Bulletin of Volcanology (2024) 86:6
https://doi.org/10.1007/s00445-023-01694-5

RESEARCH ARTICLE

Well-preserved fallout basaltic tuff in central Paraná-Etendeka Large Igneous Province: pyroclastic evidence of high fire-fountain eruptions

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Received: 13 August 2023 / Accepted: 11 December 2023 / Published online: 28 December 2023

Abstract

The Paraná-Etendeka Large Igneous Province (PELIP) is renowned for its massive and rapidly emplaced flood basalts that dominated the centre of the Gondwana supercontinent during the Early Cretaceous. However, little is currently understood about mafic explosive eruptions, which often occur simultaneously with effusive activity, as observed in young basaltic volcanism. Here, we describe the first well-preserved layer of basaltic tuff interbedded within the high-Ti basaltic lava sequence in the central part of the PELIP, Brazil. The Tapalam Tuff consists of basaltic juvenile glassy components, scoriaceous lapilli and coarse ash, with a cement containing clays, zeolites, carbonates, and iron oxides. The glassy sideromelane fragments range from well-rounded achneliths with smooth, curved surfaces to highly angular, cuspate-shaped or platy shards. Achnelith morphologies include broken droplets (Pele's tears), thread fragments (Pele's hair), dumbbells, needles, spheres, ovoids and reticulite. Elongated pyroclasts exhibit a flat orientation, and subtle bedding is defined by granulometric alternation. Our findings suggest the deposits were laid down proximal to the volcanic vent and likely indicate a fallout deposit associated with a fluid-dominated, high (hundreds of meters or more than 1 km) fountain similar to a Hawaiian-type eruption, fed by low-viscosity basaltic magma. Volcanic activity was therefore not exclusively effusive but also involved explosive eruptions, which may have significant implications for understanding PELIP's volcanic history and its relation to local and global environmental changes.

Keywords Mafic tuff · Basaltic ash · Achneliths · Lava fountain · Mafic explosive eruptions · Large igneous province

Introduction

Large igneous provinces (LIPs) encompass intraplate magmatic phenomena characterized by voluminous intrusions and vast extrusions of lava and other volcanic materials on a large scale and over time frames of 10^5 to 10^6 Ma (Coffin and Eldholm 1994). LIPs are significant for their potential to trigger noteworthy environmental and climatic fluctuations, as well as their links with mass extinctions (Ernst 2021). Most continental LIPs are characterized by mafic volcanic rocks, which are the products of extensive effusive eruptions in continental flood basalt (CFB) provinces (Jerram and Widdowson 2005). The products of mafic explosive eruptions have received comparatively less attention than their effusive counterparts or even their silicic analogues, which invariably captivate scientific inquiry due to their cataclysmic ignimbritic eruptions (Ross et al. 2005; White et al. 2009; Bryan and Ferrari 2013). Consequently, the study of mafic volcaniclastic deposits, particularly pyroclastic deposits, may provide insights into eruption dynamics, which remain poorly constrained for flood basalt volcanism (Brown et al. 2014).

The Paraná-Etendeka Large Igneous Province (PELIP) was emplaced in the centre of the Gondwana continent during the Early Cretaceous and is notorious for its extensive flood basalt eruptions, which gave rise to the *Paraná traps*. However, the occurrence of mafic ash deposits related to explosive eruptions is less-known and not yet described. Here, we describe the Tapalam Tuff, with the aim to contribute to our understanding of mafic pyroclastic deposits and provide insights into the volcanic processes that drove the construction of the PELIP.

Editorial responsibility: M. Edmonds

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Geological background

The emerged part of the PELIP comprises an extensive volcanic plateau in the south-central region of South America (~ 917,000 km^2; Baker 1923; Frank et al. 2009), as well as a separate plateau situated in Namibia, southwest Africa (~ 15,000 km^2; Erlank et al. 1984). These two areas were formerly connected through the Torres-Huab Trough before the opening of the South Atlantic Ocean (Jerram et al. 1999) (Fig. 1). The volcanic succession was emplaced within the Paraná Paleozoic–Mesozoic Basin that is underlain by a Brasiliano/Pan-African age mobile belt surrounded by cratonic areas (Porada 1989). The PELIP comprises a thick (~ 1700 m max.) and voluminous succession of extrusive rocks, including shallow intrusions of mainly mafic dikes and dolerite sills, totalling approximately 600,000 km^3 on the South American side (Frank et al. 2009). The peak of volcanic activity within the PELIP is estimated to have occurred approximately between 134.5 and 133.5 Ma (Thiede and Vasconcelos 2010; Pinto et al. 2011; Janasi et al. 2011; Rocha et al. 2020). Basalts and basaltic andesites predominate (> 90%) over andesites (7%) and dacites/rhyolites (3%) (Bellieni et al. 1986; Piccirillo et al. 1988; Nardy et al. 2008). The southern portion of the PELIP is characterized by the prevalence of low-TiO_2 (Ti/Y) magmas, while high-TiO_2 (Ti/Y) magmas are abundant in the central and northern regions (Peate et al. 1992; Peate 1997). The rocks in the southern portion are gradually overlain by those of the northern, indicating the evolution of two subprovinces (Bellieni et al. 1984; Licht 2018).

