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Cover letter

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Pyroclastic density currents from Teide-Pico Viejo (Tenerife, Canary Islands): implications on hazard assessment

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Abstract

Hazard assessment in active volcanoes requires a comprehensive knowledge of their eruption record. An incomplete geological reconstruction of their past history may lead to a biased hazard assessment which may have fatal consequences in the case of future eruptions. Teide-Pico Viejo stratovolcanoes constitute one of the major potentially active volcanic complexes in Europe and have traditionally been considered as non-explosive and not representing a potential threat to the island of Tenerife. However, the reconstruction of their eruptive record is still far from being complete, so a better knowledge of their volcano-estratigraphy and physical volcanology is required to undertake a comprehensive hazard assessment at these volcanoes. In this study we have conducted a detailed field investigation of the northern side of Teide-Pico Viejo, a still poorly known area, and we have been able to identify several deposits coming from explosive eruptions of phonolitic magmas. Here we report by the first time the presence of pyroclastic density currents, including ignimbrites and block and ash deposits, in the most recent eruptive history of Teide-Pico Viejo twin stratovolcanoes. We discuss the characteristics of these deposits, their eruption mechanisms and their implications in the hazard assessment at Teide-Pico Viejo.

Key words: Teide, explosive volcanism, ignimbrites, block and ash, hazard assessment

Introduction

Teide-Pico Viejo twin stratovolcanoes, on the island of Tenerife, form one of the largest active volcanic complexes in Europe. Their eruptive activity has traditionally been considered as effusive (Ablay and Martí, 2000, Carracedo et al., 2007), with the only exception of the subplinian eruption of Montaña Blanca, that occurred about 2000 years ago (Ablay et al., 1995), and minor pyroclastic deposits of unknown origin. This belief has led to assume that volcanic hazard at Teide-Pico Viejo is mostly related to the emplacement of lava flows (Carracedo et al., 2007), which according to their field and physical characteristics correspond to relatively cold, slow-motion flows, with fronts of several tens of metres thick, and run-out distances up to 15 km. However, a recent revision of the past history of Teide-Pico Viejo (Martí et al 2008), including a quantification of their eruption products in terms of erupted volumes and eruption mechanisms, reveals that explosive activity related to phonolitic magmas has been more significant than initially thought, so that their potential for generating explosive eruptions in the near future should not be neglected.

In order to complete these results we have conducted a detailed field revision of Teide-Pico Viejo products, focussing in particular on those derived from explosive eruptions of phonolitic magmas. Because Teide-Pico Viejo northerly directed activity may affect the Icod Valley, an important inhabited area, we have concentrated our study mostly on the northern side of Teide-Pico Viejo, a rather inaccessible and relatively unexplored area and, consequently, poorly known compared to other sectors of these volcanoes.

As a first result of this field study, we have been able to identify and document by the first time the presence of several pyroclastic density current (PDC) deposits associated with different explosive episodes of Teide-Pico Viejo. The PDC deposits observed include pumice flow deposits (ignimbrites) and block and ash deposits, which derive from different eruption and emplacement mechanisms. We describe the field characteristics of each type of the PDC deposits observed and discuss their origin and significance in the volcanological evolution of Teide-Pico Viejo. Finally, we evaluate the importance of the presence of these deposits in terms of hazard assessment at Teide-Pico Viejo. Improving our knowledge on the recent eruptive history of Teide-Pico Viejo is crucial to assess hazard in general but in particular in the Icod Valley, an area highly exposed to the volcanic activity directed to the northern side of the island.

Volcanic evolution of Teide-Pico Viejo

Teide-Pico Viejo stratovolcanoes started to grow up about 180-190 ka ago at the interior of the Las Cañadas caldera (Fig. 1) (Ablay and Martí, 2000). This volcanic depression originated by several vertical collapses of the former Tenerife central volcanic edifice (Las Cañadas edifice) following explosive emptying of high-level magma chambers. Occasional lateral collapses of the volcano flanks also occurred and modified the resulting caldera depression (Martí et al., 1994, 1997; Martí and Gudmundsson, 2000). The construction of the present central volcanic complex on Tenerife encompasses the formation of these twin stratovolcanoes, which derive from the interaction of two different shallow magma systems that evolved simultaneously, giving rise to a complete series from basalt to phonolite (Ablay et al., 1998; Martí et al., 2008).

