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Emplacement history and inflation evidence of a long basaltic lava flow located in Southern Payenia Volcanic Province, Argentina

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ABSTRACT

The El Corcovo lava flow, from the Huanul shield volcano in the southern Mendoza province (central-western Argentina) traveled a distance of 70 km and covered a minimum area of ~415 km^2. The flow emplacement was controlled both by extrinsic (e.g., topography) and intrinsic (e.g., lava supply rate, lava physicochemical characteristics) factors. The distal portion of the lava flow reached the Colorado River Valley, in La Pampa Province, where it spread and then was confined by earlier river channels. Cross-sections through the flow surveyed at several localities show two vesicular layers surrounding a dense central section, where vesicles are absent or clustered in sheet-shaped and cylindrical-shaped structures. Lavas of the El Corcovo flow are alkaline basalts with low values of viscosity.

The morphological and structural characteristics of the flow and the presence of landforms associated with lava accumulation are the evidence of inflation. This process involved the formation of a tabular sheet flow up to 4 m of thick with a large areal extent in the proximal sectors, while at terminal sectors frontal lobes reached inflation values up to 10 m. The numerous swelling structures present at these portions of the flow suggest the movement of lava in lava tubes. We propose that this aspect and the low viscosity of the lava allowed the flow travel to a great distance on a gentle slope relief.

1. Introduction

Extremely long continental lava flows are exceptional and have captured the attention of volcanologists for decades. Until recently, the development of great lengths of these flows was interpreted as being due to low viscosity, high effusion rates and a rapid emplacement (e.g., Walker, 1967, 1973; Shaw and Swanson, 1970). Recent researches carried out on active and historic lava flows from Hawaii have changed this traditional view of the process (e.g., Greeley, 1987; Walker, 1989, 1991; Wilmoth and Walker, 1993; Cashman et al., 1994, 1998; Hon et al., 1994; Keszthelyi, 1994, 1995; Pinkerton and Wilson, 1994; Helz et al., 1995; Trusdell, 1995; Keszthelyi and Denlinger, 1996; Cashman and Kauahikaua, 1997; Self et al., 1998; Riker et al., 2009). Particularly, Hon et al. (1994) proposed an emplacement mechanism for moderate volume effusions (0.1–10 km^3) known as "inflation". This process initiates with a thin lava sheet, not exceeding 0.5 m in thickness, termed "sheet flow" (Ballard et al., 1979) that becomes thicker in response to the continuous addition of lava under an external chilled crust that wraps the flow. The tensile strength that affects the external brittle crust leads to fractures through which lava escapes, generating new flow lobes. Inflation mechanism involves the formation of lava tubes which offer an efficient thermal delivery to the lava because of their lower cooling gradient (≈0.5 °C/km) (Greeley, 1987; Pinkerton and Wilson, 1994; Keszthely, 1995; Sakimoto et al., 1997; Cashman et al., 1998; Keszthelyi and Self, 1998; Sakimoto and Zuber, 1998).

The inflation process is evidenced from internal and external structural features, among which the most common are: tumuli, lava rises, lava rise ridges, lava-rise pits, lava-inflation clefts, squeeze ups (Walker, 1991; Hon et al., 1994; Whitehead and Stephenson, 1998) and typical flow profiles showing interspersed massive and vesicular layers (Aubele et al., 1988; McMillan et al., 1989; Manga, 1996; Cashman and Kauahikaua, 1997; Self et al., 1997, 1998). These aspects are linked to the control of intrinsic and extrinsic factors of volcanic activity such as duration and effusion rates of the eruption, viscosity of the lava and topography of the emplacement area. The inflation process occurs commonly on flat and smooth reliefs (Walker, 1991; Hon et al., 1994).

This paper describes for the first time the rheological, physical and morphological data and the emplacement mechanism of an extensive lava flow, here named El Corcovo, located at the southern Payenia Volcanic Province, central-western Argentina. The El Corcovo lava flow

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extends from 37°16′S to 37°36′S and from 68°32′W to 67°54′W and comprises a single and long pahoehoe flow which erupted from Huanul volcano.

2. Geological setting

The Payenia Volcanic Province (Payenia) (Polanski, 1954) comprises an extensive basaltic plateau, localized at the central-western region of Argentina, which covers the extra-Andean back-arc sector of southern Mendoza, western La Pampa and northern Neuquén provinces. This igneous province lies at a distance about 460 to 540 km east of the Chile Trench, between 33°40′S and 38°S. Recent radiometric data (Cobbold and Rosello, 2003; Kay et al., 2006; Galland et al., 2007; Folguera et al., 2009; Quidelleur et al., 2009; Germa et al., 2010; Gudnason et al., 2012) allowed to register a continuous igneous activity since Miocene to Holocene times, with a gap between the late Miocene and the early Pliocene. During the Miocene, the volcanic activity in this region of the extra-Andean back-arc occurred under a compressive regime, as the result of a flat slab subduction stage of the Nazca plate (Ramos and Folguera, 2005; Ramos and Kay, 2006). From Pliocene to Holocene times, an extensional regime developed as a consequence of a gradual steepening of the plate (Kay et al., 2006; Ramos and Kay, 2006; Gudnason et al., 2012) which produced the migration of the volcanic arc front to the west. This tectonic context led to the asthenospheric ascendance to shallower levels and the generation of a homogeneous volcanism in this region (Bermúdez et al., 1993; James and Sacks, 1999; Inbar and Risso, 2001; Kay et al., 2004, 2005; Ramos and Folguera, 2005).

Payenia comprises the largest Neogene-Quaternary volcanic province of South America and the one with a major concentration of monogenetic cones (more than 800 volcanoes) (Inbar and Risso, 2001; Bertotto et al., 2006a; Risso et al., 2008; Folguera et al., 2009). The constituent rocks are mainly basaltic to andesitic in composition with an intraplate and arc geochemical signature (Kay et al., 2006; Ramos and Kay, 2006). 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, Nevado, Llancanelo, Payun Matru, Chachahuen, Auca Mahuida and Tromen (Fig. 1).

The longest known Quaternary lava flow on earth is localized at the central region of Payenia Volcanic Province (Pasquarè et al., 2008). These authors called it "Pampas Onduladas" and described it as an individual basaltic flow which reached a length of 181 km from its source, localized in the Payún Matru Volcanic Field. This volcanic field records the largest volcanic activity of Payenia. The age of the flow is of 373 ± 10 ka as indicated by $^{40}Ar/^{39}Ar$ analysis of Espanon et al. (2014). Pasquarè et al. (2008) proposed an inflation mechanism emplacement for Pampas Onduladas lava flow, inferred from its structural and morphological features.

The study area is located within the southeastern region of Payenia, along the boundary sector of Mendoza and La Pampa provinces. This area is occupied by a small volcanic field, the Río Colorado Volcanic Field (Gudnason et al., 2012) constituted by pahoehoe lava flows mainly arranged in a northwest–southeast direction. The main eruptive center is the Huanul volcano, which comprises a shield edifice with a crater of 4 km in average diameter and 20 m height above the surrounding relief. This volcano is located at 37°17′S and 68°32′W and is composed of volcanic agglomerates and basaltic lava flows containing ultramafic mantle xenoliths (Bertotto, 2002). Based on field observations, Holmberg (1962) suggested a Pleistocene age to formation of Huanul volcano which subsequently was confirmed by Bertotto et al. (2006b) using K-Ar age (0.84 ± 0.05 Ma).