The eastern threshold of the volcanic plateau of Paraná Igneous Province is sharply delimitated by the *Serra Geral* escarpment that forms a prominent topographic feature in Brazil that reaches a maximum height of 1824 m. Pioneer observers noted that lava flows capped the cliffs, resulting in a flat-topped relief. This characteristic led to the original designation of the "Serra Geral eruptives" for this volcanic sequence (White 1908). In the present day, the Serra Geral Group encompasses not only the volcanic sequence but also includes the sandstones of the Botucatu Formation (Rossetti

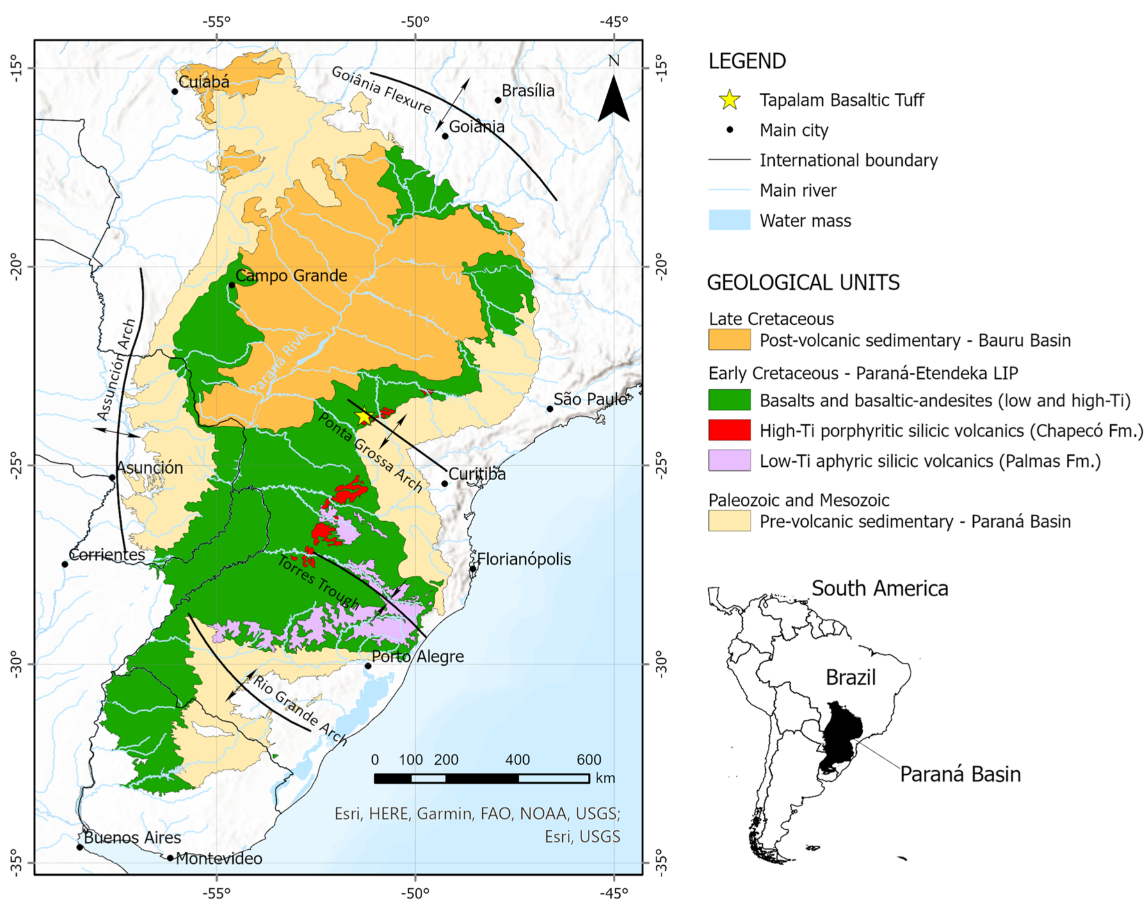

Fig. 1 Geological map of South American side of the Paraná-Etendeka LIP showing the location of the Tapalam Tuff. The cartographic data is sourced from South America Tectonic Map (Cordani et al. 2016) and the Paraná Basin Geologic Map (Horn et al. 2022), both published by the Geological Survey of Brazil (SGB-CPRM)

et al. 2018). The initial lava flows spread concordantly across an ancient erg, an area of large accumulation of sand (ca.1,500,000 km^2 Salamuni and Bigarella 1967), preserving the morphology of the aeolian dunes as they engulfed the desert landscape in the centre of Gondwana supercontinent (Jerram et al. 2000; Scherer 2000).

