

Response to the reviews

We would like to thank both reviewers for their comments. We surely think that the manuscript has been considerably improved by such advices.

Here below we reply to reviewers. We grouped comments by reviewer #1 at the beginning (we split the comment according to the topic and marked each section as “RC1”), followed by reviewer #2 ones (“RC2”). Our replies are indicated with the acronym “AC”.

At the end of the reply a version of the revised manuscript with highlighted the changes in respect to the pre-revision version is included.

10 REFEREE #1: S. Winkler

A) General comments

RC1: The discussion article addresses an interesting and important topic. Whereas the focus of research on glacial dynamics and chronology during the LGM in the European Alps naturally has focused on the well-developed moraine sequences major valley glaciers formed when they flowed from their inner Alpine valley sections out onto the foreland, the investigated former Brenta glacier system is of a different type. Confined to a narrow valley it lacks any comparable assemblage of landforms and sediment that would allow easy reconstruction of its outline and chronology, and thus also of its glacial dynamics. The authors tackle the challenge by applying a multi-proxy approach using different (mainly sedimentological) methods. They, furthermore, aim to link the lithostratigraphical record of the Brenta megafan with the morphological and sedimentological record preserved in the valley. Given the lack of chronological record within the valley itself due to apparent lack of suitable sites and problems of applying surface exposure dating on glacial landforms and bedrock, this seem an appropriate attempt.

The strength of the article is, surely, that a number of different sedimentological methods are combined and that very detailed field work has been carried out to describe and carefully interpret the investigated key sites. The related sedimentological analysis is very sound and altogether the reader can easily follow the argumentation thanks to a number of well-prepared illustrations. The latter is not trivial due to the fact that especially if a study is based on such key sites the reader unfamiliar with those often finds it difficult to assess the detailed interpretation presented in similar stories. This is not the case here.

Finally, the authors develop and discuss some hypothesis about the glacial dynamics of the former Brenta glacier based on their chronological, sedimentological, and chronological findings. Although their conclusions are valid, I have the feeling that alternative explanations could also well be brought forward as reasons to match the evidence presented. In my specific comments below I will address those and want to invite the authors to consider at least mentioning them in the discussion section. Those are hypothesis as well and I, by all means, do not insist that the authors need to change their original

interpretation. But by briefly discussing those alternatives (and potentially rejecting them based on their field experience and findings) the authors would show that they explored a wider range of possible explanations. This would further improve the already well presented and written manuscript.

5 **AC:** We are glad that the reviewer appreciated our efforts and thank him for the useful comments. Here below we reply to them:

B) Specific comments:

RC1: The authors summarise their conclusions regarding the glacial dynamics within the narrow valley as following. “Glaciers flowing across narrow gorges turned out to be possibly slowed/blocked by such morphology and, if a lateral valley
10 exists, glacial/sediment fluxes can be diverted. Moreover, narrow valleys may induce glaciers to bulge and form icefalls at their front, preventing the formation of terminal moraines”.

I have to admit that I am not familiar with the study region and base my comments on my experience in different regions and with modern mountain glaciers. For me, it is not at all surprising that terminal moraines are not present in such relatively narrow mountain valleys. I see, however, not the necessity to infer specific processes like bulging or a specific morphology of
15 the glacier front (like ice falls). Firstly, a plausible explanation for the lack of terminal moraines in the valley is their easy potential erosion. Unlike in the case of LGM valley glacier flowing onto the wide, open forelands a terminal moraine once built is hard to preserve in a setting of a narrow valley where postdepositional glaciofluvial erosion may immediately start eroding the moraine during the initial retreat from the terminal position. Subsequent fluvial erosion (confined to the narrow valley floor) and other geomorphological processes (slope processes etc.) may also contribute to the difficult preservation of
20 terminal moraines and other glacial landforms. By contrast, preservation potential of the major lobate-shaped moraine sequences in the foreland seems much easier as only where Late Glacial or postglacial (glacio)fluvial actions concentrates moraines are easily eroded.

