Mb	Non-welded fallout of Los Retamares Mb and intruded by Chasna dome	NW part dips (35°) and thickens to the caldera depression
Pedro Méndez Mb	Welded and non-welded pumice fallout	400 m SE of El Sombrero in the caldera wall and rim (Fig. 3): 16°39′50″W, 28°12′34″N	35	Inferred unconformable/ inferred unconformable	Boca de Tauce Mb	Non-welded fallout of El Sombrero Mb	
Boca de Tauce Mb	Welded ignimbrites (upper 60 m), and minor non-welded ignimbrites, co-ignimbrite breccias and surges	El Sombrerito (Fig. 1): 16°40′38″W, 28°12′34″N	70	Erosive, fragments of underlying lithologies at the base (Fig. 6 a)/inferred unconformable	Sedimentary layers and non-welded pyroclastics of the lower Ucanca Fm	Non-welded fallout of Pedro Méndez Mb	

Table 1 (continued)

Stratigraphy of the eastern caldera wall

Unit	Lithology	Type locality	Thickness (m)	Lower/upper contact	Underlying unit/lithology	Overlying unit/lithology	Others
Valle Blanco Mb	Welded and non-welded pumice fallout	500 m NE of Roque de la Grieta (Fig. 4): 16°34′54″ W, 28°13′52″N	30	Inferred unconformable/–	Welded fallout of La Grieta Mb	–	
La Grieta Mb	Welded and non-welded pumice fallout (Fig. 7 f)	400 m NE of Roque de la Grieta (Fig. 4): 16°34′59″ W, 28°13′47″N	12	Inferred unconformable/ inferred unconformable	Welded fallout of Pasajirón Mb and La Camellita Mb	Non-welded fallout of Valle Blanco Mb	SE part dips (60°) and thickens to the caldera depression
Pasajirón Mb	Welded and non-welded pumice fallout	Montaña de Pasajirón (Fig. 4): 16°35′36″W, 28° 13′13″N	60	Inferred unconformable/ inferred unconformable	Welded fallout of La Camellita Mb	Non-welded fallout of La Grieta Mb	
La Camellita Mb	Welded and non-welded pumice fallout	300 m NW of Montaña de Pasajirón (Fig. 4): 16°35′28″W, 28°13′16″N	75	Inferred unconformable/ inferred conformable	Welded ignimbrites of the lower Guajara Fm	Non-welded fallout of Pasajirón Mb	

mation in this sector of the western caldera are phonolitic welded fallout deposits. Exceptions are the Boca the Tauce Member that is mostly composed of phonolitic welded ignimbrites and the Llano de las Mesas Member that mainly consists of basaltic lavas (Fig. 2 and Table 1).

Stratigraphy of the eastern sector of the caldera wall

The stratigraphy of this area of the caldera wall consists of the Guajara Formation and the Ucanca Formation of the Upper Group overlying the Montón de Trigo Sequence of the Lower Group. The "Montón de Trigo Sequence" is composed of phonolitic and basaltic lavas and minor pyroclastic rocks, ranging in age from 3.34±0.10 to 3.00±0.10 Ma (Ancochea et al. 1999). The Ucanca Formation is up to 70 m thick in this part of the caldera wall, and comprises non-welded pyroclastic rocks, with phonolitic and basaltic lavas. The Guajara Formation overlies the Ucanca Formation with an apparently conformable contact. The Guajara Formation consists of phonolitic welded and non-welded pyroclastic rocks accompanied by phonolitic lavas in the lower part. These units are intruded by basaltic and phonolitic dykes mainly trending N–S (Fig. 4). All the stratigraphic units distinguished within the Guajara Formation in the eastern sector of the caldera are phonolitic welded fallout deposits (Fig. 2 and Table 1). We have grouped the three "welding sequences" described by Soriano et al. (2002) at the Montaña de Pasajirón stratigraphic section into two units: la Camellita Member and Pasajirón Member. La Camellita Member corresponds to the lowermost welding sequence. It is a single cooling unit, and a significant time (>100 days) may have encompassed after cooling and starting the deposition of the overlying unit (Soriano et al. 2002), while the Pasajirón Member comprises the two upper welding sequences.

Description and interpretation of conduit-vent structures and related proximal deposits

Pedro Méndez Member welded fallout and cylindrical plug

The Pedro Méndez Member consists of a welded fallout deposit that can be traced laterally in the caldera wall for a distance of 400 m (Figs. 3 and 5). It shows an up-section increase in the degree of welding, grading from non-welded at the base to moderately, through densely welded to lava-like at the top (Fig. 6). The non-welded base of the Pedro Méndez Member is a poorly sorted coarse-grained and clast-supported agglomerate of angular pumice and lithics. The upper densely welded and lava-like part is dark brown and contains sparse clasts less than 3 cm in diameter (Fig. 6b). These clasts are embedded in a foliated groundmass of the same composition than the clasts and shows small-scale folds. Lithics are restricted to the non-welded and moderately welded part of the deposit and

