Chapter

# Syn-Eruptive Lateral Collapse of Monogenetic Volcanoes: The Case of Mazo Volcano from the Timanfaya Eruption (Lanzarote, Canary Islands)

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## Abstract

The evolution of complex volcanic structures usually includes the occurrence of flank collapse events. Monogenetic cones, however, are more stable edifices with minor rafting processes that remove part of the cone slopes. We present the eruptive history of Mazo volcano (Lanzarote, Canary Islands), including the first detailed description of a syn-eruptive debris avalanche affecting a volcanic monogenetic edifice. The study and characterization, through new geological and morphological data and the analysis of a great number of documentary data, have made it possible to reinterpret this volcano and assign it to the Timanfaya eruption (1730–1736). The eruptive style evolved from Hawaiian to Strombolian until a flank collapse occurred, destroying a great part of the edifice, and forming a debris avalanche exhibiting all the features that define collapsing volcanic structures. The existence of blocks from the substrate suggests a volcano-tectonic process associated with a fracture acting simultaneously with the eruption. The sudden decompression caused a blast that produced pyroclasts that covered most of the island. This study forces to change the current low-hazard perception usually linked to monogenetic eruptions and provides a new eruptive scenario to be considered in volcanic hazards analysis and mitigation strategies development.

**Keywords:** monogenetic volcano, flank collapse, debris avalanche, volcanic hazard, Timanfaya, Canary Islands

## 1. Introduction

The origin and characteristics of flank collapses in stratovolcanoes and volcanic islands have been recognized and described around the world (eg. [1–5]). The resulting Volcanic Debris Avalanche (VDA) deposits are composed essentially of rock fragments of the affected edifice and usually show a hummocky topography around the collapsed original volcanic landform. The magnitude of these collapses and the huge volume of involved materials make these processes the most catastrophic events in the evolution of polygenetic volcanic structures. Factors inducing or triggering volcanic flank collapses include the violence of the eruption, high eruptive rates, hydrothermal alteration, existence of relatively steep slopes, presence and reactivation of faults, magma intrusion, high saturation of volcanic rocks in water, presence of lava plugs during the active period, structural heterogeneities and geotechnical differences between volcanic edifices and their basement, seismicity, caldera collapse or even climatic fluctuations ([2] and reference therein).

In contrast, instability processes in monogenetic volcanoes have been much less documented and have often received less attention given its less volume and less potential hazard (eg. [6–11]). Nevertheless, it should be taken into account that mafic monogenetic volcanic systems are the most frequent and widespread magmatism on Earth, usually located very close to population centers [7]. The most documented instability process in monogenetic cones are those related to the partial collapse and passive transport of fragments of the edifice during the emission of lava flows, process known as rafting (eg. [6–11]). The clearest evidence of rafting processes in monogenetic edifices is the existence of huge blocks on the surface of lava flows composed of agglutinated materials coming from the cone [12]. Rafting has been related to lava flows and sill emplacement at the base of the cone, changes in eruptive style or the existence of previous cones or topographical constrains ([13] and reference therein). Although flank collapses forming VDA with liquified non-turbulent granular flows are usually linked to stratovolcanoes [14] and rafting processes are the common result of instability in monogenetic cones, in this work we demonstrate VDA also happen in small volcanic cones, such as in the historical volcanic cone of Mazo (Lanzarote, Canary Islands). Here, we present the first detailed description of a syn-eruptive volcanic flank collapse in a monogenetic volcanic cone and describe the associated debris avalanche and blast deposits; as well as the conditioning and triggering factors of the collapse, and the implications for the volcanic eruption development. The finding of this volcanic flank collapse during a mafic fissure eruption has local implications in the interpretation, timing and reconstruction of the Timanfaya eruption and global implications in the understanding of hazards in monogenetic volcanic fields.

## 2. Geological setting

The geology of Lanzarote is characterized by the existence of old Miocene massifs located to the North and South of the island and by a Quaternary fissure-aligned volcanic field in the central part, in which vast volcanic fields cover discordantly the underlying Mio-Pliocene materials (**Figure 1**). Most of the eruptive centers are small monogenetic edifices arranged in several alignments trending NE–SW and ENE-WSW roughly parallel to each other, and dispersed over the territory ([15] and references therein).

Two historical eruptions took place in the central volcanic field of the island: the 1730–36 Timanfaya eruption and the 1824 eruption [16]. Both were multiple-fissure type eruptions but quite different in magnitude [17]. While in 1824 the eruption lasted nearly three months and only three small fissures (less than 500 m in length) where opened, the Timanfaya eruption lasted nearly 6 years and formed hundreds of vents aligned along a 13 km eruptive fissure, from where lava flows that covered one-third of the island were issued [9, 11, 17–21]. Thus, Timanfaya constitutes the highest magnitude eruptive process occurred in historical times in Lanzarote and the Canary Islands.

Mazo volcano is located in the central volcanic field, to the North of the eastern end of the main eruptive fissure of Timanfaya (**Figure 1**). It is a basanitic elongated