Another explanation for the lack of terminal moraines can be deduced from the different processes of moraine formation. Lateral moraines in high mountain ranges (modern as well as LGM ones) are predominately formed by dumping of supraglacial
25 debris. This well-established mechanism seems undisputed and the less compacted and consolidated character of their glacial diamicts demonstrates this very nicely (as also pointed out by the authors in their description and interpretations of lateral moraine in their study area). With terminal moraine formation there are, however, multiple individual processes involved, partly in complex interaction (ranging from simple pushing to glaciotectonic thrusting). At most modern mountain glacier where terminal moraine has been studied during the (few) occasions they advanced in more recent decades dumping of debris
30 was either absent or an insignificant contribution to moraine formation. By contrast, most processes that have been identified depend or are at least substantially influenced by the properties of the glacier bed material at the glacier margins, in particular its shear strength and deformability. This applies to situations with unfrozen bed conditions at the glacier margin (pushing) as well as with permafrost at the former glacier margins (glaciotectonic processes). As a result, even with an advancing glacier

front no or only a small terminal moraine may be formed if it rest on bedrock or a thin layer of sediment (especially if it has a high shear resistance). Based on these considerations regarding potential moraine formation processes I don't see the necessity to induce any form of "bulging" or a particular morphology of the ice front to explain a lack of terminal moraines. By contrast, I am aware of a modern analogues where a small mountain glacier advanced too fast (but did not surge) to develop a terminal moraine during the ongoing advance where it showed a steep, ice cliff-shaped glacier front. At the time the advances culminated and slowed down, a terminal moraine was pushed up in usual fashion. Summarising, a valid hypothesis for the lack of terminal moraines in the narrow sections of the valley could simply be the different framework (topography, glacier bed material etc.) during culmination of the LGM advance preventing a glacier confined to a narrow valley (possibly with some exposed bedrock at its glacier bed and the lack of deformable soft sediment) to effectively build up a terminal moraine. This hypothesis should be discussed in the related section of the manuscript – and I am more than happy that the authors present evidence that it can be rejected. But currently some readers may ask way the authors did not consider this apparent "easy" and "obvious" solution.

AC: We thank the reviewer for the detailed comment and prompts for discussion. We added in the text the proposed scenarios, discussing them in the light of our data.

All in all, we think that the most probable explanation is that material brought to the front, both during advance and stability phases, was completely carried away by proglacial streams. The location of the glacier front is constrained by lateral moraines and the Coste fluvioglacial deposits within about 250 m. The vertical drop in elevation in such a small distance between moraines and present valley floor (about 550 m) fits well with an icefall front. Being laterally constrained by hard rock steep valley flanks, proglacial fluvial processes could remove debris progressively, hindering the formation of end moraines. Bulging of the western lobe in respect of the eastern one is suggested by the location of the various morainic arcs that are about 20-to-100 m higher in elevation to the west.

RC1: The other explanation offered by the authors that I suggest could be discussed in the light of an alternative explanation is the hypothesis of narrow gorges slowing down/blocking glacier flow and cause diversion. In this context the altitudinal difference between the lateral moraines and the valley floor is additionally mentioned as indication of a blocking action (or bulging) of the glacier flowing through the narrow valley. Although I can follow the argument given by the authors, it is contradictory to common view that narrow valley channelise ice flow and cause higher flow rates (and increase erosional glacial power). According to some hypothesis promoted by researchers with a background in engineering ice flow mechanics should be seen as comparable with flow mechanics of water. Consequently a certain ice volume transferred from its accumulation area in inner Alpine catchments towards the glacier front as determined by the glacier's mass budget should theoretically speed up if the valley in its flow paths narrows (and not slow down). Any "overspill" and diversion could easily explained by the capacity of the narrow valley not sufficient even with an increased ice flow to transfer the entire ice mass. The huge difference between lateral moraines and valley bottom may indicate that the valley was at the maximum of its capacity with a huge ice mass occupying the valley. In this context, I am also not aware that supraglacial debris (even if

potentially integrated into the en- or subglacial debris transport pathways through extensive crevassing) considerably slows down ice flow in those regions currently be the home of extensively debris-covered glaciers. If theoretically a narrow valley inhibits efficient ice flow and obstructs normal mass transfer it would even be a possible cause of glacier surges (that despite multiple theories for their causes all have in common that the normal mass transfer is inhibited until a certain threshold is reached for the surge to start).

I am confident that by exploring the hypothesis mentioned above in the discussion chapter the part of the discussion paper referring to glacial dynamics could be strengthened by providing some alternative views for the author's interpretations of their great field and sedimentological evidence. I am far from insisting that they need to change their conclusions, but feel that currently there is a lack of addressing some common views in the discussion section and some readers may interpret it as some obvious explanations having been overlooked.

