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RESEARCH ARTICLE

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Pahoehoe flows from the central Paraná Continental Flood Basalts

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Abstract Inflated and compound pahoehoe flows have been identified within the central Paraná Continental Flood Basalts based upon their morphology, surface features, and internal zonation. Pahoehoe flow features have been studied at five localities in the western portion of Paraná State, Brazil: Ponte Queimada, Toledo, Rio Quitéria, Matelândia and Cascavel. We have interpreted the newly recognized flow features using concepts of Hawaiian pahoehoe formation and emplacement that have been previously applied to the Columbia River Basalt and Deccan Plateau. Surface features and/or internal structure typical from pahoehoe lavas are observed in all studied areas and features like inflation clefts, squeeze-ups, breakouts, and P-type lobes with two levels of pipe vesicles are indicative of inflation in these flows. The thinner, compound pahoehoe flows are predominantly composed of P-type lobes and probably emerged at the end of large inflated flows on shallow slopes. The presence of vesicular cores in the majority of compound lobes and the common occurrence of segregation structures suggests high water content in the pahoehoe lavas from the central PCFB. More volcanological studies are necessary to determinate the rheology of lavas and refine emplacement models.

Keywords Pahoehoe flows · Flood basalts · Inflation · Central Paraná CFB

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Introduction

We describe and discuss the importance of pahoehoe flows from the central area of Paraná Continental Flood Basalts (PCFB). The PCFB is located in central-eastern South America and is part of Paraná-Etendeka Igneous Province. This province covers an area of ca. 1.5×10^6 km^2 in South America and Africa, with and estimated volume of 1.0×10^6 km^3.

The emphasis of most previous research on the PCFB has been on geochemistry and geochronology; studies focusing on the morphology and structures of the basalts are scarce. The intense alteration of basalt flows produces deep soils, making it difficult to find good outcrops. The best outcrops are located in quarries and road cuts, which favor exposure of dense flow interiors, and make it difficult to find outcrops suitable to describe flow morphology and structures.

Pahoehoe flows have been documented in the lower part of Etendeka Igneous Province-Namibia (Jerram et al. 1999) and features printed onto the dune surface by active pahoehoe flows are described by Scherer (2002) in sandstone in base of the PCFB sequence.

This study is the first to document the occurrence of typical features of compound pahoehoe flows in the upper portion of volcanic pile in the PCFB. It lays the foundation for future studies that may seek to define the importance of this emplacement mechanism in PCFB.

Geological setting

The PCFB covers an area of 1,300,000 km^2 in South America and the study area is located in the central area of PCFB (Fig. 1).

The PCFB is a succession of volcanic rocks with a maximum thickness of approximately 1,700 m, composed mostly by tholeiitic basalts and minor rhyolites and rhyodacites in the upper portion (Melfi et al. 1988). The basalts are divided into two groups on the basis of Ti contents,

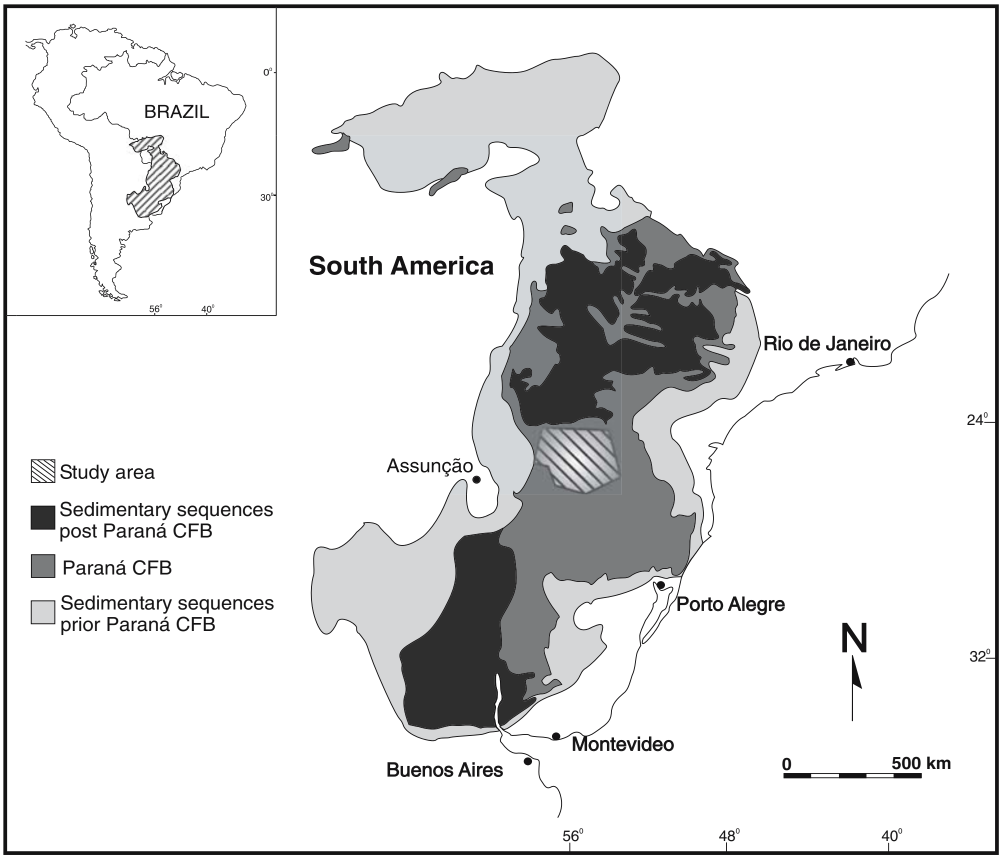

Fig. 1 Map of Paraná Basin with study area in central Paraná Continental Flood Basalts

High Ti basalts-HTi ($TiO_2 > 2\%$) and Low Ti basalts-LTi ($TiO_2 < 2\%$) (Bellieni et al. 1984; Mantovani et al. 1985).

Ar-Ar ages in PCFB samples range from 138 to 125 Ma, with a marked eruption peak at 133–129 Ma (Renne et al. 1992; Turner et al. 1994; Milner et al. 1995).

Recently, the volcanic rocks have been sub-divided into six magma types on the basis of major and trace elements abundance and/or ratios. The northern magmas are Pitanga, Paranapanema and Ribeira types-Ti/Y>300 and the southern magmas are Gramado and Esmeralda types-Ti/Y<300 (Peate et al. 1992; Peate 1997). Locally HTi lavas (Ubirici type) occur in the south and are contemporaneous with the Gramado type (Peate et al. 1999). In the study area, pahoehoe flows are tholeiites (Paranapanema type) with 48 to 53% SiO_2.