In this area, basaltic units flowed over Cretaceous and Tertiary sedimentary rocks of the Neuquén Basin (Jurassic-Paleogene) on previous Tertiary–Quaternary volcanic rocks and on Quaternary sediments linked to the Colorado River. As noted by Holmberg (1962), different eruptive pulses that originated these lava flows were interspersed with periods of rising and erosion of the region as a consequence of Neogene-Quaternary Andean tectonics, resulting in the formation of terraces and piedmont levels leading to a stepped relief.

3. El Corcovo lava flow

3.1. Megascopic aspects

A geological mapping of the studied area was performed through multispectral satellite images acquired by Landsat 7 (ETM+) and Landsat 8 missions with a spatial resolution of 30 m (Supplementary material—Fig. 1) and digital elevation models from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 90 m. Analyses of these images defined the eruptive center, the length and areal extension of the flow, and verified the influence of different external controls to the flow advance such as slopes and ground obstacles.

The Huanul volcano consists of at least eight outcropping lava units, of which the El Corcovo lava flow (ECF-Unit 1) comprises the oldest and largest areal segment (Fig. 2). The ECF reached a maximum distance of 70 km and covered a minimum area of 415 km^2. In its proximal and lower-middle sectors, the ECF spread radially over the southeast quadrant of its source and freely moved over a flat surface whose slope did not exceed 0.5°E, reaching a maximum lateral amplitude of 11 km. In its middle sector (Site 1, Fig. 2), a part of the lava flow spilled south and descended about 10 km over a substrate with a 0.8°–1° slope as a consequence of the gradual passage between two piedmonts levels (N1 and N2 in Fig. 2). In this sector, the lava flow and its substrate has been deeply undermined by a drainage network which partially exposed the contact between the basalt and the underlying rocks. The substrate is constituted by interspersed beds of red sandstones, claystones and greenish limestones related to Tertiary units of the Neuquén Basin.

At Site 1, the ECF reaches a thickness of 4 m and it is overlain by another younger lava unit, indicated as Unit 2, which has the same thickness as the ECF. At a distance of 26 km from the vent (Site 2, Fig. 2) the lava flow diverged into two subparallel branches (named SN and SS) around an elevated substrate. Both flow fronts continued to advance for a distance of about 14 km where a break occurs in the eastward general direction of the ECF as a consequence of the interposition of a previous lava flow, here named "Pampa de Luanco". This older flow was erupted from Chachahuen Volcanic Field and diverted the ECF to the south. From this breakpoint, both segments of the ECF continued parallel to the Pampa de Luanco flow, overground with a 0.5° slope, separated from each other by a lava levee generated by the SS branch. The distal portion of the SS moved to the southwest and stopped its displacement about 20 km from the breakpoint. In contrast, the SN branch flow continued its movement along the western edge of the Pampa de Luanco flow to its culmination in the Colorado River Valley. This distal sector of the flow (Site 3, Fig. 2) shows an increase in the local slope from 0.5° to more than 2° as a result of the gradual passage to the lower piedmont level (N2). At this zone, the SN branch flow moved in a west–east direction, parallel to the current Colorado River channel, over a sedimentary ground of red and white sandstones and matrix-supported conglomerate. The basalt–conglomerate contact is a thin dark-red layer resulting from the thermal effect produced by the overlying flow. At this terminal sector, the thickness of the flow front reached 10 m (southeast zone of Site 3) while in channelized flow sectors the levees are approximately 3 m in height (Site 2 and northern zone of Site 3). Central channels enclosed by levees show until 1.5 m in thickness. The calculated lava volume for the El Corcovo lava flow is 2 km^3.

Frequently, flat topography of the flow surface is interrupted by lava landforms, which are associated to the lava emplacement mechanism. These morphological features mainly comprise tumuli, lava rises, marginal levees and lava windows.

Tumuli are domed structures that demonstrate the inflation process because they formed in response to the increase of pressure that acts

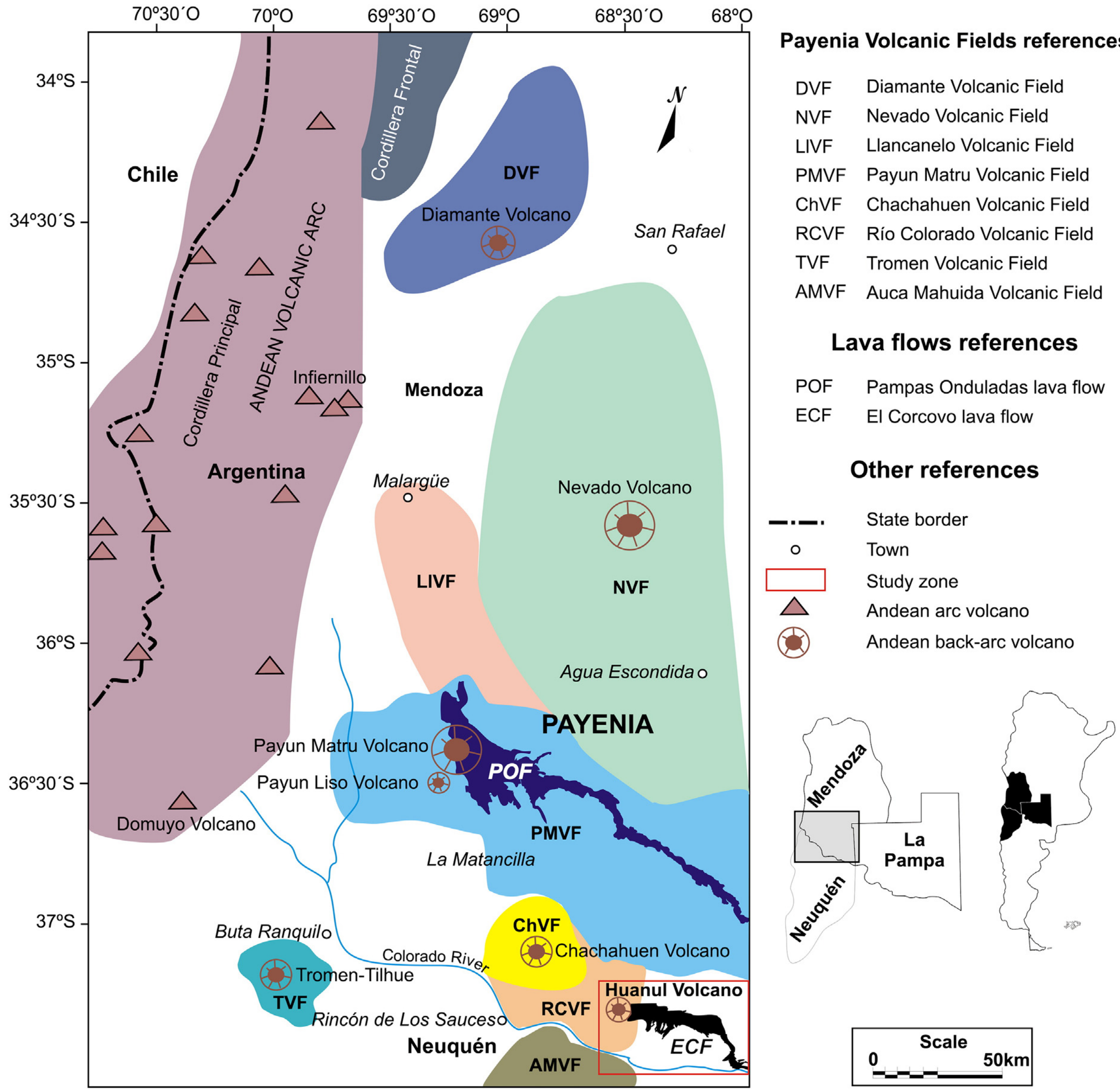

Fig. 1. Payenia Volcanic Province. Location with regard to the Andean arc. Main volcanic fields in which it was divided, according to several authors. Location of the El Corcovo and Pampas Onduladas lava flows.

uniformly over the flow core due to the continuous incoming of liquid lava. Tumuli exhibited by the ECF are between 30 and 50 m in length and up to 8 m in height with lenticular geometry in aerial view, usually elongated in the flow advance direction (Fig. 3a). The tumuli often appear isolated or in small groups in the middle sectors of the ECF, whereas in the distal sectors they form large concentrations. In these agglomerates it is usual to observe that tumuli are aligned with each other, suggesting the presence of lava tubes inside of the flow.

