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(Article begins on next page)

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Title: The 2.0-1.88 Ga Paleoproterozoic evolution of the southern Amazonian Craton (Brazil): an interpretation inferred by lithofaciological, geochemical and geochronological data.

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Abstract: The study of Paleoproterozoic rocks is crucial for understanding Earth's tectonic evolution during the time when most of the modern crust and ore deposits were formed. The rocks of the Brazilian Amazonian Craton record some of the most-complete and best-preserved Paleoproterozoic magmatic and volcanic episodes on Earth. Following previous investigations, we present new lithofaciological and stratigraphic records of the felsic rocks of the Tapajós Mineral Province (TMP) (~ 2-1.88 Ga) and the São Felix do Xingú region (SFX) (~ 1.88 Ga) which, combined with new petrological and geochronological data, help providing a more complete understanding of the tectonic, magmatic and volcanological evolution of the Amazonian Craton. This magmatism/volcanism is thought to be formed in a late-/post-orogenic to extensional regime confirmed by the new geochemical data presented here. The transition from late-convergent to extensional tectonic setting could register the beginning of the taphrogenesis that marked the Amazonian Craton throughout the Mesoproterozoic. The volcanological approach of this contribution can serve as a strategy for the modelling of the evolution of Precambrian volcano-sedimentary basins around the world. The large amount of rocks analyzed are divided into primary and secondary volcanoclastic products depending on if they resulted from a direct volcanic activity (pyroclastic) or processes that reworked pyroclastic fragments. Furthermore, the deposits are subdivided into massive and stratified, depending on their primary mechanisms of transport and emplacement. By confirming the results from previous studies, our study permits to depict a more precise paleo-environmental picture of the processes that occurred in the Amazonian Craton during the Late-Paleoproterozoic. In particular, the presence of large regional-scale fissural systems and caldera collapses produced large silicic explosive volcanic eruptions, also accompanied by the emission of large volume effusive products. Although studies on the Amazonian Craton are still scarce and controversial, the present study provides new evidence that this volcanism may have formed one of the largest Silicic Large Igneous Provinces (SLIP) on earth. Our data also confirm that at least two major Paleoproterozoic periods of formation of volcanic rocks exist in the Amazonian craton. This point is of great relevance for any future interpretation of the geological evolution of this craton.

Response to Reviewers: To reviewer 1 Nils Lenhardt:

Dear reviewer,
we respected and changed most of the corrections suggested in
particularly we followed the suggestions to divide the lithofaciological
description and simplify the geological framework.
Thank you for the time you spent reading this long manuscript.

To reviewer 2 Roberto Dall'Agnol:

Dear reviewer,
thank you for your suggestions especially those related to the geological
framework and geochemical analyses. We considered and accepted most of
the changes suggested.
Now, the manuscript appears more clear.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following
reason is given:

Data will be made available on request

Dear Editor of Gondwana Research,

Please find attached the manuscript: "*The 2.0-1.88 Ga Paleoproterozoic evolution of the southern Amazonian Craton (Brazil): an interpretation inferred by lithofaciological, geochemical and geochronological data.*" by Roverato M., Giordano D., Giovanardi T., Juliani C., and Polo L. which we would like to submit on Gondwana Research. This study documents in detail the extremely well preserved Paleoproterozoic architecture of a series of felsic volcanic and volcanoclastic rocks found in the southern part of the Amazonian Craton, Brazil. We aim to improve the current knowledge of the rare subaerial volcanism investigated in Precambrian volcanic regions by adding new textural data useful to better constrain this still poorly known volcanism. We provide also new geochemical and geochronological data that will increase the dataset of the study volcanic rocks. We use here a modern volcanological approach to describe the wide range of different lithofacies that our deposits display. We believe that this contribution will help to further our understanding of the geology of the Amazonian craton and, also, of other Precambrian volcanic areas worldwide.

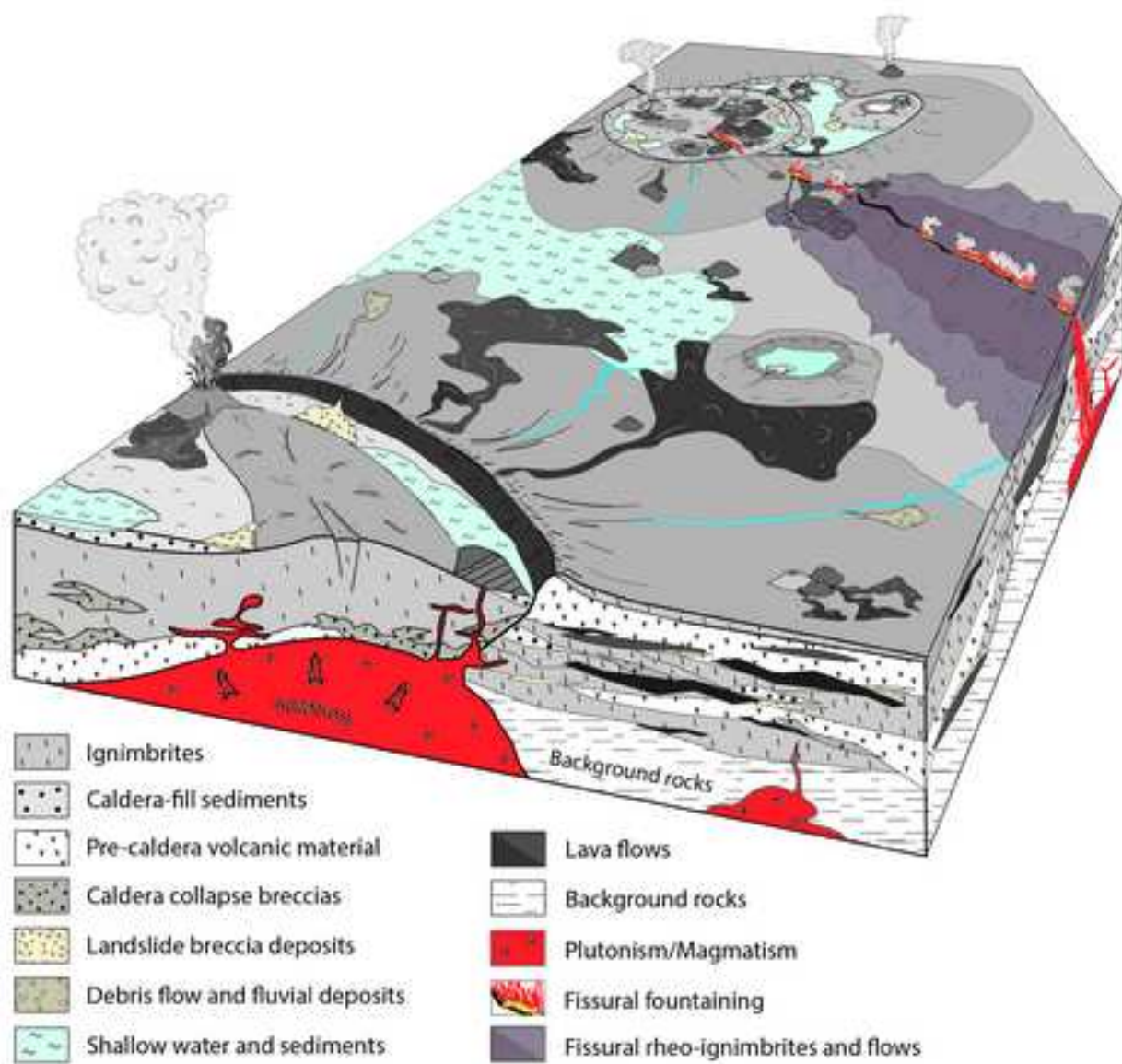
We hope that the manuscript will be of interest for a first class international journal like GR.

Yours sincerely,

Dr. Matteo Roverato

Highlights

- The modern lithofaciological approach is used here to describe the volcanic and volcanoclastic rocks of the Precambrian Amazonian Craton.
- The U-Pb geochronological data presented in the manuscript yielded three new ages of ca. 2.0 Ga and one new age of ca. 1.88 Ga that, linked with 31 geochemical analyses, increase the dataset available for the Amazonian craton and ancient terrains in general.
- The Paleoproterozoic volcanic activity that formed the large felsic rocks cropping out in the southern Amazonian craton is characterized by a fissure-fed and caldera volcanism with production of extensive lava flows and/or high-grade to rheomorphic ignimbrites, linked with other fragmental products of different type.



Reviewers' comments:

Reviewer #1: One of the main concerns of this manuscript is the lithofacies description and interpretation that oversimplifies the different lithofacies by only distinguishing them by their massive or stratified appearance. The observations and related interpretations seem to be of good value. However, I would suggest to make more subdivisions and adopt the terminology of McPhie et al. (1993) for non-genetic descriptive terms for each single lithofacies.

The manuscript contains too many different abbreviations for geological provinces, lithofacies types, etc. After a while, this appears rather confusing. Therefore, I would suggest to keep the abbreviations at a minimum, for instance for the lithofacies types and few other long terms that are constantly repeated throughout the text.

In the following paragraphs, some major suggestions are provided in detail. Further comments and suggestions (or questions) can be found in the attached commented manuscript.?

Author response:

Line 139:

Reviewer: What are the errors for the 2100 and 2875 Ma ages?

Line 148: What is the error for the 1880 Ma age?

Author: The reviewer further on suggests to simplify this chapter. We deleted the paragraph as suggested.

Lines 127-206:

Reviewer: A lot of information is presented here including many information on geochronology. Some of this information that is not particular of help for the understanding of the rest of the manuscript can probably be deleted or shortened. Furthermore, I suggest to show all mentioned locations on a map.

Author: Done! As suggested by Reviewer 1 we reduced this part by keeping some of the literature information useful to put our study in a wider context.

Rev: it would be good to see the detailed stratigraphy of the area: well we should wait for to more fieldwork.

Author: That's the problem, very few data are available nowadays, and actually this is one of the first work that try to present more detailed stratigraphy. We should organize a fieldwork there together!

line 226-229:

Rev: The way you describe the volcanoclastic rocks here, they are all fragmental rocks that are primary and syn-eruptive. However, effusive eruptions do not form fragments

Aut: yes they do! One example is a basal breccia of a thick lava flow. You can find a very well developed clastic deposit underneath the flow. In any case we deleted the point to avoid confusion.

Line 237:

Rev: Surely, no all volcanic products exhibit the same features. Otherwise, there would only be one lithofacies type. Please better describe what you mean.

Aut: Changed

Lines 239-243:

Rev: Not so many words are needed for this. Simply state that Table 1 shows all documented lithofacies including their descriptions and interpretations.

Aut: Done!

Lines 281-288

Rev: should be rephrased as they are difficult to read and understand. In particular, the paper of White and Houghton (2006) should be used here in order to define the terms pyroclastic and volcanoclastic. As it is, this part is not particularly clear. For once, effusive eruptions do not form volcanoclastic sediments. Furthermore, ignimbrites may also form due to PDCs.

Aut: Ok. We changed the sentence

Lines 297-486:

Rev.: There are some good observations and interpretations in here. However, the simplification into massive and stratified volcanoclastic rocks (containing everything from PDC deposits to autobreccias of a lava flow) and epiclastic rocks (containing everything from fluvial to mass-flow deposits) makes the chapter quite confusing. I suggest to make more subdivisions and describe the single lithofacies types one by one, probably adopting the non-genetic descriptive terms of McPhie et al. (1993). This way, the text may become slightly longer. However, the scientific value of the observations will significantly increase.

Aut.: Done! As the reviewer suggested, we divided the lithofacies descriptions and interpretations. Thank you for the suggestion!

Lines 785-789:

Rev: "Here we also image that an ideal late-convergent to extensional geotectonic environment was likely similar to that proposed in our discussion paragraph, where a post-orogenic to extensional regime for the period ~ 1.88 Ga was characterized by the emission of large volcanic felsic products." This sentence sounds very confusing and should be rephrased. For instance:

"The described volcano-sedimentary sequences that were characterized by the emission of large volcanic felsic products were formed in a post-orogenic to extensional regime during ~ 1.88 Ga."

Aut: Done! We changed the sentence!

Lines 789-791:

Rev:"With this contribution we want also stress the importance of the results obtained by investigating the lithofaciological character of the deposits instead of only carrying out geochemical studies." This should rather be obvious and can be omitted.

Aut: Done! We deleted the sentence

Reviewer #2: I appreciated your manuscript, in particular, the careful and detailed field and petrographic descriptions of lava flows and volcanoclastic sequences. Your data confirm the existence of, at least, two major Paleoproterozoic periods of formation of volcanic rocks in the Amazonian craton and this point is of great relevance for understanding the craton evolution. Your model to explain the origin of volcanic sequences is also a significant contribution. I made a series of comments and suggestions that I hope will help you to improve your manuscript. Most of them are not mandatory and should be evaluated for you. I have attached a pdf version indicating the main criticisms and indicating possible formal corrections.

Best regards,

Roberto Dall'Agnol

Author response:

1 - Abstract, p. 5, l. 41-45 - Please, rewrite. It is not clear.

Done

2 - Introduction, p. 5, l. 54-55 - I suggest to delete.

Done

3 - p. 5, l. 58-59 - References?

Done

4 - p. 5, l. 62 - the crust is...or the rocks are...???

Done

5 - p. 5, l. 63-67 - You are talking about the entire Amazonian craton but your references refer only to the regions of your direct interest. It is not reasonable to talk about mineral resources in the craton without any mention to the world-class mines of Carajás (iron, IOCG). I suggest to include also references of that province or to make clear that you are talking essentially about the Tapajós and Xingu regions.

Done

6 - p. 6, l. 71-74 - All this is the normal view of the Amazonian craton and it is correct in some degree. But I wonder if your contribution should not be directed to show that, in spite of the dominant conditions in the region, there are many areas where field information can be obtained and fresh rocks are available. This makes possible the petrological, geochemical and metallogenetic research on the craton that preserves better than one could imagine the signature of Precambrian events. You could illustrate this comment with the comprovad occurrence in the Tapajós province of Paleoproterozoic allunite (Juliani et al., 2005). In other words, better than reinforce the general view, you should show that many things are possible in the geological studies of the craton.

We deleted the sentence

7 - p. 6, l. 84-89 - This remark is very important but it looks contradictory with you have said before (cf. my remark 6) about the geological research in Amazonia. Please, make consistent changing the previous generic and not representative description of Amazonian conditions.

Done!

8. p. 66, l. 89-90 - This statement was entirely true in the pioneer works of the research group but now it looks not very appropriate to say that they 'are novel in this area'. You have said before that the present work is a continuity of previous research developed by the group in the last 15 years.

Changed it!

9 - p. 6, l. 99-101 - This description of the Amazonian craton evolution is oversimplified and do not give a clear idea of the more recent tectonic models proposed to explain it. You should present it more critically. E.g., the existence of a large Archean platform is not entirely demonstrated. You are mentioning the models of tectonic-geochronologic provinces and the existence of domains formed after the Trans-Amazonian event in the following. These topics should be better integrated and more consistent.

10 - p. 7, l. 104-107 - The relevance of the Uatumã Group in the Paleoproterozoic evolution of the craton is clearly demonstrated but it cannot be said that "All volcano/plutonic rocks forming the craton are attributed to the Uatumã Supergroup". There are many magmatic units, including Paleoproterozoic ones, that have nothing to do with the Uatumã Supergroup. You should clarify these points, showing the relevance of the Uatumã event but with a more rigorous description of it.

11 - p. 7, l. 108-110 - Your statement is not helping to show the real stage of knowledge of the Amazonian craton. I would say that we have now a general picture of the craton evolution and there are some portions of it relatively well studied, side by side with poorly known areas.

These last 3 points (9,10,11) are related to the geological framework chapter. We changed the chapter in accordance with the correct suggestions of reviewer 2 and, also the points commented by reviewer 1 who suggests to simplify the information. As suggested by Reviewer 2 we also changed figure 1 so to provide the wider context of application of our research

12 - p. 7, l. 116-119 - Is this context of ocean-continent subduction and flat subduction consistent with the hypothesis of "The transition from late-convergent to extensional tectonic setting could register the beginning of the taphrogenesis that marked the Amazonian Craton throughout the Mesoproterozoic (your abstract)"?

Yes, because the volcanic rocks studied (specially the andesitic rocks well described in Fernandes et al., 2011 and Roverato et al., 2017, but also the felsic older rocks in TMP) are related to a continental arc tectonic environment. The idea is that the system passes from an ocean-continent flat-subduction setting to a post-orogenic /extensional tectonism (as proved by the presence of younger felsic A-type rocks in SFX)

13 - p. 8, l. 148 - Some authors employ the term 'aluminous' for some A-type granites that vary generally from metaluminous to mildly peraluminous (e.g., King et al., 1997; Lamarão et al., 2002). However, this is a not rigorous term because these A-type granites are typically low Al₂O₃ granites (Dall'Agnol and Oliveira, 2007, Lithos). King et al. (Australian Journal of Earth Sciences, 2001, 48, p.501) have abandoned and advised against the use of this term because 'aluminous' can be related to S-type peraluminous granites that are entirely distinct of the A-type granites. For this reason, I suggest to the authors to avoid the use of the term 'aluminous' for A-type granites.

This is the only point where we used this term. In any case due to changes, we deleted the entire paragraph

14 - p. 8, l. 151 - Please, verify the error of 1870 +- 0.008 Ma.
It is correct in Juliani et al., 2005

15 - p. 8, l. 158 and 160 - alkaline is ambiguous in this context because it can be confused with peralkaline. I suggest to delete alkaline.

Done

16 - p. 9, l. 172, Fig. 1 and 2 - The presentation of the figures is very poor and should be improved. In figure 1, only the Brazilian part of the Amazonian craton is represented and the reference of the model of geochronologic provinces adopted is not informed in the caption of the figure. The Rio Negro province is not correctly represented.

The schematic geologic maps of Figure 2 do not follow the classical conventions. The colors adopted for different geologic units are inappropriate. I suggest to revise entirely figures 1 and 2.

Improved fig 1 and 2. In figure 2 we added the location of the outcrops and rocks presented in the paper. I don t agree that about the geological unit, I'm using my symbols well expressed in the legend.

17 - p. 9, l. 178-181 - It would be more appropriate to say that the basement of the volcano-plutonic complex is not exposed. It could be similar to the Mesoarchean units of the Carajás province, as suggested by Nd TDM ages obtained by Teixeira et al. (2002) in andesites and rhyolites of Xingu area. It was published recently a synthesis of new geochronological data about the 1.88 Ga granites of the Carajás province (Teixeira et al., 2018, J South American Earth Sci). The authors have also presented a discussion about the relevance of the 1.88 Ga event in the craton and elsewhere.

We deleted the paragraph.

19 - p. 10, l. 217-220 - Independent of the degree of alteration and lithification, pyroclastic and volcanoclastic sequences need to be defined in the field, because they mix igneous and sedimentary features. Hence, I suggest you to emphasize the relevance of field observations in your work better than to put in relief the restrictions you had. Another point is that 'alteration' should be possibly mean hydrothermal alteration and it should be distinguished of weathering alteration because readers can suppose that your rocks were intensely weathered and you are clearly showing that you were able to collect fresh samples for petrographic, geochemical and geochronologic studies.

We deleted the paragraph as also suggested by the other reviewer.

20 - p. 10, l. 230 - Coastal? Is it accurate?

YES

22 - p. 11, l. 250, Fig. 3 and its caption - It should be given a general idea of the location and informed the point of sampling where the photographs were taken and the units presented in each case. This should be done also in the captions of figures 4 and 5.

Done and thank you for the suggestion

24 - p. 11, l. 264 - 265 - pervasive does not give an idea of abundance. 10 vol % to how much in vol %?

Done!

25 - p. 13, l. 312, Fig. 5B - There is an euhedral crystal in the central lower part of Figure 5B that is named plg (plagioclase). I suspect that it can be a crystal of alkali-feldspar. Please, verify.

Sure! Changed it!

26 - p. 13, l. 326 -330, Fig. 6 - It is important to indicate the location of that sequence in the geological map of Figure 2.

Done

27 - Fig. 8, 9, 10, 11 - You present an extremely valious register of field and macroscopic aspects of the studied volcanic sequences. It looks very important to me that the location of the documented points should be given. These points will be a relevant reference for future studies.

Done

28 - p. 18, l. 491, Fig. 12 and its caption - In the caption of the figure are mentioned the TAS, AFM and SiO₂-K₂O digrams. However, in the available version of your manuscript the Figure 12 is identical to Figure 13 and the diagrams mentioned in Figure 12 are not presented. Without the figures it is difficult to evaluate the consistence of your text.

Done

29 - p. 18, l. 489 Geochemistry, Table 2 - You should give information about the methods employed and the laboratory where the chemical analyses were done.

we have added a small 'Analytical Methods' chapter to the text.

30 - Chemical Analyzes, Table 2 - It should be included on Table 2 the classification and the volcanic facies of the analyzed rock. It is important to distinguish, if possible, the rocks with I-type and A-type affinity. The meaning of V, I and R should be explained in the foot of the table.

the meaning of VC, I and R is already in the figure caption. We have reformulated the text to make it more clear. We have also added the classification of I- and A-type affinity

31 - p. 19. l. 524 - 529, Fig. 14 - The distribution of the studied rocks in the Pearce's diagram of 1984 suggest in fact that they can be related to a post-collisional setting (cf. Pearce, 1996, Episodes).

we have added the diagram to Fig. 14 and add it to the chapter.

32 - p. 20-23, l. 571-659; 7. Discussion

7.1 Subduction-related to extensional setting - In general, this topic of discussion section is well organized and looks consistent to me. I have some remarks that hope can help you in the review.

- p. 20, l. 573-576, Fig. 14 - As mentioned before, if you consider Pearce (1996), the distribution of the whole of your samples suggest a post-collisional setting for the studied rocks.

we have taken it into account and added some paragraphs at the discussion.

p. 20, l. 576-577, Fig 14, diagram FeO_t/MgO vs. Zr+Nb+Ce+Y - The analyzed rocks plot mostly to the right of the fields of typical I and S granites because they are enriched in HFSE compared to these granites. It is not correct to say that your rocks have low HFSE. On the contrary, the relatively high HFSE contents distinguish your rocks of typical I and S granites and approach them of A-type rocks.

We agree. The sentence was not clear; we want to point out that TMP volcanics have enrichment in incompatible elements with respect HSFSE which suggest the occurrence of crustal component in the melt. We have rephrased the sentence to make it more clear and pointing that our samples have also high HSFSE content which shift the volcanics composition from the I- and S-type granites to the A-type field.

It is also relevant to mention that your ~2.0 Ga volcanic rocks are a little distinct in this respect of the Vila Riozinho formation rocks (Lamarão et al., 2002) that show a little lower HFSE contents when compared to your TMP samples. Besides, the hypothesis of a more evolved character for your rocks compared to VR of Lamarão et al. (2002), you should consider the possibility that the 2.0 Ga volcanism is not uniform in composition and advocate for TMP rocks an intermediate geochemical character between the VR and MA. The rocks of TMP analyzed (Fig. 2) are dispersed in a large area and not restricted to the VR type area. So, is it reasonable that some geochemical variations could occur.

notwithstanding we think that the TMP derived from more evolved melts with respect to the VR, as observed by higher Si, K, trace elements and evidences of fractional crystallization in the TMP melts, we agree that these features could be possibly related to 'heterogeneities' in the magmatism. We have added a paragraph to point out this possibility,

- p. 22, l. 631-639 - The 2.0-1.88 Ga event in the craton and also in the scale of the planet, as indicated by Antonio et al. (2018), has effectively great relevance. A similar discussion about the 1.88 Ga anorogenic granites of the Carajás province was recently presented (Teixeira et al., 2018; SAMES) and it can allow you to go deep in this point of the discussion.

we appreciate the indication and we have provided to discuss a little further the geodynamic setting of the TMP and SFX magmatism.

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3 2 **The 2.0-1.88 Ga Paleoproterozoic evolution of the southern Amazonian Craton**
4 **(Brazil): an interpretation inferred by lithofaciological, geochemical and**
5 **3 geochronological data.**
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10 6 Roverato*^{1,2} M., Giordano^{3,4} D., Giovanardi⁵ T., Juliani² C., Polo² L.
11 7

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30 20

31 21 Keywords: Paleoproterozoic volcanism; Amazonian craton; Fissure eruption; Felsic
32 22 volcanism; Lithofacies analyses
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39 25 Abstract

40 26 The study of Paleoproterozoic rocks is crucial for understanding Earth's tectonic
41 27 evolution during the time when most of the modern crust and ore deposits were
42 28 formed~~Paleoproterozoic rocks represent some of the most interesting rocks to~~
43 29 ~~comprehend Earth's tectonic evolution during the Precambrian Supereon when most of~~
44 30 ~~modern crust and ore deposits formation occurred.~~ The rocks of the Brazilian Amazonian
45 31 Craton record one of the most-complete and best-preserved Paleoproterozoic magmatic
46 32 episodes on Earth. ~~Amazonian rocks record one amongst the most complete and best-~~
47 33 ~~preserved Paleoproterozoic magmatic episodes on Earth.~~ Following previous
48 34 investigations, we present new lithofaciological and stratigraphic records of the felsic
49 35 rocks of the Tapajos Mineral Province (TMP) (~ 2-1.88 Ga) and the São Felix do
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Xingu region (SFX) (~ 1.88 Ga) which, combined with new petrological and geochronological data, help providing a more complete understanding of the tectonic, magmatic and volcanological evolution of the Amazonian Craton. This magmatism/volcanism is thought to be formed in a late-/post--orogenic to extensional regime confirmed by the new geochemical data presented here. The transition from late-convergent to extensional tectonic setting could register the beginning of the taphrogenesis that marked the Amazonian Craton throughout the Mesoproterozoic. The modern volcanological approach of this contribution can serve as a model for the evolution of Precambrian volcano-sedimentary basins around the world. The large amount of rocks analyzed are divided into primary and secondary volcanoclastic volcanoclastic and sedimentary products depending on if they resulted from a direct volcanic activity (pyroclastic) or reworked processes that reworked pyroclastic fragments. In this second group are also included the epiclastic rocks constituted by all sediments that had been reworked before, independent of their source and composition. Furthermore, the deposits are divided in massive and stratified, depending on their different transport and emplacement mechanisms. By confirming the results from previous studies, our study permits to depict a more precise paleo-environmental picture of the processes that occurred in the Amazonian Craton during the Late-Paleoproterozoic. In particular, the presence of large regional-scale fissural systems with caldera collapses produced large silicic explosive volcanic eruptions, which were also accompanied by the emission of large volume effusive products. Although studies on the Amazonian Craton are still scarce and controversial, the present study provides new evidence that this volcanism may have formed one of the largest Silicic Large Igneous Provinces (SLIP) on earth.

1. Introduction

The Proterozoic Eon (2500 – 541 Ma) is the longest and youngest part of the Precambrian Supereon. This Eeon represents the time just before the proliferation of oxygen accumulation and complex life on Earth. This period was likely the most tectonically active in Earth's history. In fact, it is also the period during which the largest portion of the modern crust (43%) and mineral ores were produced (Condie, 2000). Studies by Condie (2000) and Rino et al. (2004) suggest that crust production took place episodically, forming predominantly granitoid crust and secondary volcanic and metamorphic rocks, some of which are extraordinarily well preserved.

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70 The Amazonian Craton (AC) is one of the largest Precambrian terrains in the
71 world (4.6x10⁶ km²) (Almeida et al., 1981). It occupies approximately half of the
72 Brazilian territory and it is the location of important mineral resources such as gold,
73 iron, copper, and tin, among others (Faraco et al., 1997; Bahia and Quadros, 2000;
74 Juliani, 2002; Klein et al., 2002, ~~;~~ ~~Klein et al.,~~ 2004; Reis et al., 2006; Klien and
75 Carvalho, 2008; Monteiro et al., 2008; Juliani et al., 2014, Dall’Agnol et al., 2017).
76 Although the geological investigation of the AC has recently seen a renewed interest of
77 the national and international scientific community, mainly because of the massive
78 presence of ore deposits, a general consensus related to the interpretation of its
79 complex ~~-~~ Paleoproterozoic evolution is still missing. Ancient volcanic regions
80 represent a challenge for the understanding of emplacement dynamics especially when
81 the stratigraphic relationships are difficult to decipher or blurred by erosion or
82 vegetation cover ~~:-~~
83 ~~In fact, the difficult access to the outcrops, due to dense forest cover and to the~~
84 ~~presence of extensive water basins together with, in most cases, the bad preservation of~~
85 ~~the ancient outcrops with frequently obliterated structures and textures, significantly~~
86 ~~complicate this task.~~
87 The present work constitutes the natural prosecution of previous investigations, carried
88 out by our research group (Juliani et al., 2005, ~~;~~ ~~Juliani et al.,~~ 2010, 2014;
89 al., 2011; ~~Juliani et al.,~~ 2014; da Cruz et al., 2015; Roverato, 2016; ~~;~~ ~~2015~~; ~~Roverato et~~
90 ~~al., 2016~~; ~~Roverato, 2016~~; Roverato et al., 2016, 2017), which are devoted to
91 characterize the dynamics of emplacement of Precambrian volcanic rocks and their
92 relationships to sedimentary facies. The study area comprises of the Tapajós Mineral
93 Province (TMP) and the São Felix do Xingú (SFX) region, Pará state, northern Brazil.
94 This contribution provides a means to interpret the volcanic processes active in this
95 region during the Precambrian, mainly based on field observation and detailed
96 lithofacies analyses. In addition, ~~-~~ new geochemical and geochronological data are
97 provided. The superb preservation of the rock textures investigated here is such that
98 they help us to better constrain the genetic mechanisms that brought to the formation of
99 the investigated felsic deposits. ~~-~~ Our study demonstrates how powerful is the approach
100 of rock structure and texture characterization to the interpretation of the eruptive
101 processes that governed the emplacement of volcanic and volcanoclastic sequences.
102 The detailed lithofacies characterization and the stratigraphic reconstruction are ~~novel~~
103 important in this area and constitute a powerful ~~new~~ key-tool to appropriately interpret

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1
2 104 the evolution of Precambrian volcano-sedimentary basins. Such an approach would
3 105 turn to be useful when employed to investigate ancient terrains associated both to the
4 106 ancient Amazonian felsic volcanism and Precambrian terrains in general.
5
6 107

8 108 2. Geological evolution of the southern portion of the Amazonian craton

9
10 The AC (Almeida et al., 1981) is located in the northern part of South America
11 and is divided into two Precambrian shields, the Central-Brazil (or Guaporé, southern
12 portion) and Guiana Shields (northern portion), which are separated by the
13 Phanerozoic Amazonian Sedimentary Basin (Fig. 1) (Almeida et al., 1981). The entire
14 craton has become stable before the end of the Precambrian (Dall'Agnol et al., 1994).

15
16
17 The AC ~~(Almeida et al., 1981)~~ has been considered (Amaral, 1974; Hasui et al.,
18 1993; Costa and Hasui, 1997) as a large Archean platform that had been reworked
19 and reactivated during the ca. 2100 Ma Trans-Amazonian event ~~(Amaral, 1974; Hasui~~
20 et al., 1993; Costa and Hasui, 1997). The AC is located in the northern part of South
21 America and is divided into two Precambrian shields, the Central-Brazil (or Guaporé)
22 and Guiana Shields, which are separated by the Phanerozoic Amazonian Sedimentary
23 Basin (Fig. 1) (Tassinari and Macambira, 1999; Santos et al., 2000). All igneous rocks
24 forming the craton are attributed to the Uatumã Supergroup, which extends to an area
25 of at least 1,500,000 km² (Dall'Agnol et al., 1999; Lamarão et al., 1999).

26
27
28 Alternative ideas Although several approaches have been used to unravel the
29 complex tectonic evolution of these huge and frequently inaccessible territories, a clear
30 understanding of the geological past of this area is still largely unknown. Based on
31 geochronological and isotopic data, Teixeira et al. (1989), (Teixeira et al., 1989;
32 Tassinari and Macambira, (1999;), and Santos et al., (2000) divided the craton into
33 several, predominantly NW-oriented geochronological provinces, which have been
34 interpreted as successive continental accretionary events, followed by granitic
35 magmatism and tectonic reworking (Tassinari and Macambira (1999), Santos,
36 (2003); and Vasquez et al., (2008) identified six and eight geochronological
37 provinces, respectively (Fig. 1).