AC: We added some sentences exploring the aspects highlighted by the reviewer. As mentioned by him, valley narrowing is known to speed up glacier flowing due to ice mechanics. Nonetheless, in some cases remarkable reductions of the valley section are known to have caused the blockage of glaciers (Burbank and Fort, 1985). In our case, the valley section reduces of about 90% (from about 1 km to 100 m), thus we consider that friction at glacier margin probably slowed down/blocked the ice flow. This situation must have lasted only for a limited amount of time: as soon as Canal La Menor became an effective path for the glacier, the western tongue became unprivileged and is likely to have stopped almost completely. Indeed, glacial/sediment fluxes can be diverted when stabilized valley glaciers can extend laterally (Barr and Lovell, 2014). Glacial surges occurred prior of the activation of the Canal La Menor, if ever occurred, left no traces in the sedimentary record and in the valley morphology. Moreover, the glacial front after such surge must have withdrawn to the Valsugana gorge in order to let the Coste section to form. That said, it seems unlikely to us that such surges may have occurred.

C) Technical corrections:

RC1: The manuscript is mostly well structured and written. A few editorial changes may be addressed during the revision. I only point out some few points here.

1.) I feel that the title is a bit strong by using the phrase "enlightens glacial dynamics". Even without considering my comments above, there are still some uncertainties that remain. Perhaps the authors could find an alternative title.

AC: We tried to find a new title to both "soften" the previous one and maintain the focus. Here is our attempt: "Glacial dynamics in Prealpine narrow valleys during the Last Glacial Maximum inferred by lowlands fluvial record (NE Italy)".

2.) In a few sentences, like page 2 line 13 ff., there is an excessive use of commas. Not all are necessary and I would recommend that during the final check of the manuscript, some may be removed.

AC: Also referee #2 found pointed out some grammar and style suggestions. We re-read completely the text, trying to improve it.

RC1: 3.) The type of radiocarbon-dated material and its position are given in the related table. I only miss information about the sampled thickness (I assume 1 cm?).

AC: A column has been added to that table, containing the requested information.

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RC1: 4.) Wasn't it possible to assess a potential difference between lodgement and melt-out till and make a judgement here?

AC: We modified the description to better clarify the differences between lodgment and melt-out till. In our case, the difference between them are: the clast shape (more rounded in the lodgment till) and the matrix (silty in the lodgment till and sandy-silty in the melt-out till).

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REFEREE #2: L. Stutenbecker

A) General comments

RC2: The discussion paper by Sandro Rossato and co-authors presents an interesting approach to infer LGM dynamics in a narrow valley in the southern Alps, mainly using a provenance tracing technique applied to sediments in the corresponding lowland. Overall the paper is well structured and it is easy to follow the central theme. The methodological description of the provenance tracing approach could be improved with regards to the following 3 points:

AC: We thank the reviewer for the useful comments, we found them very useful. Here we reply to them, one by one:

RC2: 1) I feel that the explanation of the mixing modeling approach used to infer the relative contributions of the modern Brenta, Cisonon and Piave rivers to the sediments is a bit short. Sure, your approach basically uses the same strategy as described in Vezzoli & Garzanti (2009) and the river endmembers defined in Garzanti et al. (2006), but it needs to be explained a bit more in detail (goodness of fit, errors, etc.).

AC: We improved both in the methods and in the description the strategy of the mixing provenance after Vezzoli and Garzanti (2009).

RC2: 2) In sections 4.2 to 4.4 I couldn't follow the definition of the "petrofacies" and the "units", respectively. Were the "units" of the cores defined based on the petrofacies? Or the other way round? The text is a bit ambiguous in this regard and needs clarifying. Perhaps it would make sense to describe the cores first (section 4.4) and then interpret the petrography/mineralogy/geochemistry (sections 4.2 and 4.3)?

AC: We decided to avoid the use of “unit” and re-arranged the chapter moving core description to the beginning, followed by petrography/mineralogy/geochemistry results and interpretations. “Petrofacies” remains the only subdivision criterium without stratigraphic ambiguity.