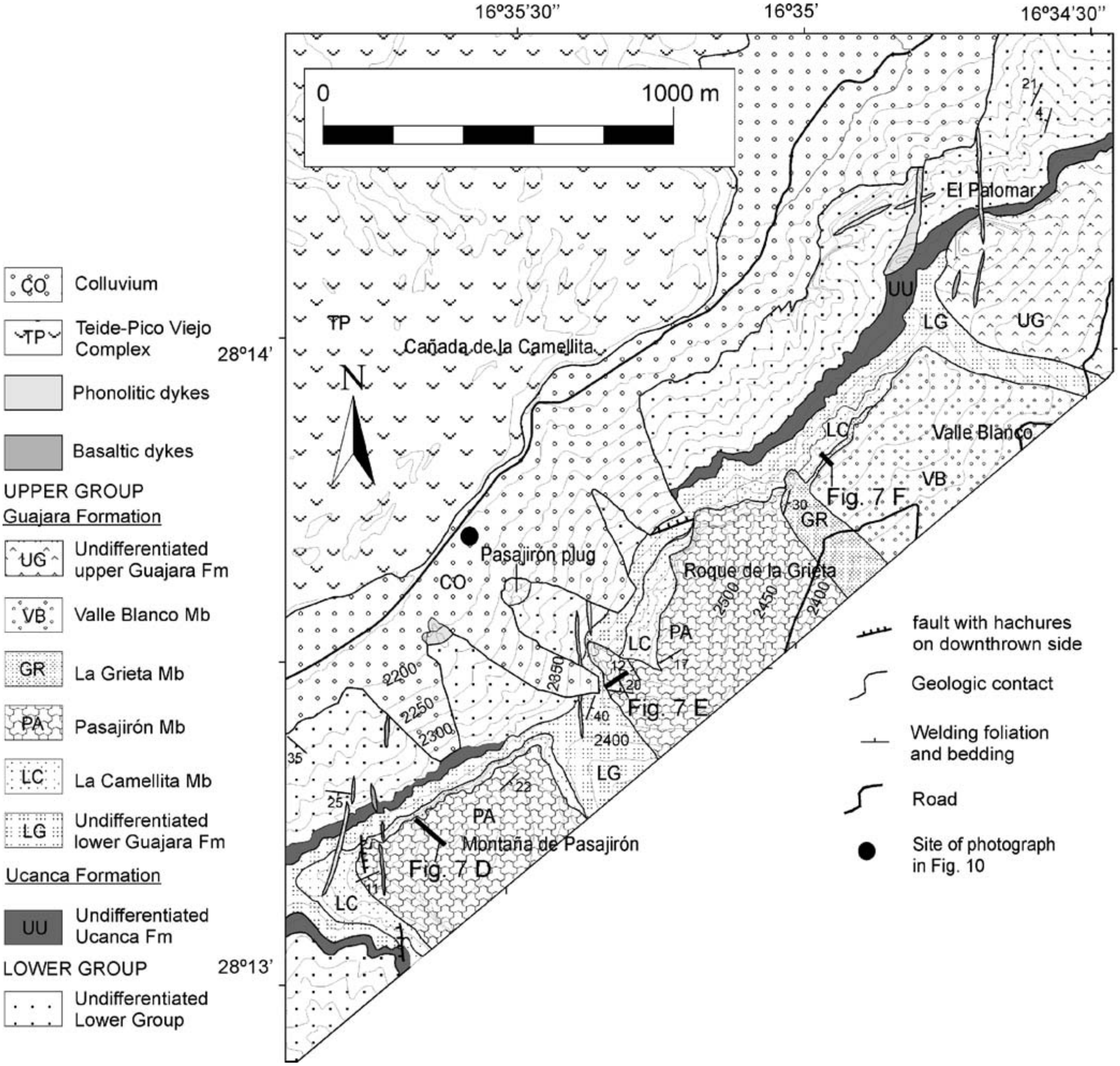

Fig. 4 Geological map of part of the eastern sector of the caldera wall

consist of phonolitic and basaltic lava fragments and welded rocks.

A nearly cylindrical eroded plug of massive phonolite intrudes rocks of the Pedro Méndez Member, surge deposits of the Boca de Tauce Member, and pyroclastic rocks that may correspond to the lower Ucanca Formation (Figs. 5 and 6b, c). The plug is lithologically identical to the densely welded and lava-like part of the Pedro Méndez Member, and shows the same distinctive dark brown colour and small clasts embedded in a foliated groundmass. In the northeastern part of the plug (Fig. 5), its margin consists of a 30-cm-thick clast-supported breccia with clasts of up to 20 cm diameter grading into an inner part that shows subvertical flow foliation. This foliation has been observed around the plug and is parallel to the contact between the plug and the rocks of the Ucanca Formation (Figs. 5 and 6c). Clasts of the margin breccia and minor interstitial matrix are of the same composition and identical to the plug lithology. The near-vertical flow foliation bends into a sub-horizontal foliation towards the upper parts of the plug. In plan view, the strike of flow foliation describes a circle, conforming to the rough cylindrical shape of the plug (Fig. 5). Measurements of flow foliation reveal an overall steep dip towards the caldera depression. In the vicinity of the plug, the welded fallout deposit dips and slightly thickens towards it, while dipping is away from the plug more to the southeast (Figs. 5 and 6b, c). The densely welded and lava-like parts of the fallout deposit drapes the

