ESTUDOS GEOLÓGICOS

VOL. 33 (2) 2023 – pp. 35-54

ISSN: 1980 - 8208

GEOLOGICAL FIELD GUIDE TO THE EARLY CRETACEOUS INHANDUÍ HOTSPRINGS AND THEIR HOST BOTUCATU PALEODUNES

Felipe P. Leitzke[1,2], Luiz H. Ronchi[2*], Camile Urban[2], Léo A. Hartmann[1]

[1]Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Avenida Bento Gonçalves, 9500; 91501-970 Porto Alegre, Rio Grande do Sul, Brazil.

[2]Centro de Engenharias, Universidade Federal de Pelotas, Praça Domingos Rodrigues; 96010-610 Pelotas, Rio Grande do Sul, Brazil. *Corresponding author: lhronchi@hotmail.com

DOI 10.18190/1980-8208/estudosgeologicos.v33n2p35-54

Abstract

Structures formed by geological processes that occurred during the Early Cretaceous are preserved in large areas of the Fronteira Oeste Rift in Rio Grande do Sul, Brazil. Among these areas, the Inhanduí Paleodune Field (IPDF), located in northeastern Alegrete, is part of the Botucatu paleoerg, the largest paleodune field in Supercontinent Gondwana. This area shows hundreds of circular and curvilinear dunes of silicified sandstone of variable sizes, which were covered by intraplate Paraná volcanic rocks. This field guide provides the information for a field trip from Porto Alegre, Brazil to two hills (Cerros) in the IPDF, Cerro Farrapo and Cerro Figueirinha. Important features formed by hot water, volcanic rock and sediment interaction are preserved in large outcrops in these hills, including extensive silicification and deformation of the buried dunes, injection of fluidized sand and explosive hydrothermal activity. Hydrothermal structures include preservation of subterranean conduits that emerged at the Earth's surface to form surging hot pools, geysers and spouts. These features are preserved as bowls, rounded to polygonal cavities and prismatic and lozenge-shaped clasts and blocks. Access to the outcrops is mostly via paved roads, with 40 km in unpaved roads.

Keywords: Hydrothermalism, Silicification, Hotspring, Paraná Basin, Fronteira Oeste rift

1. Introduction

The Fronteira Oeste Rift (15,000 km2), formed as a segment of the larger fracturing that rifted South America and Africa (e.g., Silva e al., 2004; Hartmann et al., 2010), and is located in southernmost Brazil (Figure 1). This rift comprises 100–300 m of total vertical displacement in some places (Hartmann and Cerva Alves, 2021), and is part of the Ordovician to Late Cretaceous Paraná Basin (Zalan et al., 1990). At ca. 135 Ma (Hartmann et al., 2019), lavas from the intraplate Paraná-Etendeka Large Igneous Province covered the Botucatu paleoerg (Almeida, 1953; Scherer, 2000; Bertolini et al., 2020). The buried sand sea was filled with rain water (Guarani Paleoaquifer) in a short time. During this stage, silicification, fracturing and steam venting occurred during heating of the newly-formed aquifer. Heating of groundwater to 100-250 °C by the mantle plume (raised geothermal gradient) developed a large (1.2 million km2) composite hydrothermal cell in the basin (Hartmann et al., 2022). Hot water and vapor ascended into overlying rocks, and each event of mantle partial melting and magma injection into the crust and effusion at the surface was followed by a sequence of hydrothermal events. The entire Paraná Basin was affected by hot fluid percolation (e.g., Hartmann et al., 2012, 2021). This fluid formed amethyst and agate geodes of economic importance in lava flows that had favorable internal structure (Duarte et al., 2009). In addition to the formation of geodes, it is likely that this event mobilized elements of economic importance, forming epithermal deposits of Au, Ag, Cu and other metals.

Relics of structures formed by the processes that occurred during the Early Cretaceous are preserved in large areas of the Fronteira Oeste Rift (e.g., Hartmann et al., 2023). One of these areas is the Inhanduí Paleodune Field - IPDF (Figure 2a,b), named after the Inhanduí River that crosses the field to the northeast of Alegrete town. The IPDF is part of the Botucatu paleoerg, the largest paleodune field in Supercontinent Gondwana (Hartmann et al., 2021), with hundreds of circular and curvilinear dunes of silicified sandstone of variable sizes, covered by intraplate Paraná volcanic rocks. Therefore, this field guide provides the information for a fieldtrip to the Cerros Farrapo and Figueirinha. In the IPDF, important features of hot water, lava and sediment interaction can be seen in outcrops, including extensive silicification and deformation of the buried dunes, injection of fluidized sand and explosive hydrothermal activity (breccias and mounds).

2. Geological Setting

The Fronteira Oeste Rift (15,000 km2), formed as a segment of the larger fracturing that rifted South America and Africa (e.g., Silva e al., 2004; Hartmann et al., 2010), and is located in southernmost Brazil (Figure 1). This rift comprises 100–300 m of total vertical displacement in some places (Hartmann and Cerva Alves, 2021), and is part of the Ordovician to Late Cretaceous Paraná Basin (Zalan et al., 1990). At ca. 135 Ma (Hartmann et al., 2019), lavas from the intraplate Paraná-Etendeka Large Igneous Province covered the Botucatu paleoerg (Almeida, 1953; Scherer, 2000; Bertolini et al., 2020). The buried sand sea was filled with rain water (Guarani Paleoaquifer) in a short time. During this stage, silicification, fracturing and steam venting occurred during heating of the newly-formed aquifer. Heating of groundwater to 100-250 °C by the mantle plume (raised geothermal gradient) developed a large (1.2 million km2) composite hydrothermal cell in the basin (Hartmann et al., 2022). Hot water and vapor ascended into overlying rocks, and each event of mantle partial melting and magma injection into the crust and effusion at the surface was followed by a sequence of hydrothermal events. The entire Paraná Basin was affected by hot fluid percolation (e.g., Hartmann et al., 2012, 2021). This fluid formed amethyst and agate geodes of economic importance in lava flows that had favorable internal structure (Duarte et al., 2009). In addition to the formation of

geodes, it is likely that this event mobilized elements of economic importance, forming epithermal deposits of Au, Ag, Cu and other metals.

Relics of structures formed by the processes that occurred during the Early Cretaceous are preserved in large areas of the Fronteira Oeste Rift (e.g., Hartmann et al., 2023). One of these areas is the Inhanduí Paleodune Field - IPDF (Figure 2a,b), named after the Inhanduí River that crosses the field to the northeast of Alegrete town. The IPDF is part of the Botucatu paleoerg, the largest paleodune field in Supercontinent Gondwana (Hartmann et al., 2021), with hundreds of circular and curvilinear dunes of silicified sandstone of variable sizes, covered by intraplate Paraná volcanic rocks. Therefore, this field guide provides the information for a fieldtrip to the Cerros Farrapo and Figueirinha. In the IPDF, important features of hot water, lava and sediment interaction can be seen in outcrops, including extensive silicification and deformation of the buried dunes, injection of fluidized sand and explosive hydrothermal activity (breccias and mounds).