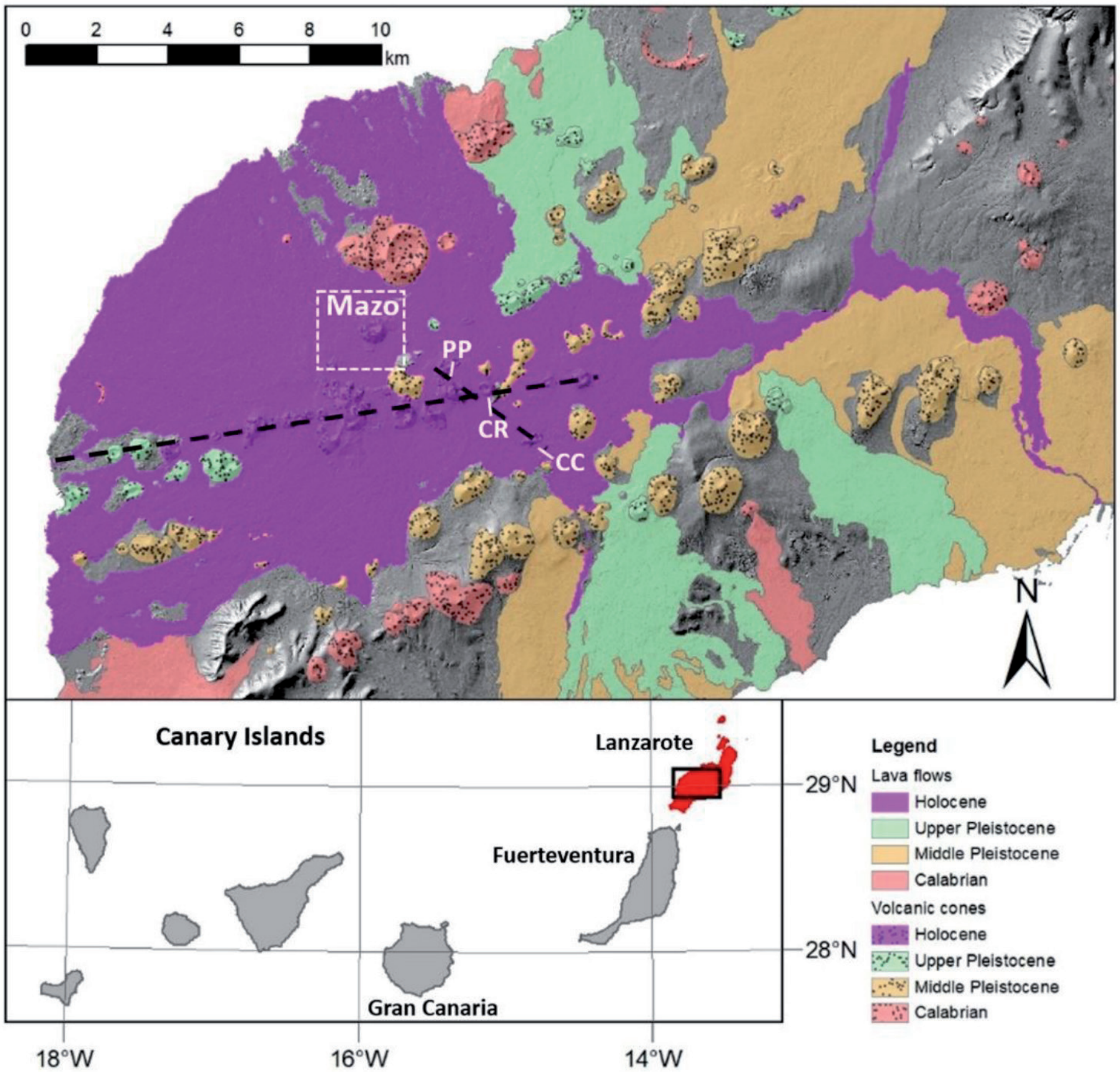


**Figure 1.**
*Location of Lanzarote Island and map of quaternary volcanic deposits of the central volcanic field of Lanzarote showing the location of Mazo volcano and the eruptive fissures of Timanfaya (dash black lines). White dashed square shows the location of* ***Figure 2****. CC: Caldera de los Cuervos; CR: Caldera de La Rilla; PP: Pico Partido.*

scoria cone trending ENE-WSW [18]. This scoria cone and the related deposits are partially overlaid by historical lava flows.

## 3. Geological analysis of Mazo volcano and deposits

Mazo is a monogenetic volcano with a relative height of 179 m, resting on a leaning volcanic substrate with a difference in height of 30 m between the highest and the lowest point of its external base. The cone and deposits are partially covered by lavas from historical eruptions, leaving exposed only the highest parts of Mazo deposits. The cone has an irregular shape and a crater with two open depressions aligned in the ENE-WSW direction, with a maximum diameter of 493 m. The main crater, located to the SW, has a funnel shape, 178 m deep inside, with an internal platform on its northern slope elevated 18 m over the bottom (**Figure 2**). The other depression is of bowl type, with an interior depth of 120 m. The rim of this double depression is higher in its southern part (429 m asl), just at the contact between both depressions. From this point, the rim appears lobed towards the NE and SW, gradually decreasing in altitude until reaching a minimum height of 280 m in its NW sector.

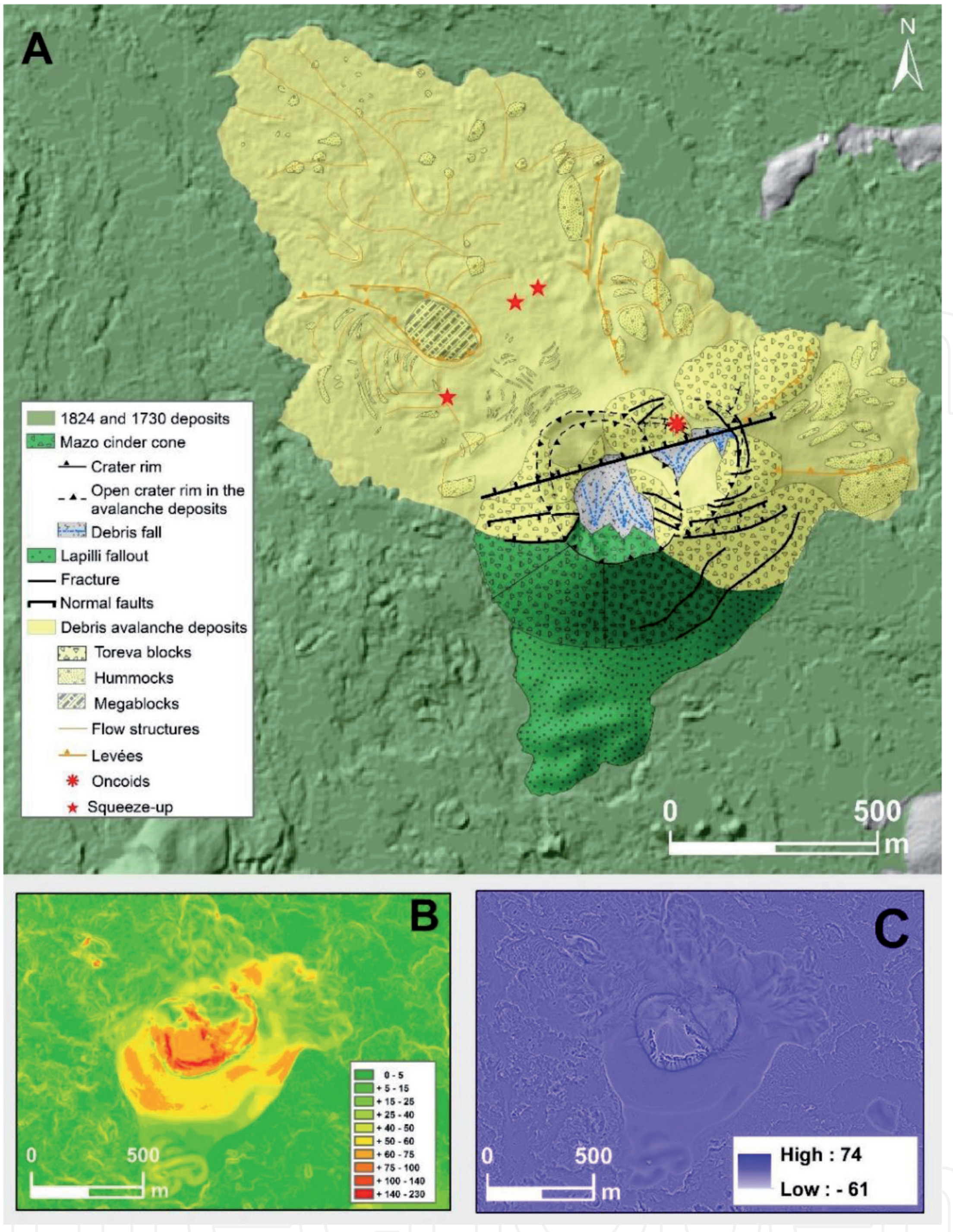


**Figure 2.**
*Geomorphological (A); slope (B); and roughness maps (C) of Mazo.*

The original cone consisted of welded pyroclastics, lapilli and bombs and some interbedded clastogenic lavas that can be identified in the SSW flank, affected by small fractures. However, most of the cone is formed by a debris avalanche deposit (DAD) that extends towards the NNW and ENE covering an area of 1218 $km^2$ and reaching a maximum distance from the vent of 1.6 km (**Figures 2** and **3**). The thickness of the deposit is difficult to estimate but minimum values of 35 m and 5 m can be assumed for the proximal and the distal area, respectively. The DAD is made of an unconsolidated breccia without stratification. Two main facies are identified: block and mixed facies.

Most of the cone, as well as proximal areas, are composed of block facies characterized by the presence of toreva blocks (**Figures 2** and **3A–C**), that are fractured and backtilting blocks that slumped in an almost completely coherent manner [22, 23].