Although some detailed chemical stratigraphy studies have been conducted, maps of individual flows and studies of the morphology and structures of the basalts have not been made, making specific flow correlation difficult or impossible.

Emplacement of continental flood basalts

Large igneous provinces (LIPs) are products of major magmatic events that generate voluminous outpourings of dominantly tholeiitic basalt in intraplate settings. LIPs include continental flood basalts (CFBs), oceanic plateaus, and some volcanic rifted margins. CFB provinces produce huge lava flows in comparatively short periods of time in continental settings (Self et al. 1998), and many workers linked CFB to the presence of mantle plumes (Richards et al. 1989; White and McKenzie 1989).

The emplacement of CFB flows was originally explained by turbulent-flow models requiring extremely high lava-supply rates (Shaw and Swanson 1970). Recent studies propose a model involving inflation of flows with lower lava-supply rates (Hon et al. 1994; Self et al. 1997, 1998). These models are based on recognition of inflated, compound pahoehoe flows in some of the CFB, such Columbia River Basalts (CRBs) and the Deccan Volcanic Province (DVP). Walker (1971) suggested that high effusion rates form simple flows, whereas low effusion rates tend to form compound flows. Both simple and compound pahoehoe flows with distinctly different morphologies have been documented in DVP (Bondre et al. 2004), suggesting that more than one emplacement mechanism may have contributed to flow emplacement in CFB.

Description of the pahoehoe flows of the central PCFB

The identification of the pahoehoe flows in sequences of CFB has been primarily based on the internal structure of the flows, and occasionally on exhumed surface features. Surface flow structures are not commonly preserved or exposed in older CFBs and in PCFB are found in very

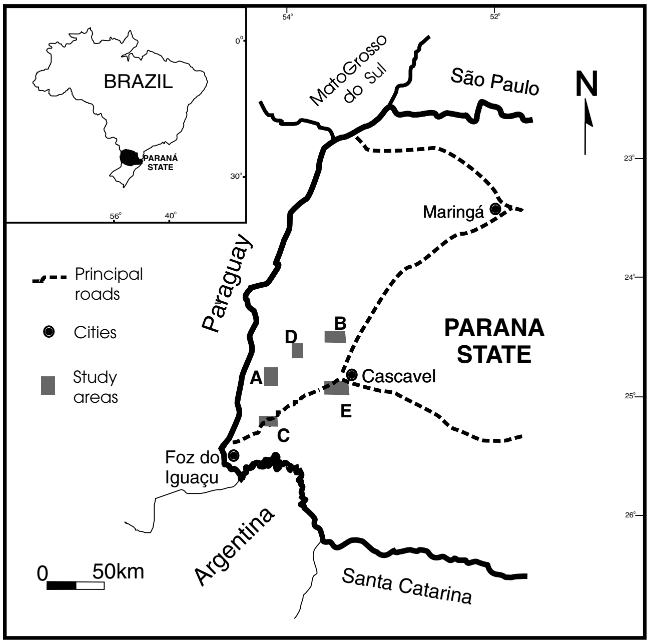

Fig. 2 Map showing study areas in west region of Paraná State. **A** Ponte Queimada, **B** Toledo, **C** Matelândia, **D** Rio Quitéria and **E** Cascavel

few outcrops. Internal zonations are better preserved; subdivisions such as upper crust, dense core, and lower crust are commonly observed.

Five areas have been the focus of most of our studies: Ponte Queimada, Toledo, Rio Quitéria, Matelândia and Cascavel (Fig. 2). Detailed description of these occurrences confirms the existence of inflated compound pahoehoe flows in the central area of PCFB. The study area is marked by discontinuous outcrops, and the schematic profiles of these regions are made based on elevation data (Fig. 3). The main characteristics of representative lobes from the study area are show in Table 1.

Terminology

We have adopted the concepts of flow emplacement and flow lobe terminology proposed by Self et al. (1997), for two reasons: (1) simplicity and (2) the ability to convey the concepts relevant to the emplacement of CFB lava flows. The eruption products are divided into flow lobe, lava flow, and flow field. These are used with caution when applied to PCFB because it is not always possible to classify highly altered, partial exposures with a great deal of certainty.

Flow lobe

Flow lobe is used to describe an individual package of lava that is surrounded by a chilled crust. In the study area, we were able to recognize S-type (spongy) and P-type (pipe vesicle bearing) lobes (Wilmouth and Walker 1993) and