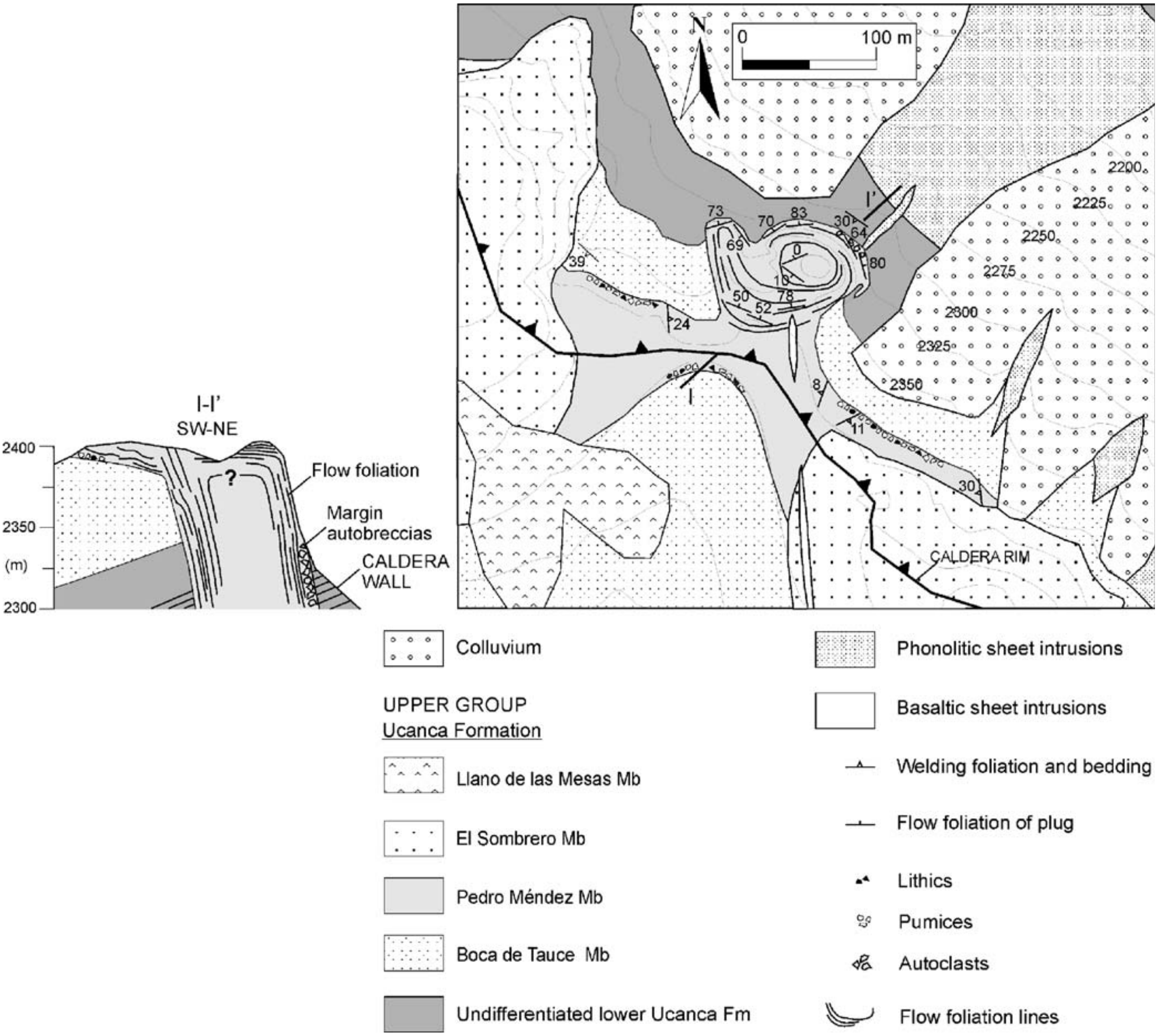

Fig. 5 Geological map and cross-section (no vertical exaggeration) of the Pedro Méndez Member and its cylindrical plug. See Fig. 3 for location

underlying non-welded part when dipping towards the plug, while bedding, welding and flow foliation are parallel away from the plug (Fig. 6c). Welding foliation and flow foliation bend against the plug contact.

The non-welded part of the Pedro Méndez Member is clast supported and lacks any matrix suggesting a fallout deposition. Coarse pumice and lithics, poor sorting and some lithics up to 2 m in diameter may indicate proximity to vent and ballistic trajectories. Gradual transition from non-welded to lava-like has been interpreted as reflecting a decrease in the explosive activity in other welded fallout deposits of the Las Cañadas caldera (Soriano et al. 2002). The same type of transition is observed in the Pedro Méndez Member and our interpretation is also that explosive activity decreased during eruption. Based on the identical lithologies shown by the plug and the Pedro Méndez Member welded fallout deposit, we interpret that the plug is the feeder conduit for this eruption. Flow foliation of the plug and contact with the wall rock are parallel wherever observed, which suggests that the plug is a rough cylindrical conduit steeply dipping to the caldera depression. We interpret the margin breccias as autobreccias produced by shearing of the viscous phonolitic magma against conduit walls. Bending of plug flow foliation towards the top and of welding and flow foliation of the welded fallout deposit against the plug contact suggest a general upwards movement of magma when intruding the conduit. Dipping and thickening of the Pedro Méndez welded fallout towards the plug, together with draping of the welded part over the underlying non-welded part, may

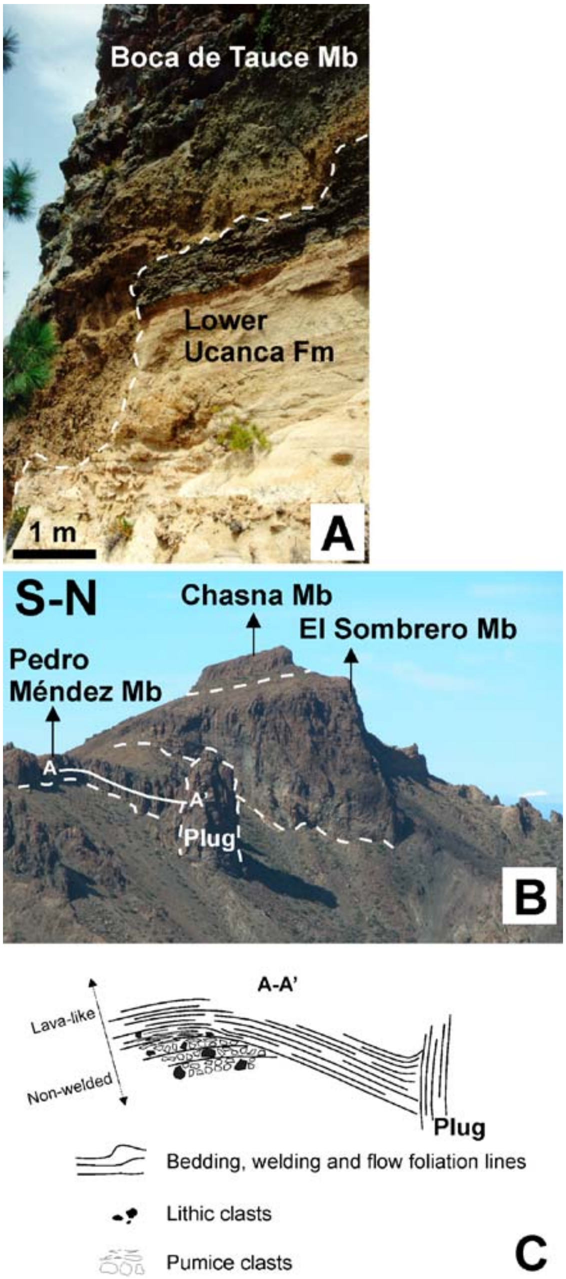

Fig. 6 **a** Erosive contact between the Boca de Tauce Member and the lower Ucanca Formation. **b** Panoramic view of part of the western caldera wall showing the stratigraphic relationships between some of the stratigraphic units distinguished in this sector and the Pedro Méndez Member cylindrical plug. Dashed lines are contacts between units. **c** Field sketch of the of the contact relationships between different facies of the Pedro Méndez Member fallout deposit and the Pedro Méndez plug

indicate fallout deposition on the flaring vent and also that down-vent rheomorphic flow occurred after emplacement.