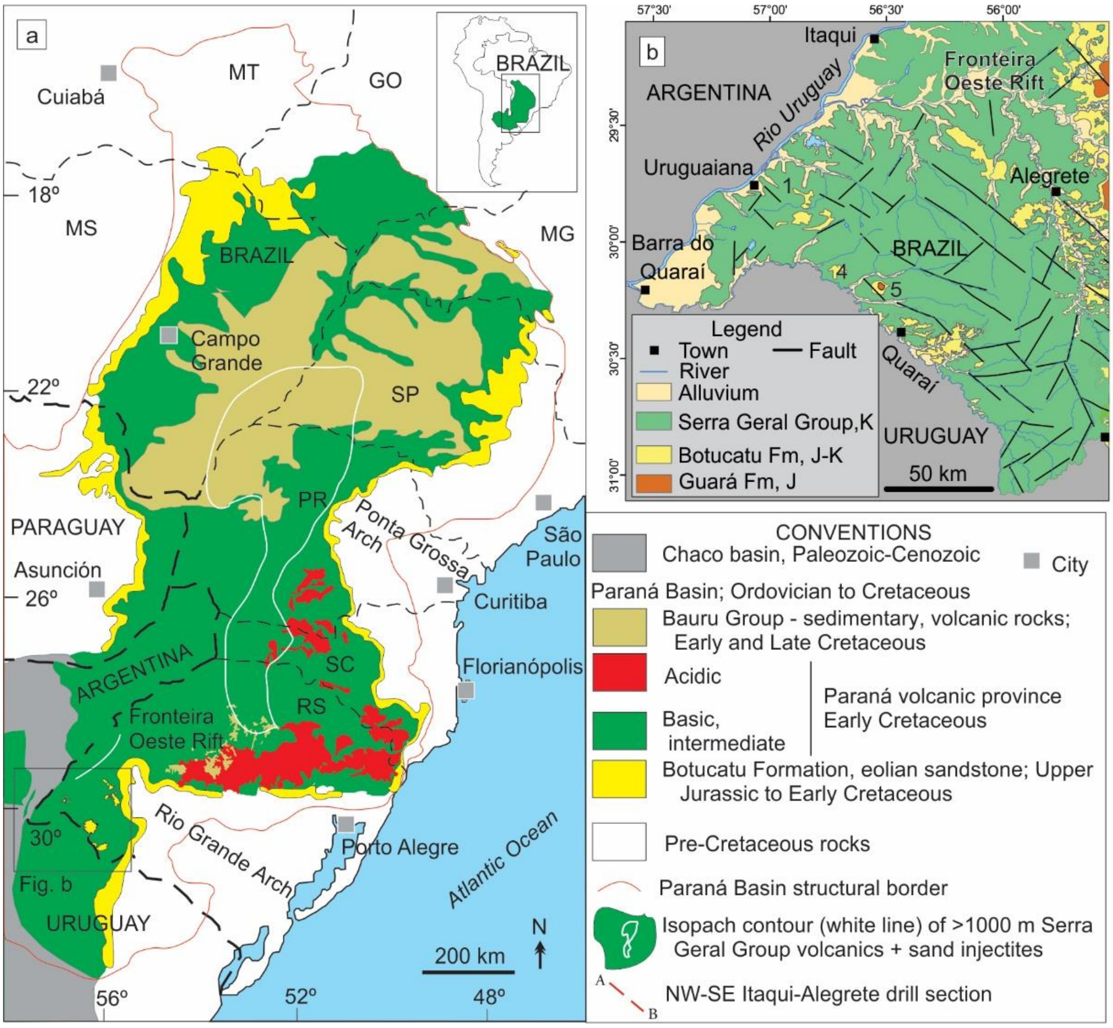

Figure 1: (a) Geological map of the Paraná Basin, emphasis on Cretaceous units – Botucatu Formation, Serra Geral Group, Bauru Group (Hartmann and Cerva-Alves, 2021a; Hartmann et al., 2022a). Geology of Corrientes, Argentina, from Locati et al. (2022). (b) Geological map of the Fronteira Oeste Rift.