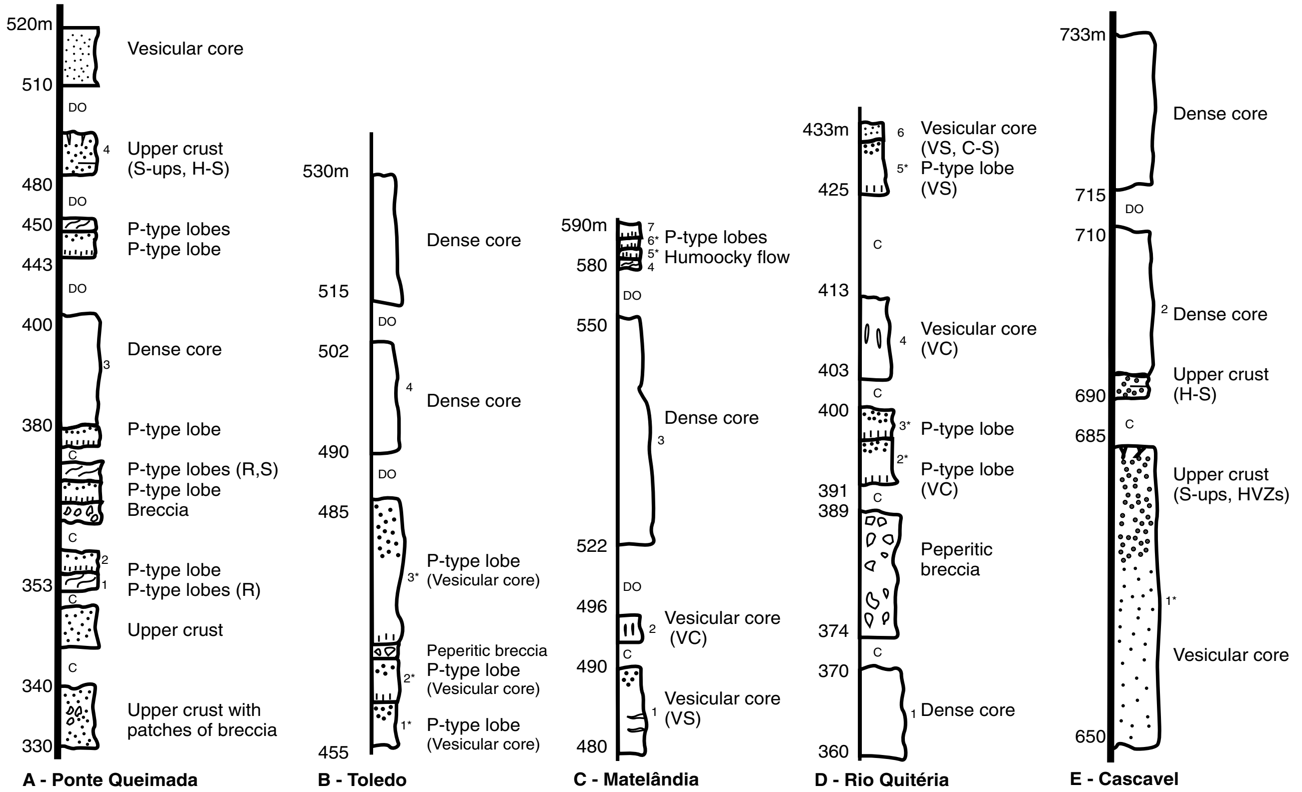

Fig. 3 Schematic profiles from study areas. S-ups = Squeeze-ups, H-S = Horizontal squeezes, R = Ropes, S = Slabby pahoehoe, HVZ = Horizontal vesicular zones, VS = Vesicle sheets, VC = Vesicle cylinders, C-S = Cylinder sheet, C = covered, DO = discontinuous outcrops. Elevation units are in meters. Numbered examples correspond to descriptions in Table 1

Table 1 Representative flow lobes from study areas (see Fig. 3 for location of flow lobes in schematic profiles)

Area	Lobes	Thickness (m)	Upper crust (m)	Core (m)	Remarks
Ponte Queimada	4	[7]	7	–	Squeeze-ups, horizontal squeezes
	3	[20]	–	20	Dense basalt, columnar jointing
	2	4	2.2	1.8	Vesicular core, PV
	1	3	–	–	Multiple P-type lobes, ropes
Toledo	4	[12]	–	12	Dense basalt, columnar jointing
	3	20	8	12	PV, vesicular core, three-tired structure
	2	4,3	2.8	1.5	PV, vesicular core, three-tired structure
	1	[5.2]	2.2	3	HVZ, vesicular core
Rio Quiteria	6	[2.5]	–	2.5	Vesicular core, VS, C-S
	5	6	3	3	Vesicular core, VS
	4	[10]	–	10	Vesicular core, VC
	3	4	2.2	1.8	Vesicular core, PV
	2	5	2.3	2.7	Vesicular core, VS, PV
	1	[24]	15	14	Dense basalt with flow-top breccia
Matelandia	7	[0.4]	–	0.4	
	6	0.7	0.3	0.3	Sheet lobe, three-tired structure ropes
	5	1.3	0.6	0.5	Sheet lobe, three-tired structure ropes
	4	[0.7]	–	–	Hummocky flow multiple P-type lobes
	3	[27]	–	27	Dense basalt, columnar jointing
	2	[3]	–	3	Vesicular core, VC
	1	[10]	2	8	Vesicular core, VS
Cascavel	2	[20]	–	20	Dense basalt, columnar jointing
	1	34	12	22	Squeeze-ups and HVZ in crust, vesicular core

Note: VC= vesicle cylinders, VS= vesicle sheets, C-S= cylinder sheets, PV= pipe vesicles, HVZ= horizontal vesicular zones. Flow lobes with thickness in square brackets are partially exposed

the use of the term is restricted to lobes up to 35 m thick (e.g., Cascavel area, Table 1) that can be easily delineated in outcrops. Flow lobes in the central area of PCFB with surface pahoehoe features are 0.5–2 m thick and internal zonation is best observed in flows with thickness varying from 2 to 10 m.

Lava flow

Lava flow is used to describe the product of a single continuous outpouring of lava. In the study areas, an estimate of the thickness of lava flows is often difficult to make because of the discontinuity in outcrops. Individual pahoehoe flows are often up to 70 m thick and are generally strongly compound on a local scale, similar to Hawaiian lavas and flows from the DVP.

Flow field

The flow field is the aggregate product of a single eruption or vent and it is built up of one or more lava flows. It is difficult (or nearly impossible) to differentiate the products of a complex pahoehoe lava flow from that of a long lived flow field in the PCFB due to lack of exposure and alteration of the rocks.

Surface features and internal structure of pahoehoe flows

Pahoehoe flows are most easily recognized by their distinctive millimeter- to decimeter-scale surface textures and features. Ropes and other small-scale features form when the flexible skin is deformed by motion of the lava (Fink and Fletcher 1978). In the transition between pahoehoe to aa lava types, transitional forms occur like spiny, toothpaste and slabby pahoehoe (Peterson and Tilling 1980, Rowland and Walker 1987). The internal structures within lava flows and lobes also provide clues to their style of emplacement. Pahoehoe flows and lobes are characterized by a three-tiered structure: vesicular upper crust, a dense core, and a lower crust (Aubele et al. 1988).

Ponte Queimada area

Multiple flow lobes dominate the basal part of the profile in the Ponte Queimada area (Fig. 3A). The lowest part (20 m

