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ON THE COVER

Ventana Group of the Middle Ordovician - Upper Devonian, Sierra de la Ventana.

Photo: *Javier I. Masú.*

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VERY LONG PAHOEHOE INFLATED BASALTIC LAVA FLOWS IN THE PAYENIA VOLCANIC PROVINCE (MENDOZA AND LA PAMPA, ARGENTINA)

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ABSTRACT

Extremely long basaltic lava flows are here presented and described. The flows originated from the great, polygenetic, fissural Payen Volcanic Complex, in the Andean back-arc volcanic province of Payenia in Argentina. The lava flows outpoured during the Late Quaternary from the summit rift of a shield volcano representing the first volcanic centre of this complex. One of these flows presents an individual tongue-like shape with a length of 181 km and therefore is the longest known individual Quaternary lava flow on Earth. Leaving the flanks of the volcano this flow reached the Salado river valley at La Pampa and, in its distal portion, maintained its narrow and straight shape without any topographic control over a flat alluvial plain. It has a hawaiite composition with low phenocryst content of prevailing olivine and minor plagioclase. Rare Earth element patterns are typical of Na-alkaline basalts, but incompatible trace element patterns and Sr -Nd isotope ratios, suggest a geodynamic setting transitional to the orogenic one.

The flow advanced following the thermally efficient "inflation" mechanism, as demonstrated by a peculiar association of well developed morphological, structural and textural features. The temperature of 1130-1160°C and the viscosity of 3-73 Pa*s, calculated by petrochemical data, may be considered, together with a very low cooling rate and a sustained and long lasting effusion rate, the main causes of the extremely long transport system of this flow. Both the extreme length of the flow and the partial lack of topographic control may provide new constraints on the physics of large inflated flows, which constitute the largest volcanic provinces on Earth and probably also on the terrestrial planets.

Keywords: *Pahoehoe lava flows, Inflated flows, Payenia.*

RESUMEN: *Flujos de lava basáltica pahoehoe muy extendidos en la provincia volcánica Payenia (Mendoza y La Pampa, Argentina).*

En este trabajo se presentan y describen flujos de lava extremadamente largos. Estos flujos se originaron en el complejo volcánico fisural Payen, dentro de la provincia volcánica Payenia en el retroarco andino. Los flujos de lava fueron emitidos durante el Cuaternario tardío desde el sector superior de un volcán en escudo, el que constituyó el primer centro volcánico de este complejo. Uno de estos flujos presenta forma de lengua y tiene una longitud de 181 km, constituyendo el flujo de lava cuaternario conocido, más largo sobre la Tierra. Este flujo alcanzó el valle del río Salado en La Pampa y mantuvo una forma angosta y recta sin ningún control topográfico, hasta su porción más distal sobre una planicie aluvial. La roca que forma esta colada es una hawaita con un bajo contenido de fenocristales de olivino y plagioclasa. Los patrones de elementos traza son típicos de basaltos alcalino-sódicos de intraplaca, sin embargo el patrón de elementos traza incompatibles y las relaciones de isótopos de Sr y Nd, sugieren un marco transicional al orogénico. El flujo estudiado fluyó siguiendo un mecanismo térmicamente eficiente denominado *inflation*, como demuestran las asociaciones de sus rasgos morfológicos, estructurales y texturales. Las causas principales de este sistema de transporte extremadamente largo pueden ser una temperatura de 1.130°-1160°C y viscosidad de 3-73 Pa*s (calculadas a partir de los datos petroquímicos), junto con una muy baja velocidad de enfriamiento y una tasa de efusión grande y sostenida en el tiempo. La gran longitud y la falta parcial de control topográfico del flujo pueden aportar nuevos conocimientos acerca de la física de los grandes flujos inflados, los que constituyen las más extensas provincias volcánicas de la Tierra y probablemente también la de otros planetas terrestres.

Palabras clave: *Coladas de lava pahoehoe, Flujos basálticos inflados, Payenia.*

INTRODUCTION

Long individual basaltic lava flows (several ten of km in length), are rare on the Earth's surface but widespread on other terrestrial planets. The longest flows, exceeding 100 km in length, are the Quaternary Undara and Toomba flows in Australia (Southerland 1998, Stephenson *et al.* 1998, 2000) and the Thjorsa flow in Iceland (Hjartarson 1994). Studying shorter but younger and best exposed hawaiian basaltic lava flows some authors have suggested that a great transport efficiency can be explained through a process of endogenous growth called inflation. This theory challenged the traditional views that large and long basaltic lava flows were formed by the rapid eruption of relatively low viscosity lavas and proposed a relatively slow emplacement. This process was firstly envisaged by Anderson (1910) and later illustrated more thoroughly by Walker (1991) and Hon *et al.* (1994). An originally few decimetres thick basalt flow is later inflated by the underlying fluid core, which remains hot and fluid thanks to the thermal-shield effect of its visco-elastic crust. Increasing and evenly distributed pressure in the liquid core leads to uniform uplift of the crust and to thickening and widening of the entire lava flow. Spreading of the flow is due to the continuous creation of new inflated lobes, which develop at the front of the flow, where the crust is thinner and the lava pressure is higher. The inflation process is most pronounced in flat areas or on very gentle slopes (< 1-2°), and a steady flow rate, sustained for a long time, is probably a necessary condition. The thermal efficiency of this process is improved by the endogenous travel of lava inside tube systems (Greeley 1987, Pinkerton and Wilson 1994, Keszthelyi and Self 1998, Cashman *et al.* 1998). Certain morphological, structural and textural features are considered to be "fingerprints" of inflation such as: tumuli, lava rises, columnar jointing patterns, dilatational surface fractures and inner layering due to the distribution of vesicles and crystallinity (Walker 1991, Glaze *et al.* 2005, Cañón-Tapia and Coe 2002, Duraiswami *et al.* 2001). Hon *et al.* (1994) introduced the term of "sheet flows" for large inflated pahoehoe flows of Kilauea, emplaced as a series of interconnected lobes on sub horizontal slopes and due to sustained input of lava during a long-lived eruption. Eventually, in the endogenous liquid core of the flow preferred pathways may develop, generating either a system of anastomosed and transient small lava tubes or larger and more stable conduits. The transport thorough lava tubes over 100 km in length lava in inflated flows permits the molten lava core to reach the flow front with a cooling rate of less than 0.5°C/km (Keszthelyi 1992, 1995, Keszthelyi and Self 1998, Sakimoto *et al.* 1997, Sakimoto and Zuber 1998). This provides feasible explanation for the development of extremely long lava flows.

The above described genetic models were applied also to the terrestrial flood basalts, especially to those of the Columbia River Plateau (Self *et al.* 1996, Thorardson and Self 1998) but in this case discrete single lava flows cannot be resolved because they are tightly intermingled into very large lava fields to be recognized. Their sources are very problematic because they actually correspond to complex and mostly hidden swarms of dikes.

This paper describes a very large compound basaltic lava flow, previously cited by Pasquarè *et al.* (2005) with the name of Pampas Onduladas lava flow. It outpoured in Late Quaternary during a single long-lasting eruption from the summit rift of a large basaltic shield volcano, which represents the first step of the magmatic and structural evolution of the Payen Volcanic Complex. This Complex is located in the Andean back-arc volcanic province of Payenia in Argentina (Polanski 1954, Ramos 1999, Ramos and Kay 2006). The total volume of Pampas Onduladas compound lava flow can be estimated in 33 km^3 and it covers an area of 1,870 km^2. The greatest part of the lava flow descended along the northern flank of the shield. The flow is separated 10 km away from the source into two branches whose main one travelled towards ESE for a total distance of 181 km, therefore being the longest Quaternary individual lava flow on Earth. The second branch flowed towards NW for 60 km and the distance covered by lava between the two opposite fronts; amounts to 210 kilometres. Minor but still conspicuous quantity of lava flowed along the southern flank of the shield.

From now onward the first branch will be cited as Pampas Onduladas flow while the second one as Pampas Onduladas northern branch. Both branches were sampled for geochemical and petrological analyses while the morphologic and textural observations herein presented are devoted only to Pampas Onduladas flow description and interpretation. Thanks to the excellent outcropping conditions of Pampas Onduladas flow, and the desertic unvegetated environment, the topographic, morphologic and structural features of the flow can be observed in great detail at different scales. All of them are indicative of an inflated and partly deflated pahoehoe basaltic lava flow. This Argentinean lava flow also shows unusual inflation values, reaching 25 m in the large sheet flow forming the upper-middle portion.

An unusual emplacement behaviour, its median and distal portions, forming characterizes also a narrow tongue with a very low width-to-length ratio.

This paper could be a basis for further investigations on the transport mechanisms of terrestrial long lava flows and on the conditions under which the lava flows lengthens downstream rather than widens, as in the case of many long planetary homologues.

THE PAYEN VOLCANIC COMPLEX

The Payen is a fissural volcanic complex, developed during the Quaternary (Germa *et al.* 2007) with a 70 km long align-

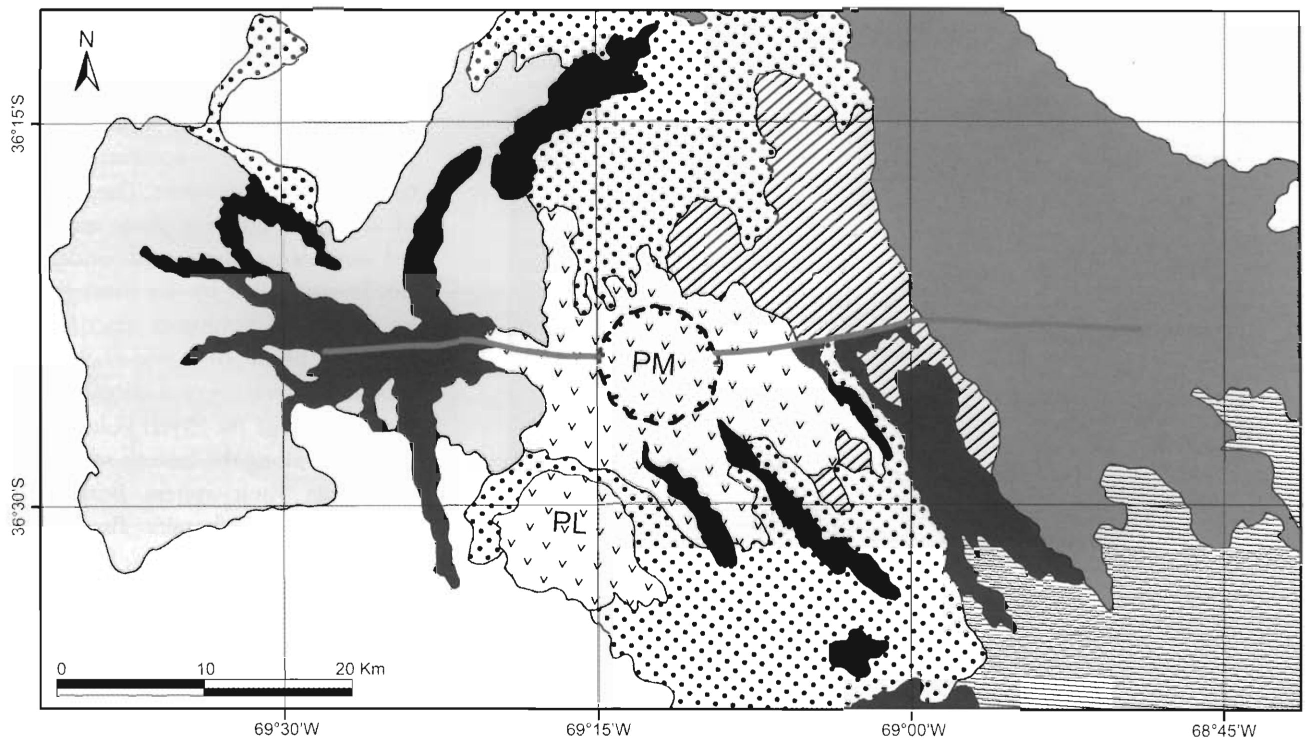

Figure 1: Geological sketch-map of the central sector of the Payen Volcanic Complex. Black represents the final basaltic lavas; light grey shows the Payen western shield volcano; dark grey indicate the Pampas Onduladas compound lava flow; horizontal lines correspond to the Los Carrizales lava field; diagonal striped pattern is the Payen eastern shield volcano; dotted area is covered by tephra from Payún Matru volcano and its caldera (PM), vvv denotes the trachytic, and trachyandesitic lavas of Payún Matru and Payen Liso (PL); thick red line refers to the Carbonilla Fault system.

ment of hundreds of eruptive centres along the W-E Carbonilla fault system (Llambías 1966, González Díaz 1972a). Its stratigraphic basement is represented by the northernmost one of the Tertiary Patagonian basaltic plateaus, defined as Palauco Formation by González Díaz (1979).