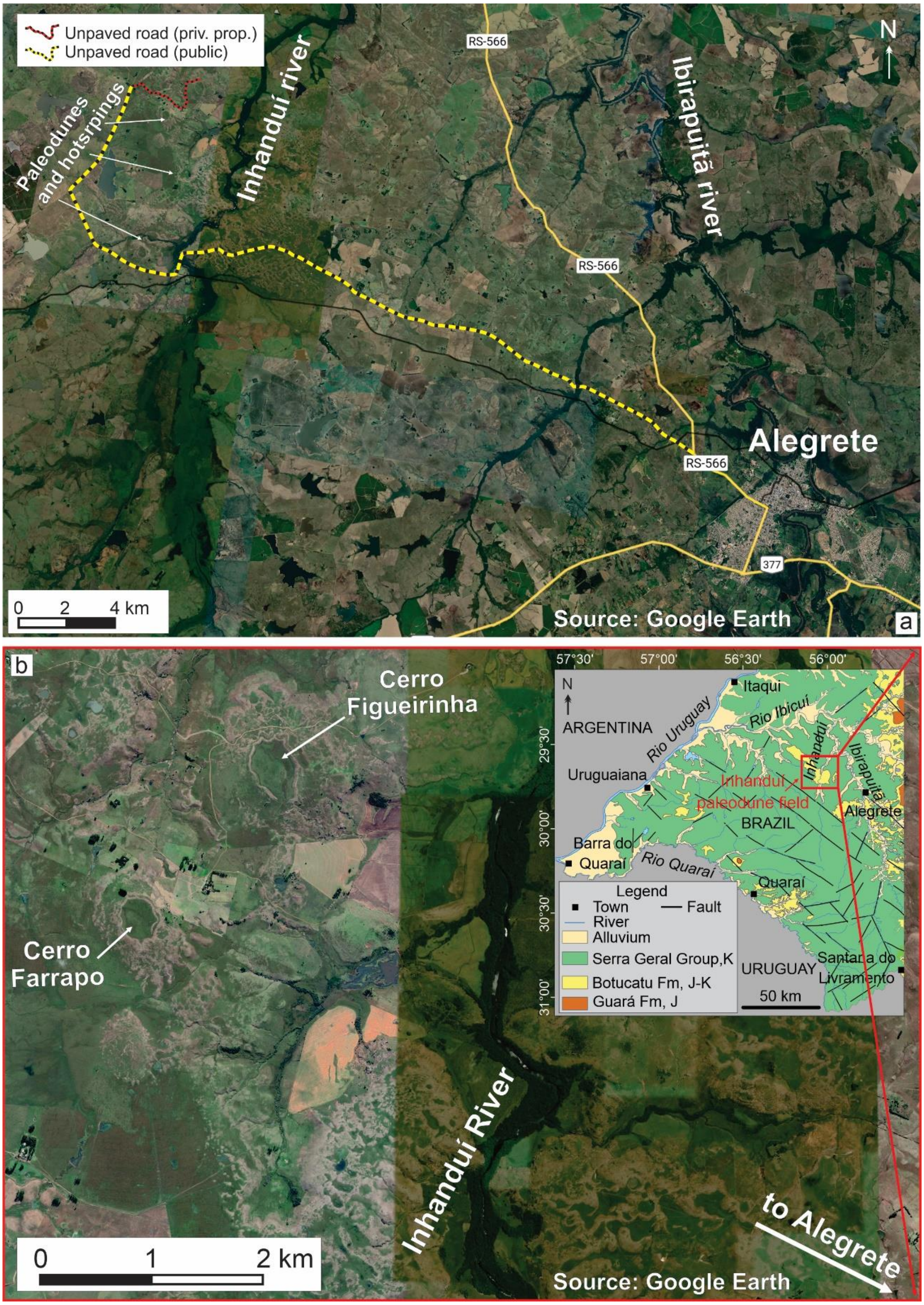

Figure 2: (a) access to the Inhanduí paleodune field from Alegrete and (b) location of the suggested outcrops for the geotrip, being two giant paleohotsprings at Cerro Farrapo and Cerro Figueirinha.

3. Field Trip Logistics

Ruben Berta Airport is the closest to the Inhanduí Paleodune Field and is located in the town of Uruguaiana, with direct flights to the cities of São Paulo, Porto Alegre and Florianópolis. However, flights to Uruguaiana are sparse. Therefore, a more appropriate option is to fly to Porto Alegre (Salgado Filho International Airport) and travel either by bus or car to the town of Alegrete, which is the closest urban area to the Inhanduí Paleodune Field. Buses run every day from Porto Alegre to Alegrete (approximately 495 km), with estimated total trip duration between 6 h 30 min and 8 h. Tickets are available at the bus company website (https://planalto.com.br/). Either by bus or car, the best route to Alegrete is via BR-290, a paved highway. Gas stations and stops for refreshment are widely spaced along the road, but can be found closer to some larger towns, such as Pantano Grande, São Gabriel and Rosário do Sul. In Alegrete, there are car rental companies that enable a visit to the outcrops (e.g., https://www.localiza.com/brasil/pt-br/rede-de-agencias/alegrete).

The town of Alegrete is crossed by the Ibirapuitã River. To the east of the river, there is a mainly commerce and services area, while to the west of the river most of the area is residential. Alegrete has excellent options for accommodation and restaurants. For example, among the accommodation options: Hotel Alegrete (Av. Liberdade, 268) and Hotel Caverá (Rua Bento Manoel, 839). Hotel Alegrete has a restaurant within the hotel (Bistrô Alegrete), which opens for dinner daily except Sunday. Other options of good quality restaurants include the Restaurante Tradição, a steak house that opens for lunch and dinner with self-service option. Two restaurants with that branded are located downtown (Rua Vasco Alves, 74) and by the highway (Rua Eleodoro-Prates García, 1035). For evening dinner, Pizzaria Ricci is a good option. This pizzaria hosts a small pub, located at Rua República Riograndense, 1044; it is open every evening except Monday.

From Alegrete, the access to the Inhanduí Paleodune Field (Figure 2a) is an unpaved road (approximately 40 km), and 3 km inside private property. Finally, to reach the outcrops, 400 m walks are required, mostly on plane pampa. Permission from landowners must be sought before entering the properties. There are no service stops along the unpaved road, so it is mandatory to pack water, lunch and any other items that will be required for the day.

4. Outcrops

The main outcrops to be visited in this field trip are located in two hills, named Cerro Farrapo and Cerro Figueirinha (Figure 2b). An additional stop is on the road to the hills, to observe the Catalán andesite lava flow (stop 1) and the interaction of fluidized sand with the rock (Figure 2b and 3). Table 1 shows the planned stops, with outcrop coordinates and a short description of each point. The main features to be seen in this geotrip are related to the pre-rift (Atlantic Ocean opening) hydrothermal activity in the Botucatu paleoerg. Hartmann et al. (2021) summarized eight evidence of intense interaction of hot water, vapor, volcanic rocks and sediments in the Fronteira Oeste region:

1) Silicification of dunes within and volcanic rocks above the Guarani Paleoaquifer;

2) Intense fragmentation of silicified dune sandstones by hot water jetting;

3) Lozenge fracturing of silicified paleodunes and volcanic rocks;

4) Injection, effusion and silicification of liquefied sand into the lozenge fractures and into the overlying volcanic column;

5) Collapse of overlying sand by seismic shaking and also into the voids left by extraction of injected sand from parent beds in Botucatu paleoerg;

6) Confinement of hot water within sealed volcanic rocks (and locally sandstones) to form amethyst and agate geodes in the upper part of the core of the flow and below the cap seal of extrudites;

7) Formation of a myriad of circular, elliptical and curvilinear structures (10 m – 50 km) in volcanic rocks, upper amygdaloidal crust of the Catalán flow;

8) Formation of an extensive paleohot spring field possibly containing low-sulphidation Au-Ag-Cu epithermal deposits.

The sedimentary rocks in the area are fine to medium grained sandstones with trough cross-bed sets. The stratifications are less than 2-3 m thick, but were blurred by intense disruption and silicification of the rock. In general, the paleocurrent data at the visited outcrops indicate dominant paleowind orientation towards the northeast (sourced from SW), but also from other directions. Sedimentary structures were not preserved in the collapsed silicified paleodunes in the core of the cerros; but were preserved a few hundred meters from the cerro.

Figure 3: (a) overview of an unaltered outcrop (29°43'14.72" S; 56° 5'29.50" W) of the Catalán lava flow showing (b) sand-lava interaction, with injectites of sand in the volcanic rock. The unaltered Catalán flow gives a response of 130 total counts per second (cps) using the gamma spectrometer and usually occurs in creeks, where the erosion has reached its level, or as loose blocks among the paleodunes. Since the volcanic rocks alters much more easily than the silificified sandstone, it is common to see only sandstones preserved in the area, and heavily altered red clay soil in the areas originally composed of volcanic rocks.

Table 1: Summary of planned stops, geographical coordinates and brief geological description of what to see.