Often, tumuli are associated with other structures of similar origin termed lava rises which show flat roofs and a greater areal extent (Walker, 1991; Fig. 3b). These landforms have irregular shapes in aerial view and are up to 2 m in height above the surrounding relief (Fig. 3c).

Many of the observed tumuli exhibit axial and radial fractures with V-shaped cross sections formed as the result of distention strength caused during the lifting of the outer crust, termed lava-inflation clefts (Walker, 1991; Gudmundsson, 1995). Fracture traces are straight or sinuous and up to 2 m in width (Fig. 3d). Lava clefts could partially or totally affect the tumulus; they are always partially filled by Aeolian sediments and therefore it was impossible to determine the crack extension and its morphology in depth. The walls of the fractures exhibit vesicular and massive sectors with similar distribution patterns to those described for profiles of different flow sites (see outcrops description). Frequently, massive lava injections coming from the inner core of the tumuli are observed (squeeze ups).

Tumuli described in El Corcovo basaltic flow correspond to a “flow-lobe tumuli” type, as proposed by Rossi and Gudmundsson (1996). These authors noted that for their formation, low rates of lava supply from the source are necessary. This would allow a better development of the outer chilled crust to withstand the incoming lava without breaking for a longer period. Therefore, this type of tumuli is common in the middle and distal portions of a lava field, where flow rates are lower and the supply pressures increase towards the flow front.

3.2. Outcrops description

The flow exhibits a well-marked distribution pattern of vesicular and massive zones. Surveyed flow profiles show two vesicular zones; an upper crust that may constitute between 30 and 50% of the flow

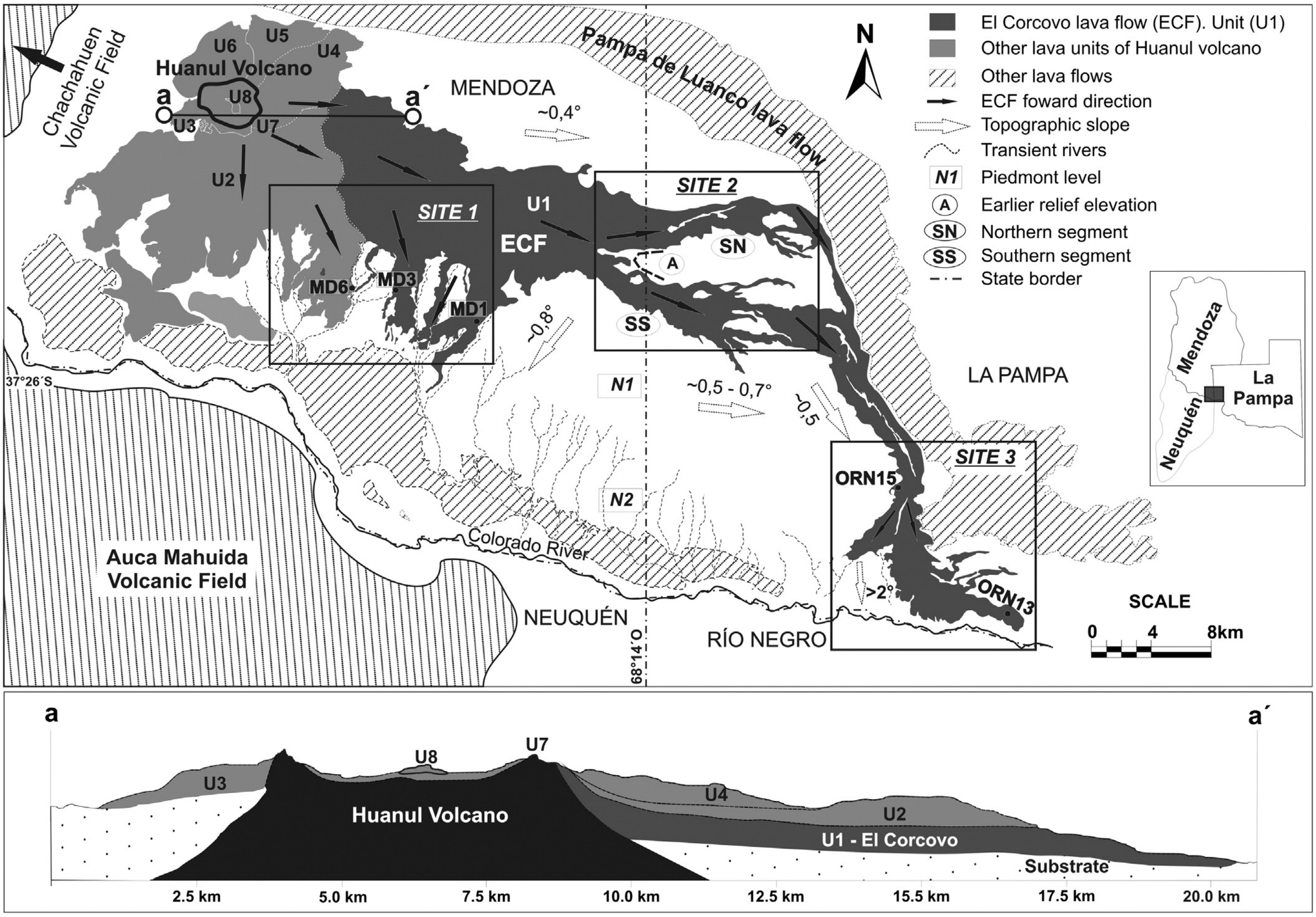

Fig. 2. Local geological setting and topographic features of the ECF emplacement area. Black boxes delimit the surveyed and sampled sites of the lava flow; a-a′ profile of the Huanul Volcano and surrounding sectors displaying the stratigraphic position of ECF regarding to other basaltic units emitted by the same center.

total thickness and a lesser development of vesicular-scoriaceous lower crust. Both crusts surround a central dense zone, in which vesicles are either absent or concentrated in horizontal sheets and vertical cylinder bodies, that exhibit petrological differences regarding the host basalt. These features correspond to structures that result from segregation of residual liquids and gas bubbles that ascend from inner and lower sectors of the flow. According to Goff (1996), the development of these structures takes place between the cessation of flow movement and the columnar joint propagation into deep zones of the flow. In addition, vesicle structures were generated during crystallization of the lava core, in which a differentiated residuum enriched in incompatible elements and volatiles, would have risen as diapirs through a secondary vesiculation process (Goff, 1996; Rogan et al., 1996).

The upper vesicular sector represents the cooling crust formed during the flow emplacement in which gas bubbles coming from the massive central zone, are retained. Frequently, this layer shows gradational changes in diameter and density of vesicles, where bubbles sizes increase with depth while their density decrease.

The lower vesicular crust is not always visible. It is a thin layer, not exceeding 30–40 cm in thickness, and generally shows vesicles with elliptical geometry and smaller sizes than those of the upper crust. This lower vesicular sector is characterized by the presence of vesicle pipes. These features result from the upward escape of gases from the base of the flow and comprise curvilinear structures with cylindrical geometry that do not exhibit magmatic fills. The pipes reach up to 15 cm in length and show circular cross-sections. Often they present carbonate fills and show a sub-perpendicular disposition with respect to the base of flow, being tilted in the direction of flow movement. Wilmoth and Walker (1993) defined those vesicle pipes-bearing lavas as P-type pahoehoe flows, and noted that these flows are commonly developed only on flat ground.