The structure and volcanic stratigraphy of the Teide-Pico Viejo stratovolcanoes were characterised by Ablay and Martí (2000), based on a detailed field and petrological study. More recently, Carracedo et al. (2007) have provided the first group of isotopic ages from Teide-Pico Viejo products. The reader will find in these works a more complete description of the stratigraphic and volcanological evolution of Teide-Pico Viejo.

The eruptive history of the Teide-Pico Viejo comprises a main stage of eruption of mafic to intermediate lavas that form the core of the volcanoes and also infill most of the Las Cañadas depression and the adjacent La Orotava and Icod valleys (Fig. 1). About 35 ka ago the first phonolites appeared, and, since then, they have become the predominant composition in the Teide-Pico Viejo eruptions. Basaltic eruptions have also continued mostly associated with the Santiago del Teide and Dorsal rift axes, the two main tectonic lineations currently active on Tenerife. Most of the phonolitic eruptions from Teide-Pico Viejo show signs of magma mixing, suggesting that eruptions were triggered by intrusion of deep basaltic magmas into shallow phonolitic reservoirs (Martí et al., 2008).

Phonolitic eruptions from Teide-Pico Viejo have occurred from central and flank vents (Martí and Geyer, 2009), range in volume from 0.01 to 1 km^3, and have mostly generated thick lava flows and domes, some of them associated with minor explosive phases developing block and ash deposits and clastogenic lavas, and some subplinian eruptions, such as the Montaña Blanca (MB) at the eastern flank of Teide, 2000 years ago (Ablay et al., 2005). New field work conducted in this study reveals that the amount of pyroclastic material in the stratigraphy of Teide-Pico Viejo is much more voluminous than identified before but the exact vents of these explosive products have not been precisely established yet.

Some significant basaltic eruptions have also occurred from the flanks or the central vents of the Teide-Pico Viejo stratovolcanoes. All basaltic eruptions have developed explosive strombolian to violent strombolian phases leading to the construction of cinder and scoria cones and occasionally producing intense lava fountaining and violent explosions with the formation of ash-rich eruption columns. Violent basaltic phreatomagmatic eruptions have also occurred from the former central craters of the Teide-Pico Viejo stratovolcanoes, generating high-energy, pyroclastic density currents (Ablay and Martí, 2000; Pérez-Torrado et al., 2004).

According to Martí et al., (2008), the minimum volume of magma erupted in the last 35 ka is of the order of 1.5-3 km^3, 83% corresponding to phonolitic magmas, while the rest includes basaltic and intermediate magmas. Therefore, phonolitic eruptions have been less frequent but much more voluminous than basaltic eruptions.

Pyroclastic density current deposits

The presence of phonolitic pyroclastic materials is widespread along the northern and southern flanks of Teide-Pico Viejo. The stratigraphy of these eruptive products is not well established, and further work combining petrology, mineral chemistry, geochronology and stratigraphy is required to determine the exact position of each unit in the geological record and its significance in the evolution of these composite alkaline volcanoes. However, we have been able to identify the presence of irregularly distributed, occasionally several meters thick, coarse to fine grained, pumice fall deposits, which suggest the existence of highly explosive eruptions associated with Teide-Pico Viejo and not related to the Montaña Blanca eruption, as well as different types of PDC deposits. Phonolitic fallout deposits have been deeply eroded and show a variable degree of preservation depending on topography and coverage by younger products. This makes difficult to establish a reliable stratigraphic and facies correlation model at present. In contrast, PDC deposits, despite having been deeply eroded too, have been partially preserved inside some of the gullies of the northern flank of Teide-Pico Viejo and show characteristic facies that allow them to be identified and interpreted in terms of eruptions dynamics and emplacement mechanisms. We have observed the presence of pumice-rich, pyroclastic flow deposits (ignimbrites) and block and ash deposits which show very distinct lithological and sedimentological characteristics.

Pumice rich, pyroclastic flow deposits (ignimbrites)

Deposits of this type have been found in several discontinuous outcrops in some gullies of the northern side of Teide-Pico Viejo (Fig. 1). Comparison between the relative stratigraphy and components of the different deposits reveals that they represent the products of several explosive episodes occurred during the recent (Holocene) history of Teide-Pico Viejo. The poor degree of preservation of most of these deposits, as well as the discontinuity of their outcrops make difficult to determine their exact stratigraphic position and possible correlations and facies variations. However, in some cases they appear intimately associated with clastogenic lava flows showing (as explained below) clear evidence of belonging to the same eruptive episode, so that a more precise stratigraphic constrain can be provided for some examples due to the wider extension (preservation) of the associated lavas.