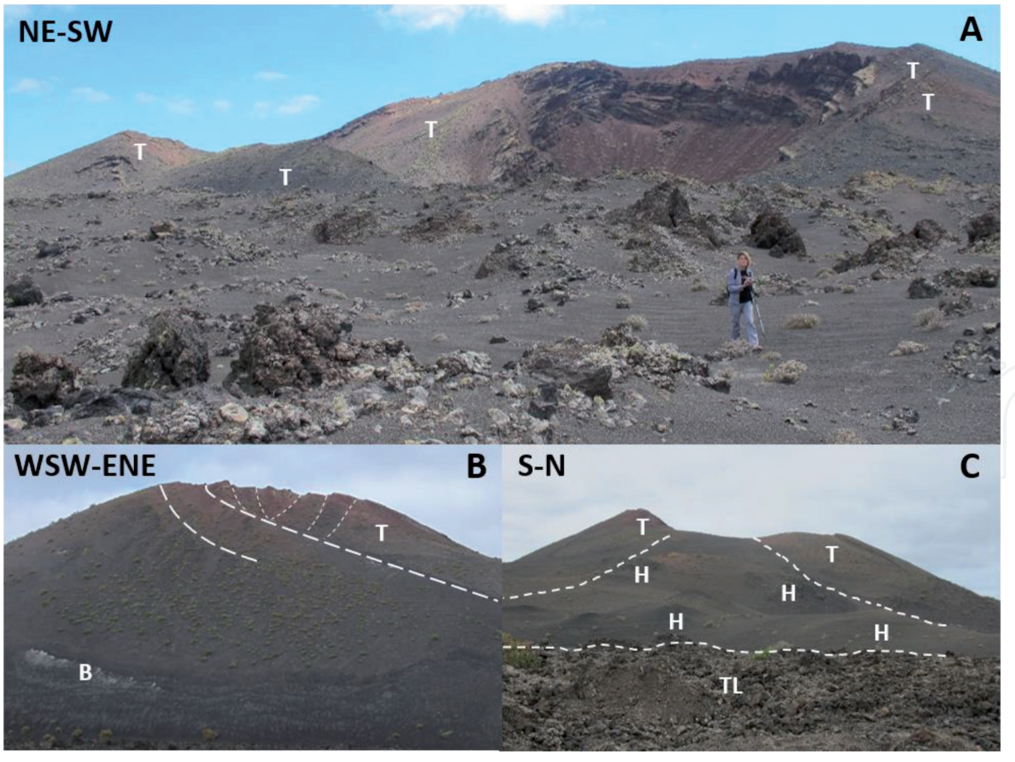


**Figure 3.**
*(A) General view of Mazo volcano showing the block facies of the proximal area with toreva blocks in the background, and the distal mixed facies in the foreground. (B) Listric faults and horst-graben structure on the flank. (C) Mixed facies with hummocky topography in between toreva blocks. B: Blast deposit; H: Hummocks; T: Toreva blocks.*

This facies consists of broken, slightly unstructured and staggered pieces of the cone (pyroclastics and clastogenic lavas), attached to the remnant cone, separated by inter-toreva depressions, normal faults and small graben structures (**Figure 2**). At the southeastern flank a set of conjugated faults, which are inserted in a listric fault plane, individualize several toreva blocks (**Figure 3B**). The eastern and northern flanks are also formed by several big blocks made of lapilli and scoria, as well as pyroclastic deposits.

The mixed facies is composed of a poorly sorted deposit, with milimetric to hectometric clasts and megablocks (**Figures 3A, C** and **4**). Most outcrops show a grain supported deposit, but matrix supported is also found (**Figure 4A** and **B**). Clast are mostly polyhedral and polymictic with abundant dense lavas and minor clast of vesicular lavas, welded scoria, weathered hydrovolcanic deposits, calcrete and paleosoils. Blocks and clasts are usually fractured, with frequent jigsaw cracks and slickensides (**Figure 4C–E**) or linked to deformation structures in the deposit (**Figure 4G**). Some of them show evidences of thermal alteration displaying a banded sequence of wine, reddish and yellowish colors suggesting decreasing of temperature towards the surface (**Figure 4F**).

From inter-toreva depressions towards the base of the cone, flows characterized by a hummocky surface topography were emplaced (**Figures 2** and **3C**). These flows were formed as toreva blocks break into smaller blocks. To the N and E of the volcanic edifice, lying on a steep slope area, these avalanche deposits consist of several flows with well-defined lobes and steep fronts. They have the highest concentration of hummocks, mostly elongated trending parallel to the flow direction. To the south of the cone there is also a hummocky surface completely covered by Mazo fallout deposits so it cannot be clearly assigned to this eruption (**Figure 2**).

To the NNW of the volcanic edifice the DAD spreads gently dipping with a roughly surface characterized by small and dispersed hummocks (**Figures 2** and **3A**).


**Figure 4.**
*Mixed facies. (A) Grain supported; (B) matrix supported; (C) jig-saw fit cracks; (D) fractured block; (E) slickensides; (F) alteration bands and (G) deformation structures under a block.*

Here the mixed facies are not related to a hummocky terrain being in turn dominated by ridges and a blocky surface. Lateral and frontal levees are also common, being the best defined those surrounding a single isolated mega-block, 120 m in diameter and 43 m high, located 472 m far from the vent (**Figures 2** and **5**). Decametric blocks (< 90 $m^3$) outcrop mainly on the distal area.

The single isolated mega-block (**Figure 5**) outcropping in this area consists of a stratigraphic sequence of several piled lava flows, hydromagmatic deposits with a paleosoil and a calcrete at the top with terrestrial gastropods, and finally a volcanic spatter deposit. The block is fractured and broken in the distal area and shows an injection of deformed hydromagmatic deposits into the overlying spatter. All these features lead us to interpret it as a substratum block. Part of the block was covered by molten lava during the debris avalanche emplacement.

Several squeeze-up structures (**Figures 2A** and **6**) have also been identified in the distal mixed facies indicating the presence of molten lava during the debris avalanche emplacement. They are made up of massive lava sheets tens of centimeters thick that make thinner and curve towards the top, constituting authentic spines with fluted and wavy surfaces. Squeeze-up are arranged in bands more or less parallel to each other with a curved longitudinal layout, and the convex side arranged in the direction of flow. Trapped between the fingerings of the intrusions there are clasts of the deposit; slickensides are common in the margins of these lava intrusions; and lava fingers have also been injected in between clasts. These structures are located along a zone of slope break suggesting they were formed due to compression processes in the avalanche when adapting to the slope during the emplacement.