A reddish scoria resulting from the oxidation of volcanic Fe-bearing minerals characterizes the flow basal zones. This lower sector presents striations and small-scale folds as the result of the flow friction with the ground.

The flow roof is frequently intercepted by columnar joints. Cross-sections of columns exhibit polygonal geometries, varying between 0.3 and 1 m. The columnar jointing development is well registered to the upper sector of the flow cores, below which columns disappear. Massive internal zones are little affected by cracking with respect to the upper vesicular zone. Usually the upper vesicular crust is partitioned by several horizontal cracks that frequently follow planes of weakness, mainly determined by vesicle alignments.

3.3. Viscosity of ECF

Viscosity controls many parameters during emplacement of silicate melts such as transport dynamic, eruptive style and speed with which the physicochemical processes occur such as degassing and crystallization, among others (Giordano et al., 2008). Therefore, it is interpreted that the emplacement mechanism that acted during the effusion of these lavas was controlled in part by this property. The viscosity of magma depends not only on temperature but also on the degree of polymerization, which is a direct function of the melt composition, mainly with respect to its silica proportion.

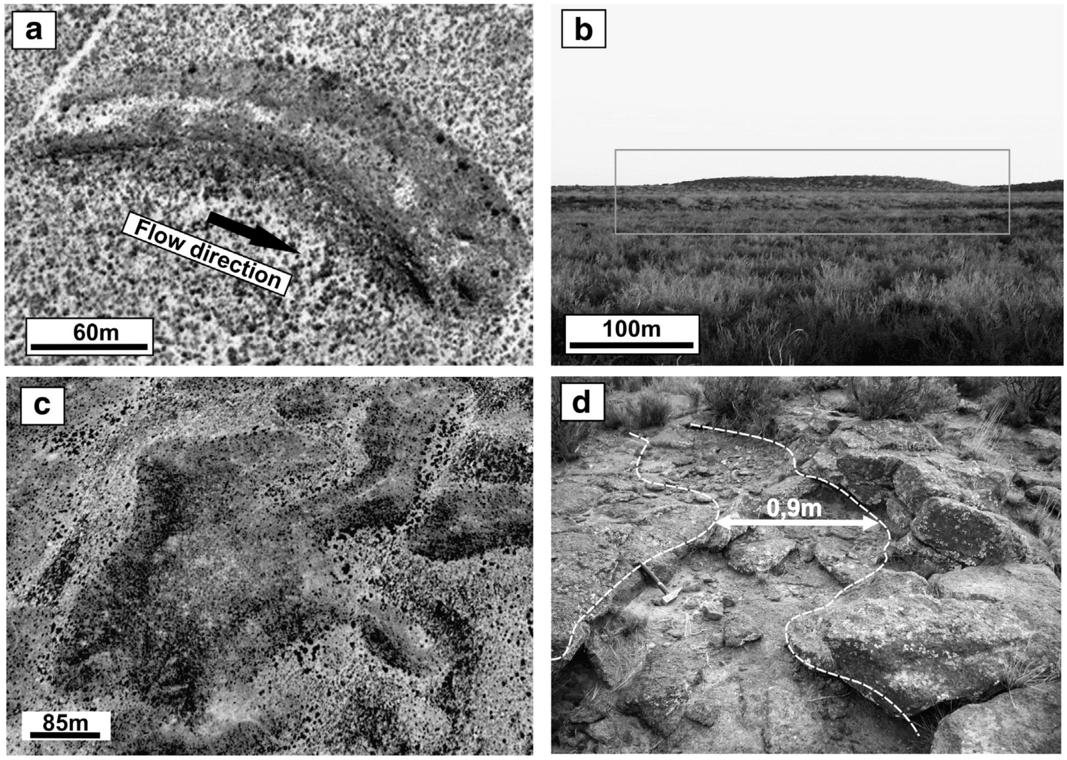

Fig. 3. Inflation features. (a) Tumulus with bent longitudinal axis showing a parallel disposal relative to the advancement direction of the flow (satellite image); (b) lava rise; (c) satellite image of a lava rise; (d) lava-inflation cleft (dashed lines) intercepting the roof of a tumulus. Axial fracture was injected by massive basalt coming from the inner sector of the structure (squeeze up) when inflation process was still active.

The bulk major element compositions in 5 samples collected from different areas of the ECF were determined by the X-ray Fluorescence (XRF) method (Table 1). Samples MD1, MD3 and MD6 were taken from the core of the proximal and middle sectors, while samples ORN13 and ORN15 correspond to the core of the distal sector. Based on the total-alkali-silica (TAS) diagram (Le Maitre et al., 2002), the analyzed rocks are classified as basalts and they plot in the alkaline field of Macdonald (1968).

From the data of analyzed major oxides, values of liquidus temperature between 1158 °C and 1167 °C were obtained according to the criteria of Sisson and Grove (1993). Viscosity values were determined using the equation of Shaw (1972), which allows to estimate the viscosity of the magma above the liquidus temperature based on chemical composition of major oxides (except MnO and P_2O_5). For the calculation a temperature of 1200 °C it was set by assuming a melt free of bubbles and phenocrysts. The resulting values of viscosity for the ECF vary in the range of 16 and 30.7 Pa s. Since the viscosity of a basaltic magma varies in an approximate range of 10 to 10^3 Pa s (Scarfe, 1973), the values obtained for the ECF are low which in part explain its high mobility and therefore the remarkable longitudinal development.

Table 1
Major elements data, viscosity and *liquidus* temperature values calculated of selected samples from the El Corcovo flow.

Location (Fig. 2)	Site 1	Site 1	Site 1	Site 3	Site 3
Sample	MD6[(1)]	MD3[(1)]	MD1[(1)]	ORN15[(2)]	ORN13[(2)]
Rock	Basalt	Basalt	Basalt	Basalt	Basalt
SiO_2 (wt.%)	49.37	49.77	48.92	49.60	49.50
TiO_2	1.37	1.60	1.45	1.50	1.30
Al_2O_3	16.21	16.99	15.74	16.90	17.00
Fe_2O_3	11.46	10.49	12.30	11.80	11.60
MnO	0.14	0.13	0.14	0.20	0.20
MgO	7.59	5.99	8.39	7.20	7.90
CaO	8.51	10.04	8.50	7.70	7.70
Na_2O	4.12	3.68	3.76	4.20	4.00
K_2O	0.91	0.95	0.59	0.70	0.70
P_2O_5	0.31	0.35	0.21	0.30	0.30
LOI	0.04%	0.62	0.04	N/A	N/A
Total	100.00	100.00	100.00	100.00	100.00
Visc. η (log Pa s)	19.5	30.7	16	25.80	23.10
T liquidus (°C)	1158	1167	1161	1158	1164

Major element analyses (wt.%) recalculated to 100% on a volatile-free basis. Viscosity (η) and liquidus temperature (T) calculated after Shaw (1972) and Sisson and Grove (1993), respectively. N/A: not analyzed.
(1) Analyzed at University of Tokyo (Japan), XRF method as in Tani et al. (2002).
(2) Analyzed at Universidad de Jujuy (Argentina), XRF method as in Caffe et al. (2002).