This is the case, for example, of the Abrunco ignimbrite, a non-welded, pumice-rich, pyroclastic flow deposit found in the northern side of Teide, between Pico Cabras and Abejera lava domes (Fig. 1). The Abrunco ignimbrite can be recognized at least in three separated outcrops where it overlies previous lava flows and reworked deposits and shows an irregular and discontinuous upper contact with a clastogenic lava of the same mineralogical composition. The ignimbrite is not homogeneous and shows different facies irregularly distributed along the deposit (Fig. 2). A *matrix rich facies* is composed of scarce dense and expanded, including tube and spherical, pumice clasts surrounded by an abundant lapilli and ash matrix of the same composition. The size of pumices ranges from a few centimetres to 30 cm. Few vent-derived, angular lithic clasts also appear in this facies, being in size of the same order than pumices. The matrix rich facies is normally found at the upper part of the ignimbrite defining an irregular contact with the clastogenic lavas above. This, together with the fact that fragments of the clastogenic lavas are engulfed by the ignimbrite while some pumice blocks have been eroded and incorporated into the lava, suggest that the emplacement of the clastogenic lava occurred when the ignimbrite was still unconsolidated. This indicates that the emplacement of the ignimbrite and the clastogenic lava were not separated by a significant time break, probably corresponding to two consecutive phases of the same eruption.

A *pumice-rich facies*, forming a non-welded, poorly sorted, massive deposit, is normally found at the central part of the ignimbrite. It contains abundant angular clasts of both dense and vesicular (i.e. spherical and tube) pumice of several centimetres across, which are supported by a fine ash size matrix. Sometimes this facies forms lenses surrounded by the matrix-rich facies towards the lower part of the ignimbrite. A *fine-grained laminated facies* appears at the base of the ignimbrite irregularly distributed along the three outcrops. It is mostly composed of coarse to fine ash material of the same type than the one forming the matrix of the previous facies, together with subordinate ash size lithic clasts. However, it does not contain pumice fragments of lapilli size or larger. This facies is thinly laminated and occasionally show cross bedding. The characteristics of this facies suggest that it could correspond to a pyroclastic surge deposit immediately preceding the emplacement of the ignimbrite.

The contacts between the different ignimbrite facies are always irregular, sometimes discontinuous and even gradual in some occasions, but we have not observed clear shear or erosional contacts among them. The absence of fragments from the clastogenic lavas and the presence of vent derived lithic clasts in the ignimbrites suggest that they formed from an open vent rather than by gravitational collapse of lava domes or flows as it occurs with the block and ash deposits (see below). The variety of facies observed in the Abrunco ignimbrite may have resulted either from chances at the vent or by flow changes during emplacement. The presence of the thinly laminated unit at the base of the deposits suggests a first episode of column collapse generating a very diluted PDC probably from the outer parts of the eruption column. This was followed by the collapse of a more massive sector of the column richer in pumices fragments. The abrupt and irregular topography of the northern side of Teide, characterised by frequent slope changes, may have favoured changes in the flow regime during the emplacement of the ignimbrites, thus creating localised highly turbulent conditions which lead to the elutriation of fines and the deposition of isolated pumice lenses and the pumice rich facies. Continuation of the flow on a topographically modified ground may have lead to the deposition of the matrix rich facies. These characteristics and the small volume (< 0.001 km^3) of these pyroclastic flow deposits and their relatively restricted distribution suggest that they may represent pulses of partial column collapse during a plinian or subplinian eruption. However, we have not been able to correlate these ignimbritic deposits with the pumice fallout deposits that crop out at the north of Teide, in order to confirm this hypothesis. Anyway, the intimate association of the studied ignimbrites with clastogenic lavas at the top suggest that ignimbrites and lavas derive from the same eruption, which would have initiated with a highly explosive event progressively decreasing in intensity till a fire fountaining episode which would have generated the clastogenic lavas. The existence of stratigraphically different pumice fall deposits, ignimbrites and clastogenic lavas suggest that different phonolitic explosive eruptions may have occurred during Holocene at Teide-Pico Viejo.