38
39
40 In a recent review Teixeira et al. (2019) report that the AC is the host of four
41 LIP-scale (or SLIP) magmatic events discriminated by the Orocaima, Uatumã,
42 Avanavero and Rincón del Tigre events, among other intra-plate activity through time
43 and space. The igneous rocks described in the present manuscript are widely attributed
44 to the Uatumã event (Dall'Agnol et al., 1999; Lamarão et al., 1999). More recently,
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2 138 ~~The studied Juliani and Fernandes (2010), Fernandes et al. (2011) and Roverato et al.~~
3 139 ~~(2017) suggested that the entire region is located~~ between TMP and SFX, ~~which may~~
4 140 ~~beis considered to be~~ related to a continental arc, with a NE-SW arc migration ~~as~~
5 141 ~~suggested by Juliani and Fernandes (2010), Fernandes et al. (2011) and Roverato et al.~~
6 142 ~~(2017).~~ -According to these authors a migration from the Serra do Cachimbo graben (in
7
8 143 TMP where the subduction trench is located) towards the SFX could be explained by a
9
10 144 change in the subducting angle of the oceanic plate beneath the continental plate. This
11
12 145 is in agreement with the flat-subduction plate settings proposed by previous authors ~~in~~
13 146 ~~other parts of the world~~ (Ferrari et al., 2012; Gutscher et al., 2000; Kay et al., 2005;
14
15 147 Mori et al., 2007; Manea et al., 2012; ~~Fernandes et al., 2011; Juliani et al., 2014~~).
16
17 148

19 149 2.1. The TMP (Tapajós Mineral Province)

20
21 150 The TMP (Fig. 2a) is primarily situated in the Tapajós–Parima
22
23 151 geochronological/tectonic province (Santos et al., 2000) with the eastern part
24
25 152 belonging to the Amazonia Central geochronological/tectonic province (Fig. 1). Based
26
27 153 on Sm–Nd data and U–Pb ages (2100–1870 Ma), Santos et al. (2001, 2004) and
28
29 154 Vasquez et al. (2008), identified several different domains for the Tapajós–Parima
30
31 155 geochronological province and consider the TMP as a sequence of continental
32
33 156 magmatic arcs ~~(Ferreira et al., 2000; Santos et al., 2000, 2004; Vasquez et al., 2000;~~
34
35 157 ~~Klein et al., 2001; Lamarão et al., 1999, 2002).~~ ~~The oldest granitoids and gneisses in~~
36
37 158 ~~this region belong to the Cuiú–Cuiú magmatic arc complex; the Conceição tonalite~~
38
39 159 ~~(Cuiú–Cuiú magmatism) yielded a U–Pb zircon age of 2019 ± 23 Ma (Santos et al.,~~
40
41 160 ~~2000). The supracrustal sequences of the Jacareacanga Group are considered broadly~~
42
43 161 ~~coeval with the Cuiú–Cuiú complex. Both units are related to early stages of magmatic~~
44
45 162 ~~arc development (Ferreira et al., 2000; Klein et al., 2001). Detrital zircon ages of ca.~~
46
47 163 ~~2100 and ca. 2875 Ma have been obtained for the Jacareacanga Group (Santos et al.,~~
48
49 164 ~~2000). Stratigraphically above the Jacareacanga Group is the Vila Riozinho Formation,~~
50
51 165 ~~formed by ca. 2000–1990 Ma intermediate to felsic volcanic rocks (Lamarão et al.,~~
52
53 166 ~~2002). These units are intruded by the ca. 2000–1970 Ma syn- to late-orogenic calc-~~
54
55 167 ~~alkaline granitoids of the Creporizão suite (Lamarão et al., 1999; Vasquez et al., 2000).~~
56
57 168 ~~Following this first intrusive event, a second intrusive event was characterized by the~~
58
59 169 ~~1907 ± 9 and 1892 ± 6 Ma granitoid rocks of the Tropas Suite (Santos et al. 2001,~~
60
61 170 ~~2004). The ca. 1880 Ma Parauari suite corresponds to a younger generation of post-~~
62
63 171 ~~orogenic, calc-alkaline granitoids and is mainly exposed in the northeastern part of the~~
64
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172 ~~region. The Maloquinha ca. 1880 Ma aluminous A-type granite plutons are also found~~
173 ~~in the province and closes the sequence.~~ Late Paleoproterozoic volcanism of the
174 Tapajós domain is represented ~~by the Vila Riozinho Formation, formed by ca. 2000-~~
175 ~~1990 Ma intermediate to acid volcanic rocks (Lamarão et al., 2002), and~~ by the Iriri
176 Group that can be divided into the Bom Jardim (Almeida et al., 2000), Salustiano
177 (1870 ± 0.008 Ma; Juliani et al., 2005) and Aruri (Pessoa et al., 1977) formations.
178 -The Bom Jardim Formation (1898 ± 5 Ma, Santos et al., 2001) consists of
179 mafic to intermediate high-K to shoshonitic calc-alkaline rocks while the latter
180 formations are characterized by rhyolites, dacites and their pyroclastic and epiclastic
181 derivatives. Juliani et al. (2005) considered the Bom Jardim volcanism as a preliminary
182 step of the Iriri event representing pre-caldera volcanism followed by the Salustiano
183 and Aruri caldera-related felsic activity. Post-caldera volcanism is characterized by
184 ring-felsic volcanic structures that produced ~~alkaline~~ A-type (Vasquez and Dreher,
185 2011) rhyolitic lavas and volcanoclastic deposits. Lamarão et al. (2002, 2005) described
186 the ~~alkaline~~ felsic A-type Moraes Almeida volcanic sequence (1890 ± 6 Ma rhyolite,
187 1875 ± 4 Ma ignimbrite) represented by lavas and ignimbrites as part of the Iriri Group.
188 Juliani et al. (2014) consider these last A-type ~~alkaline~~ rocks as similar in composition
189 and age to the Santa Rosa Formation that crops out in the São Felix do Xingú region
190 (SFX), which is considered to have formed by the same fissural-type volcanism
191 (Juliani and Fernandes, 2010; Fernandes et al., 2011; Roverato et al., 2016).
192 Preliminary data indicate that these rocks, ~~for~~ both ~~-~~TMP and SFX, display a very low
193 grade of metamorphism, falling into the prehnite-pumpellyite field (Echeverri-Misas,
194 2010; Lagler et al., 2011; Fernandes et al., 2011).

196 2.2. The SFX (São Felix do Xingú region)

197 According to the work of Santos (2003) and Vasques et al. (2008) the SFX
198 region belongs to the Amazonia Central province (Fig. 1). The study area (Fig. 2b) is
199 located near to São Felix do Xingú ~~city~~, which corresponds to the southern portion
200 of the Carajás Province. ~~The geographical limits of SFX are still uncertain, mainly due~~
201 ~~to the difficult access to the area. The eastern limit is marked by the Archean TTG~~
202 ~~rocks several km east to Xingu River while the dense vegetation cover does not permit~~
203 ~~access to the south. The northern limit is roughly marked by the Archean Xingu~~
204 ~~complex and younger intrusive formations (Macambira and Vale, 1997). The basement~~
205 ~~of the SFX region is represented by the Archean Rio Maria Granite-Greenstone~~

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2 206 ~~Terrain and the metavolcano-sedimentary units of the Itacaiúnas Supergroup (Araújo et~~
3 207 ~~al., 1988).~~ The Paleoproterozoic volcanic sequences in the SFX comprise the basal
4
5 208 Sobreiro and upper Santa Rosa formations (Macambira and Vale, 1997; Juliani and
6
7 209 Fernades, 2010), which are crosscut by the Sn-bearing A-type granitoids of the Velho
8
9 210 Guilherme Suite (Teixeira et al., 2002). Antonio et al. (2017) published the first U-Pb
10
11 211 ages on zircons for the Santa Rosa Formation with 1877.4 ± 4.3 Ma for a rhyolite and
12
13 212 1895 ± 11 Ma for a dike. Recent geochronological data on a felsic porphyritic dike
14
15 213 belonging to the Velho Guilherme suite yielded an age of 1857 ± 8.4 Ma (Shrimp U/Pb
16
17 214 zircon analyses; Roverato, 2016). Other available geochronological data yielded ca.
18
19 215 1880 ± 6 Ma (TIMS Pb–Pb in zircon) for the Sobreiro Formation and ca. 1879 ± 2 Ma
20
21 216 (TIMS Pb–Pb in zircon) for the Santa Rosa Formation (Fernandes et al., 2011; Pinho et
22
23 217 al., 2006; Teixeira et al., 2002). Despite their similar ages, their geochemical
24
25 218 compositions, geological features and eruption styles point to their non-cogeneticity
26
27 219 (Fernandes et al., 2011). ~~The Sobreiro Formation was defined for the first time by~~
28
29 220 ~~Macambira (1997) and Macambira and Vale (1997) as constituted by andesitic, trachy-~~
30
31 221 ~~andesitic and trachytic magmatism.~~ The Sobreiro Formation (SF) comprises basaltic
32
33 222 andesite, andesite and less dacite massive lava flows and volcanoclastic rocks with
34
35 223 high-K calc-alkaline signature (Fernandes et al., 2011; Roverato et al., 2017).
36
37 224 According to da Cruz et al. (2015) late- to post-magmatic hydrothermal alteration in
38
39 225 these rocks is responsible for a secondary paragenesis characterized by epidote,
40
41 226 chlorite, carbonate, clinozoisite, sericite, quartz, albite, hematite and pyrite. The Santa
42
43 227 Rosa Formation (SRF) is described by Fernandes et al. (2011) as characterized by four
44
45 228 lithological facies with A-type signature: (i) rhyolitic lava flow and thick dikes of
46
47 229 banded rhyolite and ignimbrite; (ii) highly rheomorphic felsic ignimbrite associated
48
49 230 with un-welded ash tuff; (iii) felsic crystal tuff, lapilli-tuff and co-ignimbritic breccias;
50
51 231 (iv) granitic porphyry stocks and dikes and subordinate equigranular granitic
52
53 232 intrusions.
54
55 233

234 ~~3. Results~~

235 ~~Lithofaciological, petrological, geochemical and geochronological analyses were~~
236 ~~carried out in the course of this study in order to understand the geodynamic evolution~~
237 ~~of the study area. 31 new geochemical data for the TMP rock samples are presented~~
238 ~~here and compared with published data of Lamarão et al. (2002) and SFX previous~~
239 ~~results (Fernandes et al. (2011)). The geochemical signature of SFX rock samples have~~

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240 already recently been reported by Fernandes et al. (2011) who made unnecessary new
241 analysis for our study. Four new geochronological data of rock samples from the TMP
242 (3 samples) and SFX (1 sample) are also provided to compare with dating available for
243 the AC. Finally, so far it concerns with the lithofaciological analysis we remind that a
244 characterization of the granulometry of the deposits and of the shape of the fragments
245 was qualitatively defined in the field, since the degree of alteration and lithification
246 would have been impossible in the laboratory.

250 34. Lithofacies analyses and stratigraphy

251 Lithofaciological analyses were carried out in the course of this study in order
252 to understand the geodynamic evolution of the study area. Here we report on the
253 lithofacies analysis of rocks recognized during our field campaigns (and after in
254 petrological thin section) at the TMP and SFX provinces. Within the study area (TMP
255 and SFX), massive to banded lava flows and rheomorphic ignimbrites (Fig. 3) as well
256 as felsic volcanoclastic rocks of various origin (Figs. 4-8, 11) are frequently found.
257 Massive and banded lava flows and rheomorphic ignimbrites deposits (fig. 3) as well
258 as volcanoclastic felsic rocks of various origin (e.g. pumiceous, effusive, ignimbritic)
259 (fig. 4,5,6,7,8,11) are frequently found in both the studied areas (TMP and SFX).
260 Reworked (secondary) volcanoclastic rocks (Fig. 9,10) and sedimentary
261 alluvial/coastal clastic deposits (epiclastic) are also widely distributed in both TMP and
262 SFX areas. Primary volcanoclastic rocks are here defined as those fragmental
263 products formed during a syn-eruptive explosive or effusive events, which were
264 deposited regardless of whether their transport occurs through air, water, granular
265 debris or a combination of them (McPhie et al., 1993; White and Houghton, 2006,
266 Manville et al., 2009; Roverato et al., 2017). On the other hand, all the units deposited
267 as a consequence of a reworking process of pre-existing volcanic units are defined here
268 as sedimentary/reworked secondary volcanoclastic rocks. We also introduce into this
269 group all those epiclastic products that constitute sediments that had been reworked
270 before, independent of their source and composition. All TMP and SFX volcanic
271 products share the same features both at outcrop scale and at hand specimen scale and
272 for such a reason they will be presented together in the lithofaciological description. In
273 Table 1 we propose shows a description and interpretation of the volcanoclastic

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1
2 274 lithofacies, both primary (~~volcaniclastic~~) and ~~reworked (secondary sedimentary)~~, for
3 275 the deposits identified in the study areas. ~~In the following we will also provide an~~
4 276 ~~interpretation of the processes involved in their transport and emplacement.~~

6 277
7
8 278 ~~4.14.~~ Lava flows and rheo-ignimbrites

9 279 As already discussed by Roverato et al. (2016), the absence of unequivocal
10 280 vitroclastic textures complicates the distinction between volcaniclastic and layered lava
11 281 flows in general and, more in particular, for the ancient volcanic rocks investigated
12 282 here. Lava flows found in the TMP and SFX provinces have both massive and banded
13 283 structures (Ffig. 3) while still maintaining, in some cases, glassy (obsidian) and
14 284 aphanitic to porphyritic texture. Their composition varies from trachytic to rhyolitic with
15 285 various content of alkalis (see section 58). The phenocryst assemblage consists
16 286 mainly of plagioclase, quartz, Fe–Ti oxides and accessory-amount of zircon and
17 287 apatite. Plagioclase and bipiramidal quartz crystals (Ffig. 3a), with a maximum size of
18 288 3-4 mm, range from euhedral to anhedral, showing moderate to intense resorption.
19 289 Plagioclase shows sieve texture indicating non-equilibrium conditions likely
20 290 determined by magmatic transport. ~~Potassic-K-~~feldspar is also present as anhedral
21 291 crystals in the groundmass often associated with sericite as alteration phase. Samples
22 292 are generally affected by variable intensity of hydrothermal alteration. Plagioclase
23 293 phenocrysts, in particular, present diffuse potassic and minor propylitic alterations.
24 294 Abundant spherulites and lithophysae of variable size, from millimetric to decimetric,
25 295 were recognized in almost every sample and are thus common in these rocks (Ffig. 3b,
26 296 c). The spherulites (radiating fibers of K-feldspar and cristobalite), ranging from few
27 297 millimeters to 2 cm, are typically associated with perlitic fractures. Their content can
28 298 vary from 10 vol% to ~~pervasive-70%~~ in the investigated rocks. A large amount of the
29 299 spherulites developed into lithophysae commonly reaching 10-12 cm as a consequence
30 300 of cooling and degassing processes. In the obsidian-type lavas (Ffig. 3c), the
31 301 groundmass is characterized by a micro-granophiric-like devitrification texture
32 302 characterized by crystallization of amorphous quartz and alkali feldspar, a process that
33 303 occurred after the emplacement of lava bodies. Several rocks show textures that are not
34 304 easy to be associated to either lava flows or flows of fragmented material which
35 305 underwent rheomorphism (Ffig. 3d-g). Both banded lavas and rheo-ignimbrites display
36 306 folds (Ffig. 3d-g, see also Ffig. 11e) and sub-parallel bands on mm- to dm-scale,
37 307 planar to wavy (Ffig. 3e, see also Ffig. 6 and 7) (parataxitic fabric), that deform and

1
2 308 flattened around lithic fragments and crystals which alignment suggests the flow
3 309 direction. In thin sections, the bands are characterized by extremely flattened
4 310 vitroclastic textures with the former glass completely replaced by a mixture of quartz
5 311 and feldspar (Roverato et al., 2016).
6
7
8 312

9
10 313 ~~5.4.2. V~~Primary volcaniclastic rocks

11 314 We consider primary volcaniclastic rocks those dense, scoriaceous and
12 315 pumiceous products of fragmental character emplaced by ~~primary low intensity~~
13 316 explosive processes, ~~frequently associated to effusive manifestations or highly~~
14 317 ~~explosive events associated to fall out, small pyroclastic density currents (PDC) or~~
15 318 ~~ignimbrites~~. With pyroclastic we refer to fragmental material generated by any kind of
16 319 explosive volcanic activity and transported as ash-fall and pyroclastic density currents
17 320 ~~by an explosive volcanism~~ (Manville et al., 2009), which deposition occurs by
18 321 suspension settling, from traction, by en masse freezing, or any combination of these
19 322 (White and Houghton, 2006). Depending on the mechanism of transport and the
20 323 eruptive style these clastic rocks were distinguished into two different categories, i.e.
21 324 massive and stratified; and they can vary from well sorted, poorly sorted or unsorted.
22 325 The rocks are predominantly rhyolitic in composition (Fernandes et al., 2011, Roverato
23 326 et al., 2016) and there is no significant geochemical difference from the lava flows.
24 327 Nine main lithofacies (Lf) have been recognized for the volcaniclastic rocks: six of
25 328 them are massive and three are stratified.
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35 329

36 330 ~~5.1. 4.2.1.~~Massive

37 331 Six massive lithofacies (mAL, mLA, mLB, l-gwLA, m-gwLA and h-gwLA)
38 332 were recognized during our field campaign, three of them belong to the welded
39 333 ignimbrites sub-group (Table 1). By using the granulometric classification proposed by
40 334 Fisher (1961), ash is defined as any fragment with size <2 mm, lapilli are fragments
41 335 with size between 2 to 64 mm and blocks (or bombs) have sizes > 64 mm. Massive
42 336 lithofacies includes all those deposits that display a massive coherent structure.
43 337 Outcrops of such kind of lithofacies are constituted by a high percentage of ash up to
44 338 block-rich textures. Most of the observed samples appear to have been affected by
45 339 devitrification processes of the juvenile pyroclastic fragments and matrix. The presence
46 340 of juvenile material linked with other observed textures such as broken crystals (Best
47 341 and Christiansen, 1997) and eutaxitic fabric allows us to confirm that the rocks

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1 342 belonging to lithofacies mAL, mLA, l-gwLA, m-gwLA and h-gwLA are fragmental
2 343 and pyroclastic in origin. We discuss the meaning of Lf mLB below in section 5.1.2.

3 344
4 345 5.1.1. Lf mAL; mLA (massive Ash to Lapilli; massive Lapilli and Ash)

5 346 Description: the ash to lapilli (mAL) and lapilli and ash (mLA) deposits (Fig.
6 347 4a-e, Fig.6) are heterolithologic, matrix supported, containing angular to sub-rounded
7 348 medium to coarse devitrified lapilli (displaying axiolitic fabric), banded fragments,
8 349 occasional (or absent) lithics and angular-shaped broken crystals of plagioclase,
9 350 bipiramidal quartz and rare oxides (Fig. 5). In mLA, clasts <25 cm in size are
10 351 randomly immersed in the groundmass (Fig 4d and 4e, 11d). Some of them are altered
11 352 by carbonate minerals. Groundmass of mAL and mLA is formed by K-feldspar and
12 353 quartz crystals, devitrified ash fragments and sericite crystals as phase of alteration
13 354 (Fig. 5).

14 355 Interpretation: the general massive aspect and the poor sorting of mAL and
15 356 mLA point to a laminar granular flow transport regime and the fine content suggests
16 357 the deposition from a dilute fluid escape-dominated flow-boundary zone in which
17 358 turbulent shear-induced tractional segregation is suppressed (Branney and Kokelaar,
18 359 2002; Sulpizio et al., 2007, Roverato et al., 2017). These lithofacies are interpreted as
19 360 ash flow deposits suggesting the deposition from a pyroclastic density current (PDC)
20 361 (Lenhardt et al., 2011; Sulpizio et al., 2014; Roverato et al., 2017). The coarser
21 362 lithofacies mLA (fig. 4e) could be related to proximal co-ignimbritic breccias as result
22 363 of deposition by denser pyroclastic granular flows (Branney and Kokelaar, 2002). The
23 364 angular aspect of the clasts indicates short-period transport.

24 365
25 366 5.1.2. Lf mLB (massive Lapilli and Block)

26 367 Description: this lithofacies (fig. 4f, fig.7) represents monolithologic coarse-
27 368 grained rocks having high-clast content (clast:matrix ratios up to 3:1). Angular/sub-
28 369 angular coarse lapilli and blocks up to 50-60 cm of devitrified banded or massive lava
29 370 fragments are immersed in a devitrified fine lapilli and coarse ash matrix.

30 371 Interpretation: the blocky and monolithologic coarse-grained aspect of the
31 372 lithofacies mLB and its position underneath thick flow-deposits is attributed to the
32 373 basal auto-brecciation of lava flows and/or rheo-ignimbrite flows. Despite the
33 374 lithofacies is likely a consequence of an effusive volcanic activity (in the lava-flow

case) it is considered anyway as part of the volcaniclastic group due to its fragmental character.

5.1.3. Lf *l*-gwLA; *m*-gwLA; *h*-gwLA (welded Ignimbrites)

Description: all massive deposits displaying welding characteristics have been grouped in the “welded ignimbrites” group (table 1), following the idea of “grade of welding” (Walker, 1983) (i.e. the amount of welding and compaction exhibited by deposits). The rocks are matrix-supported with sub-rounded to angular lapilli and ash lithic clasts, euhedral, subhedral and broken crystals (plagioclase and less quartz) and deformed devitrified juvenile fragments (*fiamme*). Slightly- (low-grade, *l*-gwLA), medium- (medium-grade, *m*-gwLA), well-stretched (high-grade, *h*-gwLA) *fiamme* (Fig. 6), as well as, devitrified shards define the eutaxitic fabric (Roverato et al., 2016). These fragments varying from millimetric to 3–4 cm in size are immersed in a homogeneous micro-granophiric-like devitrified groundmass (see Roverato et al., 2016 for details). Figure 6 shows a stratigraphic column representing a 35 m thick sequence of ignimbrite deposits found in the TMP, displaying very low-grade to high-grade welded fabric where the grade of welding increases toward the top of the succession. The very top of the sequence is characterized by columnar jointing.

Interpretation: the massive aspect and the poor sorting of the lithofacies *l*-gwLA, *m*-gwLA and *h*-gwLA point to a laminar granular flow transport regime, interpreted to be deposited from a pyroclastic density current (PDC). The welded character of these lithofacies is indicative of hot PDC emplacement and compaction that result into the low- up to high-grade eutaxitic fabric. This process is favored by loading-compaction, low-viscosity fragments, high temperature (i.e. > 900°C), cooling of gas-permeable fragments (pumices) and dissolved water (Branney and Kokelaar, 2002; Roverato et al., 2016 and references therein).

~~Six massive lithofacies were recognized during our field campaign, three of them belong to the ignimbrites sub-group (Table 1). By using the granulometric classification proposed by Fisher (1961), ash is defined as any fragment with size < 2 mm, lapilli are fragments with size between 2 to 64 mm and blocks (or bombs) have sizes > 64 mm. Massive lithofacies includes all those deposits that display a massive coherent structure. Outcrops of such kind of lithofacies are constituted by a high percentage of ash up to block rich textures. The ash to lapilli (mAL) and lapilli and ash~~

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1
2 409 (mLA) deposits (fig. 4a/b/c/d/e, fig.6) are heterolithologic, matrix supported,
3 410 containing angular to sub-rounded medium to coarse devitrified lapilli (displaying
4 411 axiolitic fabric), banded fragments, occasional (or absent) lithics and angular-shaped
5 412 broken crystals of plagioclase, bipiramidal quartz and rare oxides (fig. 5). In mLA,
6 413 clasts <25 cm in size are randomly immersed in the groundmass (Fig 4d/e, 11d). Some
7 414 of them are altered by carbonate minerals. Groundmass of mAL and mLA is formed by
8 415 K-feldspar and quartz crystals, devitrified ash fragments and sericite crystals as phase
9 416 of alteration (Fig. 5). mLB (massive Lapilli and Block) facies (fig. 4f, fig.7) represent
10 417 monolithologic coarse-grained rocks having high-clast content (clast:matrix ratios up
11 418 to 3:1). Angular/sub-angular coarse lapilli and blocks up to 50-60 cm of devitrified
12 419 banded or massive lava fragments are immersed in a devitrified fine lapilli and coarse
13 420 ash matrix.

21 421
22 422 All massive deposits displaying welding characteristics have been grouped in
23 423 the “ignimbrites” group (table 1), following the idea of “grade of welding” (Walker,
24 424 1983) (i.e. the amount of welding and compaction exhibited by deposits). The rocks
25 425 are matrix-supported with sub-rounded to angular lithic clasts, euhedral, subhedral and
26 426 broken crystals (plagioclase and less quartz) and deformed devitrified juvenile
27 427 fragments (fiamme). Slightly (low grade, l-gwLA), medium (medium grade, m-
28 428 gwLA), well-stretched (high grade, h-gwLA) fiamme (Fig. 6), as well as, devitrified
29 429 shards define the eutaxitic fabric (Roverato et al., 2016). These fragments varying from
30 430 millimetric to 3–4 cm in size are immersed in a homogeneous micro-granophiric like
31 431 devitrified groundmass (see Roverato et al., 2016 for details). Figure 6 shows a
32 432 stratigraphic column representing a 35 m thick sequence of ignimbrite deposits found
33 433 in the TMP, displaying very low grade to high grade welded fabric where the grade of
34 434 welding increases toward the top of the succession. The very top of the sequence is
35 435 characterized by columnar jointing.

46 436 47 437 4.2.2. Interpretation —

48 438 Most of the observed samples appear to have been affected by devitrification
49 439 processes of the juvenile pyroclastic fragments and matrix. The presence of juvenile
50 440 material linked with other observed textures such as broken crystals (Best and
51 441 Christiansen, 1997) and eutaxitic fabric allows us to confirm that the rocks belonging
52 442 to lithofacies mAL, mLA, l-gwLA, m-gwLA and h-gwLA are fragmental and

1
2 443 pyroclastic in origin. The general massive aspect and the poor sorting of mAL and
3 444 mLA point to a laminar granular flow transport regime and the fine content suggests
4 445 the deposition from a dilute fluid escape dominated flow boundary zone in which
5 446 turbulent shear induced tractional segregation is suppressed (Branney and Kokelaar,
6 447 2002; Sulpizio et al., 2007, Roverato et al., 2017). These lithofacies are interpreted as
7 448 ash flow deposits suggesting the deposition from a pyroclastic density current (PDC)
8 449 (Lenhardt et al., 2011; Sulpizio et al., 2014; Roverato et al., 2017). The coarser
9 450 lithofacies mLA (fig. 4e) could be related to proximal co-ignimbritic breccias as result
10 451 of deposition by denser pyroclastic granular flows (Branney and Kokelaar, 2002). The
11 452 angular aspect of the clasts indicates short period transport. The blocky aspect of the
12 453 lithofacies mLB is attributed to the basal auto-brecciation of lava flows and/or rheo-
13 454 ignimbrite flows. The welded character of the lithofacies l-gwLA, m-gwLA and h-
14 455 gwLA is indicative of hot PDC emplacement and compaction that result into the low-
15 456 up to high grade eutaxitic fabric. This process is favored by loading compaction, low-
16 457 viscosity fragments, high temperature (i.e. > 900°C), cooling of gas permeable
17 458 fragments (pumices) and dissolved water (Branney and Kokelaar, 2002; Roverato et
18 459 al., 2016 and references therein).

30 461 5.4.2.23. Stratified

31 462 These lithofacies, although commonly associated with ignimbrites, are not very
32 463 spread in the studied areas. We also didn't find any alternation between massive and
33 464 stratified deposits even if this association is a common occurrence in PDC deposits
34 465 (Sulpizio et al., 2014; Roverato et al., 2017), alternating dilute (stratified deposits
35 466 resulting) and concentrated (massive deposits resulting) regimes during transport
36 467 (Sulpizio et al., 2014). Just one example has been found in TMP and is reported in the
37 468 stratigraphic reconstruction of fig.11.

44 470 5.2.1 Lf sA; xsA; dsAL (stratified Ash; cross-stratified Ash; diffusely stratified Ash to 45 471 lapilli)

46 472 Description: The stratified samples and outcrops analyzed comprise well
47 473 sorted very fine to fine ash organized in millimetric to sub-millimetric parallel (sA) or
48 474 cross-stratified (xsA) layers, with sharp or gradational changes in grain size (Fig. 8).
49 475 The fragments are represented by devitrified shards, crystals (plagioclase), and rare (or
50 476 absent) lithics (fig. 8d) immersed in a devitrified groundmass. Diffuse-stratified

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2 477 lithofacies dsAL display a coarser character with coarse lithic and devitrified ash and
3 478 lapilli fragments forming well developed parallel continuous meter-long stratification
4
5 479 (or very-low angle cross-stratification) at centimeter scale (fig. 11b), with gradational
6
7 480 changes in grain-size. The sorting varies from well to moderate.
8
9 481

10 482
11 483 4.2.4. Interpretation:

12 484 tThe fine parallel layering of shards material displayed by lithofacies sA is
13
14 485 interpreted here as being deposited under the product of sedimentation by the upper
15
16 486 and highly dilute ash-cloud that accompany a pyroclastic-density current. We don't
17
18 487 exclude the direct sedimentation from tephra fall-out activity. Cross-stratified (Lf xsA)
19
20 488 and diffuse-stratified (Lf dsAL) deposits indicate tractive processes usually attribute to
21
22 489 pyroclastic surge-type depositional condition from dilute currents (Cas and Wright
23
24 490 1987; Lenhardt et al., 2011; Roverato et al., 2017). We interpreted these as pyroclastic
25
26 491 surge deposits although Lf dsAL could also be the product of coarse ash fall-out
27
28 492 processes. Pyroclastic surge deposits usually display small volume and rarely reach
29
30 493 more than 10 km from their source (Lenhardt et al., 2011). Conversely, fall-out
31
32 494 deposits could emplace tens of kilometers from their source.
33
34 495

35 496 6.——4.3. Secondary volcanoclastic/epiclastic Sedimentary rocks

36 497 The nomenclature of Fisher et al. (1961) is applied also for the sedimentary
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38 498 secondary volcanoclastic rocks as follow: silt ($2 <> 64 \mu\text{m}$), sand ($64 \mu\text{m} <> 2 \text{ mm}$), gravel
39
40 499 ($2 <> 64 \text{ mm}$), cobble ($64 <> 256 \text{ mm}$). These rocks are considered as the product of
41
42 500 reworking and erosive processes. The clasts belonging to this group show a wide range
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44 501 of composition, size and shape variations. Based on their component, texture and
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46 502 fabric, we recognized five massive, both matrix- and clast-supported, and four
47
48 503 stratified lithofacies (fig. 9).
49
50 504

51 505 6.4.3.1.1. Massive

52 506 6.1.1. Lf mS (massive Sand)

53 507 Description: this lithofacies consists of reddish moderately to well-sorted,
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55 508 massive, fine- to medium grained sand forming parallel strata intercalated to clast-
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57 509 supported conglomerate deposits (Lf csG) (fig. 9a). The sandstone strata extend tens of
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59 510 meters and present thinness between 0.4-0.8 m. Lf mS is predominantly composed of

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2 511 quartz, feldspar and minor rock fragments. Contacts between mS and csG are sharp
3 512 with rare slightly erosional surfaces. The tops of the sandstone are characterized by the
4
5 513 presence of centimeters ripples (fig. 9b).

6 514 Interpretation: the massive sand (mS) and the small ripples found at the top of
7
8 515 the strata indicate low energy under tractional currents in shallow water conditions
9
10 516 (Collison and Thompson, 1982; Lenhardt et al., 2011). The alternation of Lf csG and
11 517 mS indicates changes in energy conditions of sedimentation. We interpret these
12 518 oscillations as belonging to a subaqueous-subaerial fan-delta interface setting where
13 519 continental supply of material alternates to under-water sand accumulation (Lf mS).

16 520 17 18 521 6.1.2. Lf csG (clast supported Gravel)

19 522 Description: this lithofaciesThe Lf esG (Fig. 9a, c, d) is massive, clast to matrix
20 523 supported, with heterolithic felsic rounded high-spherical coarse gravel with a
21 524 sandy inter-clast matrix. Clasts are mainly characterized by massive and banded
22 525 medium- to coarse-size felsic lava fragments (and rare quartz; size does not exceed 5
23 526 cm) and present rounded with low- to high-sphericity. We found lithofacies csG also
24 527 associated to xsSG (see below section 6.2.2.) (Fig. 9c, 10b).

28 528 Interpretation: lithofacies csG is dominated by water flow processes where
29 529 matrix plays a secondary role. The clast-supported character and less matrix content
30 530 indicates that water removed the finer particles during transport and deposition. Lf csG
31 531 display rounded clasts and well-sorting indicative of good selection during transport
32 532 and emplacement. The rounded character of csG and the presence of matrix in the
33 533 deposits suggest a laminar debris-flow regime in medial reaches of stream-dominated
34 534 fluvial/alluvial fans (Mueller and Corcoran, 1998).

39 535 40 41 536 6.1.3. Lf csGS (clast supported Gravel to Sand)

42 537 Description: Lf csGS (Fig. 9e, 11c) is massive, moderately well-sorted and
43 538 clast-supported. Clasts (gravel to sand) present sub-rounded to sub-angular with
44 539 low/medium sphericity with maximum size of 2-3 cm. The rocks belonging to this
45 540 lithofacies are mainly formed by massive felsic lava fragments with different color and
46 541 crystallinity.

49 542 Interpretation: Lf csGS is dominated by water flow processes where matrix
50 543 plays a secondary role. The clast-supported character and less matrix content indicates
51 544 that water removed the finer particles during transport and deposition. This lithofacies

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represents deposition within a debris-flow dominated fluvial/alluvial environment.
Poor sorting, clast-supported and sub-angular clasts point to deposition by localized
laminar hyperconcentrated-flows in volcanic fans fringing flanks of volcanic edifices.
Single cross-beds are usually ca. 1 cm thick

6.1.4. Lf csGC (clast supported Gravel and Cobble)

Description: Lithofacies csGC (Fig. 9f) is massive, low-sorted and clast-supported. The clast population is characterized by sub-rounded, low/medium sphericity, massive felsic porphyritic fragments with maximum size up to 20 cm. This lithofacies has an interstitial matrix characterized by medium to coarse sand.

