

Volcanology and inflation structures of an extensive basaltic lava flow in the Payenia Volcanic Province, extra-Andean back arc of Argentina

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ABSTRACT. The El Puesto lava flow is located in the Payenia Volcanic Province (central-western Argentina), has a length of 70 km and is Middle Pleistocene in age (0.200 ± 0.027 Ma). The flow shows a P-type pahoehoe structure and exhibits several inflation structures, mainly tumuli and also inflation ridges and lava rises. Lava rise pits and radial or annular clefts are common features associated with inflation structures. The gentle slope on which the flow moved ($\approx 0.5^\circ$) allowed the lateral coalescence of lobes at the flow front and the development of an external rigid crust that insulated the liquid core. Lava tunnels are frequent and the lava tunnel named “Cueva de Halada” which is located at its medium portion is the best example of a drainage master tube which formed from the cooling of the crust around a stable inflated flow. Tumuli alignments and long inflation ridges reveal the existence of larger tunnels within the flow. Inflation structures may occur in high concentration belts that converge on a single main belt which is assigned to an anastomosed network of internal flow pathways within the main lava body. The development of inflation structures and lava tunnels require low to moderate effusion rates. An average lava supply rate of 1.8×10^{-4} m³/s and an inflation time of about 15 days were estimated for an average tumulus of this flow. A high and sustained supply of low viscosity lava ($\eta = 1550\text{--}483$ Pa s) was inferred that initially generated a sheet flow of great areal extension. The reduction in effusion rates could then allowed the development of tunnels that carried lava to the distal fronts, generating localized inflation phenomena throughout the lava flow.

Keywords: Lava flow, Inflation structures, Back-arc volcanism, Basalts.

RESUMEN. Volcanología y estructuras de inflación de un extenso flujo de lava basáltica en la Provincia Volcánica Payenia, retroarco extraandino de Argentina. El flujo de lava El Puesto se localiza en la Provincia Volcánica de Payenia (centro-oeste de Argentina), tiene una longitud de 70 km y se emplazó en el Pleistoceno medio ($0,200\pm 0,027$ Ma). La colada muestra una estructura de flujos *pahoehoe* tipo “P” y exhibe numerosas estructuras de inflación como túmulos, dorsales de inflación y elevaciones de techo plano. Los pozos y las fracturas radiales o anulares de inflación son rasgos comunes asociados a estas estructuras. La colada El Puesto se movilizó sobre una pendiente suave ($\approx 0,5^\circ$) que favoreció la coalescencia lateral de lóbulos en el frente de la colada y el desarrollo de una corteza externa rígida que aisló térmicamente el núcleo de lava líquida. Los túneles de lava son frecuentes y el túnel de lava conocido como “Cueva de Halada”, situado en la porción media del flujo, es un excelente ejemplo de un túnel maestro drenado que se formó a partir del enfriamiento de la corteza externa alrededor de un flujo inflado estable. Los alineamientos de túmulos y las extensas dorsales de inflación revelan la existencia de túneles mayores sin drenar en el interior del flujo. Las estructuras de inflación pueden concentrarse en fajas alargadas que convergen hacia una única faja principal, lo que se interpreta como producto de una red anastomosada de vías internas de transporte del flujo dentro del cuerpo de lava principal. El desarrollo de estructuras de inflación y túneles de lava requieren de tasas de efusión moderadas a bajas. Se estimó una tasa promedio de suministro de lava de $1,8 \times 10^{-4}$ m³/s y un tiempo de inflación de aproximadamente 15 días para

un túmulo típico de esta colada. Se infirió un suministro alto y sostenido de lava de baja viscosidad ($\eta' = 1550\text{--}483 \text{ Pa s}$) que inicialmente generó un flujo tabular de gran extensión areal. La reducción en las tasas de efusión permitió luego, el desarrollo de túneles a través de los cuales la lava se transportaba hacia los frentes distales, generando fenómenos de inflación localizada en todo el ámbito de la colada.

Palabras clave: Flujo de lava, Estructuras de inflación, Volcanismo de retroarco, Basaltos.

1. Introduction

One of the most common forms of volcanic activity on Earth is that in which lava flow effusions take place; however, extremely long subaerial lava flows are a rare feature on our planet. The main cases cited in the literature correspond to the Quaternary lava flows that are situated in northeastern Australia, known as Undara (*e.g.*, Atkinson and Atkinson, 1995) and Toomba (*e.g.*, Stephenson and Griffin, 1976; Stephenson *et al.*, 1998) with lengths greater than 100 km; the lavas from the Neogene basaltic plateau of the Columbia River, USA (*e.g.*, Waters, 1961; Self *et al.*, 1996); and the Thjorsa lava flow (>140 km) of 8.5 ka age (Hjartarson, 1988; Halldorsson *et al.*, 2008) in Iceland. The long pahoehoe lava flows of the basaltic plateau of the Deccan Trap in India, with flows of over 400 km and reaching up 1,000 km in length in some cases, have been considered the remnants of the longest lava flows on Earth (*e.g.*, Agashe and Gupta, 1971; Keszthelyi *et al.*, 1999; Self *et al.*, 2008). In Argentina, the Payenia Volcanic Province comprises an extensive basaltic plateau localized in the Andean foothills. It is mainly constituted by lava flows associated to Neogene-Quaternary extra-Andean back-arc volcanic activity. At the central region of this volcanic province, Pasquaré *et al.* (2008) and Espanon *et al.* (2014) describe a single lava flow that reached up to over 160 km from its source which is localized in the Payún Matrú volcanic field. It was named Pampas Onduladas and it has been proposed as the most extensive Quaternary lava flow on Earth. In spite of this, Pampas Onduladas lava flow is associated to other contemporaneous and very extensive lava flows named Pampa de Los Carrizales (Pasquaré *et al.*, 2008) which reached up 181 km in length (Bernardi, 2016) and was extruded from La Carbonilla fracture (Llambías, 1966) which is the same fissural effusion center as lavas of Pampas Onduladas. The lavas of Pampa de Ranquelcó and Pampa de Luanco, of 116 and 122 km in length, respectively (Bernardi, 2016) and the El Corcovo lava flow, of 70 km in length (Bernardi *et al.*, 2015;

Bernardi, 2016) situated in southern Payenia comprise other lava flows of notable length (Fig 1).

Based on observations on the behavior of Hawaiian active lava flows, Hon *et al.* (1994) proposed a model for effusions of moderate volume, also applicable to high-volume lava eruptions, known as inflation. Initially, lava advances through a series of individual lobes that coalesce laterally and increase in thickness thanks to the injection of lava below an outer cooling crust having ductile behavior, which becomes brittle as it cools and thickens. This crust supports the increasing pressure of the addition of lava to the isolated liquid core. Initial inflation is general throughout the entire lava body and it becomes localized as the lava movement is restricted to an internal network of lava tubes.

According to this model, pahoehoe flows develop through a combination of areal dispersal and inflation with the formation of ruptures and lava squeeze-ups through the margins of the lobes (Hon *et al.*, 1994; Keszthelyi and Denlinger, 1996; Harris *et al.*, 2007). Inflation is the dominant process until the internal lobule pressurization reaches values that are large enough to break the flow margins and start again a cycle of lateral dispersion-inflation (Hoblitt *et al.*, 2012). At moderate rates of effusion, inflation and cortical growth occur at similar rates.

The inflation process occurs locally and the flow advances from leaks through fractures caused by swelling. In contrast, when the effusion rates are higher and sustained over time, the flow is able to inflate evenly, resulting in a sheet flow which evolves into a hummocky flow when effusion rates begin to decrease. The hummocky flow generates a micro-relief defined by inflation structures, which modifies the previous smooth surface of the flow (Self *et al.*, 1998). These structures include: tumuli, flat-roof lava rises, lava-rise ridges and lava-rise pits (Walker, 1991; Hon *et al.*, 1994; Whitehead and Stephenson, 1998). It is also common that flow cross-sections exhibit massive and vesicular sectors, where patterns of vesicle size distribution and changes in vesicle density are regularly observed (*e.g.*, Aubele