Chasna member welded fallout and fissure dome

The Chasna Member crops out in the uppermost part of the western Las Cañadas caldera at El Sombrero and Roque de Los Almendros (Fig. 3). It is a fallout unit that shows an upsection increase in the degree of welding and a decrease in thickness towards the northwest (Fig. 7). The non-welded base is relatively fine-grained and well sorted in comparison to the non-welded part of the Pedro Méndez Member. This non-welded part consists of a clast-supported framework of blocky pumice, lithic and obsidian clasts that range from a few cm to a few dm in diameter, although a few lithics can be 1 m large. Pumice clasts are pale grey, brown and pink, and may show reverse grading. Some flattened pumices are enclosed in the closely packed pumice framework (Fig. 8a). Lithics in the Chasna Member are restricted to the non-welded and moderately welded parts of the succession and, in order of decreasing abundance, they are composed of phonolitic lavas, basaltic lavas showing pyroxene phenocrysts, and ignimbrites. This unit has been K-Ar dated at 1.07±0.01 Ma (Zafrilla 2001). The non-welded part of the Chasna Member is well sorted, closely packed and lacks any matrix indicating a fallout deposition. Flattened pumices enclosed in a framework of clast supported blocky pumice show the flattening plane parallel to bedding and suggest deformation of hot juveniles upon landing by the kinetic energy of the falling clast (Wolff and Sumner 2000).

At Roque de los Almendros, the member lies on an eroded surface above laminated lacustrine mudstones and, 5 m above the base; it has a 15-cm-thick layer composed of broken feldspar crystals, lithics of basaltic rocks and pumices of up to 5 mm in diameter embedded in a vitric ash matrix containing crystals of up to 25 µm (Fig. 7). This ash layer disappears toward the northwest, where the non-welded fallout lies on volcaniclastic sandstones showing imbricated clasts, and a lithic-rich horizon composed of lithic and pumice clasts less than 1 cm in diameter occur 2 m above the base. The lacustrine and fluvial sediments indicate the occurrence of water, perhaps an ephemeral lake drained by water currents. The thin ash layer and the lithic-rich horizon can be interpreted as phreatomagmatic, suggesting the entrance of water into the conduit-vent area during the early stages of the eruption.

A distinctive feature of the Chasna Member is the occurrence of porphyritic mafic benmoreite enclaves in the densely welded and lava-like parts of the unit (Fig. 7). The enclaves have zoned anorthoclase and kaersutite phenocrysts embedded in a vesiculated groundmass containing smaller crystals of the same minerals. They are up to 15 cm in diameter, and show lobate, embayed boundaries and intimate mixing features with the host phonolite, indicating that the benmoreite magma was partly liquid at the time of the Chasna Member eruption.

A 500-m-long and up to 150-m-wide phonolitic dome (Chasna dome in Fig. 3) is exposed east of the Chasna Member welded fallout deposit at Roque de los Almendros. The dome crops in the caldera wall and on the uppermost flanks, and intrudes the deposits of the caldera wall beneath the Chasna Member. It shows a pervasive flow foliation that describes an antiform with an axial plane parallel to the long axis of the dome (Fig. 3). Flow foliation orientations, length/width ratio, and contact relationships with deposits underlying the Chasna Member indicate that

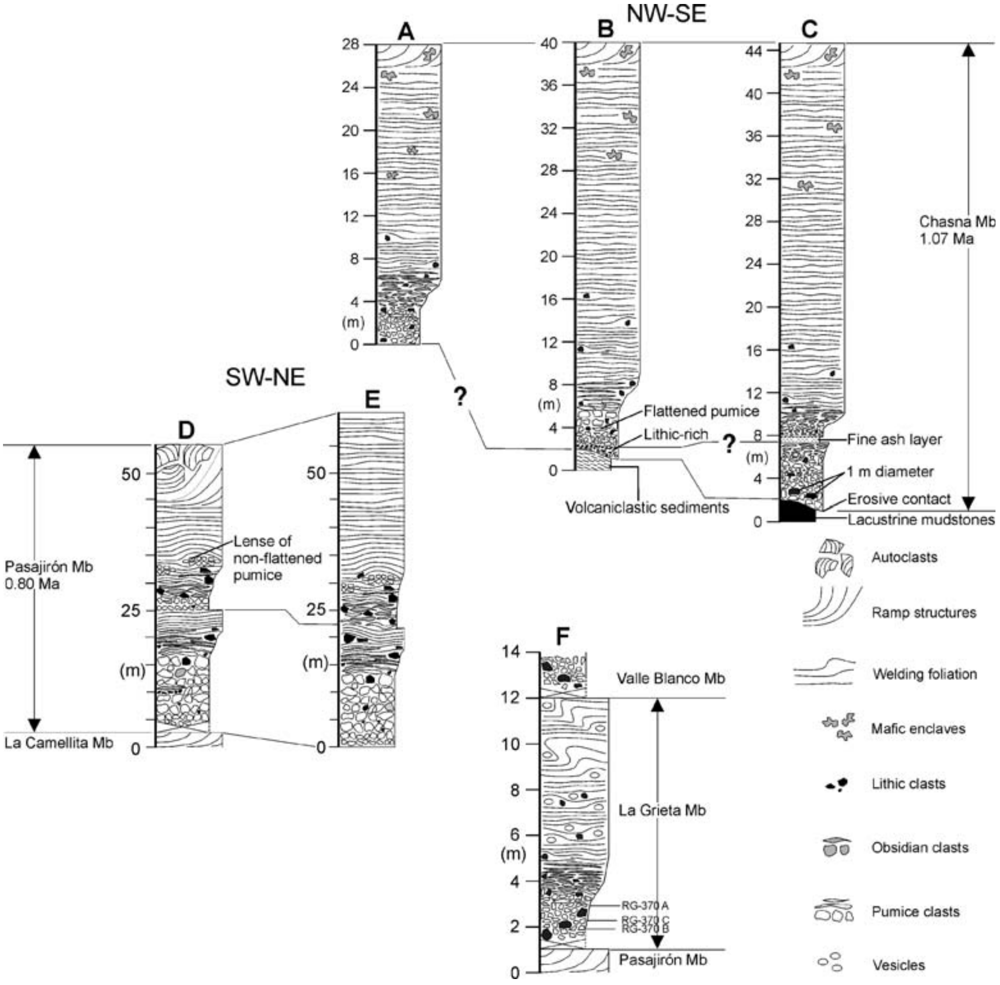

Fig. 7 Stratigraphic sections of the Chasna, Pasajirón and la Grieta members. See Figs. 3 and 4 for location