4.3.2. Interpretation:

~~Lf esG, esGS and csGC (fig. 9a/d/f) is~~ dominated by water flow processes where matrix plays a secondary role. The clast-supported character and less matrix content indicates that water removed the finer particles during transport and deposition. ~~This Lf esG display rounded clasts and well sorting indicative of good selection during transport and emplacement. The rounded character of esG and the presence of matrix in the deposits suggest a laminar debris flow regime in a medial reaches of stream-dominated fluvial/alluvial fans (Mueller and Corcoran, 1998). The alternation of Lf esG and mS (fig. 9a) indicates changes in energy conditions of sedimentation. We interpret these oscillations as belonging to a subaqueous subaerial fan-delta interface setting where continental supply of material alternates to under-water sand accumulation (Lf mS). The massive sand grain size (mS) and the small ripples found at the top of the strata indicate low energy under tractional currents in shallow water conditions (Collison and Thompson, 1982; Lenhardt et al., 2011).~~ Lithofacies ~~esGS and esGC~~ represents deposition within a debris-flow dominated fluvial/alluvial environment. Poor sorting, clast-supported and sub-angular clasts likely points to deposition by localized ~~laminar hyperconcentrated flows (esGS) and non-cohesive debris-flows (esGC), in volcanic fans fringing flanks of volcanic edifices. Single cross-beds are usually ca. 1 cm thick.~~

6.4.3.23. Stratified

6.2.1 Lf xsS (cross-stratified Sand)

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2 579 Description: Lithofacies cross-stratified ~~Ssandstone (xsS)~~ (Fig. 10a) consist of
3 580 white to brownish low-angle cross-stratified coarse quartzitic sandstone. The
4 581 sandstones are characterized by lobe to sheet-shaped bodies. Major bedsets are
5 582 recognized ranging in thickness from 0.5 to 1.5 m, composed of fine-grained sandstone
6 583 dominated by medium-angle cross strata (18-20°). Single cross-beds are usually 0.7-
7 584 1cm thick. The outcrops displaying this lithofacies extend tens of meters with sharp
8 585 upper and lower contact.

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12 586 Interpretation: the cross-stratification of xsS is interpreted as formed in fluvial
13 587 channels attesting the deposition from crested dune bed-forms that formed under
14 588 condition of lower flow regime (Collinson, 1996; Miall, 1996; Capuzzo and Wetzel,
15 589 2004; Went, 2016). The deposition of medium-angle cross-bedding within large-scale
16 590 examples of beds indicates that these larger beds are likely a product of bar migration.
17 591 The beds are interpreted as channel-fill deposits (Lenhardt et al., 2017) related to a
18 592 fluvial environment likely associated to meandering or braided rivers. Shoreline
19 593 deposition developed around margins of immature marine basins is also considered.

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27 595 6.2.2. Lf xsSG (cross-stratified Sand and Gravel)

28 596 Description: Lf xsSG ~~Lf xsSG~~ (Fig. 10b) is characterized by crystal-lithic fine
29 597 to coarse sand and fine gravel (max 5-6 mm in size) organized in cross-bedded
30 598 stratification. Clasts display medium roundness and sphericity and are mostly
31 599 composed by felsic fragments. Stratification is defined by alternating of well to poorly
32 600 sorted, fine to coarse millimeters-thick strata. The finer black layers are formed by sub-
33 601 millimetric hematite sand.

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38 602 Interpretation: Lf xsSG correspond to cross-stratified water reworked deposits.
39 603 The cross-stratified thicker fine gravelly strata, alternated with sandy layers laterally
40 604 discontinuous, were interpreted as different pulses as the result of rapid deposition
41 605 from hyperconcentrated flows (Zanchetta et al., 2004) in a stream-dominated
42 606 fluvial/alluvial setting. Alternation with csG (Fig. 9c) represents difference of energy
43 607 condition.

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49 609 6.2.3. Lf dsSt (diffusely layered Silt)

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51 610 Description: ~~Lf dsSt~~ this lithofacies consists of parallel, lenticular, truncated,
52 611 and locally low-angle cross-stratified multicolor millimetric well-sorted fine- to very
53 612 fine-grained sand and silt strata (Fig. 10c). Within the sandy bedset, a thinning- and

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2 613 fining-upward trend may be distinguished. Small and straight groove marks have been
3 614 detected and reduced tiny slump folding is also presence in some parts.

4
5 615 Interpretation: lithofacies dsSt displays diffuse fine stratification with tiny
6 616 ripples, suggesting transport and sedimentation in shallow water. The thin sheet-shaped
7 617 is interpreted as flood sediments (Lenhardt et al., 2011). These deposits are interpreted
8 618 to have been formed in low energy lacustrine environment or ponds (Collinson, 1996;
9 619 Roverato et al., 2017) characterized by small turbidities successions affected by
10 620 scouring and tiny deformations (slumps) of the sediments.

11 621

12 622 6.2.4. Lf bChS (bedded Chert and Sand)

13 623 Description: tThe bedded chert lithofacies (with sand) (bChS) (Ffig. 10d) crops out in
14 624 both regions and it is characterized by outcrops that can be traced on strike for
15 625 hundreds of meters. The facies consist of thin laminated pinkish chert (layers < 1mm in
16 626 thickness) with darker laminae intercalated, formed predominantly by hematite
17 627 (Lenhardt et al., 2017). The layers are composed by microcrystalline quartz. In some
18 628 portions, these lithofacies are associated with fine to medium sand composed mainly
19 629 by quartz and less volcanic fragments.

20 630

21 631

22 632 4.3.4 _- Interpretation: this lithofacies is interpreted as inorganic precipitation of silica
23 633 in a closed lake basin mainly due to its association with volcanic rocks and fine
24 634 sandstone (Blatt et al., 1980; Eriksson et al., 1994). The picture in figure 10d shows
25 635 elongated ripped-up millimetric fragments of chert immersed in the sandstone eroded
26 636 by low-energy stream flow or local lacustrine turbidites. As suggests by Lenhardt et al.
27 637 (2017) the chert may have formed during repeated pulses of hydrothermal fluids that
28 638 circulated into the lake water during hiatuses in the volcanism (Van Kranendonk,
29 639 2006).

30 640

31 641 7. Analytical methods for geochemistry and geochronology

32 642 A total of 19 new samples (9 volcaniclastics and 10 lava flows) from the
33 643 Tapajos region (associated with the data published in Roverato et al., 2016; Table 2)
34 644 were analysed for bulk rock major and trace elements. Major element bulk rock
35 645 analyses were performed by X-ray fluorescence, using a wavelength dispersive Philips
36 646 PW 2400 spectrometry, using fused glass disks according to procedures described by

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1 647 Mori et al. (1999). Accuracy was greater than 2%. Trace element analyses in selected
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3 648 samples were performed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
4
5 649 using the procedure described by Navarro et al. (2008). Accuracy, determined with
6
7 650 respect to the reference standards BHVO-2 and BR, was 0.5–2%.

8 651 Zircon grains were examined with a FEI-QUANTA 250 scanning electron
9
10 652 microscope equipped with secondary-electron and cathodoluminescence (CL) detectors
11
12 653 at the Instituto de Geociências - Centro de Pesquisas Geocronológicas - Universidade
13 654 de São Paulo (IGc-CPGeo-USP); the most common conditions used in CL analysis
14 655 were 60 µA of emission current, 15.0 kV of accelerating voltage, 7 µm of beam
15 656 diameter, 200 µs of acquisition time, and a resolution of 2048x1887 pixels and 345 dpi.
16
17 657 Selected samples were analyzed for U-Pb isotopes using a SHRIMP-IIe also at IGc-
18
19 658 CPGeo-USP, following the analytical procedures of Williams (1998) as reported by
20
21 659 Giovanardi et al. (2015). Correction for common Pb is based on the measured ²⁰⁴Pb,
22 660 and the typical error for the ²⁰⁶Pb/²³⁸U ratio is less than 2%; U abundance and U-Pb
23
24 661 ratios were calibrated against the TEMORA-II standard. The dataset consists of 56 new
25
26 662 U-Pb SHRIMP-II analyses and is reported in Table 3. Thirty-five analyses were
27 663 performed on zircon grains from the Tapajos region as follow: 11 analyses on sample
28 664 NP380-C, 11 analyses on sample NP183 and 13 analyses on sample NP396-B. Eleven
29
30 665 analyses were performed on zircon grains from Xingu sample XU08. For all samples,
31
32 666 ²⁰⁷Pb/²³⁵U and ²⁰⁶Pb/²³⁸U concordia ages (with 95% of confidence level and 2σ error)
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34 667 are calculated using Isoplot 4.1 software (Ludwig, 2009).

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38 670 ~~The cross-stratification of lithofacies xsS is interpreted as formed in fluvial~~
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40 671 ~~channels attesting the deposition from crested dune bedforms that formed under~~
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42 672 ~~condition of lower flow regime (Collinson, 1996; Miall, 1996; Capuzzo and Wetzel,~~
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44 673 ~~2004; Went, 2016). The deposition of medium-angle cross-bedding within large-scale~~
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46 674 ~~examples of beds indicates that these larger beds are likely a product of bar migration.~~
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48 675 ~~The beds are interpreted as channel-fill deposits (Lenhardt et al., 2017) related to a~~
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50 676 ~~fluvial environment likely associated to meandering or braided rivers. Shoreline~~
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52 677 ~~deposition developed around margins of immature marine basins is also considered. Lf~~
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54 678 ~~xsSG correspond to cross-stratified water-reworked deposits. The cross-stratified~~
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56 679 ~~thicker fine-gravelly strata, alternated with sandy layers laterally discontinuous, were~~
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58 680 ~~interpreted as different pulses as the result of rapid deposition from hyperconcentrated~~

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2 681 | flows (Zanchetta et al., 2004) in a stream-dominated fluvial/alluvial setting.
3 682 | Alternation with csG (fig. 9c) represents difference of energy condition. Lithofacies
4 683 | dsSt display diffuse fine stratification with tiny ripples, suggesting transport and
5 684 | sedimentation in shallow water. The thin sheet-shaped is interpreted as flood sediments
6 685 | (Lenhardt et al., 2011). These deposits are interpreted to have been formed in low
7 686 | energy lacustrine environment or ponds (Collinson, 1996; Roverato et al., 2017)
8 687 | characterized by small turbidities successions affected by scouring and tiny
9 688 | deformations (slumps) of the sediments. The Lf bChS is interpreted as inorganic
10 689 | precipitation of silica in a closed lake basin mainly due to its association with volcanic
11 690 | rocks and fine sandstone (Blatt et al., 1980; Eriksson et al., 1994). The picture in figure
12 691 | 10d shows elongated ripped-up millimetric fragments of chert immersed in the
13 692 | sandstone eroded by low-energy stream flow or local lacustrine turbidites. As suggests
14 693 | by Lenhardt et al. (2017) the chert may have formed during repeated pulses of
15 694 | hydrothermal fluids that circulated into the lake water during hiatuses in the volcanism
16 695 | (Van Kranendonk, 2006).
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28 698 | 85. Geochemistry of the TMP samples

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30 699 | Independently of their nature (lavas or volcaniclastic), the rocks of the TMP
31 700 | follow a typical calc-alkaline trend (Fig. 12). They are mostly rhyolitic in composition
32 701 | (Table 2), with four exceptions which fall in the trachytic field. In addition, their low
33 702 | LOI values (0.32-3.51%) and the low FeO content (0.78 – 3.26%) together with the
34 703 | negative correlation FeO vs SiO₂ appears to indicate that the investigated volcanic
35 704 | rocks neither underwent significant alteration processes nor they belong to sedimentary
36 705 | suites which commonly contain water rich clay minerals. TMP volcaniclastic and lava
37 706 | flows show similar negative correlation between TiO₂, Al₂O₃, MgO, FeO, CaO, Na₂O
38 707 | and P₂O₅ with SiO₂. A negative correlation between K₂O and SiO₂ also exists for the
39 708 | volcanoclastic, but not for the lava flows. The similar trends observed suggest that both
40 709 | these kind of rocks are originated by similar the same magmatic sources. Such a
41 710 | conclusion is supported by similar variation paths, although with different values, of
42 711 | minor and trace elements (Figs. 13). In particular, TMP lava flows show LREE
43 712 | enrichment ((La/Yb)_N=10.68-21.45; normalization to Chondrite I from Anders &
44 713 | Ebihara, 1982) and a negative Eu anomaly which increases from trachytes
45 714 | ((Eu/Eu*)_N=0.89-0.78) to rhyolites ((Eu/Eu*)_N=0.69-0.31) (Fig. 13). The Eu negative
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715 anomaly, shown from all the samples, is expression of feldspar fractionation. On the
 716 other hand, volcanoclastic rocks show similar LREE enrichment ($(La/Yb)_N=11.12-$
 717 28.10) and negative Eu anomaly ($(Eu/Eu^*)_N=0.97-0.37$) (Fig. 13). In addition,
 718 volcanoclastics have higher LREE abundances with respect to lavas (La between 35.5-
 719 91.3 ppm and between 40.5-71.9 ppm, respectively) while they have similar MREE
 720 and HREE contents (Yb between 1.56-3.43 ppm and between 1.83-4.11 ppm,
 721 respectively). Volcanoclastics commonly show higher Rb (121-272.9 ppm) and Pb
 722 (4.5-137.1 ppm) with respect to lavas (Rb=96.1-232 ppm and Pb=2.7-45.8 ppm).
 723 Volcanoclastics are enriched in LILE, Th and U with respect to MORB (Fig. REE13;
 724 normalization to MORB from Hoffman, 1988), with the exception of Sr, which
 725 commonly show a pronounced negative anomaly ($(Sr/Sr^*)_N=0.55-0.05$). The Sr
 726 negative anomaly is consistent with feldspar fractionation. Negative anomalies are also
 727 present for Nb and Ta, while Ba and Pb are commonly enriched (Fig. 13). Lavas show
 728 a similar trace pattern, but higher values dispersion (Fig. REE13). The Ba enrichment
 729 is less pronounced with respect to volcanoclastics (Ba between 75-1965 ppm and 310-
 730 2245 ppm, respectively) and the Nb/Ta ratio show higher dispersion (3.29-14.63 and
 731 6.73-13.9, respectively), indicating more limited fractionation of feldspar. According
 732 to the fractionation of feldspar, the trachytes have less pronounced negative Sr
 733 anomalies with respect rhyolites ($(Sr/Sr^*)_N=0.61-0.35$ and $0.34-0.04$, respectively).
 734 Geochemical affinity of Tapajos volcanoclastics and lava flows suggests that the
 735 magmatism occurred in active continental margin setting (Fig. 14). Using the tectonic
 736 discriminant diagrams of Zr+Nb+Ce+Y (ppm) vs FeOtot/MgO (wt.%), Yb vs Ta and
 737 Th-Ta-Hf/3 (Wahlen et al., 1987; Pearce et al., 1984; Wood, 1980), the magmatism in
 738 the Tapajos region appears related to a syn- to post-collisional setting with few samples
 739 falling into the intraplate field (Fig. 14). According to the refined diagram Nb+Y vs Rb
 740 of Pearce (1996), all the Tapajos volcanics, together with the majority of volcanic
 741 rocks from the Sobreiro formation (Fernandes et al., 2011) are consistent with a late- to
 742 post-collisional setting (Fig. 14).

96. U-Pb zircon Geochronology

746 Zircons from Tapajos samples are colorless, sometimes fractured and euhedral
 747 to sub-euhedral. They can contain inclusions of apatite or spinel and are display
 748 commonly low emission in Cathodoluminescence (CL). All crystals show magmatic

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2 749 oscillatory zoning and commonly a dark core which, in most cases, appears to be
3 750 homogenous. Nonetheless, in few cases an inner core with discordant and partially
4 751 reabsorbed domains is recognized. Some of the zircons also show a bright CL rim with
5 752 transgressive or sub-concordant contacts with the inner oscillatory zoning. Zircons
6 753 from sample XU08 from the Xingu region are colourless, rarely fractured and sub-
7 754 euhedral. Inclusions of apatite or spinel are also observed sometimes. Crystals are
8 755 medium in CL emissions and commonly show a homogeneous core and a concordant
9 756 magmatic oscillatory zoning. Few zircons show a core with discordant zoning. No
10 757 transgressive bright CL rims were recognized. Analyses were carried out on zircons
11 758 that do not show transgressive or resorption features and discordant inner cores.
12 759 Zircons from sample NP183 (Ignimbrite) provide 4 discordant ~~ages~~ and 7 concordant
13 760 analyses that provide ~~for~~ an upper intercept at 1984 ± 8.5 Ma (95% confident decay-
14 761 const. errs included, MSWD 1.09) and a concordia age at 1986 ± 8.2 Ma (2σ , decay-
15 762 const. errs included, MSWD 1.08, Probability of concordance = 0.30; Fig. 15). Single
16 763 spot $^{206}\text{Pb}/^{207}\text{Pb}$ ages range between 2010 ± 17 Ma and 1909 ± 53 Ma with an average
17 764 age of 1985 ± 11 Ma (95% confident decay-const. errs included, MSWD 1.6,
18 765 Probability of concordance = 0.15; Fig. 15). Zircons from sample NP380 (Ignimbrite)
19 766 show slightly older single spot $^{206}\text{Pb}/^{207}\text{Pb}$ ages between 2023 ± 31 Ma and 1981 ± 24
20 767 Ma with an average age of 1998 ± 5.9 Ma (95% confident decay-const. errs included,
21 768 MSWD 0.74, Probability of concordance = 0.68; Fig. 14). Analyses are slightly
22 769 discordant (up to 4%) providing an upper intercept at 1998 ± 7.7 Ma (95% confident
23 770 decay-const. errs included, MSWD 0.74). Zircons from sample NP396 (Banded lava)
24 771 provide 5 discordant ages and 8 concordant analyses, which provide ~~for~~ an upper
25 772 intercept at 1994 ± 8.2 Ma (95% confident decay-const. errs included, MSWD 1.40)
26 773 and a concordia age at 1997 ± 7.0 Ma (2σ , decay-const. errs included, MSWD 5.70,
27 774 Probability of concordance = 0.02; Fig. 15). Single spot $^{206}\text{Pb}/^{207}\text{Pb}$ ages range between
28 775 2014 ± 14 Ma and 1973 ± 8 Ma with an average age of 1994 ± 8.7 Ma (95% confident
29 776 decay-const. errs included, MSWD 1.6, Probability of concordance = 0.12; Fig. 14).
30 777 Pooling together the analyses of the Tapajós samples provides an average age of 1991
31 778 ± 12 Ma (2σ , MSWD 1.50, Probability of concordance = 0.06). Zircons from sample
32 779 XU08 (Lava flow) provide a concordia age at 1882 ± 6.4 Ma (2σ , decay-const. errs
33 780 included, MSWD 2.70, Probability of concordance = 0.10; Fig. 16). Single spot
34 781 $^{206}\text{Pb}/^{207}\text{Pb}$ ages range between 1899 ± 10 Ma and 1875 ± 13 Ma, with an average at

1 782 1884 ±5.2 Ma (95% confident decay-const. errs included, MSWD 0.60, Probability of
2 concordance = 0.82).

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5 785 107. Discussion

6 786 ~~7.1~~ 10.1. Subduction-related to extensional setting

7 787 The geochemistry of the TMP samples presented in this work display a high-K
8 788 calc-alkaline signature (Fig. 12); ~~most of them are related to a volcanic are setting~~
9 789 ~~(fig. 14), although few samples display a geochemical signature that vary from the~~
10 790 ~~trend and they majorly~~ fall into the A-type intra-plate granite field and tectonic
11 791 discriminant diagrams suggest a late- to post-collisional setting for the TMP volcanism
12 792 (Fig. 14). This interpretation is also supported by enrichment in low-HSFE and the
13 793 high-LILE, Th, U and LREE contents of our samples, which suggest a strong crustal
14 794 component in the parent melt, consistent with a subduction/post orogenic
15 795 geodynamic setting (Fig. 12), and the high HSFE which shifted the TMP volcanics
16 796 composition in the A-type granites showing however FeO/MgO which are low and
17 797 comparable with I- and S-types granites (Fig. 14). Similar features are. ~~These two~~
18 798 ~~distinct signatures are also well~~ reported in previous works (Lamarão et al., 1999;
19 799 Lamarão et al., 2002) for volcanics in the Tapajós region, which are grouped into the
20 800 Vila Riozinho (VR) and Maraes Aldeida (MA) formations, respectively. The Vila
21 801 Riozinho rocks are intermediate to felsic in composition (Lamarão et al., 2002) with a
22 802 calc-alkaline signature, while the rhyolites and ignimbrites of Moraes Almeida are
23 803 slightly enriched in silica compared to the rhyolites of Vila Riozinho and are
24 804 geochemically similar to evolved A-type granites (Lamarão et al., 2002). Our results
25 805 show similarities with these data, suggesting that our specimens could be part of the
26 806 VR and/or MA formations. The identification of two volcanic series has important
27 807 implications for the understanding of the magmatic evolution of the Amazonian craton
28 808 in late Paleoproterozoic. A model for the evolution of the TMP involves a first stage of
29 809 subduction-related magmatism followed by an intracontinental magmatism related to a
30 810 distensional event (Lamarão et al., 2002). Geochronological analyses by Lamarão et al.
31 811 (2002) yielded ages of ca. 2 Ga for the VR rocks and ca. 1.88-1.87 Ga for the MA
32 812 volcanism. The three new U-Pb geochronological analyses reported in this study yielded
33 813 ages of ca. 2000 Ma (fig. 15) are, concordant with the ages presented by Lamarão et al.
34 814 (2002) for the VR magmatism, thus suggesting that the TMP rocks could be part of the
35 815 VR volcanic sequence. However, TMP rocks are geochemically more evolved with

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2 816 respect to VR in terms of SiO₂ (63.8-76.6 wt.% and 54.4-71.8 wt.%, respectively),
3 817 K₂O (2.3-7.1 wt.% and 2.1-5.8 wt.%, respectively) and REE abundances (Fig. 12) and
4 818 are more similar to MA rocks (Fig-s. 11, 12 and 13). In particular, REE patterns of the
5 819 TMP samples are comparable with the rocks of the MA formation (Fig. 12) while they
6 820 are more enriched in REE with respect to VR rocks. Conversely, TMP rocks are
7 821 enriched in Ba (Fig. 12), while ~~MA~~ are depleted, and have compositions for Rb/Zr
8 822 and Nb, considered as a proxy for arc maturity (Brown et al., 1984), similar to VR and
9 823 different from MA (Rb/Zr between 0.3-1.1 in TMP, 0.2-0.7 in VR and 0.2-1.7 in MA;
10 824 Lamarão et al., 2002). Thus, according to geochronological and petrological data, we
11 825 proposed that the TMP rocks in this study ~~represent the more felsic and evolved facies~~
12 826 ~~of the VR magmatism and~~ must be ascribed ~~at this~~ to the VRs formation. Geochemical
13 827 differences in our rocks and VR volcanics could be explained by a more evolved
14 828 character of the TMP rocks. The ~~The~~ evidences of plagioclase fractionation from the
15 829 parent melts of the TMP (negative Eu and Sr anomalies, Fig. 12) and their absence in
16 830 less evolved VR rocks reinforce this interpretation, and suggest fractional
17 831 crystallization as the prominent process controlling the VR magmatism evolution.
18 832 However, we want to point out that due to the large area covered by the presented
19 833 investigation (Fig. 2), together with the VR area, the geochemical variations between
20 834 our rocks (TMP) and VR could be the result of local/regional heterogeneities in the
21 835 magmatism. This hypothesis is supported by the intermediate characteristics of the
22 836 TMP samples with respect to the VR and MA volcanics (Figs 11, 12 and 13).

23 837 Recently, new authors (Juliani et al., 2014) suggest the geochemical and
24 838 geochronological signature of the MA ~~(TMP)~~ formation could be correlated to the felsic
25 839 Santa Rosa (SR) formation cropping out in the SFX region. Our new U-Pb
26 840 geochronological analyses on one rock sample from the SR formation yielded an
27 841 average age of 1884 ± 5.2 Ma (Fig. 168) that is consistent with previous Pb-Pb ages on
28 842 other locations. Juliiani and Fernandes (2010) published two Pb-Pb ages on zircons of
29 843 1879 ± 2 Ma and 1884 ± 1.7 for a rhyolite and an ash tuff, respectively. Recently
30 844 Antonio et al. (2017) publishes the first U-Pb ages on zircons for the Santa Rosa
31 845 Formation with 1877.4 ± 4.3 Ma for a rhyolite and 1895 ± 11 Ma for a dike. All
32 846 geochronological results support a ca. 1880 Ma age for the emplacement of these
33 847 rocks.

34 848 The southern Amazonian craton, as well as other ~~P~~recambrian terrains
35 849 worldwide (Condie, 2002; Hoffman, 1988; Zhao et al., 2002), are considered to be

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2 850 characterized by a series of orogenic to post-orogenic events from 2.0 up to 1.88 Ga.
3 851 The amalgamation of cratonic blocks worldwide established connections between
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5 852 South America and West Africa and other cratonic terrains such as Western Australia
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7 853 and South Africa, Laurentia and Baltica, Siberia and Laurentia, Laurentia and Central
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9 854 Australia, etc (Zhao et al., 2002). These late-Paleoproterozoic collisional processes
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11 855 likely formed the controversial supercontinent Columbia (Zhao et al., 2004). This
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13 856 period also coincides with a major peak in orogenic gold resources (Goldfarb et al.,
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15 857 2001, Juliani et al., 2014) and understanding the geodynamic of this period is crucial
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17 858 for economic interests. Antonio et al. (2017) highlight that for the period 1.88 Ga,
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19 859 many cratonic terrain have been characterized by extensive magmatism. These authors
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21 860 report as examples the 1880 Ma NE-trending Ghost dike swarm and the 1880 Ma
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23 861 Circum-Superior LIP in the Canadian shield (Minifie et al., 2013), the 1880 Ma
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25 862 Southern Bastar- Cuddapah LIP in India (French et al., 2008), the Mashonaland sills
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27 863 and the Post-Waterberg dolerites in Kalahari craton (Hanson et al., 2004), an extensive
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29 864 A-type magmatism in Baltica and in Siberia. The A-type affinity of the 1.88 Ga rocks
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31 865 is widely described by other authors in different regions into the Amazonian craton
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33 866 (Ferron et al., 2010; Pierosan et al., 2011; Fernandes et al., 2011; Klein et al., 2012;
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35 867 Barreto et al., 2014; Teixeira et al., 2018). Currently, the significance of the 1.88 Ga A-
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37 868 type magmatism in the Amazonian craton is still matter of debate, also due to the
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39 869 extremely large aerial cover which interested several different domains with different
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41 870 basements and geologic evolutions. For example, studies on the Carajas region suggest
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43 871 that the 1.88 Ga anorogenic magmatism in this domain was provoked by delamination
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45 872 and fusion of the Archean basement by a mantle plume which originated an
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47 873 extensional setting (Dell'Agnol et al., 2005; Silva et al., 2016; Teixeira et al., 2018;
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49 874 Teixeira et al., 2019).
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51 875 Conversely, the geochemical features of the TMP and SFX magmatism
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53 876 presented in this work and in literature (Lamarão et al., 2002, 2005; Fernandes et al.,
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55 877 2011) mainly support an extensional regime of these regions related to a late- to post-
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57 878 collisional event, being possibly related to the end of the subduction process.-
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59 879 According to these authors we suggest that the A-type rocks emplaced during
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61 880 the period 1.88 Ga in both TMP and SFX are related to an intraplate environment in an
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63 881 extensional regime.The transition from convergent (syn/post-orogenic) to extensional
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65 882 tectonic setting could register the beginning of the taphrogenesis that marked the
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67 883 Amazonian Craton throughout the Mesoproterozoic (Brito Neves, 1999; Lamarão et

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884 al., 2002). The ca. 1.88 Ga felsic magmatism in different provinces of the Amazonian
885 craton could represent the oldest magmatism related to this event. It should be
886 mentioned that in term of textural features, the products emitted during the transition
887 between the post-collisional to extensive events don't display substantial variations. In
888 other words, the lithofaciological signature of the volcanic and volcanoclastic rocks that
889 characterized the 2 Ga VR event (subduction related) is similar for those products
890 erupted during the 1.88-1.87 Ga extensional volcanism that characterized the MA and
891 SR events. Moreover, the post-orogenic to extensional setting emphasizes the
892 continental setting where the studied volcanic products have been emitted. Following
893 the idea of Roverato et al. (2017) for the Late-Paleoproterozoic andesitic Sobreiro
894 Formation, we stress the lack of any evidences in favour of subaqueous eruptions for
895 the emitted felsic products such as pillow lavas as well as hyaloclastites. This suggests
896 the subaerial character of the volcanism and its emitted products acted in both regions.

107.2. Eruptive style and emplacement

899 The study areas are widely characterized by volcanic deposits whose eruptive
900 style is hard to differentiate. Distinguishing between banded lavas and high grade
901 ignimbrites is, sometime, extremely challenging (Henry and Wolff, 1992; Manley,
902 1995). This is made even more complicated when the investigated deposits are ancient
903 and the outcrops intensely eroded, such as those Precambrian terrains investigated here
904 (Lenhardt et al., 2012; Roverato et al., 2016; Lenhardt et al., 2017). Evidences in the
905 field show that a great volume of the volcanic activity is represented by the emission of
906 lava flows and/or high-grade to rheomorphic ignimbrites, although an important
907 amount of other fragmental products of different type (Lf mAL, mLA, l-g/m-g/h-
908 gwAL) are also well represented in both regions. High-grade welded and rheomorphic
909 (up to lava-like) ignimbrites share similar features with lavas, displaying banding and
910 ductile folds formed by the elongation of fiamme and vesicles (Schmincke and
911 Swanson, 1967; Chapin and Lowell, 1979; Wolff and Wright, 1981; Branney et al.,
912 1992; Sumner and Branney, 2002; Pioli and Rosi, 2005; Andrews and Branney, 2011;
913 Brown and Bell, 2013). Although the ignimbrites investigated here have a fragmental
914 derivation their origin largely differ from those characteristic of fallout deposits that
915 form by a sustained column explosive-driven eruption. High-grade welded and
916 rheomorphic ignimbrites are correlated with highly explosive plinian-type eruptions

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1 917 which produce, during their column collapse stage, large PDC. In addition, high-grade
2 918 rheomorphism of silicic products, either deriving from an explosive or effusive
3 919 eruption, are favored by high temperature low-viscosity emplacement conditions and
4 920 the presence of some residual water. The high temperatures condition of our deposits is
5 921 also confirmed by the pervasive presence of spherulites and lithophysae formed during
6 922 the slow-cooling regimes of large silica-rich lavas and welded ignimbrites (Lofgren,
7 923 1971; Breitzkreuz, 2013). The eruptive scenario showed in figure 17 giving origin to the
8 924 frequent eruption of large volume and high discharge rate lava flows and ignimbrites
9 925 was likely characterized by fissure-fed and caldera collapses systems as those
10 926 described by previous authors (Legros et al., 2000; Aguirre et al., 2003; Cas et al.,
11 927 2011; Lesti et al., 2011; Lenhardt et al., 2012; Willcock et al., 2013). Eruptions fed by
12 928 extensive fissures of large size, in fact, appear to be the most favourable volcanic
13 929 systems to minimize cooling during emplacement and produce an alternance of low-
14 930 height sustained column eruptions feeding PDC and eruptions characterized by the
15 931 effusion of low viscosity lava flows, coulees and domes, while maintaining high
16 932 discharge rates (e.g. Bachmann et al., 2000; Aguirrez-Diaz & Labarthe-Hernandez,
17 933 2003; Polo et al., 2018a, b; Simões et al., 2017). The sustained fountaining and
18 934 entrainment of air in the eruptive jet is strongly influenced by the geometry of the
19 935 conduit (Legros et al., 2000) as well as the transition from sustained to collapsing
20 936 eruptive column. A wide-geometry conduit would impede much air entrainment into
21 937 the pyroclastic fountain and, at the same time, would favors magmatic escape of
22 938 volcanic gases, favoring the low fountaining and promoting a “boil-over” style
23 939 eruption (Branney and Kokelaar, 1992, 2002; Lenhardt et al., 2017) with high
24 940 discharge rate. Moreover, the low air injection would inhibit the dilution of the
25 941 eruptive material making it thermodynamically isolated from the surrounding
26 942 environment (Lesti et al., 2011), preserving the high temperatures and enhancing the
27 943 agglutination of fragments (welding) (e.g. Quane and Russell, 2004; Russell and
28 944 Quane 2005; Giordano et al., 2005). When the low-altitude pyroclastic fountaining or
29 945 the emission of high temperature lavas would be maintained for long time the high
30 946 flow-mobility is ensured (Sulpizio et al., 2014). If the material supply from the vent
31 947 continues for long time and with high discharge rate, the mobility could be maintained
32 948 even on very low slope angles (Sulpizio et al., 2014; Giordano et al., 2017; Kolzenburg
33 949 et al., 2017), and flowing various kilometers up to hundreds of kilometers far from the
34 950 vent (Aguirre-Diaz et al., 2008; Cas et al., 2011; Giordano et al., 2017). This could

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2 951 explain the presence of large silicic volcanic areas characteristic of the ancient
3 952 Amazonian volcanism (Roverato et al., 2016). Although, volcanoclastic rocks seem to
4 953 be volumetrically less important in the study areas than the lava flows and/or
5 954 rheomorphic ignimbrites the recognition of fragmental rocks during our field
6 955 campaigns is important to understand their significance into our paleogeographic
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8 956 reconstruction (Fig. 17). An idealized deposit sequence of a caldera forming eruption
9 957 displays an air-fall deposit overlain by an ignimbrite (Druitt and Sparks, 1984) and the
10 958 transition from the sustained column phase to the pyroclastic flow phase is often
11 959 accompanied by a strong increase in the discharge rate (Bursik and Woods, 1996). The
12 960 stratigraphic sequence of figure 11 shows this association of a possible air-fall deposit
13 961 (Lf dsAL) linked with pyroclastic flow-dominated deposits (Lf mAL and *m-gwLA*). In
14 962 some cases, pyroclastic eruptions commonly precede lava emplacement (Fink 1983;
15 963 Heiken and Wohletz 1987). The sequence presented in figure 7 shows a low-grade
16 964 welded ignimbrite deposit (Lf *l-gwAL*) overlaid by a thick banded body that we are
17 965 interpreting here as a lava flow. At the base of the banded lava is a breccia (Lf mLB)
18 966 consisting of clasts of a mix of lava textural types, including massive, vesicular, flow
19 967 banded and flow-folded, glassy, pumiceous and devitrified. Autobrecciation in lavas or
20 968 rheomorphic ignimbrites occurs when more rigid layers and the external parts are
21 969 broken in response to the applied shear stress locally exceeding the tensile strength
22 970 (Fink and Manley; 1987). Some polymictic breccia deposits (Lf mLA) are
23 971 characterized by lithic angular clasts and devitrified fragments that could point to co-
24 972 ignimbritic breccias with short transport of the emitted material. These deposits could
25 973 be also related to collapse-caldera-breccias falling down into the caldera ring during
26 974 the roof subsidence (Fig. 8). Air-fall (sA) and dilute pyroclastic flow (xsA) deposits
27 975 (surge type) crop out in both regions. These, linked with the glassy and lithic
28 976 pyroclastic material described above, are evidence of intense explosive phases from
29 977 more sustained column eruptions of smaller intra-caldera volcanic centers and/or
30 978 associated to events of caldera collapse (Fig. 17).