4. Discussion

4.1. Emplacement mechanisms. Morphological and structural evidence

The El Corcovo lava flow exhibits a transition between three emplacement modes. The proximal and lower-middle zones present sheet flow characteristics with flat roofs (Hon et al., 1994) uniform thickness and an accentuated radial scattering. In the middle and upper-middle portions, the flow was divided into two segments, which were diverted from their path and drastically reduced to two narrow and channeled fronts whereby the distal section presents hummocky flow characteristics with inflation structures that led to a metric-scale relief (Supplementary material—Fig. 2). Based on morphological features of the ECF, we interpret that during the initial stages of the emplacement the lava effusion rates were high and sustained over time. This aspect added to an almost flat substrate, led to the formation of a tabular sheet flow that grew and moved throughout the development and coalescence of lobes at the proximal lava flow front. This advance mode is the “lobe by lobe emplacement” (Hon et al., 1994; Self et al., 1997) and promoted radial spreading with generalized and uniform inflation across the entire lava body, which reached maximum height values of 4 m. A particular feature that evidences this process can be observed in most of the edges of the proximal and middle

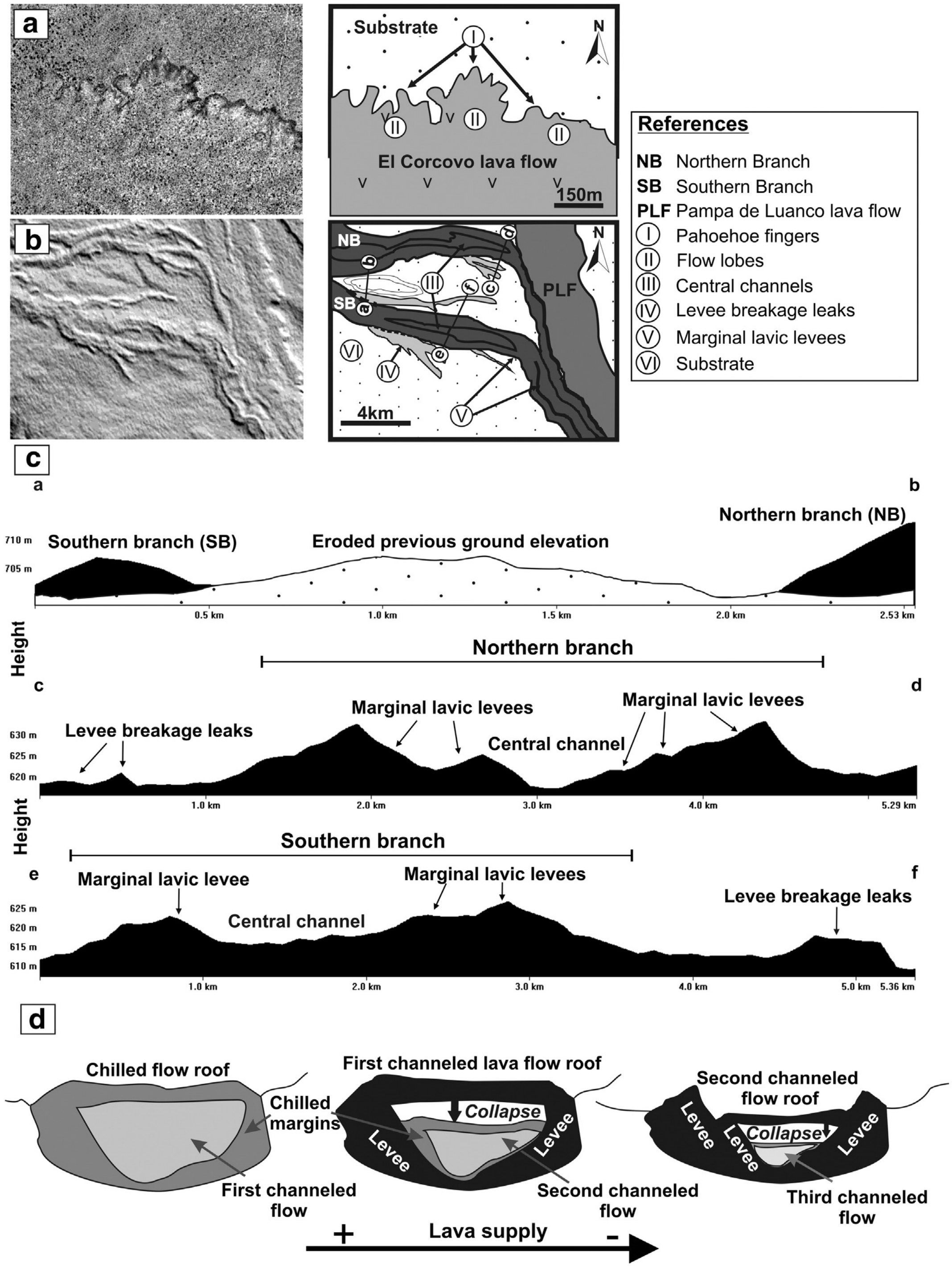

Fig. 4. (a) Satellite image and scheme of pahoehoe lobes and fingers developed at marginal sectors of the sheet flow emplaced near the lava source. (b) SRTM-DEM satellite image and scheme of the flow bifurcation in its middle section (NB = northern branch; SB = southern branch). (c) a-a′ Cross-profile: substrate topographic high remnant that possibly led to the bifurcation of the ECF on its middle sector; b-b′ cross-profile: northern segment (NB); c-c′ cross-profile: southern segment (SB) (profiles obtained from digital analysis of SRTM-DEM images, using Global Mapper and Envi 4.7 software). (d) Schematic sequence showing the levees successive formation as the lava supply decreased.

portions of the sheet flow whereby these sectors are characterized by the presence of numerous lava lobes which fronts show “pahoehoe fingers” in a radial arrangement (Fig. 4a).

On the ECF middle section, the presence of a positive relief in the substrate led to the bifurcation of the flow front in two secondary channelized branches. These individual and uninflated flows display similar geomorphologic features in their cross-sections. The two profiles obtained at the middle sectors of both segments show raised and stepped edges that enclose a depressed central and narrow channel (Fig. 4b and c). Positive marginal relief of each branch corresponds to lava levees formed at different stages during the progress of the flows as the result of rapid cooling of their margins. It is estimated that by the decreasing of lava supply the volume occupied by the flow becomes smaller, which allows the formation of increasingly narrow roofed channels whose collapse led to a stepped cross-section (Fig. 4d).

At adjacent external sectors of lava levees, numerous rectilinear ridges are observed, which correspond to spills or breakouts from the main lava body as a result of breakage or collapse of a levee section.

The linear forms of these small ridges would be defined by a previous fluvial drainage system installed on the substrate, where the temporary channels have controlled the lava spills. The obstruction of the previous Pampa de Luanco flow led to the deviation of the two secondary flows in the south direction. Then the two narrow fronts continued moving over a substrate with an irregular relief, confined to the western margin of the Pampa de Luanco flow. They possibly were fed through secondary lava tubes formed inside the proximal sheet flow.

The cross-section morphology of terminal sectors of both segments shows similar characteristics of their previously described initial and middle portions, i.e. depressed central portions bordered by raised and stepped edges. In the last stages of their emplacement, the flows arrived to a sector made up of terrace levels of the Colorado River, possibly accessing to an abandoned fluvial channel (Fig. 5). This latter aspect is evidenced by deposits of conglomerates and sandstones that underlie the distal sector of the ECF. The second piece of evidence is in the terminal flow lobes following previous and current river beds.