The activity of the Payen Volcanic Complex probably started during the Early Quaternary, with a pahoehoe basaltic lava shield and related scoria and spatter cones representing the basal portion of the Payen Volcanic Complex, here after Payen Eastern Shield. Its product partly correspond to the Morado Alto Formation of González Díaz (1972b) and partly to the Basalts III and IV of Groeber (1946).

They were emplaced over the eastern end of the Carbonilla Fault system (Fig. 1). These lavas are pahoehoe basalts rich in horizontal vesicular zones showing large inflated lobes with elliptical croos section (Fig. 2). After a long volcanic hiatus marked by erosion, the Payen Eastern Shield was involved in a new phase of strong eruptive activity and the Carbonilla fault acted again as its summit rift. A large volume of olivine-basaltic lavas covered the shield with large fields of compound and single pahoehoe inflated lava flows. The longest ones reached the Salado river valley at La Pampa province and the Llancanelo Lake to the North. These lava flows were previously mapped by Groeber (1929, 1946), González Díaz (1972a, b, 1979) and Núñez (1976) as a unique huge lava field but were not distinguished the single flows and their exceptional dimensions. Moreover González Díaz (1972a) attributed a sector of this lava flow to the Holocene El Mollar Formation. In addition to this single basaltic lava flow González Díaz (1972a) proposed a vent area near Escorial de la Cruz and a length of about 80 km.

Besides the already cited Pampas Onduladas compound flow, Pasquarè *et al.* (2005) distinguished the Los Carrizales lava field reaching about the same length but showing a very much greater volume (Fig.3). Radiometric dating of Los Carrizales lava field, stratigraphically underlying the younger Pampas Onduladas Lava Flow, yields a K-Ar age of 0.40 ± 0.1 Ma (Melchor and Casadío 1999).

Another pahoehoe basaltic inflated lava field with similar morphology, texture and age, was emplaced along the western flank of the Payen Volcanic Complex. These lavas represent the base of a large and still preserved shield volcano, here named as Payen Western Shield. It was formed by repeated emissions of pahoehoe olivine basalts covered by aa lava flows, showing spectacular channel-levees systems. Three cosmogenic ^{3}He exposure ages on primary lava flow surfaces belonging to El Puente Formation (at ~ 36.31°S; 69.66°W) near the Río Grande river, indicate a Pleistocene age of 41±1 ka (37 ± 3 to 44 ± 2 ka) (Marchetti *et al.* 2006). By the way, the last aa lava flows were very recent as proved by the local oral tradition since the colonial times (González Díaz 1972b). The stratigraphic relations between lavas of the Payen

Figure 2: Section of an inflated pahoehoe lobe with its dense elliptical core from the early activity of the Payen eastern shield volcano.

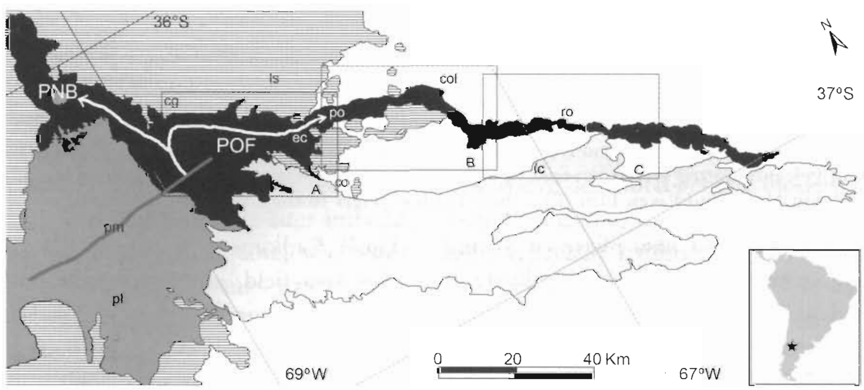

Figure 3: Areal distribution of the inflated pahoehoe lava flows representing the late activity of the Payen Eastern Shield volcano. Black represents the Pampas Onduladas compound flow with its eastern branch (POF) and its northern branch (PNB). Light grey: Los Carrizales lava field, dark grey: central sector of the Payen Volcanic Complex, horizontal lines: pre-Quaternary basement, white: Quaternary Andean piedmont deposits and basaltic lavas from Chachahuen volcanic centres along the southern margin of the figure. The arrows indicate the longitudinal axes of the main branches of the Pampas Onduladas compound flow.
po: Pampas Onduladas, **lc:** Los Carrizales, **ec:** Escorial de la Cruz, **ls:** La Salinilla, **co:** El Cortaderal, **col:** Las Coloradas, **ro:** Rincón del Olmo, **cg:** Cerro Guadaloso, **pm:** Payún Matru, **pl:** Payen Liso.

Western Shield and the remaining portion of the Payen Volcanic Complex, suggest that the Payen Western Shield developed its activity during the entire life of the Complex itself.

After the main growth of the Payen Eastern Shield a new widespread volcanic activity, along the central sector of the Carbonilla Fault system was responsible of the formation of two great trachytic and trachyandesitic stratovolcanoes, called respectively Payen Liso and Payún Matru volcanoes. While Payen Liso was not involved anymore in other relevant volcanic events, the original cone of Payún Matru was partially destroyed by a 8 km wide caldera collapse (dated at around 168 ka; Germa *et al.* 2007). The presence of abundant loose or welded tephra deposits were formerly recognized by Groeber (1933, 1937) and later classified as ignimbrites by González Díaz (1972b).

After the collapse, highly viscous trachytic and trachyandesitic lavas were erupted from intra and extracalderic vents forming thick and levee-bordered flows, well described by Llambías (1966).

The Carbonilla fault provided once more a very efficient feeding system for a new phase of basaltic volcanism developed on the fault terminations. The main vents of this great effusion phase are associated with dense clusters of cinder cones clearly controlled by the main fault and by its several conjugate fractures. This youngest phase of olivine-basaltic lava production was very noticeable in the western side of the Payen Volcanic Complex. Also along the eastern sector of the Carbonilla Fault system both aa and pahoehoe, olivine-basaltic flows outpoured on the south-eastern flank of the Payen Volcanic Complex, and partly covered Pampas Onduladas and Los Carrizales lava fields. The very recent age of the volcanic activity along the eastern sector of the Payen Volcanic Complex is proved by the Holocene age of some cinder cones called "El Rengo Group" (Inbar and Risso 2001). However age determination and statigraphic relationships among the last volcanic activities of the complex needs to be still clarified.

THE EASTERN ARM OF PAMPAS ONDULADAS COMPOUND LAVA FLOW

General description

The Pampas Onduladas flow is an individual basaltic pahoehoe lava flow very clearly recognizable in the satellite images and aerial photos and remarkably evident in the field (Figs. 3, 4, 5).

The uppermost crust of Pampas Onduladas flow, commonly with a maximum thickness of 40-50 cm, appears to be a spongy pahoehoe (Walker, 1989) with around 40 % vol. bubbles covered by a very thin chilled top and whose spherical vesicles have a nearly constant average size of 3-5 mm in diameter (Fig. 6a). Immediately under this skin, microlites begin to appear in the same vesciculated lava. This coupled surface textures and features of Pampas Onduladas flow are remarkably diffused over the entire lava

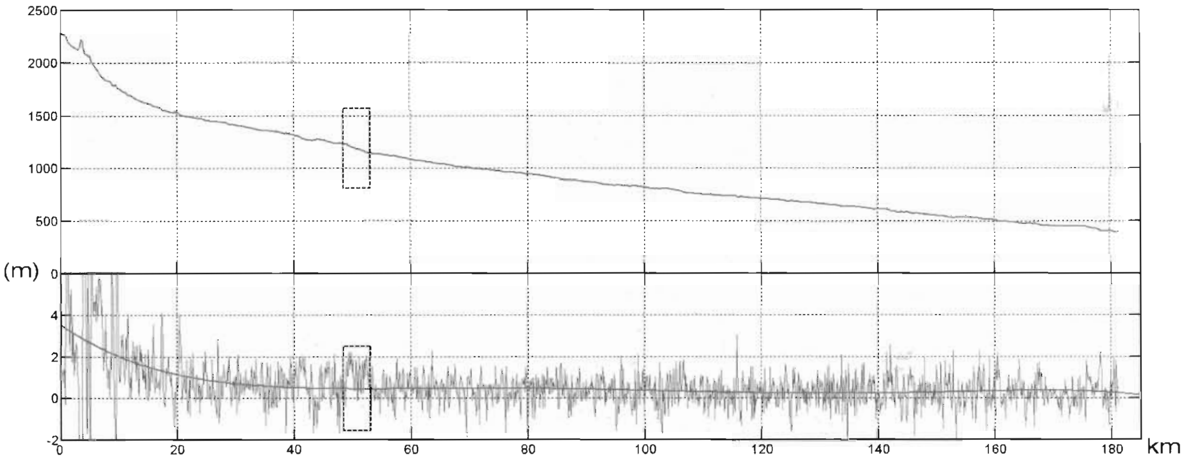

Figure 4: POF longitudinal elevation (top) and slope (botton profile). Vertical scale is highly exaggerated. The rectangles indicate the relatively steep descent of the lava flow East of La Salinilla- El Cortaderal road.

flow. Under this crust the crystallinity increases while the relative abundance of the vesicles sharply decreases. Their size presents a marked variability reaching sizes of many centimetres and their shapes are often irregular (Fig. 6b). This dense lava layer is dissected by regular joint sets which form short and rough polygonal columns and merge at shallow depth into dilated, widely spaced, and curvilinear discontinuities.

Under this layer, and often separated from it by a subhorizontal and billowy physical discontinuity, the dense basalt loses most of its joints and cracks and shows horizontal alignments of great oblate or prolate vesicles, commonly of few decimetres (Fig. 6c). This layer, when entirely visible, gradually passes downward to a more massive rock hosting horizontal short discontinuities formed by coalesced large oblate bubbles (Fig. 6d), or to a dense and massive layer crossed by subvertical joints and microvesiculated pipes (Fig. 6e). This ideal section, collected from few isolated vertical scarps, do not exceed a total thickness of four metres.

The scarcity of erosional scarps or artificial excavations all over the lava flow makes difficult to estimate the total thickness of Pampas Onduladas flow but in a hand-made water-well crosscutting a thick central part of the flow, it has been observed a 15 m thick layered crust formed by several repetitions of the sequence above described. The dense massive layers can reach up to two metres of thickness while the vesiculated layers maintain a decimetric average thickness. Between 15 and 22 metres the water-well reached a massive basalt with high crystallinity (up to 90 % vol.) and larger grain size. Vesicle rich layers are not frequent. The base of the flow is composed by a thin glassy vesicular crust (15-50 cm thick), including fragments of the substratum, which is composed by older volcanic rocks (close to the volcano), or by Miocene-Pliocene deposits (Cerro Azul Formation) near the Salado river valley at La Pampa Province. Its superficial texture is mostly that of a shelly or slabby pahoehoe flow forming a basal, many metres wide, thin platform flanking the main flow.