980 107.2.1 The sedimentary response

981 Sets of small basins intra-calderas and probable relatively immature shallow
982 marine deposits are interpreted as forming part of a tectonically unstable setting of a
983 young extensional environment that characterized the southern Amazonian craton
984 during the Paleoproterozoic. Reworked sediments can accumulate into volcano-

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1 985 tectonic depressions created by the eruption, which often collects an intra-caldera lake
2 986 (Heiken et al., 2000 Németh et al., 2009, Manville et al., 2009). The sedimentation into
3 987 intra-volcano shallow-water lacustrine basins would have be facilitated (Fig. 17). The
4 988 alternation of subaerial to shallow-water sedimentation displayed by the alternation of
5 989 Lf mS and csG is indicative of this volcano-tectonic depressions, which could be also
6 990 interpreted as immature marine depressions. Subaerial and subaqueous talus coarse-
7 991 grained up to finer grained turbidites (dsSt) and suspension deposits formed during
8 992 quiescent periods into lakes or pounds is also inferred (Bacon et al., 2002). Silica-rich
9 993 accumulations into shallow water basins (Chipera et al., 2008; Manville et al., 2009)
10 994 deriving from hydrothermal activity in a dynamic volcanic context is also thought to be
11 995 responsible for the formation of chert accumulation (Lf bChS). Post caldera uplifting
12 996 (Fig. 17), resurgence or central volcanism could also contribute to produce new
13 997 sediments to be reworked and transported. Fluvial erosion and reworking of primary
14 998 deposits produced wide range of different sediments from localized cross-bedded,
15 999 well-sorted sand (Lf xsS) and gravel (Lf xsSG) beds to massive clast-supported sand
16 1000 and gravel (Lf csGS, csG) and cobble (Lf csGC) deposits. Fluvial deposits occur
17 1001 throughout all successions, representing periods of stream and river reworking and re-
18 1002 establishment after an eruptive phase (Zernack et al., 2011; Roverato et al., 2017).
19 1003 Debris-flows, hyperconcentrated flows, sheet-floods and active sandy braided river
20 1004 systems existed and the probable absence of vegetation during the Precambrian
21 1005 (Oberholzer and Eriksson, 2000; Roverato et al., 2017) permitted that copious rainfalls
22 1006 easily reworked the available sediments.
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38 1008 119. Conclusion

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40 1010 This study is the result of the lithofaciological analysis carried out during the
41 1011 2013, 2014 and 2015 field campaigns in the Amazon Craton in the TMP and SFX
42 1012 regions and the successive geochemical and geochronological analysis of samples
43 1013 collected in the field. This work constitutes a further step ahead toward the
44 1014 comprehension of significance, chronostratigraphic distribution and the dynamic of
45 1015 eruption and emplacement of felsic volcanic products in the region. Our results
46 1016 complete previous studies and confirm that products present in the Amazonia Craton
47 1017 could be related either to caldera-type systems (e.g. Lamarão et al., 2002; Juliani et al.,
48 1018 2005; Lamarão et al., 2005; Pierosan et al., 2011) and to fissure-fed eruptive
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2 1019 environment following the model proposed by Aguirre-Diaz and Labarthe-Hernandez
3 1020 (2003) for the “Sierra Madre Occidental” formation and by Juliani and Fernandes
4 1021 (2010) for the Xingu region. The two models are in fact very similar only differing for
5 1022 the size of the hypothesized magma chambers and the shape of the fissural vents. The
6 1023 described volcano-sedimentary sequences that were characterized by the emission of
7 1024 large volcanic felsic products were likely formed in a late- to post-orogenic (~ 2 Ga) to
8 1025 extensional regimes (~ 1.88 Ga).

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14 1027 ~~Here we also image that an ideal late-convergent to extensional geotectonic~~
15 1028 ~~environment was likely similar to that proposed in our discussion paragraph, where a~~
16 1029 ~~post-orogenic to extensional regime for the period ~1.88 Ga was characterized by the~~
17 1030 ~~emission of large volcanic felsic products. With this contribution we want also stress~~
18 1031 ~~the importance of the results obtained by investigating the lithofaciological character of~~
19 1032 ~~the deposits instead of only carrying out geochemical studies.~~

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25 1034 Acknowledgments

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7 1499 Figure Captions

8 1500
9 1501 Figure 1: location map of the northern South America and the Amazonian Ceraton and
10 1502 divided into several its geochronological provinces and other domains according to
11 1503 Santos et al. (2000); TMP = Tapajós Mineral Province, SFX = São Felix do Xingú
12 1504 Region. ; G = Guyana, GF = French Guyana, S = Suriname.
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17 1506 Figure 2: distribution map of the outcrops analyzed during the field campaigns in both
18 1507 regions a) Tapajós Mineral Province (TMP) and b) São Felix do Xingú region (SFX);
19 1508 PW=distribution of the Santa Rosa formation inferred during the present work;
20 1509 F=distribution of the Santa Rosa formation inferred by Fernandes et al. (2011);
21 1510 BIF=Banded Iron Formation; red and white dot refers to primary andesitic deposits
22 1511 analyzed in Roverato et al. (2017).- In both figures are reported the outcrops described
23 1512 in the paper.
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29 1513
30 1514 Figure 3: massive and banded lavas and rheo-ignimbrite (?) deposits. a) Np173
31 1515 (7°33'52.31" S, 55°10'58.80" W), b) Xu23 (6°41'08.65" S, 52°25'55.67" W), c) Xu101
32 1516 (6°52'12.82" S, 52°09'16.12" W), d) Xu52 (6°28'19.32" S, 51°50'08.90" W), e), f), g)
33 1517 Np396 (6°32'41.06" S, 55°23'59.37" W); see Fig. 2 for the outcrops location. For the
34 1518 lithofacies description and more details see the text.
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39 1520 Figure 4: massive primary volcanoclastic rocks with different proportion of ash, lapilli
40 1521 and blocks. All the deposits are interpreted to be emplaced from pyroclastic density
41 1522 currents except (f) that is interpreted as a basal-breccia of a lava body. a) Xu104
42 1523 (6°52'22.96" S, 52°08'15.91" W), -b) Np183 (7°32'04.13" S, 55°08'50.02" W), c)
43 1524 Np93 (6°44'16.60" S, 55°27'12.96" W), d) Xu29 (6°41'42.51" S, 52°01'23.06" W), e)
44 1525 Xu07 (6°41'56.36" S, 52°08'42.27" W) f) Xu192 (6°31'31.92" S, 53°02'36.60" W);
45 1526 see Fig. 2 for the outcrops location. For the lithofacies description see the text and
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50 1527 Table 1.
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53 1529 Figure 5: microphotographs of different massive ash and lapilli ignimbrite deposits in
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2 1530 thin section: a) broken crystals suggesting the fragmental character of the rock; b)
3 1531 detail of a devitrified juvenile ~~(?)~~ fragment displaying axiolitic fabric; c) banded sub-
4 1532 millimetric to millimetric lithic fragments immersed in a devitrified groundmass.
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8 1534 Figure 6: reconstructed schematic stratigraphic column and associated photographs
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10 1535 representing the evolution of ignimbrite deposits cropping out in the TMP (Np183;
11 1536 7°32'04.13" S, 55°08'50.02" W); note the increase of welding from the base to the top.
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13 1537
14 1538 Figure 7: schematic stratigraphic column and relative photographs of a >150 m thick
15 1539 felsic banded lava(s) cropping out in SFX (Xu192; 6°31'31.92" S, 53°02'36.60" W)
16 1540 overlying a basal breccia (Lf ~~m~~LB) and an ignimbrite deposit characterized by a low
17 1541 grade of welding (Lf *l-gw*LA).
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19 1542
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21 1543 Figure 8: stratified primary volcanoclastic rocks, a) related to sedimentation by highly
22 1544 dilute ash-cloud (Np130; 6°54'16.09" S, 55°10'59.38" W) and, b) ~~-~~attribute to
23 1545 pyroclastic surge-type depositional condition from dilute currents (XU162;
24 1546 6°32'28.39" S, 52°25'26.07" W); see Fig. 2 for the outcrops location. ~~-~~ Relative thin
25 1547 section microphotographs (~~c~~*b*/~~d~~) showing micrometric shards. For the lithofacies
26 1548 description see the text and Table 1.
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28 1549
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30 1550 Figure 9: massive sedimentary rocks. ~~(a)~~ ~~-~~The alternation of lithofacies *csG* and *mS*
31 1551 indicates changes in energy conditions of sedimentation belonging to a subaqueous-
32 1552 subaerial fan-delta interface (Np146; 6°42'58.24" S, 55°28'53.49" W); ~~(b)~~ ~~d~~Detail of
33 1553 centimeters ripples of Lf *mS* (Np89; 6°54'39.36" S, 55°26'12.28 W); ~~(c)~~ ~~-~~Lf *csG* is
34 1554 also associated to Lf *xsSG* (see stratified rocks in section 6.2) (Np27; 8°08'18.43" S,
35 1555 54°54'37.33" W); ~~(d)~~ ~~Np27, ~~e~~/~~f~~~~ ~~(e)~~ Xu209 (6°13'55.26" S, 52°42'29.25" W), ~~(f)~~
36 1556 Np158 (7°03'33.79" S, 55°24'11.84" W); ~~t~~The rounded and clast supported character
37 1557 of these lithofacies is linked with fluvial/alluvial deposition by debris-flow dominated
38 1558 processes; see Fig. 2 for the outcrops location. ~~-~~For a more detailed lithofacies
39 1559 description see the text and Table 1.
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41 1560
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43 1561 Figure 10: stratified sedimentary rocks. ~~(a)~~ The quartzitic sandy cross-bedded
44 1562 lithofacies is interpreted as formed in fluvial channel or around margins of immature
45 1563 marine basins (?) (Xu 201; 6°16'12.95" S, 52°52'18.84" W); ~~(b)~~ ~~t~~The cross-stratified

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2 1564 | water reworked lithofacies is linked with stream-dominated fluvial/alluvial settings
3 1565 | [\(Np82; 8°03'40.79" S, 54°50'43.52" W\)](#); ~~-(c)-~~ ~~t~~The silty sedimentation likely belong to
4 1566 | a lacustrine environment characterized by small turbidities [\(Np158; 7°03'33.79" S,](#)
5 1567 | [55°24'11.84" W\)](#); ~~-(d)-~~ ~~t~~The top of the photographs shows the Lf *bChs* interpreted as
6 1568 | inorganic precipitation of silica (chert) in a closed lake basin; white arrows show
7 1569 | fragments of the chert deposit eroded by low-energy sandy stream flows or local
8 1570 | lacustrine turbidites [\(Np90; 6°49'50.20" S, 55°28'15.47" W\)](#); see Fig. 2 for the
9 1571 | [outcrops location](#). For a more detailed lithofacies description see the text and Table 1.
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17 1574 | Figure 11: sketch of a wide (300 x 80 m) outcrop in the TMP [\(Np407; 6°40'35.21" S,](#)
18 1575 | [55°21'14.63" W\)](#). The stratigraphic sequence is tilted showing sub-vertical contacts of
19 1576 | the different deposits. The sequence is interpreted displaying at the base banded (or
20 1577 | rheo-ignimbrite) and massive lava flows passing to fragmental deposits to the top. ~~(a)~~
21 1578 | ignimbrite medium-grade welded; b) the diffuse-stratified lithofacies indicates tractive
22 1579 | processes usually attribute to pyroclastic surge-type depositional condition from dilute
23 1580 | currents; c) sedimentary clast-supported deposit ~~(see descriptions in chapter 4.3)~~; d)
24 1581 | non-welded lapilli to ash ignimbrite; e) banded lava o highly reomorphic ignimbrite
25 1582 | (lava-like). For a more detailed lithofacies description see the text and Table 1.
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33 1584 | Figure 12: classification diagrams for the Tapajos volcanics (TMP-V) and lava flow
34 1585 | (TMP-LF). TAS diagram with limits of alkaline series from Kuno (1968), dashed line,
35 1586 | and Irvine and Baragar (1971), solid line. AFM diagram with alkaline field from Irvine
36 1587 | and Baragard (1971). SiO₂ vs K₂O classification diagram (Ewart, 1982). Literature
37 1588 | values are from: VR (a) Vila Rozinho and MA (a) Moraes Almeida volcanic sequences
38 1589 | from Lamarão et al. (2002); [SF \(b\) Sobreiro Formation and](#); SRF (b) Santa Rosa
39 1590 | Formation from Fernandes et al. (2011).
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46 1592 | Figure 13: REE and spider-diagrams of volcanics and lava flow rocks from the Tapajos
47 1593 | region (TMP-V and TMP-LF). REE data are normalized to Chondrite I (CI; values
48 1594 | from Ander and Ebihara, 1982) and trace elements are normalized to Mid Ocean Ridge
49 1595 | Basalt (MORB; values from Hoffman, 1988). Literature values are from: VR (a) Vila
50 1596 | Rozinho and MA (a) Moraes Almeida volcanic sequences are average values from
51 1597 | Lamarão et al. (2002); SRF (b) Santa Rosa Formation from Fernandes et al. (2011)
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1 1598 divided in -V volcanoclastics and -LF lava flow. Due to the lack of literature data,
2 1599 comparison of VR (a) and MA (a) is reported only for REE diagram.

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4 1601 Figure 14: tectonic affinity discriminant diagrams for the Tapajos volcanics (TMP-V)
5 1602 and lava flow (TMP-LF). Zr+Nb+Ce+Y (ppm) vs FeO_{tot}/MgO (wt.%) diagram. Yb vs
6 1603 Ta diagram. La/Yb vs Nb/La diagram. Th-Ta-Hf/3 diagram. Literature values are from:
7 1604 VR (a) Vila Rozinho and MA (a) Moraes Almeida volcanic sequences from Lamarão
8 1605 et al. (2002); SF (b) Sobreiro Formation and SRF (b) Santa Rosa Formation from
9 1606 Fernandes et al. (2011).

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11 1608 Figure 15: geochronological U-Pb data from Tapajos zircons. Average ²⁰⁶Pb/²⁰⁷Pb age
12 1609 (errors are calculated as 2σ) of the three samples. Probability density plot of ²⁰⁶Pb/²⁰⁷Pb
13 1610 ages. Calculated concordia age for sample NP396 (lava flow) and NP183 (ignimbrite).

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15 1612 Figure 16: geochronological U-Pb data from Xingu zircons. Calculated concordia age
16 1613 for ignimbrite sample XU-08. Probability density plot of ²⁰⁶Pb/²⁰⁷Pb ages.

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18 1615 Figure 17: pelegographic reconstruction of the fissural and calderic volcanic activity
19 1616 during the Late-Paleoproterozoic in the southern part of the Amazonian craton. In the
20 1617 foreground is shown a section of a caldera and a post-caldera ignimbrite uplift that
21 1618 could facilitate the production of new sediments to be reworked and transported. The
22 1619 rising magma could form sporadic intra-caldera domes and volcanic centers as also
23 1620 shown in the background calderas. Reworked sediments can accumulate into volcano-
24 1621 tectonic depressions, which often collects intra-caldera lakes. In the background a
25 1622 fissure-fed volcanism is the responsible of the emission of lava flows and/or high-
26 1623 grade to rheomorphic ignimbrites. Fluvial deposits that occur throughout all
27 1624 successions represent periods of stream and river reworking. The area in punctuated by
28 1625 little scoria cones and maars that contribute to the amount of the fragmental products
29 1626 well represented in the study regions.

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34 1631 Tables

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2 1632
3 1633 Table 1: Summary of the main characteristics of volcanoclastic lithofacies of the
4
5 1634 primary and secondary felsic products analyzed and their interpretation.
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7 1635
8 1636 Table 2: Major and trace element bulk rock composition of Tapajos samples. Class
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10 1637 identify the lithological features of the rocks: VC: volcanoclastic; I: ignimbrite; R:
11 1638 rhyolite; Type identify the geochemical affinity according to the granite classification
12 1639 (Zr+Nb+Ce+Y (ppm) vs FeO_{tot}/MgO (wt.%) diagram, Fig. 14): I is for I-type granites
13 1640 and A is for A-type granites; b.d.l. is below detection limits; Mg# is calculated as Mg²⁺
14 1641 /(Fe²⁺_t + Mg²⁺); (*) major elements analyses already published in Roverato et. (2016).
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16 1641 ~~Table 2: Major and trace element bulk rock composition of Tapajos samples. VC:~~
17 1642 ~~volcanoclastic; I: ignimbrite; R: rhyolite; b.d.l. is below detection limits; Mg# is~~
18 1643 ~~calculated as Mg²⁺ / (Fe²⁺_t + Mg²⁺); (*) major elements analyses already published in~~
19 1644 ~~Roverato et. (2016).~~
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1 **The 2.0-1.88 Ga Paleoproterozoic evolution of the southern Amazonian Craton**
2 **(Brazil): an interpretation inferred by lithofaciological, geochemical and**
3 **geochronological data.**

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33 **Keywords:** Paleoproterozoic volcanism; Amazonian craton; Fissure eruption; Felsic
34 volcanism; Lithofacies analyses
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39 **Abstract**
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41 The study of Paleoproterozoic rocks is crucial for understanding Earth's
42 tectonic evolution during the time when most of the modern crust and ore deposits
43 were formed. The rocks of the Brazilian Amazonian Craton record some of the most-
44 complete and best-preserved Paleoproterozoic magmatic and volcanic episodes on
45 Earth. Following previous investigations, we present new lithofaciological and
46 stratigraphic records of the felsic rocks of the Tapajós Mineral Province (TMP) (~ 2-
47 1.88 Ga) and the São Felix do Xingú region (SFX) (~ 1.88 Ga) which, combined with
48 new petrological and geochronological data, help providing a more complete
49 understanding of the tectonic, magmatic and volcanological evolution of the
50 Amazonian Craton. This magmatism/volcanism is thought to be formed in a late-/post-
51 orogenic to extensional regime confirmed by the new geochemical data presented here.
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36 The transition from late-convergent to extensional tectonic setting could register the
37 beginning of the taphrogenesis that marked the Amazonian Craton throughout the
38 Mesoproterozoic. The volcanological approach of this contribution can serve as a
39 strategy for the modelling of the evolution of Precambrian volcano-sedimentary basins
40 around the world. The large amount of rocks analyzed are divided into primary and
41 secondary volcanoclastic products depending on if they resulted from a direct volcanic
42 activity (pyroclastic) or processes that reworked pyroclastic fragments. Furthermore,
43 the deposits are subdivided into massive and stratified, depending on their primary
44 mechanisms of transport and emplacement. By confirming the results from previous
45 studies, our study permits to depict a more precise paleo-environmental picture of the
46 processes that occurred in the Amazonian Craton during the Late-Paleoproterozoic. In
47 particular, the presence of large regional-scale fissural systems and caldera collapses
48 produced large silicic explosive volcanic eruptions, also accompanied by the emission
49 of large volume effusive products. Although studies on the Amazonian Craton are still
50 scarce and controversial, the present study provides new evidence that this volcanism
51 may have formed one of the largest Silicic Large Igneous Provinces (SLIP) on earth.
52 Our data also confirm that at least two major Paleoproterozoic periods of formation of
53 volcanic rocks exist in the Amazonian craton. This point is of great relevance for any
54 future interpretation of the geological evolution of this craton.

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56 1. Introduction

57 The Proterozoic Eon (2500 – 541 Ma) is the longest and youngest part of the
58 Precambrian Supereon. This Eon represents the time just before the proliferation of
59 oxygen accumulation and complex life on Earth. This period was likely the most
60 tectonically active in Earth's history. In fact, it is also the period during which the
61 largest portion of the modern crust (43%) and mineral ores were produced (Condie,
62 2000). Studies by Condie (2000) and Rino et al. (2004) suggest that crust production
63 took place episodically, forming predominantly granitoidal crust and secondary
64 volcanic and metamorphic rocks, some of which are extraordinarily well preserved.
65 The Amazonian Craton (AC) is one of the largest preserved Precambrian terrains in the
66 world ($4.6 \times 10^6 \text{ km}^2$) (Almeida et al., 1981). It occupies approximately half of the
67 Brazilian territory and it is the location of important mineral resources such as gold,
68 iron, copper, and tin, among others (e.g. Faraco et al., 1997; Bahia and Quadros, 2000;
69 Juliani, 2002; Klein et al., 2002, 2004; Reis et al., 2006; Klien and Carvalho, 2008;

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70 Monteiro et al., 2008; Juliani et al., 2014, Dall’Agnol et al., 2017). Although the
71 geological investigation of the AC has recently seen a renewed interest of the national
72 and international scientific community, mainly because of the massive presence of ore
73 deposits, a general consensus related to the interpretation of its complex
74 Paleoproterozoic evolution is still missing. Ancient volcanic regions represent a
75 challenge for the understanding of emplacement dynamics especially when the
76 stratigraphic relationships are difficult to decipher or blurred by erosion or vegetation
77 cover. The present work constitutes the natural prosecution of previous investigations,
78 carried out by our research group (Juliani et al., 2005, 2010, 2014; Fernandes et al.,
79 2011; da Cruz et al., 2015; Roverato, 2016; Roverato et al., 2016, 2017), which are
80 devoted to characterize the dynamics of emplacement of Precambrian volcanic rocks
81 and their relationships to sedimentary facies. The study area comprises of the Tapajós
82 Mineral Province (TMP) and the São Felix do Xingú (SFX) region, Pará state, northern
83 Brazil. This contribution provides a means to interpret the volcanic processes active in
84 this region during the Precambrian, mainly based on field observation and detailed
85 lithofacies analyses. In addition, new geochemical and geochronological data are
86 provided. Our study demonstrates how powerful is the approach of rock structure and
87 texture characterization to the interpretation of the eruptive processes that governed the
88 emplacement of volcanic and volcanoclastic sequences. The detailed lithofacies
89 characterization and the stratigraphic reconstruction are important in this area and
90 constitute a powerful key-tool to appropriately interpret the evolution of Precambrian
91 volcano-sedimentary basins. Such an approach would turn to be useful when employed
92 to investigate ancient terrains associated both to the ancient Amazonian felsic
93 volcanism and Precambrian terrains in general.

94 95 2. Geological evolution of the southern portion of the Amazonian craton

96 The AC (Almeida et al., 1981) is located in the northern part of South America
97 and is divided into two Precambrian shields, the Central-Brazil (or Guaporé, southern
98 portion) and Guiana Shields (northern portion), which are separated by the
99 Phanerozoic Amazonian Sedimentary Basin (Fig. 1) (Almeida et al., 1981). The entire
100 craton has become tectonically stable before the end of the Precambrian (Dall’Agnol et
101 al., 1994).

102 It has also been considered (Amaral, 1974; Hasui et al., 1993; Costa and Hasui,
103 1997) as a large Archean platform that had been reworked and reactivated during the

104 ca. 2100 Ma Trans-Amazonian event. Alternative proposals based on geochronological
105 and isotopic data (Teixeira et al., 1989; Tassinari and Macambira, 1999; Santos et al.,
106 2000) divided the craton into several, predominantly NW-oriented, geochronological
107 provinces, which have been interpreted as successive continental accretionary events,
108 followed by granitic magmatism and tectonic reworking (Santos, 2003; Vasquez et al.,
109 2008).

110 In a recent review Teixeira et al. (2019) report that the AC is the host of four
111 LIP-scale (or SLIP) magmatic events discriminated by the Orocaima, Uatumã,
112 Avanavero and Rincón del Tigre events. The igneous rocks described in the present
113 manuscript are widely attributed to the Uatumã event (Dall'Agnol et al., 1999;
114 Lamarão et al., 1999). The studied region is located between TMP and SFX, which is
115 considered to be related to a continental arc, with a NE-SW arc migration as suggested
116 by Juliani and Fernandes (2010), Fernandes et al. (2011) and Roverato et al. (2017).
117 According to these authors a migration from the Serra do Cachimbo graben (in TMP
118 where the subduction trench is located) towards the SFX could be explained by a
119 change in the subducting angle of the oceanic plate beneath the continental plate. This
120 is in agreement with the flat-subduction plate settings proposed by previous authors in
121 other parts of the world (Ferrari et al., 2012; Gutscher et al., 2000; Kay et al., 2005;
122 Mori et al., 2007; Manea et al., 2012).

124 2.1. The TMP (Tapajós Mineral Province)

125 The TMP (Fig. 2a) is primarily situated in the Tapajós–Parima
126 geochronological/tectonic province (Santos et al., 2000) with the eastern part
127 belonging to the Amazonia Central geochronological/tectonic province (Fig. 1). Based
128 on Sm–Nd data and U–Pb ages (2100–1870 Ma), Santos et al. (2001, 2004) and
129 Vasquez et al. (2008), identified several different domains for the Tapajós–Parima
130 geochronological province and consider the TMP as a sequence of continental
131 magmatic arcs (Ferreira et al., 2000; Santos et al., 2000, 2004; Vasquez et al., 2000;
132 Klein et al., 2001; Lamarão et al., 1999, 2002). Late Paleoproterozoic volcanism of the
133 Tapajós domain is represented by the Vila Riozinho Formation, formed by ca. 2000–
134 1990 Ma intermediate to acid volcanic rocks (Lamarão et al., 2002), and by the Iriri
135 Group that can be divided into the Bom Jardim (Almeida et al., 2000), Salustiano
136 (1870 ± 0.008 Ma; Juliani et al., 2005) and Aruri (Pessoa et al., 1977) formations.

137 The Bom Jardim Formation (1898 ± 5 Ma, Santos et al., 2001) consists of

138 mafic to intermediate high-K to shoshonitic calc-alkaline rocks while the latter
139 formations are characterized by rhyolites, dacites and their pyroclastic and epiclastic
140 derivatives. Juliani et al. (2005) considered the Bom Jardim volcanism as a preliminary
141 step of the Iriri event representing pre-caldera volcanism followed by the Salustiano
142 and Aruri caldera-related felsic activity. Post-caldera volcanism is characterized by
143 ring-felsic volcanic structures that produced A-type (Vasquez and Dreher, 2011)
144 rhyolitic lavas and volcanoclastic deposits. Lamarão et al. (2002, 2005) described the
145 felsic A-type Moraes Almeida volcanic sequence (1890 ± 6 Ma rhyolite, 1875 ± 4 Ma
146 ignimbrite) represented by lavas and ignimbrites as part of the Iriri Group. Juliani et al.
147 (2014) consider these last A-type rocks as similar in composition and age to the Santa
148 Rosa Formation that crops out in the São Felix do Xingú region (SFX), which is
149 considered to have formed by the same fissural-type volcanism (Juliani and Fernandes,
150 2010; Fernandes et al., 2011; Roverato et al., 2016). Preliminary data indicate that
151 these rocks, for both TMP and SFX, display a very low grade of metamorphism, falling
152 into the prehnite-pumpellyite field (Echeverri-Misas, 2010; Lagler et al., 2011;
153 Fernandes et al., 2011).

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155 2.2. The SFX (São Felix do Xingú region)

156 According to the work of Santos (2003) and Vasques et al. (2008) the SFX
157 region belongs to the Amazonia Central province (Fig. 1). The study area (Fig. 2b) is
158 located near to São Felix do Xingú city, which corresponds to the southern portion of
159 the Carajás Province. The Paleoproterozoic volcanic sequences in the SFX comprise
160 the basal Sobreiro and upper Santa Rosa formations (Macambira and Vale, 1997;
161 Juliani and Fernandes, 2010), which are crosscut by the Sn-bearing A-type granitoids of
162 the Velho Guilherme Suite (Teixeira et al., 2002). Antonio et al. (2017) published the
163 first U-Pb ages on zircons for the Santa Rosa Formation with 1877.4 ± 4.3 Ma for a
164 rhyolite and 1895 ± 11 Ma for a dike. Recent geochronological data on a felsic
165 porphyritic dike belonging to the Velho Guilherme suite yielded an age of 1857 ± 8.4
166 Ma (Shrimp U/Pb zircon analyses; Roverato, 2016). Other available geochronological
167 data yielded ca. 1880 ± 6 Ma (TIMS Pb–Pb in zircon) for the Sobreiro Formation and
168 ca. 1879 ± 2 Ma (TIMS Pb–Pb in zircon) for the Santa Rosa Formation (Fernandes et
169 al., 2011; Pinho et al., 2006; Teixeira et al., 2002). Despite their similar ages, their
170 geochemical compositions, geological features and eruption styles point to their non-
171 cogeneticity (Fernandes et al., 2011). The Sobreiro Formation (SF) comprises basaltic

172 andesite, andesite and less dacite massive lava flows and volcanoclastic rocks with
173 high-K calc-alkaline signature (Fernandes et al., 2011; Roverato et al., 2017).
174 According to da Cruz et al. (2015) late- to post-magmatic hydrothermal alteration in
175 these rocks is responsible for a secondary paragenesis characterized by epidote,
176 chlorite, carbonate, clinozoisite, sericite, quartz, albite, hematite and pyrite. The Santa
177 Rosa Formation (SRF) is described by Fernandes et al. (2011) as characterized by four
178 lithological facies with A-type signature: (i) rhyolitic lava flow and thick dikes of
179 banded rhyolite and ignimbrite; (ii) highly rheomorphic felsic ignimbrite associated
180 with un-welded ash tuff; (iii) felsic crystal tuff, lapilli-tuff and co-ignimbritic breccias;
181 (iv) granitic porphyry stocks and dikes and subordinate equigranular granitic
182 intrusions.

184 3. Lithofacies analyses

185 Lithofaciological analyses were carried out in the course of this study in order
186 to understand the geodynamic evolution of the study area. Here we report on the
187 lithofacies analysis of rocks recognized during our field campaigns (and after in
188 petrological thin section) at the TMP and SFX provinces. Within the study area (TMP
189 and SFX), massive to banded lava flows and rheomorphic ignimbrites (Fig. 3) as well
190 as felsic volcanoclastic rocks of various origin (Figs. 4-8, 11) are frequently found.
191 Reworked (secondary) volcanoclastic rocks (Fig. 9,10) and sedimentary alluvial/coastal
192 clastic deposits (epiclastic) are also widely distributed in both TMP and SFX areas.
193 Primary volcanoclastic rocks are here defined as those fragmental products formed
194 during a syn-eruptive explosion, which were deposited regardless of whether their
195 transport occurs through air, water, granular debris or a combination of them (McPhie
196 et al., 1993; White and Houghton, 2006, Manville et al., 2009; Roverato et al., 2017).
197 On the other hand, all the units deposited as a consequence of a reworking process of
198 pre-existing volcanic units are defined here as secondary volcanoclastic rocks. We also
199 introduce into this group all those epiclastic products that constitute sediments that had
200 been reworked before, independent of their source and composition. Table 1 shows a
201 description and interpretation of the volcanoclastic lithofacies, both primary and
202 secondary, for the deposits identified in the study areas.