At the terminus, the front of the lava flow has a relatively uniform thickness of about 10 m. It is inferred that this abrupt change in the ECF thickness at its terminus could be due to two aspects: 1) income, confinement and accumulation of the flow inside an earlier channel of the Colorado River and 2) progress of the inflation mechanism which increased the average thickness of the flow in this sector. The second aspect is evidenced by the presence of an inflation structure field covering an area of 38 km^2 and a distinctive complete profile exposed and preserved at the flow front (Fig. 6a and b). The most important features of the profile are:

Vesicular upper crust: it has a variable thickness of 3–4 m. Blistering in the upper half occupies a volume between 30 and 50%. The vesicles exhibit chaotic distribution, displaying spherical geometries and diameters of 0.5 to 1 cm ([1] in Fig. 6a). In the middle section ([2] in Fig. 6a), the population of vesicles is gradually reduced to 25% in volume, while their sizes are increasing, reaching diameters of up to 2–3 cm (Fig. 6c). The lower section of the vesicular upper crust ([3] in Fig. 6a) is represented by a vertical sequence of thin vesicle sheets with planar to curviplanar morphologies, each one separated by a thin layer of massive basalt. Cross-sections of the sheets are constituted by a single line of elongated vesicles with sizes in the range 1 to 3 cm on average with the presence of coalesced and oversized vesicles. These vesicle planes are presented as a whole with dip angle near to 30° W, in opposite to the flow front advancing direction.

Core: this occupies the middle sector of the flow profile, with a maximum thickness of 5 m (Fig. 6d). The core exhibits two distinct sections. The upper section ([4] in Fig. 6a) is composed of massive basalt, which hosts vesicular structures. Vesicle cylinders present variable morphologies and sizes, showing some specimens of up to 2 m in length and 15 to 20 cm in diameter. It is usual that in those sectors most affected by weathering, vesicular structures can be seen in three dimensions, as its resistance is greater than that of their host basalt (Fig. 6d′). The vesicle sheets exhibit remarkable lateral extensions and maximum thicknesses of about 20 cm. The cylinders are associated with one or more vesicle sheets. Downward of this upper zone underlies a massive basaltic section which reaches up to 1 m in thickness and vesicular structures are virtually absent, except for the presence of a few small vesicle cylinders located almost on the limit with the upper section ([5] in Fig. 6a).

Vesicular lower crust: this occupies from 40 to 75 cm above the flow base and exhibits three sections with different characteristics. The upper section is characterized by the presence of a vertical sequence of thin vesicle layers, spaced at intervals of 3 to 4 cm, where vesicles show elongated shapes and do not exceed 2 cm in diameter ([6] in Fig. 6a and e). Unlike the sheets sequence in the base of the upper vesicular sector, these latter vesicle planes show an almost horizontal disposition. The midsection of the vesicular lower crust exhibits blistering density varying between 20 and 40% and consists mostly of very small vesicles of up to 0.5 cm in diameter ([7] in Fig. 6a). Underlying this middle section, the lower section presents predominantly vesicle pipes ([8] in Fig. 6a and e). These latter features reach up to 15 cm in length and show a subperpendicular arrangement with respect to the lava flow floor, verging towards the flow front. In cross-section, the pipes exhibit circular shapes with diameters up to 3–4 cm. They are completely filled with carbonate precipitates and septa which separate them show meager blistering. Finally, the basal plane of the flow is constituted by agglomerate with scoriaceous structure. The flow floor displays folds, parallels great grooves and striations in northwest–southeast direction as well as clasts of basalt boulders coming from the underlying substrate ([9] in Fig. 6a and f).

4.2. Active inflation at the El Corcovo flow distal sector

Inflation was described on active lava flows in Hawaii. It was determined that during the inflation process the continued growth of the vesicular upper crust occurs and the blistering observed in this layer is mainly due to fluctuations in internal pressure or in the supply of liquid lava to the core (Hon et al., 1994; Cashman and Kauahikaua, 1997). The occurrence of vesicular structures (sheets and cylinders) is limited to the time when the inflation of the flow lobe is finalizing and the core has begun to crystallize. From this and other aspects, coupled with the construction of inflation and cooling curves of the flows, Hon et al. (1994) developed an empirical method to estimate the duration of active inflation in a lava lobe as $t = 164.8\,H^2$, here H is the thickness in meters of the vesicular upper crust and t is the time in hours. According to Thordarson and Self (1998), this cooling model can overestimate cooling rates and thus underestimate the emplacement duration of an inflated lobe because cooling rates are affected by many external and intrinsic factors. However, currently this technique is the only quantitative method of estimating the duration of active emplacement of ancient lava flows. Based on the expression of Hon et al. (1994), it was estimated that the approximate duration of active inflation in the terminal segment of the ECF was between 40 and 60 days. This period should

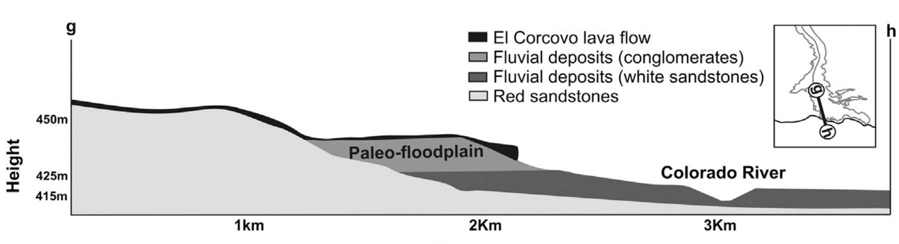

Fig. 5. Longitudinal profile of the ECF distal segment (profile obtained from digital analysis of SRTM-DEM images, using Global Mapper and Envi 4.7 software).