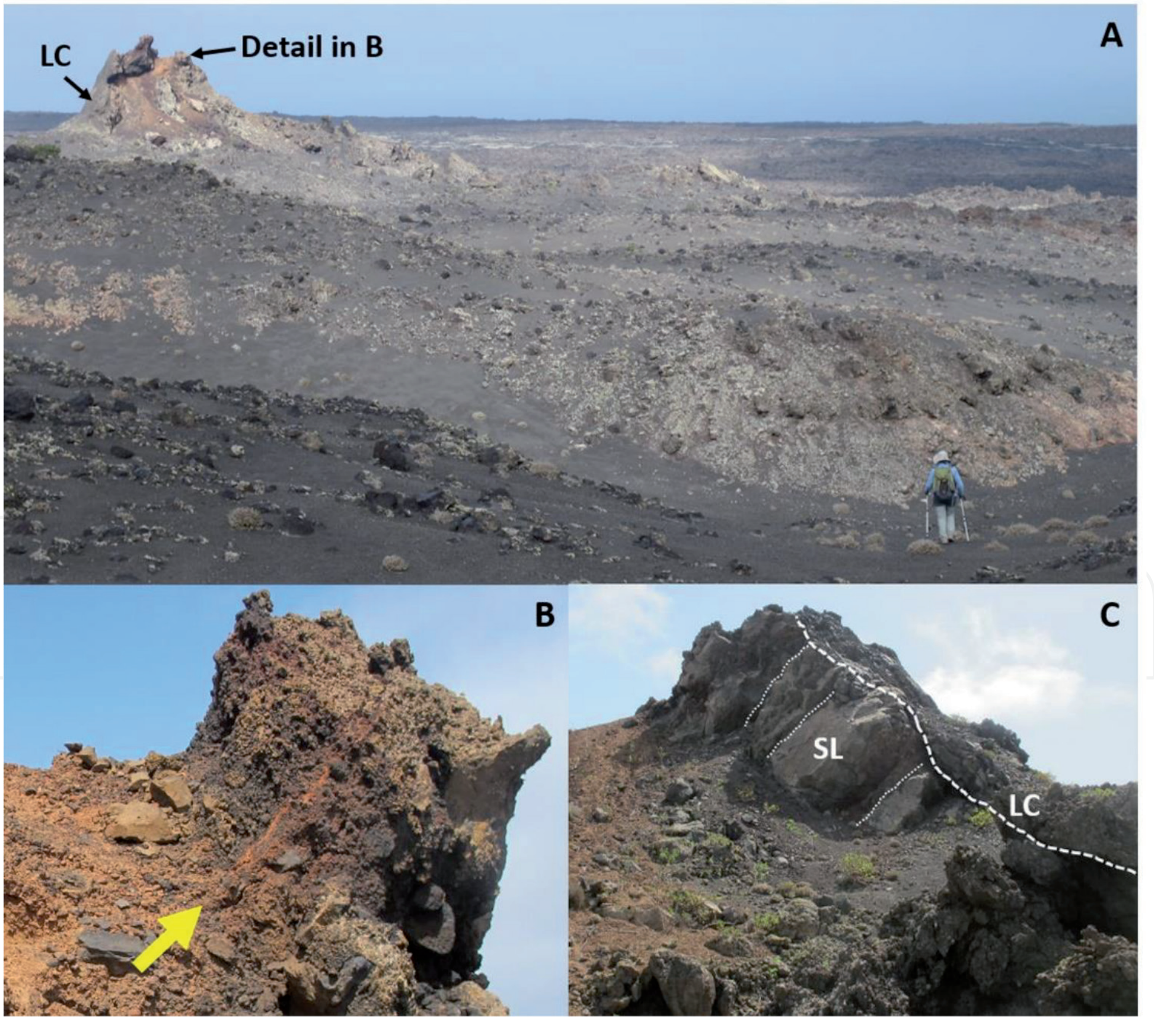


**Figure 5.**
*Isolated substrate megablock to the NNW of Mazo: (A) general view of the megablock inserted in a hummocky topography, indicating the location of the lava cover and B; (B) unstructured part of the megablock with clay injections into a scoria deposit; (C) layered deposits forming the megablock (for scale, the scar is around 10 m high). LC: Lava cover; SL: Substrate lava.*

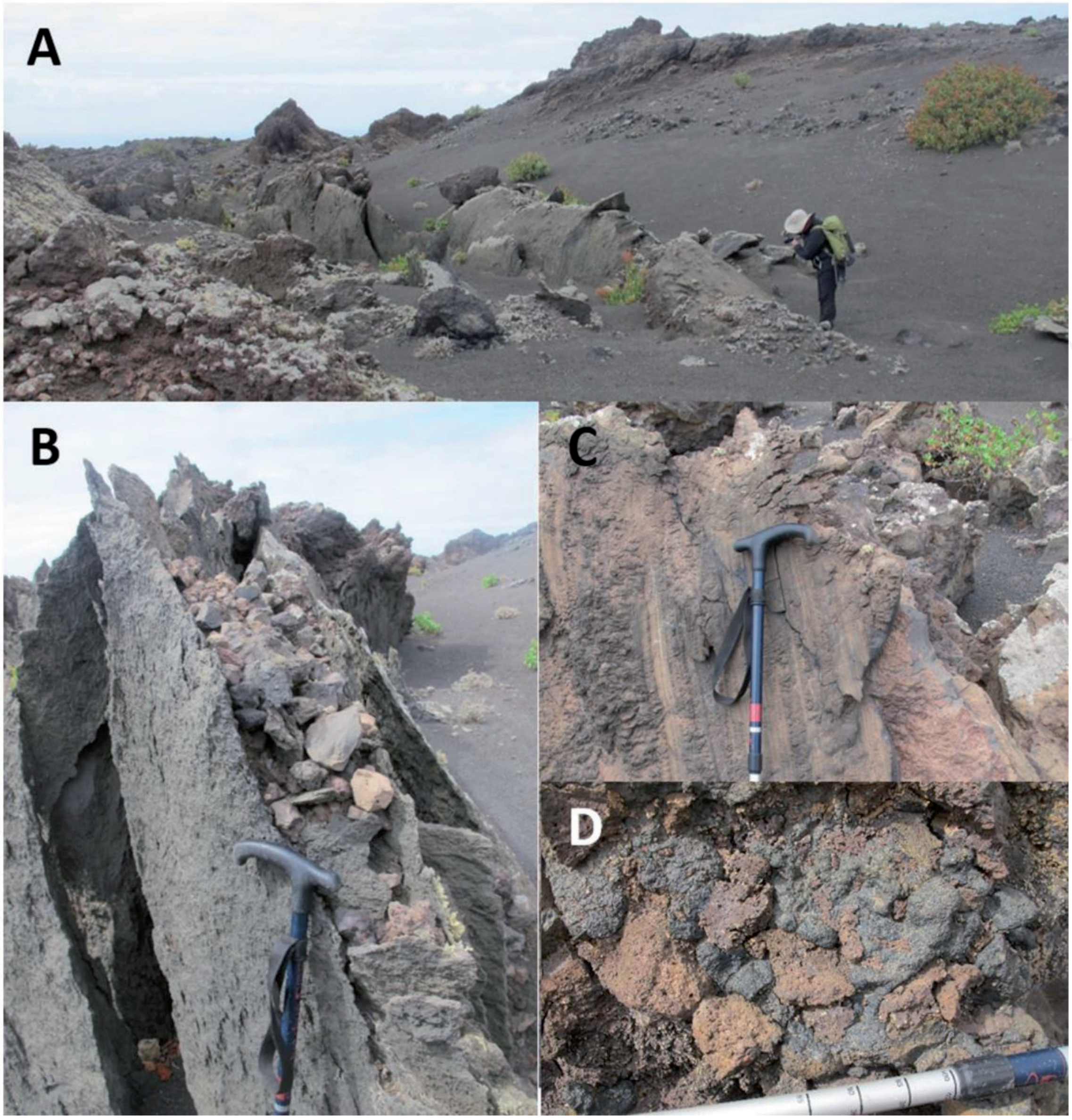


**Figure 6.**
*Squeeze-up structures in the DAD of Mazo: (A) curving pressure ridge; (B) DAD between the fingers of the squeeze-ups; (C) slickensides in a squeeze-up margin; and (D) injection of lava between DAD lithics.*

The DAD is overlaid with a blast deposit in which three main layers have been identified (**Figure 3B** and 7). The first layer consists of big bombs and blocks up to 40 $m^3$, composed of fragments of DAD or mafic dense blocks that appear scattered in proximal areas up to a distance of 500 m from the vent. Some of them are broken, split and wrapped in a fine layer of lava. Juvenile breadcrust bombs are also present. The second layer consist of a gray, clast-supported, well sorted and normal grading deposit (gravel to fine sand size) of clasts with parallel lamination up to 84 cm. Content of juvenile fragments is low. Finally, covering all previous deposits and adapting to the topography, a gray to yellow sand, matrix-supported and wavy laminated deposit is observed, being formed by hydromagmatic surges. It is better exposed in proximal areas with a thickness of around 40 cm decreasing to few centimeters in distal areas.