204 4. Lava flows and rheo-ignimbrites

205 As already discussed by Roverato et al. (2016), the absence of unequivocal

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206 vitroclastic textures complicates the distinction between volcanoclastic and layered lava
207 flows in general and, more in particular, for the ancient volcanic rocks investigated
208 here. Lava flows found in the TMP and SFX provinces have both massive and banded
209 structures (Fig. 3) while still maintaining, in some cases, glassy (obsidian) and
210 aphanitic to porphyritic texture. Their composition varies from trachytic to rhyolitic with
211 various content of alkalis (see section 8). The phenocryst assemblage consists mainly
212 of plagioclase, quartz, Fe–Ti oxides and accessory-amount of zircon and apatite.
213 Plagioclase and bipiramidal quartz crystals (Fig. 3a), with a maximum size of 3-4 mm,
214 range from euhedral to anhedral, showing moderate to intense resorption. Plagioclase
215 shows sieve texture indicating non-equilibrium conditions likely determined by
216 magmatic transport. K-feldspar is also present as anhedral crystals in the groundmass
217 often associated with sericite as alteration phase. Samples are generally affected by
218 variable intensity of hydrothermal alteration. Plagioclase phenocrysts, in particular,
219 present diffuse potassic and minor propylitic alterations. Abundant spherulites and
220 lithophysae of variable size, from millimetric to decimetric, were recognized in almost
221 every sample and are thus common in these rocks (Fig. 3b, c). The spherulites
222 (radiating fibers of K-feldspar and cristobalite), ranging from few millimeters to 2 cm,
223 are typically associated with perlitic fractures. Their content can vary from 10 vol% to
224 70% in the investigated rocks. A large amount of the spherulites developed into
225 lithophysae commonly reaching 10-12 cm as a consequence of cooling and degassing
226 processes. In the obsidian-type lavas (Fig. 3c), the groundmass is characterized by a
227 micro-granophiric-like devitrification texture characterized by crystallization of
228 amorphous quartz and alkali feldspar, a process that occurred after the emplacement of
229 lava bodies. Several rocks show textures that are not easy to be associated to either
230 lava flows or flows of fragmented material which underwent rheomorphism (Fig. 3d-
231 g). Both banded lavas and rheo-ignimbrites display folds (Fig. 3d-g, see also Fig. 11e)
232 and sub-parallel bands on mm- to dm-scale, planar to wavy (Fig. 3e, see also Fig. 6 and
233 7) (parataxitic fabric), that deform and flattened around lithic fragments and crystals
234 which alignment suggests the flow direction. In thin sections, the bands are
235 characterized by extremely flattened vitroclastic textures with the former glass
236 completely replaced by a mixture of quartz and feldspar (Roverato et al., 2016).

238 5. Primary volcanoclastic rocks

239 We consider primary volcanoclastic rocks those dense, scoriaceous and

240 pumiceous products of fragmental character emplaced by explosive processes. With
241 pyroclastic we refer to fragmental material generated by any kind of explosive volcanic
242 activity and transported as ash-fall and pyroclastic density currents (Manville et al.,
243 2009), which deposition occurs by suspension settling, from traction, by en masse
244 freezing, or any combination of these (White and Houghton, 2006). Depending on the
245 mechanism of transport and the eruptive style these clastic rocks were distinguished
246 into two different categories, i.e. massive and stratified; and they can vary from well
247 sorted, poorly sorted or unsorted. The rocks are predominantly rhyolitic in composition
248 (Fernandes et al., 2011, Roverato et al., 2016) and there is no significant geochemical
249 difference from the lava flows. Nine main lithofacies (Lf) have been recognized for the
250 volcanoclastic rocks: six of them are massive and three are stratified.

251

252 5.1. Massive

253 Six massive lithofacies (mAL, mLA, mLB, *l-gwLA*, *m-gwLA* and *h-gwLA*)
254 were recognized during our field campaign, three of them belong to the welded
255 ignimbrites sub-group (Table 1). By using the granulometric classification proposed by
256 Fisher (1961), ash is defined as any fragment with size <2 mm, lapilli are fragments
257 with size between 2 to 64 mm and blocks (or bombs) have sizes > 64 mm. Massive
258 lithofacies includes all those deposits that display a massive coherent structure.
259 Outcrops of such kind of lithofacies are constituted by a high percentage of ash up to
260 block-rich textures. Most of the observed samples appear to have been affected by
261 devitrification processes of the juvenile pyroclastic fragments and matrix. The presence
262 of juvenile material linked with other observed textures such as broken crystals (Best
263 and Christiansen, 1997) and eutaxitic fabric allows us to confirm that the rocks
264 belonging to lithofacies mAL, mLA, *l-gwLA*, *m-gwLA* and *h-gwLA* are fragmental
265 and pyroclastic in origin. We discuss the meaning of Lf mLB below in section 5.1.2.

266

267 5.1.1. Lf mAL; mLA (massive Ash to Lapilli; massive Lapilli *and* Ash)

268 Description: the ash to lapilli (mAL) and lapilli *and* ash (mLA) deposits (Fig.
269 4a-e, Fig.6) are heterolithologic, matrix supported, containing angular to sub-rounded
270 medium to coarse devitrified lapilli (displaying axiolitic fabric), banded fragments,
271 occasional (or absent) lithics and angular-shaped broken crystals of plagioclase,
272 bipiramidal quartz and rare oxides (Fig. 5). In mLA, clasts < 25 cm in size are
273 randomly immersed in the groundmass (Fig 4d and 4e, 11d). Some of them are altered

274 by carbonate minerals. Groundmass of mAL and mLA is formed by K-feldspar and
275 quartz crystals, devitrified ash fragments and sericite crystals as phase of alteration
276 (Fig. 5).

277 Interpretation: the general massive aspect and the poor sorting of mAL and
278 mLA point to a laminar granular flow transport regime and the fine content suggests
279 the deposition from a dilute fluid escape-dominated flow-boundary zone in which
280 turbulent shear-induced tractional segregation is suppressed (Branney and Kokelaar,
281 2002; Sulpizio et al., 2007, Roverato et al., 2017). These lithofacies are interpreted as
282 ash flow deposits suggesting the deposition from a pyroclastic density current (PDC)
283 (Lenhardt et al., 2011; Sulpizio et al., 2014; Roverato et al., 2017). The coarser
284 lithofacies mLA (fig. 4e) could be related to proximal co-ignimbritic breccias as result
285 of deposition by denser pyroclastic granular flows (Branney and Kokelaar, 2002). The
286 angular aspect of the clasts indicates short-period transport.

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288 5.1.2. Lf mLB (massive Lapilli and Block)

289 Description: this lithofacies (fig. 4f, fig.7) represents monolithologic coarse-
290 grained rocks having high-clast content (clast:matrix ratios up to 3:1). Angular/sub-
291 angular coarse lapilli and blocks up to 50-60 cm of devitrified banded or massive lava
292 fragments are immersed in a devitrified fine lapilli and coarse ash matrix.

293 Interpretation: the blocky and monolithologic coarse-grained aspect of the
294 lithofacies mLB and its position underneath thick flow-deposits is attributed to the
295 basal auto-brecciation of lava flows and/or rheo-ignimbrite flows. Despite the
296 lithofacies is likely a consequence of an effusive volcanic activity (in the lava-flow
297 case) it is considered anyway as part of the volcanoclastic group due to its fragmental
298 character.

299

300 5.1.3. Lf *l-gwLA*; *m-gwLA*; *h-gwLA* (welded Ignimbrites)

301 Description: all massive deposits displaying welding characteristics have been
302 grouped in the “welded ignimbrites” group (Table 1), following the idea of “grade of
303 welding” (Walker, 1983) (i.e. the amount of welding and compaction exhibited by
304 deposits). The rocks are matrix-supported with sub-rounded to angular lapilli and ash
305 lithic clasts, euhedral, subhedral and broken crystals (plagioclase and less quartz) and
306 deformed devitrified juvenile fragments (*fiamme*). Slightly- (low-grade, *l-gwLA*),
307 medium- (medium-grade, *m-gwLA*), well-stretched (high-grade, *h-gwLA*) *fiamme*

308 (Fig. 6), as well as, devitrified shards define the eutaxitic fabric (Roverato et al., 2016).
309 These fragments varying from millimetric to 3–4 cm in size are immersed in a
310 homogeneous micro-granophiric-like devitrified groundmass (see Roverato et al., 2016
311 for details). Figure 6 shows a stratigraphic column representing a 35 m thick sequence
312 of ignimbrite deposits found in the TMP, displaying very low-grade to high-grade
313 welded fabric where the grade of welding increases toward the top of the succession.
314 The very top of the sequence is characterized by columnar jointing.

315 Interpretation: the massive aspect and the poor sorting of the lithofacies *l*-
316 *gw*LA, *m-gw*LA and *h-gw*LA point to a laminar granular flow transport regime,
317 interpreted to be deposited from a pyroclastic density current (PDC). The welded
318 character of these lithofacies is indicative of hot PDC emplacement and compaction
319 that result into the low- up to high-grade eutaxitic fabric. This process is favored by
320 loading-compaction, low-viscosity fragments, high temperature (i.e. > 900°C), cooling
321 of gas-permeable fragments (pumices) and dissolved water (Branney and Kokelaar,
322 2002; Roverato et al., 2016 and references therein).

323

324 5.2. Stratified

325 These lithofacies, although commonly associated with ignimbrites, are not very
326 spread in the studied areas. We also didn't find any alternation between massive and
327 stratified deposits even if this association is a common occurrence in PDC deposits
328 (Sulpizio et al., 2014; Roverato et al., 2017), alternating dilute (stratified deposits
329 resulting) and concentrated (massive deposits resulting) regimes during transport
330 (Sulpizio et al., 2014). Just one example has been found in TMP and is reported in the
331 stratigraphic reconstruction of fig.11.

332

333 5.2.1 Lf sA; xsA; dsAL (stratified Ash; cross-stratified Ash; diffusely stratified Ash to 334 lapilli)

335 Description: the stratified samples and outcrops analyzed comprise well sorted
336 very fine to fine ash organized in millimetric to sub-millimetric parallel (sA) or cross-
337 stratified (xsA) layers, with sharp or gradational changes in grain size (Fig. 8). The
338 fragments are represented by devitrified shards, crystals (plagioclase), and rare (or
339 absent) lithics (fig. 8d) immersed in a devitrified groundmass. Diffuse-stratified
340 lithofacies dsAL display a coarser character with coarse lithic and devitrified ash and
341 lapilli fragments forming well developed parallel continuous meter-long stratification

342 (or very-low angle cross-stratification) at centimeter scale (fig. 11b), with gradational
343 changes in grain-size. The sorting varies from well to moderate.

344 Interpretation: the fine parallel layering of shards material displayed by
345 lithofacies sA is interpreted here as being deposited under the product of sedimentation
346 by the upper and highly dilute ash-cloud that accompany a pyroclastic-density current.
347 We don't exclude the direct sedimentation from tephra fall-out activity. Cross-stratified
348 (Lf xsA) and diffuse-stratified (Lf dsAL) deposits indicate tractive processes usually
349 attribute to pyroclastic surge-type depositional condition from dilute currents (Cas and
350 Wright 1987; Lenhardt et al., 2011; Roverato et al., 2017). We interpreted these as
351 pyroclastic surge deposits although Lf dsAL could also be the product of coarse ash
352 fall-out processes. Pyroclastic surge deposits usually display small volume and rarely
353 reach more than 10 km from their source (Lenhardt et al., 2011). Conversely, fall-out
354 deposits could emplace tens of kilometers from their source.

355

356 6. Secondary volcanoclastic/epiclastic rocks

357 The nomenclature of Fisher et al. (1961) is applied also for the secondary
358 volcanoclastic rocks as follow: silt ($2 <> 64 \mu\text{m}$), sand ($64 \mu\text{m} <> 2 \text{ mm}$), gravel ($2 <> 64$
359 mm), cobble ($64 <> 256 \text{ mm}$). These rocks are considered as the product of reworking
360 and erosive processes. The clasts belonging to this group show a wide range of
361 composition, size and shape variations. Based on their component, texture and fabric,
362 we recognized five massive, both matrix- and clast-supported, and four stratified
363 lithofacies (fig. 9).

364

365 6.1. Massive

366 6.1.1. Lf mS (massive Sand)

367 Description: this lithofacies consists of reddish moderately to well-sorted,
368 massive, fine- to medium grained sand forming parallel strata intercalated to clast-
369 supported conglomerate deposits (Lf csG) (fig. 9a). The sandstone strata extend tens of
370 meters and present thinness between 0.4-0.8 m. Lf mS is predominantly composed of
371 quartz, feldspar and minor rock fragments. Contacts between mS and csG are sharp
372 with rare slightly erosional surfaces. The tops of the sandstone are characterized by the
373 presence of centimeters ripples (fig. 9b).

374 Interpretation: the massive sand (mS) and the small ripples found at the top of
375 the strata indicate low energy under tractional currents in shallow water conditions

376 (Collison and Thompson, 1982; Lenhardt et al., 2011). The alternation of Lf csG and
377 mS indicates changes in energy conditions of sedimentation. We interpret these
378 oscillations as belonging to a subaqueous-subaerial fan-delta interface setting where
379 continental supply of material alternates to under-water sand accumulation (Lf mS).

380

381 6.1.2. Lf csG (clast supported Gravel)

382 Description: this lithofacies (Fig. 9a, c, d) is massive, clast to matrix supported,
383 with heterolithologic felsic rounded high-spherical coarse gravel with a sandy inter-
384 clast matrix. Clasts are mainly characterized by massive and banded medium- to
385 coarse-size felsic lava fragments (and rare quartz; size does not exceed 5 cm) and
386 present rounded with low- to high-sphericity. We found lithofacies csG also associated
387 to xsSG (see below section 6.2.2.) (Fig. 9c, 10b).

388 Interpretation: lithofacies csG is dominated by water flow processes where
389 matrix plays a secondary role. The clast-supported character and less matrix content
390 indicates that water removed the finer particles during transport and deposition. Lf csG
391 display rounded clasts and well-sorting indicative of good selection during transport
392 and emplacement. The rounded character of csG and the presence of matrix in the
393 deposits suggest a laminar debris-flow regime in medial reaches of stream-dominated
394 fluvial/alluvial fans (Mueller and Corcoran, 1998).

395

396 6.1.3. Lf csGS (clast supported Gravel to Sand)

397 Description: Lf csGS (Fig. 9e, 11c) is massive, moderately well-sorted and
398 clast-supported. Clasts (gravel to sand) present sub-rounded to sub-angular with
399 low/medium sphericity with maximum size of 2-3 cm. The rocks belonging to this
400 lithofacies are mainly formed by massive felsic lava fragments with different color and
401 crystallinity.

402 Interpretation: Lf csGS is dominated by water flow processes where matrix
403 plays a secondary role. The clast-supported character and less matrix content indicates
404 that water removed the finer particles during transport and deposition. This lithofacies
405 represents deposition within a debris-flow dominated fluvial/alluvial environment.
406 Poor sorting, clast-supported and sub-angular clasts point to deposition by localized
407 laminar hyperconcentrated-flows in volcanic fans fringing flanks of volcanic edifices.
408 Single cross-beds are usually ca. 1 cm thick

409

410 6.1.4. Lf csGC (clast supported Gravel and Cobble)

411 Description: Lithofacies csGC (Fig. 9f) is massive, low-sorted and clast-
412 supported. The clast population is characterized by sub-rounded, low/medium
413 sphericity, massive felsic porphyritic fragments with maximum size up to 20 cm. This
414 lithofacies has an interstitial matrix characterized by medium to coarse sand.

415 Interpretation: Lf csGC is dominated by water flow processes where matrix
416 plays a secondary role. The clast-supported character and less matrix content indicates
417 that water removed the finer particles during transport and deposition. This lithofacies
418 represents deposition within a debris-flow dominated alluvial environment. Poor
419 sorting, clast-supported and sub-angular clasts likely points to deposition by localized
420 non-cohesive debris-flows.

421

422 6.2. Stratified

423 6.2.1 Lf xsS (cross-stratified Sand)

424 Description: lithofacies cross-stratified Sand (Fig. 10a) consist of white to
425 brownish low-angle cross-stratified coarse quartzitic sandstone. The sandstones are
426 characterized by lobe to sheet-shaped bodies. Major bedsets are recognized ranging in
427 thickness from 0.5 to 1.5 m, composed of fine-grained sandstone dominated by
428 medium-angle cross strata (18-20°). Single cross-beds are usually 0.7-1cm thick. The
429 outcrops displaying this lithofacies extend tens of meters with sharp upper and lower
430 contact.

431 Interpretation: the cross-stratification of xsS is interpreted as formed in fluvial
432 channels attesting the deposition from crested dune bed-forms that formed under
433 condition of lower flow regime (Collinson, 1996; Miall, 1996; Capuzzo and Wetzel,
434 2004; Went, 2016). The deposition of medium-angle cross-bedding within large-scale
435 examples of beds indicates that these larger beds are likely a product of bar migration.
436 The beds are interpreted as channel-fill deposits (Lenhardt et al., 2017) related to a
437 fluvial environment likely associated to meandering or braided rivers. Shoreline
438 deposition developed around margins of immature marine basins is also considered.

439

440 6.2.2. Lf xsSG (cross-stratified Sand and Gravel)

441 Description: Lf xsSG (Fig. 10b) is characterized by crystal-lithic fine to coarse
442 sand and fine gravel (max 5-6 mm in size) organized in cross-bedded stratification.
443 Clasts display medium roundness and sphericity and are mostly composed by felsic

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444 fragments. Stratification is defined by alternating of well to poorly sorted, fine to
445 coarse millimeters-thick strata. The finer black layers are formed by sub-millimetric
446 hematite sand.

447 Interpretation: Lf xsSG correspond to cross-stratified water reworked deposits.
448 The cross-stratified thicker fine gravelly strata, alternated with sandy layers laterally
449 discontinuous, were interpreted as different pulses as the result of rapid deposition
450 from hyperconcentrated flows (Zanchetta et al., 2004) in a stream-dominated
451 fluvial/alluvial setting. Alternation with csG (Fig. 9c) represents difference of energy
452 condition.

453 454 6.2.3. Lf dsSt (diffusely layered Silt)

455 Description: this lithofacies consists of parallel, lenticular, truncated, and
456 locally low-angle cross-stratified multicolor millimetric well-sorted fine- to very fine-
457 grained sand and silt strata (Fig. 10c). Within the sandy bedset, a thinning- and fining-
458 upward trend may be distinguished. Small and straight groove marks have been
459 detected and reduced tiny slump folding is also presence in some parts.

460 Interpretation: lithofacies dsSt displays diffuse fine stratification with tiny
461 ripples, suggesting transport and sedimentation in shallow water. The thin sheet-shaped
462 is interpreted as flood sediments (Lenhardt et al., 2011). These deposits are interpreted
463 to have been formed in low energy lacustrine environment or ponds (Collinson, 1996;
464 Roverato et al., 2017) characterized by small turbidities successions affected by
465 scouring and tiny deformations (slumps) of the sediments.

466 467 6.2.4. Lf bChS (bedded Chert and Sand)

468 Description: the bedded chert lithofacies (with sand) (bChS) (Fig. 10d) crops
469 out in both regions and it is characterized by outcrops that can be traced on strike for
470 hundreds of meters. The facies consist of thin laminated pinkish chert (layers < 1mm in
471 thickness) with darker laminae intercalated, formed predominantly by hematite
472 (Lenhardt et al., 2017). The layers are composed by microcrystalline quartz. In some
473 portions, these lithofacies are associated with fine to medium sand composed mainly
474 by quartz and less volcanic fragments.

475 Interpretation: this lithofacies is interpreted as inorganic precipitation of silica
476 in a closed lake basin mainly due to its association with volcanic rocks and fine
477 sandstone (Blatt et al., 1980; Eriksson et al., 1994). The picture in figure 10d shows

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478 elongated ripped-up millimetric fragments of chert immersed in the sandstone eroded
479 by low-energy stream flow or local lacustrine turbidites. As suggests by Lenhardt et al.
480 (2017) the chert may have formed during repeated pulses of hydrothermal fluids that
481 circulated into the lake water during hiatuses in the volcanism (Van Kranendonk,
482 2006).

483 484 7. Analytical methods for geochemistry and geochronology

485 A total of 19 new samples (9 volcanoclastics and 10 lava flows) from the
486 Tapajós region (associated with the data published in Roverato et al., 2016; Table 2)
487 were analysed for bulk rock major and trace elements. Major element bulk rock
488 analyses were performed by X-ray fluorescence, using a wavelength dispersive Philips
489 PW 2400 spectrometry, using fused glass disks according to procedures described by
490 Mori et al. (1999). Accuracy was greater than 2%. Trace element analyses in selected
491 samples were performed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)
492 using the procedure described by Navarro et al. (2008). Accuracy, determined with
493 respect to the reference standards BHVO-2 and BR, was 0.5–2%.

494 Zircon grains were examined with a FEI-QUANTA 250 scanning electron
495 microscope equipped with secondary-electron and cathodoluminescence (CL) detectors
496 at the Instituto de Geociências - Centro de Pesquisas Geocronológicas - Universidade
497 de São Paulo (IGc-CPGeo-USP); the most common conditions used in CL analysis
498 were 60 μ A of emission current, 15.0 kV of accelerating voltage, 7 μ m of beam
499 diameter, 200 μ s of acquisition time, and a resolution of 2048x1887 pixels and 345 dpi.
500 Selected samples were analyzed for U-Pb isotopes using a SHRIMP-IIe also at IGc-
501 CPGeo-USP, following the analytical procedures of Williams (1998) as reported by
502 Giovanardi et al. (2015). Correction for common Pb is based on the measured ^{204}Pb ,
503 and the typical error for the $^{206}\text{Pb}/^{238}\text{U}$ ratio is less than 2%; U abundance and U-Pb
504 ratios were calibrated against the TEMORA-II standard. The dataset consists of 56 new
505 U-Pb SHRIMP-II analyses and is reported in Table 3. Thirty-five analyses were
506 performed on zircon grains from the Tapajós region as follow: 11 analyses on sample
507 NP380-C, 11 analyses on sample NP183 and 13 analyses on sample NP396-B. Eleven
508 analyses were performed on zircon grains from Xingú sample XU08. For all samples,
509 $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ concordia ages (with 95% of confidence level and 2σ error)
510 are calculated using Isoplot 4.1 software (Ludwig, 2009).

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513 8. Geochemistry of the TMP samples

514 Independently of their nature (lavas or volcanoclastic), the rocks of the TMP
515 follow a typical calc-alkaline trend (Fig. 12). They are mostly rhyolitic in composition
516 (Table 2), with four exceptions which fall in the trachytic field. In addition, their low
517 LOI values (0.32-3.51%) and the low FeO content (0.78 – 3.26%) together with the
518 negative correlation FeO vs SiO₂ appears to indicate that the investigated volcanic
519 rocks neither underwent significant alteration processes nor they belong to sedimentary
520 suites which commonly contain water rich clay minerals. TMP volcanoclastic and lava
521 flows show similar negative correlation between TiO₂, Al₂O₃, MgO, FeO, CaO, Na₂O
522 and P₂O₅ with SiO₂. A negative correlation between K₂O and SiO₂ also exists for the
523 volcanoclastic, but not for the lava flows. The similar trends observed suggest that both
524 these kind of rocks are originated by similar magmatic sources. Such a conclusion is
525 supported by similar variation paths, although with different values, of minor and trace
526 elements (Fig. 13). In particular, TMP lava flows show LREE enrichment
527 ((La/Yb)_N=10.68-21.45; normalization to Chondrite I from Anders & Ebihara, 1982)
528 and a negative Eu anomaly which increases from trachytes ((Eu/Eu*)_N=0.89-0.78) to
529 rhyolites ((Eu/Eu*)_N=0.69-0.31) (Fig. 13). The Eu negative anomaly, shown from all
530 the samples, is expression of feldspar fractionation. On the other hand, volcanoclastics
531 rocks show similar LREE enrichment ((La/Yb)_N=11.12-28.10) and negative Eu
532 anomaly ((Eu/Eu*)_N=0.97-0.37) (Fig. 13). In addition, volcanoclastics have higher
533 LREE abundances with respect to lavas (La between 35.5-91.3 ppm and between 40.5-
534 71.9 ppm, respectively) while they have similar MREE and HREE contents (Yb
535 between 1.56-3.43 ppm and between 1.83-4.11 ppm, respectively). Volcanoclastics
536 commonly show higher Rb (121-272.9 ppm) and Pb (4.5-137.1 ppm) with respect to
537 lavas (Rb=96.1-232 ppm and Pb=2.7-45.8 ppm). Volcanoclastics are enriched in LILE,
538 Th and U with respect to MORB (Fig. 13; normalization to MORB from Hoffman,
539 1988), with the exception of Sr, which commonly show a pronounced negative
540 anomaly ((Sr/Sr*)_N=0.55-0.05). The Sr negative anomaly is consistent with feldspar
541 fractionation. Negative anomalies are also present for Nb and Ta, while Ba and Pb are
542 commonly enriched (Fig. 13). Lavas show a similar trace pattern, but higher values
543 dispersion (Fig. 13). The Ba enrichment is less pronounced with respect to
544 volcanoclastics (Ba between 75-1965 ppm and 310-2245 ppm, respectively) and the
545 Nb/Ta ratio show higher dispersion (3.29-14.63 and 6.73-13.9, respectively), indicating

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546 more limited fractionation of feldspar. Geochemical affinity of Tapajós volcanics
547 and lava flows suggests that the magmatism occurred in active continental setting (Fig.
548 14). Using the tectonic discriminant diagrams of $Zr+Nb+Ce+Y$ (ppm) vs FeO_{tot}/MgO
549 (wt.%), Yb vs Ta and $Th-Ta-Hf/3$ (Wahlen et al., 1987; Pearce et al., 1984; Wood,
550 1980), the magmatism in the Tapajós region appears related to a syn- to post-
551 collisional setting with few samples falling into the intraplate field (Fig. 14).
552 According to the refined diagram $Nb+Y$ vs Rb of Pearce (1996), all the Tapajós
553 volcanics, together with the majority of volcanic rocks from the Sobreiro formation
554 (Fernandes et al., 2011) are consistent with a late- to post-collisional setting (Fig. 14).
555

556 9. U-Pb zircon Geochronology

557 Zircon from Tapajós samples are colorless, sometimes fractured and euhedral
558 to sub-euhedral. They can contain inclusions of apatite or spinel and display commonly
559 low emission in Cathodoluminescence (CL). All crystals show magmatic oscillatory
560 zoning and commonly a dark core which, in most cases, appears to be homogenous.
561 Nonetheless, in few cases an inner core with discordant and partially reabsorbed
562 domains is recognized. Some of the zircons also show a bright CL rim with
563 transgressive or sub-concordant contacts with the inner oscillatory zoning. Zircons
564 from sample XU08 from the Xingu region are colourless, rarely fractured and sub-
565 euhedral. Inclusions of apatite or spinel are also observed sometimes. Crystals are
566 medium in CL emissions and commonly show a homogeneous core and a concordant
567 magmatic oscillatory zoning. Few zircons show a core with discordant zoning. No
568 transgressive bright CL rims were recognized. Analyses were carried out on zircons
569 that do not show transgressive or resorption features and discordant inner cores.
570 Zircons from sample NP183 (Ignimbrite) provide 4 discordant and 7 concordant
571 analyses that provide an upper intercept at 1984 ± 8.5 Ma (95% confident decay-const.
572 errs included, MSWD 1.09) and a concordia age at 1986 ± 8.2 Ma (2σ , decay-const.
573 errs included, MSWD 1.08, Probability of concordance = 0.30; Fig. 15). Single spot
574 $^{206}Pb/^{207}Pb$ ages range between 2010 ± 17 Ma and 1909 ± 53 Ma with an average age of
575 1985 ± 11 Ma (95% confident decay-const. errs included, MSWD 1.6, Probability of
576 concordance = 0.15; Fig. 15). Zircons from sample NP380 (Ignimbrite) show slightly
577 older single spot $^{206}Pb/^{207}Pb$ ages between 2023 ± 31 Ma and 1981 ± 24 Ma with an
578 average age of 1998 ± 5.9 Ma (95% confident decay-const. errs included, MSWD 0.74,

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579 Probability of concordance = 0.68; Fig. 15). Analyses are slightly discordant (up to
580 4%) providing an upper intercept at 1998 ± 7.7 Ma (95% confident decay-const. errs
581 included, MSWD 0.74). Zircons from sample NP396 (Banded lava) provide 5
582 discordant ages and 8 concordant analyses, which provide an upper intercept at 1994
583 ± 8.2 Ma (95% confident decay-const. errs included, MSWD 1.40) and a concordia age
584 at 1997 ± 7.0 Ma (2σ , decay-const. errs included, MSWD 5.70, Probability of
585 concordance = 0.02; Fig. 15). Single spot $^{206}\text{Pb}/^{207}\text{Pb}$ ages range between 2014 ± 14 Ma
586 and 1973 ± 8 Ma with an average age of 1994 ± 8.7 Ma (95% confident decay-const.
587 errs included, MSWD 1.6, Probability of concordance = 0.12; Fig. 15). Pooling
588 together the analyses of the Tapajós samples provides an average age of 1991 ± 12 Ma
589 (2σ , MSWD 1.50, Probability of concordance = 0.06). Zircons from sample XU08
590 (Lava flow) provide a concordia age at 1882 ± 6.4 Ma (2σ , decay-const. errs included,
591 MSWD 2.70, Probability of concordance = 0.10; Fig. 16). Single spot $^{206}\text{Pb}/^{207}\text{Pb}$ ages
592 range between 1899 ± 10 Ma and 1875 ± 13 Ma, with an average at 1884 ± 5.2 Ma (95%
593 confident decay-const. errs included, MSWD 0.60, Probability of concordance = 0.82).

594 595 10. Discussion

596 10.1. Subduction-related to extensional setting

597 The geochemistry of the TMP samples presented in this work display a high-K
598 calc-alkaline signature (Fig. 12); they mainly fall into the A-type intra-plate granite
599 field and tectonic discriminant diagrams suggest a late- to post-collisional setting for
600 the TMP volcanism (Fig. 14). This interpretation is also supported by enrichment in
601 LILE, Th, U and LREE of our samples, which suggest a strong crustal component in
602 the parent melt consistent with a subduction/post orogenic geodynamic setting (Figs.
603 12, 13, 14), and the high HSFE which shifted the TMP volcanics composition in the A-
604 type granites showing however FeO/MgO which are low and comparable with I- and
605 S-types granites (Fig. 14). Similar features are reported in previous works (Lamarão et
606 al., 1999; Lamarão et al., 2002) for volcanics in the Tapajós region, which are grouped
607 into the Vila Riozinho (VR) and Maraes Aldeida (MA) formations, respectively. The
608 VR rocks are intermediate to felsic in composition (Lamarão et al., 2002) with a calc-
609 alkaline signature, while the rhyolites and ignimbrites of MA are slightly enriched in
610 silica compared to the rhyolites of VR and are geochemically similar to evolved A-type
611 granites (Lamarão et al., 2002). Our results show similarities with these data,

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612 suggesting that our specimens could be part of the VR and/or MA formations. The
613 identification of two volcanic series has important implications for the understanding
614 of the magmatic evolution of the Amazonian craton in late Paleoproterozoic. A model
615 for the evolution of the TMP involves a first stage of subduction-related magmatism
616 followed by an intracontinental magmatism related to a distensional event (Lamarão et
617 al., 2002). Geochronological analyses by Lamarão et al. (2002) yielded ages of ca. 2
618 Ga for the VR and ca. 1.88-1.87 Ga for the MA volcanisms. The three new U-Pb
619 geochronological analyses reported in this study yielded ages of ca. 2000 Ma (fig. 15)
620 are concordant with the ages presented by Lamarão et al. (2002) for the VR
621 magmatism, thus suggesting that the TMP rocks could be part of the VR volcanic
622 sequence. However, TMP rocks are geochemically more evolved with respect to VR in
623 terms of SiO₂ (63.8-76.6 wt.% and 54.4-71.8 wt.%, respectively), K₂O (2.3-7.1 wt.%
624 and 2.1-5.8 wt.%, respectively) and REE abundances and are more similar to MA
625 rocks (Figs. 11, 12 and 13). In particular, REE patterns of the TMP samples are
626 comparable with the rocks of the MA formation (Fig. 12) while they are more enriched
627 in REE with respect to VR rocks. Conversely, TMP rocks are enriched in Ba (Fig. 12),
628 while MA are depleted, and have compositions for Rb/Zr ratio and Nb, considered as a
629 proxy for arc maturity (Brown et al., 1984), similar to VR and different from MA
630 (Rb/Zr between 0.3-1.1 in TMP, 0.2-0.7 in VR and 0.2-1.7 in MA; Lamarão et al.,
631 2002). Thus, according to geochronological and petrological data, we proposed that the
632 TMP rocks in this study must be ascribed to the VR formation. Geochemical
633 differences in our rocks and VR volcanics could be explained by a more evolved
634 character of the TMP rocks. The evidences of plagioclase fractionation from the parent
635 melts of the TMP (negative Eu and Sr anomalies, Fig. 12) and their absence in less
636 evolved VR rocks reinforce this interpretation, and suggest fractional crystallization as
637 the prominent process controlling the VR magmatism evolution. However, we want to
638 point out that due to the large area covered by the presented investigation (Fig. 2),
639 together with the VR area, the geochemical variations between our rocks (TMP) and
640 VR could be the result of local/regional heterogeneities in the magmatism. This
641 hypothesis is supported by the intermediate characteristics of the TMP samples with
642 respect to the VR and MA volcanoclastic material (Figs 11, 12 and 13).