Stop nr.	S	W	What to see
1	29°43'14.72" S	56° 5'29.50" W	Volcanic rocks of the Catalán andesite; sand injectites
2	29°39'54.69" S	56° 4'23.82" W	Silicified andesite and paleodune structure
3	29°39'56.43" S	56° 4'21.41" W	Silicified andesite and paleodune structure
4	29°40'00.5" S	56°04'36.7" W	Main hydrothermal structures, vents and bowls preserved in sandstone
5	29°39'54.4" S	56°04'26.1" W	Eucalyptus Grove - Lunch break
6	29°39'00.6" S	56°03'41.4" W	Different fracture patterns
7	29°39'26.8"S	56°03'27.1"W	Circular structures of different sizes among the paleodunes
8	29°39'31.46" S	56° 3'27.07" W	Altered volcanic rock with sand interaction

The slightly elliptical, southwestern larger Cerro Farrapo is 320 m in the east-west direction and 360 m from north to south. Figure 2b shows that it is composed of concentric, aligned, silicified, light colored, collapsed paleodunes surrounded by smaller similar circular structures. The smaller mounds occur especially towards SE, associated with sand sheets and weathered volcanic rocks covered by green grass. The rock occurring below the grasslands is the Catalán Flow, as indicated by gamma spectrometry measurements (120 cps). Cerro Figueirinha is the larger, elliptical northeastern structure, roughly 420 m east-west and 560 m from north to south. Similar to Cerro Farrapo, it has aligned light colors of silicified paleodunes composing a main oval structure. The ellipse is surrounded towards the north and the east by several smaller elliptically linked paleodune structures, mounds, sand sheet deposits and flows of weathered volcanic rocks also covered by green grass of the Catalán Flow (Figure 2 and Figure 11 a, b). In both cerros, there is an association between circular shapes and the silicified paleodune.

In the Inhanduí Paleodune Field, there are several hydrothermal structures preserved in the sandstones, namely: (1) Circular and elongated bowls, (2) Rounded cavities 1 to 5 cm large, (3). Small (<1cm) vesicular-like cavities, and (4) Radial prismatic and lozenge-shaped fracturing.

The circular and elongated bowls (Figure 8a, b) with diameters between 10 to 50 cm and vertical extent ranging from 1 to 10 cm are characterized by a clogged central vent. Also, lateral vertical fractures 1 to 4 cm long form dissolution grooves in the bowl borders. These structures are cut by two to five irregularly distributed rounded cavities ranging in size from 1 to 5 cm, and dozens of <1 cm vesicular-like cavities radially concentrated in the bowl center (Figure 9a). Some of the bowls show a spout-like projecting structure with triangular opening, narrowing at the end, suggesting water flowing over loose sediment (Figure 9b). Several pillow-like structures are found throughout the surface area as a result of recent erosional processes. The removal of some of these pillows reveals a circular or elongated cavity similar to the bowls, including the central fracture, but without the radial fractures, the small spotted circular cavities and the spout-like structure. In sequence, we list the structures present in the outcrops:

a) The 1-5 cm circular cavities can be isolated or scattered in small groups; they are found locally concentrated in random clusters in some outcrops, eventually parallel to cross stratification (Figure 7c). One cavity shows a neck (Figure 8c) suggesting that it was the end of a small conduit. The cavities are locally linked forming 3 or 4 cm-long, continuous cavities suggesting fluid flow parallel to void elongation.

b) The <1 cm circular cavities usually occur agglomerated and radially concentrated in the bowl center (Figure 9a) or in random clusters in some outcrops.

c) Sub-rounded to angular clasts and blocks of triangular prism and lozenge-shape range in size from <10 cm to >30 cm. They were formed by shallow surficial fractures in random directions in some cases radiating from the bowls (Figure 10a,b) or even from some of the 5 cm- large isolated circular cavities (Figure 8d). Their shape is similar to sinter clast breccia consisting of angular, broken blocks.

Below, we describe the planned stops at Cerro Farrapo and Cerro Figueirinha to see the evidence of volcanic rock, hot water and sand interaction, in order of distance from the town of Alegrete. A summary of the stops is given in Table 1.

Stop 1 (29°43'14.72" S 56° 5'29.50" W). Volcanic rocks in the creek on the road to the cerros. This is an outcrop of the Catalán quartz andesite (Hartmann et al., 2010), the first flow to cover the Inhanduí paleodunes in the area. Note the rhombohedral pattern of fractures and the presence of sand injectites (Figure 3b), indicating the hydrothermal activity and heating of the water present in the Guarani paleoaquifer up to 250 °C (e.g., Hartmann et al., 2021b).

Stop 2 (29°39'54.69" S 56° 4'23.82" W). On the edges and outside of Cerro Farrapo, there are pink and silicified fine to medium grained sandstones, composed mainly of quartz. Cross bedding is marked (Figure 5a) showing associated rounded cavities >1 cm in size aligned in the paleocurrent direction. Where cavities are aligned in the paleocurrent direction (e.g., Figure 5b), the rock presents millimetric circular structures similar to small channels filled with silica.

Stop 3 (29°39'56.43" S 56° 4'21.41" W). Inner portion of Cerro Farrapo, pink and silicified fine to medium grained sandstones, composed mainly of quartz. These rocks are similar to the edges, but with a higher frequency of fractures obliterating the original structure. Note the lozenge pattern of fractures, indicating a vertical □1 stress force, as well as the conchoidal fracture of the silicified sandstone.

Stop 4 (29°40'00.5" S 56°04'36.7" W). Cerro Farrapo. There is a continuous exposure of the four main hydrothermal structures in five outcrops (Figure 6). These structures are widespread throughout Cerro Farrapo, but they predominate in the upper portion of the structure. Each of the points in this stop is described:

Outcrop 1: Sub-rounded to angular clasts and blocks of triangular prismatic and lozenge shape either with or without 1-5 cm circular cavities (Figures 7a, b).

Outcrop 2: Circular cavities >1cm parallel to the cross stratification as indicated by arrows (Figure 7c).

Outcrop 3: Associated, nearly coalescent circular and elongated bowls (Figure 8a). Circular bowl with grooves and dozens of <1 cm vesicular-like cavities radially concentrated in the bowl borders (Figure 8b).

Outcrop 4: Circular cavity showing a neck, diameter 3 cm (Figure 8c). Main circular cavity, diameter 5 cm, associated to several other smaller cavities, including those that are <1 cm (Figure 8d). Observe the radial fractures.

Outcrop 5: Three bowls, one with a spout-like structure and dozens of <1 cm vesicular-like cavities radially distributed and concentrated in the bowl center, different from Figure 8b. Two coalescent bowls on the right side. Arrows point to some the radial fractures outside the bowl (Figure 9a). Detail of the spout-like structure, grooves, vesicle-like cavities and ripple mark-like structure (Figure 9b). Group of bowls converging to a spout-like structure indicated by an arrow (Figure 9c).

Stop 5 (29°39'54.4"S 56°04'26.1"W). Eucalyptus grove, a shaded site for refreshment or lunch, given the lack of trees in most of the area.

Stop 6 (29°39'00.6" S 56°03'41.4" W). Cerro Figueirinha. In this outcrop (Figures 10 a, b), there is a difference between the sub-rounded to angular clasts and blocks of triangular prism and lozenge shape of hydrothermal origin from the rectangular blocks formed by NE regional fractures.