A blast deposit can be easily identified by a light gray layer below the strombolian fallout deposit. This layer can be observed over several cinder cones, at a distance larger than 7 km away from Mazo volcano. Although the blast deposit is distributed in patches, it should have covered the entire area, being better preserved in areas with thermal alteration like those close to the crater and in most of the

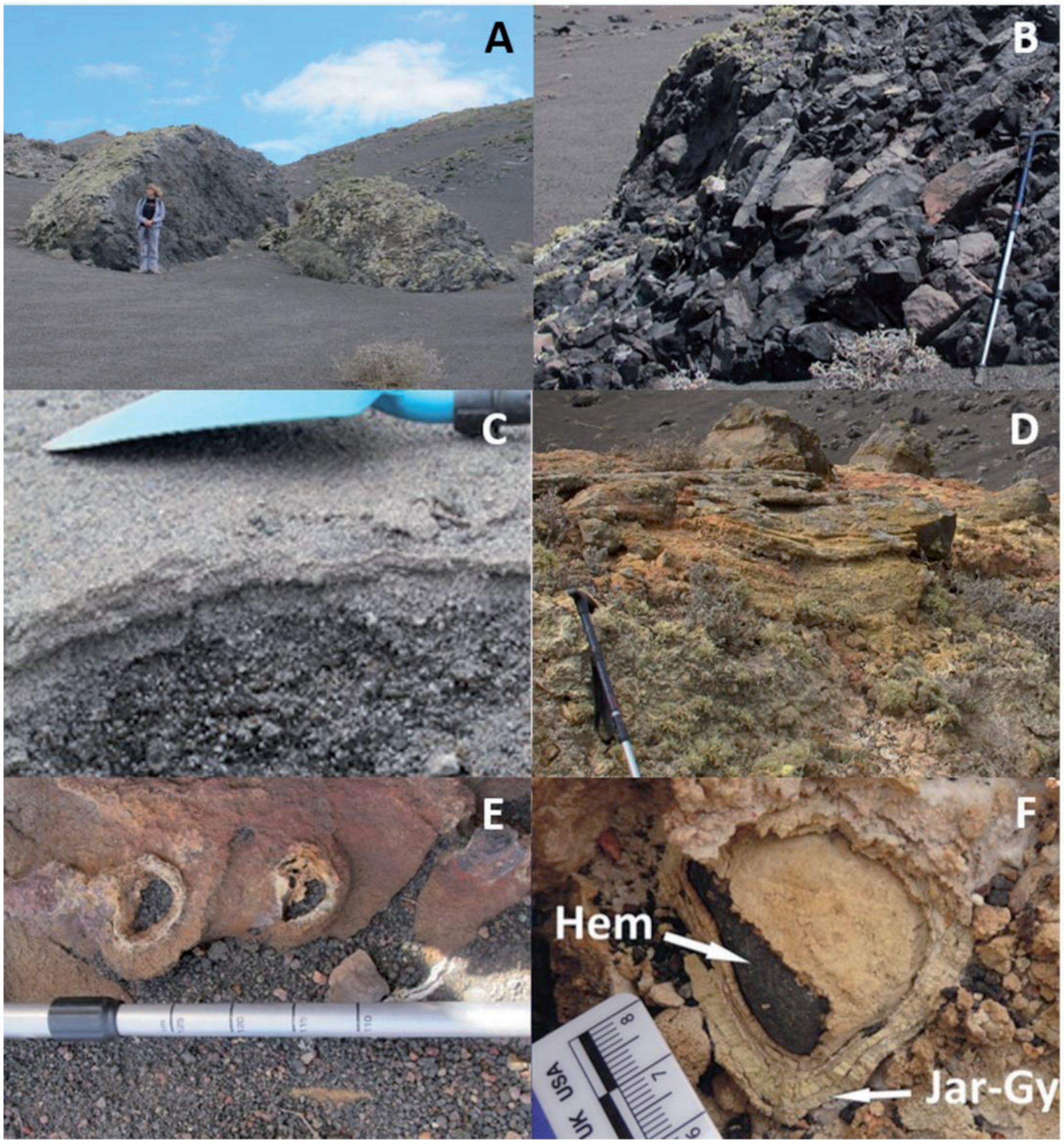


**Figure 7.**
*Blast deposit. (A) Broken bomb 500 m far from the vent; (B) core of bomb in* **A** *consisting of DAD; (C) layer two; (D) layer three overlaying an oncoids mound; (E) hydrothermal fluids escape pipes in layer 3; (F) Oncolite structure made up of a lithic nuclei covered by hematite (black in color) and several layers composed of native sulfur, gypsum, jarosite, and minor anhydrite (yellow in color).*

megablocks and hummocks. The alteration affects both the DAD and the blast deposit that cover them, giving place to yellowish-colored crusts which are broken into sheets in the steepest sectors. Degassing structures are also observed affecting these deposits. At the top of the sequence there is a strombolian fallout deposit, thicker in proximal areas (**Figure 3B**). A simplified stratigraphic column has been included in **Figure 8A**.

In the northern sector of the cone and along the graben fractures near to the crater, there are clear evidences of hydrothermal alteration and fumaroles activity. At this site a mound-type deposit with an external structure similar to a cauliflower covered by hydromagmatic surges is found. This mound is formed by soldered centimetric to decimetric oncoids (**Figure 7F** and **H**), yellow to cream in color; all of them have concentric build-ups around a lithic nucleus. Mineralogy of different laminae are determined by X-ray diffraction method and major chemical analyses were made on the IGME laboratories being their general structure and composition as follows: 1) single or composed subrounded lithic nuclei that have a thin black Fe-hydroxides coating; 2) several (three to six) concentric yellow laminae of native