this dome has been erupted from a fissure trending NW–SE. Enclaves identical to those observed in the densely welded and lava-like parts of the Chasna fallout are abundant in the dome but have larger sizes up to 30 cm in diameter, and also show intimate mixing features between mafic magma and phonolitic magmas (Fig. 8b). These enclaves are unique to the Chasna welded fallout and dome; they have not been observed in any of the other stratigraphic units forming the western part of the Las Cañadas caldera. The Chasna welded fallout and the Chasna dome occupy the same stratigraphic position in the caldera wall, the thickness of the welded fallout deposit increases towards the dome, and the larger lithics are close to the dome (Fig. 7). For all these reasons we interpret this dome as the fissure vent that fed the Chasna welded fallout deposit, and that the dome was emplaced from the same fissure during the waning stages of the Chasna Member eruption.

Los Almendros member welded fallout and elongated vent

The Los Almendros unit crops out in the uppermost part of Roque de los Almendros (Fig. 3). The northeastern part of this unit is exposed in the vertical cliffs of the caldera wall, while the rest of it crops out on the caldera rim and adjacent outer flank (Fig. 9). In map view, it is a closed structure showing a lower unconformable contact with the Chasna Member welded fallout that can be traced throughout the whole exposure of Los Almendros unit. This is the youngest phonolitic unit of the Ucanca Formation in the western part of the Las Cañadas caldera and its upper contact is not exposed. Los Almendros unit consists of an outer collar of flattened obsidian and minor pumice clasts showing eutaxitic foliation and lacking any matrix. This outer collar grades towards the centre of the structure into a densely welded tuff consisting of flattened pumice and devitrified obsidian clasts. The inner zone is slightly more densely welded than the outer and shows a few lenses parallel to the welding foliation of non-flattened spatter fragments. Lithics of phonolitic lavas and minor basaltic lavas occur in both the inner and outer collars. The thickness of Los Almendros unit is up to 15 m and increases towards the centre of the structure. In the southern part of the structure, a north–south-directed apophasis shows a near vertical tip and is mostly composed of obsidian (Fig. 9). Los Almendros structure shows a welding foliation parallel to the lower contact with the Chasna Member welded fallout. The dip of foliation

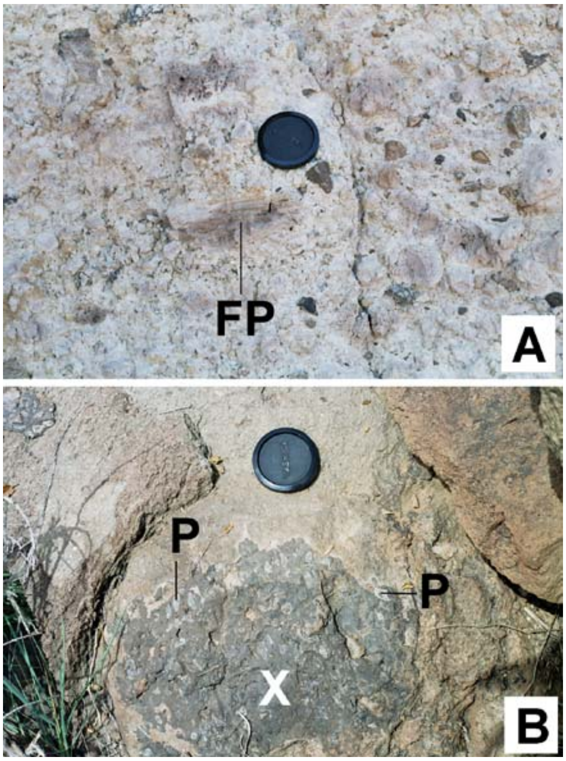

Fig. 8 **a** Detail of the non-welded part of the Chasna Member fallout showing a flattened pumice fragment (*FP*) enclosed in a closely-packed and clast-supported pumice framework. **b** Mafic enclave (*X*) of the Chasna Member fissure dome showing lobate and engulfed boundaries and anorthoclase phenocrysts (*P*)

decreases from the outer collar to the inner collar showing a sort of fan in cross-section (Fig. 9). Near the transition between the outer and inner collars, the welding foliation shows a few small-scale asymmetric folds indicating vergence toward the centre of the structure.

The rocks of Los Almendros Member lack any matrix and exhibit a welding foliation parallel to the underlying depositional surface, which are characteristic features of welded fallout deposits (Sparks and Wright 1979). However, in most of the structure, the lower contact and the parallel welding foliation are steep (>50°), and in the southern apophasis they are nearly vertical (Fig. 9). Welding of pyroclasts has been interpreted to be produced by agglutination on steep conduit-vent walls (Reedman et al. 1987; Kano et al. 1997), thus the steep lower contact of Los Almendros Member is more likely to be interpreted as a conduit-vent wall rather than a fallout depositional surface. In addition, the structure of Los Almendros Member shows most of the features described in the literature for other conduit-vent structures: (1) the overall geometry is that of an inverted cone (though highly elongated) representing a flared vent (Reedman et al. 1987); (2) it shows a steep welding foliation dipping inward and parallel to the wall-rock contact (Almond 1971; Koronovsky 1971; Ekren and Byers 1976; Wolff 1986; Reedman et al. 1987; Kano et al. 1997) and (3) the dip of welding foliation decreases towards the centre of the vent (Ekren and Byers 1976; Kano et al. 1997).

Some loose pumice clasts found outside Los Almendros structure, on the underlying Chasna Member welded fallout, could have been erupted from the Los Almendros conduit-vent. Apart from these pumice clasts, no other deposits likely to be related to this conduit-vent structure have been observed in the surrounding area.