Stop 7 (29°39'26.8" S 56°03'27.1" W). Cerro Figueirinha. Bowls with spout-like structure, grooves and a fracture on the right border (Figure 10c) and a narrow bowl also with spout-like projecting structure (Figure 10d). Outcrop view of a rounded mound (Figure 11a) depicted in Figure 10c and 10d. View of a circular structure (Figure 11b) from the mound in Figure 11a.

Stop 8 (29°39'31.46" S 56° 3'27.07" W). Cerro Figueirinha. In this stop, sand shows interaction with a heavily altered vesicular volcanic rock; small agate geodes are present. (Figure 12). This is probably the altered portion of the Catalán quartz andesite, given its gammaspectrometric response.

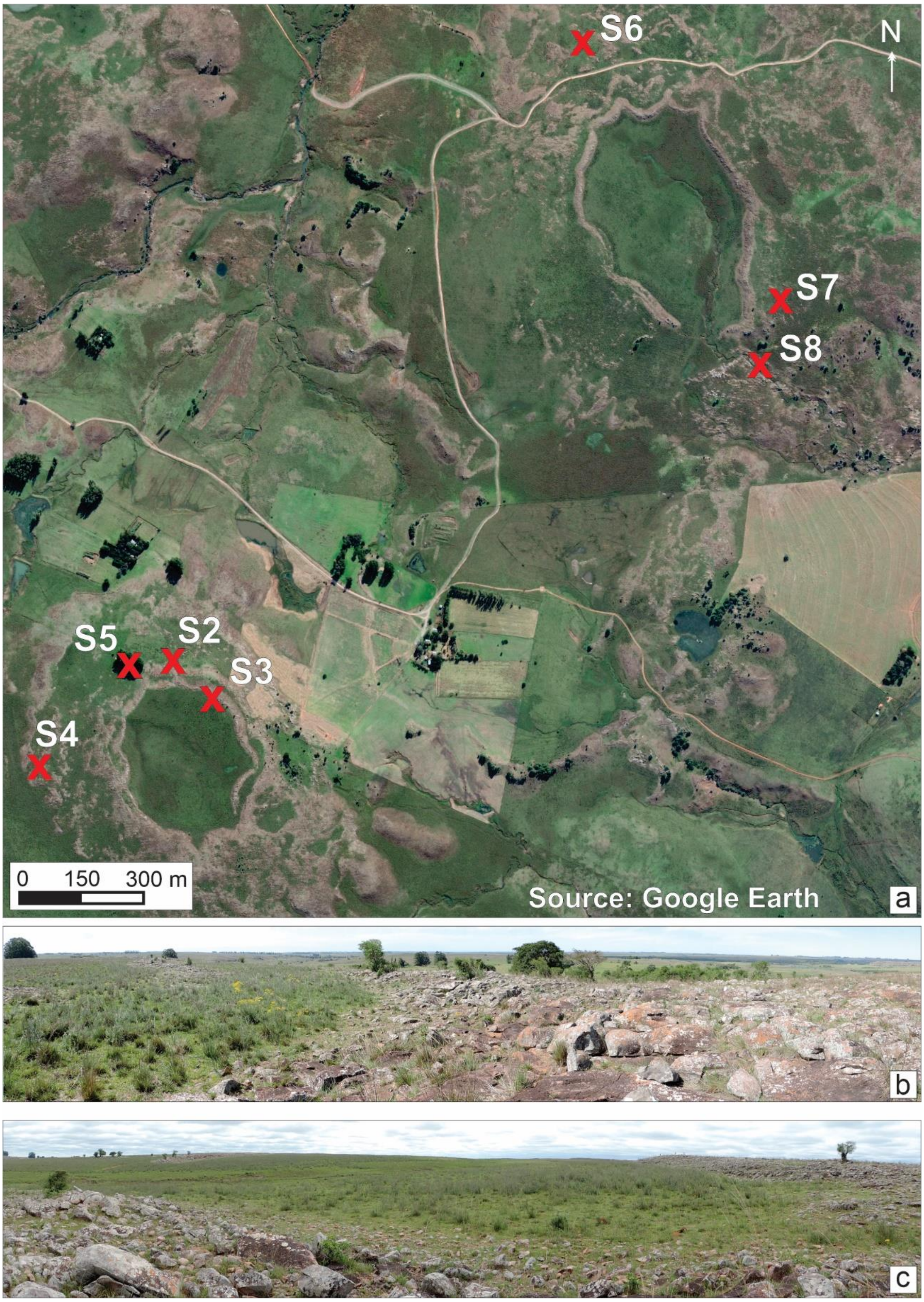

Figure 4: Overview of the stops (a) and panoramic views of Cerro Farrapo (b) and Cerro Figueirinha (c). Note that stop 1 is not plotted because it is outside the field of view.

Figure 5: Silicified sanstones at Cerro Farrapo (a) cross-bedding structure and (b) hydrothermal cavities aligned in the paleocurrent direction.

Figure 6: Zoom at the Cerro Farrapo Stop 4, showing the location of outcrops 1 to 5 (Source: Google Earth).