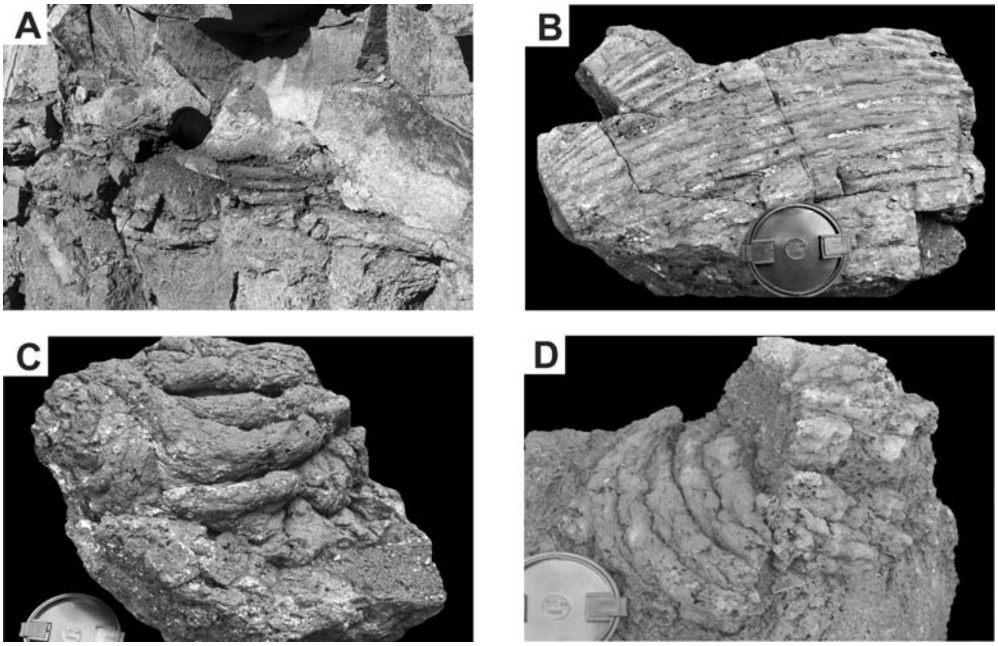

Fig. 4 Ponte Queimada area. **A** Ropes in vertical section, **B** and **C** Ropes on horizontal surface, **D** Detail of the fragmentation process of slabs. Lens cap= 55 mm

thick) is very altered vesicular basalt and patches of breccia; recognition of individual lobes is difficult. Overlying this part, P-type lobes (0.5–1.0 thick) are intercalated with patches of breccia (Fig. 3A). Ropy surfaces are generally exposed both in situ (Fig. 4A) and on surfaces of fallen blocks (Figs. 4B, 4C). Despite the age and weathering of these flows, these features are very well preserved.

Toothpaste and slabby pahoehoe are also present in the Ponte Queimada area. These features are found in fallen blocks near the locality where ropy pahoehoe are exposed in vertical section and mark changes in lava viscosity and local increase in shear rate.

The fragmentation and immersion of ropy pahoehoe slabs into the flow interior forms slabby pahoehoe. Large blocks show slabs with different dispositions and locally the fragmentation process are observed in detail (Fig. 4D). This feature forms when the crust completely disrupts due to the high rate of lava flow that is too great for the crust to accommodate the shear strain plastically (Duraiswami et al. 2003).

The occurrence of these pahoehoe types can be related to the initial transition of pahoehoe to aa lavas (Peterson and Tilling 1980; Rowland and Walker 1987), nevertheless true aa lavas are not reported in central PCFB and this argues against this hypothesis. Alternatively, slabby pahoehoe patches within sheet flows can be generated by breakouts from the fronts of inflated flow lobes (Hon et al. 1994) and are not indicative of transition from pahoehoe to aa lavas, but instead are related to local temporal change in shear rate.

Lobes in the Ponte Queimada area display a three-tiered structure with a highly vesicular upper crust, a vesicular core, and a thin vesicular lower crust. Jointing is absent in these lobes.

Above the strongly compound lower section is a dense flow (20 m thick) of aphyric basalt exhibiting spaced and irregular columnar jointing. Many aspects of this flow (thickness, dense rock, jointing style, and absence of structures) highly contrast with the underlying lobes. Segregation structures are absent in the core and the upper portion is not exposed (Fig. 3A). The basal portion of the flow lacks pipe vesicles and rests on a breccia layer without a chill margin. No fragments of the breccia were incorporated by the flow suggesting that it moved over the breccia gently. This is not consistent with a turbulent flow emplacement hypothesis.

Thinner, compound pahoehoe flows appear again in the central portion of the section (Fig. 3A). P-type lobes predominate and pipe vesicles occurring at two different levels are observed. Wilmouth and Walker (1993) infer that this feature is formed by multiple lava injections and suggest endogenous growth. Similar features are described by Bondre et al. (2004) in the DVP.

A partially exposed lobe with an upper vesicular crust (7 m thick) occurs in the upper portion of the profile. The upper part of the crust display several squeeze-ups of brownish glassy basalt occupying the inflation clefts and patches of breccias. In the lowermost part of the crust, injections of lava have intruded horizontally; similar features have been reported in the DVP (Duraiswami et al. 2001).

Toledo area

A schematic profile from the Toledo area is based on three isolated outcrops. Two lava lobes and an inflated sheet flow compose the lower portion of the profile in Toledo Quarry. In the basal lobe (lobe 1), only the upper crust and vesicular core are exposed, whereas, the upper lobe (lobe 2) and sheet flow are complete (Fig. 3B).

Lobe 1 is 6 m thick and based on the extent of upper and central zone the presumed total thickness is 7–8 m. The upper crust displays an irregular pattern with alternate vesicle-rich and vesicle-poor bands (horizontal vesicular zones-HVZ). HVZs preserved in crust can be interpreted

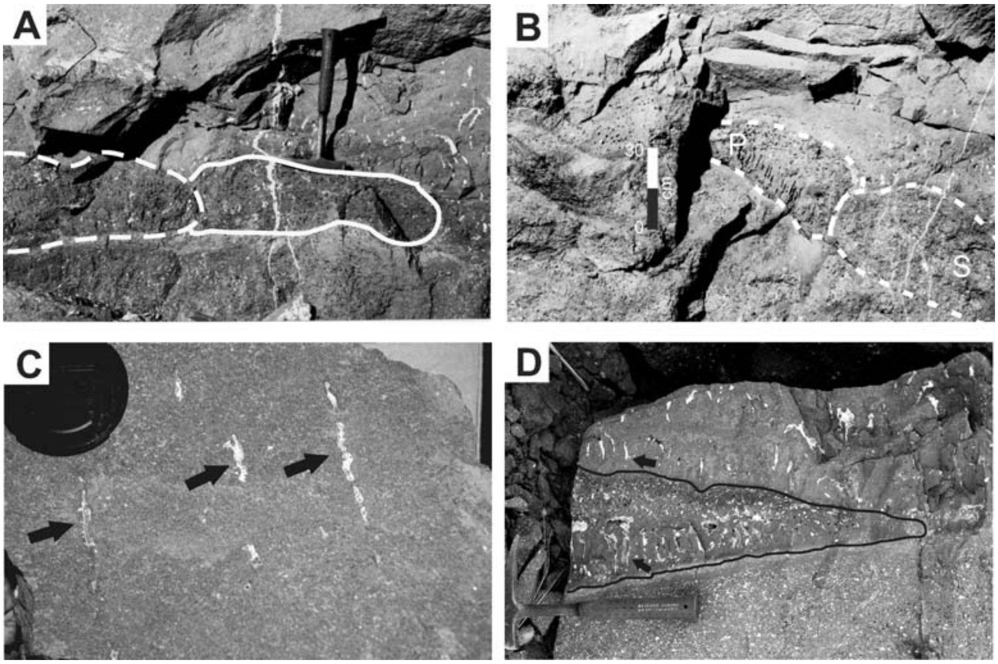

Fig. 5 Toledo area. **A** Thin lobes with ellipsoidal form in vertical section, probably formed by breakouts, **B** P-type and S-type lobes, **C** "Vertical irregular vesicles" in core of lobe 2, **D** P-type toe overrun by a P-type inflated sheet flow. Hammer=33 cm, lens cap=55 mm

when the lobe is depressurized by sudden breakouts and bubbles form inside the lobe (Hon et al. 1994). A second possibility is that vesicular zones are the result of a more bubble-rich batch passing through the lobe (Self et al. 1997), but the occurrence of thin lobes probably formed by breakouts in the contact between lobe 1 and lobe 2 (described below) suggests the first alternative. The core is composed of basalt with small irregular vesicles and diktytaxitic texture.