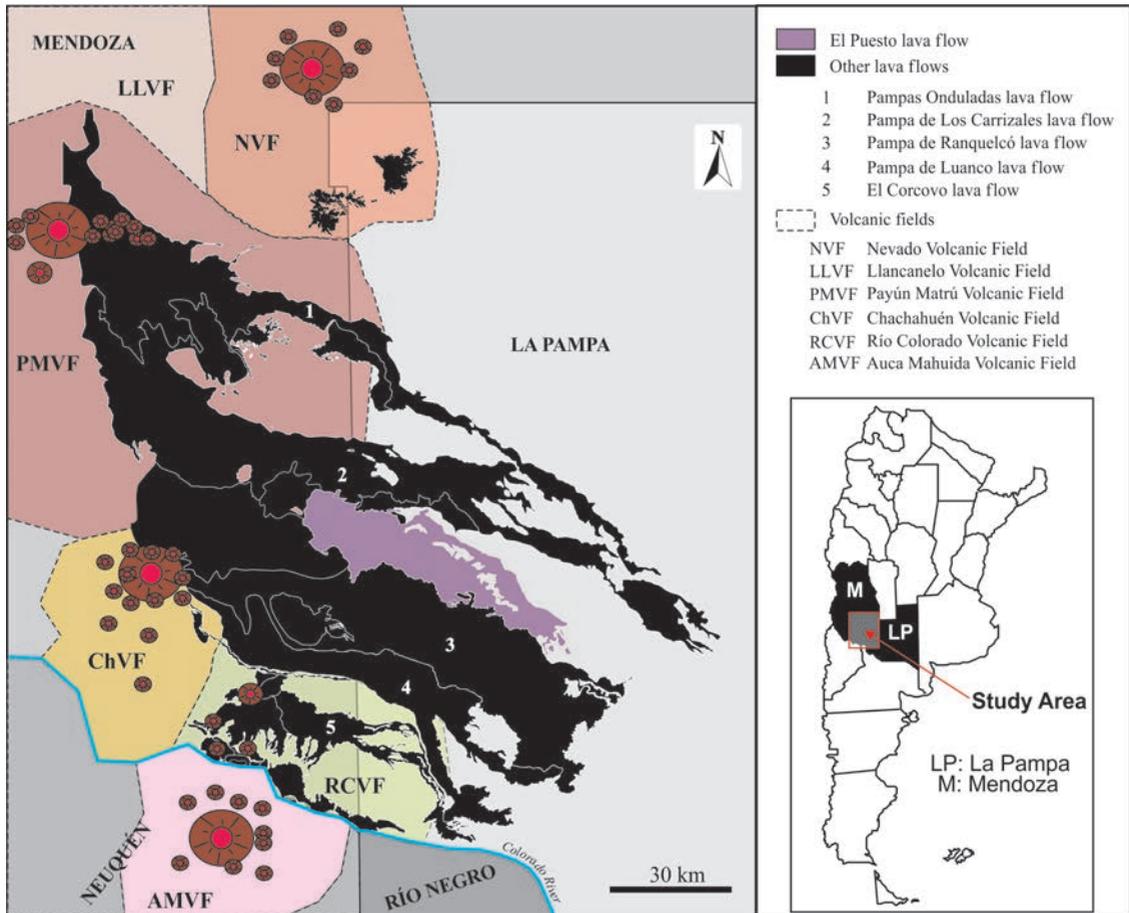


FIG. 1. Map of the southeastern region of Payenia Volcanic Province indicating some of the main volcanic fields in which it was divided, according to Bermúdez *et al.* (1993), Ramos and Folguera (2011) and Gudnason *et al.* (2012). The main lava flows considered in this work are also shown.

et al., 1988; McMillan *et al.*, 1989; Manga, 1996; Cashman and Kauahikaua, 1997).

These morphological and structural features that are related to the inflation mechanism have been observed in numerous ancient lava flows (*e.g.*, Hjartarson, 1988; Thordarson and Self, 1996; Keszthelyi *et al.*, 1999; Whitehead and Stephenson, 1998; Pasquaré *et al.*, 2008), particularly in those of considerable extension, from which it was postulated that this process was essential in the development and emplacement of these lava flows.

The main objective of this work is to characterize the emplacement mode of the El Puesto lava flow (EPLF) and to recognize and parameterize the inflation process from the different inflation structures that it generates.

2. Geological setting

2.1. Payenia Volcanic Province

Payenia Volcanic Province comprises an extensive basaltic plateau localized in the extra-Andean back-arc sector of central-western Argentina, 460 to 540 km east of the Chile Trench. It extends between 33° 40'S and 38°S and from the current volcanic arc to the Salado River Valley covering central-southern Mendoza, northern Neuquén and western La Pampa provinces (Fig. 1).

Payenia comprises the greatest Neogene-Quaternary volcanic province of South America with more than 800 monogenetic cones (*e.g.*, Inbar and Risso, 2001; Bertotto *et al.*, 2006; Risso *et al.*,

2008; Mazzarini *et al.*, 2008; Folguera *et al.*, 2009). Geochemically, rocks range from basalts to andesites, with arc to intraplate signatures (*e.g.*, Kay *et al.*, 2006; Ramos and Kay, 2006; Bertotto *et al.*, 2009). Payenia has been divided into several volcanic fields according to their geographical and geochemical characteristics (Bermúdez *et al.*, 1993; Ramos and Folguera, 2011; Gudnason *et al.*, 2012). The main volcanic fields are: Diamante (not shown in Fig. 1), Nevado, Llananelo, Payún Matrú, Chachahuén, Auca Mahuida and Tromen (not shown in Fig. 1). Field relationships (*e.g.*, Groeber, 1946; González Díaz, 1979) and radiometric dates (*e.g.*, Kay *et al.*, 2006; Quidelleur *et al.*, 2009; Folguera *et al.*, 2009; Germa *et al.*, 2010; Gudnason *et al.*, 2012; Ramos *et al.*, 2014; Dyrh *et al.*, 2013; Marchetti *et al.*, 2014; Espanon *et al.*, 2014; May *et al.*, 2018) allowed to infer a continuous igneous activity in Payenia from Miocene to Holocene, with a gap between late Miocene and early Pliocene. Basaltic units that form Payenia have been considered as indicators of extensional events that were produced after a Tertiary compressive stage. Bermúdez *et al.* (1993) indicated that the melts were generated from thermal and mechanical disturbances of the mantle. Meanwhile, Kay (2002) and Kay *et al.* (2004, 2006) related the generation of these magmas with the melting of a hydrated mantle after a low-angle subduction episode which occurred between 8 and 5 Ma (Late Miocene).

3. El Puesto lava flow

3.1. Location and eruptive center

The El Puesto lava flow (EPLF) comprises a basaltic flow of notable extension located in the southern-central sector of the Payenia Volcanic Province (Fig. 1). The effusion center was the Morado volcano, located at 36°51'S and 68°21'W (Fig. 2A) and the EPLF culminated its advance in the proximities of the La Copelina salt flat (37°12'S-67°35'W).

Bertotto (2003) describes the Morado volcano as an elevation with semicircular contour without crater. It shows an average height of 25 m with respect to the surrounding surface, an average basal diameter of 260 m and an upper diameter of approximately 45 m. It exhibits slopes with angles between 11° and 17° and it is constituted by lava flows, pyroclasts and subvertical vesicular dykes.

The rocks of the Morado volcano were assigned to the Pliocene (Wichmann, 1928), Pleistocene (Sobral, 1942) and Holocene (Núñez, 1976) by geological relationships. Here we present a K-Ar whole rock age of 0.200±0.027 Ma (Middle Pleistocene) for a sample of the EPLF (Table 1). The analyzed sample (M129, lat/long: 36°51'S/68°21'W, Fig. 2a) was collected from the massive core of the lava flow, in the southeast sector of the Morado volcano (site EP1 in Fig. 2A). Detailed petrography of the sample is described at the Petrology Features section. The age was obtained by the “unspiked K-Ar” method. The Ar analysis was performed using a noble gas mass spectrometer (modified VG5400/MS-III) at the University of Tokyo, Japan. The errors in the determination of ⁴⁰Ar and ⁴⁰Ar/³⁶Ar ratio were estimated at 5% and 0.2%, respectively, based on repeated measurements of the atmospheric standard containing 1.5×10⁻⁷ cm³ STP of ⁴⁰Ar. The concentration of K was determined by X-Ray fluorescence Spectrometry, XRF (Phillips PW2400) for an aliquot of the same total rock sample that was used for the analysis of Ar. The analytical precision was checked using the international rock standard JB-1a (Geological Survey of Japan). Details of the procedure applied with respect to the K-Ar dating are described by Nagao *et al.* (1991) and Orihashi *et al.* (2004).

3.2. Geomorphometry

The El Puesto lava flow presents a predominantly southeasterly sense of movement with some minor spills to the west, northwest, and south of the eruptive center. The flow reached a longitudinal development

TABLE 1. ANALYTICAL DATA OF ANALYZED SAMPLE.

Sample	K (wt%)	⁴⁰ ArRad (10 ⁻⁸ cm ³ STP/g)	³⁸ Ar/ ³⁶ Ar	AIR fraction (%)	Age (±1σ Ma)
M129	0.829±0.041	0.644±0.084	0.18805±0.00079	96.51	0.200±0.027

of 70 km, has an average width of 11 km with a maximum of 20 km in its middle sector and covers an area of approximately 856 km² (Fig. 2A). The flow presents a wide coverage of sandy sediments on the roof, which only highlight the inflated structures. These local inflation landforms reach variable heights of between 3 and 8 m with respect to the adjacent terrain. For those sectors of the flow that show large-scale inflation (areas greater than 3 km²) an average thickness of up to 5 m was determined. An estimation of the volume of lava for this flow yielded a minimum value of 4 km³.

Initially, the EPLF advanced as a single front over a lavic substrate conformed in the northern sector by the southern margin of the Pampa de Los Carrizales lava flow (Pasquarè *et al.*, 2008; Bernardi, 2016) and in the central and southern sectors by the Llano del Tapa and Pampa de Ranquelcò lava flows (Bernardi, 2016, Fig. 2A). At 12 km to the east of the extrusion site the northern margin of the EPLF shows the first of numerous and successive northeast-trending spills into a wide erosion channel, known as Bardas Bayas depression (Fig. 2A). The northeast margin of this depression partially dissects the lavas of the Pampa de Los Carrizales flow and also exposes Cretaceous-Paleogene calcareous rocks belonging to the Neuquén basin, which are underlying these lavas. The Bardas Bayas depression has a variable width of between 5 and 8 km and extends for about 60 km with a southeast direction, culminating in the La Copelina salt flat. The lava flows that came into the erosive channel gave rise to the formation of a secondary flow, parallel to the main body, which occupied almost all of the depression (northern branch, Fig. 2A). This branch has a length of 46 km and widths varying between 1.5 and 5 km.

The EPLF has an elongated morphology with irregular margins and numerous kipukas, which lead to infer a substrate with topographic irregularities. This last aspect could be the result of the presence of inflation structures in the substrate, as observed in the exposed sectors of the lava flows that underlies and borders the EPLF.

The highest elevation in the area of the Morado volcano (site EP1) has an altitude of 960 m a.s.l., while the lowest elevation of the emplacement area of the EPLF corresponds to La Copelina salt flat with an altitude of 550 m a.s.l. (section A-A', Fig. 2B).

3.3. Morphology and structure

The cross-sections of outcrops of the EPLF show the typical features of a P-type pahoehoe flow (Wilmoth and Walker, 1993) with two external vesicular sectors surrounding a massive core, in which vesicular segregation structures with cylindrical and tabular geometries were observed (Bernardi *et al.*, 2016, 2018). Notwithstanding, the most important structural aspects observed in the EPLF are those which were originated mainly by local accumulations of lava. A modal counting of inflation structures was carried out on the base of satellite images (Google Earth) in which three areas of between 40 and 60 km² located in the proximal, medium and distal portions of the flow were delimited. Out of a total of 3,000 quantified points, it was determined that between 81 and 85% of the inflation structures corresponds to tumuli (Figs. 3A and 3B) and lava-rise ridges (elongated tumuli) and between 15 and 19% corresponds to flat roof lava rises (Figs. 3C and 3D). These latter type of structures usually present internal holes called lava-rise pits (Figs. 3E and 3F) corresponding to sectors of the structure that remained without inflation. Other types of observed structures are those related to the displacement and the internal interactions of the flow and between the flow and the relief of the substrate. Those landforms comprise pressure ridges and kipukas.