In the vicinity of the uplifted area of Ponta Grossa arc (Fig. 1), the stratigraphy of the Serra Geral Group comprises the following units, according to the cartography updates of the Geological Survey of Brazil (Besser et al. 2021). At the base, there are aeolian sandstones of the Botucatu Formation. They are covered by porphyritic rhyolitic to trachytic lava flows of the Chapecó Formation. The Pitanga Formation overlies both Botucatu and Chapecó formations and is mainly composed of a wide range of basaltic lava flows types, along with mafic volcaniclastic deposits and sedimentary rocks interbedded. The upper and last unit of Serra Geral Group is the Paranapanema Formation, which is characterized by thick (> 25 to 50 m), tabular, inflated pahoehoe basaltic flows, often with rubbly top morphology. There is a progressive decrease in the intercalations of volcaniclastic deposits towards the upper flows. The Pitanga and Paranapanema Formations correspond respectively to the Pitanga and Paranapanema magma types (Peate 1997), as well as the type 4 and type 1-CN basalts (Licht 2018). The Tapalam Tuff is part of the Pitanga Formation, within which the diversity of basaltic lava morphologies includes thin simple and compound pahoehoe flows with locally well-preserved ropy/corded surfaces, spongy flows, hypohyaline flows and thick pahoehoe flows and lava paleo-lakes exhibiting well-developed columnar jointing and upper entablature. In the distant northern borders of PELIP, the Pitanga Formation volcanism records greater interaction with surface water, evidenced by hyaloclastites and pillow lavas (Moraes et al. 2020) . The Pitanga sequence is characterized by numerous intercalations of mafic volcaniclastic and sedimentary deposits (Licht and Arioli 2018; Valore et al. 2023), such as wet peperites (Waichel et al. 2006, 2007) in which fossils may be found (Del Mouro et al. 2023).

Methods

Fieldwork was conducted as part of the "Geological Map and Mineral Resources of Paraná State" project, which was proposed and funded by the Geological Survey of Brazil (SGB-CPRM) for the purpose of publishing an updated geological map of the state. The mapping of the tuff was carried out during a visit to the Tapalam quarry, situated in the municipality of Marilândia do Sul, Paraná State, Brazil. This quarry is known for producing gravel and crushed stone for civil construction, but now it is inactive. Thin sections of the tuff samples were prepared at the Lamination Laboratory (LAMIN) of the Department of Geology (DEGEOL) at the Federal University of Paraná (UFPR). Photomicrographs were captured using the Olympus microscope at the Institute of Mineral and Rock analysis (LAMIR) and scanning electron microscopy (SEM) images and energy dispersive X-ray spectroscopy (EDS) data were obtained using instruments at the Center for Electron Microscopy (CME) also located at UFPR. The classification of the tuff follows the criteria proposed or revised by White and Houghton (2006), while the analysis of volcanic ash morphology was conducted following the methods of Heiken and Wohletz (1985), and textures were assessed according to McPhie et al. (1993).

Results

The Tapalam quarry, situated in the northern region of Paraná State, lies on the central axis of the Ponta Grossa arc and at the interface between the Pitanga and Paranapanema formations. The former is observed either overlying or in lateral contact with high-Ti porphyritic trachyte flows from the Chapecó Formation, or directly overlying aeolian sandstones of the Botucatu Formation. The quarry consists of two levels, one at approximately 800 m and the other around 820 m in altitude. The main focus of mining operations is the extraction of texturally homogeneous and thicker pahoehoe lava flows from these levels. Within these benches, the interflow deposits preserve mine reject materials in situ, including mafic volcaniclastic deposits and thin, simple vesicular pahoehoe flows. The stratigraphy of the quarry comprises the following layers (Figs. 2 and 3a–d): (i) ~ 10 m thick homogeneous pahoehoe lava flow with irregular and highly concave decimetric width columnar jointing, lacking well-defined geometric patterns; (ii) ~ 4–8-m-thick irregular layer of scoriaceous volcanic mafic breccia with epiclastic well-sorted reddish brown matrix (including volcanic and non-volcanic particles) (Fig. 3b, c); (iii) < 1-m-thick irregular layer of basaltic primary volcaniclastic deposit, the Tapalam Tuff (Fig. 3c, d); (iv) ~ 2–6-m-thick sequence of thin sheet pahoehoe lava flows, with ropy/corded surface (Fig. 3b); (v) ~ 10–12-m-thick pahoehoe lava flow with irregular and concave columnar jointing similar to the basal one (Fig. 3a).