Pasajirón Member welded fallout and plug

The Pasajirón Member is a welded fallout deposit that crops out at Montaña de Pasajirón and Roque de la Grieta in the eastern sector of the caldera wall, and extends laterally along the caldera wall for a distance of 1.7 km (Fig. 4). This member forms a subhorizontal sheet on the caldera wall along most of its outcrop area, except for a narrow portion of the deposit that dips and thickens towards the caldera depression (Fig. 4). To the east of this portion and to the north of Roque de la Grieta, the unit mantles the fault plane of an ENE–WSW trending normal fault that affects the lower stratigraphic units (Figs. 4 and 10). The Pasajirón welded fallout deposit is up to 60 m thick and grades from non-welded fallout at the base, with some pyroclastic surges, to densely welded and lava-like with autobreccias at the top. The vertical facies succession of this unit has been described and interpreted by Soriano et al. (2002) and we refer the reader to this work. This member has been K-Ar dated at 0.80±0.05 Ma (Martí et al. 1994).

At the base of the caldera wall and 200 m beneath the narrow portion of the Pasajirón welded fallout that dips and thickens towards the caldera depression, an irregular shape and eroded plug of phonolite intrudes basaltic lavas of the Lower Group (Figs. 4 and 10). The plug is 70 m diameter, mostly massive at the centre, showing phenocrysts of sanidine embedded in a foliated groundmass. At the margins, it displays flow folds, clasts of foliated phonolite up to 30 cm in diameter, pumice clasts and basaltic lithics in a matrix of coherent phonolite (Fig. 10). Pumice clasts are up to 15 cm diameter and some of them appear to be slightly deformed. Close to the plug margins, the foliation dips steeply and is roughly parallel to them, while it is subhorizontal toward the centre of the plug (Fig. 10). The flow folds have fold axes dipping to the SE, which suggest that magma filling the plug was injected upwards and from the NW (Fig. 10).

Flow folds and clasts of phonolites at the plug margins suggest viscous flow and clast formation by shearing within the flow. Viscous shearing is expected to be higher at the plug margins due to frictional forces against wall-rock. Hence, despite the fact that the wall-rock contact has not been preserved, we infer that the margins of the plug roughly represent the contact with the intruded rocks. Occurrence of pumice clasts and basaltic lithics suggests that this plug may have fed a pyroclastic eruption. The Pasajirón Member welded fallout shows a narrow portion of the deposit that dips and thickens towards the caldera depression just above the plug. In this area, the fallout deposit is thicker and more densely welded than at Montaña de Pasajirón (Fig. 7), which suggests more proximity to a vent. Considering all these features, it seems reasonable to interpret that this plug fed the Pasajirón Member eruption and that the narrow portion of the deposit can be dipping toward the vent flaring area, while the plug may correspond to a deeper part of the conduit-vent structure.

Discussion

Magma fragmentation

Angular blocky pumices may form by fragmentation of magma near the glass transition (Heiken and Wohletz 1984; Martí et al. 1999) when the structural relaxation time of magma is overcome by high strain rates leading to the brittle failure of magma (Dingwell 1996; Papale 1999; Alidibirov and Dingwell 2000; Martel et al. 2000). Opposite to pure brittle fragmentation of magma, non-brittle fragmentation occurs near the ductile regime and there is a transition between both regimes (Dingwell 1996; Martí et al. 1999). In non-brittle fragmentation, juvenile particles may undergo textural modification and viscous deformation after fragmentation, while in brittle fragmentation near the glass transition, viscous deformation after fragmentation is more restricted. A number of textures and processes may account for non-brittle fragmentation and subsequent deformation of magma. Amongst them, expansion of gas before quenching (Thomas et al. 1994), agglutination upon landing, and welding.

A common feature of the proximal fallout deposits described above, and of most of the welded fallout deposits in the Las Cañadas caldera, is that they show a lower non-welded part, with angular blocky pumices and lithics at the base, grading into a densely welded part without lithics toward the top (Fig. 7). Brittle fragmentation can be assumed for most of the lower non-welded part of these proximal fallout deposits where no evidence of juvenile deformation after fragmentation has been observed. However, it can no longer be assumed for the densely welded part where juveniles agglutinate and weld. In the welded fallout deposits of the Las Cañadas caldera, the transition from the non-welded to densely welded part of the deposits occurs in a short stratigraphic interval (<3 m) where welding is observed to rapidly increase up-section and agglutination of pumices upon landing (Figs. 7). We interpret this transition as to represent the transition from brittle to non-brittle fragmentation of magma, which in most cases is concomitant with a decrease in the explosive activity during eruption (Soriano et al. 2002) and may be also accompanied by a decrease in the strain rate of magma within the conduit. Perhaps, the flattened pumice clasts enclosed within closely packed angular pumice framework observed towards the top of the non-welded part of some fallout deposits (Fig. 7) records the arrivals of the first non-brittle fragmented particles.