Tumuli appear isolated and frequently grouped and associated with flat roof lava rises and lava-rise ridges in highly-concentrated inflation structures zones. The most common morphologies of the tumuli are lenticular and ovoid, and their longitudinal axes are normally straight but often show a slight curvature. Axial and radial fractures are a common feature of the tumuli; they are known as inflation cleft and exhibit "Y" patterns (Figs. 4 and 5A). These domed structures have average lengths of between 30 and 50 m, with some individuals with lengths up to 80 m, widths between 10 and 20 m and heights between 2 and 5 m. External edges exhibit dips ranging from 35° to 45°. Tumuli exhibit an external crust with extensive polygonal joints (Fig. 5B). The inflation clefts are then formed following the planes of weakness resulting from this fracturing by cooling of the rigid outer crust.

The internal walls of the axial inflation clefts show slightly more closed dip angles, varying between 45° and 70° (Fig. 5C). The widths of the

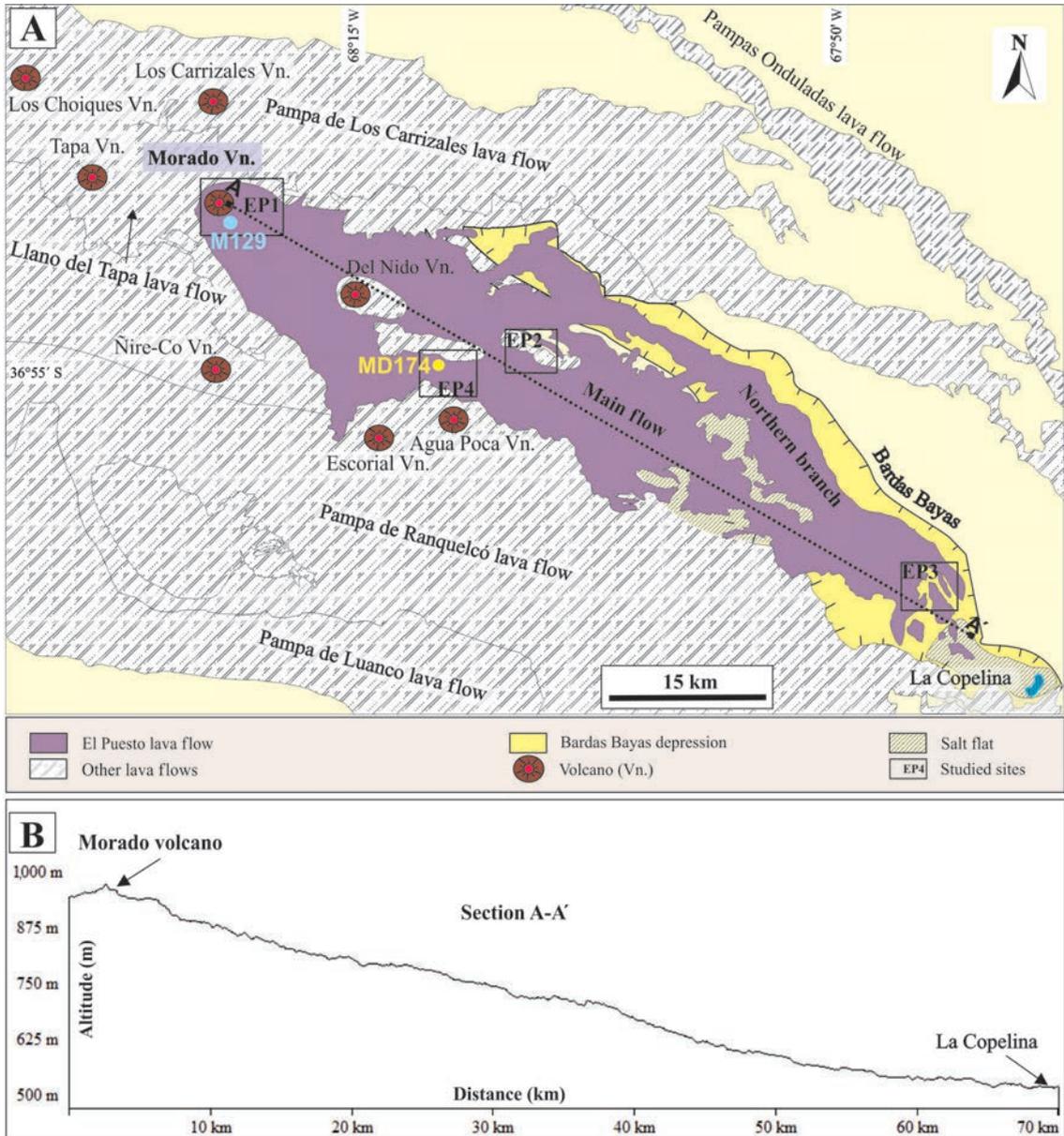


FIG. 2. El Puesto lava flow. **A**. Detailed map of the EPLF indicating the field relationship with other lava flows, the eruptive center (Morado volcano) location and the trace of the A-A' longitudinal section. Also indicated are the nearby volcanoes and the sites studied in the field (EP1, EP2, EP3 and EP4). The dots indicated as MD174 and M129 correspond to the samples of the chemical and K-Ar analysis, respectively; **B**. A-A' longitudinal section of the EPLF.

fractures measured on the roof of the tumuli vary between 2 and 3 m and are partially filled with sandy sediments and dense vegetation. The depths that were determined in some inflation clefts with scarce sedimentary filling reach half the thickness of the structure. Frequently, these fractures exhibit

injections of massive lava occupying almost all the fracture (Fig. 5D) or localized squeeze-ups coming from the liquid core of the tumuli (Fig. 5E). These features lead to infer that the propagation of the fracture occurred concomitantly with the formation of the rigid outer crust and the inflation of the

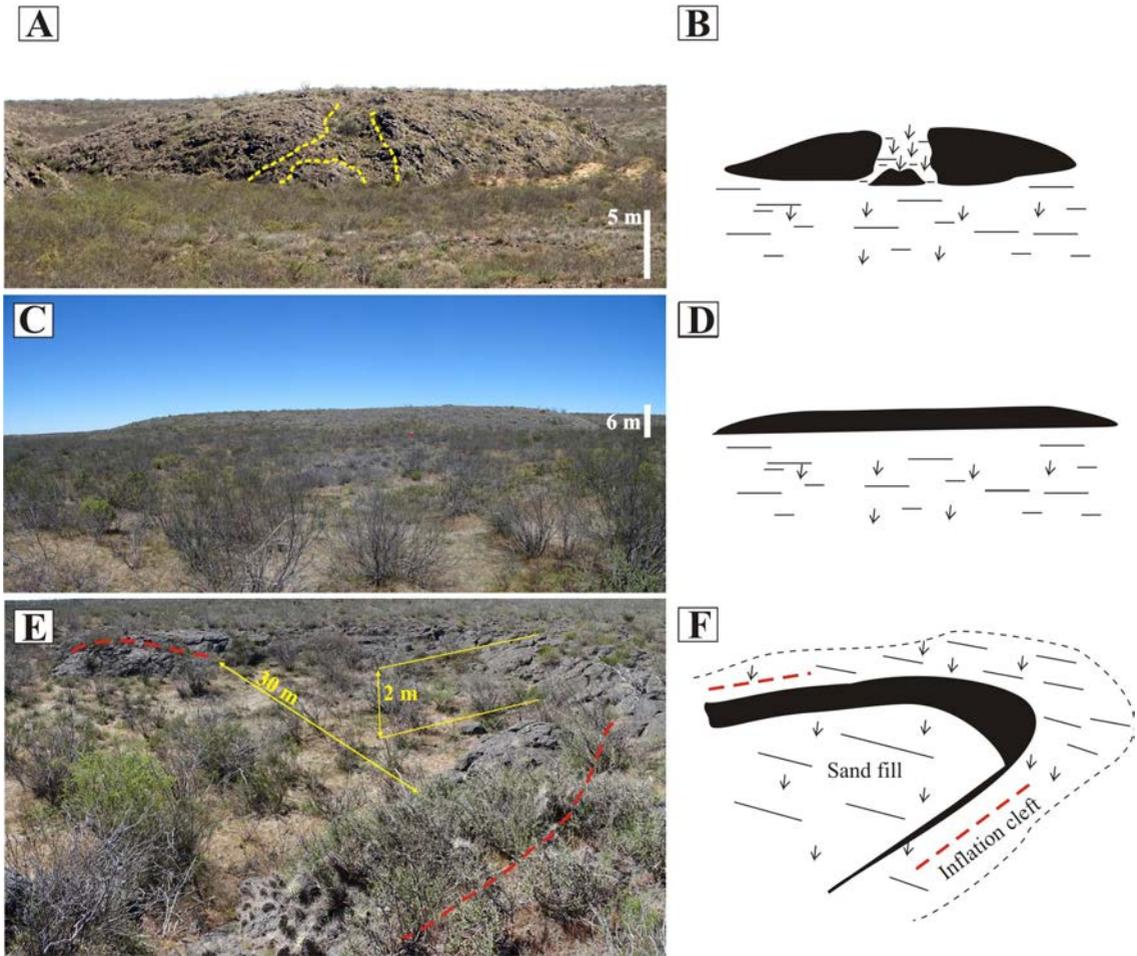


FIG. 3. Inflation structures observed in El Puesto lava flow at site EP3. **A.** Giant tumulus with radial Y-shaped inflation cleft (in red); **B.** Sketch of figure A; **C.** Flat roof lava rise; **D.** Sketch of figure C; **E.** Lava-rise pit located on the edge of a flat roof lava rise; **F.** Sketch of figure E. The red dashed lines indicate some segments of the inflation clefts that surround the depressed structure. These fractures were filled with sandy sediments.

tumuli. This latter aspect is also observed in the first centimeters of the cleft walls, as secondary radial vertical to subvertical fractures, with planes that present perpendicular disposal with respect to the inflation cleft trace (Fig 5F). In several of the described tumuli it was observed that the internal structure of the walls of the inflation fractures presents high density vesiculation with diameters of up to 1 cm in the upper sectors, whereas towards the core of the structure the vesiculation is reduced to less than 25% and the sizes of the vesicles become greater.