The tuff layer has a pale reddish-beige to gray colour and is distinguished by its irregular contact with the overlying basaltic breccia, filling depressions formed by the fragments of the breccia on its top surface (Fig. 3d). Thin-sheet pahoehoe basaltic flows overlay a sharp contact with the tuff. The ash and lapilli fragments are dark brown, while their surfaces are coated with a light red coating. The tuff is bound together by beige/white cement (Fig. 4a). Both lapilli and ash exhibit magnetic properties. The presence of weak lamination is evident through the flat orientation of elongated clasts and alternating millimetric grain sizes (Fig. 4b).

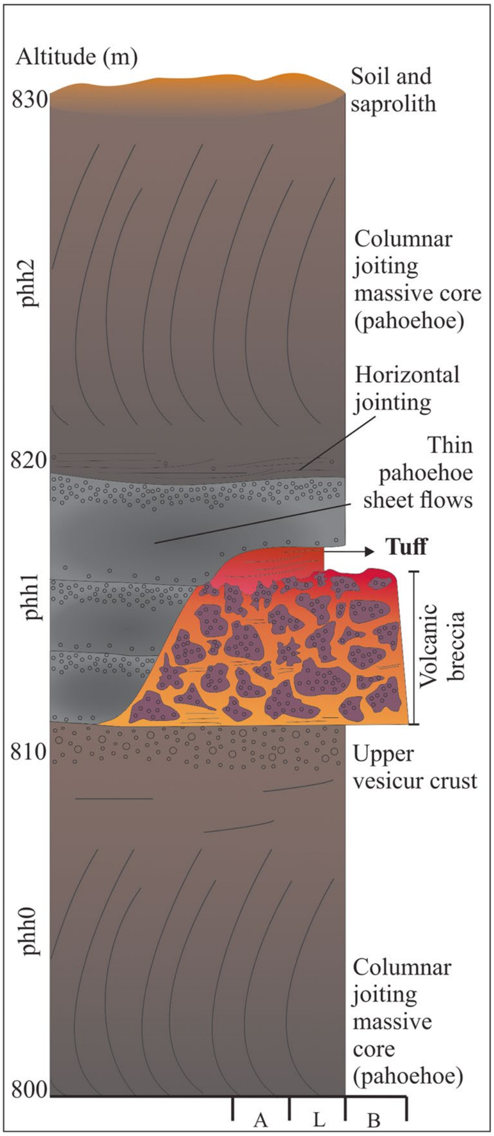

Fig. 2 Tapalam Quarry geologic profile. Basal pahoehoe (phh0), thin sheet and ropy pahoehoe sequence (phh1) and upper pahoehoe (pph2)

The morphological diversity within the tuff is significant, including elongated achneliths and cusp-shaped fragments (Fig. 4c, d). Grain size estimates via petrographic examination reveal a predominance of coarse ash (~60%) ranging from 0.1 to 2 mm, bound by a microcrystalline zeolite cement (~25%). Scoriaceous lapilli fragments (~15%) range from 2 to 5 mm, sometimes reaching 1 cm. Holohyaline light orange clasts, identified as sideromelane (Fig. 5), contain vesicles and rare euhedral to subeuhedral microliths (50–100 µm). The distinctive pyroclastic morphology of the clasts indicates a juvenile origin (Figs. 5 and 6). Rare isolated crystals (< 1 mm) can be found (e.g., augite). No lithoclasts or accidental fragments were identified in the samples.

Pyroclasts display prominent variations in roundness and sphericity. A distinct group of coarse achneliths exhibit fluidal shapes characterized by smooth and curved surfaces. Another population of glass shards is highly angular, cuspate and platy, suggesting they are remnants of broken vesicle walls. Rare achneliths occur with broken, long threads, reminiscent of Pele's hairs (Fig. 5a). These strands can extend over 1 cm in length and measure between 50 and 200 µm in width. Fragments of reticulite are also present, with an intricate lattice-like open vesicularity network composed of glass rods (Fig. 5b). A variety of achnelith shapes are present, including needles, spheres, ovoids, Pele's tears (Fig. 6a), fluidal fragments (Fig. 6b–d) and dumbbells (Fig. 5c, d). Some pyroclasts retain an internal flow structure, marked by darker lines that follow the outline of the fragment, parallel to the vesicle flattening (Fig. 6b, d). The pyroclasts are cemented by a mass of fibrous zeolite, clays, carbonates and iron oxides (Fig. 7a–c).

Vesicularity in the pyroclasts is 5 to 90 area%. Generally, vesicles appear spherical to slightly oval in shape. However, in some fibre pyroclasts, as the Pele's hair, vesicles are notably stretched and elongated (Fig. 6b, d). Radially fibrous zeolite lines the vesicles, and vesicles are in filled by either massive zeolite or microcrystalline silica (chalcedony). The alteration processes have effectively preserved the morphologies of the clasts. These processes have also given rise to cracks on the surfaces of pyroclasts, primarily due to hydration. Additionally, unique types of zeolite, such as the heulandite-clinoptilolite series, have crystallized as part of the alteration, contributing to the cementing of the pyroclasts.