The upper contact of lobe 1 is marked by the coalescence of various small lobes probably representing small surface breakouts (Fig. 5A). Thin glassy rinds delimit individual lobes. Some lobes have vesicles distributed throughout the lobe (S-type lobe from Walker 1989); other lobes contain pipe vesicles at the base, a dense interior, and more vesicular exteriors (Fig. 5B; P-type lobe from Wilmouth and Walker 1993). P-type lobes are predominant, 10–40 cm thick, and show an ellipsoidal form in vertical section. P-type lobes were produced during the initial breakouts from highly pressurized inflated flow fronts; as the breakouts continues, the lava becomes more vesiculated and S-type were produced due to a drop in pressure (Hon et al. 1994).

Lobe 2 is approximately 4 m thick and displays a three-tired structure: upper crust, vesicular core, and thin lower crust. The lower crust (average thickness of 20 cm) shows a basal contact that is either nearly planar or undulating where it overlies breakouts. In this latter case, pipes vesicles are inclined in varying directions. The core is composed of vesicular basalt. The vesicles are irregular in shape, a few millimeters in size, and generally empty or partially filled by celadonite. In the central part of the core, vesicles coalesced into large vesicles that rose forming "vertical irregular vesicles" (Fig. 5C). These vesicles originate by secondary vesiculation (second boiling). The irregular shape and vertical orientation indicates that they rise during the later stages of crystallization, after stagnation of flow and when little space is available in the crystal framework for bubbles to rise. Vesicles in the upper crust (~2 m thick) show an increase in size and decrease in number per unit area from top to bottom of the crust, similar to observations by Cashman and Kauahikaua (1997) and Bondre et al. (2004).

The contact between lobe 2 and sheet flow has a large surface exposure in the quarry and is marked by a layer (0.30–1.00 m thick) composed by siltstone and patches of peperitic breccia.

The P-type inflated sheet flow has a thickness of 20 m. The lower crust is thin (~30 cm) and locally P-type toes were overrun by the P-type inflated sheet flow (Fig. 5D). The core is 12 m thick, composed by vesicular basalt without structures, rare thin dikes (2–5 cm thick) of sediment occur in the core. In the upper crust (~8 m thick), vesicles show an increase in size and decrease in number per unit area from top to bottom.

Matelandia area

In the Matelandia area, the lower and upper sections of the profile have clearly recognizable features of pahoehoe lavas. They are separated by a thick dense flow (Fig. 3C).

In the lower section, the basal lobe is 10 m thick with a vesicular core (7 m thick) and an upper crust (3 m thick). The core is composed by vesicular basalt and marked by presence of segregation sheets. The segregation sheets are horizontally continuous in extensive vertical section (reaching 50 m in length) and are made up of highly vesicular basalt (Fig. 6A). The contacts between the sheets and the host basalt are always sharp, and the thickness of individual sheets decreases upwards from about 20 to 1.0 cm, while the number of sheets increases upwards. The

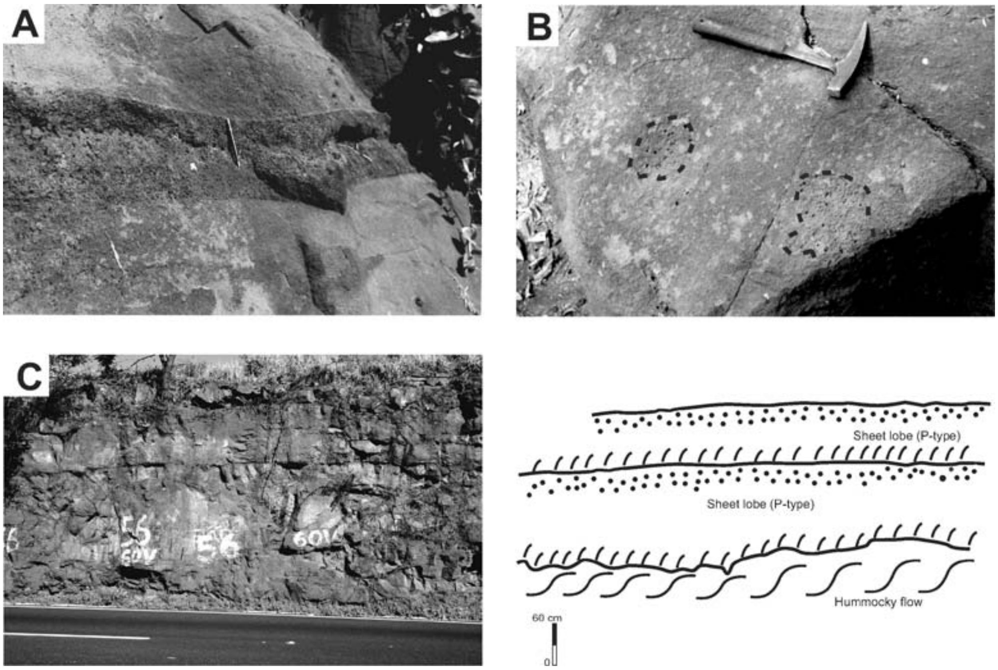

Fig. 6 Matelandia area. **A** Contact of vesicle sheet with host basalt, **B** Vesicle cylinders in horizontal surface, **C** Photograph and drawing of a hummocky flow composed by multiple thin P-type lobes overlaid by two sheet lobes

upper crust is very altered and poorly exposed. In the second lobe, only the core is exposed and is composed of vesicular basalt; a horizontal exposure surface shows vesicle cylinders (Fig. 6B).

The central section is a dense core (27 m thick) constituted by aphyric basalt displaying a spaced and irregular columnar jointing. Boreholes performed in the floor of the quarry verify the existence of vesicular basalt (probably upper crust) nearly 1.0 m below the ground.