Flat roof lava rises are the second type of dominant inflation structure in the EPLF, and they exhibit dimensions of up to 6 times the average of

those of the tumuli. Generally, they present sizes of between 150 and 350 m length although some isolated cases of kilometric scale were observed, such as the great elliptical elevation of figure 6A which exhibits a diameter of 1.5 km in its major axis. The morphologies of the lava rises are irregular, with rounded and engulfed margins, and sub-circular geometries rarely appear. The heights with respect to the adjacent terrain vary between 2 and 8 m. Flat roof lava rises formed in the same way as tumuli with the exception that the inflation process covered a larger area, and the swelling was uniform in the entire internal perimeter of the structure. Because of this, they do not exhibit the typical axial inflation

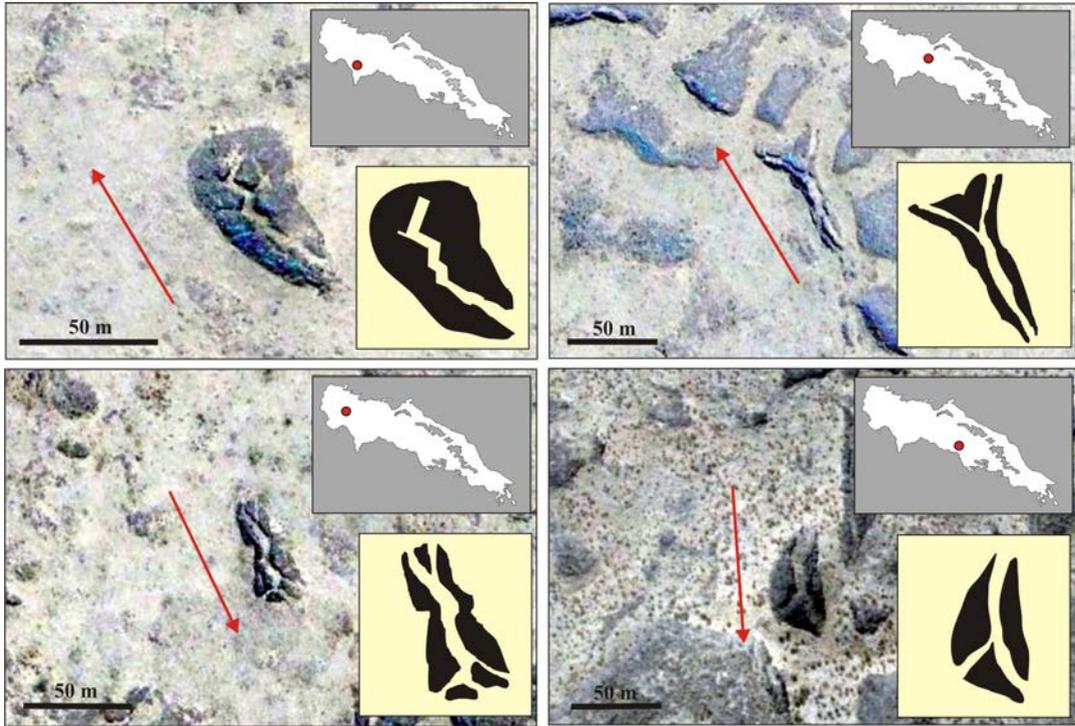


FIG. 4. Satellite images of some typical tumuli observed in El Puesto lava flow displaying different geometries and axial inflation cleft patterns. Red arrows indicate the sense of flow advance, upper inset in each image shows image location in the outline of the El Puesto lava flow (red dot), lower inset shows the sketch of the structure (Google Earth images).

cleft of tumuli, but instead exhibit a sub-vertical annular fracturing that affects the entire perimeter of the structure. Sometimes, flat roof elevations present deflation processes throughout the central sector, maintaining elevated margins and giving rise to a bucket bordered by the perimeter fracture and filled with sandy sediments (Figs. 6B and 6C). This process occurs when the lava exerting pressure under the cooled crust of the elevation is drained away. It is common for flat roof lava rises to be linked by lava-rise ridges, known in these cases as apophyses (Fig. 6D). Lava-rise pits are non-inflated structures that are present as holes in the surfaces of the flat roof lava rises, with sub-circular geometries, diameters varying between 30 and 100 m and depths of up to 2 m (see Figs. 3E and 3F). They form as the result of the inflation of the adjacent sectors into a rapidly cooled thin sector of the flow. They are partially filled with sandy material and frequently show an annular fracture at the rims of the hole, similar to the perimeter inflation cleft of the flat roof lava rise that contains the lava-rise pits (Fig. 6D).

Lava-rise ridges were defined by Whitehead and Stephenson (1998) as tumuli with a length/width ratio >10 . The axial ratios determined in the inflation ridges of the EPLF show values between 12 and 15, with some ratios being out of that range (up to 28). The average length of the ridges varies between 120 and 250 m, the average width varies between 10 and 20 m and some isolated cases have shown extreme lengths of about 600 m. Frequently, the longitudinal axes are curved (Fig. 6E) and in rare cases they present straight formats. As in the tumuli, the axial inflation clefts exhibit similar “Y” patterns that affect the total length of the structures, without being conditioned by the remarkable lengths they present. Usually, they are observed as isolated, although as with the tumuli, they can be exhibited in small clusters of parallel individuals (Fig. 6F).

Another type of structure that was generated by the mechanism of inflation and is possibly linked to the great longitudinal development that presents this flow corresponds to lava tubes. Depending on their size they can be differentiated into major or

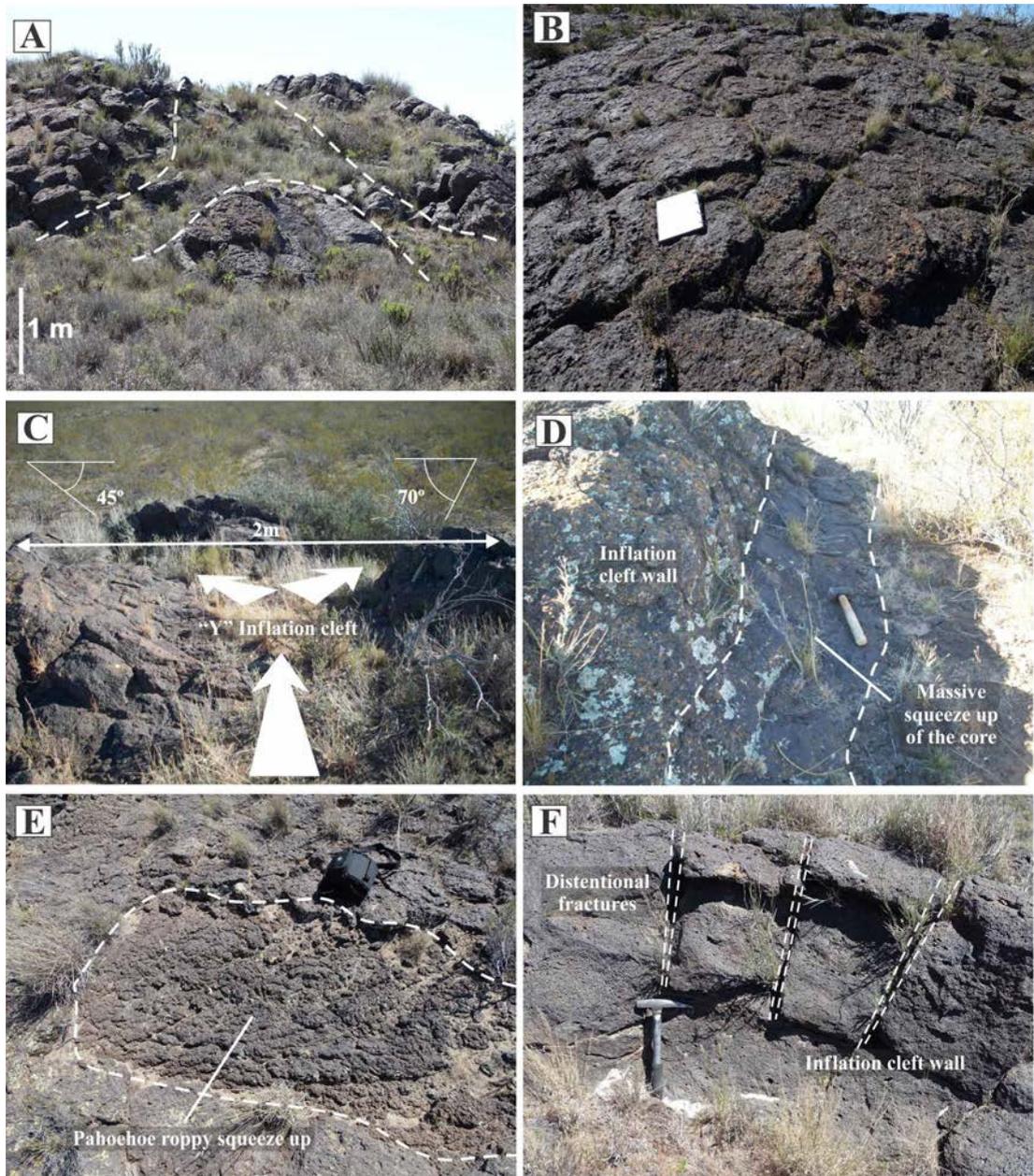


FIG. 5. Inflation structures located in the distal sector of the EPLF (site EP3 in Fig. 2). **A.** Tip of a tumulus crossed by a Y-shaped inflation cleft. **B.** External crust of a tumulus affected by polygonal joints; **C.** Typical Y-shaped geometry of an inflation cleft; **D.** Massive lava dike-like squeezed-up, injected into the inflation cleft. This occurs when the inflation fracture reaches up to the liquid core of the structure during the inflation process; **E.** Pahoehoe squeeze-up with roppy flow structure located in the roof of a tumulus; **F.** Fracture pattern of an inflation cleft wall as a consequence of the distention forces that were concentrated in upper sectors of the structure during the inflation process.