Another characteristic of these ignimbritic deposits is the presence of lenses of reworked material interbedded with the pyroclastic facies (Fig. 2). These lenses may erode and may be eroded by the ignimbrite, indicating a total lack of induration of the ignimbrite during these reworking episodes. These reworked lenses are composed of abundant sub-rounded to rounded lithic and pumice fragments supported by a scarce reworked matrix. Pumices and lithics of these epiclastic lenses are of the same nature than those from the associated ignimbrite. These characteristics suggest a syn-depositional reworking of the ignimbrite by aqueous flows probably generated by a heavy rainfall triggered by the eruption (see e.g. Woods, 1993; Martí, 1996). This would also explain the lack of preservation of most of the ignimbrite deposit(s). They would have been eroded out during and immediately after their deposition by heavy rainfalls caused by the entrance of ash into the surrounding atmosphere, and/or latter by seasonal rain that usually causes torrential effects on such steep topography.

Block and ash deposits

The second type of pyroclastic density current deposits that we have recognised associated with Teide-Pico Viejo corresponds to block and ash deposits that can also be observed inside some of the main gullies at the northern side of Teide-Pico Viejo stratovolcanoes. These deposits are always of relatively small volume compared to some lavas, and can be followed for several kilometres. Thickness varies from less than one metre to several metres depending on the paleotography on which they were emplaced. In some cases they grade dawn slope into debris flow deposits, some of them arriving at the northern cost of Tenerife. These deposits are nearly monolithologic and are mostly composed of fragments of clastogenic lavas, and minor non-welded dense and expanded pumices of the same composition than the clastogenic lava fragments (Fig. 3). All these fragments are surrounded by an ash to fine lapilli size matrix mostly composed of juvenile clasts and some lithic fragments derived from the fragmentation and attrition of the previous components.

Field relationships and comparison of chemical and mineral compositions and textures show that the observed block and ash deposits derive from clastogenic lavas flows or lave domes. Most of the recent phonolitic lava domes and lava flows from Teide and Pico Viejo really correspond to clastogenic lavas formed by agglutination and stretching of large juvenile fragments parallel to the flow direction. In some occasions these clastogenic lavas and domes include abundant non-welded pumices, suggesting that they derive from explosive episodes (e.g: fire fountaining) rather than from purely effusive eruptions. We propose that some of these clastogenic lavas, which were still very rich in gases, became block and ash flows when they collapsed gravitationally and disrupted explosively at an abrupt slope change (Fig. 4), a common morphological feature at the northern side of Teide-Pico Viejo.

Discussion

A detailed field study has allowed us to identify the presence of ignimbrites and block and ash deposits associated with the recent (Holocene) eruptive history of Teide-Pico Viejo. A full interpretation of the eruption and depositional mechanisms of such pyroclastic deposits is beyond the main purpose of this paper. However, it is important to remark that the existence of these deposits, together with other pyroclastic products, in the geological record of Teide-Pico Viejo tells us that we should reconsider the generally accepted idea that Teide-Pico Viejo are mostly effusive volcanoes that do not represent a significant threat to their surroundings.

The fact that the volume of pyroclastic deposits visible today is small compared to that of lavas does not necessarily imply that explosive activity has been anecdotal in the recent evolution of Teide-Pico Viejo. On the contrary, we claim that phonolitic explosive activity has been significant in Teide-Pico Viejo during the Holocene. The evidence we have presented for the syn-depositional erosion of ignimbrites suggests the existence of heavy rainfalls in the area during these eruptions, which could already explain the rapid disappearance of a significant part of these deposits. Moreover, we must take into account the existence of important seasonal rainfall that would have also contributed to the erosion of the unconsolidated pyroclastic material. In fact, the Icod valley is characterised by the presence of prominent S-N narrow gullies that deeply erode the Teide-Pico Viejo products, and of abundant lahar and debris flow deposits that infill their lower parts.

Another evidence of the relevance of explosive volcanism in Teide-Pico Viejo is the presence of several discontinuous outcrops of thick (occasionally up to 4 m), primary (non-reworked) pumice fall deposits in some sectors of the north of Teide (Fig. 1). Some of these outcrops have a different stratigraphic position (they are older) than the 2000 bp Montaña Blanca pumice, so they cannot be correlated with the only explosive episode from Teide that has been documented till present. In other cases, the pumice fall deposits from the northern side of Teide have an uncertain stratigraphic position which does not discard a possible correlation with the Montaña Blanca pumice. The same happens with the available radiometric ages of some of these pumice fall deposits (Carracedo et al., 2007) that give an age similar than that of Montaña Blanca. However, if that was the case it would imply that the Montaña Blanca eruption would have been much bigger than interpreted (Ablay et al., 1995, Folch and Felpeto, 2005), thus opening the door to the existence of true plinian eruptions at Teide-Pico Viejo. A first comparison of the mineralogy and geochemistry of all these pumice deposits does not provide definitive clues to discriminate them, so a more detailed petrological work will be required to interpret the sequence of explosive eruptions in the recent geological record of Teide-Pico Viejo.