643 Recently, new authors (Juliani et al., 2014) suggest the geochemical and
644 geochronological signature of the MA formation could be correlated to the felsic Santa
645 Rosa formation (SRF) cropping out in the SFX region. Our new U-Pb geochronological

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646 analyses on one rock sample from the SRF yielded an average age of 1884 ± 5.2 Ma
647 (Fig. 16) that is consistent with previous Pb-Pb ages on other locations. Juliani and
648 Fernandes (2010) published two Pb-Pb ages on zircons of 1879 ± 2 Ma and 1884 ± 1.7
649 for a rhyolite and an ash tuff, respectively. Recently Antonio et al. (2017) publishes the
650 first U-Pb ages on zircons for the Santa Rosa Formation with 1877.4 ± 4.3 Ma for a
651 rhyolite and 1895 ± 11 Ma for a dike. All geochronological results support a ca. 1880
652 Ma age for the emplacement of these rocks.

653 The southern Amazonian craton, as well as other Precambrian terrains
654 worldwide (Condie, 2002; Hoffman, 1988; Zhao et al., 2002), are considered to be
655 characterized by a series of orogenic to post-orogenic events from 2.0 up to 1.88 Ga.
656 The amalgamation of cratonic blocks worldwide established connections between
657 South America and West Africa and other cratonic terrains such as Western Australia
658 and South Africa, Laurentia and Baltica, Siberia and Laurentia, Laurentia and Central
659 Australia, etc (Zhao et al., 2002). These late-Paleoproterozoic collisional processes
660 likely formed the controversial supercontinent Columbia (Zhao et al., 2004). This
661 period also coincides with a major peak in orogenic gold resources (Goldfarb et al.,
662 2001; Juliani et al., 2014) and understanding the geodynamic of this period is crucial
663 for economic interests. Antonio et al. (2017) highlight that for the period 1.88 Ga,
664 many cratonic terrains have been characterized by extensive magmatism. These
665 authors report as examples the 1880 Ma NE-trending Ghost dike swarm and the 1880
666 Ma Circum-Superior LIP in the Canadian shield (Minifie et al., 2013), the 1880 Ma
667 Southern Bastar- Cuddapah LIP in India (French et al., 2008), the Mashonaland sills
668 and the Post-Waterberg dolerites in Kalahari craton (Hanson et al., 2004), an extensive
669 A-type magmatism in Baltica and in Siberia. The A-type affinity of the 1.88 Ga rocks
670 is widely described by other authors in different regions into the Amazonian craton
671 (Ferron et al., 2010; Pierosan et al., 2011; Fernandes et al., 2011; Klein et al., 2012;
672 Barreto et al., 2014; Teixeira et al., 2018). Currently, the significance of the 1.88 Ga A-
673 type magmatism in the AC is still matter of debate, also due to the extremely large
674 aerial cover which interested several different domains with different basements and
675 geologic evolutions. For example, studies on the Carajas region suggest that the 1.88
676 Ga anorogenic magmatism in this domain was provoked by delamination and fusion of
677 the Archean basement by a mantle plume which originated an extensional setting
678 (Dell'Agnol et al., 2005; Silva et al., 2016; Teixeira et al., 2018; Teixeira et al., 2019).

679 Conversely, the geochemical features of the TMP and SFX magmatism

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680 presented in this work and in literature (Lamarão et al., 2002, 2005; Fernandes et al.,
681 2011) mainly support an extensional regime of these regions related to a late- to post-
682 collisional event, being possibly related to the end of the subduction process. The
683 transition from convergent (late-/post-orogenic) to extensional tectonic setting could
684 register the beginning of the taphrogenesis that marked the Amazonian Craton
685 throughout the Mesoproterozoic (Brito Neves, 1999; Lamarão et al., 2002). The ca.
686 1.88 Ga felsic magmatism in different provinces of the Amazonian craton could
687 represent the oldest magmatism related to this event.

688 It should be mentioned that in term of textural features, the products emitted
689 during the transition between the late-/post-collisional to extensive events don't display
690 substantial variations. In other words, the lithofaciological signature of the volcanic
691 and volcanoclastic rocks that characterized the 2 Ga VR event (subduction related) is
692 similar for those products erupted during the 1.88-1.87 Ga extensional volcanism that
693 characterized the MA and SRF events. Moreover, the post-orogenic to extensional
694 setting emphasizes the continental setting where the studied volcanic products have
695 been emitted. Following the idea of Roverato et al. (2017) for the Late-
696 Paleoproterozoic andesitic Sobreiro Formation, we stress the lack of any evidences in
697 favour of subaqueous eruptions for the emitted felsic products such as pillow lavas as
698 well as hyaloclastites. This suggests the subaerial character of the volcanism and its
699 emitted products acted in both regions.

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701 10.2. Eruptive style and emplacement

702 The study areas are widely characterized by volcanic deposits whose eruptive
703 style is hard to differentiate. Distinguishing between banded lavas and high grade
704 ignimbrites is, sometime, extremely challenging (Henry and Wolff, 1992; Manley,
705 1995). This is made even more complicated when the investigated deposits are ancient
706 and the outcrops intensely eroded, such as those Precambrian terrains investigated here
707 (Lenhardt et al., 2012; Roverato et al., 2016; Lenhardt et al., 2017). Evidences in the
708 field show that a great volume of the volcanic activity is represented by the emission of
709 lava flows and/or high-grade to rheomorphic ignimbrites, although an important
710 amount of other fragmental products of different type (Lf mAL, mL, l-g/m-g/h-
711 gwAL) are also well represented in both regions. High-grade welded and rheomorphic
712 (up to lava-like) ignimbrites share similar features with lavas, displaying banding and

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713 ductile folds formed by the elongation of fiamme and vesicles (Schmincke and
714 Swanson, 1967; Chapin and Lowell, 1979; Wolff and Wright, 1981; Branney et al.,
715 1992; Sumner and Branney, 2002; Pioli and Rosi, 2005; Andrews and Branney, 2011;
716 Brown and Bell, 2013). Although the ignimbrites investigated here have a fragmental
717 derivation their origin largely differ from those characteristic of fallout deposits that
718 form by a sustained column explosive-driven eruption. High-grade welded and
719 rheomorphic ignimbrites are correlated with highly explosive plinian-type eruptions
720 which produce, during their column collapse stage, large PDC. In addition, high-grade
721 rheomorphism of silicic products, either deriving from an explosive or effusive
722 eruption, are favored by high temperature low-viscosity emplacement conditions and
723 the presence of some residual water. The high temperatures condition of our deposits is
724 also confirmed by the pervasive presence of spherulites and lithophysae formed during
725 the slow-cooling regimes of large silica-rich lavas and welded ignimbrites (Lofgren,
726 1971; Breikreuz, 2013). The eruptive scenario showed in figure 17 giving origin to the
727 frequent eruption of large volume and high discharge rate lava flows and ignimbrites
728 was likely characterized by fissure-fed and caldera collapses systems as those
729 described by previous authors (Legros et al., 2000; Aguirre et al., 2003; Cas et al.,
730 2011; Lesti et al., 2011; Lenhardt et al., 2012; Willcock et al., 2013). Eruptions fed by
731 extensive fissures of large size, in fact, appear to be the most favourable volcanic
732 systems to minimize cooling during emplacement and produce an alternance of low-
733 height sustained column eruptions feeding PDC and eruptions characterized by the
734 effusion of low viscosity lava flows, coulees and domes, while maintaining high
735 discharge rates (e.g. Bachmann et al., 2000; Aguirrez-Diaz & Labarthe-Hernandez,
736 2003; Polo et al., 2018a, b; Simões et al., 2017). The sustained fountaining and
737 entrainment of air in the eruptive jet is strongly influenced by the geometry of the
738 conduit (Legros et a., 2000) as well as the transition from sustained to collapsing
739 eruptive column. A wide-geometry conduit would impede much air entrainment into
740 the pyroclastic fountain and, at the same time, would favors magmatic escape of
741 volcanic gases, favoring the low fountaining and promoting a “boil-over” style
742 eruption (Branney and Kokelaar, 1992, 2002; Lenhardt et al., 2017) with high
743 discharge rate. Moreover, the low air injection would inhibit the dilution of the
744 eruptive material making it thermodynamically isolated from the surrounding
745 environment (Lesti et al., 2011), preserving the high temperatures and enhancing the
746 agglutination of fragments (welding) (Quane and Russell, 2004; Russell and Quane

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747 2005; Giordano et al., 2005). When the low-altitude pyroclastic fountaining or the
748 emission of high temperature lavas would be maintained for long time the high flow-
749 mobility is ensured (Sulpizio et al., 2014). If the material supply from the vent
750 continues for long time and with high discharge rate, the mobility could be maintained
751 even on very low slope angles (Sulpizio et al., 2014; Giordano et al., 2017; Kolzenburg
752 et al., 2017), and flowing various kilometers up to hundreds of kilometers far from the
753 vent (Aguirre-Diaz et al., 2008; Cas et al., 2011; Giordano et al., 2017). This could
754 explain the presence of large silicic volcanic areas characteristic of the ancient
755 Amazonian volcanism (Roverato et al., 2016). Although, volcanoclastic rocks seem to
756 be volumetrically less important in the study areas than the lava flows and/or
757 rheomorphic ignimbrites the recognition of fragmental rocks during our field
758 campaigns is important to understand their significance into our paleogeographic
759 reconstruction (Fig. 17). An idealized deposit sequence of a caldera forming eruption
760 displays an air-fall deposit overlain by an ignimbrite (Druitt and Sparks, 1984) and the
761 transition from the sustained column phase to the pyroclastic flow phase is often
762 accompanied by a strong increase in the discharge rate (Bursik and Woods, 1996). The
763 stratigraphic sequence of figure 11 shows this association of a possible air-fall deposit
764 (Lf dsAL) linked with pyroclastic flow-dominated deposits (Lf mAL and *m-gwLA*). In
765 some cases, pyroclastic eruptions commonly precede lava emplacement (Fink 1983;
766 Heiken and Wohletz 1987). The sequence presented in figure 7 shows a low-grade
767 welded ignimbrite deposit (Lf *l-gwAL*) overlaid by a thick banded body that we are
768 interpreting here as a lava flow. At the base of the banded lava is a breccia (Lf mLB)
769 consisting of clasts of a mix of lava textural types, including massive, vesicular, flow
770 banded and flow-folded, glassy, pumiceous and devitrified. Autobrecciation in lavas or
771 rheomorphic ignimbrites occurs when more rigid layers and the external parts are
772 broken in response to the applied shear stress locally exceeding the tensile strength
773 (Fink and Manley; 1987). Some polymictic breccia deposits (Lf mL) are
774 characterized by lithic angular clasts and devitrified fragments that could point to co-
775 ignimbritic breccias with short transport of the emitted material. These deposits could
776 be also related to collapse-caldera-breccias falling down into the caldera ring during
777 the roof subsidence. Air-fall (sA) and dilute pyroclastic flow (xsA) deposits (surge
778 type) crop out in both regions. These, linked with the glassy and lithic pyroclastic
779 material described above, are evidence of intense explosive phases from more
780 sustained column eruptions of smaller intra-caldera volcanic centers and/or associated

781 to events of caldera collapse (Fig. 17).

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783 10.2.1 The sedimentary response

784 Sets of small basins intra-calderas and probable relatively immature shallow
785 marine deposits are interpreted as forming part of a tectonically unstable setting of a
786 young extensional environment that characterized the southern Amazonian craton
787 during the Paleoproterozoic. Reworked sediments can accumulate into volcano-
788 tectonic depressions created by the eruption, which often collects an intra-caldera lake
789 (Heiken et al., 2000 Németh et al., 2009, Manville et al., 2009). The sedimentation into
790 intra-volcano shallow-water lacustrine basins would have be facilitated (Fig. 17). The
791 alternation of subaerial to shallow-water sedimentation displayed by the alternation of
792 Lf mS and csG is indicative of this volcano-tectonic depressions, which could be also
793 interpreted as immature marine depressions. Subaerial and subaqueous talus coarse-
794 grained up to finer grained turbidites (dsSt) and suspension deposits formed during
795 quiescent periods into lakes or pounds is also inferred (Bacon et al., 2002). Silica-rich
796 accumulations into shallow water basins (Chipera et al., 2008; Manville et al., 2009)
797 deriving from hydrothermal activity in a dynamic volcanic context is also thought to be
798 responsible for the formation of chert accumulation (Lf bChS). Post caldera uplifting
799 (Fig. 17), resurgence or central volcanism could also contribute to produce new
800 sediments to be reworked and transported. Fluvial erosion and reworking of primary
801 deposits produced wide range of different sediments from localized cross-bedded,
802 well-sorted sand (Lf xsS) and gravel (Lf xsSG) beds to massive clast-supported sand
803 and gravel (Lf csGS, csG) and cobble (Lf csGC) deposits. Fluvial deposits occur
804 throughout all successions, representing periods of stream and river reworking and re-
805 establishment after an eruptive phase (Zernack et al., 2011; Roverato et al., 2017).
806 Debris-flows, hyperconcentrated flows, sheet-floods and active sandy braided river
807 systems existed and the absence of vegetation during the Precambrian (Oberholzer and
808 Eriksson, 2000; Roverato et al., 2017) permitted that copious rainfalls easily reworked
809 the available sediments.

810

811 11. Conclusion

812 This study is the result of the lithofaciological analysis carried out during the
813 2013, 2014 and 2015 field campaigns in the Amazon Craton in the TMP and SFX
814 regions and the successive geochemical and geochronological analysis of samples

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815 collected in the field. This work constitutes a further step ahead toward the
816 comprehension of significance, chronostratigraphic distribution and the dynamic of
817 eruption and emplacement of felsic volcanic products in the region. Our results
818 complete previous studies and confirm that products present in the Amazonia Craton
819 could be related either to caldera-type systems (e.g. Lamarão et al., 2002; Juliani et al.,
820 2005; Lamarão et al., 2005; Pierosan et al., 2011) and to fissure-fed eruptive
821 environment following the model proposed by Aguirre-Diaz and Labarthe-Hernandez
822 (2003) for the “Sierra Madre Occidental” formation and by Juliani and Fernandes
823 (2010) for the Xingu region. The two models are in fact very similar only differing for
824 the size of the hypothesized magma chambers and the shape of the fissural vents. The
825 described volcano-sedimentary sequences that were characterized by the emission of
826 large volcanic felsic products were likely formed in a late-/post-orogenic (~ 2 Ga) to
827 extensional regimes (~ 1.88 Ga).

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- 1288
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1291 Figure Captions

1292

1293 Figure 1: location map of the northern South America and the Amazonian Craton

1294 divided into several geochronological provinces and other domains according to Santos
1295 et al. (2000); TMP = Tapajós Mineral Province, SFX = São Felix do Xingú Region.

1296

1297 Figure 2: distribution map of the outcrops analyzed during the field campaigns in both

1298 regions a) Tapajós Mineral Province (TMP) and b) São Felix do Xingú region (SFX);

1299 PW=distribution of the Santa Rosa formation inferred during the present work;

1300 F=distribution of the Santa Rosa formation inferred by Fernandes et al. (2011);

1301 BIF=Banded Iron Formation; red and white dot refers to primary andesitic deposits

1302 analyzed in Roverato et al. (2017). In both figures are reported the outcrops described

1303 in the paper.

1304

1305 Figure 3: massive and banded lavas and rheo-ignimbrite (?) deposits. a) Np173

1306 (7°33'52.31" S, 55°10'58.80" W), b) Xu23 (6°41'08.65" S, 52°25'55.67" W), c) Xu101

1307 (6°52'12.82" S, 52°09'16.12" W), d) Xu52 (6°28'19.32" S, 51°50'08.90" W), e), f), g)

1308 Np396 (6°32'41.06" S, 55°23'59.37" W); see Fig. 2 for the outcrops location. For the

1309 lithofacies description and more details see the text.

1310

1311 Figure 4: massive primary volcanoclastic rocks with different proportion of ash, lapilli

1312 and blocks. All the deposits are interpreted to be emplaced from pyroclastic density

1313 currents except (f) that is interpreted as a basal-breccia of a lava body. a) Xu104

1314 (6°52'22.96" S, 52°08'15.91" W), b) Np183 (7°32'04.13" S, 55°08'50.02" W), c) Np93

1315 (6°44'16.60" S, 55°27'12.96" W), d) Xu29 (6°41'42.51" S, 52°01'23.06" W), e) Xu07

1316 (6°41'56.36" S, 52°08'42.27" W) f) Xu192 (6°31'31.92" S, 53°02'36.60" W); see Fig.

1317 2 for the outcrops location. For the lithofacies description see the text and Table 1.

1318

1319 Figure 5: microphotographs of different massive ash and lapilli ignimbrite deposits in

1320 thin section: a) broken crystals suggesting the fragmental character of the rock; b)

1321 detail of a devitrified juvenile fragment displaying axiolitic fabric; c) banded sub-

1322 millimetric to millimetric lithic fragments immersed in a devitrified groundmass.

1323

1324 Figure 6: reconstructed schematic stratigraphic column and associated photographs

1325 representing the evolution of ignimbrite deposits cropping out in the TMP (Np183;
1326 7°32'04.13" S, 55°08'50.02" W); note the increase of welding from the base to the top.

1327

1328 Figure 7: schematic stratigraphic column and relative photographs of a >150 m thick
1329 felsic banded lava(s) cropping out in SFX (Xu192; 6°31'31.92" S, 53°02'36.60" W)
1330 overlying a basal breccia (Lf mLB) and an ignimbrite deposit characterized by a low
1331 grade of welding (Lf *l-gw*LA).

1332

1333 Figure 8: stratified primary volcanoclastic rocks, a) related to sedimentation by highly
1334 dilute ash-cloud (Np130; 6°54'16.09" S, 55°10'59.38" W) and, b) attribute to
1335 pyroclastic surge-type depositional condition from dilute currents (XU162;
1336 6°32'28.39" S, 52°25'26.07" W); see Fig. 2 for the outcrops location. Relative thin
1337 section microphotographs (c/d) showing micrometric shards. For the lithofacies
1338 description see the text and Table 1.

1339

1340 Figure 9: massive sedimentary rocks. a) The alternation of lithofacies *csG* and *mS*
1341 indicates changes in energy conditions of sedimentation belonging to a subaqueous-
1342 subaerial fan-delta interface (Np146; 6°42'58.24" S, 55°28'53.49" W); b) detail of
1343 centimeters ripples of Lf *mS* (Np89; 6°54'39.36" S, 55°26'12.28 W); c) Lf *csG* is also
1344 associated to Lf *xsSG* (see stratified rocks in section 6.2) (Np27; 8°08'18.43" S,
1345 54°54'37.33" W). d) Np27, e) Xu209 (6°13'55.26" S, 52°42'29.25" W), f) Np158
1346 (7°03'33.79" S, 55°24'11.84" W); the rounded and clast supported character of these
1347 lithofacies is linked with fluvial/alluvial deposition by debris-flow dominated
1348 processes; see Fig. 2 for the outcrops location. For a more detailed lithofacies
1349 description see the text and Table 1.

1350

1351 Figure 10: stratified sedimentary rocks. a) The quartzitic sandy cross-bedded
1352 lithofacies is interpreted as formed in fluvial channel or around margins of immature
1353 marine basins (?) (Xu 201; 6°16'12.95" S, 52°52'18.84" W); b) the cross-stratified
1354 water reworked lithofacies is linked with stream-dominated fluvial/alluvial settings
1355 (Np82; 8°03'40.79" S, 54°50'43.52" W); c) the silty sedimentation likely belong to a
1356 lacustrine environment characterized by small turbidities (Np158; 7°03'33.79" S,
1357 55°24'11.84" W); d) the top of the photographs shows the Lf *bChs* interpreted as
1358 inorganic precipitation of silica (chert) in a closed lake basin; white arrows show

1359 fragments of the chert deposit eroded by low-energy sandy stream flows or local
1360 lacustrine turbidites (Np90; 6°49'50.20" S, 55°28'15.47" W); see Fig. 2 for the
1361 outcrops location. For a more detailed lithofacies description see the text and Table 1.

1362

1363

1364 Figure 11: sketch of a wide (300 x 80 m) outcrop in the TMP (Np407; 6°40'35.21" S,
1365 55°21'14.63" W). The stratigraphic sequence is tilted showing sub-vertical contacts of
1366 the different deposits. The sequence is interpreted displaying at the base banded (or
1367 rheo-ignimbrite) and massive lava flows passing to fragmental deposits to the top. a)
1368 ignimbrite medium-grade welded; b) the diffuse-stratified lithofacies indicates tractive
1369 processes usually attribute to pyroclastic surge-type depositional condition from dilute
1370 currents; c) sedimentary clast-supported deposit ; d) non-welded lapilli to ash
1371 ignimbrite; e) banded lava o highly reomorphic ignimbrite (lava-like). For a more
1372 detailed lithofacies description see the text and Table 1.

1373

1374 Figure 12: classification diagrams for the Tapajos volcanics (TMP-V) and lava flow
1375 (TMP-LF). TAS diagram with limits of alkaline series from Kuno (1968), dashed line,
1376 and Irvine and Baragar (1971), solid line. AFM diagram with alkaline field from Irvine
1377 and Baragard (1971). SiO₂ vs K₂O classification diagram (Ewart, 1982). Literature
1378 values are from: VR (a) Vila Rozinho and MA (a) Moraes Almeida volcanic sequences
1379 from Lamarão et al. (2002); SF (b) Sobreiro Formation and SRF (b) Santa Rosa
1380 Formation from Fernandes et al. (2011).

1381

1382 Figure 13: REE and spider-diagrams of volcanics and lava flow rocks from the Tapajos
1383 region (TMP-V and TMP-LF). REE data are normalized to Chondrite I (CI; values
1384 from Ander and Ebihara, 1982) and trace elements are normalized to Mid Ocean Ridge
1385 Basalt (MORB; values from Hoffman, 1988). Literature values are from: VR (a) Vila
1386 Rozinho and MA (a) Moraes Almeida volcanic sequences are average values from
1387 Lamarão et al. (2002); SRF (b) Santa Rosa Formation from Fernandes et al. (2011)
1388 divided in -V volcanoclastics and -LF lava flow. Due to the lack of literature data,
1389 comparison of VR (a) and MA (a) is reported only for REE diagram.

1390

1391 Figure 14: tectonic affinity discriminant diagrams for the Tapajos volcanics (TMP-V)
1392 and lava flow (TMP-LF). Zr+Nb+Ce+Y (ppm) vs FeO_{tot}/MgO (wt.%) diagram. Yb vs

1393 Ta diagram. La/Yb vs Nb/La diagram. Th-Ta-Hf/3 diagram. Literature values are from:
1394 VR (a) Vila Rozinho and MA (a) Moraes Almeida volcanic sequences from Lamarão
1395 et al. (2002); SF (b) Sobreiro Formation and SRF (b) Santa Rosa Formation from
1396 Fernandes et al. (2011).

1397

1398 Figure 15: geochronological U-Pb data from Tapajos zircons. Average $^{206}\text{Pb}/^{207}\text{Pb}$ age
1399 (errors are calculated as 2σ) of the three samples. Probability density plot of $^{206}\text{Pb}/^{207}\text{Pb}$
1400 ages. Calculated concordia age for sample NP396 (lava flow) and NP183 (ignimbrite).

1401

1402 Figure 16: geochronological U-Pb data from Xingu zircons. Calculated concordia age
1403 for ignimbrite sample XU-08. Probability density plot of $^{206}\text{Pb}/^{207}\text{Pb}$ ages.

1404

1405 Figure 17: peoleogeographic reconstruction of the fissural and calderic volcanic activity
1406 during the Late-Paleoproterozoic in the southern part of the Amazonian craton. In the
1407 foreground is shown a section of a caldera and a post-caldera ignimbrite uplift that
1408 could facilitate the production of new sediments to be reworked and transported. The
1409 rising magma could form sporadic intra-caldera domes and volcanic centers as also
1410 shown in the background calderas. Reworked sediments can accumulate into volcano-
1411 tectonic depressions, which often collects intra-caldera lakes. In the background a
1412 fissure-fed volcanism is the responsible of the emission of lava flows and/or high-
1413 grade to rheomorphic ignimbrites. Fluvial deposits that occur throughout all
1414 successions represent periods of stream and river reworking. The area in punctuated by
1415 little scoria cones and maars that contribute to the amount of the fragmental products
1416 well represented in the study regions.

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1421 Tables

1422

1423 Table 1: Summary of the main characteristics of volcanoclastic lithofacies of the
1424 primary and secondary products analyzed and their interpretation.

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1426 Table 2: Major and trace element bulk rock composition of Tapajos samples. Class
1427 identify the lithological features of the rocks: VC: volcanoclastic; I: ignimbrite; R:
1428 rhyolite; Type identify the geochemical affinity according to the granite classification
1429 (Zr+Nb+Ce+Y (ppm) vs FeO_{tot}/MgO (wt.%) diagram, Fig. 14): I is for I-type granites
1430 and A is for A-type granites; b.d.l. is below detection limits; Mg# is calculated as Mg^{2+}
1431 / ($Fe^{2+}_t + Mg^{2+}$); (*) major elements analyses already published in Roverato et. (2016).
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Figure 1
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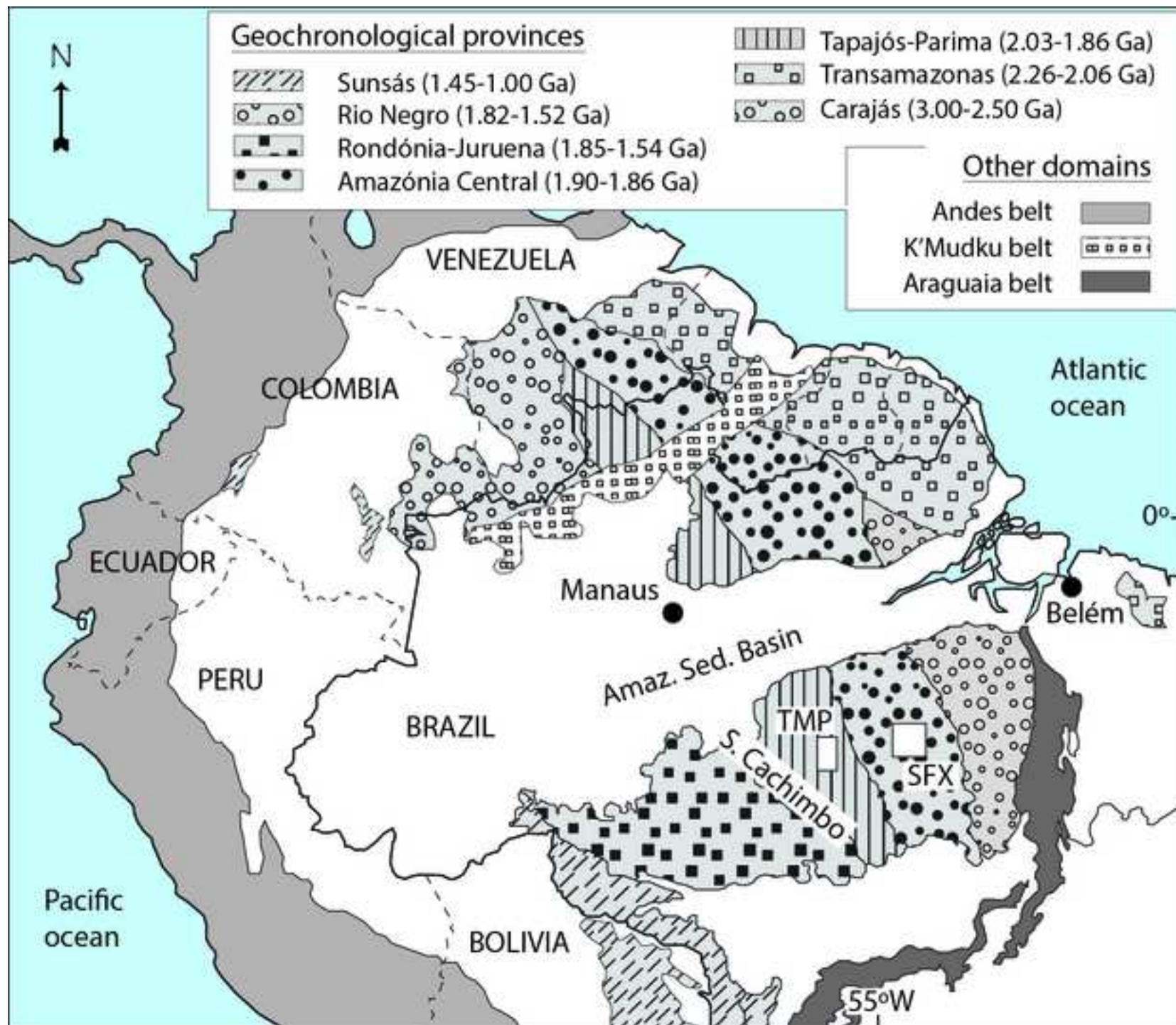


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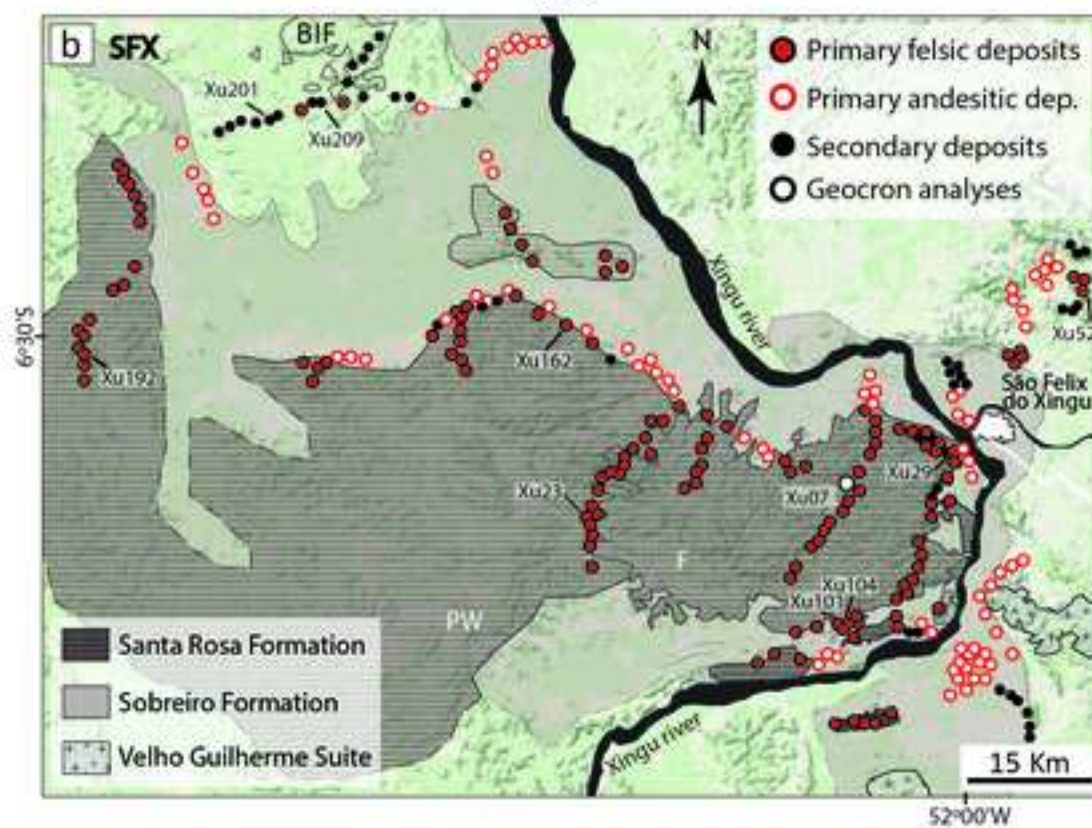
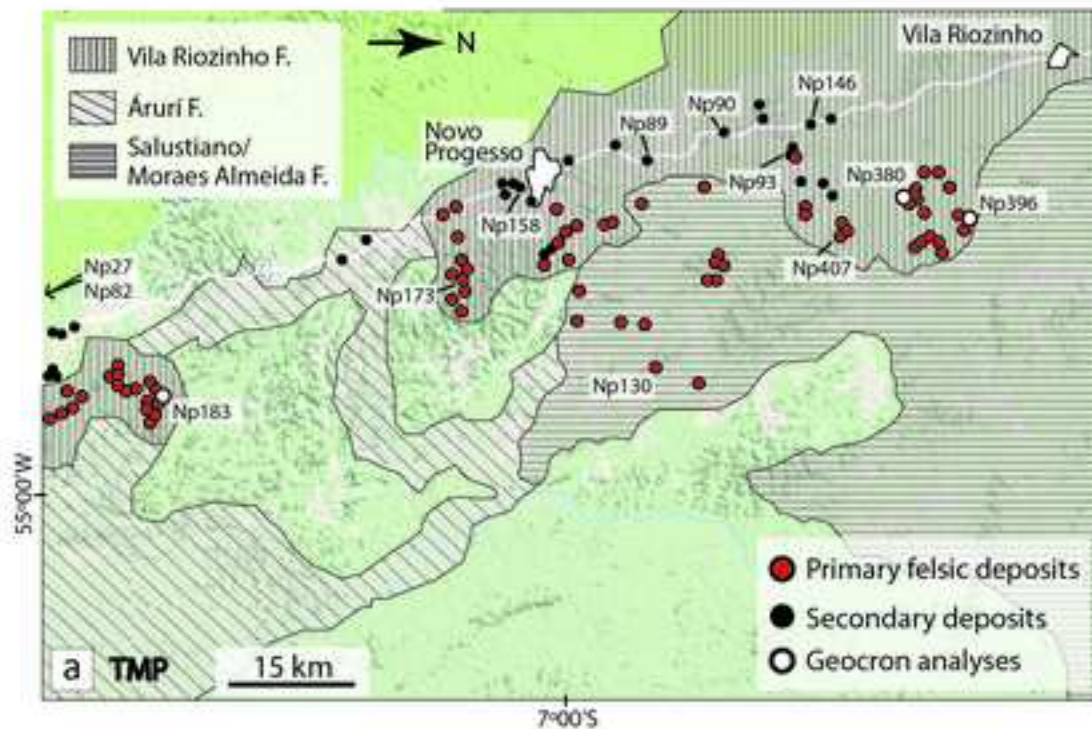