master tubes, secondary tubes and capillary tubes. The larger structures that feed the distal fronts of the lava flow are constructed from the convergence of

networks of secondary tubes that formed during the cooling of the proximal sectors of the flow. Some of the lava tubes of the EPLF were inferred through

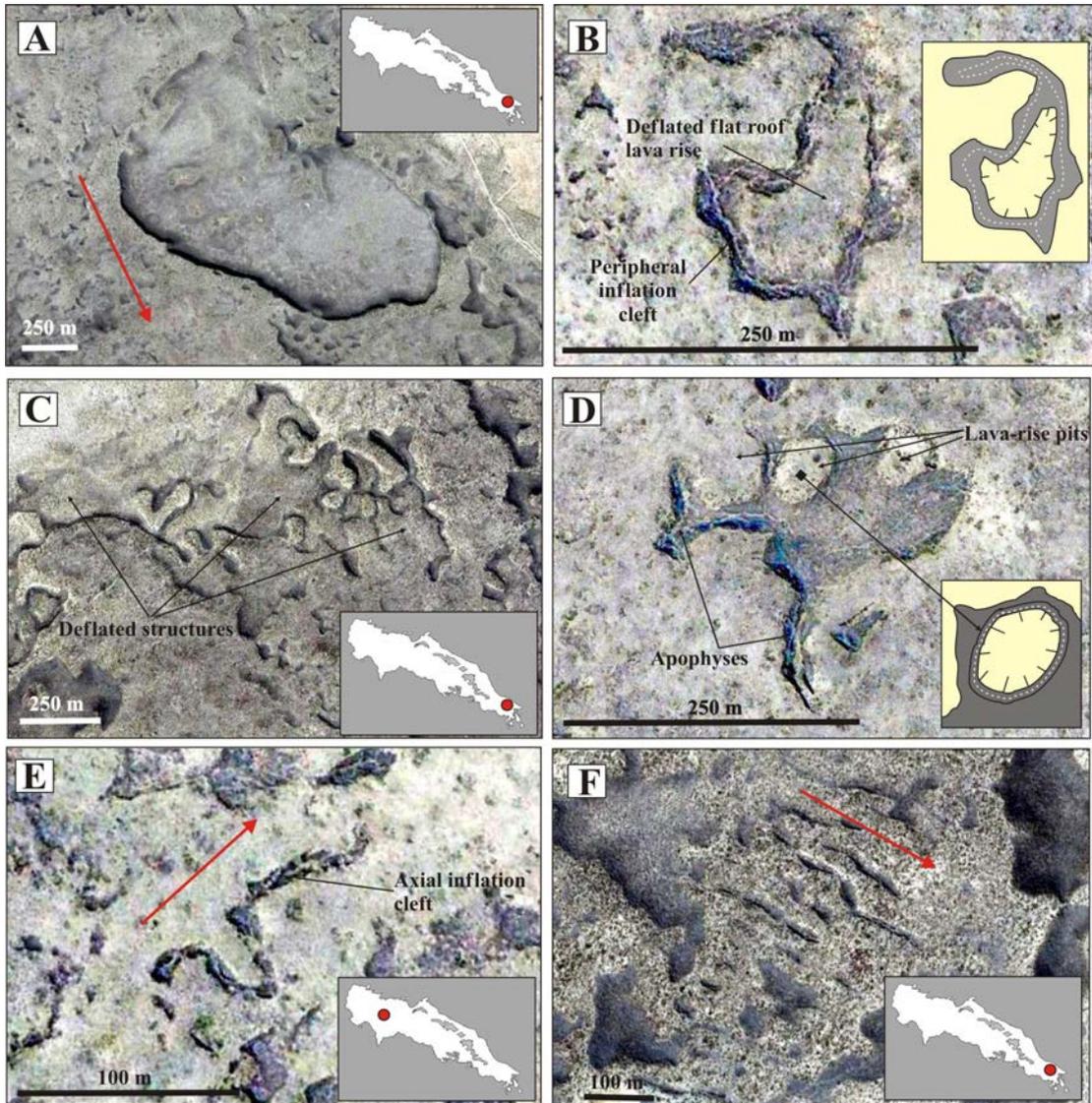


FIG. 6. Satellite imagery (Google Earth) of inflation structures located in the distal sector of the EPLF (site EP3), red dot in the inset indicates the image location in EPLF. The red arrows indicate the flow direction. **A.** Giant flat roof elevation which exhibits an elliptical geometry in aerial view. It exceeds 1500 m in length and has heights greater than 10 m with respect to the surrounding flow. It is the biggest lava rise that was surveyed in this flow; **B.** and **C.** Flat roof lava rises with deflation in its central sector. In figure B the peripheral inflation cleft that is generated in the structure rims during inflation is clearly observed; **D.** Lava-rise pits of sub-circular geometry, filled by sandy sediments and with annular fractures at their rims. The inflation ridges that take off the lava rise are known as apophyses and frequently link two or more of the lava rises; **E.** Markedly curved inflation ridge with axial inflation cleft; **F.** Cluster of inflation ridges and tumuli with parallel arrangement.

the processing of satellite images via morphological evidence on the flow roof. Others were observed during the fieldwork as in the case of the lava tunnel known as “Cueva de Halada”. It is a fully drained master tube located at $36^{\circ}57'S$ and $68^{\circ}05'W$, in the

medial sector of the EPLF (Fig. 7A). Morphologically, it comprises a main gallery of arched roof that branches into three secondary galleries of shorter length. The total length of the tunnel is 369.50 m, the maximum height is 2.20 m and the maximum

width is 22.90 m (Figs. 7A and 7B) (Bertotto, 1996; Martínez, 1998). The entry of the cave is a small skylight of 0.60 m in diameter. The basalt that forms the tunnel roof shows a vesicular structure (amygdaloidal) that becomes more massive towards

the walls (Fig. 7C). The inner roof of the tunnel may have an irregular structure (Fig. 7D) or is smooth with polygonal joints. It is covered by patches and small stalactites of carbonates (Fig. 7E) and in some sections it exhibits lava drops of up to 2 cm.

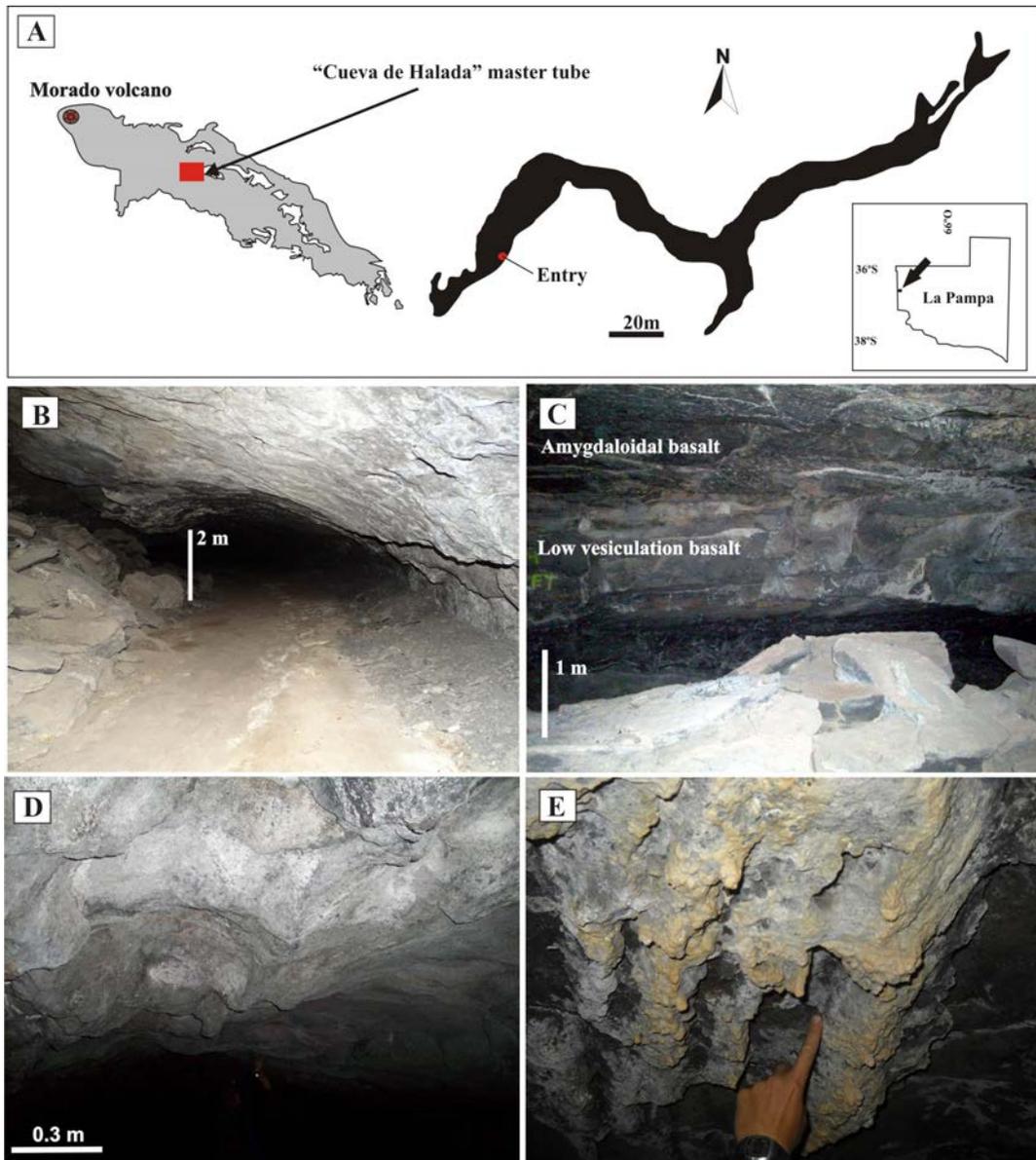


FIG. 7. Master lava tunnel “Cueva de Halada”. Internal structure. **A**. Location of the “Cueva de Halada” in the EPLF (site EP2 in Fig. 2). The aerial view morphology and the speleometric data were taken from Bertotto (1996) and Martínez (1998); **B**. Cross-section of the tunnel sector below the access opening. This section presents the largest width of the entire structure and corresponds to the main gallery; **C**. Structure of walls and roof; **D**. Roof with irregular structure; **E**. Stalactites of the calcareous material that cover some section of the tunnel roof.