Hazard assessment at Teide-Pico Viejo, one of the largest volcanic complexes in Europe, is still a pending action to reduce risk in Tenerife, an island extensively populated and one of the main tourist destinations in Europe. It is widely accepted that pyroclastic density currents are one of the main volcanic hazards. Therefore, the presence of these pyroclastic deposits in the recent phonolitic volcanism of Teide-Pico Viejo has strong implications on their potential hazard and on the threat their represents for the Tenerife island, and in particular for the Icod valley. In contrast with those who consider that Teide-Pico Viejo only represent a modest hazard level for Tenerife (Carracedo et al., 2007), we claim that the existence of clear evidence of phonolitic highly explosive volcanism during Holocene at Teide-Pico Viejo volcanoes and the existence of unquestionable signs of activity in historical times (fumaroles, seismicity) and even a clear unrest episode in 2004 (Martí et al., 2009), implies that hazard at Teide-Pico Viejo is considerably higher than suggested. Therefore, hazard assessment based on a detailed reconstruction of the recent stratigraphy, geochronology, and and eruptive styles and products is urgently needed at Teide-Pico Viejo as a necessary tool to reduce volcanic risk in Tenerife.

Conclusions

The presence of pyroclastic density current deposits, ignimbrites and block and ash, in the recent geological record of Teide-Pico Viejo stratovolcanoes is reported by the first time. This has strong implications on the hazard assessment at these active volcanoes, traditionally considered as effusive and potentially non dangerous. The presence of highly explosive episodes, also indicated by several pumice fall deposits, in the recent eruptive history of Teide-Pico Viejo implies that this kind of activity may repeat in the future, increasing significantly the potential risk for the island of Tenerife and in particular for the Icod Valley.

Acknowledgments

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List of Figures

Figure 1. Simplified geological map of Teide-Pico Viejo stratovolcanoes, based on IGME (2009) and Ablay and Martí (2000), and location of the main outcrops (in red) of phonolitic pyroclastic deposits identified in this study

Figure. 2 Field details of the Abrunco ignimbrite. a) detail of the ignimbrite showing the pumice-rich and reworked facies. b) detail of the ignimbrite showing the matrix-rich and pumice-rich facies. Note the irregular contact of the ignimbrite with the clastogenic lava above and how fragments of the clastogenic lavas are engulfed by the ignimbrite while some pumice blocks have been eroded and incorporated into the lava. c) detail of the pumice-rich facies showing the three main pumice components of the deposit: dense pumices, tube pumices and vesicular (spherical) pumices.

Figure 3. Example of a block and ash deposit found at the northern side of Teide-Pico Viejo in the Icod Valley. A) Large blocks (up to 1 m in diameter) of clastogenic lavas are supported by an ash-lapilli size matrix of the same composition than the blocks. B) Detail of the deposit showing sub-rounded to rounded fragments of clastogenic lavas and dense and expanded pumices surrounded by floating in a ash to lapilli size matrix of juvenile fragments of the same composition.

Figure 4. Sketch explaining the formation of the block and ash deposits by gravitational collapse of a clastogenic lava. (see text for more explanation)