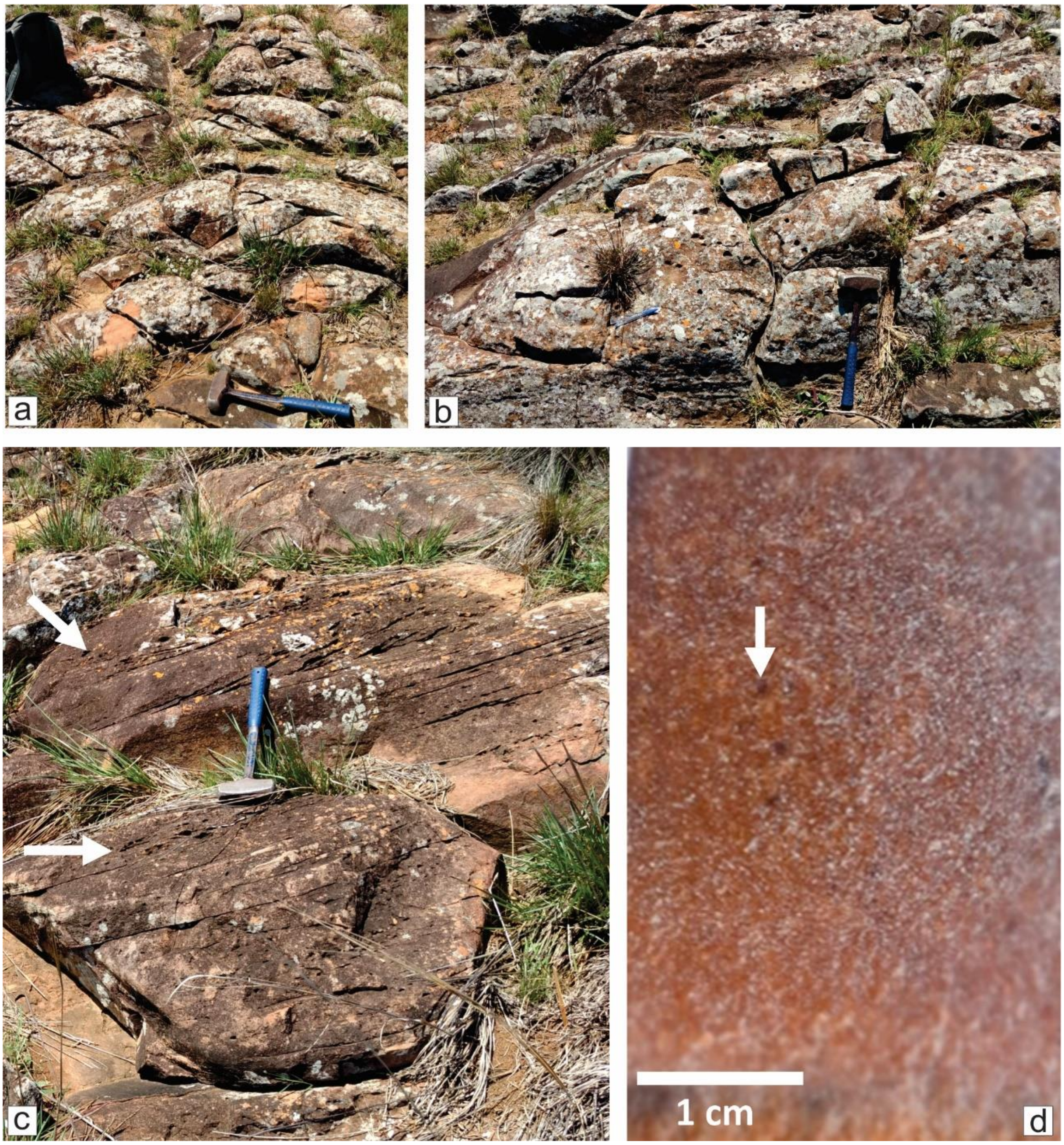

Figure 7: Hydrothermal structures at Cerro Farrapo, Stop 4, Outcrops 1 and 2. (a) Outcrop 1 - Sub-rounded to angular clasts and blocks of triangular prismatic and lozenge-shape. (b) Outcrop 1 – Clasts and blocks with 1-5 cm circular cavities. (c) Outcrop 2 - circular cavities paralleling the cross stratification as indicated by the arrows. (d) Typical silicified sandstone with rounded cavity structure filled with quartz.

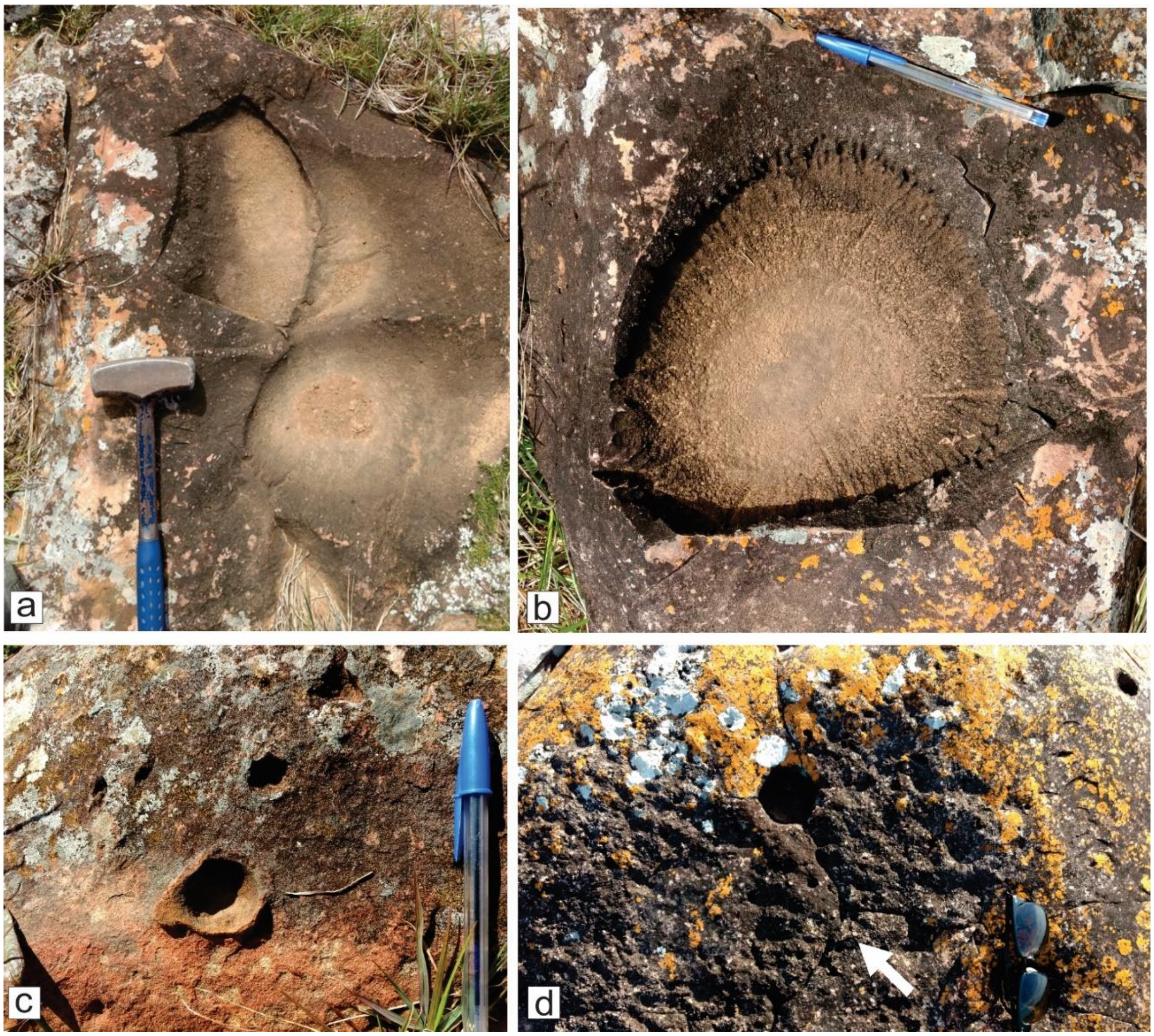

Figure 8: Hydrothermal structures at Cerro Farrapo, Stop 4. (a) Outcrop 3. Associated almost coalescent circular and elongated bowls. (b) Circular bowl with grooves and dozens of <1cm vesicular-like cavities radially concentrated in the bowls center. (c) Outcrop 4. Circular cavity showing a neck, diameter 3cm. (d) Outcrop 4. Main circular cavity, diameter 5 cm, associated to several other smaller cavities, including those <1cm. See the radial fractures indicated by arrows.