Discussion and conclusions

The Tapalam Tuff stands out as an exceptional instance of well-preserved basaltic pyroclastic record within the entire Paraná-Etendeka LIP up to this point. The presence of well- to moderately sorted pyroclasts with a predominance of ash particles and the presence of achneliths (Pele's tear, broken Pele's hair, etc.) suggest a pyroclastic fall deposit. The preservation of fine textures may be attributed to unique conditions such as rapid burial by effusive activity, countering the usual quick erosion of tephra deposits. Delicate ash particles are typically prone to weathering or reworking. It is also possible that the continuity of the tuff deposit was disrupted by later lava flows, as observed in other volcanic settings, for example in the Roza Member of Columbia River Basalt Province, where inflating sheet lobes partially or totally buried the pyroclastic edifices (Brown et al. 2014). Dynamic and evolving environments prevail around volcanic vents, especially during long-lasting flood basalt eruptions. Massive lava flows may eventually cover extensive areas,

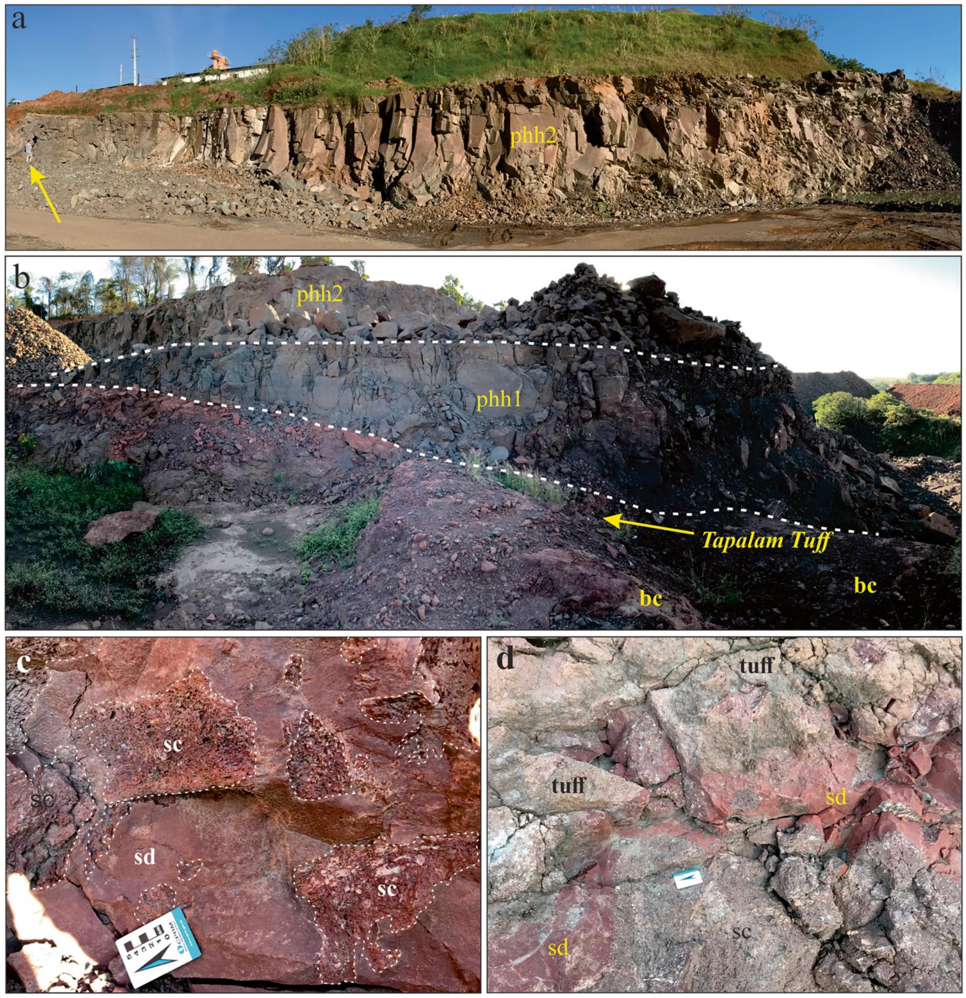

Fig. 3 Overview of field features within the Tapalam Quarry. **a** Upper basalt flow (phh2) (yellow arrow indicates a person for scale). **b** Cross-section displaying at the base the volcaniclastic scoriaceous breccia (bc), the location of the tuff, the thin vesiculated ropy pahoehoe flows (phh1) forming the quarry floor and the upper basalt flow in the background (phh2). **c** Detail of scoriaceous basalt block fragments within volcaniclastic matrix. **d** Irregular contact between scoriaceous blocks and bombs (sc), volcaniclastic matrix (sd) and the pyroclastic layer (tuff)

potentially burying significant pyroclastic material, leading to complex interactions and intercalation between products from various vents, resulting in complex stratigraphy (Brown et al. 2015). The palaeogeographic context of the Tapalam Tuff introduces another variable: the substantial quantity of sand from the vast Botucatu desert. This sand was continuously blown over the newly formed volcanoes, particularly at the base of the volcanic sequence. Much of the tephra might have been swept away by the same wind currents that transported the sand dunes.