Figure 1

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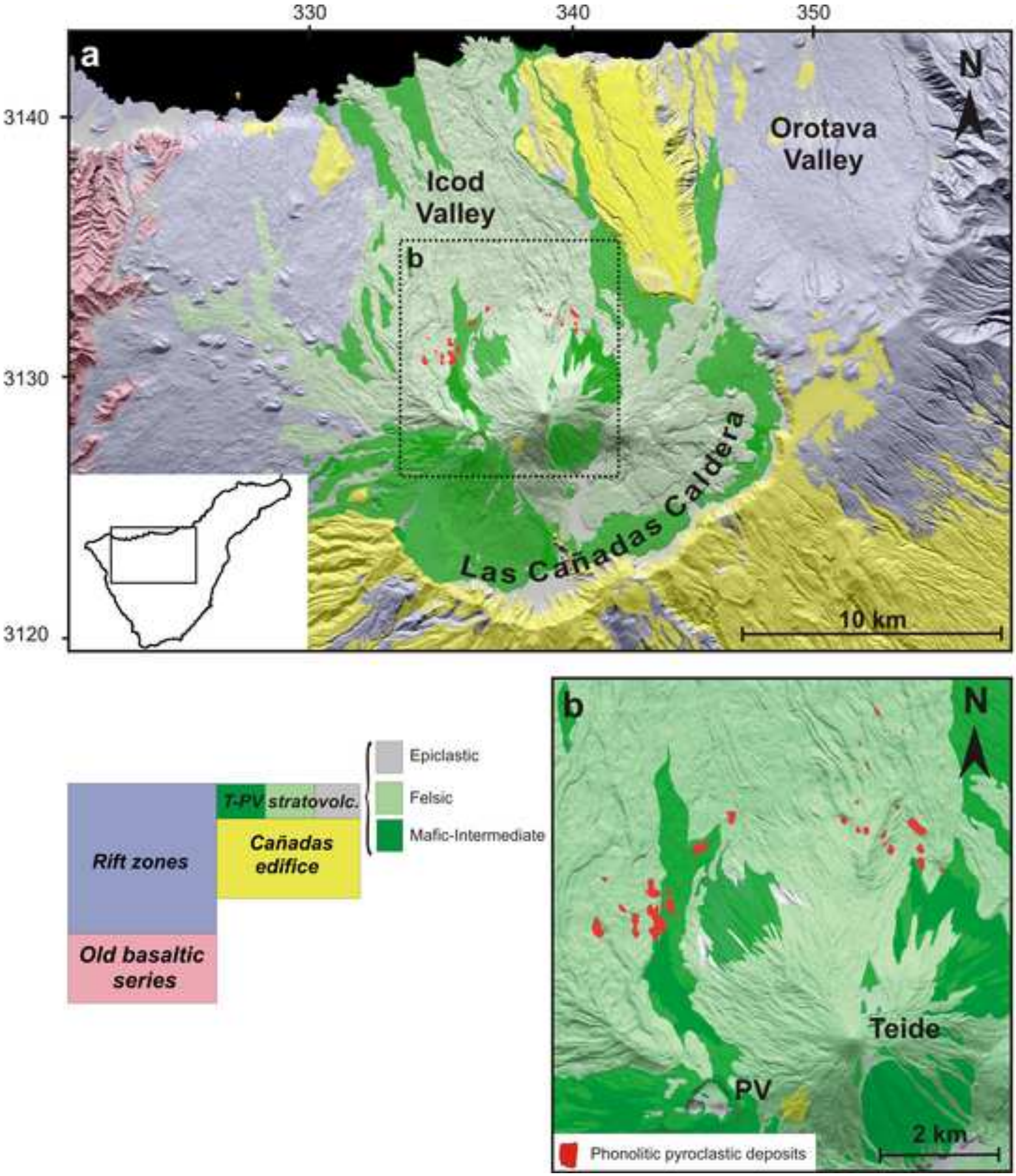

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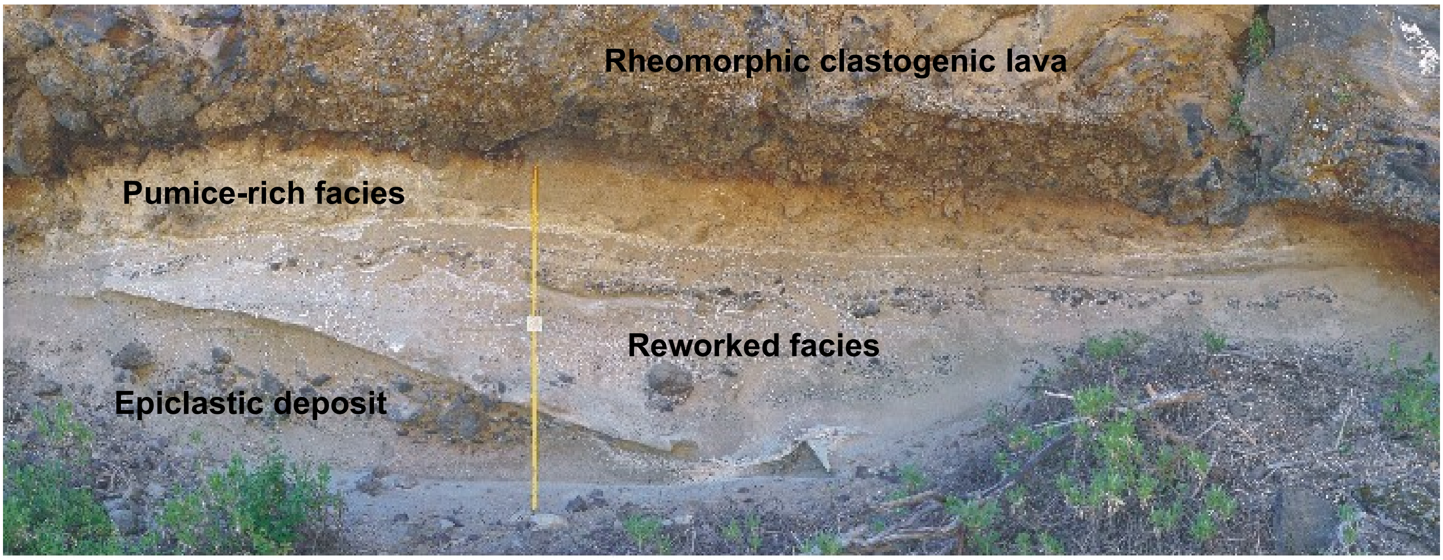