The Pampas Onduladas flow emission area is located on the eastern sector of the master E-W feeding fracture system of the Payen Volcanic Complex. The vents are constituted by long fissures marked by alignments of scoria cones and spatter ramparts with associated lava ponds, showing evidences of quick temporal and spatial changes of the eruption sources.

In the near-vent area, the Pampas Onduladas flow appears to be constituted by a great number of pahoehoe different uninflated cooling units formed by overriding ropy and slabby pahoehoe flows sometimes channellized into levees. The leeves are formed by broken and tilted lava slabs, and therefore suggest a transition to aa lavas. When the slope decreases from 2° to around 1°(*), the proximal cooling units are to be transformed into several progressively inflated lobes and toes cooled one against the other. The fronts of the single lower lobes appear to be arranged in a unique very large front. In this sector the Pampas Onduladas flow drowned and levelled the underlying nearly horizontal topography can be considered as an uniform very wide flowed, a sheet flow (Fig. 7a, b). The contact between some lobes and the sheet flow is marked by open arcuate tension gashes showing downstream oriented convexity. Several kilometres long fractures, occur also inside the initial portion of the sheet flow. All of them are probably due to the inner traction of the liquid core of the flow on its solidified crust. Some gashes are partly filled by great squeeze-ups having the shape of long vesicle-like swellings, sharply cut by marginal and axial clefts.

Reaching the E-W faulted margin of Cerro Guadaloso Tertiary volcano, the sheet flow divides into two opposite directions: one moving eastward belongs to the Pampas Onduladas flow main branch, the other flowing westward constitutes the Pampas Onduladas flow northern branch (Fig. 3). The total area covered by this huge sheet flow amounts

(*) Slopes were calculated by SRTM (Shuttle Radar Topogra-phy Mission) altimetry data, using ArcInfo.

to 978 km². The sheet flow portion of the main branch of Pampas Onduladas flow, entirely subdues all the underlying topography except some older isolated volcanic cones (Fig. 5a). Its morphology is characterized by a considerable density of tumuli, flat lava rises, and other inflation-related features, which will be described in the next paragraph. From the northern margin of this large lava field some apophyses, up to 10 km in length, spreads in fillings of valleys previously going down towards the area now covered by the main sheet flow. It indicates a markedly depressed palaeotopography here covered by the sheet flow. This is also confirmed by the E-W normal fault scarp representing the margin between Pampas Onduladas flow and the Tertiary volcanic centres of Cerro Guadaloso.

Because of the thick aeolian deposits covering the basal contact of the lava flows, it is difficult to find a complete section of the flow itself and to evaluate its stratigraphy and thickness. Some topographic measurements were performed on the flow apophyses above cited, and an estimate of 20 m as the minimum sheet flow thickness was derived in this area.

East of the La Salinilla-El Cortaderal road, occurs a remarkable altimetric and morphological change, with a relatively steep 40 m descent of the lava flow over a distance of one kilometre (Fig. 4) and a sharp reduction of the average width from 10 to 3 km up to its end. Here the Pampas Onduladas flow is confined along its southern side by a Tertiary volcanic tabular relief and on the northern side by a river channel coming from the San Rafael massif. This place marks also the sudden disappearance of the lava rises, above described as the more widespread superficial features of Pampas Onduladas sheet flow.

In this central sector of the Pampas Onduladas flow, the distribution of tumuli becomes very discontinuous and they tend to be associated in isolated clusters. Their size generally is uneven and in some cases they reach a height of 10-12 metres, never observed in the sheet flow portion of Pampas Onduladas. Tumuli are mostly concentrated in the more depressed portions of the flow, but some of them were placed along the axis of

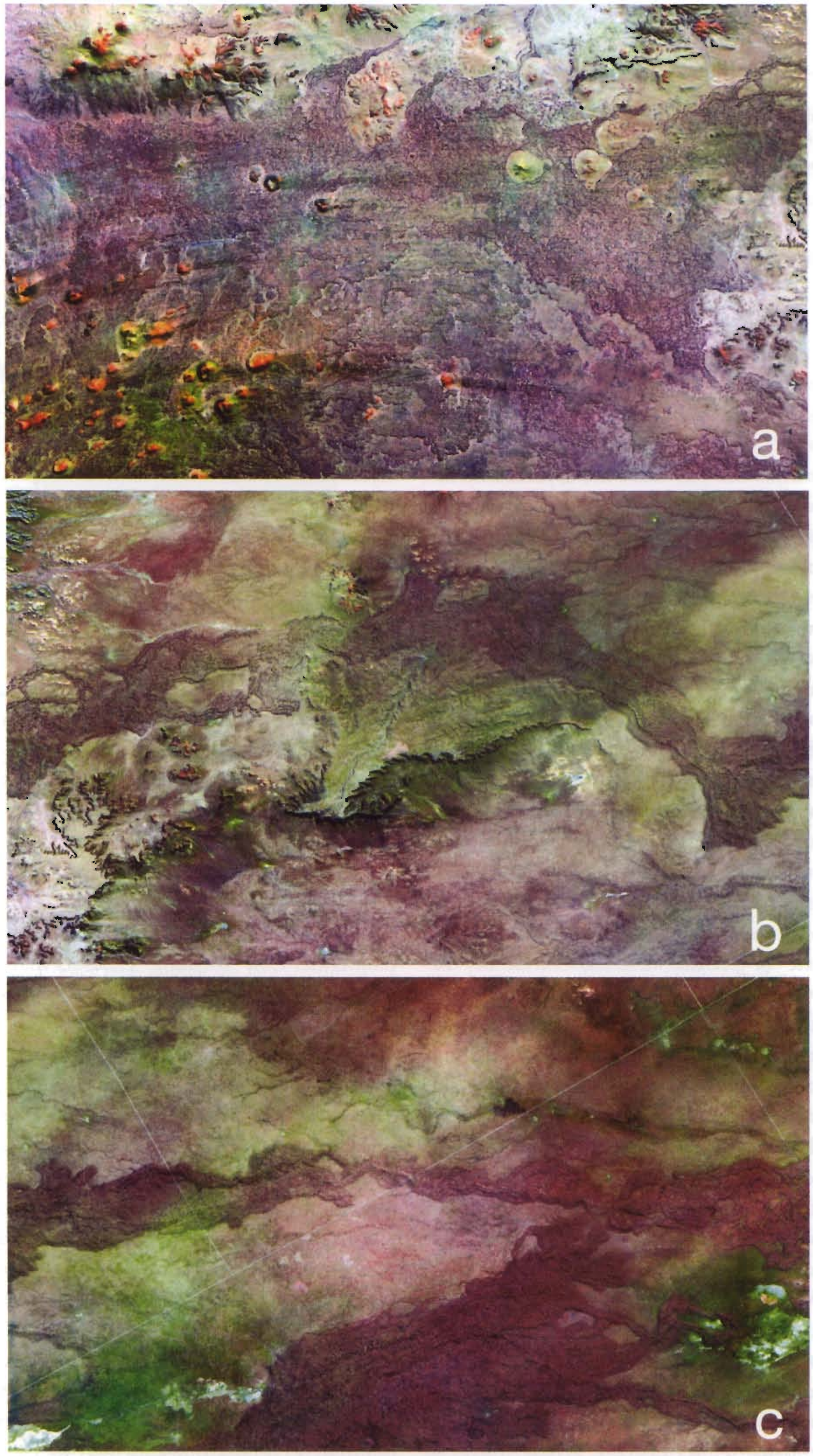

Figure 5: LANDSAT false colour images along POF. LANDSAT 7 ETM + false color composite images (RGB= 742) of different sectors of POF. For their locations see Fig. 3.

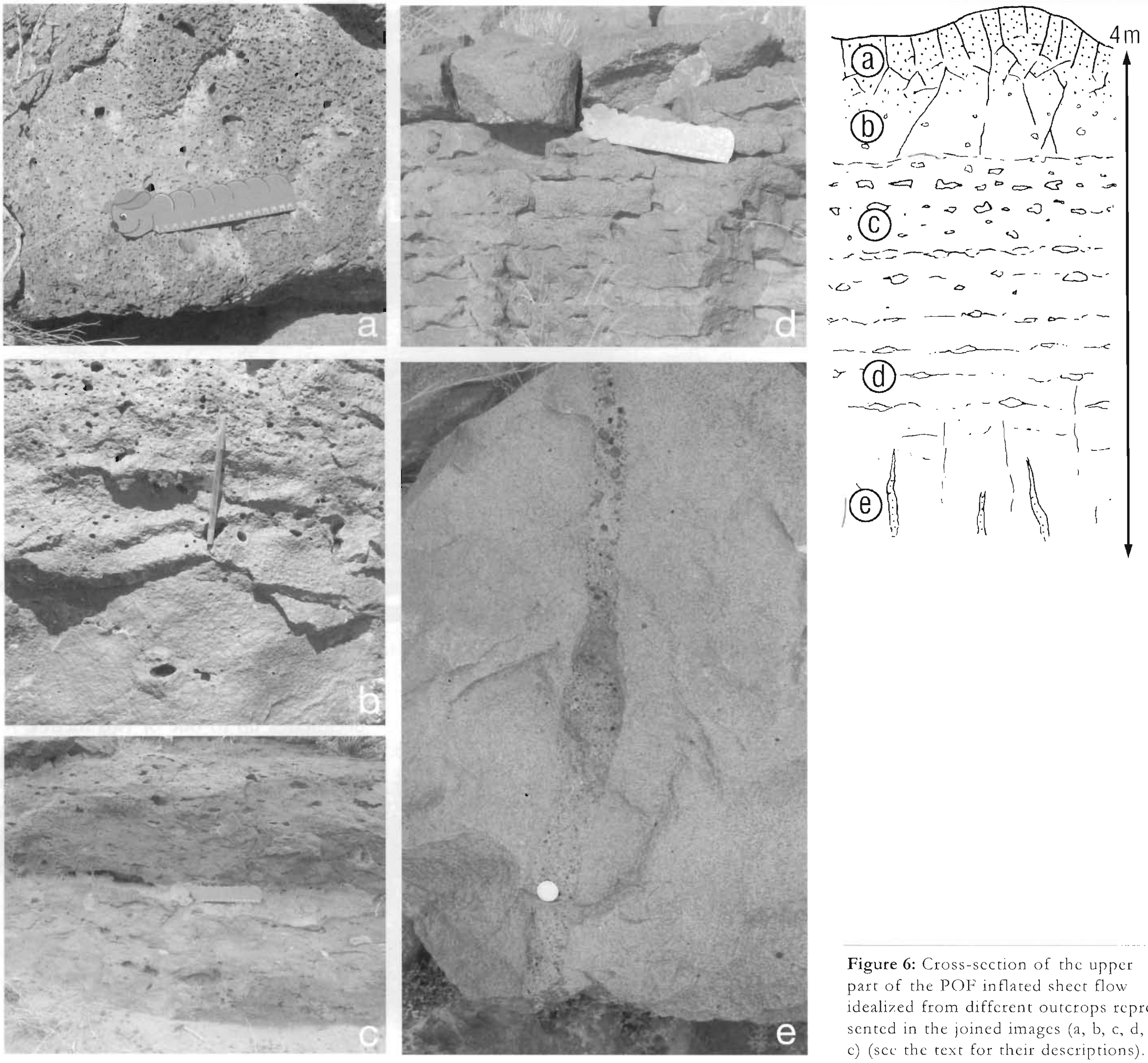

Figure 6: Cross-section of the upper part of the POF inflated sheet flow idealized from different outcrops represented in the joined images (a, b, c, d, e) (see the text for their descriptions).

the long marginal ridges characterizing part of the central portion of Pampas Onduladas flow, at an intervening distance of hundreds of metres (Fig. 5b).