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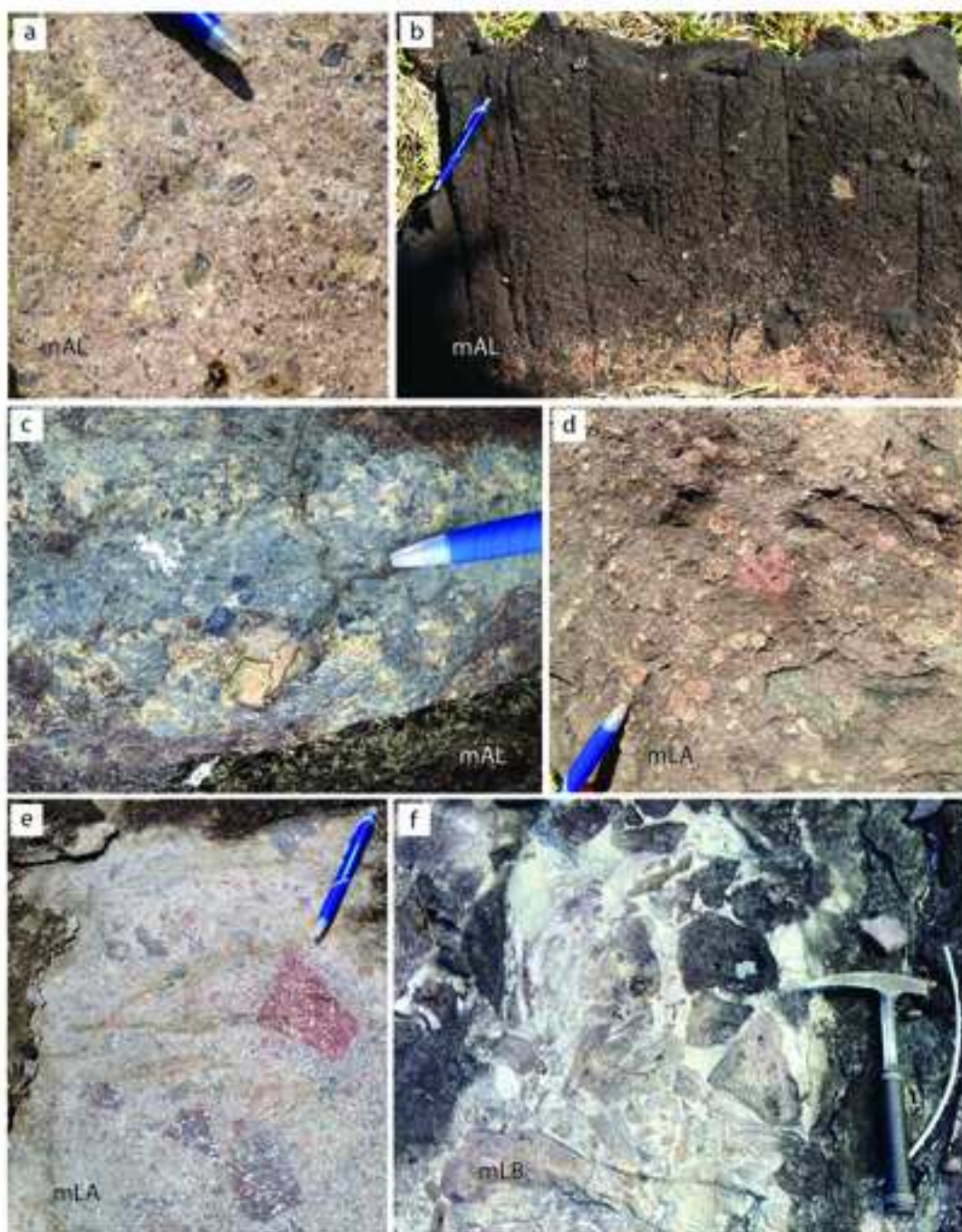


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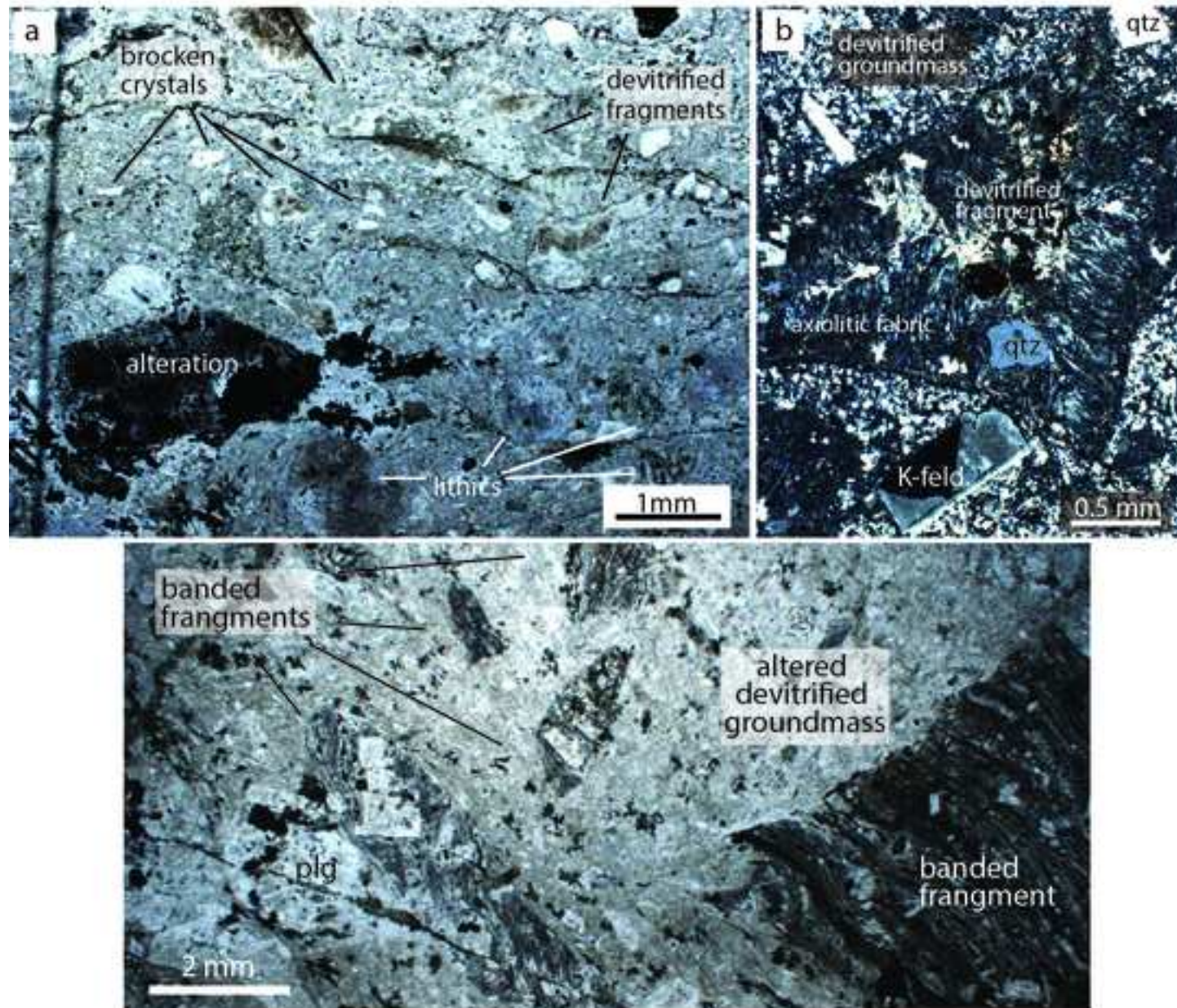


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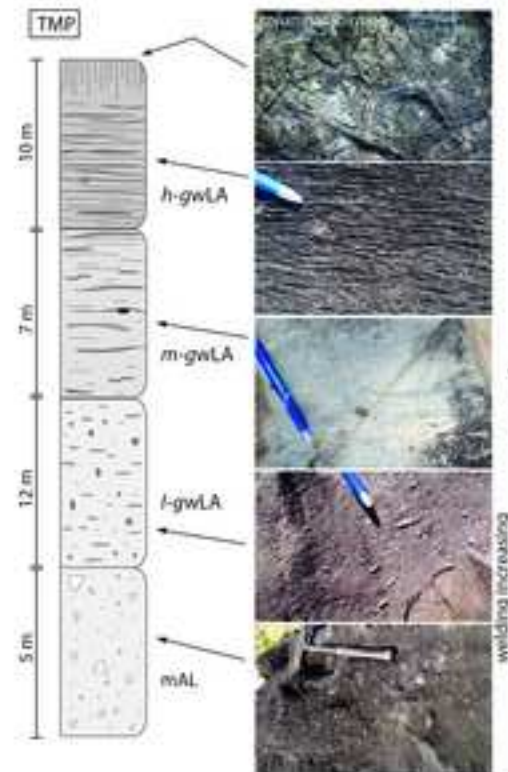


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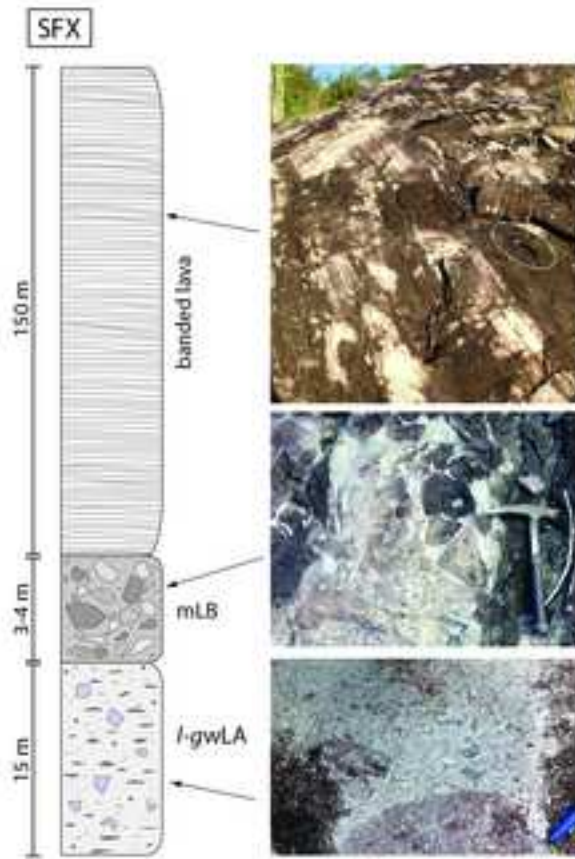


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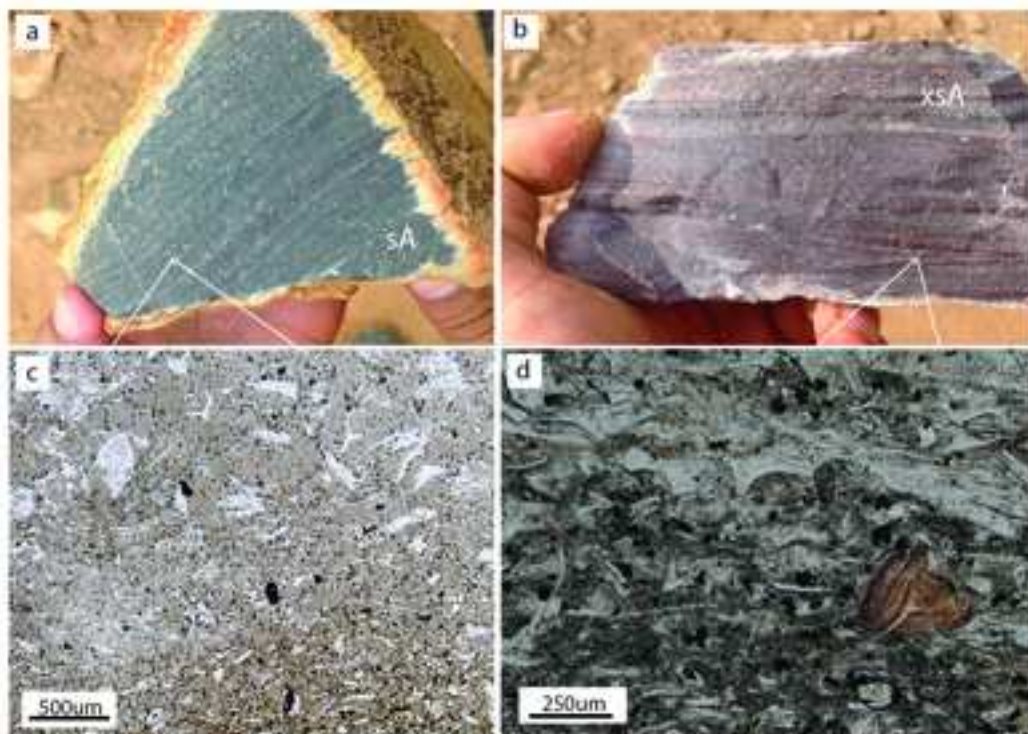


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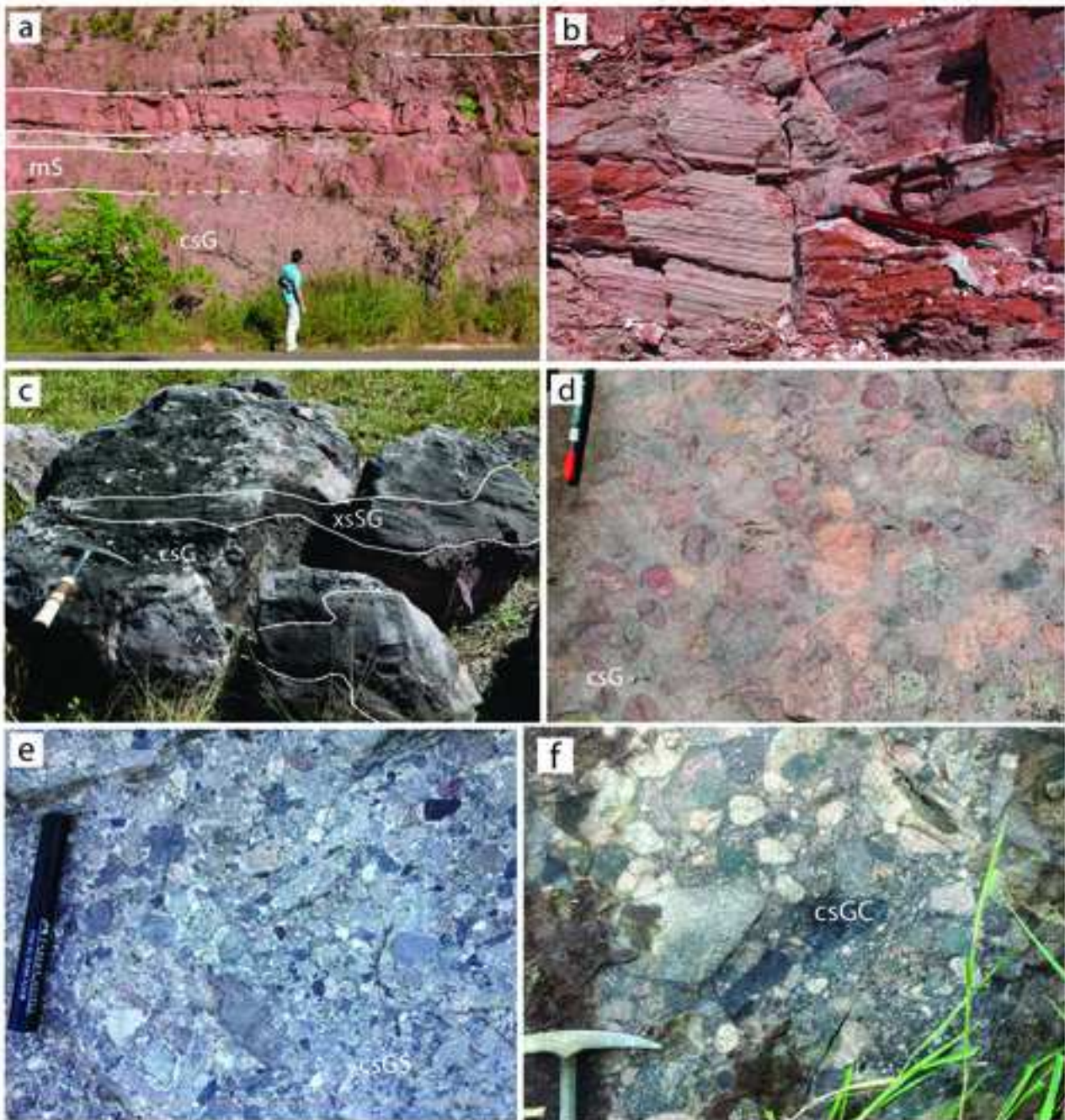


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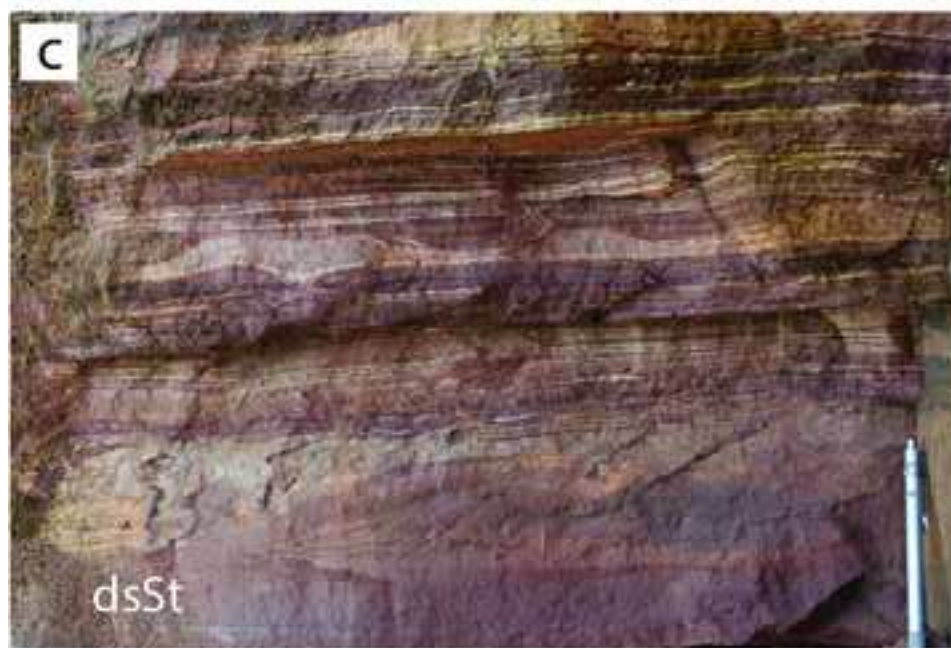


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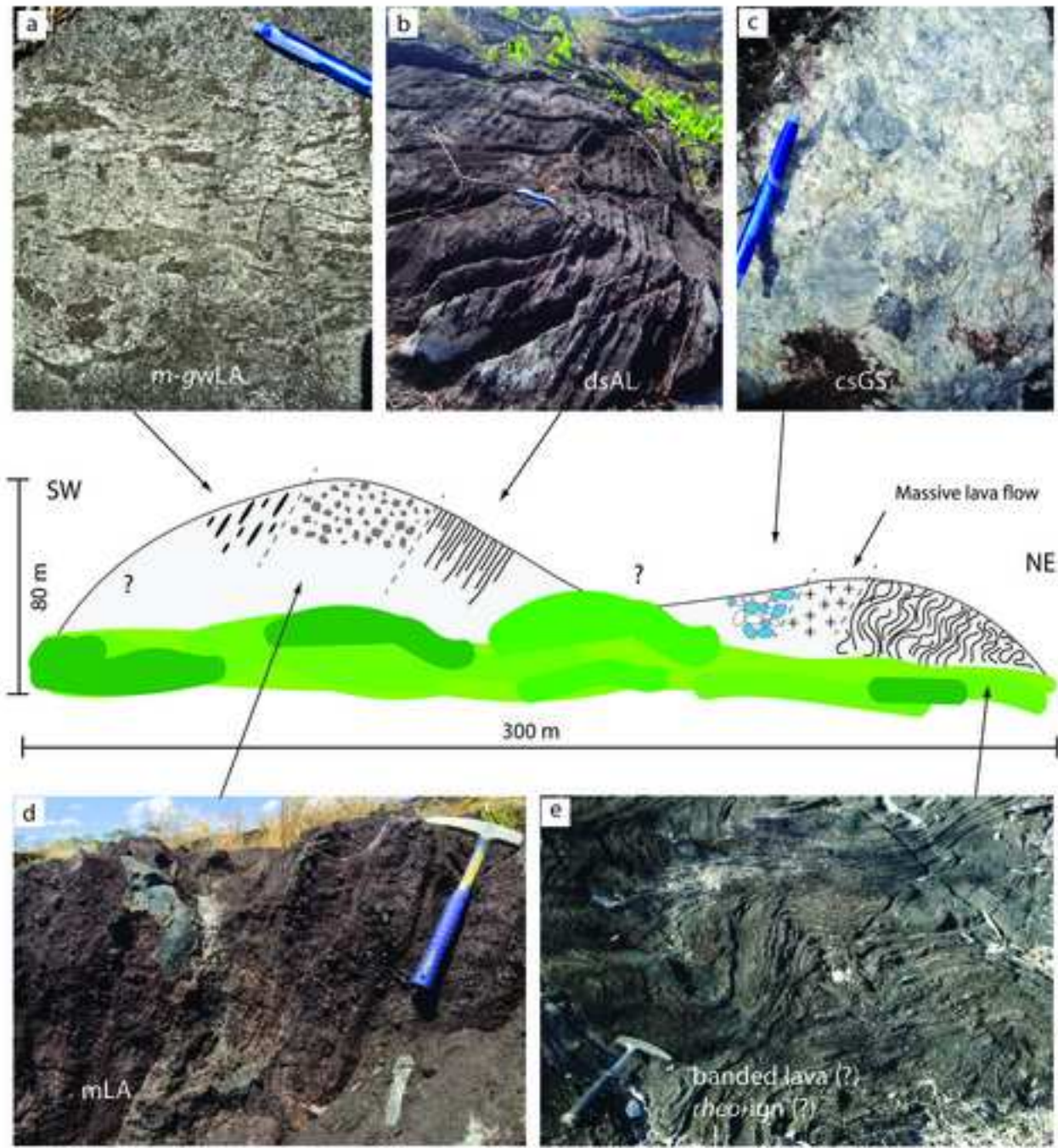


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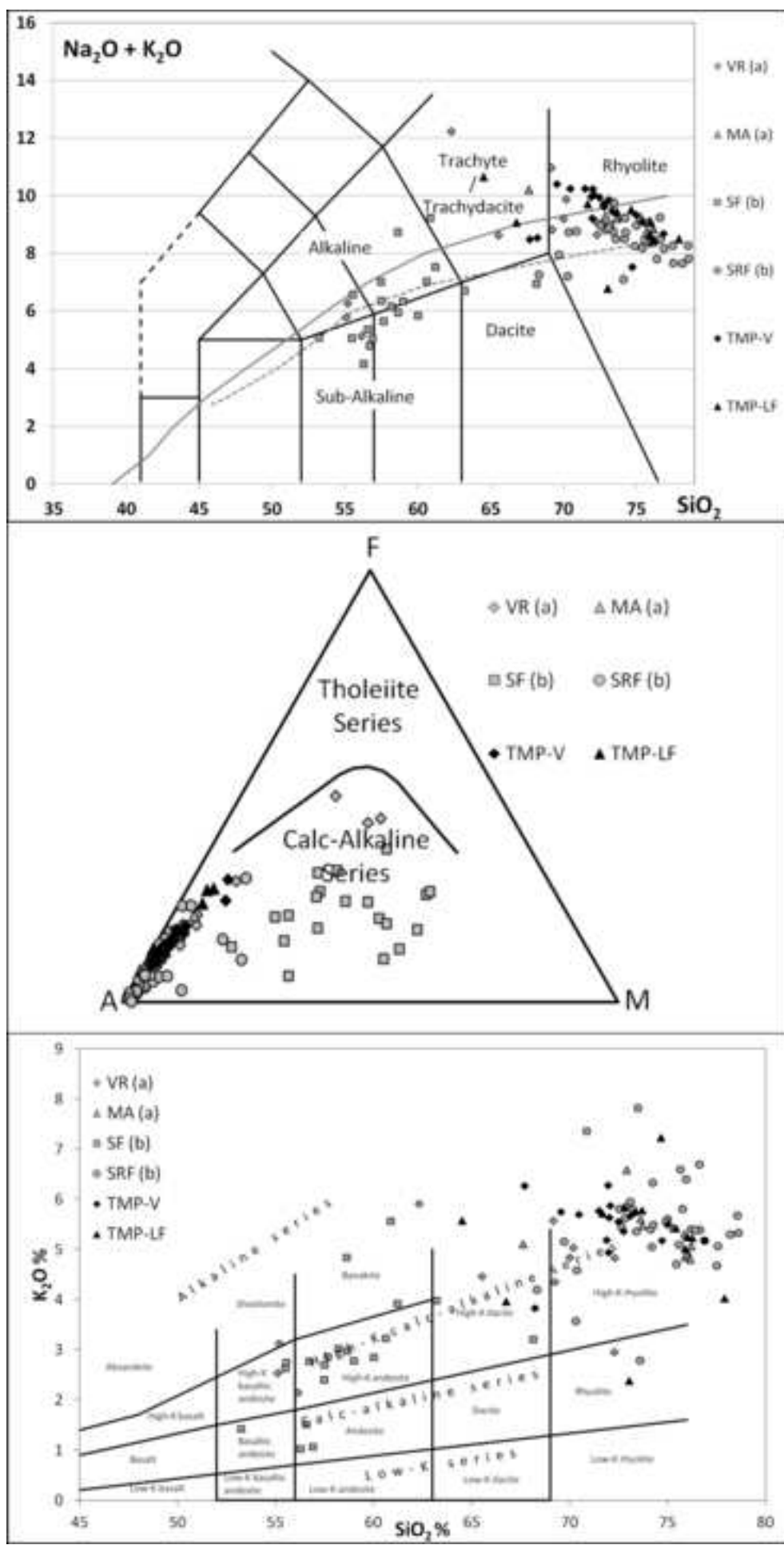


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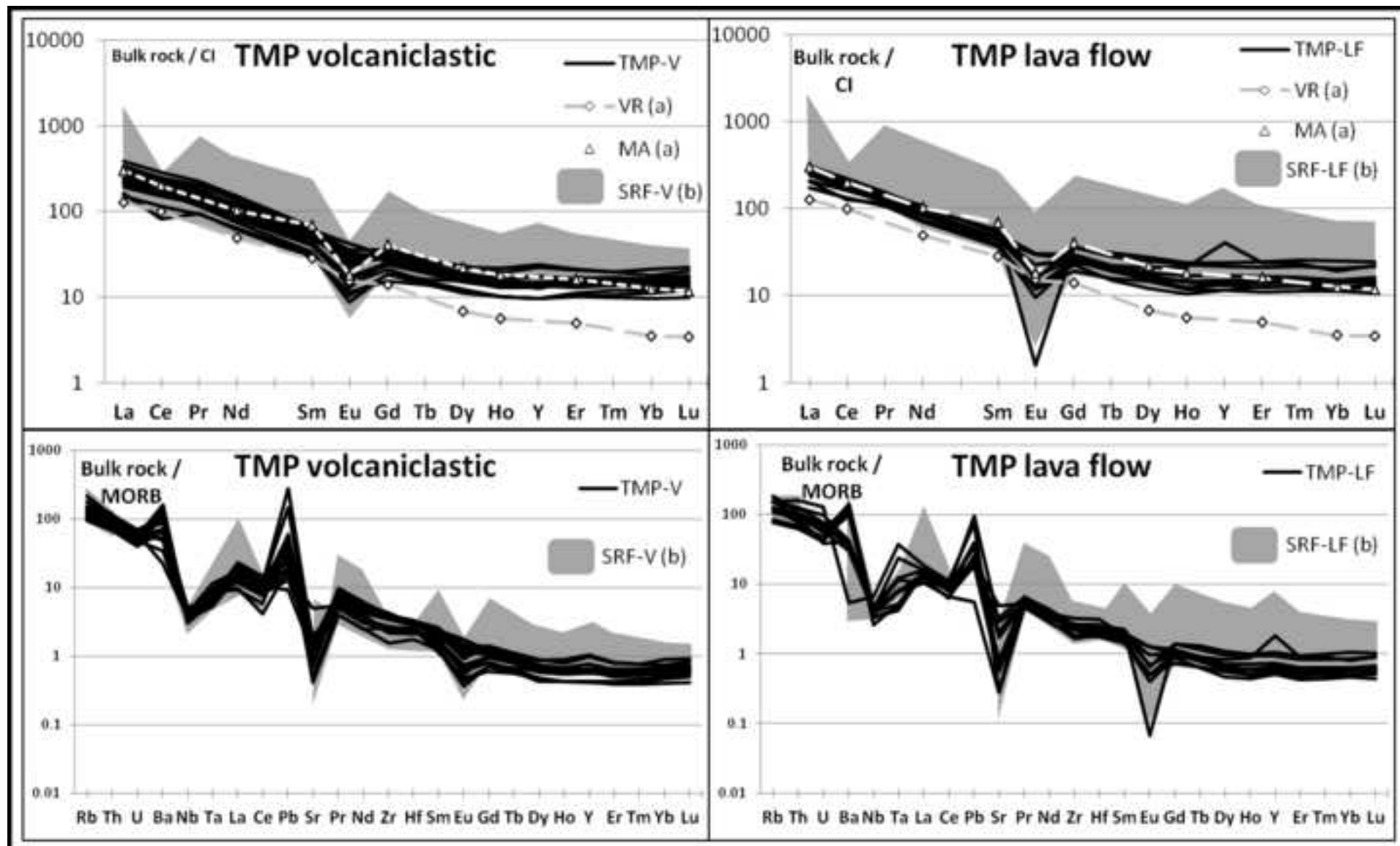