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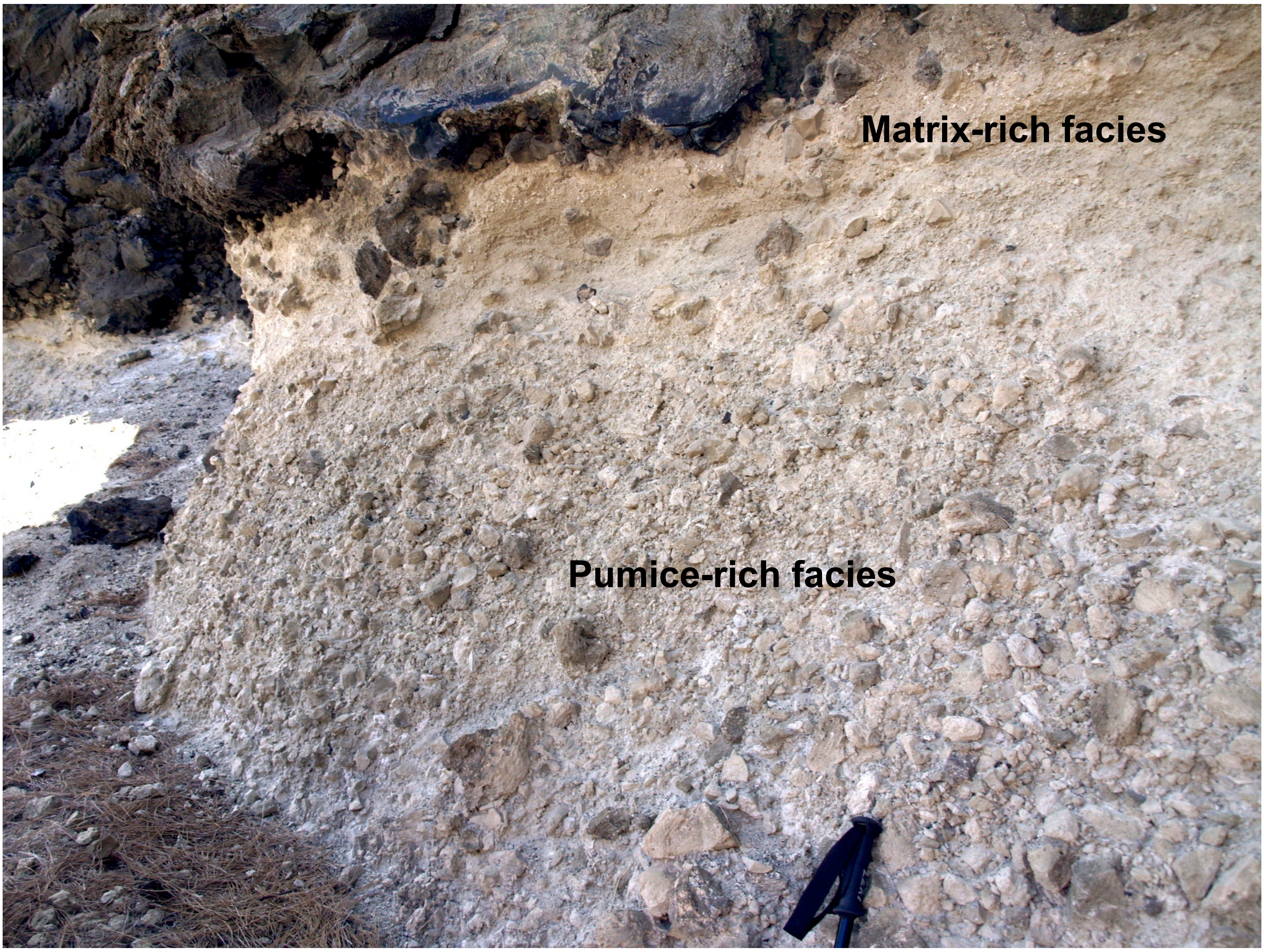