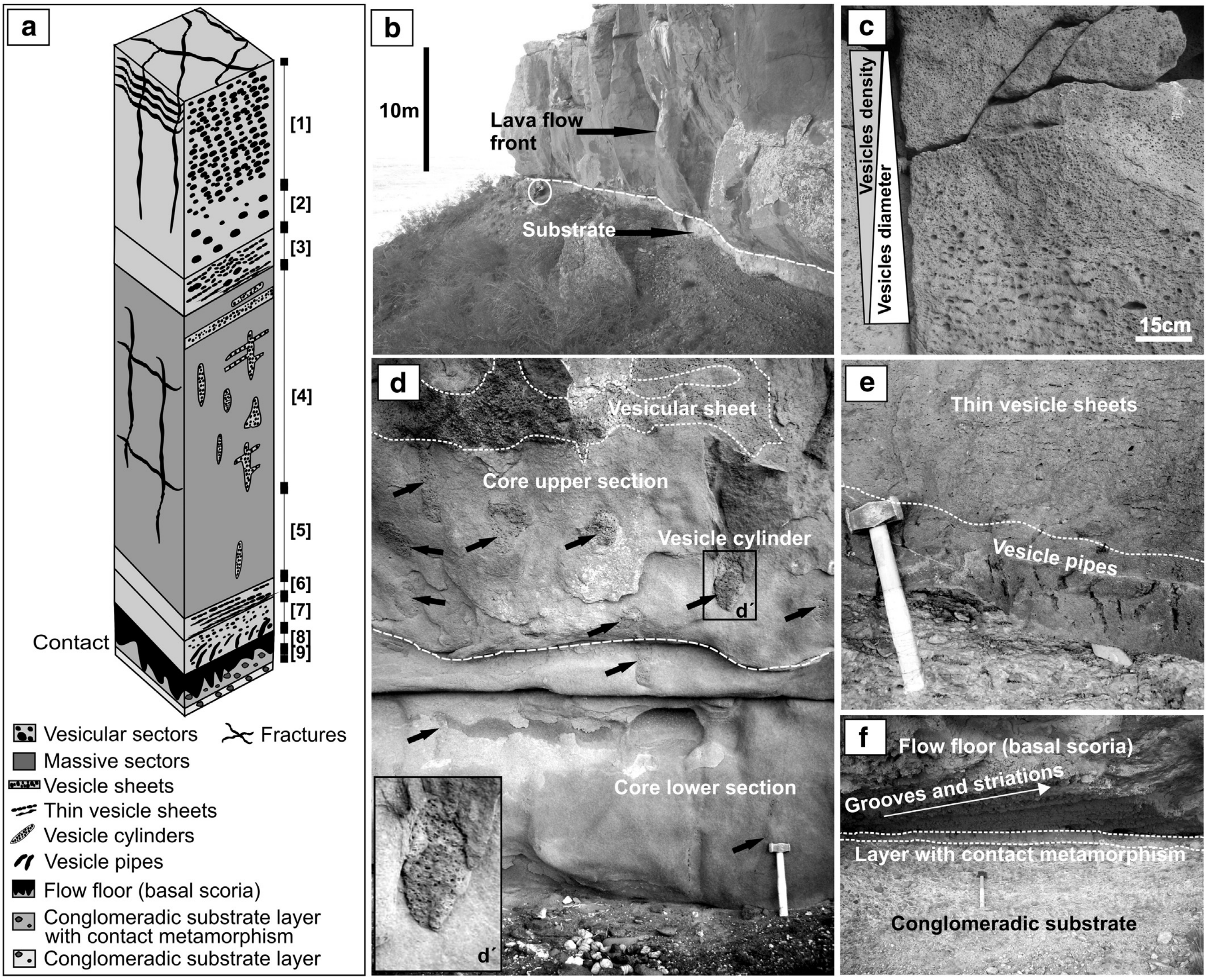

Fig. 6. (a) Schematic cross-section of the terminal flow portion. Numbered sections are detailed in text. (b) Lava flow front. (c) Upper vesicular crust and vesicles distribution pattern. (d) Sections in which core is divided. It can be appreciated the greater presence of vesicular structures (black arrows) in the core upper section with respect to its lower section; (d′) detail of a vesicle structure. (e) Lower vesicular crust with thin vesicle sheets and vesicle pipes. (f) Flow floor and its bedrock.

be considered a minimum value which takes into account the loss of thickness of the upper vesicular crust as result of erosion. The lower section of the upper vesicular crust exhibits a set of vesicle sheets with a dip in the opposite direction to the advancing front of the flow. This aspect would indicate that the inflation process was still active during the formation of the sheets and that the pressure exerted by the incoming liquid lava was higher towards the front section of the flow.

The inflation structure field that occupies the top of the flow in this final stage (Fig. 7) may have formed during and after the general thickening of the flow. As previously mentioned, the flow arrived at this sector channeled into two segments, moving over a stepped relief. The channeled flow could meet with a smoother slope relief, possibly corresponding to a paleo-floodplain adjacent to the Colorado River channel. The reduction of the slope angle could have caused a decrease in forward speed, allowing the confined flow to expand and occupy depressions and abandoned channels (Fig. 8). The inflation process began after the stagnation of the flow on this site. At first, the lava effusion rates could still be high, leading to a generalized uplift of the flow terminal segment. As the lava supply from the source was declining, the lava body began to solidify and its core began to crystallize, limiting the migration of lava to narrow preferential pathways (lava tubes). When lava arrived to a tube endpoint or a blocked segment it began to accumulate, pushing up the overlying flow upper crust, resulting in localized inflation structures that masked the morphology of the sheet flow surface initially formed.

5. Conclusions

The lava flow here termed El Corcovo was originated in the Huanul volcano and represents the oldest and largest of the lava flows emitted by this volcanic center. The El Corcovo lava flow reached up to a distance of 70 km and covered a minimum area of 415 km^2. The trajectory, morphology and emplacement of this lava flow were controlled in part by previous topographic irregularities (old volcanic reliefs or substrate elevations) and by local changes in the slope of the area covered by the flow.

The surveyed profiles at different points of the flow exhibit a characteristic cross section defined by an upper vesicular sector, by a massive core containing vesicular structures and by a lower vesicular sector displaying vesicle pipes formed by the escape of gases towards the inner sectors of the flow.

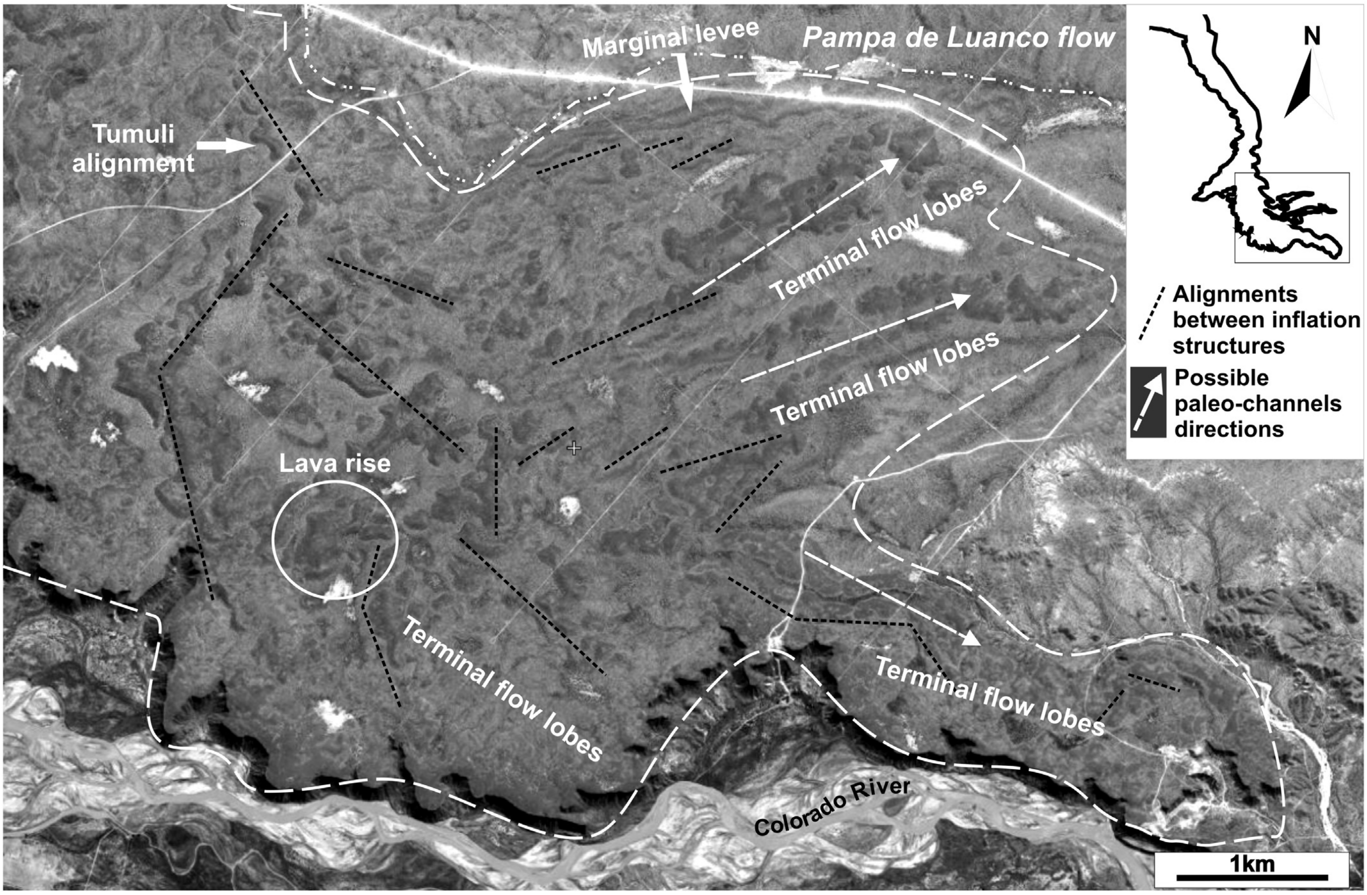

Fig. 7. Inflation structure field occupying the lava flow roof at its distal portion. Black short dashed lines indicate alignments of inflation structures (mostly of them are tumuli). White dashed arrows indicate the possible direction and location of palaeochannels linked to the Colorado River that could have been acted as confining channels of the latest lava lobes developed on the active flow front.