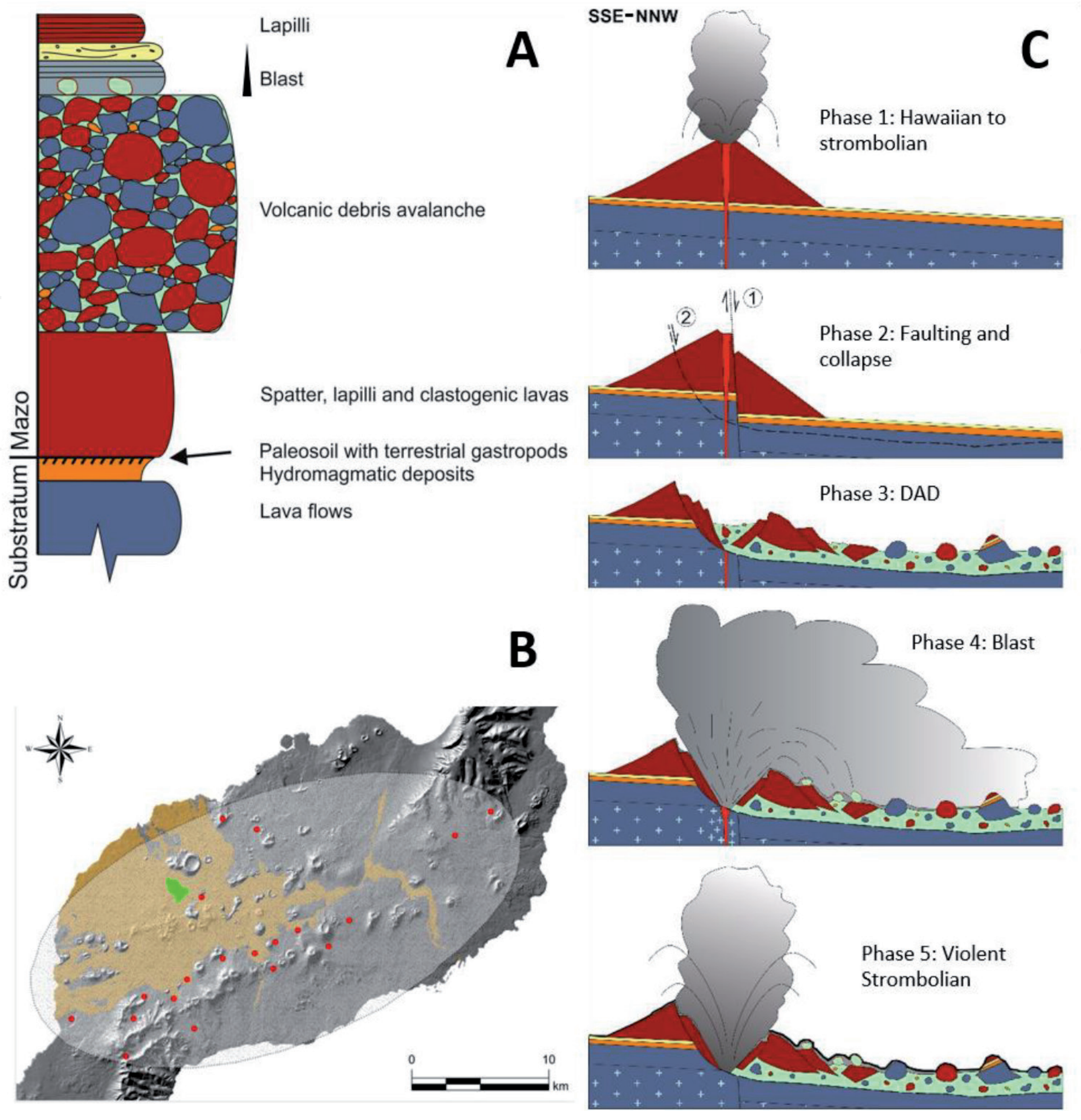


**Figure 8.**
*(A) Schematic stratigraphic column of Mazo. (B) Minimum area affected by ash dispersion (oval in gray) from Mazo volcano (in green) based on the location of affected villages (red dots). (C) Cartoons showing the main phases of Mazo eruption (see text for explanation).*

sulfur, jarosite, gypsum and anhydrite; 3) a white laminae made of amorphous silica and opal-A. Occasionally, oncoids are composed of Fe-hydroxide coatings, opal-A white laminae and yellow laminae.

## 4. Age of Mazo eruption

Within the eruptive system of Timanfaya (1730–1736) there are very few volcanic episodes sufficiently documented in historical chronicles to establish their precise spatial and temporal location in order to reconstruct Timanfaya's complete eruptive history. This fact has made it difficult to establish the complex formation sequences of the entire eruptive system. Although some authors have proposed evolutionary sequences that interpret the Timanfaya individual eruptions by analyzing historical information combined with chronostratigraphical studies and geological and geomorphological mapping (eg. [9, 11, 18–21]), there are still uncertainties about when, where and what volcanic processes occurred in each of the multiple eruptive vents and fissures developed during those

6 years of the 18th century [11]. This is the case of Mazo volcano whose age and eruptive style are quite controversial.

Most authors suggest that Mazo volcano was one of the multiple eruptive fissures of Timanfaya eruption [9, 11, 17, 24–26], while others assume that it was formed during a pre-Timanfaya eruption. Published geological maps include it as a Middle Pleistocene volcano but pointing out the possible existence of an historical emission center in the area due to the very recent aspect of several bombs and scoria [27, 28]. Other authors consider Mazo as an eruption prior to Timanfaya based on the following considerations [19]: 1) a visual recognition of this volcano suggest an old cone due to its color and eroded aspect; 2) paleomagnetic data of Mazo volcano show differences in magnetic parameters (declination and inclination) compared to other Timanfaya's well studied volcanoes; and 3) this volcano is surrounded by lava flows issued by vents from the Timanfaya initial eruptions, previous to Mazo.

All these criteria can be discarded if we consider that: 1) the eroded aspect of Mazo is due to the hydrothermal alteration caused by fumarolic activity and remnant heating and gas escape through the DAD; 2) the previously considered as Mazo lava flows are in fact a DAD so paleomagnetic orientations can be nearly uniform in every single block but the declination changes between blocks and from the source [14]; and 3) the origin of lava flows surrounding Mazo is not clear. It is evident that the lava flows emitted by the first vent of Timanfaya (Caldera de Los Cuervos), destroyed the village of Mazo on September 11th [9, 11, 17, 19, 24–26]; however, there is a disagreement on the source of the lava flows that overlie the eastern sector of Mazo, that have been assigned both to Caldera de Los Cuervos [19] and Pico Partido [21].

Our detailed map of lavas around Mazo (**Figure 9**) indicates that its deposits are surrounded, on the west, by lava flows from 1824 eruption and, on the east, by lava flows without direct connection to any emission center but probably coming from later eruptive phases of Pico Partido. Pre-Mazo lava flow, probably coming from Caldera de los Cuervos outcrop to the north of Mazo, partially covered by lapilli.

For more information on the possible assignment of Mazo to Timanfaya eruption we have reviewed historical chronicles. The information comes from several

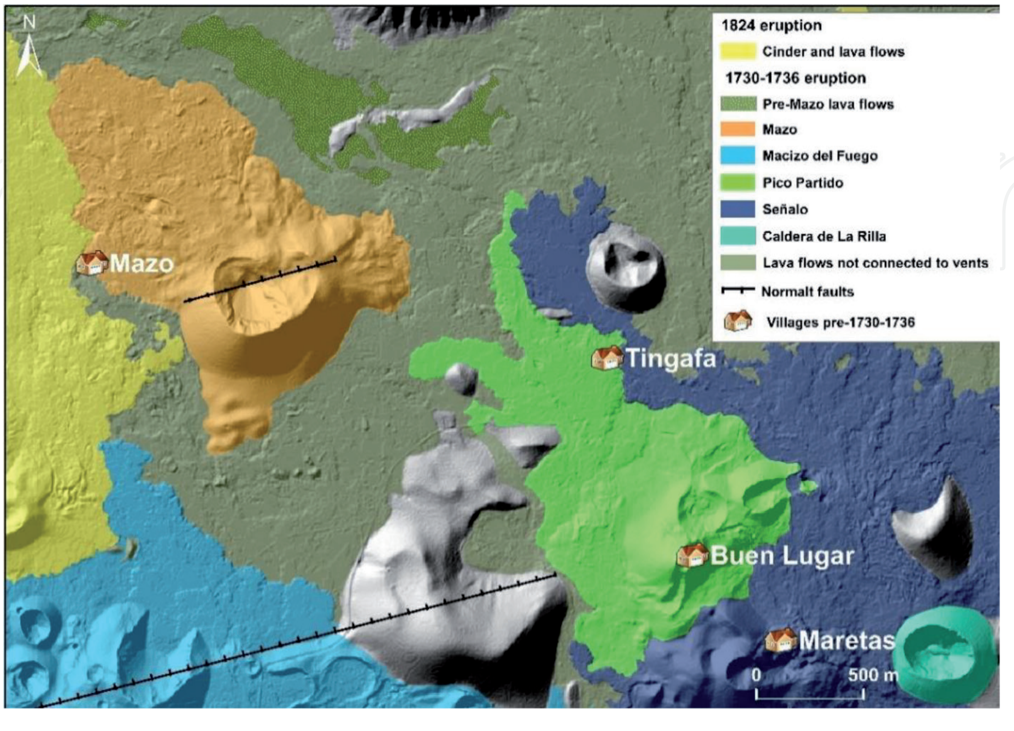


**Figure 9.**
*Lava flows and historical volcanic cones around Mazo volcano. Main normal faults trending parallel to Timanfaya main fissure are also shown.*

sources: 1) the description of the eruption made in 1744 by the priest of Yaiza in his diary (hereinafter CY) (referred in [29]); 2) the data contained in a manuscript with the dossier promoted by the Royal Court of the Canary Islands, which is currently preserved in the General Archive of Simancas (hereinafter MsS) [9, 16]; and 3) notarial and religious data contemporary with the eruptions [25, 30].