The topographic confinement of Pampas Onduladas flow disappears near Puesto Las Coloradas where the flow sharply deviates towards SSE and obliquely crosses various small creeks belonging to the pampean alluvial piedmont plain 22 km far from Las Coloradas. After another sharp deviation, Pampas Onduladas flow recovers its ESE direction under the obstacle effect of a thick lava fan previously formed by the lava flow itself. From here until the lava flow front, Pampas Onduladas flow does not show any external confinement but nevertheless maintains its tongue-like shape in a well directioned ESE pathway (Fig. 5c).

In the median and terminal sector, Pampas Onduladas flow loses its long-distance morphological and structural uniformity and acquires significant variety along its still long remaining segment. In the initial part of this segment the flow is self-confined by lateral ridges while its flat internal portions present a depressed, slightly hummocky surface. More downstream, near Rincón del Olmo, the flow reduces, for a short stretch, its width to 500 m after which presents a central longitudinal hundreds of metres wide tabula ridge, showing a deep axial cleft partly filled with squeeze-ups of various sizes and shapes, as well as by horizontal clefts indicating a consistent component of lateral inflation. Lateral breakouts from the central ridge produced many short lobes and toes. After this 13 km long segment of Pampas Onduladas flow another bottle neck-like narrowing

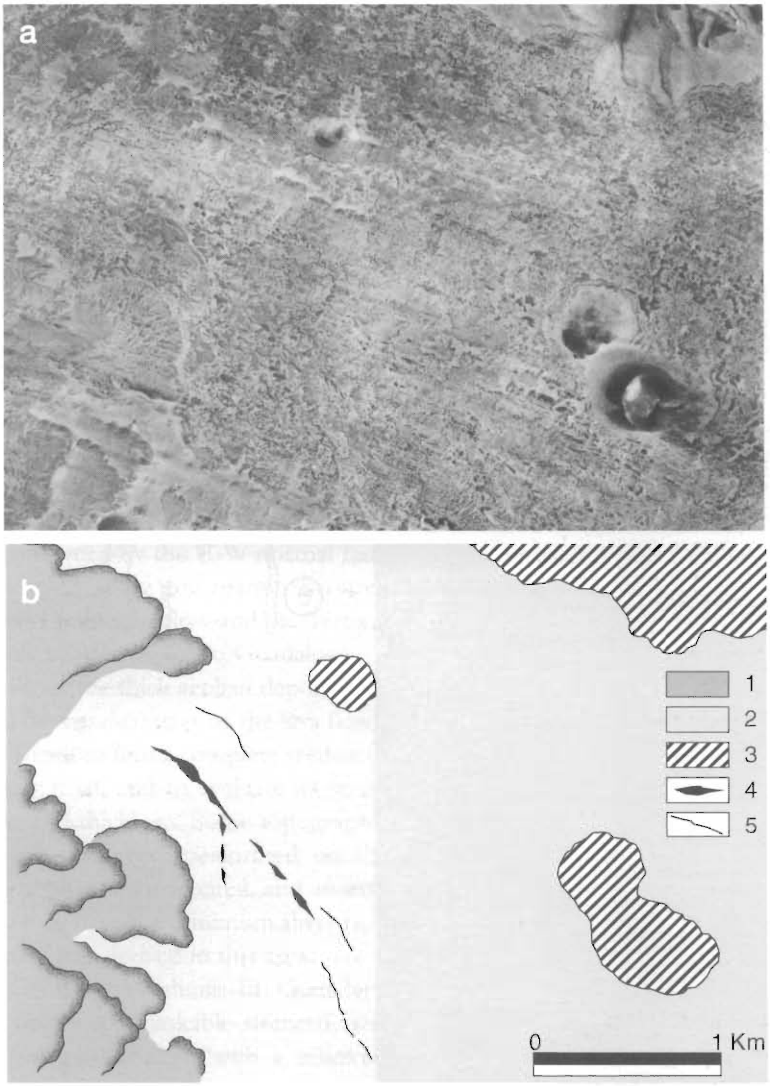

Figure 7: a) Aerial photo of the transitional area between POF near-vent area and POF sheet flow. b) Proposed interpretation of the photo image. 1) overriding and coalescing inflated lobes of the POF near-vent area; 2) POF sheet flow; 3) older volcanic centres; 4) liquid core squeeze-ups; 5) tensional fissures.

of the lava flow marks the end of the previously described tubular ridge and the onset of a new morphological and textural feature of Pampas Onduladas flow, characterizing its final stretch for 40 km onwards. From here the flow is formed by a great number of interconnected, very wide, long and billowy braided lobes, separated by flat elongated depressions covered by aeolian sand from which several large smooth lava hummocks appear. After reaching the alluvial terrace of the Salado river, the lava flow jumps down a 25 metres scarp, resumes its course for 4 km more and ends in chaotic block piles.

Relevant morphological and structural features of Pampas Onduladas sheet flow

The surface morphology of the Pampas Onduladas sheet flow is represented by a great variety of small scale inflation features, strictly depending from the physical processes of lava injected and transported beneath the surface crust. The inflated sheet flow is commonly flanked by a very thin and flat uninflated lava sheet, mostly formed by slabby pahoehoe basalts (Fig.10).

The most common features of this kind are lava rises in the sense proposed by Walker (1991) but showing some morphological and structural characters rather different from their original definition. Other common surface features are tumuli, indirectly connected to the lava rises thorough their apophyses. Finally other positive features are represented by narrow and elongated ridges close to pre-existing obstacles. The lava rises are scattered all over the sheet flow and assume very different sizes and forms, from few thousands of square metres up to square kilometres. Their elevation does not exceed 10 m. The largest lava rises are markedly flat-topped and commonly bounded by monoclinal flexures showing dipping values between 20° and 40°. The hinges are marked by long tensional fractures, sometimes hosting vertical squeeze-ups of a dense basalt, enriched in scattered large plagioclase phenocrysts (Fig. 9).

The upper crust of the lava rises everywhere polygonally jointed, but the size of the polygons varies in width, from few decimetres up to one or two metres. Along the external side of the lava rises, groups of polygons of similar size are often separated from other groups with different size by cooling joints generally at high angles relatively to the margin of the lava rise.

The edge of the flat-topped lava rises is extremely irregular for the presence of elongated, sinuous and convolute apophyses giving to these structures a polypform aspect (Fig. 11). The apophyses are usually lower than the related flat-topped lava rises, except when they contain a tumulus that commonly reaches the topographic level of the lava rise itself. Their longitudinal development registers many axial elevations and depressions, the latter often filled by sandy aeolian deposits. In the axial depressions of the apophyses may appear sub circular, dense basaltic squeeze-ups (Fig. 12). Commonly the apophyses act as connections between adjacent flat-topped lava rises making the sheet flow surface as an uninterrupted network of lava rises and related apophyses.

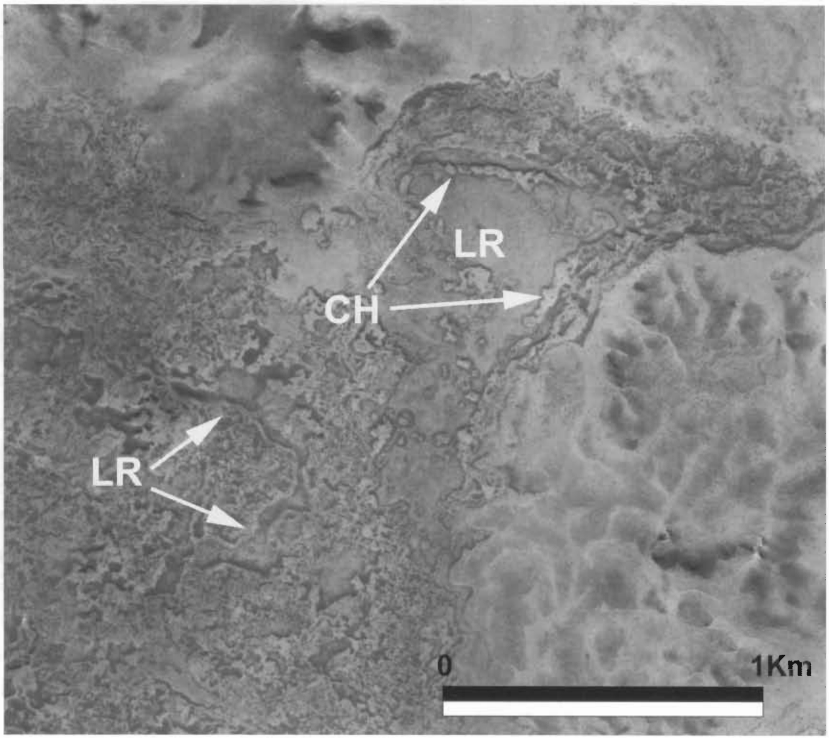

Figure 8: Aerial photo of the northern margin of the POF sheet flow with a lava tongue moving eastward counter current into a pre-existing valley. LR lava rises, CH collapse channels.

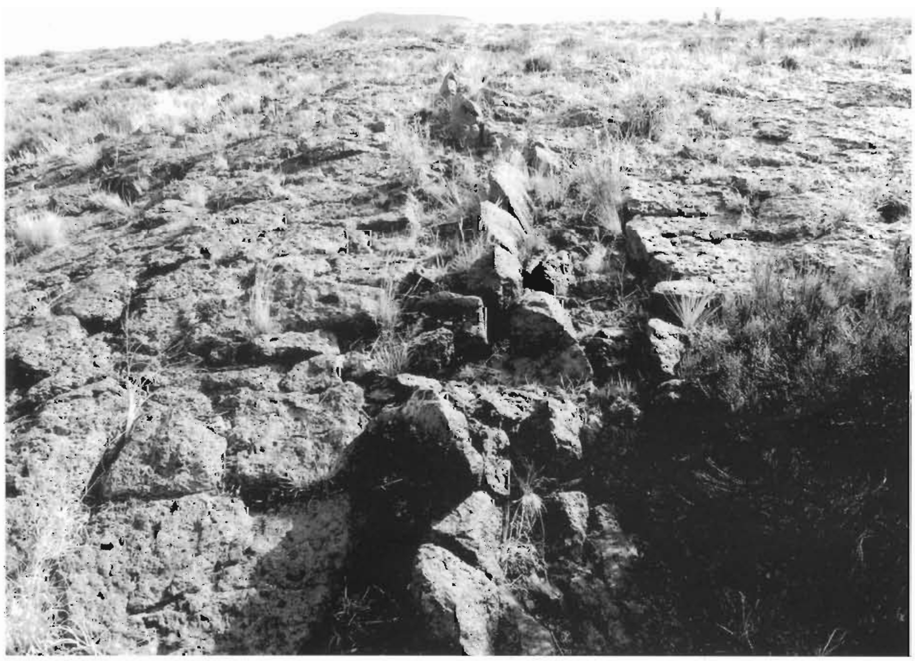

Figure 9: A large, flat lava rise in the central part of the POF sheet flow. Its large marginal cleft is filled by a denser, less vesiculated lava, squeezed-up from the liquid core.