- 5 **RC2:** 3) I would highly recommend using principal component analysis (PCA) for the interpretation and visualization of the petrographical, mineralogical and chemical datasets. PCA has become a standard tool in provenance analysis and the compositional biplots really help visualizing differences between samples and identifying clusters (see e.g. Aitchison, 1982, *Biometrika*; Aitchison & Greenacre, 2002, *Applied Statistics*; Vermeesch, 2013, *Chemical Geology*). The ternary plots are okay to use for a first visualization, but I wonder which additional conclusions could be drawn from a compositional biplot.
- 10 You could for example try plotting all parameters together (petrography, mineralogy, chemistry) to see how the clustering goes. Don't forget to also plot your modern river endmembers.

I would recommend the CoDaPack from the group at the University of Girona: <http://www.compositionaldata.com/codapack.php> (reference to use: Comas, M., Thió-Henestrosa, S., 2011. CoDaPack 2.0: a stand-alone multi-platform compositional software. In: Egozcue, J.J., Tolosana-Delgado, R., Ortego, M.I. (Eds.), *CoDaWork'11: 4th International Workshop on Compositional Data Analysis*. Saint Feliu de Guixols, Girona, Spain). You just import your table as a .csv or .txt file and then go to Graphs/centered-log-ratio (CLR) biplot. Alternatively, if you like playing with R, you might consider using the “Provenance” toolbox of Pieter Vermeesch (Vermeesch, P., Resentini, A. and Garzanti, E., 2016. An R package for statistical provenance analysis. *Sedimentary Geology*, 336, 14-25)

15

AC: We used the PCA (CoDaPack 2.0) for the interpretation of the petrographical dataset because we have endmembers to plot. We presented the results with the new diagrams in Fig. 7.

20

We tried to use PCA also for visualization and interpretation of mineralogical and geochemical data, but clusters identified for different petrofacies have not substantially changed. Moreover, lacking appropriate data concerning mineralogical and geochemical analyses of end members (i.e., different lithologies of modern river endmembers), a complete provenance evaluation cannot be done. For these reasons, we prefer to maintain conventional descriptive diagrams, which are useful for a first visualization, but also evidence the main distinctive features of petrofacies.

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B) Detailed comments

AC: minor comments are grouped together where no specific clarification is needed. More detailed explanations are given where necessary.

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RC2: p. 2 line 20: "allow FOR" instead of "allow to TO"

p. 2 line 32: there is no plural for “evidence”.

p. 3 line 17: “Last glaciation”. Either you use Last Glaciation (both capital letters) if you use this as a proper noun or “last glaciation” without any capital letters.

p. 3 line 20: Add “(Fig. 1)” after “left well-preserved terminal moraines”.

p. 4 line 12: use either the singular or the plural for the rock types. I suggest to use “porphyries” instead of “porphyry” here

5 **AC:** Done.

RC2: p. 4 lines 11-14: This paragraph about the geology doesn’t really fit into “3.1 Field survey”. Either you move this paragraph to “2 Setting” if it’s just a description of the geology or into another heading if your aim is to describe your provenance strategy.

10 I am a bit confused by the “granites, porphyries and metamorphic rocks” you mention. In Fig. 1 you only show group of rocks (“volcanic” or “plutonic”), which is understandable in order for the figure to be legible, but into which groups do the “granites, porphyries and metamorphic rocks” belong? I guess the metamorphic rocks belong to the Variscan basement and the porphyries into the “Permian volcanic rocks”?

I guess you mean that the Brenta drainage area comprises plutonic and volcanic rocks, which are not present in the neighboring

15 Astico and Piave valleys, and that this difference makes it possible to identify the respective deposits? Please make all of this clearer by writing 2-3 more sentences.

AC: We modified the text to avoid misinterpretation and added some sentences, as suggested. Lines 11-14 remains in the same chapter but have been modified to better reflect our approach.

20 **RC2:** p. 5 line 2: “0.0625-2” Did you use this particular grain size fraction in order to compare your dataset with the river endmembers from Garzanti et al. (2006)? If so, please state this in the methods. By taking such a wide grain size window one risks to introduce bias by grain size sorting...

AC: Yes, we used the entire sand fraction in the Gazzi-Dickinson method in order to compare our samples to the endmembers from Garzanti et al. (2006) and Monegato et al. (2010). We modified also the text to make it clear.

25

RC2: p. 5 lines 4-5: Please rephrase the sentence about the point counting, for example “Following the Gazzi-Dickinson method 400 points per thin section were counted using a 0.5 mm grid spacing (Ingersoll et al. 1984).” Did you use the same grain classes as Vezzoli & Garzanti (2009)? If so, please state so in this paragraph.

p. 5 line 6 “Data and parameters were reported in Table 2 AND plotted in ternary diagrams.”