The El Corcovo lava flow can be subdivided into three main sectors according to the emplacement mode: at the proximal sector it moved as a large sheet flow over a flat relief (~0.5°SE); then, at its middle sector, a substrate elevation led to the flow division in two secondary branches. Both segments, initially channeled through the adjacent relief, self-channeled among its lava levees and diverted their trajectory after meeting the older Pampa de Luanco flow. Branches kept their advance parallel to the mentioned flow for several kilometers, over a substrate with a slope ranging between 0.5 and 0.7° until reaching the distal portion. Near to the terminal sector of the ECF lava flow, one segment stopped its travel while the other segment remained active and descended by an irregular slope with 2° of inclination, approximately. Finally, it was dispersed when entering an ancient flood plain of the Colorado River, concluding its travel while being confined by relief depressions and earlier channels of the Colorado River.

Throughout its extension, the El Corcovo lava flow exhibits numerous morphologies and swelling structures formed as the result of lava flow intrinsic factors and its advance mode. These landforms are mainly abundant at its lower-middle and distal portions, being absent in those sectors where the flow seems to have been channelized.

During the emplacement of proximal sheet flow, radial dispersion was the predominant process that resulted from an advance mechanism given by a continuous formation and coalescence of lava lobes at the lava flow front, enabled by a sustained regime of high effusion rates and a gentle slope relief. The inflation mechanism acted uniformly across the inner perimeter of the flow which, despite its low viscosity, reached thicknesses up to 4 m. Based on the presence of tumuli and flat roof elevations, isolated or clustered on the sheet flow roof, it was inferred that the development of preferential lava paths within the core occurred during its solidification. This latter aspect was crucial so that the lava flow continued its progress. The distal sector shows an irregular-small scale “hummocky” relief constituted by a field of inflation structures occupying a surface of about 38 km^2. At this site, the inflation process initially operated under high rates of supply regime, leading to a tabular lava body of up to 10 m of thickness. As the time passed, the decrease in the lava supply led to the development of lava tunnels that continued feeding terminal lobes. Finally, when lava arrived to a blocked section or reached high points of tubes, it accumulated there, leading to localized inflation of different parts of flow surface. It was determined a period of time of between 40 and 60 days approximately for the duration of the active inflation at the distal sector of the flow. Although the inflation process by formation and coalescence of lobes comprises a slow emplacement mechanism, it involves the lava tubes formation, which allows an almost isothermal delivery of lava. It is interpreted that this latter aspect as well as the lower viscosity values calculated for this flow (16 to 30.7 Pa s) determined the great areal and longitudinal development achieved by the El Corcovo flow.

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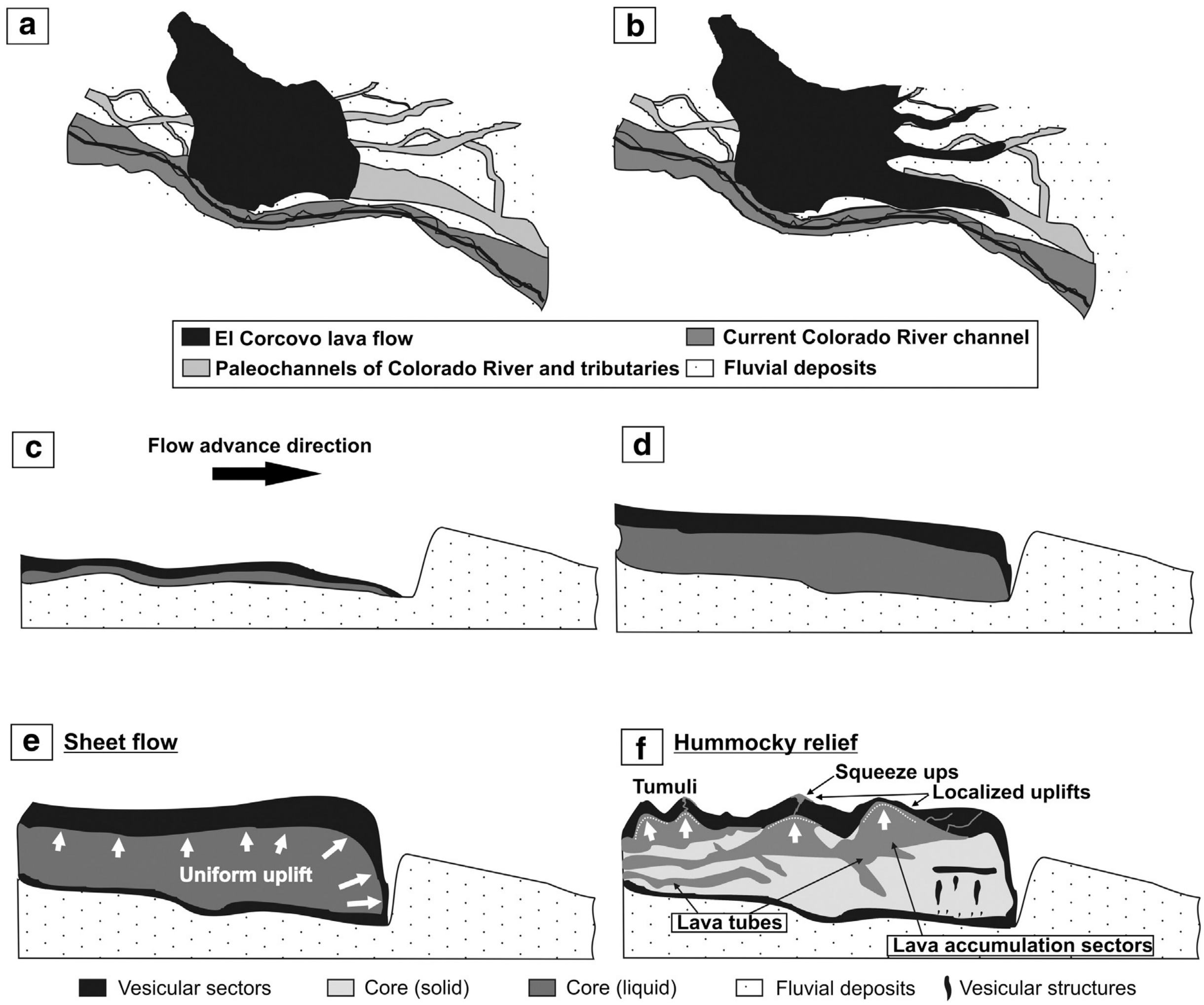

Fig. 8. Emplacement model schemes of the El Corcovo flow at its distal sector. (a) Income and dispersion in the floodplain of the Colorado River. (b) Confinement of terminal lobes within abandoned channels of Colorado River or its tributaries. (c) And (d) advance, confinement and accumulation of the flow inside the channels and formation of a thin upper vesicular crust. (e) Generalized inflation due to continuous lava income below the upper crust. (f) Partial solidification of the flow core at emplacement final stages. The lava began to move through narrows paths within de core (lava tubes). If a section of a tube were blocked, then lava accumulates leading to the located swelling on the sheet flow surface resulting in tumuli and lava rises.

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