The morphological characteristics of the pyroclasts, preserving the deformation of molten droplets in response to aerodynamic forces and surface tension by quenching, provide insights into the eruptive style (Wolff and Sumner 2000). The extensive morphological diversity of Tapalam Tuff pyroclasts, coupled with the presence of smooth-skinned rounded droplets, broken elongated strands (Pele's hairs; Villermaux 2012) and broken, ragged, irregular droplets, as well as fragments with external forms partly influenced by surface tension, are indicative of a fire-fountain fissural eruption similar to the Hawaiian-type (Walker and Croasdale 1971; Heiken 1972; Schmith et al. 2017). The morphological irregularity of the pyroclasts suggest processes of complete fragmentation (rather than partial), signifying the occurrence of high-intensity explosions and magmatic fragmentation in a fire-fountain setting (Edwards et al. 2020).

A fluid-dominated lava fountain and ductile fragmentation generates mainly fluidal clasts from millimetre (achneliths, Pele's tears, Pele's hair) up to centimetre or decimetre scale (spatter or bombs) (Cannata et al. 2019; Spina et al. 2021), while an ash-dominated lava fountain driven by brittle failure of magma forms very smaller solid clasts from hundreds of microns up to a few millimetres (Parfitt 1998; Houghton and Gonnermann 2008; Spina et al. 2021). In the Tapalam Tuff the presence of pyroclast populations exhibiting both fluid- and ash-dominated characteristics may suggest a fall deposit resulting from more than one lava fountain feeding ash clouds along a fissure with multiple and concurrent vents. This scenario was observed in the long-lasting eruption of Hekla Volcano, Iceland (Thorarinsson and Sigvaldason 1972). Alternatively, a single lava source

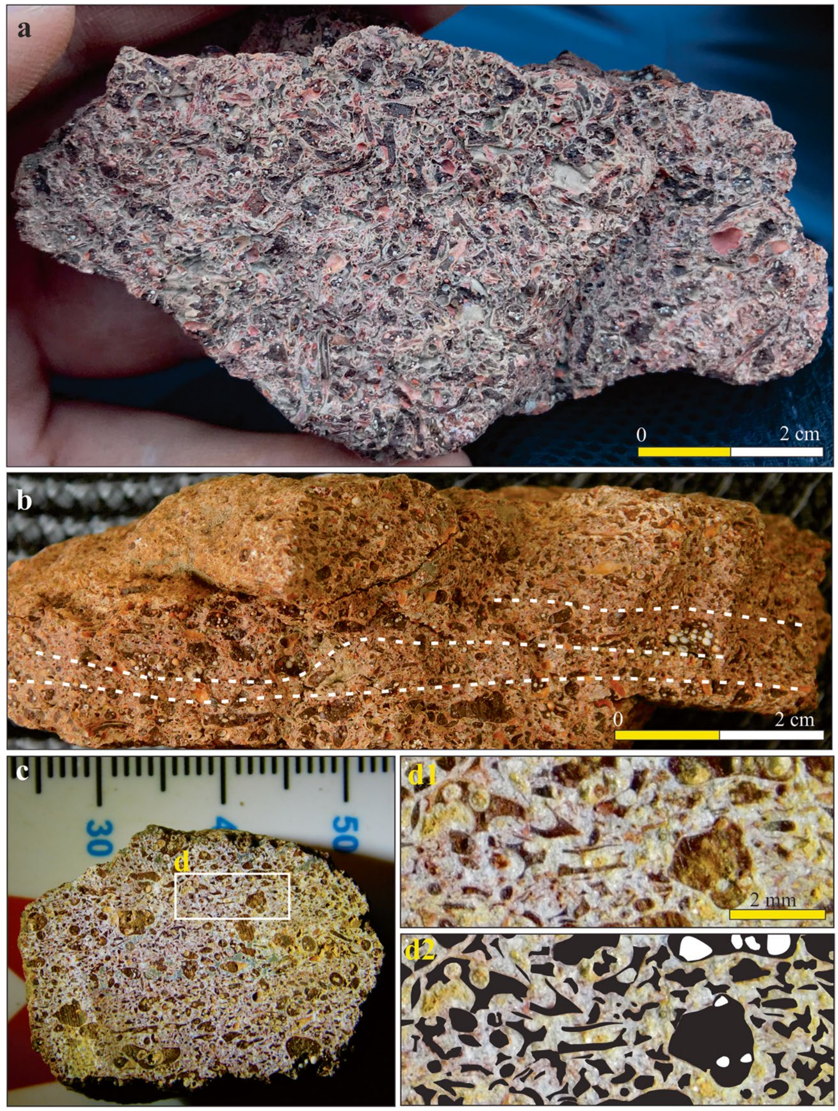

Fig. 4 Tapalam Tuff. **a** Hand specimen shows diversity of coarse ash and lapilli pyroclasts. **b** Cross-section of a sample indicating weak alternation between coarser and finer bands (white dashed lines) and elongated pyroclasts. **c**, **d** Morphologic diversity of mafic glass pyroclasts (shape, roundness, sphericity), large number of elongated achneliths and cuspate to platy-shaped shards

might alternate between phases dominated by different fragmentation styles, ductile and brittle, as observed in eruptions of Kīlauea, Hawai ʻi (Namiki et al. 2021) and giving rise to subtle intercalation between finer and coarser layers.