30 p. 5 lines 6-9: Please describe more thoroughly the strategy behind this approach (defining endmembers, applying a linear mixing model, reporting the goodness of fit,)

p. 5 line 12: Avoid the word “adopt” in this context.

p. 7 line 4: left side? Please use geographic directions (west/east)

p. 7 line 27: “found at THE surface”

- p. 7 line 28: “Evidence” has no plural: “All evidence shows...”
- p. 7 line 29: “...which was collecting material from an area located at least 25 km to the north...”
- p. 8 line 10: right side? Please use geographic directions (west/east)
- p. 9 line 1: “The lower unit could be attributed to...”
- 5 p. 9 line 19: What is “CE”? I couldn’t find it in the text.
- p. 9 line 22: “...while the content of felsic volcanic fragments remains high.”
- p. 9 line 23-24: Please rephrase to something like “Although the spectrum of lithic fragments contained in petrofacies 2 is similar to that of petrofacies 1, petrofacies 2 contains more carbonate clasts, generally above 35%. Micritic limestone fragments are particularly common.”
- 10 p. 9 lines 25-28. This is a long and convoluted sentence. Rephrase to something like “The single sample of petrofacies 3 shows a completely different composition. The carbonate fragment content increases to 55% at the expense of quartz (only 10 %) and other grain types (below 10 %)” ...Also I do not understand how the chert is embedded into the limestone... is it a partially dissolved and then recrystallized limestone or ...?
Please specify by including a better petrographic description.
- 15 p. 10 line 2: “...with an enrichment of carbonate rock fragments...”
- p. 10 lines 5-6: “Finally, petrofacies 3 with its high carbonate clast content is more similar to the modern Piave River sediment.”
- AC:** Done.
- RC2:** p. 10 lines 6-9: Couldn’t this be interpreted simply as a reworking of deposits from the Piave catchment?
- 20 **AC:** We rephrased the sentences after statistical analysis. The Piave sediments are excluded as possible source.
- RC2:** p. 10 lines 13-25: Do “unit 1” and “unit 2” refer to “petrofacies 1” and “petrofacies 2” from before? If so, please use the same name, either “petrofacies” or “unit”.
- AC:** As above, we decided to avoid completely the use of the term “unit” in favor of “petrofacies”.
- 25
- RC2:** p. 11 lines 7-8: No capital letters for quartz and feldspar!
- p. 11 line 10...” and two of them have been dated”
- p. 11 line 14: Again, no capital letters for quartz and feldspar.
- p. 11 line 21: Again, no capital letters for quartz and feldspar.
- 30 p. 11 lines 22-23: “... the dolomite content is significantly higher (Fig. 8).”
- p. 12 lines 2-3: Again, no capital letters for quartz and feldspar.
- p. 12 line 28: parts
- p. 13 line 2: left valley side? Please use geographic directions (west/east)
- p. 13 line 8: “Based” instead of “Basing”

AC: Done.

RC2: p. 13 lines 8-11: I do not understand this interpretation... Which of your data supports this? Please specify

AC: Referee number 1 had many comments on this section, please refer to its reply for details.

5

RC2: p. 13 line 23: consisted of

p. 13 line 33: the “so” in the sentence can be deleted

p. 15 line 13: Not sure what you mean by “looked to”? Linked to?

p. 16 line 1: in respect to

10 **AC:** Done.

C) References

RC2: I did not thoroughly check all the references, but there are at least two where author’s names are not capitalized (e.g. page 19 line 23 “Andò” or page 20, line 1 “Anderson”).

15 **AC:** We checked and correct references.

D) Comments on figures and tables

RC2: Figure 1: In the legend you use UPPER Permian for the sandstones but EARLY Permian for the plutonic rocks. Use either “Upper and Lower” or “Early and Late” to make this consistent. See for instance Haile 1987 (Marine and Petroleum Geology) for the use of this nomenclature.

Figure 2: Increase the size of the yellow square indicating the drill site.

Figure 6: What is the red square in the uppermost left corner and why is it red?

Figure 7: Add to the figure caption the explanations of the ternary corners (CE, Lm, Lv, Ls...). Did you group together certain grain classes?