It is generally accepted that Timanfaya multiple eruption began at Caldera de Los Cuervos volcano on September 1th, 1730 and lasted until mid-September [9, 11, 19, 21]. After a short rest, on October 10th, 1730 two new eruptive fissures were opened at Caldera de la Rilla and Pico Partido volcanoes forming a NW-SE alignment with Caldera de Los Cuervos (**Figure 1**). Activity in these fissures ended on November 1730 and January 16th, 1731, respectively [30]. On 20th January 1731 a new volcano erupted. Although, some authors assume that this new volcano was Caldera de la Rilla [19], the chronicles say it was located half a quarter of a league (2.4 km) from the previous eruption of Pico Partido [30] and at the destroyed village of Mazo (MsS, letter of February 19th 1731), which was burned and covered by lava flows from Caldera de Los Cuervos volcano on September 11th 1730 (MsS, letter of 17th October 1731 [29], previously to Mazo eruption. There is only one eruptive complex that meets all the conditions, namely: location in the place where the burned village of Mazo was located and distance from the Pico Partido complex of about 2.4 km. That volcano is undoubtedly Mazo. In addition, it is in the continuation of the first volcanic alignment of Timanfaya (**Figure 1**) and have a similar composition (basanitic) of those volcanoes on the NW-SE alignment [18].

Assuming Mazo is the fourth eruptive fissure of Timanfaya some information about the eruption can be extracted from the chronicles. However, it is interesting that there is no reference to this volcanic episode of January 20th in the CY manuscript, which is one of the main sources of information on the eruption. In turn, there is a mention to an eruption starting the 10th of the same month that does not appear in the rest of the consulted documentary sources. Some errors regarding the start dates of some volcanic episodes of the eruption are relatively common in this chronicle [11, 26], probably due to the great spatio-temporal extension of the eruption, to the lack of a continuous monitoring of the eruptive vents, and also to the fact that this manuscript was written 8 years after the ending of the eruption [11], or even to transcription and translation errors of the original document [26].

Even so, if the specific dates are ignored, the sequence of events is similar in all the chronicles consulted. In fact, eruptive activity developed in January 1731, whatever the source consulted or the specific dates, is characterized by the cessation of activity of the volcano opened in the sector of Pico Partido on October 10th, followed by the occurrence of a seismic crisis of considerable intensity whose effects were felt in Gran Canaria Island [9], more than 190 km away, and by the beginning of a new eruption [16, 25, 30].

The narration realized by the Priest of Yaiza for the eruption of January 20th also says: "On the $10^{th}$ [in place of $20^{th}$] of January a mountain raised that the same day crumbled with and incredible crash inside its own crater, and covered the island with stones and ashes. Incandescent currents of lava collapsed onto the malpais up to the sea" [29]. Evidently, CY is describing the sudden collapse of Mazo volcanic cone and the formation of incandescent currents that reached the sea, with a total length of 6 km. The concatenation of later phenomena described in the documentary sources put in evidence that this process gave place to the formation of a high eruptive column that dispersed the pyroclasts over the whole island of Lanzarote (CY, MsS) and part of Fuerteventura (MsS). In mid-February the documentary sources (letter from Ambrosio Cayetano de Ayala; MsS) cite a score of villages in the central part of Lanzarote affected by ash fall [16, 30] (**Figure 8B**). The eruptive event of Mazo volcano lasted only seven days, as CY mentions that this eruption ended on January 27th, 1731.

## 5. Evolution of Mazo eruption and causes of the flank collapse

On January 20th 1731, after an intense seismic crisis, Mazo eruption started being the fourth eruptive fissure of Timanfaya. The initial activity was of hawaian type, documented in the outcrops of agglutinates of scoria and clastogenic lavas in the flank of the preserved edifice, and also by the presence of the same type of material integrated in toreva blocks and in some hummocks of the DAD. Later the style of the eruption shifted to strombolian type with emission of scoria (**Figure 8C**).

The rapid growth of the volcanic cone and a high emission rate may have been determining factors of the flank collapse that took place the same day as the eruption began. In this way, part of the collapse could be favored by accumulation processes in the cone that made it grow extremely quickly, exceeding its stability limit. Thus, once this limit is exceeded, small mass additions can generate debris avalanches [31, 32]. Also, the presence of a huge amount of lava in the crater or at the base of the cone could have favored the collapse [14, 33–35].

Doming process does not seem to be the trigger for the collapse, as the faults and fractures affecting the cone are practically parallel and do not follow the fracturing patterns associated with the intrusion and inflation processes [36, 37]. Even so, the geometry of the fractures can vary substantially depending on whether the intrusion is located within, below, or outside a volcanic edifice, and may vary according to the local geology and cause very different consequences [38]. The doming process cannot be ruled out because the original fracture pattern has been obliterated during displacement.

The existence of fractures that generate a graben structure arranged perpendicular to the direction of collapse, together with the presence of a higher and proximal toreva domain and a hummock domain at the bottom of the collapsed flank, could be related to the existence of basal layers with low viscosity and ductile behavior on the substrate of the volcanic cone, located during movement under the hummock domain [39]. The presence of a basal layer with these characteristics is evidenced in the lava injection processes and squeeze-ups formations in the avalanche sectors subject to compression. In stratovolcanoes, this hypothetical low-viscosity layer belongs to the initial stratigraphic sequence of the stratovolcano and may originally be composed of weak material such as poorly consolidated proximal pyroclasts, coarse-grained tephra sequences, pyroclastic flows, or even blocky lava flows [39].

In monogenetic mafic volcanoes, the existence of basal spatter layers emitted during the initial stages of the eruption and subject to charging processes by accumulation of pyroclasts, has been used to explain rafting processes of volcanic cones. In the case of the flank collapse of a monogenetic edifice like Mazo, this layer may correspond to the spatter emitted during the initial phases, configuring the base of the stratigraphic sequence so that as the height of the volcano increases its weight and so their plasticity increases, thus causing the collapse. Any case, analogue models realized by [2], shows that the deformation of the base is needed for the formation of deep collapses that affect the central area of the cone, as well processes linked to the fracturing of the basement, both through horizontal, oblique or vertical motions.

In Mazo, the existence of a well-defined fault in the cone, parallel to a normal fault affecting recent deposits of Timanfaya [40] (**Figure 9**) with a fault displacement of at least 45 m, suggests a structural control. These faults are also parallel to the main eruptive fissure of Timanfaya. A change in the stress field during Mazo eruption is evident if we consider that Mazo is located at the end of the Timanfaya first NW-SE alignment and that Mazo fault is trending parallel to the second ESE-WSW Timanfaya fissure where the volcanic activity was concentrated after Mazo eruption. The intense seismicity previous to Mazo eruption could also be connected with the modification of the stress regime that conditioned latter magma intrusion. The regional extension that facilitates the ascent of magma is accommodated by the formation of normal faults [41]. This orientation of extensional stress field in Timanfaya area is also confirmed by studies of fault population analysis [42]. Tectovolcanic processes affecting the basement are also supported by the large distal megablock included in the DAD. The generation of the collapse in the northern sector of the building reveals the influence of the stress regime within the volcano motivated by regional tectonic stresses in the first phase of Timanfaya or by the geometry of contact with the substrate, as it has been observed in central volcanic building collapses [43–45].

The flank collapse produced a volcanic debris avalanche that affected most of the volcanic edifice, including the summit area and part of the basement. The characteristics of the Mazo DAD are equivalent to those observed in stratovolcanoes, with a proximal area characterized by the presence of block facies through which more fractured material was emplaced forming flows at high slope and relatively short paths, while the most disaggregated material due to friction between blocks and fluidized by the presence of molten lava reached a longer distance producing more dispersed hummocks. The collapse formed a 500 m long amphitheater on the southern flank of the cone, and a DAD that, according to chronicles, reached the sea on the coast more than 6 km away. The volume of slipped cone and DAD is impossible to calculate as they are partially covered by lavas from subsequent eruptions.