The aphyric basalt from Matelandia is similar to other dense cores exposed in other study areas (Fig. 3), but stratigraphic correlation is not possible because the discrepancy in altitude and discontinuity of the exposures. In the study area, apparently the dense flows do not have a great lateral extent in comparison with similar flows from CRB (>100 km in length, Tolan et al. 1989) or DVP (80 km in length, Bondre et al. 2004). However, more work in other areas coupled with petrography and chemical studies are necessary to confirm any regional correlations.

In the upper portion of the profile, P-type lobes overlain by two sheet lobes may be observed (Figs. 3C and 6C). The basal part of the upper section is composed by multiple P-type lobes. Discerning individual lobes is difficult, and the observed contacts between lobes are irregular and generally show high angles (30–45°). This characteristic confers an undulating surface typical of a hummocky flow (Fig. 6C). Sheet lobes are 1.3 and 0.7 m in thickness, up to 50 m in length and display a planar top and a three-tired structure. The basal crust is thin (15 cm in average) and exhibits pipe vesicles. Pipe vesicles in a sheet lobe overlying the hummocky flow are inclined in different directions. The geometry of the contact with underlying lobes depends primarily on the microtopography on which the lobes were emplaced (Duraiswami et al. 2002) and the undulating contacts suggest the presence of underlying hummocky flow. The core constitutes about half of the lobe thickness, and is composed of weakly vesicular basalt.

Vesicles in the upper crust of sheet lobes show an increase in size and decrease in number per unit area from top to bottom and vesicle layering the lowermost part of the upper crust.

Rio Quitéria area

The Rio Quitéria area has five pahoehoe lobes overlying a dense flow (Fig. 3D). The dense flow that occurs in the lower section of the profile is 10 m thick and it is composed of massive, aphyric basalt with irregular and spaced vertical jointing. A layer of peperitic breccia (∼15 m thick) with centimeter- to decimeter-size fragments of vesicular basalt in a reddish sedimentary matrix overlie the dense flow.

The pahoehoe lobes are 4–10 m thick and usually exhibit a three-tired structure with upper crust, vesicular core, and thin basal crust. The upper crusts comprise nearly a half of the thickness of the lobe and display a typical vesicle pattern, with increase in size and decrease in number per unit area from top to bottom. Cores are composed of vesicular basalt with diktytaxitic texture commonly with segregation structures, such as vesicle sheets and vesicle cylinders. The vesicles in cores are irregular in shape, between 0.5 and 3.0 mm and filled by celadonite (Fig. 7A). The vesicle sheets are 10–20 cm thick and the contact with host rocks is sharp (Fig. 7B). Goff (1996) describes vesicle cylinders in Panorama Point basalt flow (Columbia River) that end within a single horizontal vesicle vein to form "cylinder sheets" C-S (Caroff et al. 2000). The upper limit of C-S is associated with horizontal cracks formed as a result of thermal contraction associated with cooling; probably horizontal cracks act as barrier to the ascending

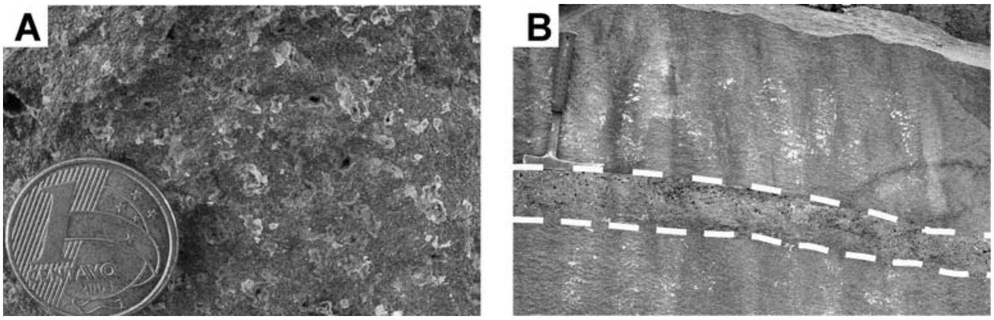

Fig. 7 Rio Quitéria area. **A** Irregular vesicles (0.5–3.0 mm length) in vesicular core, coin=1.7 cm, **B** Vesicle sheet with sharp contact in lobe core. Hammer=33 cm

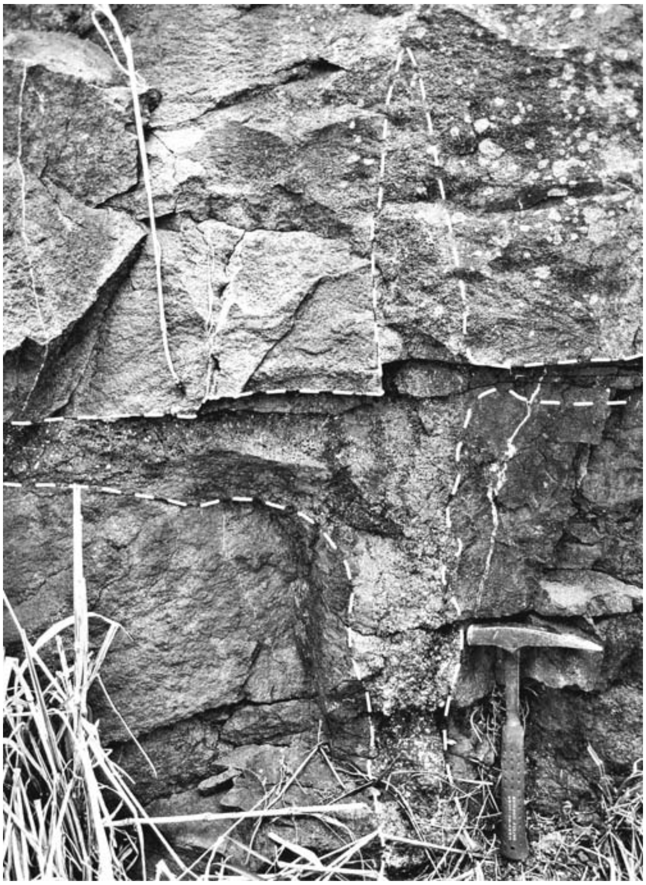

Fig. 8 Rio Quitéria area. C-S type structure, showing part of vesicle cylinder penetrating in direction of the top of the lobe. Hammer=33 cm

residual liquids forcing the horizontal movement. Segregation structures similar to cylinder sheets are also found in Rio Quitéria lobes. However, some vesicle cylinders do not end in horizontal vein but instead, continue upwards (Fig. 8). Vesicle cylinders are common on horizontal exposures and can reach 10 cm in diameter. The basal crusts of these flows are thin (30 cm) and exhibit a near planar basal contact with local pipe vesicles.