Figure 9: Hydrothermal structures at Cerro Farrapo, Stop 4, Outcrop 5. (a) Three bowls, one with the spout-like projecting structure and dozens of <1cm vesicular-like cavities radially concentrated in the bowl center. The two bowls at the right side are coalescent. Arrows indicate some the radial fractures outside the bowl. (b) Detail of the spout-like structure, grooves, vesicula-like cavities and supposed ripple marks. (c) Group of bowls converging to a spout-like structure indicated by one arrow.

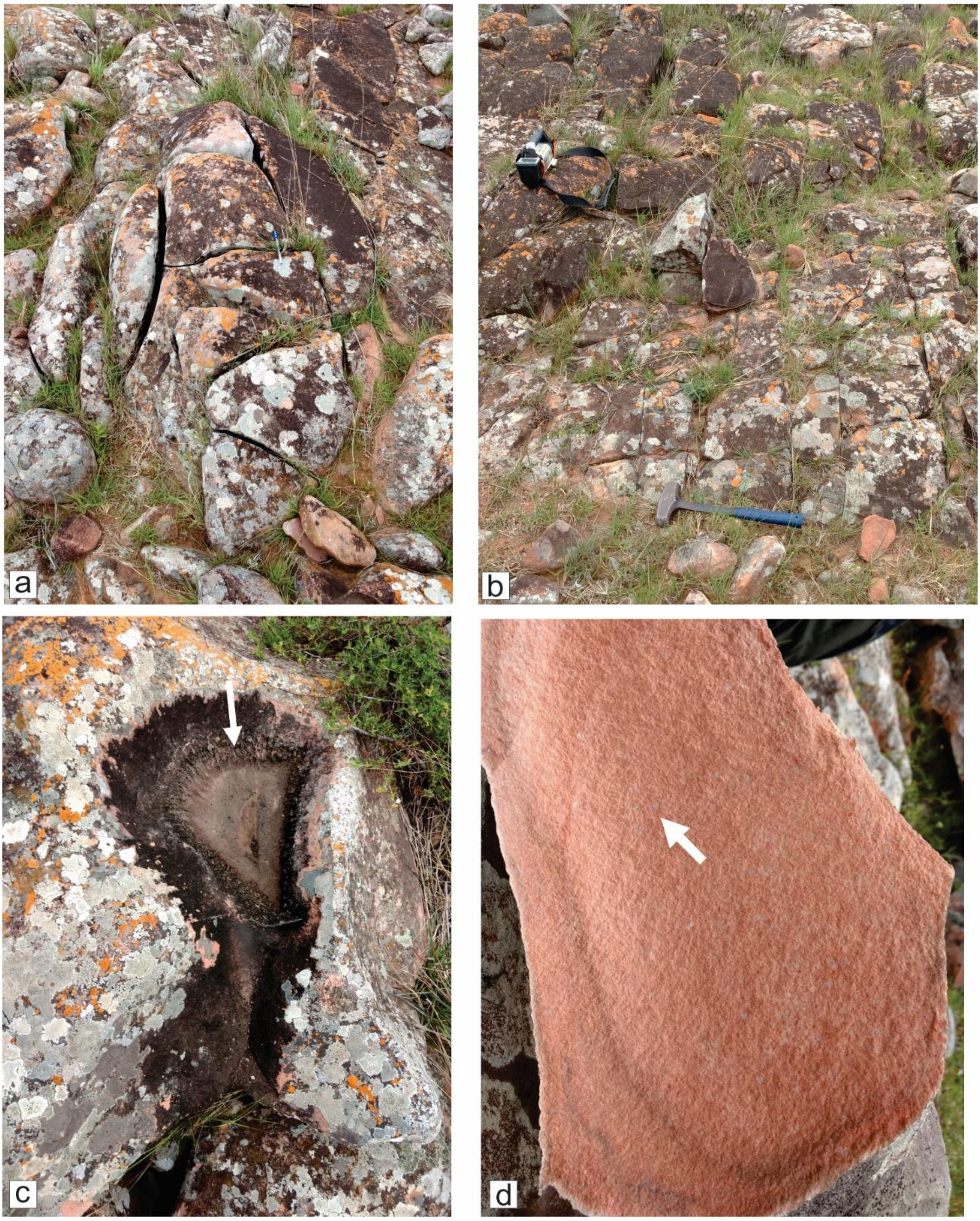

Figure 10: Hydrothermal structures at Cerro Figueirinha, Stop 6. (a). Sub-rounded to angular clasts and blocks of triangular prism and lozenge-shape. (b). Rectangular blocks cut by NE fractures. Stop 7. (c) Bowl with spout-like projecting structure, grooves and a fracture on the right border. (d). Typical silicified sandstone with rounded cavity structure filled with quartz and conchoidal fracture, similar to figure 7d.

Figure 12: General views of circular structures from Cerro Figueirinha. Stop 7. (a) Outcrop view of a rounded mound were the structures depicted in figure 10 c and d can be found. (b) View of a circular structure from the mount in figure 11a.

Figure 12: Altered vesicular volcanic rock probably originally from the Catalán andesite with sand interaction. At this stop, there is presence of agate geodes.

5. Final Comments

The Fronteira Oeste Rift is unique in the geology of continents, because intraplate volcanism erupted over loose sand of a paleoerg during the Early Cretaceous. This field guide leads to places with evidence of hydrothermal fluid circulation linked to this event. Four main, smaller described hydrothermal structures predominate among larger structure tops, suggesting that hot water passed through subterranean conduits, debouched at the Earth's surface to form surging hot pools, geysers and spouters preserved as bowls, rounded cavities and prismatic and lozenge-shaped clasts and blocks. We found no spring sinter, but fluids similar to sinter were responsible for the paleodune silicification over extensive areas. Intensely silicified sediments may display the same outcrop morphology as sinters forming erosion-resistant mounds and sheet deposits (Hamilton et al. 2019). The lozenge shape is known to occur in sinter around active hot springs in Iceland and Yellowstone, for example. According to Hamilton et al. (2019), "hydrothermal eruptions may occur prior to sinter formation, generating craters that fill with ambient-temperature meteoric waters to form lakes and ponds, or the craters may serve as conduits for thermal fluid outflow, initiating hot pool development. Hydrothermal eruptions may occur pre-, syn- or post-depositionally with respect to sinter formation." Cerro Farrapo and Cerro Figueirinha are the main local hydrothermal structures. The other four smaller structures that occur in the upper part of the oval craters evolved synchronously with the two cerros.

Finally, the route suggested here can be coupled with the field trip proposed by Hartmann et al. (2023), which provides a broader view of the processes combining sand, lava and hot water that occurred during the Early Cretaceous in the Fronteira Oeste Rift.

Acknowledgments

The authors thank CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for a research grant to L.A. Hartmann (grant 403556/2021-0), as well as the Federal University of Pelotas and Federal University of Rio Grande do Sul. We are grateful to the landowners of Fronteira Oeste for access to the area. All authors contributed equally to the manuscript.