According to the classification suggested by Calvari and Pinkerton (1999), based on the morphology of the lava tunnels, the “Cueva de Halada” tunnel exhibits characteristics of a simple and symmetrical tunnel, formed from the crust cooling around a stable and inflated flow. The detailed morphometric surveys carried out in the “Cueva de Halada” (Bertotto, 1996; Martínez, 1998) revealed that there are two sectors in which there are changes by up to 90° in the general direction of the trajectory of the master gallery (Fig. 7E). The shape of the cross-section of the tunnel at several points shows certain asymmetry. This is interpreted as the result of differential lava accumulation due to local changes in the direction of the main path of the tunnel.

Another type of lava tube was observed in an area of inflation structures located about 27 km southeast of the “Cueva de Halada”, in the distal sector of the EPLF (site EP3 in Fig. 2A). These are capillary tubes that display a centimetric scale and cross over the tumuli in which they are hosted (Fig. 8A and sketches). These features show cross-sections of about 0.5 m in width and up to 0.25 m in height (~0.4 m²) with a morphology that is characterized by an arched roof and slightly flat floor. The peripheral basalt surrounding the tubes shows a vesicular structure and frequently presents radial fractures that converge towards the center of the tunnel. Small-scale lava tubes were also found in a field of inflation structures located near the Morado volcano, hosted by pahoehoe fingers (Fig. 8B and sketches).

Other morphology aspects that reveal the existence of lava tubes inside the flow include: tumuli alignments, the development of extremely long inflation ridges (Fig. 9A) and the apophyses that join and feed flat roof lava rises. It is interpreted that the presence of these structures indicates that tubes were not drainage tubes, keeping filled with the flow that moved inside as a consequence of collapse or blocking of a segment of the tunnel. Large-scale channel-like reliefs observed in some sectors of the flow surface were interpreted as drainage master tubes where roof has collapsed (Fig. 9B).

The kipukas and pressure ridges are not related to the inflation process. The kipukas are the product of the presence of positive substrate relief that hindered the flow path. The wind activity eroded the substrate rocks and generated a depressed relief that constitute small endorheic drainage depressions.

Shallow ephemeral water courses or springs flow to these depressions and can form salt flats (Fig. 10A). The pressure ridges are long and narrow individual features that result from lateral pressures within the flow. The best example of a pressure ridge was observed in the distal sector of the EPLF, where the main flow comes into the depression of Bardas Bayas and joins with the secondary northern branch, colliding with it. In this area, the pressure between both flows generated a ridge of 12.6 km in length and up to 100 m in width, with variable heights of between 2 and 4 m (Fig. 10B).

3.4. Petrology features

As mentioned above, El Puesto lava flow mainly advanced over a basaltic lava substrate while the northern branch that circulated through the Bardas Bayas depression, mobilized over Cretaceous-Paleogene calcareous rocks. In general terms, the basalt samples collected from the EPLF presents porphyritic to glomeruloporphiritic texture with intergranular groundmass. The phenocrystalline fraction is represented by olivine and plagioclase. Olivine exhibits mostly euhedral to subhedral individuals showing prisms or short columns with hexagonal to pseudo-hexagonal sections, being granular in the microlithic phases. The olivine phenocrysts reach sizes of up to 1 mm, present abundances of 7 to 10 vol.% and they are generally fresh. Plagioclase occurs in crystals with uniform sizes averaging 0.6 mm. It is observed in groups oriented in oblique directions to each other, resulting in a felted microtexture. In general, plagioclase exhibits subhedral grains with polysynthetic twins and constitutes the more abundant mineral phase (~60-80 vol.%). Occasionally, it shows tabular individuals up to 1 mm, with screened textures. Clinopyroxene is mostly microlithic and interstitial, and abounds in approx. 10 vol.%, surpassing the olivine at this scale. It is anhedral (granular) and in few cases it reaches sizes of up to 0.5 mm. The opaque minerals do not exceed 2 vol.% in abundance, occupying the interstices with olivine and clinopyroxene and generally exhibiting anhedral (granular) to subhedral (prismatic) forms.

In table 2 is presented the major elements composition of an alkaline basalt of EPLF (MD174, lat/long: 36°58'S/68°8'W, Fig 2A). The viscosity of EPLF has been calculated from major elements composition, using the algorithm of Shaw (1972) at

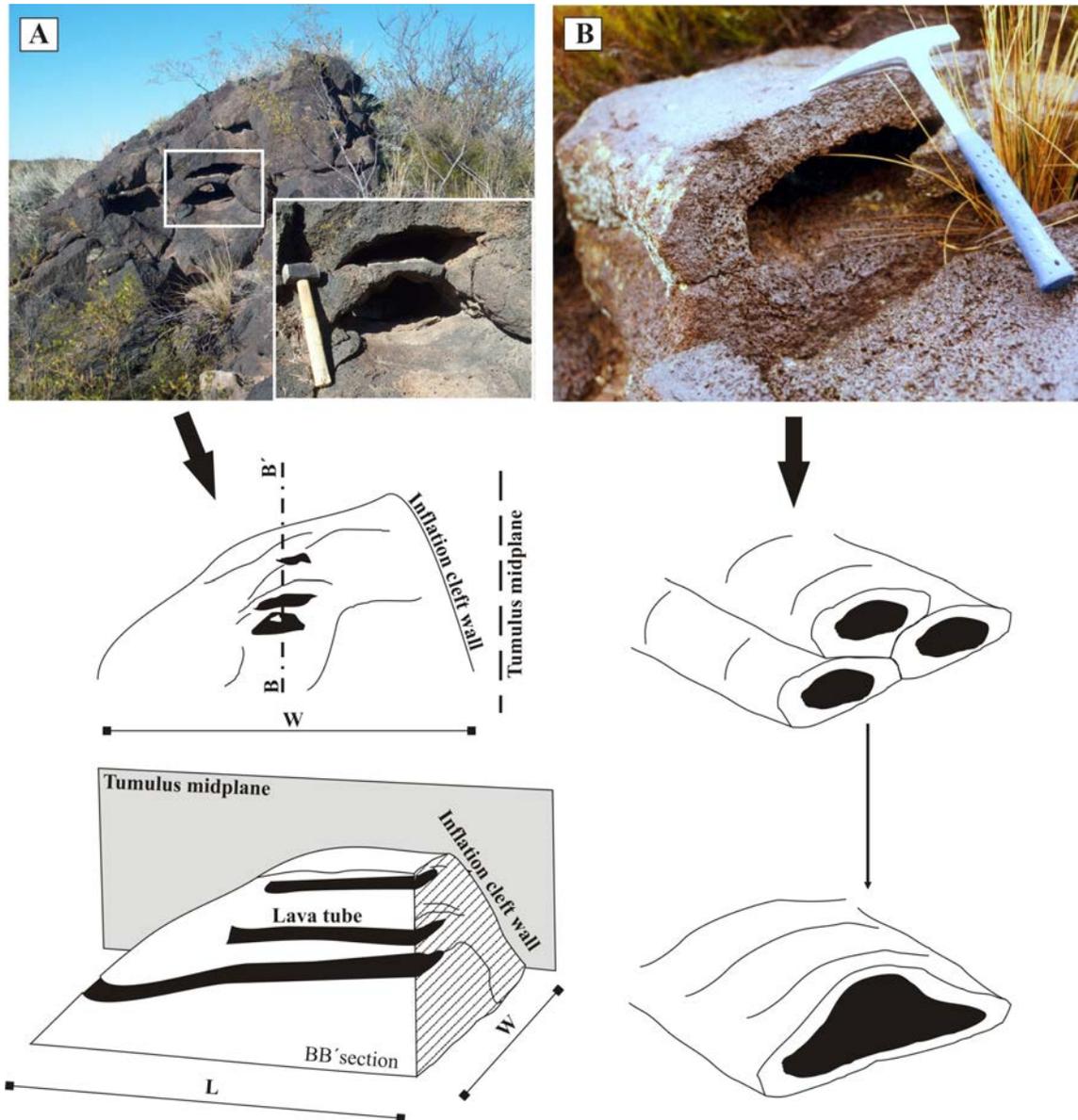


FIG. 8. Inflation structures. **A.** Centimeter-scale lava tubes extending longitudinally through the body of a tumulus located in a field of inflation structures in the distal portion of the EPLF; **B.** Capillary lava tube hosted in pahoehoe finger, near the eruptive center. The diagram shows a stacking of pahoehoe fingers with development of capillary tubes which can evolve into secondary tunnels and then to master tunnels by eliminating the partitions that separate them, due to the erosion of the flow that circulates inside (Wentworth and Macdonald, 1953; Greeley, 1987).