25 Table 2: Add a heading for the last column of this table (e.g. “Relative contribution of endmembers” or something like that). Do the numbers (0.886 and so on) refer to R2? Please explain this! What’s up with sample RB1-8? Why is it “not representative”?

AC: all comments have been considered and included.

Glacial Lowlands fluvial sedimentation enlightens glacial dynamics in Prealpine narrow valleys during the Last Glacial Maximum inferred by lowlands fluvial record (NE Venetian Forealps, Italy)

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Abstract. During the Last Glacial Maximum (LGM), most of the major glaciated basins of the European Southern Alps had piedmont lobes with large outwash plains; only few glaciers remained within the valley. The formers left well-preserved terminal moraines, whose investigation allowed to infer their evolution and chronology. Valley glaciers remnants, on the contrary, are often scantily preserved and changes can be detected only through the correlation with the glaciofluvial deposits in downstream alluvial basins. The Brenta glacial systems dynamics in its terminal tract was inferred through a wide range of sediment analysis techniques on an alluvial stratigraphic record of the Brenta megafan (NE Italy) and the mapping of in-valley glacial/glaciofluvial remnants. Glaciers flowing across narrow gorges turned out to be possibly slowed/blocked by such morphology and, ~~if a lateral valley exists,~~ glacial/sediment fluxes ~~being~~ diverted to lateral valleys. Moreover, narrow valleys may induce glaciers to bulge and form icefalls at their front, preventing the formation of terminal moraines. The Brenta glacier was probably slowed/blocked by the narrow Valsugana gorge downstream of Primolano and was effectively diverted eastwards across a windgap (Canal La Menor valley), joining the Cison/Piave glaciers near Rocca and ending ~2 km downstream. The Cison and Piave catchments River started to contribute flow along its present path just before 27 ka cal BP, ~~while the Piave catchment contributed~~ to the Brenta system right after 27 ka cal BP up at the acme of LGM, from ~27 to, at least, ~19.5 ka cal BP. After the glaciers collapse the Piave River flowed again into its main valley, whilst the Cison continued to merge with the Brenta.

Our investigation shows that glacial catchments may significantly vary over time during a single glaciation in rugged Alpine terrains. Sand petrography and chemical/mineralogical composition of sediments are good tracer of such variations, that reflects in the glacial and glaciofluvial systems and can be recognized in the alluvial stratigraphic record far downstream from the glacier front.

1 Introduction

Mountain glaciers are complex systems, whose evolution affects both their mountain basins and the alluvial plains that receive the glaciofluvial water-and-sediment flux (e.g. Russell et al., 2006). Few minor valley glaciers are currently present in the highest areas of the European Alps (Evans, 2006), whereas during Pleistocene glaciations large ice-streams flowed along most

of the Alpine valleys, leading to deep landscape modifications (e.g. Koppes and Montgomery, 2009; Preusser et al., 2010; Wirsig et al., 2016). Most of the major glaciated basins had piedmont lobes with large outwash plains, where the stratigraphic reconstruction and available chronology allowed to infer the evolution of the glacial system (Monegato et al., 2007; Preusser et al., 2011; Ravazzi et al., 2012; Fontana et al., 2014). However, there are catchments whose glacier remained within the valley and their evolution could be detected through the correlation with the related glaciofluvial deposition in the piedmont area (van Husen and Reitner, 2011; Rossato et al., 2013).

The Last Glacial Maximum (LGM) was the last cold extreme on Earth and it provided the best-preserved sedimentary and geomorphic record among all Pleistocene glaciations (Bowen, 2009; Clark et al., 2009; Hughes and Gibbard, 2015). In Europe, the Alps and their foreland constitute a key region for LGM studies, as evidence of this event is widespread and chronologically well framed between 30 and 17.5 ka cal BP (e.g., Ivy-Ochs et al., 2008; Ivy-Ochs, 2015; Rossato and Mozzi, 2016; Monegato et al., 2017). Moreover, they constitute an effective barrier for wind circulation (Florineth and Schlüchter, 2000; Luetscher et al., 2015) and offer the unique opportunity to validate climate models (e.g. Smiatek et al., 2009; Torma et al., 2015) and study how glacial processes affect mountain chains (e.g. Norton et al., 2010). LGM glaciers were filling the valleys fed by the major accumulation zones located in the axial and highest part of the Alps (e.g., van Husen, 1987; Kelly et al., 2004; Wirsig et al., 2016). In the southern alpine sector, due to different wind circulation regime (Luetscher et al., 2015), topography greatly influenced glacier evolution (Wirsig et al., 2016). Alpine glaciers, and their sedimentary outputs, proved to react differently to climatic signals, both along the ~~north-south~~North-South (e.g. Luetscher et al., 2015) and the ~~west-east~~West-East directions (Becker et al., 2016; Monegato et al., 2017; Seguinot et al., 2017). Differences arise also when dealing with neighboring glacial systems, due to their size, catchment topography and possible glaciers confluences and transfluences (e.g., Kelly et al., 2004; Monegato et al., 2007; Rossato et al., 2013).