Tumuli are widespread, randomly distributed features, always arising from the above described apophyses and never from the lava rises flat tops. They are either circular or elliptical in plan view (Fig. 13a, b, c) and dissected by summit extensional fissures. They usually measure less than 7 m in height, around 20 m in width and not over 50 m in length. The central fissure clefts often end into triple junctions or more complex branched systems of dilatation fissures. The short columnar joints, always perpendicular to the cooling surfaces, regularly follow the bending of the tumuli surfaces.

Some peculiar surface features were observed along the margins of older isolated cinder or lava cones surrounded by the Pampas Onduladas sheet flow. They are bundles of parallel ridges and channels following the pre-existing obstacles border; the ridges are flat-topped and the channels show a ditch-shaped morphology, ranging from less than 1 m to up to about 10 m in depth and from few metres to over 100 m in width. Their spatial arrangement suggests that they where originated because of a preferential cooling of the sheet flow around the pre-existing obstacles and by the development of thermally preferred pathways inside the liquid core of the inflating flow. The evolution of this frozen area, after the evacuation of the remnants elongated magma batches, was consequently dominated by the partial roof collapse of these previously active pathways. Similar channels were also noticed on some inflated lava flows moving laterally from the main sheet flow body, along its northern margin. Each channel exhibits the side facing towards the flow rim (external side) always steeper and less elevated respect with the side facing towards the inner part of the lava flow (internal side) which, on the other hand, shows gentle inclination and higher elevation (Fig. 8).

Typically the external flanks have an elevation slightly smaller than the main flow body and are characterised by internal slopes steeper than the main body borders. In addition, evidences of brittle to semi-brittle collapse associated to alignments of narrow arched trenches have been found locally at the internal slope of the levee. Such film slides have not been found at the more gentle slope between channels and the main body. Both characteristics suggest they were originated by mechanisms of preferential cooling along the margin of Pampas Onduladas

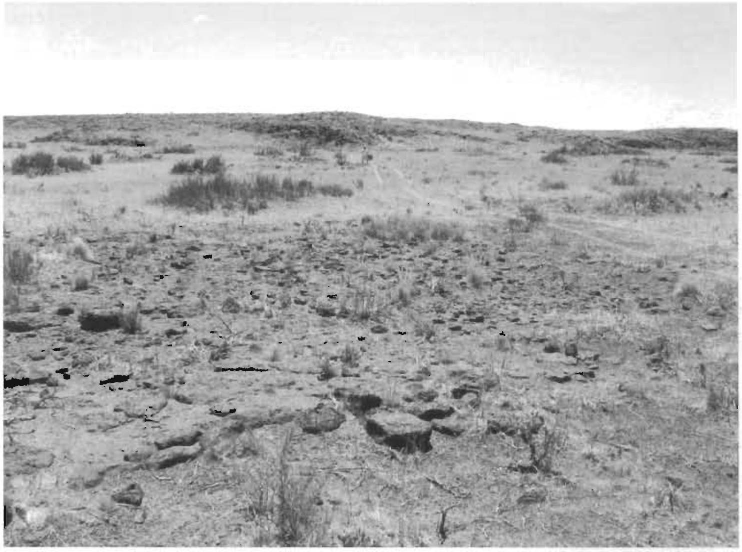

Figure 10: Uninflated, thin slabby pahoehoe sheet (in foreground) along the southern margin of POF sheet flow, herein represented by a large flat-topped lava rise with several sinuous apophyses.

flow and consequent rapid withdrawal of magma from no more alimented transport pathways.

The main general attributes of the Pampas Onduladas sheet flow are a relevant thickness, a great volume of lava, a long-lasting extrusive activity and a vigorous endogenous growth and inflation. They permit to suppose that older flow units of this compound flow are overtopped by the youngest one, whose surface shows a continuous network of flat-topped lava rises and sinuous ridges containing tumuli, without any evidence of important breakouts and subsequent lobe by lobe activity. We consider that the surface morphology of this huge sheet flow is the result of its latest evolutionary step leading to the concentration of the lava transport into narrow pathways, mixing flat sheets with features typical of hummocky flows, partially driven by interconnected capillary tubes but not related to the great distributaries tubes as in the examples proposed by Self *et al.* (1998).

Petrochemical and mineralogical studies of Pampas Onduladas rocks

Several samples have been collected from Pampas Onduladas and adjoining lavas in order to investigate their petrology and geochemistry. The magmatism of the Payen Volcanic Complex mainly belongs to the Na-alkaline series and is prevailingly constituted by basaltic rocks ranging from hawaiites to slightly sub-alkaline basalts (Fig. 14). More evolved magmas, up to trachytic compositions, are however relatively abundant, especially in the volcanism occurred after Pampas Onduladas compound lava flow (González Díaz 1972b). Furthermore, a sub-alkaline series, ranging between basalt to andesite and displaying higher MgO and lower incompatible element contents, seems also to be present among the magmatism older than Pampas Onduladas flow (Figs. 14, 15).

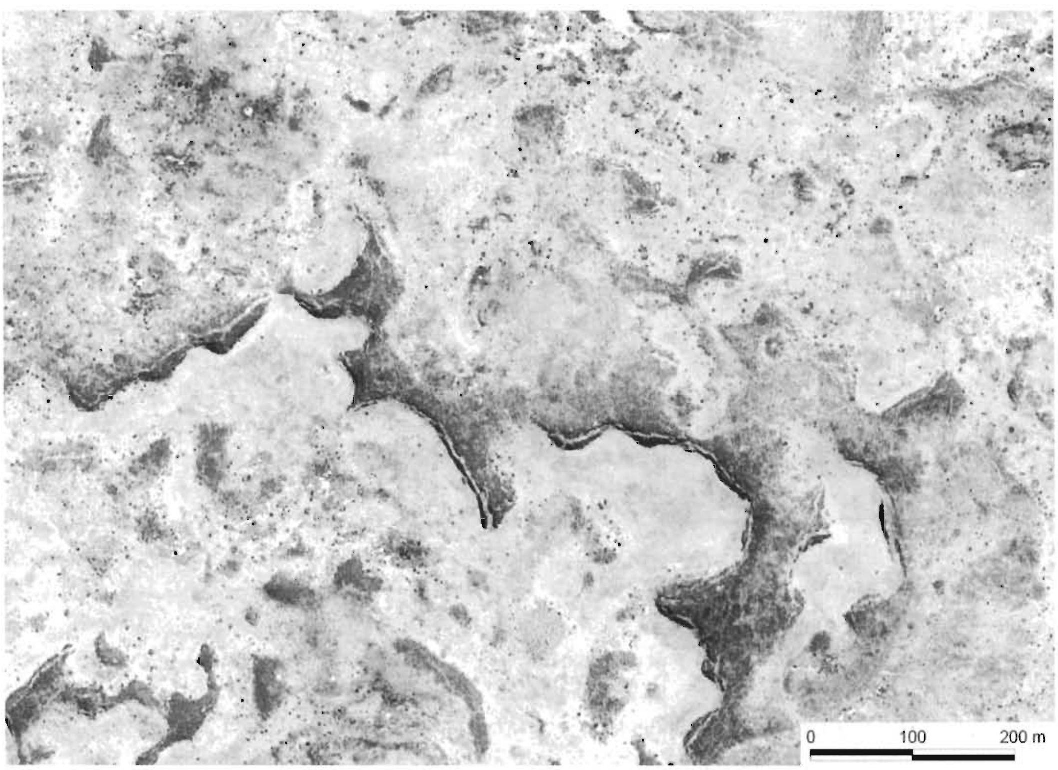

Figure 11: Satellite image of a POF lava rise and its apophyses, partly buried by a thin deposit of aeolian sand. Aster false color composite image (RGB=321).

Figure 12: Roundish squeeze-up of dense basalt in a depressed long ridge connecting two contiguous flat-topped lava rises.

The Pampas Onduladas, the northern branch rocks and the Los Carrizales lava-field are slightly silica-undersaturated to silica-saturated hawaiites with a Na-alkaline character (mainly between 3.8% of normative *ne* and 2.0% of normative *hy*) (Table 1). The two samples of the older Los Carrizales lava-field are slightly less alkaline than Pampas Onduladas rocks, whereas the basic lava flows younger than Pampas Onduladas tend to be more alkaline than them (Figs. 14, 15). Thus, a general increase of the alkaline character with time seems to be occurred.

The Pampas Onduladas, the northern branch rocks and the Los Carrizales lava-field have similar petrographic characteristics. They are holocrystalline rocks with low phenocryst contents of olivine (usually ca. 5 vol.%) ± plagioclase (usually <5 vol.%). Groundmass textures of Pampas Onduladas are intergranular with intergrowth of lath-shaped plagioclase (An_{60-68}) ± Ti-augite ($En_{36}Wo_{46}$-$En_{43}Wo_{44}$) and interstitial olivine (Fo30-70), opaque minerals (Usp_{73-78}) ± Ti-augite (En_{32}Wo46-$En_{40}Wo_{46}$). The groundmass crystal size is variable depending on where the sample is located in the lava flow, which in turn determines different cooling rates. The samples PY34a and PY34b, for example, are collected from a same place of the lava flow, very close to the lava front, but they show different textures of the groundmasses. The internal sample PY34a has a well-defined holocrystalline groundmass, whereas the external sample PY34b shows a porphyritic texture with cryptocrystalline groundmass. Similar petrographic characteristics to those of PY34b are found in a sample (PY44) from Pampas Onduladas northern branch. Olivine phenocrysts (Fo_{72-85}) often show skeletal textures and Cr-Spinel inclusions (Cr# 0.23-0.65). Phenocrysts, micro-phenocrysts and groundmass crystals of olivine are normally zoned. Clinopyroxene from the two samples analyzed for mineral chemistry have slightly different compositions, with Mg-number between 0.65-0.75 and 0.58-0.67 for PY4ar and PY2ar, respectively.

The Pampas Onduladas lava samples display some small variations in major and trace elements (Fig. 16). TiO_2 contents range between 1.5-2.0 wt% and it is well positively correlated with P_2O_5, K_2O, Sr and Nb (Fig. 16, Table 1). PY34b sample is slightly less evolved, with MgO up to 9 wt.% and 400 ppm of Cr, although deriving from the lava front together with PY34a sample. The samples from the Pampas Onduladas - northern branch plot along the continuation of the Pampas Onduladas lava trends at lower TiO_2 and incompatible trace elements, even if the PY44 sample has similar composition with the sample PY34b. The two samples of Los Carrizales lava-field are slightly different in composition (TiO_2 = 1.3 - 1.6 wt%; Fig. 16) and tend to have lower trace element contents.

The Rare Earth Element (REE) patterns of Pampas Onduladas rocks are typical for alkaline basalts with fractionated heavy and light REE (Fig. 17a). REE patterns of Pampas Onduladas northern branch plot in the same field of Pampas Onduladas patterns, at slightly lower LREE enrichments, whereas Los Carrizales lava-field has lower REE contents and light/heavy REE fractionation.

Patterns of incompatible trace elements normalised to the primordial mantle have similar shapes for all the samples reported in Figure 17b, with Los Carrizales lava-field being less enriched in incompatible elements. The patterns have evident peaks for Ba and K and negative anomalies for Nb-Ta and Th-U, whereas P ranges from negative to positive anomaly.

Sr and Nd isotope ratios of Pampas Onduladas rocks are well correlated, showing slight variations, except for PY34b sample, which have similar isotope ratios to PY44 sample from Pampas Onduladas northern branch (Fig. 18). Nd isotope ratios are also well positively correlated with silica (Table 1).

TABLE 1: Major and trace element data, Sr and Nd isotope ratios and C.I.P.W. normative calculations of samples from POF and Los Carrizales lava-field.