1,100 and 1,200 °C, assuming voids-free magma and taking into account an average volume of phenocrysts of 8% with average size of 0.5 mm. For this lava flow, values for effective viscosity (η') were obtained in the range between 1,550 and 483 Pa s, whereas values for lava glass viscosity (η) were obtained

in the range between 28 and 8.7 Pa s. For basaltic melts ($\text{SiO}_2=49\text{-}51$ wt.%), with liquid temperatures ranging between 1,050 and 1,200 °C and phenocrysts volume between 0 and 25%, the viscosity has been estimated to range from 10 to 10^3 Pa s (Scarfe, 1973) and from 10^2 to 10^3 Pa s (Keszthelyi and

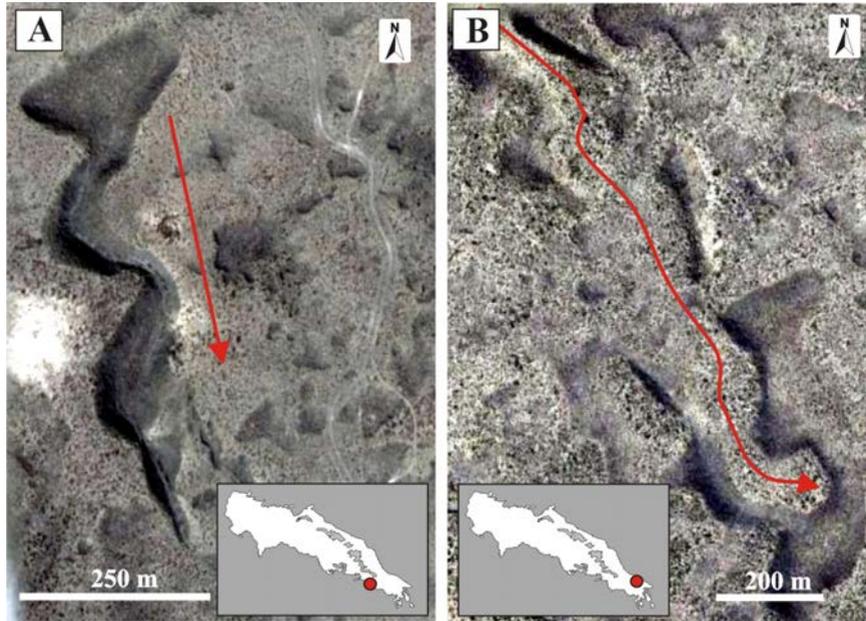


FIG. 9. Satellite imagery (Google Earth) showing two different structures from which the presence of lava tunnels of important dimensions is inferred. **A.** Sinuous and extremely long inflation ridge (670 m); **B.** Large-scale channel-like relief interpreted as a drainage master tunnel which roof has collapsed. This relief extends several hundred meters towards the northwest. The local direction of the flows movement is indicated with red arrows and the images location is shown by the red dots in the EPLF.

TABLE 2. MAJOR ELEMENTS DATA AND NORMATIVE MINERALS OF MD 174 SAMPLE FROM THE EL PUESTO LAVA FLOW.

Sample	MD174
SiO ₂	47.64
TiO ₂	1.66
Al ₂ O ₃	14.24
Fe ₂ O ₃	12.85
MnO	0.15
MgO	10.60
CaO	8.49
Na ₂ O	3.23
K ₂ O	0.64
P ₂ O ₅	0.29
Total (wt%)	99.78
Normative minerals	
Or	3.78
Ab	27.01
An	22.5
Ne	0.21
Di	14.44
Ol	24.52
Mt	3.76
Il	3.16
Ap	0.63

Analyzed at Università di Modena e Reggio Emilia (Italy), XRF method as Franzini *et al.* (1975).

Pieri, 1993; Crisp *et al.*, 1994; Thordarson, 1995; Ho and Cashman, 1997). Effective viscosity values of EPLF could be considered inside the range of basalt melt viscosities, but glass viscosities show very low values with respect to the values obtained experimentally.

4. Discussion

The EPLF comprises a lava flow formed by a single flow unit that reached thicknesses of up to 5 m, subsequently developing local inflation structures with similar thicknesses. The lava flow moved southeast over a substrate with a slope of up to 0.5°, in which it encountered some previous obstacles, such as small pyroclastic cones in its lower half section and other positive reliefs, which generated kipukas. A segment of the northern sector was channeled in the depression of Bardas Bayas while the main body had no relief confinement, which is evidenced by some secondary spills to the south and into the mentioned depression. The development of a P-type pahoehoe flow is commonly associated to the following aspects: **1.** Low-angle slopes (<2°), that allow slow and discontinuous displacements

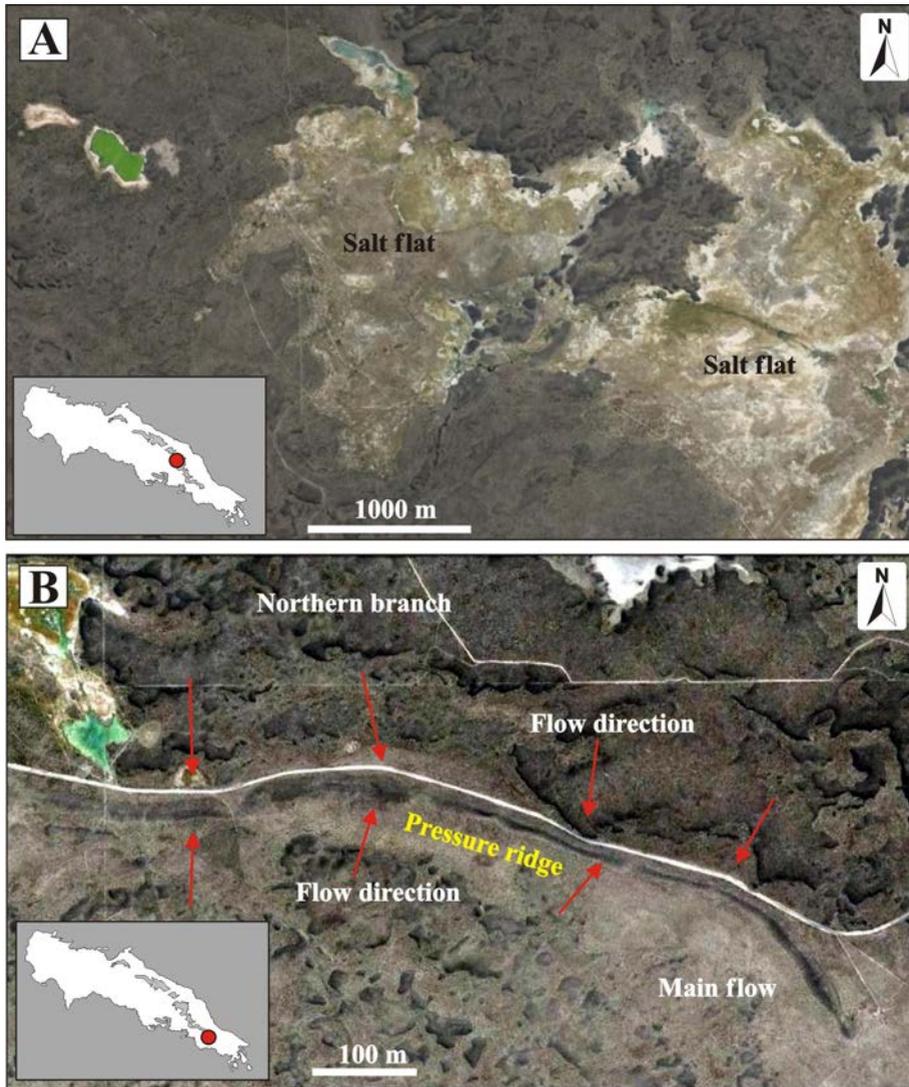


FIG. 10. Other landforms originated during the emplacement of the El Puerto lava flow. **A.** Salt flats installed in depressed reliefs developed inside the kipukas; **B.** Pressure ridge generated by the collision between the main body of the flow and the northern branch, in their distal portions. The structure was formed by lateral compression and not by inflation. The local directions of movement of the flows are indicated with red arrows. Red dots in the insets show the image location in the EPLF.

through the generation and lateral coalescence of lobes in the front of the flow, 2. thermal insulation of the inner liquid core of the lobes by development of an external cooling crust, 3. development of capillary, secondary and master tubes through which the lava flows to the distal sectors, and 4. inflation process with development of localized structures. The inflation rates and the local or regional extension of this process were conditioned mainly by the lava supply of the source (Hon *et al.*, 1994; Self *et al.*,

1998). The landforms which developed during the inflation are distributed throughout the surface of the flow and frequently they are observed forming belts with a high concentration of structures that seem to converge to a single main belt (Figs. 11A and 11B). These features were interpreted as internal preferential lava pathways (secondary tubes) within the main lava body. Inflation structures generally have their longitudinal axes disposed according to the belt direction.

In the distal sectors of the flow, some landforms such as flat roof lava rises and lava-rise ridges exhibit better development, while the tumuli show clusters of 15, 20 or more individuals. It is inferred that this aspect may be a consequence of the abrupt slope change observed in the last 20 km of the flow, where it reduces from 0.5° to 0.15° in the main lava flow and from 0.35° to 0.11° in the northern branch of Bardas Bayas. In addition, the height difference between the eruptive center and the terminal portion of the flow exceeds 400 m which possibly maintained an increasing overpressure towards the terminal portions of the flow, enough to keep a sustained inflation process in these sectors (Rossi, 1996; Rossi and Gudmunsson, 1996).