The present availability of a wide range of proxies, coupled with the increased accuracy of geochronological methods (Brauer et al., 2014), allow ~~for~~ a better assessment of LGM glaciers' behavior compared to earlier studies in the Alps, mostly based on landforms and deposits characterization (e.g. Penck and Brückner, 1909; Sacco, 1937; Venzo et al., 1977; Schlüchter, 1986; van Husen, 1987). The analysis of loess and palaeosols has been coupled with biological proxies, such as pollen, chironomids, charcoal and many more (e.g., Heiri et al., 2014; Samartin et al., 2016). Petrographic/mineralogical study of sediments have supported palaeoenvironmental reconstructions and allowed to infer variations in the sedimentary systems (Garzanti et al., 2011).

In this paper we investigate the interaction between the LGM glaciers in the middle Brenta valley (also known as “Valsugana”, Italian Forealps) and the related glaciofluvial system in the piedmont plain (Fig. 1). During the LGM, the Brenta glacial system received contribution from the major Adige (Etsch) glacier (Trevisan, 1939; Tessari, 1973; Avanzini et al., 2010; Rossato et al., 2013), and fed a fluvial megafan, which is one of the most prominent sedimentary alluvial systems on the southern side of the Alpine chain (Mozzi, 2005; Fontana et al., 2014). The main aim of this paper is to explore and define the possibility of correlating glacial advances and transfluences in mountain areas with sedimentation pulses in the lowlands using integrated geomorphic, sedimentary, petrographic, mineralogical, geochemical and geochronological evidences.

2 Setting

The Venetian Forealps are geologically detached from the Dolomites by the Valsugana fault (Castellarin et al., 2006) and are characterized by a belt of carbonate plateaus deeply carved by the lower reaches of the Astico, Brenta, Cison and Piave valleys (Fig. 1). Except for the Astico River, whose catchment is restricted to the western part of the Venetian Forealps, the others have their upper catchments in the Dolomites, which include the Permo-Triassic sedimentary successions (sandstones, dolostones, limestones and volcanic rocks), the low-grade ~~metamorphic~~ crystalline basement and the Permian porphyries (e.g., Bartolomei et al., 1969; Avanzini et al., 2010; Fig. 1). The Brenta and Cison catchments also include the Permian plutonic rocks of Cima d'Asta (Fig. 1). In the footwall of the Valsugana Fault the Jurassic-Tertiary sedimentary succession crops out, including different types of limestones, turbiditic sequences and the terrigenous units of the Southalpine foredeep (e.g., Massari et al., 1986; Barbieri and Grandesso, 2007; Stefani et al., 2007). In particular, in the Cison catchment, all around Lamon (Fig. 1), micritic limestones crop out extensively (Tessari, 19739). Here, a remarkable fluvial aggradation took place during/after deglaciation, later followed by river incision and ~~the formation of a five-step~~ terrace staircase ~~is preserved~~, the highest ~~and largest~~ terrace being located at about 600 m a.s.l., 200 m above the Cison valley bottom. The deposition of such an amount of sediment was ~~due~~ probably ~~due~~ to the damming of the Cison valley south of Lamon, possibly by a large dead-ice mass or a landslide event, but no direct evidence of it has been found (Tessari, 19739).