	PY2ar	PY3ar	PY6ar	PY16	PY20	PY23	PY24	PY25	PY34a	PY34b	SAL1	SAL4	PY39	PY40	PY42	PY43	PY44	PY36	PY48b
	POF	**POF**	**POF**	**POF**	**POF**	**POF**	**POF**	**POF**	**POF**	**POF**	**POF**	**POF**	**POF-N**	**POF-N**	**POF-N**	**POF-N**	**POF-N**	**LosCar**	**LosCar**
SiO_2	48,66	48,41	48,41	47,82	47,73	47,56	47,25	47,86	48,75	47,25	48,86	47,86	48,75	48,37	47,76	47,74	46,65	47,74	49,32
TiO_2	1,75	1,93	1,75	1,63	1,65	1,90	1,83	1,77	1,73	1,49	1,85	1,78	1,57	1,70	1,63	1,46	1,50	1,30	1,61
Al_2O_3	16,93	16,48	16,75	17,88	18,28	17,53	17,20	17,56	17,49	16,83	16,48	16,20	17,80	17,73	17,68	17,33	17,41	16,92	17,67
Fe_2O_3	11,30	11,43	11,26	1,58	0,76	1,52	0,43	1,91	0,86	1,71	11,21	11,10	1,68	0,99	0,47	3,65	1,02	0,25	1,51
FeO	-	-	-	9,28	9,27	9,22	10,22	9,24	9,79	9,10	-	-	8,29	9,13	9,70	6,54	9,01	10,37	8,74
MnO	0,16	0,17	0,16	0,14	0,16	0,16	0,16	0,16	0,16	0,18	0,17	0,16	0,16	0,16	0,16	0,17	0,16	0,16	0,16
MgO	7,53	7,05	7,45	7,91	7,61	6,87	7,35	7,30	7,62	9,14	6,96	7,05	7,13	7,14	7,24	8,17	8,39	8,15	7,01
CaO	9,05	9,37	9,28	8,36	9,53	9,50	9,39	8,96	8,75	9,32	9,78	10,17	9,28	8,96	9,43	9,50	9,78	9,25	8,14
Na_2O	3,39	3,47	3,44	3,82	3,27	3,47	3,50	3,46	3,50	3,43	3,74	3,61	3,62	3,74	3,63	3,58	3,25	2,98	4,08
K_2O	1,22	1,25	1,21	1,04	0,84	1,01	0,91	0,93	0,86	0,82	1,28	1,22	0,94	0,78	0,77	0,85	0,85	0,68	0,92
P_2O_5	0,45	0,50	0,46	0,39	0,32	0,37	0,35	0,35	0,29	0,26	0,44	0,44	0,28	0,28	0,26	0,30	0,30	0,17	0,27
LOI	0,01	0,22	0,06	0,15	0,58	0,91	1,42	0,51	0,20	0,47	0,01	0,67	0,51	1,02	1,27	0,70	1,70	2,04	0,57
Total	100,45	100,28	100,23	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,60	100,30	100,00	100,00	100,00	100,00	100,00	100,00	100,00
or	7,25	7,44	7,21	6,17	4,99	5,96	5,36	5,49	5,08	4,84	7,58	7,26	5,56	4,59	4,52	5,06	5,01	4,01	5,45
ab	27,15	27,35	26,29	26,21	27,59	28,52	29,62	28,78	29,60	23,95	24,67	25,11	29,51	31,64	30,73	26,82	27,50	25,21	33,74
an	27,53	25,89	26,90	28,54	32,67	29,28	28,50	29,65	29,45	28,13	24,45	24,57	29,56	29,29	29,64	28,76	30,39	30,74	27,20
ne	0,92	1,21	1,65	3,33	0,05	0,45	0,00	0,27	0,00	2,75	3,81	3,06	0,61	0,00	0,00	1,93	0,00	0,00	0,42
di	11,93	13,29	13,18	7,74	7,19	7,97	5,57	7,62	8,85	10,97	17,38	15,63	9,32	5,65	6,07	9,83	4,42	0,91	6,37
hy	-	-	-	-	-	-	1,37	-	0,54	-	-	-	-	2,06	0,52	0,00	1,60	17,92	0,00
ol	18,86	17,47	18,28	21,63	20,41	19,27	20,06	20,75	20,06	22,82	15,60	16,47	18,77	18,66	20,01	20,64	21,79	11,69	19,90
mt	1,96	1,99	1,96	2,05	1,91	2,03	2,03	2,10	2,02	2,04	1,94	1,93	1,88	1,92	1,94	1,89	1,90	2,03	1,94
il	3,34	3,69	3,35	3,10	3,13	3,60	3,46	3,36	3,29	2,83	3,53	3,41	2,98	3,23	3,09	2,78	2,84	2,47	3,05
ap	1,05	1,17	1,07	0,90	0,75	0,85	0,80	0,82	0,66	0,59	1,02	1,03	0,66	0,64	0,59	0,71	0,68	0,39	0,64
cc	0,02	0,51	0,13	0,34	1,32	2,07	3,23	1,16	0,45	1,07	0,02	1,53	1,16	2,32	2,89	1,60	3,87	4,63	1,30
V	202	231	205	133	192	179	187	188	152	197	210	217	202	183	157	-	191	141	-
Cr	210	190	190	298	196	221	256	256	247	417	240	220	231	254	251	306	383	263	229
Co	39	37	36	44	43	45	46	45	50	53	42	41	42	47	46	44	49	53	47
Ni	110	100	100	109	73	82	97	103	115	190	110	110	87	89	95	142	151	192	105
Sc	22	26	23	-	-	-	-	-	-	-	23	25	-	-	-	-	-	-	-
Cu	40	40	40	52	43	46	47	51	43	60	60	40	34	48	46	43	52	47	49
Zn	90	90	80	87	86	94	95	94	97	93	100	100	86	96	94	86	87	101	93
Rb	23	24	23	18	15	15	15	15	14	18	23	26	13	11	12	16	17	14	10
Sr	622	610	627	600	587	583	571	564	553	518	627	621	519	477	490	522	531	351	466
Y	22,5	25,7	21,7	16	16	16	16	18	15	16	21,6	23,5	16	17	15	13	15	14	15

	PY2ar	PY3ar	PY6ar	PY16	PY20	PY23	PY24	PY25	PY34a	PY34b	SAL1	SAL4	PY39	PY40	PY42	PY43	PY44	PY36	PY48b
Zr	146	161	152	*123*	*123*	*130*	*124*	*125*	*119*	*118*	151	144	*109*	*131*	*117*	*113*	*118*	*104*	*122*
Nb	16,1	17,5	15,6	*15*	*14*	*18*	*17*	*17*	*14*	*11*	16,2	15,1	*11*	*14*	*11*	*10*	*11*	*10*	*14*
Cs	0,6	0,7	0,7	0,3	0,5	0,3	0,3	0,4	0,3	0,7	0,7	0,8	0,2	0,2	0,2	-	0,5	0,2	-
Ba	315	375	326	*305*	*356*	*293*	*257*	*251*	*238*	*298*	303	443	*306*	*231*	*303*	*326*	*332*	*266*	*240*
La	19,9	21,3	19,9	14,9	16,0	17,7	16,9	16,6	14,4	16,2	19	19,1	14,2	14,2	14,3	*17*	16,5	11,4	*16*
Ce	41,7	44,7	41,5	31,5	34,7	37,8	36,2	36,1	30,9	35,0	40,2	40,8	31,3	31,6	31,6	*40*	35,9	24,7	*32*
Pr	5,45	5,82	5,35	3,91	4,45	4,64	4,46	4,44	3,85	4,40	5,12	5,44	4,03	4,06	3,75	-	4,50	3,06	-
Nd	21,9	23,5	22,4	17,3	20,1	20,9	20,0	20,5	17,5	19,5	20,9	21,6	18,5	18,5	17,3	*24*	20,1	14,2	*18*
Sm	5,4	5,8	5,28	4,28	4,98	5,00	4,93	5,13	4,47	4,78	5,13	5,36	4,57	4,81	4,61	-	4,77	3,57	-
Eu	1,83	1,97	1,84	1,57	1,82	1,84	1,84	1,88	1,63	1,73	1,81	1,86	1,64	1,80	1,64	-	1,69	1,42	-
Gd	4,94	5,48	4,96	4,27	4,86	4,94	4,81	5,00	4,39	4,52	4,8	5,14	4,48	4,97	4,43	-	4,66	3,87	-
Tb	0,8	0,88	0,8	0,69	0,79	0,80	0,78	0,82	0,72	0,76	0,78	0,81	0,73	0,79	0,71	-	0,74	0,66	-
Dy	4,49	4,94	4,53	3,86	4,41	4,37	4,37	4,45	4,03	4,24	4,52	4,53	4,26	4,52	3,96	-	4,25	3,75	-
Ho	0,84	0,92	0,81	0,71	0,85	0,83	0,82	0,81	0,74	0,79	0,82	0,83	0,78	0,85	0,74	-	0,79	0,70	-
Er	2,27	2,48	2,25	1,88	2,26	2,21	2,17	2,20	2,03	2,14	2,24	2,26	2,12	2,32	2,05	-	2,22	1,93	-
Tm	0,322	0,346	0,314	0,257	0,303	0,304	0,290	0,299	0,272	0,295	0,312	0,317	0,294	0,318	0,285	-	0,319	0,261	-
Yb	1,96	2,16	1,93	1,53	1,80	1,80	1,73	1,78	1,62	1,83	1,96	1,96	1,77	1,93	1,71	-	1,95	1,56	-
Lu	0,282	0,32	0,277	0,222	0,271	0,254	0,257	0,266	0,224	0,269	0,288	0,291	0,252	0,273	0,239	-	0,271	0,231	-
Hf	3,7	4,1	3,8	2,5	3,3	3,4	3,2	3,3	3,0	3,1	3,6	3,6	3,0	3,4	2,9	-	3,2	2,8	-
Ta	1,25	1,33	1,21	0,73	0,68	1,00	0,95	0,93	0,71	0,55	1,27	1,12	0,50	0,78	0,56	-	0,55	0,44	-
Pb	-	-	-	*3*	-	*2*	*2*	*1*	-	*6*	-	-	*2*	*2*	*1*	-	*2*	*2*	*3*
Th	2,84	3,21	3,09	1,46	1,64	1,68	1,61	1,62	1,37	2,27	2,99	2,73	1,79	1,17	1,49	-	2,35	1,25	-
U	0,78	0,8	0,71	-	0,49	0,49	0,46	0,46	0,35	0,65	0,72	0,7	0,28	0,36	0,33	-	0,65	0,36	-
$^{87}Sr/^{86}Sr$	0,703762	0,703759	0,703811	-	0,703900	0,703833	-	-	0,703897	0,704151	0,703771	0,703848	-	-	-	-	0,704188	-	-
2 σ	0,000007	0,000007	0,000007	-	0,000007	0,000008	-	-	0,000007	0,000006	0,000007	0,000007	-	-	-	-	0,000006	-	-
$^{143}Nd/^{144}Nd$	0,512820	0,512823	0,512809	-	0,512794	0,512807	-	-	0,512810	0,512752	0,512822	0,512808	-	-	-	-	0,512749	-	-
2 σ	0,000005	0,000005	0,000005	-	0,000005	0,000005	-	-	0,000005	0,000005	0,000004	0,000006	-	-	-	-	0,000005	-	-
easting	444603	440785	458083	532164	521295	554782	572621	573798	634291	634291	526156	524102	485440	482408	491684	491253	495935	631469	512255
northing	5982382	5969489	5955635	5972301	5983640	5964883	5963385	5954269	5907373	5907373	5985354	5983367	6033171	6013689	6005244	6003427	6005137	5897830	5955121

Major and trace element analyses are determined by X-Ray Fluorescence (data in italics) at the Department of Earth Sciences of Florence, Italy, and by ICP-MS at Actlabs, Canada. Sr and Nd isotope ratios were analysed at the Department of Earth Sciences of Florence using the analytical procedures reported in Avanzinelli *et al.* (2005). POF = Pampas Onduladas lava flow; POF-N = Northern Branch of Pampas Onduladas lava flow; LosCar = Los Carrizales lava-field.