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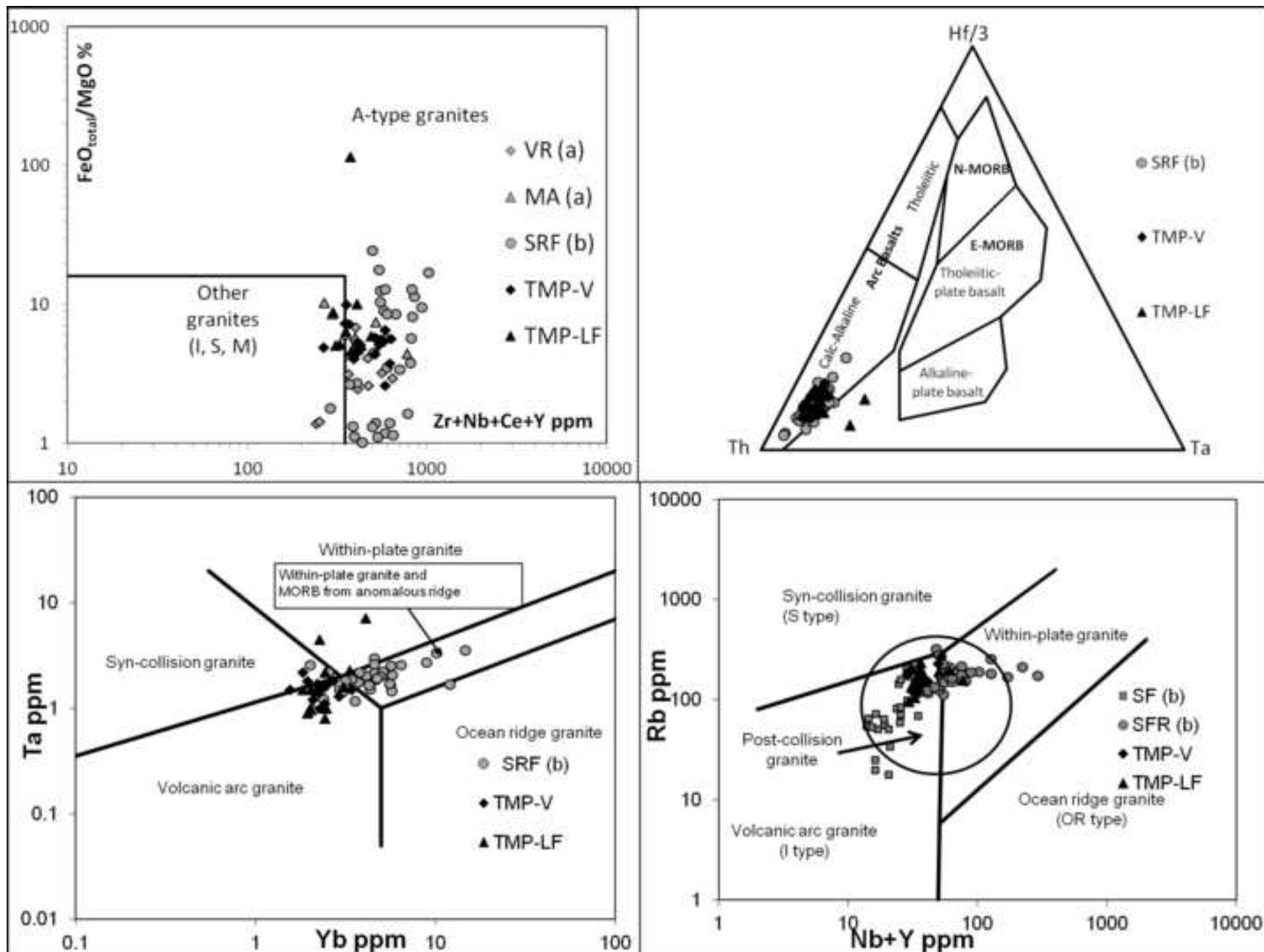


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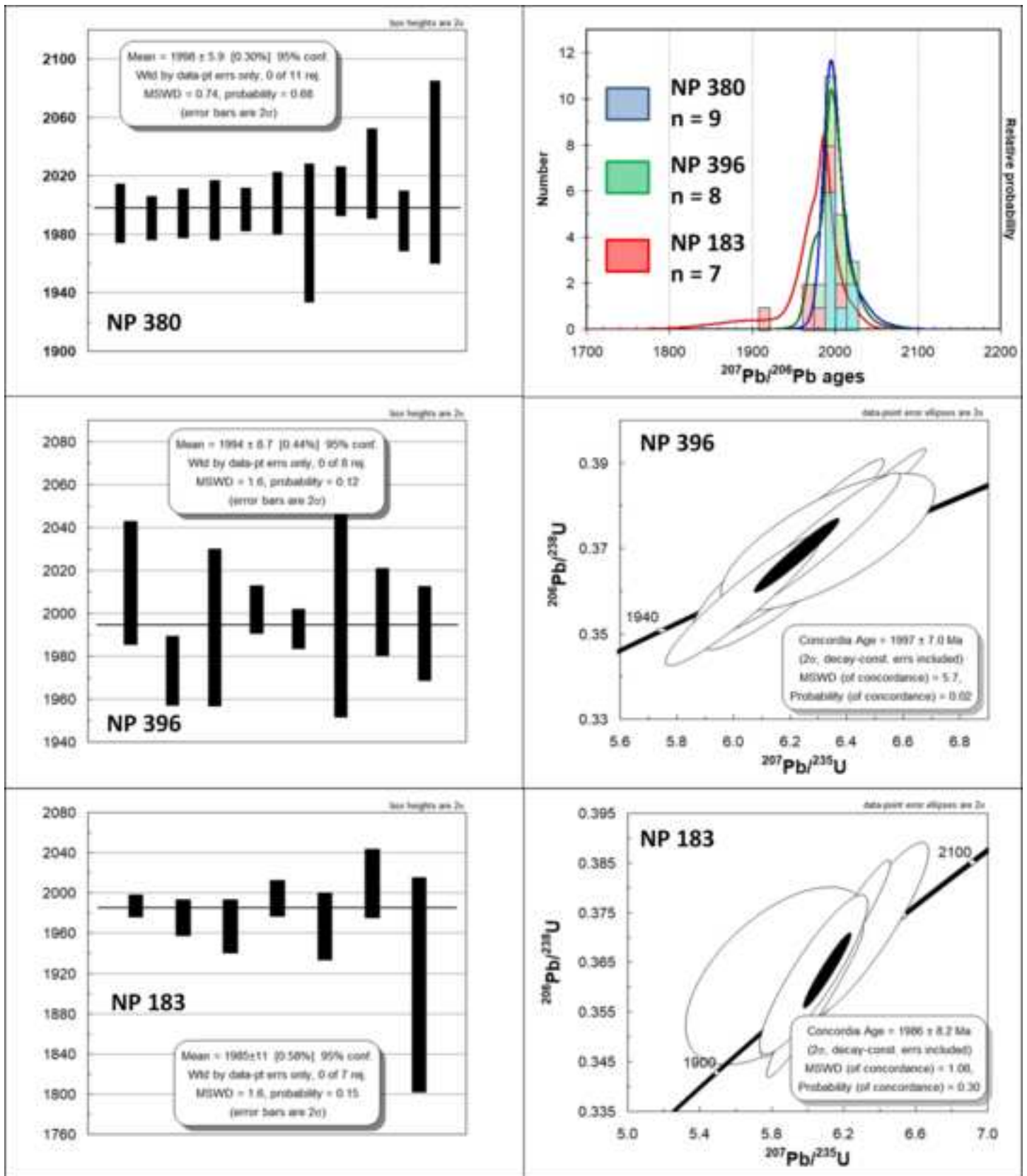


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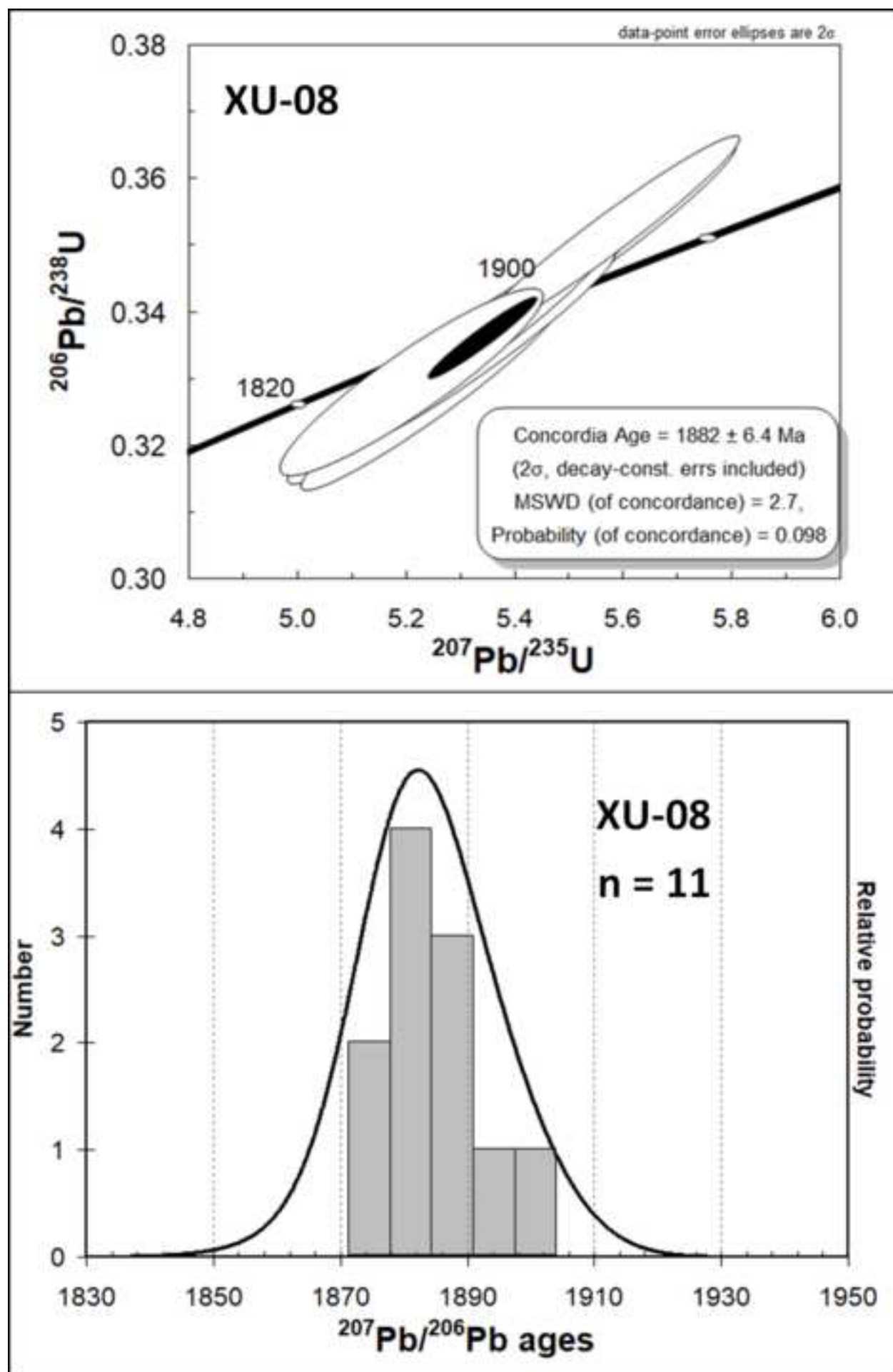


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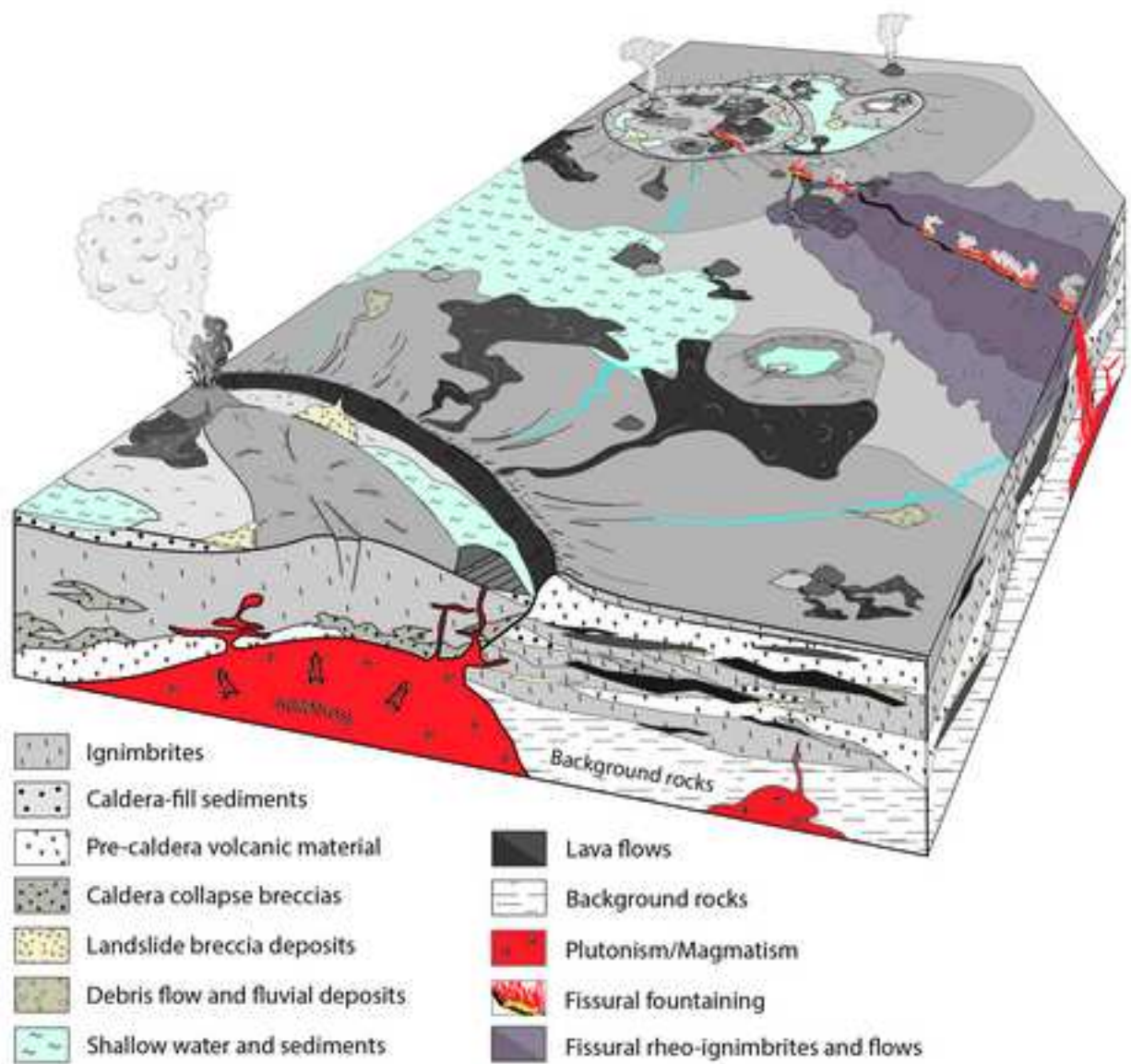


Table 1

		Lithofacies	Description	Interpretation	
Primary volcaniclastic rocks	Massive	mAL Massive Ash to Lapilli	Massive fine and coarse ash and variable fine to coarse lithic lapilli content. Devitrified fragments immersed. Brocken crystal (plg/prx) content. Moderate to bed sorting.	The massive fine aspect suggests deposition from a dilute pyroclastic density current (PDC). Brocken crystals confirm the fragmental character. Granular flow regime.	
		mLA Massive Lapilli and Ash	Massive, fine, fine to coarse and coarse devitrified lapilli immerse in ash matrix, less blocks immersed, maximum size 20-25 cm. Moderate sorting.	The massive aspect suggests deposition from a dilute PDC. The coarser character could be also related to proximal co-ignimbritic breccias as result of deposition by denser pyroclastic granular flows.	
		mLB, Massive Lapilli and Block	Massive, monolithologic, angular coarse lapilli and blocks (50-60 cm) immersed in lapilli matrix. Moderate sorting.	Basal auto-brecciation of lava flows and/or rheo-ignimbrite flows	
	Banded	Welded ignimbrites	l-gwLA, m-gwLA, h-gwLA low-, medium-, high-grade welded Lapilli and Ash	Massive, fine to coarse, moderately to strongly flattened devitrified lapilli (<i>fiamme</i>) varying from millimetric to 3–4 cm in size and lithic lapilli and ash. Crystal content. Clasts are immersed in a homogeneous ashy matrix. Low- to high-grade welded deposits. Eutaxitic texture. Moderate sorting.	The massive aspect suggests deposition from a pyroclastic density current. Welding is the result of post-depositional loading and are favored by low-viscosity pyroclasts that are promoted by high emplacement temperature, porosity and dissolved water.
			rheo-ign Rheoignimbrite (lava -like)	Layering of thin, dark and light bands and boudinaged <i>fiamme</i> . Parataxitic fabric displays subhorizontal bands and intricate small-scale intrafolial folds are present. The bands are deformed and flattened around lithic fragments and crystals.	The vitric fragments immersed in the welded ignimbrite distort and stretch up to the volcaniclastic flow becomes banded and starts to flow viscously.
	Stratified		sA Stratified Ash	Stratification of millimetric fine, devitrified, angular, sharply ash fragments.	The stratification is due to the bedding of shards fragments from a fall-out activity or from a dilute ignimbrite cloud.
			dsAL Diffusely stratified Ash to Lapilli	Diffusely stratified lithic and devitrified coarse ash and lapilli. Thickness of individual bedding surfaces ranges between few to several centimeters. Moderate sorting.	The diffuse stratification could indicate a flow boundary which is influenced by traction processes such as for pyroclastic density currents. Fall-out deposit (?).

Secondary volcaniclastic/epiclastic rocks		<p style="text-align: center;">xsA Cross-stratified Ash</p>	<p>Cross-stratified fine ash formed by angular and sharply devitrified fragments (shards). Cross stratification is discontinuous over decimeters in macro-scale and as well as over millimeters in microscopic scale. Well to moderate sorted.</p>	<p>The internal cross-stratification indicates a grain by grain deposition process from a turbulent current with a flow boundary zone dominated by traction mechanism. Pyroclastic density currents (surge).</p>
	Massive	<p style="text-align: center;">mS Massive Sand</p>	<p>Massive quartzitic sand, good sorting. No internal structures. centimeter ripples at the top of the strata.</p>	<p>Continental supply in a shallow, low energy, water sedimentary setting. Subaerial to sub-aqueous transition.</p>
		<p style="text-align: center;">csG Clast supported Gravel</p>	<p>Clast supported polymictic gravel with rounded clasts, good sphericity and sorting. Clasts are mainly characterized by massive and banded felsic lava fragments.</p>	<p>Clast-supported with minor matrix content is indicative of water flow. Shallow water to subaerial. Laminar debris-flow regime in a medial reaches of stream-dominated fluvial/alluvial fans.</p>
		<p style="text-align: center;">csGS Clast supported Gravel to Sand</p>	<p>Clast supported polymictic, gravel to coarse sand with sub-rounded/sub-angular fragments, low-medium shericity.</p>	<p>Clast-supported with minor matrix content is indicative of water flow. Deposition within a debris-flow dominated fluvial/alluvial environment.</p>
		<p style="text-align: center;">csGC Clast supported Gravel and Cobble</p>	<p>Clast supported polymictic, gravel and cobble with sub-rounded fragments (<20 cm), low-medium shericity, low-sorted.</p>	<p>Water removed the finer particles during transport and deposition. Deposition within a debris-flow dominated alluvial environment.</p>
	Stratified	<p style="text-align: center;">xsS Cross-stratified Sand</p>	<p>Low angle cross-stratified quartzitic sand, good sorting. Layers ranges between millimeters to centimeters.</p>	<p>Wave-induce structure in a coastal sub-aqueous marine-basin environment or fluvial channels environment in low energy regime.</p>
		<p style="text-align: center;">xsSG Cross-stratified Sand and Gravel</p>	<p>Fine to coarse sand and fine crystal-lithic gravel, poor sorting, layers ranges between millimeters to centimeters.</p>	<p>Low to medium energy processes. Hyperconcentrated flood in stream reworking setting.</p>
		<p style="text-align: center;">dsSt Diffusely layered Silt</p>	<p>Diffusely millimetric layered silt. Presence of ripples and low energy wave structures, good sorting.</p>	<p>Shallow water basin, sedimentation in lacustrine basin and/or ponds. Some turbidite sedimentation.</p>
		<p style="text-align: center;">bChS Bedded Chert (and Sand)</p>	<p>Bedded chert with local sand contribution. Thinly multicolor laminated deposit with < 1 mm microcrystalline quartz-dominate layers.</p>	<p>Precipitation of silica particles in closed lake basins in association with volcanic rocks and sandstone.</p>

Table 1

Table 2

Region	Tapajos										
Sample	NP – 079*	NP269a	Np380b	Np411c	NP- CO67*	NP - 080C	NP – 084A*	NP – 101*	NP - 123	NP - 156B*	NP - 159B
Class	VC	I	I	I	I	I	I	I	I	I	I
Type	A	A	A	A	A	A	A	A	A	A	A
XRF(%)											
SiO ₂	71.80	68.78	72.20	66.36	70.81	70.80	68.15	72.22	72.80	71.59	65.48
TiO ₂	0.34	0.32	0.35	0.72	0.40	0.40	0.48	0.32	0.31	0.36	0.58
Al ₂ O ₃	14.16	15.37	14.24	15.57	14.76	14.52	15.43	14.28	13.59	14.27	18.22
Cr ₂ O ₃	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
FeOt	1.41	1.81	1.48	3.64	1.53	1.59	2.02	1.34	1.64	1.39	2.86
MnO	0.04	0.02	0.05	0.07	0.09	0.07	0.09	0.04	0.06	0.04	0.04
MgO	0.32	0.25	0.29	0.90	0.35	0.31	0.54	0.25	0.37	0.19	1.10
CaO	1.04	0.15	0.94	1.49	0.91	0.63	0.98	0.59	1.29	0.50	0.14
Na ₂ O	3.75	2.80	4.31	4.57	4.42	4.07	4.56	4.12	2.28	3.63	2.14
K ₂ O	5.73	6.00	5.32	3.73	5.71	5.77	5.63	5.60	5.04	5.60	6.06
P ₂ O ₅	0.04	0.06	0.05	0.22	0.07	0.06	0.09	0.04	0.06	0.04	0.10
LOI	0.99	3.51	0.32	1.30	1.03	1.48	1.34	0.82	2.59	1.28	3.42
Tot	99.62	99.07	99.55	98.57	100.08	99.70	99.31	99.62	100.03	98.89	100.14
Mg#	0.29	0.20	0.26	0.31	0.29	0.26	0.32	0.25	0.29	0.20	0.41
ppm											
V	20	11	11	34	14	17	29	13	28	10	38
Co	34	38	2	15	17	31	29	43	25	32	12
Ni	1.20	2.50	0.50	0.50	0.40	0.70	0.90	0.80	0.60	0.60	2.80
Zn	28	33	45	71	55	50	55	36	33	27	55
Rb	185	194	179	121	155	144	122	191	230	174	273
Sr	221	188	209	557	141	124	187	174	172	148	127
Y	15	15	22	23	21	22	21	22	37	15	35
Zr	267	241	277	245	361	371	440	276	224	272	401
Nb	13	15	14	12	12	13	11	14	13	14	18
Cs	2.10	1.20	2.30	3.0	2.70	2.10	2.80	2.60	15	2.10	7.1
Ba	673	945	1425	1536	2185	1813	2245	1365	898	1362	1202
La	53	67	56	57	64	72	79	51	70	38	72
Ce	100	98	111	110	117	136	149	99	126	50	129
Pr	10	12	11	11	13	16	18	11	13	8.4	16
Nd	34	40	39	42	47	53	63	37	45	28	54
Sm	4.9	5.8	6.4	6.9	7.3	7.9	9.0	6.0	8.0	4.3	8.2
Eu	0.58	0.80	0.98	1.52	1.83	1.58	2.36	0.90	1.23	0.64	1.67
Gd	3.6	4.1	5.0	5.4	5.4	5.4	6.1	4.8	7.2	3.0	6.7
Tb	0.52	0.56	0.73	0.76	0.73	0.78	0.76	0.69	0.99	0.50	0.97
Dy	2.69	3.0	3.9	4.1	3.8	4.0	3.9	3.6	5.4	2.92	5.6
Ho	0.57	0.57	0.74	0.76	0.78	0.75	0.77	0.73	1.21	0.57	1.06
Er	1.61	1.65	2.19	2.17	2.08	2.33	2.19	2.21	3.3	1.77	3.3
Tm	0.24	0.26	0.35	0.36	0.33	0.34	0.34	0.36	0.48	0.29	0.48
Yb	1.56	1.83	2.38	2.22	2.30	2.12	2.08	2.41	3.43	1.95	2.90
Lu	0.24	0.29	0.38	0.35	0.36	0.36	0.34	0.36	0.54	0.33	0.49
Hf	7.7	7.0	7.3	6.4	8.4	8.5	8.9	7.2	6.3	7.6	9.8
Ta	1.50	2.20	1.00	1.50	1.00	1.40	1.20	1.70	1.50	1.80	1.30
Pb	23	6.3	13	7.3	24	73	20	10	26	9.2	4.5
Th	21	21	19	13	15	17	14	20	22	20	21
U	4.9	3.4	5.0	2.90	3.3	3.6	2.90	4.0	2.90	4.6	4.8

Table 2: continued

Region	Tapajos										
Sample	NP - 175A	NP - 176*	NP - 178B*	NP - 179*	NP - 180*	NP - 183A*	NP - 184*	NP - 093	NP - 094	Np272a	Np393A
Class	I	I	I	I	I	I	I	VC	VC	R	R
Type	A	I	A	A	A	A	A	A	A	A	A
XRF (%)											
SiO ₂	73.86	75.93	70.86	72.53	69.73	71.25	70.99	60.36	62.46	71.13	76.57
TiO ₂	0.24	0.20	0.39	0.37	0.44	0.41	0.37	0.81	0.89	0.49	0.09
Al ₂ O ₃	13.40	12.71	14.62	14.44	15.20	14.65	14.54	15.42	16.36	14.44	11.93
Cr ₂ O ₃	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.01	b.d.l.	b.d.l.	0.01	b.d.l.	b.d.l.	b.d.l.
FeOt	1.10	0.78	1.57	1.67	2.03	1.57	1.75	5.70	4.97	2.52	1.16
MnO	0.07	0.06	0.07	0.09	0.09	0.09	0.08	0.11	0.09	0.06	0.03
MgO	0.11	0.16	0.29	0.30	0.36	0.24	0.30	3.24	1.68	0.51	0.01
CaO	0.50	0.34	0.88	0.65	0.88	0.56	0.68	4.59	3.03	1.57	0.14
Na ₂ O	3.78	3.46	4.70	4.38	4.49	4.54	4.97	2.79	3.11	4.27	4.39
K ₂ O	5.41	5.11	5.11	5.56	5.64	5.57	4.87	4.67	5.86	2.32	3.95
P ₂ O ₅	0.02	0.01	0.06	0.06	0.07	0.05	0.06	0.35	0.39	0.06	b.d.l.
LOI	1.15	0.88	1.28	0.85	1.00	0.81	1.07	1.37	0.64	1.38	0.58
Tot	99.64	99.64	99.83	100.90	99.94	99.74	99.68	99.43	99.48	98.75	98.85
Mg#	0.15	0.27	0.25	0.24	0.24	0.21	0.23	0.50	0.38	0.27	0.02
ppm											
V	b.d.l.	b.d.l.	14	b.d.l.	17	b.d.l.	10	112	59	11	b.d.l.
Co	36	34	32	40	28	37	38	27	24	2.60	63
Ni	0.50	0.50	0.80	2.30	3.4	1.50	0.60	19	0.50	0.60	1.10
Zn	20	32	45	51	46	52	60	55	73	55	33
Rb	156	158	136	153	136	133	127	116	169	105	196
Sr	54	46	179	120	115	78	103	614	620	321	33
Y	27	20	23	27	22	23	20	16	23	21	37
Zr	223	162	397	370	423	402	360	174	257	279	181
Nb	13	13	13	14	11	12	12	7.3	11	12	23
Cs	3.2	3.9	2.10	3.10	2.60	1.80	0.70	4.2	6.2	1.70	1.60
Ba	477	310	2021	998	880	746	2243	1362	2063	1363	75
La	45	36	75	76	91	80	64	35	53	59	72
Ce	92	70	140	138	174	151	122	70	106	108	133
Pr	11	8.3	15	15	20	18	14	8.5	13	11	14
Nd	39	29	57	52	69	64	52	31	48	38	45
Sm	6.7	4.7	8.9	8.1	10	9.4	7.9	5.2	7.6	6.5	8.1
Eu	0.72	0.49	1.98	1.36	1.63	1.51	1.84	1.35	1.71	1.27	0.09
Gd	5.3	3.7	6.9	6.9	6.6	6.6	5.7	4.3	5.5	4.9	7.0
Tb	0.81	0.59	0.76	0.87	0.92	0.91	0.78	0.57	0.81	0.70	1.14
Dy	4.7	3.7	4.5	4.3	4.4	4.6	4.0	3.0	4.3	3.7	6.8
Ho	0.90	0.72	0.86	0.91	0.80	0.83	0.82	0.56	0.82	0.69	1.31
Er	2.63	2.25	2.73	2.57	2.23	2.31	2.51	1.52	2.32	1.99	3.9
Tm	0.41	0.35	0.39	0.36	0.36	0.37	0.36	0.23	0.32	0.31	0.62
Yb	2.61	2.21	2.44	2.71	2.25	2.43	2.32	1.43	2.08	1.95	4.1
Lu	0.39	0.33	0.42	0.43	0.36	0.40	0.37	0.24	0.33	0.30	0.60
Hf	6.6	5.2	8.7	8.5	9.6	9.3	8.4	4.3	6.2	7.1	7.4
Ta	1.80	1.70	1.10	1.80	1.40	1.60	1.60	0.60	1.00	0.90	7.1
Pb	16	29	137	10	17	11	28	4.0	6.9	46	36
Th	17	18	17	16	16	17	17	6.1	11	13	30
U	3.4	4.4	3.5	3.9	3.5	3.7	4.0	1.30	2.10	3.4	9.1

Table 2: continued

Region	Tapajos									
Sample	Np405	Np406	NP - 039B	NP - 073	NP - 114	NP - 121	NP - 173*	NP - 175B	NP - 182C	
Class	R	R	R	R	R	R	R	R	R	
Type	A	A	A	A	A	A	I	I	I	
XRF (%)										
SiO ₂	73.67	69.79	65.32	72.82	63.80	75.09	75.58	75.03	74.44	
TiO ₂	0.33	0.45	0.86	0.31	0.74	0.27	0.20	0.22	0.22	
Al ₂ O ₃	13.09	14.72	16.61	13.84	17.99	13.16	12.96	13.46	13.50	
Cr ₂ O ₃	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	
FeOt	1.33	1.78	3.27	1.29	3.30	1.01	0.99	0.96	1.23	
MnO	0.05	0.05	0.09	0.04	0.05	0.03	0.07	0.09	0.02	
MgO	0.26	0.30	0.51	0.28	0.70	0.10	0.19	0.19	0.14	
CaO	0.53	0.76	2.07	0.89	1.54	0.15	0.72	0.42	0.04	
Na ₂ O	2.25	3.87	4.99	3.61	5.02	3.78	3.21	3.69	3.56	
K ₂ O	7.13	5.57	3.88	5.71	5.51	5.19	5.18	5.39	4.92	
P ₂ O ₅	0.03	0.07	0.22	0.04	0.22	0.03	0.02	0.02	0.02	
LOI	0.55	1.26	1.50	0.75	1.45	0.95	1.49	0.83	2.09	
Tot	99.22	98.62	99.32	99.58	100.32	99.76	100.61	100.30	100.18	
Mg#	0.26	0.23	0.22	0.28	0.27	0.15	0.25	0.26	0.17	
ppm										
V	8	<8	55	14	83	18	<8	<8	<8	
Co	1.00	36	19	19	14	52	25	45	100	
Ni	0.40	2.40	2.20	3.60	1.90	0.60	0.70	0.70	1.30	
Zn	30	38	49	21	48	18	16	28	8	
Rb	232	194	96	200	153	190	156	158	133	
Sr	204	229	552	193	377	91	79	63	32	
Y	23	22	20	18	26	34	64	24	18	
Zr	272	336	228	246	265	245	173	191	189	
Nb	14	15	9.2	14	12	17	13	14	13	
Cs	2.20	2.50	2.10	2.30	1.30	3.1	4.1	3.5	1.10	
Ba	1634	1965	1615	534	1918	583	485	413	569	
La	63	62	50	57	58	62	48	41	41	
Ce	120	117	96	101	107	112	76	80	80	
Pr	12	12	11	11	13	13	10	10	10	
Nd	43	42	38	38	49	45	34	32	32	
Sm	6.6	6.9	6.4	5.6	7.5	8.4	5.4	5.8	5.4	
Eu	0.93	1.27	1.68	0.68	1.70	0.87	0.69	0.53	0.66	
Gd	5.2	5.3	5.1	4.5	5.8	7.0	5.0	4.6	3.8	
Tb	0.73	0.74	0.69	0.55	0.80	1.02	0.80	0.76	0.58	
Dy	3.9	4.0	3.8	3.0	4.4	6.1	5.2	4.2	3.6	
Ho	0.82	0.79	0.79	0.58	0.94	1.25	1.17	0.80	0.66	
Er	2.21	2.31	2.31	1.76	2.64	3.4	3.8	2.42	2.02	
Tm	0.35	0.34	0.34	0.27	0.39	0.52	0.56	0.36	0.31	
Yb	2.47	2.28	2.01	1.83	2.43	3.3	3.1	2.43	2.03	
Lu	0.39	0.37	0.30	0.26	0.35	0.53	0.54	0.36	0.33	
Hf	8	9.3	5.9	7.3	6.3	7.6	5.5	6.0	5.3	
Ta	1.00	4.5	1.00	1.50	0.80	2.30	1.60	2.20	1.50	
Pb	10	11	10	19	8.6	16	13	9.2	2.70	
Th	20	17	12	24	14	23	19	17	17	
U	4.5	3.9	2.90	5.4	3.2	6.9	5.0	4.2	2.70	