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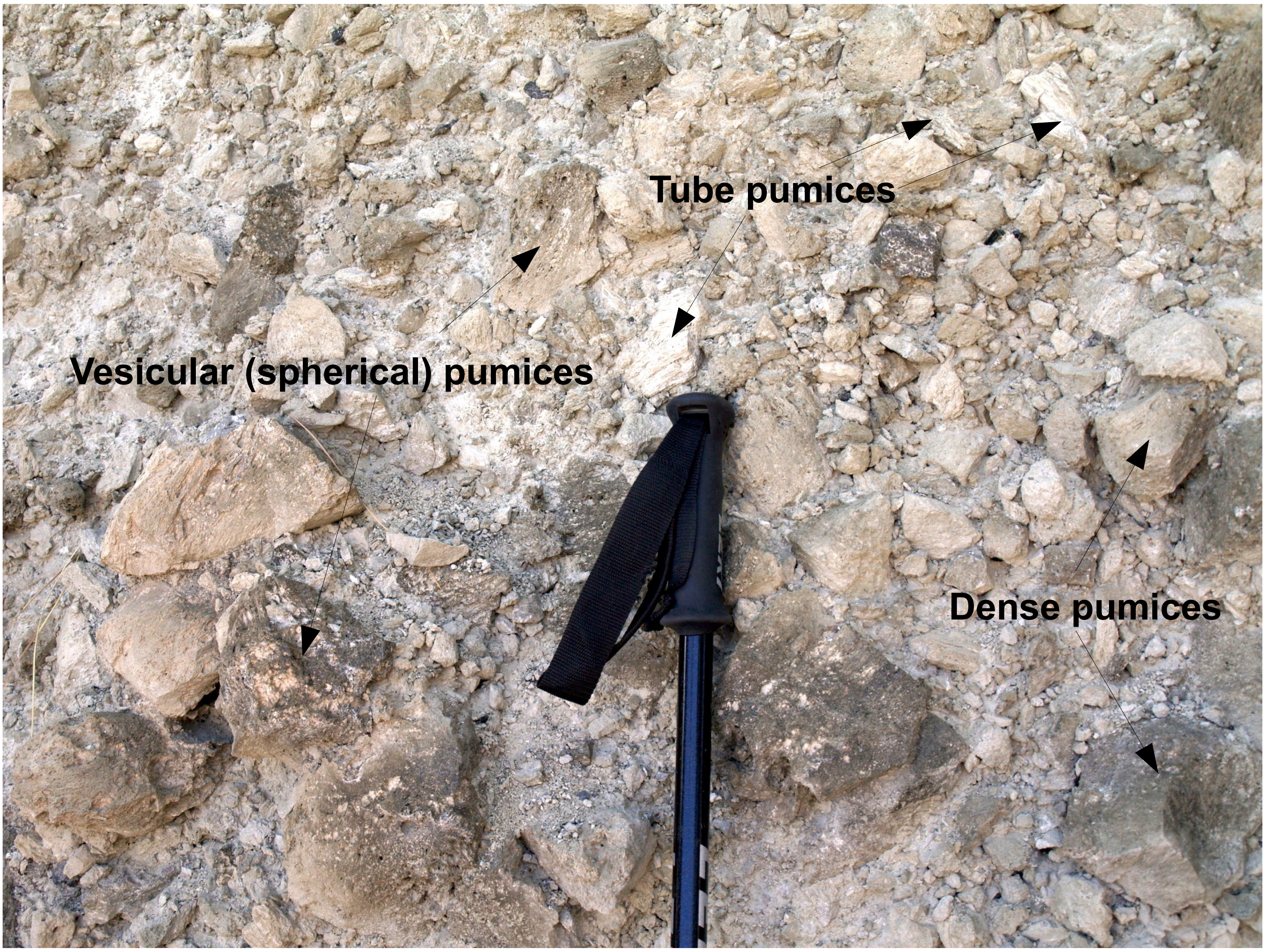

C)

Figure 3a
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A)

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B)

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