From their morphological characteristics, the described tumuli of the EPLF (see Section 3.3) are

classified within the flow-lobe tumuli category as proposed by Rossi and Gudmundsson (1996) from their survey of numerous inflation structures in Icelandic lava fields. According to their observations, flow lobe tumuli are common in the middle and distal sectors of the pahoehoe lava fields. They have low dip flanks and exhibit small volume squeeze ups that are restricted to the limits of the axial fracture. The internal distribution of vesicles is similar to that of P-type flows. For its formation, low rates of lava supply from the source are necessary, which allows a better development of the external crust to be able to hold up the incoming lava without fracturing for a longer period of time. These authors noted that the flow-lobe tumuli described in these lava flows are practically absent in those sectors where master lava tubes are located. In the flow of the present

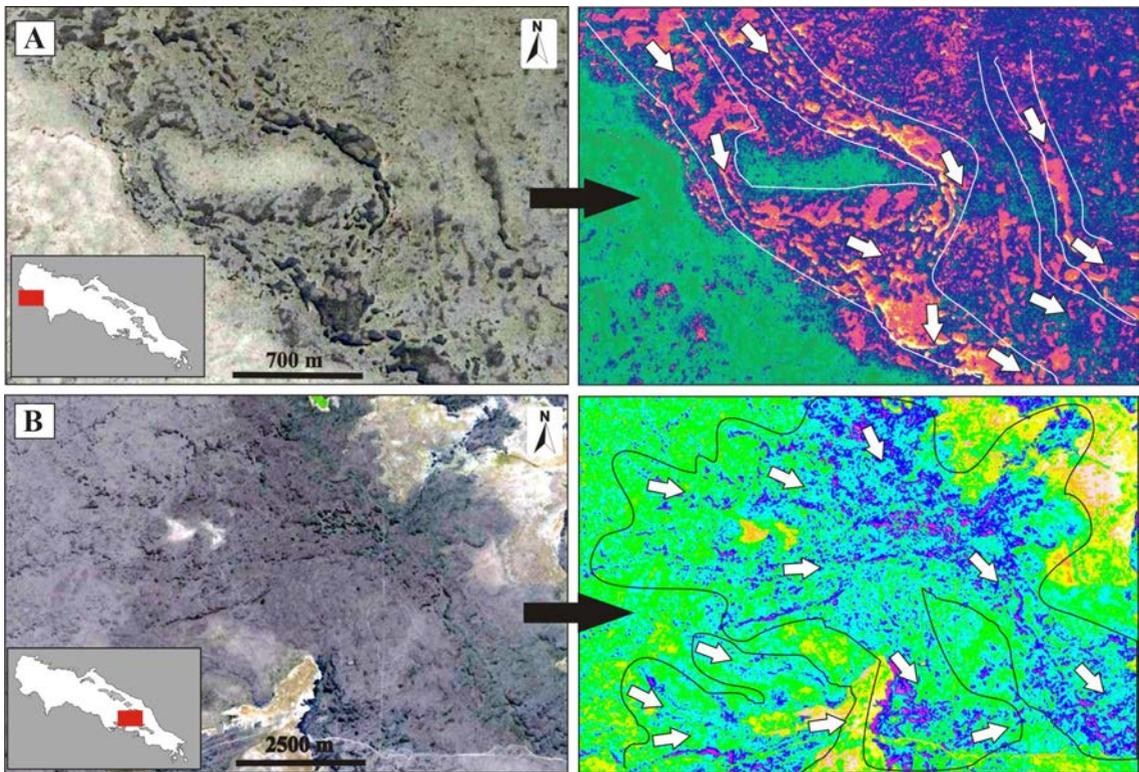


FIG. 11. Satellite imagery (Google Earth) processed with image processing software in which are highlighted the belts with high concentration of inflation structures within the flow. The first image **A**, corresponds to the lower-half section of the EPLF; the magenta and yellow colors represent the inflated structures. The second image **B**, belongs to the distal portion of the flow; the blue and violet colors represent the inflated structures while the green color corresponds to the flow sectors without processes of local inflation. In both, the convergence of smaller belts into one belt of greater development is observed. Red squares in the insets indicate the image location in the EPLF.

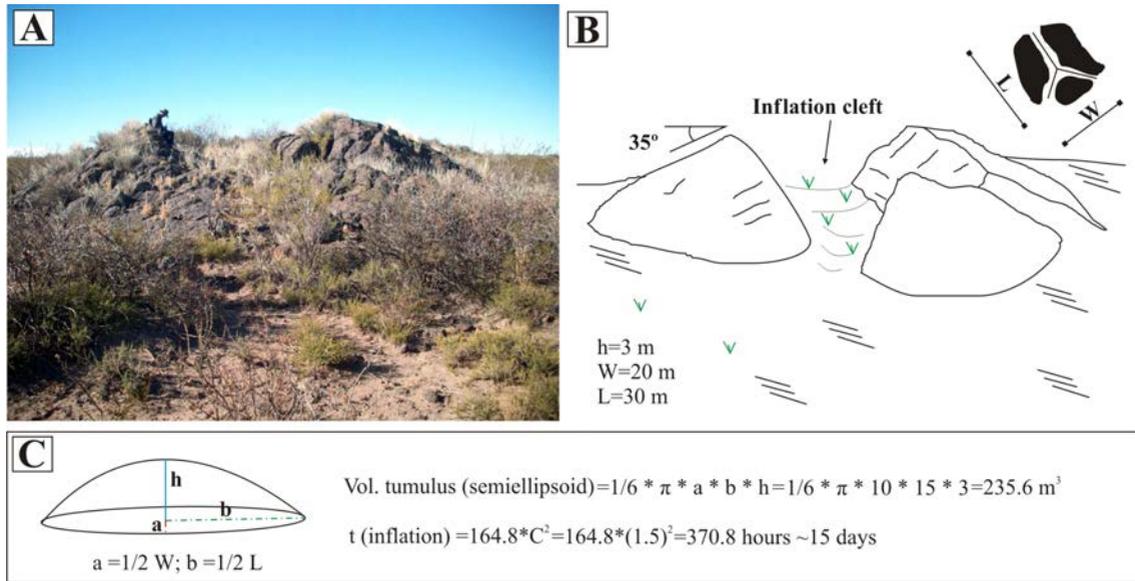


FIG. 12. Volume and time of inflation calculus of a typical tumulus of El Puesto lava flow. **A.** Field image of the parameterized structure; **B.** Measured parameters of the tumulus; **C.** The volume of the tumulus was determined by approximating its geometric shape to that of a semi-ellipsoid. The inflation time (t) is calculated according with the algorithm of Hon *et al.* (1994).

study this situation is fulfilled in the sectors nearby the “Cueva de Halada” lava tube and for the sites where landforms were observed and interpreted as drained and collapsed tunnels.

We have made an estimation of the rate of the lava supply required to inflate an average tumulus of the EPLF located in a distal position (site EP3, Fig 2A). The algorithm of Hon *et al.* (1994), which was modeled in Hawaiian lava flows for the estimation of the time of inflation, was used. The measured structure has a length of 30 m (L), a height of 3 m (h) and a basal width of approximately 20 m (W) (Figs. 12A and 12B). The thickness of its upper vesicular crust is 1.5 m (C) and was measured vertically in the wall of the axial fracture. For the calculation of the volume of the structure, its geometry was approximated to the geometry of a semi-ellipsoid (Fig. 12C).

Assuming a sustained effusion of lava and a uniform daily inflation rate, the value of the lava supply rate for this average tumulus was $1.8 \times 10^{-4} \text{ m}^3/\text{s}$ during 15 days. These values are consistent with those obtained from Icelandic lava fields by Rossi and Gudmunsson (1996), who noted that flow-lobe tumuli formed in those fields under very low effusion rates of between 10^{-2} and $10^{-5} \text{ m}^3/\text{s}$ in a time range of between 4 and 21 days.

The high density of inflation structures resulted in a hummocky flow throughout the EPLF area. The formation process of these structures, including the lava tunnels, through which they are fed, requires low to moderate effusion rates for their development (Hallworth *et al.*, 1987; Rossi and Gudmunsson, 1996). From this last concept, the structural characteristics of the flow and its remarkable length (70 km) show a continuous and sustained supply of lava over a very long time period. The flow could be high at first, giving rise to the formation of a sheet flow of great lateral extension. Subsequently, fluctuations in effusion rates could favor the development of internal pathways (tubes) that delivered lava to the distal fronts, generating both inflation and deflation processes which extended throughout the lava flow.

5. Conclusions

The El Puesto lava flow is a single basaltic flow of $0.200 \pm 0.027 \text{ Ma}$ located in the southern-central Payenia Volcanic Province which was extruded from the Morado volcano.

The lava flow presents a longitudinal development of 70 km and a coverage area of 856 km^2 . A minimum volume of 4 km^3 of lava was estimated for this flow.

The tumuli represent up to 85% of the structures originated by local accumulations of lava and to a lesser extent appear inflation ridges and flat roof lava rises. The tumuli of the EPLF classify in the category of flow-lobe tumuli. Lava-rise pits are frequently observed in flat-roof lava rises and represent sectors of these structures that remained uninflated. Axial Y-shaped fractures and annular clefts are the common feature of all inflation structures and are formed by localized distension associated with the inflation process.

The slope on which the EPLF moved was up to 0.5° SE which allowed slow displacements and lateral coalescence of lobes at the flow front and the development of an external rigid crust that allowed the thermal insulation of liquid internal core. The heterogeneous cooling of the interior of the lava flow led to the development of lava tubes simultaneously with the lobe inflation process. The “Cueva de Halada” represents a simple and largely symmetrical master tunnel, formed from the cooling of the crust around a stable inflated flow. As it is a drained tunnel, there are no landforms of accumulation linked to it. Tumuli alignments, inflation ridges, and apophyses joining flat roof lava rises reveal the existence of larger tunnels within the flow, which may have remained filled by the internal flow.

The occurrence of belts with high concentration of inflation structures are interpreted as the result of a network of secondary internal flows within the main lava body.

The major development of flat roof lava rises and inflation ridge in the distal portions of the flow is a consequence of the abrupt slope change in the distal sector and the increasing overpressure towards the terminal portions of the flow, as a consequence of a lava supply sustained over time and the marked elevation difference between the effusion center and the distal portion of the flow (~400 m).

It was inferred that a high, continuous and sustained supply of low viscosity lava initially generated a sheet flow of great lateral extension. The reduction in effusion rates could then favor the development of tubes that carried lava to the distal fronts, generating localized inflation and deflation phenomena throughout the lava flow.

The flow advance through lateral coalescence and lobe inflation with the subsequent formation of lava tubes, and the low to moderate lava viscosity ($\eta=28\text{--}8.7\text{ Pa s}$, $\eta'=1.550\text{--}483\text{ Pa s}$) were the determining

factors in the emplacement of the El Puesto lava flow, which traveled a distance of 70 km from its effusion center.

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