References

Almeida, F.F.M., 1953. Botucatu: a triassic desert of South America. 19th International Geological Congress – International Union of Geological Sciences, Argel (Argélia). Comptes Rendus, 19(7), 9–24.

Amarante, F.B., Scherer, C.M.S, Aguilar, C.A.G., Reis, A.D., Mesa, V., Soto, M., 2019. Fluvial-eolian deposits of the Tacuarembó formation (Norte Basin–Uruguay): depositional models and stratigraphic succession. Journal of South American Earth Sciences, 90, 355-376.

Bellieni, G., Comin-Chiaramonti, P., Ernesto, M., Melfi, A. J., Pacca, I. G. & Piccirillo, E. M., 1984. Flood basalt to rhyolite suites in the southern Paraná plateau (Brazil): paleomagnetism, petrogenesis and geodynamic implications. Journal of Petrology, 25, 579–618.

Bertolini, G., Marques, J.C., Hartley, A.J., Basei, M.A.S., Frantz, J.C., Santos, P.R., 2021. Determining sediment provenance history in a Gondwanan erg: Botucatu Formation, Northern Paraná Basin, Brazil. Sedimentary Geology, 417, 105883.

Bromley, C.J., Mongillo, M.A., 1994. Hydrothermal eruptions: a hazard assessment. Proceedings 16th New Zealand Geothermal Workshop, 45-50.

Duarte, L.C., Hartmann, L.A., Vasconcellos, M.A.Z., Medeiros, J.T.N., Theye, T., 2009. Epigenetic formation of amethyst-bearing geodes from Los Catalanes gemological district, Artigas, Uruguay, southern Paraná Magmatic Province. Journa of Volcanology and Geothermal Research, 184, 427–436.

Fernandes, L.A., Magalhães Ribeiro, C.M., 2015. Evolution and palaeoenvironment of the Bauru Basin (Upper Cretaceous, Brazil). Journal of South American Earth Sciences, 61, 71-90.

Frank, H. T., Gomes, M. E. B. & Formoso, M. L. L., 2009. Review of the extent and the volume of the Serra Geral Formation, Paraná Basin, South America. Pesquisas em Geociências (UFRGS/Porto Alegre), 36, 49–57.

Fulfaro, V.J., Saad, A.R., Perinotto, J.A.J., Etoherehere, M.L.C., Verolavsky, G., Paraná Basin: Mineral Resource Potentials in Brazil, Uruguay, and Paraguay.

International Geology Review, 39(8), 703-722.

Gallagher, A., Montanaro, C., Cronin, S., Scot, B., Dingwell, D.B., Scheu, B., 2020. Hydrothermal eruption dynamics reflecting vertical variations in host rock geology and geothermal alteration, Champagne Pool, Wai-o-tapu, New Zealand. Bulletin of Volcanology, 82, 77.

Hamilton, A.R. Campbell, K.A., Guido, D. M., 2019 Atlas of siliceous hot spring deposits (sinter) and other silicified surface manifestations in epithermal environments. GNS Science Report 2019/06. 62 p.

Hartmann, L.A., Arena, K.R., Duarte, S.K., 2012. Geological relationships of basalts, andesites and sand injectites at the base of the Paraná volcanic province, Torres, Brazil. Journal of Volcanology and Geothermal Research, 238, 97–111.

Hartmann, L.A., Baggio, S.B., Brückmann, M.P., Knijnik, D.B., Lana, C., Massonne, H.J., Opitz, J., Pinto, V.M., Sato, K., Tassinari, C.C.G., Arena, K.R., 2019. U-Pb geochronology of Paraná volcanics combined with trace element geochemistry of the zircon crystals and zircon Hf isotope data. Journal of South American Earth Sciences, 89, 219–226.

Hartmann, L.A., Cerva-Alves, T., 2021. Resurfaced paleodunes from the Botucatu erg amid Cretaceous Paraná volcanics. Geomorphology, 383, 107702.

Hartman, L.A., Cerva-Alves, T., Pinto, V.M., Michelin, C.R.L., 2023. Geology of the Fronteira Oeste Rift – a Field Guide. Estudos Geológicos (UFPE), 32, 37-55.

Hartmann, L.A., Pertille, J., Cerva-Alves, T., Duarte, S.K., 2021. Paraná quartz andesite rings and arcs formed by distal imprint of dune design from the Botucatu paleoerg. Journal of South American Earth Sciences, 112(2), 103612.

Hartmann, L.A., Pertille, J., Bicca, M.M., Santos, C.B., 2022. Hydrothermal bowls in the giant Cretaceous Botucatu paleoerg. Brazilian Journal of Geology, 52, e20210058.

Hartmann, L.A., Wildner, W., Duarte, L.C., Duarte, S.K., Pertille, J., Arena, K.R., Martins, L.C., Dias, N.L., 2010. Geochemical and scintillometric characterization and correlation of amethyst geode bearing Paraná lavas from the Quaraí and Los Catalanes districts, Brazil and Uruguay. Geological Magazine,147, 954–970.

Kocurek, G., 1981. Erg reconstruction: the Entrada Sandstone (Jurassic) of northern Utah and Colorado. Palaeogeography, Palaeoclimatology, Palaeoecology, 36, 125-153.

Santos, J.O.S., Hartmann, L.A., 2021. Chemical classification of common volcanic rocks based on degree of silica saturation and CaO/K2O ratio. Anais da Acadêmia Brasileira de Ciências, 93(3), e20201202.

Scherer, C.M.S., 2000. Eolian dunes of the Botucatu Formation (Cretaceous) in southernmost Brazil: morphology and origin. Sedimentary Geology, 137, 63–84.

Scherer, C.M.S., Lavina, E.L.C., 2006. Stratigraphic evolution of a fluvial–eolian succession: the example of the Upper Jurassic-Lower Cretaceous Guará and Botucatu formations, Paraná Basin, Southernmost Brazil. Gondwana Research, 9, 475-484.

Silva, M.A.S., Favilla, C.A.C., Wildner, W., Ramgrab, G.E., Lopes, R.C., Sachs, L.L.B., Silva, V.A., Batista, I.H., Santos, J.O.S., Abram, M.B., Leão Neto, R., Matos, G.M.M., Vidotti, R.M., Ramos, M.A.B., de Jesus, J.D.A., 2004. Folha SH.21-Uruguaiana. In: Schobbenhaus, C., Gonçalves, J.H. (Eds.), Carta Geológica do Brasil ao Milionésimo, Sistema de Informações Geográficas. Programa Geologia do Brasil. CPRM, Brasília. CD-ROM.

Zalán, P.V., Wolff, S., Astolfii, M.A.M., Vieira, I.S., Conceição, J.C.J., Appi, V.T., Neto, E.V.S., Cerqueira, J.R., Marques, A., 1991. The Paraná basin, Brazil. In: Leighton, M.W., Kolata, D.R., Oltz, D.F., Eidel, J.J. (Eds.), Interior Cratonic Basins. American Association of Petroleum Geologists Memoir, 51, 681–708.