Cascavel area

The schematic profile from the Cascavel area shows a 34-m-thick pahoehoe lobe at the base overlain by two dense flows (Fig. 3E). The pahoehoe lobe is the thickest lobe from the study areas. The upper crust is 12 m thick and is divided into a highly vesicular uppermost part (6 m thick) and a lower part composed of less vesicular basalt (6 m thick).

In the upper part of upper crust, vertical squeeze-ups or lavas filling inflation cracks (Fig. 9A) as well horizontal injections are quite common (Fig. 9B). Inflation cracks are formed when continuous inflation causes an uplift of the brittle crust, thereby producing a network of large and small cracks on the flow surface (Walker 1991; Hon et al. 1994). Most of these cracks are later occupied by lava injections forming squeeze-ups, filled by lava from the overlying flows or by sediments.

Patches of breccia or a thin layer of brownish glassy basalt marks the contact with the overlying dense flow. Similar to the Ponte Queimada area, scouring of substrate is not observed. Locally, the breccia is uplifted, forming features similar to tumulis, reaching 2.0 m in height above the contact level with until 20 m in amplitude. The dense flow overlies this uplifted breccia without scouring it.

The lower part of the upper crust displays horizontal layers of increased vesicularity (horizontal vesicular zones-HVZ). The HVZs are found in upper crusts and are distinguished from the vesicle sheets found in cores. The HVZs in this lobe are 5–20 cm thick with gradational contacts. These probably result from fluctuations of pressure and/or flux during active inflation (Hon et al. 1994; Cashman and Kauahikaua 1997).

The core has a thickness of 22 m and is composed of vesicular basalt without structures or jointing. Vesicles are irregular in shape with millimeter dimensions and filled by celadonite.

The dense flows are made up of aphyric basalt with irregular columnar jointing. These two flows are very similar but the upper flow displays rare gabbroic veins and vesicles. Similar gabbroic veins (but of large size) occur in southwest Paraná State. The chemical composition of latter veins and host basalt are similar to segregation veins found in CRB (Puffer and Horter 1993).

Emplacement of the flows

Compound pahoehoe flows

The flows and lobes from central PCFB display typical characteristics of compound pahoehoe flows and provide

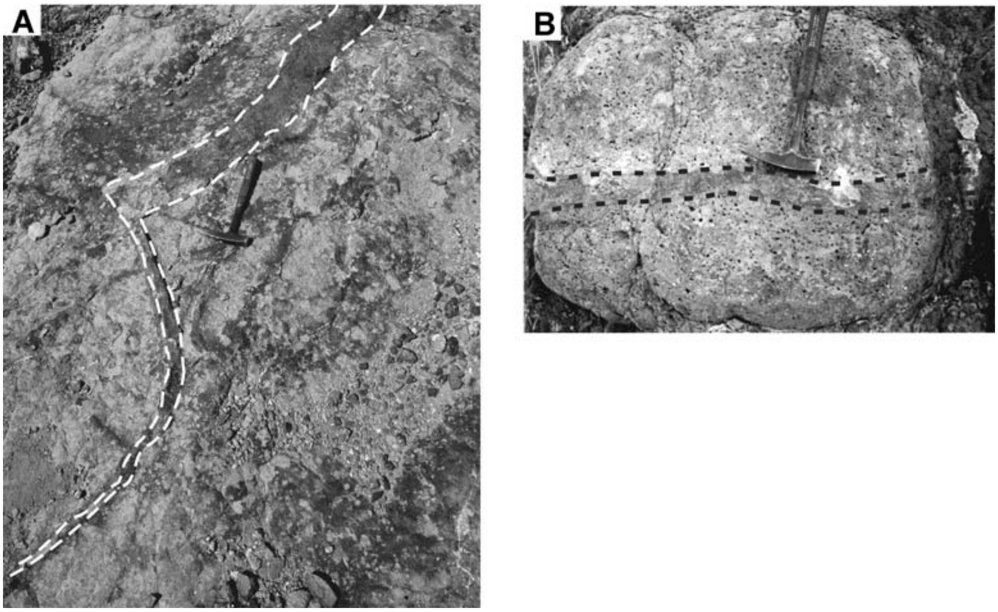

Fig. 9 Cascavel area. **A** Squeeze-ups and **B** horizontal injections in upper crust of pahoehoe lobe. Hammer=33 cm

evidence of formation by active inflation. These lavas are similar to inflated pahoehoe flows from Hawaii (Hon et al. 1994), CRB (Thordason and Self 1998) and DVP (Bondre et al. 2004).

Macdonald (1953) observed that pahoehoe flows from Hawaii are produced by long-duration, low-effusion rate eruptions. Rowland and Walker (1990) estimated a flow rate of <5–10 m^3/s for pahoehoe flows in Hawaii. Thordason and Self (1998) estimated flow rates of up to 4,000 m^3/s for the Rosa member of the CRB and suggested that these higher eruption rates are not unreasonable given the potential lengths of the fissures involved (Self et al. 1997).

Ropy textures occur in about 20–30% of the flow surfaces in Hawaii (Hon et al. 1994). Despite the low preservation potential of such features, those found in the central PCFB are very well preserved. The three-tired structure of pahoehoe flows: upper crust, core, and lower crust are common in lobes with thickness ranging from 0.5 to 34 m. The cores are generally composed by vesicular basalt with diktytaxitic texture attesting the high residual water content in magma.

The predominance of P-type lobes in compound flows of study area can be related to breakouts emerged from larger inflated sheet flows (Hon et al. 1994, 2003). According to Wilmouth and Walker (1993), these lobes can be found in almost anywhere in the pahoehoe flow field, but is common in areas with shallow slopes (<4°).

The P-type lobes have lower extrusion temperatures, higher density, degassed outer glassy selvage and a well-developed crystalline interior, as compared to S-type, and this characteristic indicates that lavas that form P-type lobes were relatively long enough in residence to exsolve considerable vapor in lava distributor system before extrusion (Wilmouth and Walker 1993; Oze and Winter 2005). Alternatively, Hon et al. (1994) suggested that the P-type may represent pressurized lava containing more dissolved volatiles that S-type, the dense outer crust of P-type increases the pressure dissolving pre-existing bubbles back into the melt.