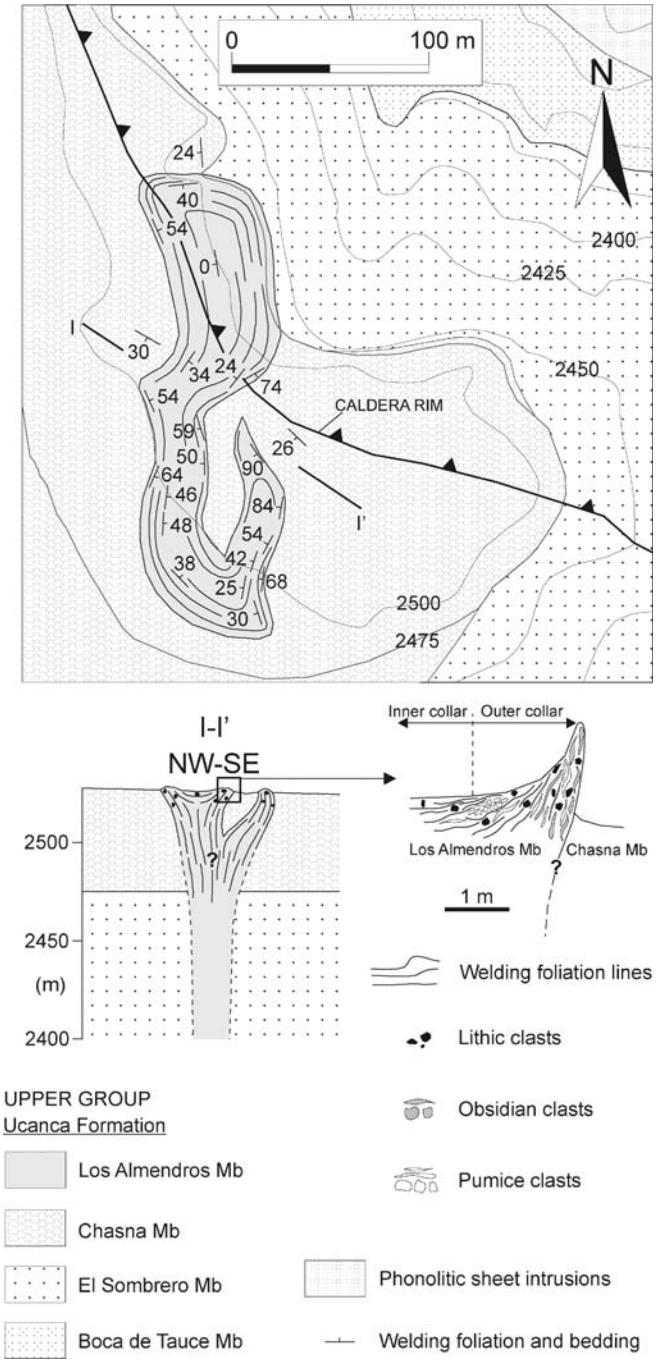

Fig. 9 Geological map and cross-section (no vertical exaggeration) of Los Almendros Member conduit-vent structure. See Fig. 3 for location

Vent-like structures as revealed by rheomorphic features

Rheomorphism of fallout deposits is a secondary process and post-date deposition by definition (Wolff and Wright 1981; Mahood 1984). Rheomorphic flowage of fallout units has been well documented for many deposits in the Las Cañadas caldera (Gottsmann and Dingwell 2001; Soriano et al. 2002) and elsewhere (Sparks and Wright

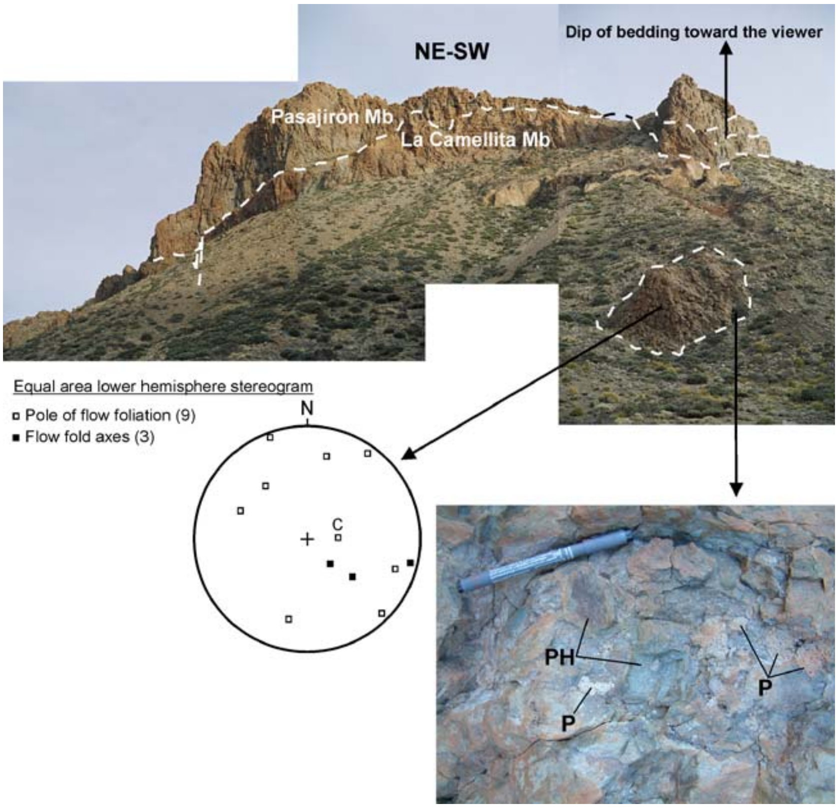

Fig. 10 Panoramic view of part of the caldera wall, viewed from the caldera floor (see also Fig. 4). It shows a portion of the Pasajirón Member dipping towards the caldera depression (towards the viewer), and its irregular and eroded plug at the base of the caldera. *Dashed lines* are contacts between stratigraphic units, bedding, and plug margins. The orientation of flow foliation and flow folds is shown in the stereogram. They correspond to the plug margins except the one pole (*C*) of subhorizontal flow foliation that corresponds to the centre of the plug. A detail of the plug margins is also shown. *P* pumice clast, *PH* phonolite clast

1979; Turbeville 1992; Stevenson and Wilson 1997). Thickening of densely welded tuffs that exhibit flow folds and stretching lineation plunging toward the conduit has been documented during rheomorphic flowage in other conduit-vent structures (Reedman et al. 1987; Kano et al. 1997). Some of the welded fallout deposits described above dip and thicken toward the conduit-vent structure (for example the Pedro Méndez, Los Almendros, and Pasajirón members), and a few small-scale asymmetric folds verging toward the vent have been observed (Los Almendros Member).

Some of the welded fallout deposits that dip and thicken toward the caldera depression were previously interpreted as relating to caldera collapse events (Martí et al. 1994). El Sombrero Member and Los Retamares Member in the western caldera wall and La Grieta Member in the eastern caldera wall are welded fallout deposits that extend more or less subhorizontally along most of their exposure in the caldera wall, while a narrow portion of these units dips and thickens towards the caldera depression (Figs. 3, 6b and Table 1). These portions may dip up to 60° toward the caldera depression, and may thicken up to four times the thickness observed along most of their exposure in the caldera wall (Figs. 3 and 6b). They are densely welded and drape the underlying non-welded parts of their respective fallout units, similarly to the Pedro Méndez Member (Fig. 6c), and also drape the underlying stratigraphic units. Dipping and thickening towards the caldera depression appear to be controlled by some sort of previous topographies that constrains the morphology, thickness and dip of these inwards dipping portions. These topographies do not seem to be a subplanar feature associated with a depression as would be a fault plane or caldera wall scarp, but they resemble some sort of circular or elongated depression. Some hypotheses can be invoked to explain such previous topographies. Amongst the most likely are deeply rilled caldera wall scarps and irregular shape flared vents from where the welded fallout deposits were erupted. While neither of the two hypotheses can be totally ruled out, no deeply incised gullies are located in the caldera wall beneath those portions dipping toward the caldera depression. On the contrary the present topography corresponds to crests between gullies rather than to valleys (Figs. 3 and 6b). For this reason, and given the evidence presented above of other welded fallout deposits dipping and thickening towards their respective conduit-vent structures, the hypothesis of a former deeply rilled caldera wall seems more unlikely. In this view, rheomorphic flow is to be expected in the steep slopes of the vent area, and conduit-vent walls could have acted as barriers confining the rheomorphic flow and yielding thicker welded deposits than those of the outward dipping portions (Table 1).