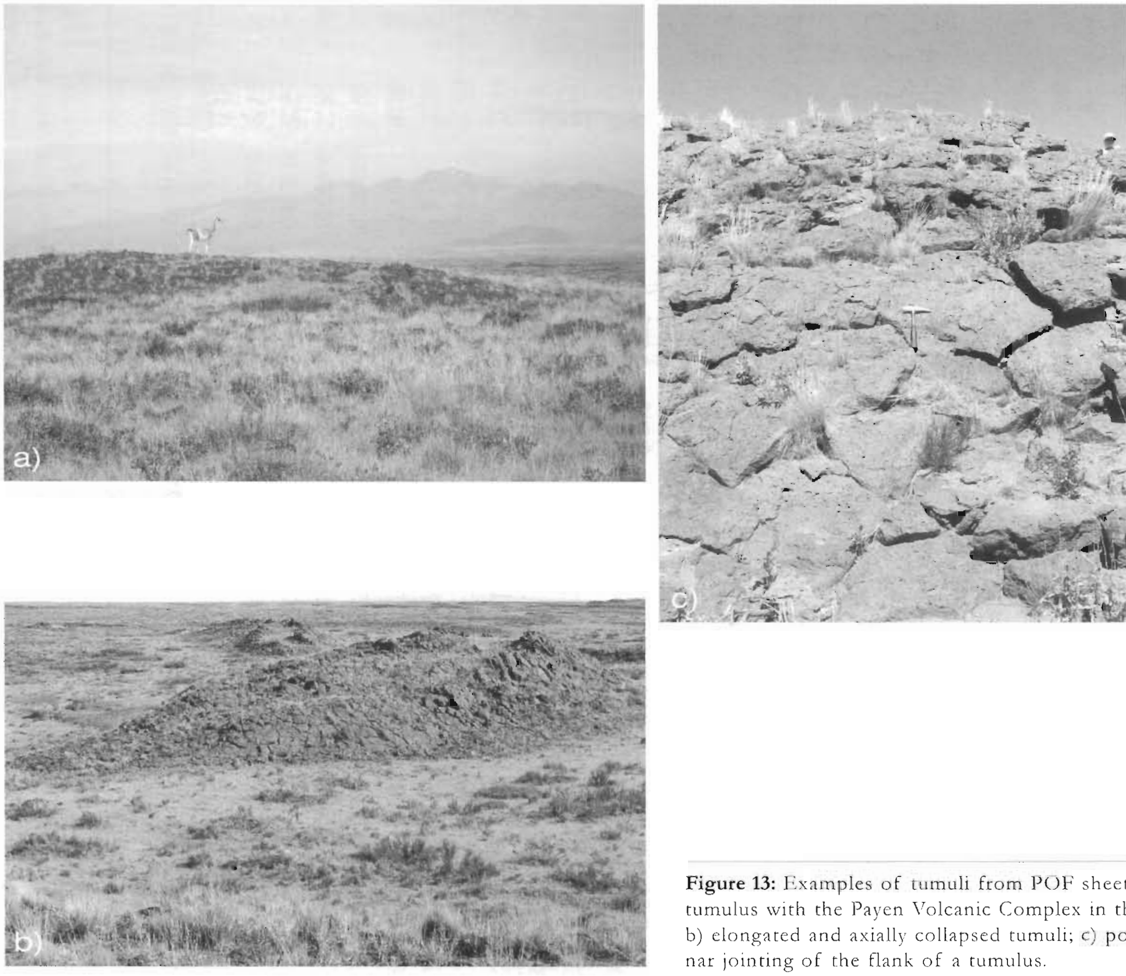

Figure 13: Examples of tumuli from POF sheet flow. a) large tumulus with the Payen Volcanic Complex in the background; b) elongated and axially collapsed tumuli; c) polygonal columnar jointing of the flank of a tumulus.

These results have shown that Pampas Onduladas composition is slightly variable and form variation trends together with the Pampas Onduladas Northern Branch rocks (Fig. 16). In particular, one sample collected at the Pampas Onduladas lava front (PY34b) has compositional characteristics very similar to the Pampas Onduladas Northern Branch rocks (more close to the PY44 composition). These evidences strongly suggest that the Pampas Onduladas northern branch flow was outpoured together with the main Pampas Onduladas lava flow, at least during the eruption of PY34b lavas and similar.

The compositional variations of Pampas Onduladas and the northern branch rocks can be explained by a little fractional crystallization of olivine + Cr-spinel, which leads to increase TiO_2 together with K_2O and incompatible trace elements and to decrease MgO, Cr and other compatible trace element contents. Sr and Nd isotope ratios are negatively correlated with the degree of magma evolution. Indeed, the highest $^{87}Sr/^{86}Sr$ and lowest $^{143}Nd/^{144}Nd$ values have been registered in the rocks with the highest MgO and Cr contents. These correlations suggest the occurring of a crustal assimilation process similar to that proposed by Huppert and Sparks (1985) and Devey and Cox (1987) and found to have acted in several magma systems of arc volcanoes (e.g., Francalanci *et al.* 2007 and reference therein). According to this process, hotter mafic magmas are able to assimilate higher amounts of crustal material during their ascent to the surface than cooler, more evolved liquids, thus changing at higher extent their isotopic signatures. The fact that higher Sr isotope ratios are found in the samples PY44 and PY34b (Fig. 18), which also show petrographic textures indicating faster cooling probably in the external part of the lava flows, might indicate some sort of lava-bed-rock digestion by the most mafic lava flows during their emplacement.

According to light and heavy REE fractionation (Fig. 17a), the parental magmas of Pampas Onduladas rocks are generated in a garnet lherzolite by small degrees of mantle partial melting, leaving garnet in the residue of melting. The negative anomalies of Nb and Ta in patterns of figure 17b suggest that, in spite of their geodynamic setting, mantle source of Pampas Onduladas parental magmas was probably affected by slab-derived metasomatism.

Temperature and viscosity of Pampas Onduladas lavas. Due to the high mobility of this flow, it is of fundamental importan-

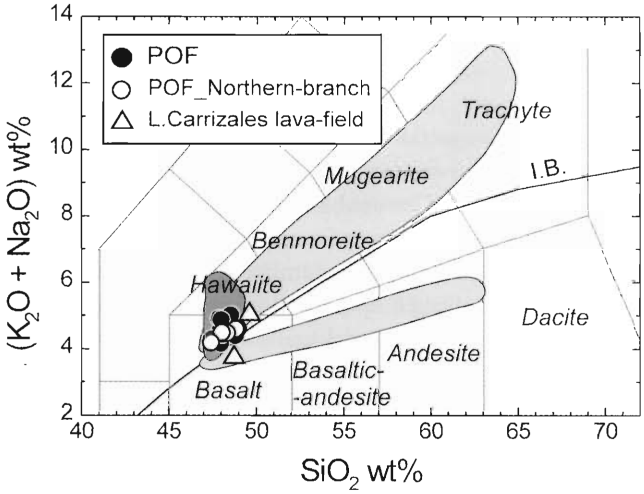

Figure 14: Total Alkali-Silica classification diagram (Le Bas *et al.* 1992) for rocks belonging to the Payen Volcanic Complex. The grey fields report the compositions of the analysed samples from older rocks (light grey fields) and younger rocks (dark grey field) than the Pampas Onduladas compound lava flow and the Los Carrizales lava-field. I.B. = Irvine and Baragar (1971) line. Rocks are reported on water-free basis.

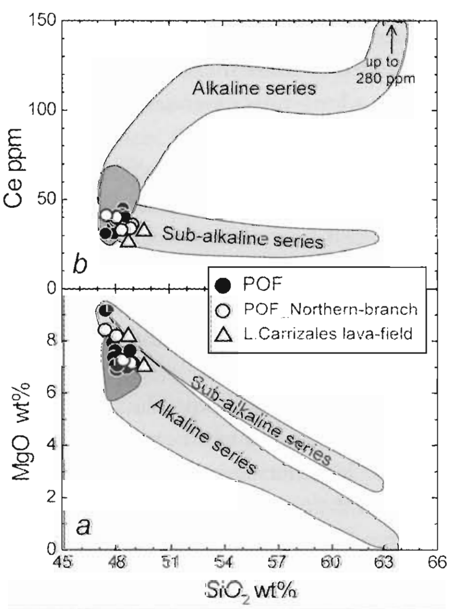

Figure 15: Diagrams of silica versus MgO and Ce for POF and PNB lava flows and Los Carrizales lava-field. The compositional fields of older rocks (light grey fields) and younger rocks (dark grey field) than the Pampas Onduladas compound lava flow and the Los Carrizales lava-field are also reported.

ce to estimate the temperature and viscosity of these magmas. Thus, we used mineral and whole rock chemistry to calculate these rheological parameters. Temperature calculations of Pampas Onduladas lavas, based on mineral/liquid geothermometers (Roeder and Emslie 1970, Roeder 1974, Nielsen and Drake 1979), give values of 1130-1160 °C. Viscosity of Pampas Onduladas flow has been calculated by chemical analyses, using algorithms of Shaw (1972) and Bottinga and Weil (1972), at 1100 and 1200 °C and with 0.5-2% volatile elements (assuming a phenocryst-free and voids-free magma). The calculated viscosity values are low, ranging between 3-73 Pa*s, in agreement with the high mobility of Pampas Onduladas lava flows.

CONCLUSIONS

Pampas Onduladas compound lava flow belongs to the fissural Payen Volcanic Complex and originated during a single long-lasting eruption, when a volume of 33 km³ was emitted from the eastern tip of the Carbonilla Fault system, the huge E-W structure which controlled the growth of the Complex during its entire life. Pampas Onduladas flow outpoured from the summit rift of a large elongated shield volcano, now partially covered with younger volcanic products. The active rift fissures measured about 16 km in length and the lava moved mostly northward with minor outflows in the opposite direction. After reaching a very large saddle of the Tertiary basement, the lava flow diverged into two opposite paths, one of them flowing in ESE direction (Pampas Onduladas flow), for a total distance of 181 km from its source, and the other following a NW direction for 60 km away from the divergence point (Pampas Onduladas northern branch). Pampas Onduladas flow is the longest known Quaternary individual lava flow on Earth, approaching in dimensions and shape some long lava flows of the terrestrial planets.

From a compositional point of view, Pampas Onduladas samples are hawaiites with a low phenocryst content of olivine and plagioclase. Trace element patterns suggest that mantle source of Pampas Onduladas parental magmas was probably affected by metasomatism from the subducted slab below the Andean continental margin. The small compositional variations observed among the different Pampas Onduladas samples indicate olivine + Cr-spinel fractional crystallization associated with crustal assimilation. The latter process, in particular, has been more efficient in the most mafic magmas of Pampas Onduladas rocks, probably due to its higher temperature. Petrochemical data also confirm that Pampas Onduladas northern branch flow belongs to the same eruptive event of Pampas Onduladas flow. On the bases of mineral and whole rock chemistry a temperature of 1130-1160 °C and a viscosity between 3-73 Pa*s (at 1100 and 1200 °C and with 0.5-2% volatile elements) have been calculated. Those physical values can be considered, together with a very low cooling rate and a sustained and long lasting effusion rate, the main causes of the extremely long transport system of Pampas Onduladas flow.