The decompression caused immediately after the debris avalanche generated a blast cloud and ballistic projectiles composed of heavy blocks and bombs that were deposited in proximal areas and as far as 500 m from the vent. The blast cloud was a driven-gravity flow, probably divided in two parts [46]: 1) a coarse-grained basal flow of rock fragments; and (2) a fine-grained turbulent upper flow that originated the blast surge covering all the previous deposits. The blast deposit has been found at distances up to 6 km from the vent, and based on the historical chronicles, the fine-grained fragments affected the whole central area of Lanzarote. This deposit covered the DAD but now is only preserved in the areas where they either 1) suffered hydrothermal alteration due to its location onto hot toreva blocks or hummocks, or 2) overlaid by pyroclasts from the last phase. Hydrothermal alteration in hummocks and squeeze-ups in the DAD also support this was a syn-eruptive collapse.

The presence of oncoids in an inter-toreva depression located in the proximal area indicates that hydrothermal activity related to degassing along fractures was generated after the collapse. Mazo oncoids were then formed under boiling water in a degassing-phase related to a fracture close to the crater vent. Oncoids, travertine and sulfur laminated mound-type deposits have been described in other volcanic environments related to hydrothermal activity, warm and hot springs and geyser deposits [47–49].

After the blast, the eruption went on with a last strombolian phase finishing six days later. The lapilli emitted in this stage completely covered the topography burying smaller irregularities of the surface and homogenizing the geological landscape of the whole area of Mazo volcano.

## 6. Implications for volcanic risk assessment

Recent studies point out that monogenetic eruptions, usually characterized by hawaiian-strombolian eruptive episodes, can also include sudden and more violent episodes that imply a higher risk for the population [6, 12, 14]. The identification of a syn-eruptive flank collapse and the associated blast of Mazo during the 1730–36

Timanfaya eruption provide evidence of a new hazard to be considered. It is also important to emphasize that this is not an isolated phenomenon since the historical chronicles refer to other collapse phases during the month of April 1731 that affected more than one volcanic edifice at a time [29]. However, there is no detailed description of the features of these processes except for some mentions to fractures, probably associated to semicircular collapses [9, 19, 50].

A flank collapse like that occurred during the eruption of Mazo volcano, besides the DAD and the associated blast, may originate hydromagmatic and violent strombolian episodes due to the post-collapse depressurization that significantly increases the eruption energy and form eruptive columns of great height and wide dispersion. Nevertheless, the studies on volcanic hazards in monogenetic volcanic fields are mainly concerned with the analysis of volcanic susceptibility and with the development of scenarios of lava flows, pyroclastic density currents (PDC), and pyroclastic ballistics and fallout [51–53]. Volcanic hazard assessment is rarely multi-hazard and is normally focused on lava flows invasion. In this context, is has not been considered eruptive scenarios including instability processes of volcanic edifices, ranging from less violent processes like rafting to flank collapses like this described for Mazo volcano.

The probability of flank collapses development during future mafic eruptions rises the potential risk for the population, even more when it is considered that the population has increased from 5000 inhabitants in Lanzarote in 1730 (as stated in MsS) to 205,910 nowadays plus 3,065,575 visitors [54]. An eruption with similar characteristics to that of Mazo at present times, not only would cover with ashes the whole island of Lanzarote and part of Fuerteventura but would also cause the closure of the two islands airports and ports. This would in turn cause serious damage to air and maritime transport of the islands, which are key aspects of the current economic system of both islands based on tourism and totally dependent on the outside.

In fact, the intensity of Mazo eruption and the syn-eruptive flank collapse show a high impact at a regional scale which exceeded the capacity of the insular and regional authorities. It was this fourth eruption that prompted the Royal Court of Canary Islands to carry out a dossier file to request the intervention of the King of Spain. This file is presently archived in the General Archive of Simancas in Valladolid province (Spain) and constitutes one of most complete documentary sources of the eruption. Fortunately, the fact that the eruption occurred in an area already devastated by the first episodes of Timanfaya eruption reduced its risk in 1730.

The development of debris avalanches and the generation of eruptive columns with high altitude associated to a collapse during a mafic monogenetic eruption oblige us to change the perception of hazards linked to the growth of such volcanic cones. All this indicates that we should pay more attention to this kind of processes and shows the need for detailed studies to identify and characterize them, more when the studied DAD had been previously described as lava flows [26, 27]. This will allow to obtain a deeper knowledge of the triggering factors and causes of this type of processes in order to carry out effective volcanic hazard assessment policies.

## 7. Conclusions

Based on detailed field work on Mazo volcano and the exhaustive review of historical documents we have been able to propose a new eruptive sequence for the first months of 1730–36 Timanfaya eruption. The inclusion of Mazo volcano as the fourth eruptive fissure of Timanfaya and the formation of a tectonic controlled collapse previous to an important change in the eruptive dynamics is quite significant since it occurred at a time of important stress changes that notably affected the Timanfaya eruption and led to the formation of a large (>13 km) eruptive fissure along which the eruption developed from that moment on. The existence of faults affecting Timanfaya volcanic products demonstrate that there was an important structural control during the eruption. Thus, the eruptive processes produced during the first six months of this eruption, which is the best recorded in contemporary documentation, show that the previously established geological history constitutes a simplification of the events that took place in this area and that a reinterpretation of the historical chronicles and new field work should be carried out to clarify the evolution of the whole Timanfaya eruption, the largest historical eruption of the Canary Islands, and one of the most important in recent times in the world.

The example of Mazo illustrates that flank collapses are not processes uniquely linked to stratovolcanoes. Mazo is an example that during the construction of a scoria cone volcano-tectonic process might trigger a flank collapse as well, although the size of the amphitheater and the avalanche deposits are significantly smaller than those developed in stratovolcanoes. Mazo deposits display features and morphologies similar to those described to characterize volcanic instability processes generated in large volcanic structures, being the main difference the scale. This research emphasizes that mafic monogenetic volcanic eruptions can result in rafting or flank collapse. In both processes, morphology and structures in the cone can be similar, being the main difference the impact of the phenomena: while rafting is a relatively quiet emission of lavas with rafts, during a flank collapse occurs a sudden dramatic formation of an avalanche debris and a blast.

Understanding the causes of syn-eruptive collapses in monogenetic mafic eruptions is essential to correctly interpret the signs of active volcanoes during risk management for land planning and risk reduction in this type of eruptions. In addition to its implications for the Timanfaya eruption comprehension, the morphology of Mazo volcano, and its well exposed DAD deposits make it an ideal case study to characterize flank collapses and formation of DAD in monogenetic edifice, reason why it has been proposed as a geosite in the Canary Islands geoheritage inventory, being suitable to be proposed as a Global Geosite of international relevance for Spain.

## Acknowledgements

This research is part of LIGCANARIAS Project (ProID2017010159) that has been partially funded by the Canary Islands Agency for Research, Innovation and Information Society (ACIISI) of the Government of the Canary Islands, co-financed by the Operational Programs FEDER and FSE of Canarias 2014-2020. The initial study was carried out within the framework of a Specific Agreement between Lanzarote Council and the Spanish Geological Survey (IGME). We would also like to highlight the collaboration of the Environmental Agents staffs from Timanfaya National Park, the National Parks Autonomous Organism, and the UNESCO Global Geopark of Lanzarote and Chinijo Islands. We appreciate the work done by Alberto Acosta thanks to a stay as a fellow of the University of Las Palmas de Gran Canaria (ULPGC) in the Unit of Canary Islands of the Spanish Geological Survey. We appreciate the review and comments made by the editor and reviewers of the manuscript.

## Conflict of interest

There are no conflicts of interest.

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