A stratigraphic implication of conduit-vent structures and related proximal fallout deposits in the upper part of the western caldera wall is that these units were not erupted from a centre located at a higher altitude as suggested by Ancochea et al. (1999). They were erupted from different centres located on the caldera wall and most likely do not correspond to the Guajara unit of Ancochea et al. (1999), but rather to the Ucanca Formation of Martí et al. (1994).

Conduit-vent filling processes and dynamics

Welding of pyroclasts has been interpreted in different ways, regarding vent infilling processes and conduit dynamics. On one hand, it has been proposed that welding of pyroclasts inside the conduit occur by horizontal compression of conduit walls against hot pyroclasts, yielding eutaxitic foliation parallel to conduit walls (Almond 1971; Ekren and Byers 1976; Wolff 1986). On the other hand, welding of pyroclasts is interpreted as primary and produced by agglutination on conduit walls at the waning stages of the eruption (Reedman et al. 1987; Kano et al. 1997). The sequence of conduit-vent filling at the Los Almendros structure is stratigraphically continuous from the wall-rock contact to a denser part in the centre of the structure without interruption in deposition. This suggests that pyroclasts forming the inner collar were emplaced upon pyroclasts formerly deposited in the outer collar during the same eruption. Pyroclasts forming the outer collar were deposited on subvertical conduit-vent walls (Fig. 9). Hence, they may have been laterally agglutinated against conduit-vent walls during the waning stages of the eruption, while permitting the extrusion and fallout deposition of pyroclasts forming the inner collar. Vergence of minor flow folds at the contact between the inner and outer collars suggests that, following emplacement, down-vent rheomorphic flow occurred prior to solidification of magma. Agglutination on conduit walls has been interpreted as indicating an annular flow regime in which degassed magma accretes on conduit walls (Vergniolle and Jaupart 1986; Doubik and Hill 1999). In this view, the conduit is progressively chocked by agglutination of pyroclasts onto conduit walls, and the last magma ponds and rheomorphically deforms as it flows backs down the vent. Welding of pyroclasts by horizontal compression of conduit walls may superimpose on primary agglutination and can be impossible to distinguish from it. However, this seems more likely in deeper parts of the conduit where confining stresses are higher than in the upper flaring part.

Rheomorphic fallout deposits filling the vent area are in some cases fairly well preserved from erosion and, together with preserved conduits, roughly permit the reconstruction of the morphology and dimensions of vent flaring areas and deeper conduits. Down-vent rheomorphic flow of welded fallout deposits may mainly depend on the height attained by magma intruding the conduit. If magma filling the conduit intrudes at high structural levels of the conduit-vent structure (Pedro Méndez Member cylindrical plug) or extrudes (Chasna Member fissure dome), less space is available for down-vent rheomorphic flow to fill the vent than if it intrudes at lower levels (Pasajirón Member).

The conduit-vent structures described above have been filled by several processes: agglutination of pyroclasts onto conduit-vent walls, rheomorphic flow of densely welded proximal deposits backward the vent and intrusion of lava plug or dyke. As recorded by the evolution in the fragmentation mechanisms from brittle to non-brittle conditions and by eruption dynamics of most welded fallout deposits in the Las Cañadas caldera (Soriano et al. 2002), the explosive activity decreases during eruption to spatter-fed and eventual lava fountain. Magma filling conduit-vent structures correlate to the last magma erupted to form the welded fallout units (the densely welded and lava-like parts of each unit); indeed the uppermost part of welded fallout units as defined here can be considered as representing the eruption of degassed magma at the end of individual eruptions, during the explosive-effusive transition at the end of pyroclastic eruptions. In terms of conduit flow dynamics, the conduit-vent structures and related welded fallout represent different stages of the evolution from a gas-dispersed turbulent flow (the lower non-welded part of fallout units) through annular flow (the moderately and densely welded part), to a laminar flow regime (lava-like, lava plug and dome).

Conclusions

Mapping the Las Cañadas caldera wall has permitted the distinction of new stratigraphic units within the stratigraphic framework proposed by Martí et al. (1994). In particular, parts of the Ucanca and Guajara Formations have been divided into members that correspond to individual eruptions. Detailed mapping also revealed the occurrence of conduit-vent structures and welded fallout deposits erupted from these vents, a feature rarely preserved in volcanic systems but that can be more common than previously thought in caldera walls. Conduit-vent structures usually consist of an upper flared part and a narrower subcylindrical lower conduit. In some cases, the welded fallout deposits are physically connected to conduits filled by a plug of phonolitic lava. Conduit-vent dimensions and geometries are variable including cylindrical plug and fissure-shaped conduits, and elongated upper vents. Most conduit-vent structures dip steeply towards the caldera depression. The flaring area has likely been filled by rheomorphic flow of welded fallout deposits down the vent area. The deeper conduits have been filled by lava plugs, agglutination of magma onto conduit walls and dyke intrusion with eventual dome extrusion.

Mapping the caldera wall confirms that welded fallout deposits are widespread along the Las Cañadas caldera. Many of these welded fallout units extend laterally along the caldera wall and have a narrow portion that dips and thickens toward the caldera depression. These portions are interpreted as infilling the flared vent structures, which causes a rheomorphic thickening of up to several times the thickness observed in the caldera wall. Fragmentation of magma during the eruption of welded fallout units evolves from brittle to non-brittle behaviour. The uppermost part of the welded fallout units correlates to the magma filling the conduits and, represents the end of individual eruptions. These eruptions evolve from explosive to non-explosive and, in terms of conduit flow dynamics, from turbulent flow to the annular flow regime, in which the conduit is progressively choked, and to laminar flow yielding the final conduit filling.

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