Segregation structures (vesicle cylinders and vesicle sheets) are found in many pahoehoe flows from central PCFB and display a great variety in dimensions, mineralogy, texture, and bubble content. These structures are formed when differentiated liquids flow from host basalt by gas filter-pressing (Anderson et al. 1984). According to Goff (1996), basalt-containing vesicle cylinders show positive correlations among increasing cylinder abundance, increasing lava porosity, and increasing groundmass crystal size, and these features may suggest an unusually high water content in the magma.

Dense flows

The dense flows are present in five study areas and their occurrence is independent of different stratigraphic level. All of these flows are composed of similar aphyric basalt with irregular columnar jointing. The discontinuity between outcrops and limited exposure (generally lacking the upper portion) makes it difficult to determine emplacement mechanisms. Nevertheless, in flows where the basal contacts are exposed no evidence of scouring of the substrate has been observed. This characteristic argues against an emplacement analogous to typical aa flows or a turbulent, high-discharge rate emplacement (Shaw and Swanson 1970).

Each dense flow appears to be a single cooling unit and no evidence to indicate the presence of multiple lobes has been directly observed. The dense flows may possibly constitute the core of large inflated flows and the thin P-type lobes are breakouts, but more studies involving fieldwork, textural analysis, geochemistry, and possibly anisotropy of magnetic susceptibility (AMS) are needed to understand whether the dense flows are single flows or compound flows.

Table 2 Calculation of emplacement time of individual lobes from the study areas. M=months, h=hours. Lobes used are indicate by * in Fig. 3

Area	Lobes	Thickness upper crust (m)	Time
Cascavel	1	12	33 M
Toledo	3	8	14.6 M
	2	2	0.9 M
	1	2.5	1.4 M
Rio Quitéria	3	3	2 M
	2	2	0.9 M
	1	2.5	1.4 M
Matelândia	2	0.3	0.6 h
	1	0.6	2.5 h

Eruption duration

The model for the formation of the internal divisions within an inflated pahoehoe lobe provides the means to estimate the duration of the effusive activity that fed the lobe (Self et al. 1997, see Fig. 3). Self et al. (1997) proposed that the boundary between the upper crust and core marks the time when the flux of fresh lava into a lobe ended and the fluid interior became stagnant. In four of the study areas (Toledo, Matelandia, Rio Quitéria and Cascavel), an estimate of the eruption duration can be made for lobes with complete internal structure preserved (Table 2). Estimating the duration in Ponte Queimada is rendered difficult by the presence of highly compound flows with numerous lobes and intense alteration.

An empirical equation,

$$t = 164.8\,H^2 \qquad (1)$$

where t is time in hours and H is the thickness of the upper crust in meters (Hon et al. 1994 ; Self et al. 1998) is used to calculate the time of formation of upper crust.

The calculated time of formation of upper crusts in complete lobes from study areas varies from hours to several months. The larger lobe calculated is from the Cascavel area with time formation of 33 months. This indicates that the eruption of central PCFB flows may take place over months or years, thus their effects on the environment are attenuated. The eruption duration data presented here are preliminary and are intended only to give an approximate duration, given the poor exposures and lack of stratigraphic correlation. Estimating the duration for a greater area (including the entire PCFB) will require many, more-detailed volcanological studies, along with a revaluation of total volume of erupted lavas.

Lava transport and heat loss

The emplacement of large flood basalts involving an occurrence of compound pahoehoe flows requires efficient magma transport with small heat loss.

Efficient lava transport may occur through tube systems as in Hawaii (Hon et al. 1994; Keszthelyi 1995; Helz et al. 2003), in Italy-Mount Etna (Calvari and Pinkerton 1998) and the Canary Islands (Solana et al. 2004). Field data and calculations show that Hawaiian lava tubes typically cool about ∼1°C/km (Keszthelyi 1995; Cashman et al. 1994; Helz et al. 2003) and Ho and Cashman (1997) obtained cooling rates of 0.02–0.04°C/km in the 500-km-long Ginkgo flow of CRB, consistent results with an efficient lava transport resulting from a insulated flow beneath a thick crust. Nevertheless, magma distribution systems or tubes are difficult to identify in ancient CFB, and well-developed tube systems have not been reported both in CRB and DVP (Self et al. 1997; Bondre et al. 2004).

This work describes the occurrence of thin lobes formed by breakouts from large inflated sheet flows (dense flows). This scenario requires a highly efficient transport mechanism probably associated with tube systems (Swanson 1973; Self et al. 1998; Kauahikaua et al. 2003), but true tubes are not recognized in the study area.

Alternatively, sheet-like preferred pathways (Hon et al. 1994; Keszthelyi and Self 1998) could have been responsible for the long-distance transport of lava. Similarly, several emplacement units may have been fed simultaneously from different fissure segments from long vent systems (Keszthelyi et al. 1999). Volcanological studies in PCFB are just beginning and much more work is necessary before we can expect to fully understand emplacement mechanisms.

Conclusions

The study area consists of flows, which, in general, cannot be correlated over distances greater than 50 km; suggesting that flows in central PCFB are minor in length in comparison with CRB and DVP flows. This characteristic might be related to the occurrence of highly compound pahoehoe flows and the location of the study area in relation to vents. However, limitations like a lack of unique chemical and physical features in flows and limited exposure may currently be preventing more widespread correlation of flows.

Surface features and/or internal structures typical from pahoehoe lavas are observed in the study areas and features like inflation cracks, squeeze-ups and breakouts are indicative of inflation in these flows.

The predominance of P-type lobes in compound pahoehoe flows can be related to breakouts emerged from larger inflated sheet flows. The characteristics of these lobes, as compared to S-type, indicate that lavas that form the P-type were relatively in residence long enough to exsolve considerable vapor in lava distributor system before extrusion (Wilmouth and Walker 1993; Oze and Winter 2005).

The nature of dense flows is obscured by the poor exposure and absence of distinctive internal structures. Observed basal contacts do not show a scouring of substrate and argue against a turbulent flow eruption model. Possibly the dense flows may constitute the core of large inflated flows and the compound pahoehoe flows are thin lobes (breakouts) at the end of large flows. More studies involving fieldwork, textural analysis, and geochemistry are needed to confirm this hypothesis.

The existence of compound pahoehoe flows and dense flows in the study area requires an efficient magma transport with small heat loss. Tube systems or sheet-like preferred pathways could have been responsible for the long-distance transport of lava, but related structures are not recognized in study area.

The cores of lobes of compound flows are composed of vesicular basalt with a diktytaxitic texture. The common occurrence of segregation structures suggests high residual water content in the inflated pahoehoe lavas from the central PCFB. More volcanological studies are necessary to better determine the rheology of lavas and refine emplacement models.

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