The textural analysis of Pampas Onduladas flow shows that the upper crust of the lava flow is commonly layered and characterized by an upper layer of spongy pahoehoe (Walker 1989), rich in spherical vesicles rapidly passing below to a massive basalt containing a few larger irregular scattered vesicles. The upper layer, with an average thickness of 40-50 cm, shows a rough columnar jointing whose roots are commonly interrupted by column-normal cracks at the contact with the underlying layer. The latter is constituted by a massive basalt, up to 2-3 m thick, showing large, horizontally oriented oblate and prolate vesicles, often coalescing into discrete planar disconti-

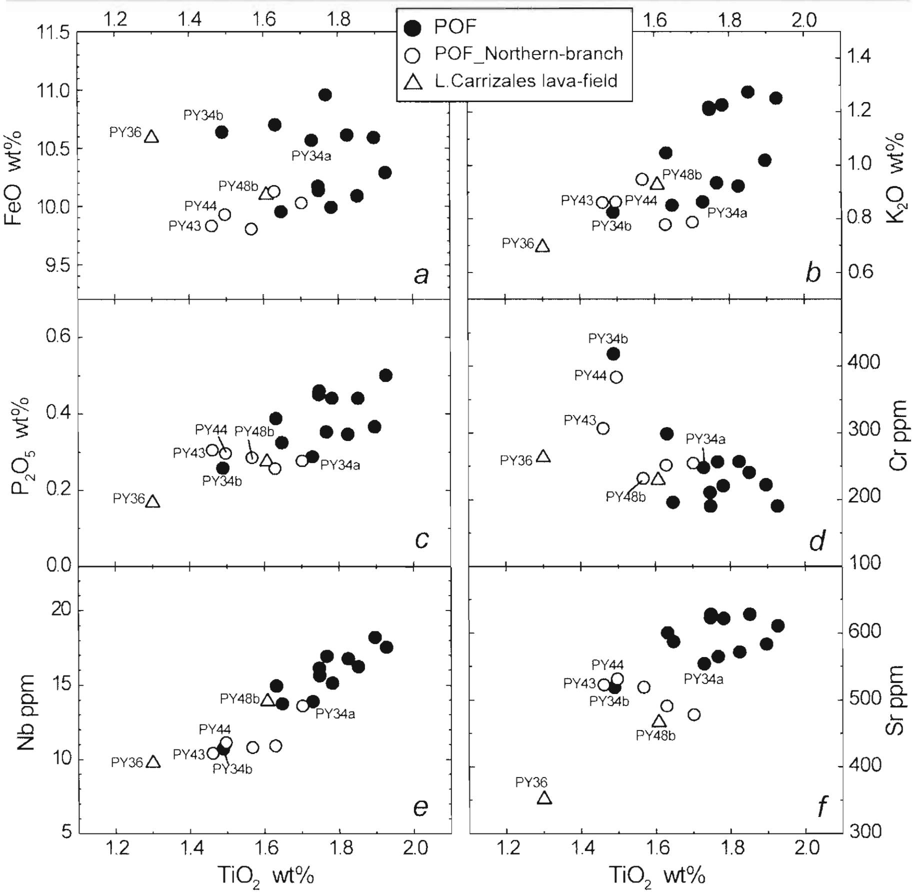

Figure 16: Diagrams of TiO2 plotted against FeO, K2O, P2O5, Cr, Nb and Sr for POF and PNB lava flows and the Los Carrizales lava-field. The names (e.g., PY34a) of some samples are also reported on the diagrams.

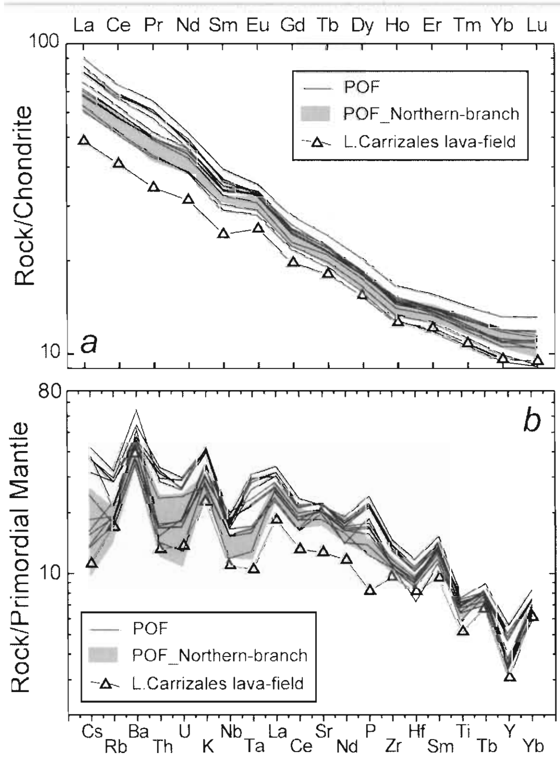

Figure 17: Patterns of Rare Earth Elements (REE) and incompatible trace elements normalised to the a) Chondrite and b) Primor-dial Mantle compositions (Sun and McDonough 1989), respectively, for POF and PNB lava flows and Los Carrizales lava-field.

nuities as well as vertical vesicle pipes. The upper layer must have been formed initially under low strain rates, when the vesicles and the dissolved gas were carried away from the vent by a fluid lava having probably a Newtonian rheology. The bubbles failed to escape because of the sharp increase of the viscosity due to the great number of such undeformed rigid spheres (Pinkerton and Stevenson 1992) enclosed in a very rapidly cooling lava. Under this thin primitive crust the liquid core moved and inflated, progressively losing its gas without significant cooling. The upper part of this dense core appears to be disrupted by systems of oblique and curved joints, probably because of changes in directions of local main stresses and thermal perturbations during a long-time extended cooling process.

The morphological and textural analysis of Pampas Onduladas flow permits to distinguish four main sectors in its longitudinal development (Fig. 19) which can help the understanding of the long and complex emplacement history of the flow itself.

The first sector is the product of sustained extrusion and rapid emplacement of basaltic lava during a single, long-lasting eruptive event and is characterized by very large flow lobes, coalescing and overriding each other on a slope of about 2°-3°, often originated at outbreaks from the inflated front of a previous lobe.

The second sector is represented by a pahoehoe sheet flow covering a large tectonic depression extended beyond the Eastern foothill of the Payen Volcanic Complex, showing a uniformly levelled surface with a slope of 1°-0.80° and missing significant outbreaks. The overall morphology, shape and dimensions of this sector should suggest an origin regulated by a powerful, continuous and long-lasting magma emplacement, where a uniform liquid interior cooled as a continuous sheet-like body, as in the continental flood basalts (Hon *et al.* 1994, Self *et al.* 1998). The initial pahoehoe flow submerged and levelled the underlying topographic irregularities and created a smooth, subhorizontal lava field and created the essential external conditions for the development of the Pampas Onduladas sheet flow. These conditions changed during the late stage of its life, probably because of thermal perturbations in the previously uniform process of conductive cooling inside the sheet flow itself, according to the model proposed by Hon *et al.* (1994). This change is attested by the development of a network of sinuous, tumulus-bearing ridges, interconnecting the flat-topped lava rises, probably related to a system of capillary lava tubes of late generation. This evolution, deserving in this case further investigations, determined the coexistence of sheet flow and hummocky flow features in the same lava flow.

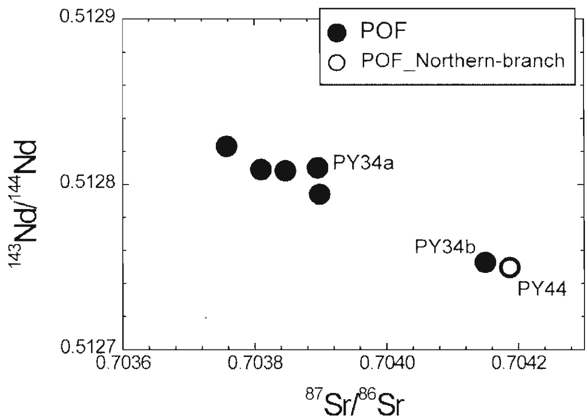

Figure 18: $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ diagram for POF and PNB lava flows. 2σ errors for Sr and Nd isotope ratios are within the size of symbol. PY34a, PY34b and PY44 are sample names.

Figure 19: The four main sectors in which the lava pathway of POF can be divided according to its morphology and structure as well as to its small-scale surface features and its overall topography.

This sheet flow could have been the main magma storage area, capable of providing lava supply to the very long and narrow following sectors, despite possible irregularities in lava input from vents.

The third sector of Pampas Onduladas flow begins where the sheet flow enters into a short, narrower and lower tectonic depression and flows across a relatively inclined step, like a rapid-forming stream. Downflow of this critical point the third sector of Pampas Onduladas flow moves SE with a slope of 0.25° over the alluvial deposits of the proximal Andean piedmont as a gently sinuous tongue partly deviated by small Permian-Triassic outcrops or self-deviated by its own temporary lateral lava fans. In this sector the liquid-cored flow tends to be concentrated in preferential pathways constituted by very long longitudinal inflation ridges preferentially located near the margins of Pampas Onduladas flow and delimitating a large, flat central depression. The dimensions of these ridges, up to 1 km wide and 20 m high, indicate a very efficient and probably rapid uplift, preventing in time the opposite effect of the crustal thickening of the lava flow. The occasional presence of tumuli alignments along the hinge of the ridges shows the evolution of the remaining liquid-core pathways into lava-tube systems. The central depression seems mostly to be the negative counterpart of the lateral inflation ridges, even though some collapsed escarpments limiting the depressions could be partly attributed to late deflation sinks.

The fourth sector of Pampas Onduladas flow follows a rectilinear path over the flat distal Andean piedmont plain, in absence of any topographic confinement. The initial part of this sector presents a very long and straight inflation ridge, flanked by several flow lobes repeatedly emitted from lateral breakouts of this relevant structure. The ridge axis presents several intermitted breakouts of the underlying liquid core, forming narrow strips of very dense and glassy lava. The internal pressure of the lava stored inside the ridge was not enough to generate tumuli, which on the contrary appear on top of the inflation ridges of the previous sector.

Moving downflow, where the central ridge disappears, this sector is formed by a tight boundle of long and wide flow lobes, generated by the progressive breakouts from the fronts of the preceding lobes.

The main conceptual problem of this sector, as well as the previous one, is the origin of the exceptional length of Pampas Onduladas Flow with respect to its width. This particular behaviour requires a self-confinement mechanism, still to be identified, which avoided the radial spread of the flow over the plain near Salado river valley at La Pampa province. Further investigations, including detailed topographic and morphometric surveys of the flow surface, precise assessments of the flow thickness, evaluation of rheological and thermal parameters (including the effect of vesiculation), and estimates of the duration of the eruption and flow rates, are needed to explain this behaviour.

Understanding the processes controlling Pampas Onduladas Flow emplacement is of paramount importance for the comprehension of lava emplacement, also in the other terrestrial bodies of the solar system, where similar flows have been found, like in the case of the Tharsis related flows on Mars, the long flows of the Imbrium basin on the Moon, and the flows of Strenia Fluctus on Venus (e.g.

Schaber 1973, Zimbelman 1998, Zimbelman *et al.* 2003, Giacomini *et al.* 2007). For example on Mars lava rises, tumuli, lava ridges and huge squeeze-ups similar to the one showed by Pampas Onduladas flow have been detected at Daedalia planum (Giacomini *et al.* 2007), whereas channels morphologically similar to the channel-like depression of Pampas Onduladas flow were already observed in the low-viscosity lava flows encountered in the Tharsis region (Zimbelman 1998). These channels were recently ascribed to a thermal erosion process (Zimbelman *et al.* 2003), but our analysis of Pampas Onduladas flow suggests that also syn-emplacement mechanisms cannot be ruled out.

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