In dry magmatic fragmentation eruptions, slower cooling rates commonly result in the formation of tachylite, a microlite-rich glass (White and Valentine 2016), whereas in phreatomagmatic eruptions, sideromelane is more common, a rapidly quenched pristine volcanic glass characteristic of basaltic magma quenched by water (Heiken 1974). However, either type of basaltic glass can occur during both dry and wet fragmentation (Moreland et al. 2019). While sideromelane is typically rare in dry basaltic eruptions, it can be produced in vigorous lava fountains (Stovall et al. 2012), such as those which formed the Tapalam tuff. Notable historic eruptions further underscore the potential for high lava fountains and ash dispersal. During the 1983–1984 Pu ʻu ʻŌ ʻō eruption at Kīlauea, Hawai ʻi, lava jets reached ~ 400 m in height with plumes of 5–7 km (Parfitt 2004). In the 2013 Mount Etna (Italy) eruption, a lava fountain 2.5 km high produced an eruption column reaching approximately 6 km in height and a dense plume that dispersed ash up to 400 km away (Bonaccorso et al. 2014). The 1783–1784 fire-fountains at Laki (Iceland) probably reached > 1 km in height with sustained eruption columns up to 15 km in altitude (Thordarson and Self 1993). High sustained plumes have also been associated with large flood basalt eruptions, as recognized in the Columbia River Basalt Province through the pyroclastic deposits of the Roza Member flow field (Brown et al. 2014; Glaze et al. 2017).

Our observations regarding the occurrence of high lava fountains within the Paraná-Etendeka LIP provide insights into understanding the scale of eruptions' impact on atmospheric contamination and their interrelation with local/regional moisture patterns in the heart of Gondwana (Glaze

Fig. 5 Photomicrographs of Tapalam Tuff under plane-polarised light. **a** Broken Pele's hair (red arrows). **b** Rare reticulate (red arrow) and scattered fluidal fragments. **c** Needles (red arrow) and spheres of glass (black arrow) and many shards. **d** Twisted droplets or dumbbells

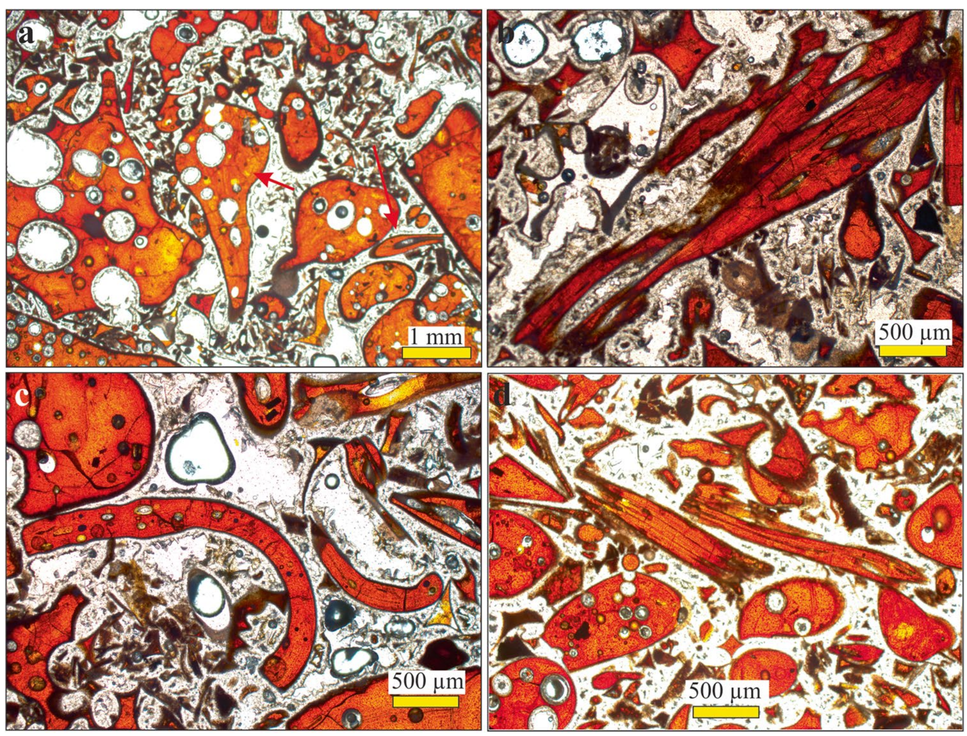

Fig. 6 Photomicrographs of Tapalam Tuff under plane-polarised light. **a** Pele's tears, droplets of volcanic glass. **b–d** Fluidal curved pyroclasts, shards and fine zeolite mass as a cement (maybe palagonitized fine ash)

et al. 2017; Cruz et al. 2021; Cavalheiro et al. 2021; Bacha et al. 2021).

While mafic pyroclastic deposits are less common in LIPs compared to felsic ones, their presence holds significant implications for specific regions, contributing to our understanding of a magmatic province evolution. The observed characteristics strongly indicate proximity to the volcanic vent, suggesting the Tapalam Tuff is a fall-out pyroclastic deposit (primary volcaniclastic) originating from a high fountain eruption, fed by low viscosity

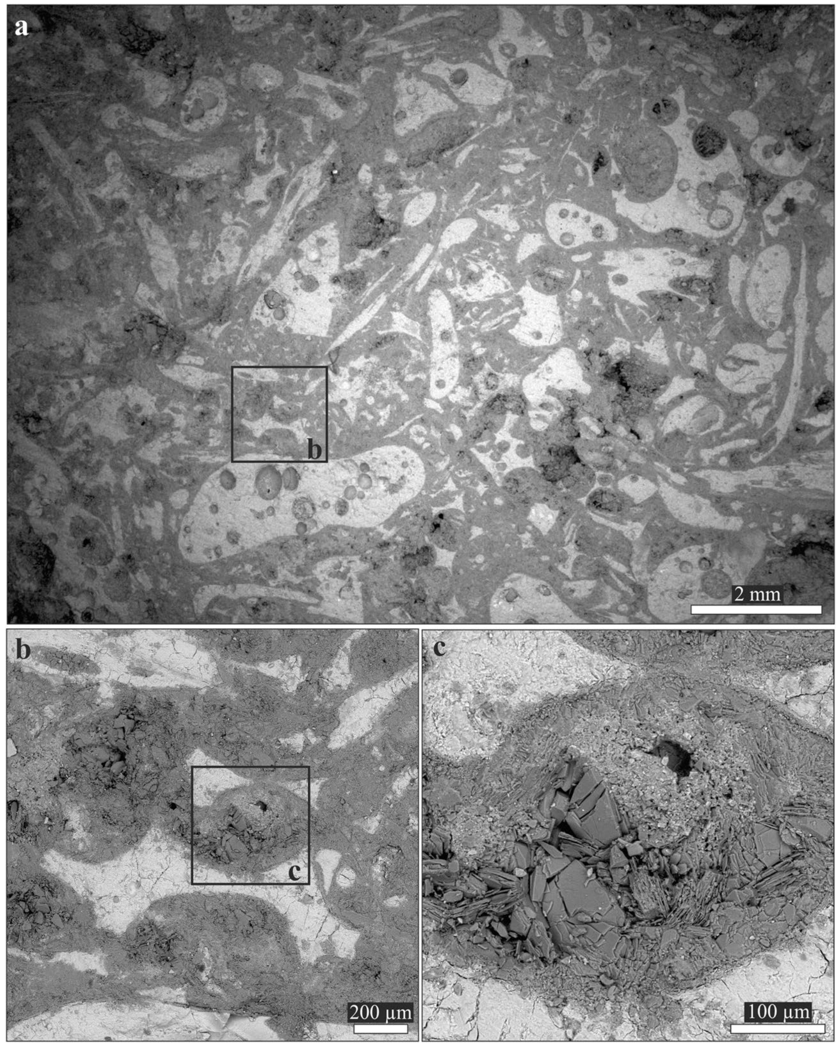

Fig. 7 SEM (SE) images of Tapalam Tuff. **a** Overview of the pyroclasts. **b** Detail of two sideromelane shards. **c** Clay minerals and zeolites probably formed via a palagonitization process

and high-temperature basaltic magma. Furthermore, the presence of the Tapalam Tuff, the first documented mafic fall pyroclastic deposit within the Paraná-Etendeka LIP, provides valuable insights into the volcanic history and geodynamic processes associated with these extensive, high-volume eruptions that have played a significant role in shaping Earth's past.

Acknowledgements We also extend our appreciation to the Federal University of Paraná for the lab support, including the Department of Geology, the Institute of Mineral and Rock Analysis, and the Electron Microscopy Center. Additionally, we would like to express our gratitude to the reviewers of this article for their valuable input. I would also like to thank my colleague "Matinho" who accompanied the initial fieldwork and "Guto" for his indispensable help and support.

Funding The Geological Survey of Brazil (SGB-CPRM) of the Ministry of Mines and Energy funded this work.

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