The plateaus characterizing the Venetian Forealps (Castiglioni et al., 1988) have mean elevations from 900 to 2000 m a.s.l. and ~~they~~ hosted small cirque or plateau glaciers during the ~~L~~ast glaciation (Trevisan, 1939; Carraro and Sauro, 1979; Baratto et al., 2003; Barbieri and Grandesso, 2007). The major Astico (Cucato, 2001; Rossato et al., 2013) and Piave (Venzo, 1977; Carton et al., 2009) valleys were carved by ice-streams that reached the lower valley ~~reaches~~ segments and left well-preserved terminal moraines (Fig. 1).- Despite the large megafan ascribed to the LGM (Mozzi, 2005; Fontana et al., 2008; Rossato and Mozzi, 2016), the Brenta glacier is the only major system in the south-eastern Alps that left no clear evidence of terminal moraines (Castiglioni, 2004). The reason why the Brenta system did not follow such evolutionary path remains unresolved, although some early authors already dealt with this challenging topic (e.g. Taramelli, 1882; Penck and Brückner, 1909; Castiglioni, 1940). Taramelli (1882) and Castiglioni (1940) placed the Brenta glacier front near the town of Valstagna, about 10.5 km south of the confluence between the Brenta and Cison valleys (Fig. 1), while Penck and Brückner (1909) located it about 6 km further to the south, near the town of Solagna. Due to the lack of direct geomorphic or sedimentary evidence ~~of~~ the glacier's front, both interpretations were based on the speculation that the glacier thinned gradually downstream of the last preserved lateral moraine at Enego (elevation 790-760 m a.s.l.). The terminal tract of the Cison valley, named Corlo valley, ~~was~~ closed by a dam ~~in 1953~~ and filled by the artificial ~~Corlo Lake~~ lake of the same name (Fig. 1), ~~so no further survey is presently possible~~ since 1953 and any direct observation of sediments is prevented.

The Brenta fluvial megafan is part of the foreland basin of the uplifting Eastern Southalpine chain (e.g., Castellarin et al., 2006; Stefani et al., 2007). This ~~megafan~~ landform extends from the Brenta valley mouth to the ~~present~~ Venetian coastline. It can be roughly separated into two sectors: i) piedmont (~20 km from the apex), made of gravel and with an average topographic

gradient of 3-5‰, ii) low plain, made of sandy fluvial ridges and silty-clayey floodplains, with a decreasing of topographic gradient to less than 1‰ (Mozzi, 2005; Fontana et al., 2008; Mozzi et al., 2013).

3 Methods

This investigation was carried out through field survey, coring, petrographic and mineralogical analyses and remote sensing.

5 All methods and results are presented independently, whilst their meaning, implications and interconnections are discussed thereafter.

3.1 Field survey

An extensive mapping of the Quaternary sediments cropping out in the area of the middle Valsugana and the junctions with Canal La Menor and lower Cison (Corlo) valley, was performed (Fig. 2). Sedimentary facies were observed and described
10 in the outcrops to identify their original depositional setting; particular attention was devoted to the lithology of the clasts, which provided information on the provenance of the sediments. ~~In this perspective~~~~As it is possible to appreciate in Fig. 1~~, the geology of the eastern Southern Alps (Fig. 1) allows a clear distinction of each drainage basin with different petrographic signatures. ~~Porphyries, granites~~~~Granites, porphyry~~ and metamorphic rocks (i.e. Permian volcanic rocks, Lower Permian plutonic rocks and pre-Permian Variscan basement in Fig. 1, respectively) are indicators of Brenta and Cison valleys and,
15 thanks also to their high resistance to weathering, can help in identifying glacial deposits upon a carbonate bedrock.

Relevant landforms were accurately surveyed, with particular attention to the LGM moraines which are generally well preserved and quite easily identifiable in these areas, where little anthropogenic activity took place.

3.2 Cores

Two 30-m-long cores were drilled near the city of Piazzola sul Brenta, in the upper part of the Brenta megafan, about five km
20 apart and at a topographic elevation of about 30 m a.s.l. (Fig. 3). These cores were part of a pilot study on groundwater geochemistry (Carraro et al., 2013; 2015). They were described basing on the lithofacies of the sediments and sampled for sand petrography and mineralogical analyses. Five organic samples were collected from the inner part of the cores to minimize contamination and dated with the ¹⁴C AMS method at the radiocarbon laboratory of the University of Zurich (Switzerland) (Table 1). OxCal software (version 4.2, Bronk Ramsey, 2009; IntCal13 calibration curve, Reimer et al., 2013), has been used
25 to calibrate laboratory ages.

A single hand-core was drilled in the Guarda area, on the northern flank of the Canal La Menor valley, uphill of an elongated ridge that has been identified as a LGM lateral moraine (see Results chapter and Fig. 2 for location), at about 660 m a.s.l.. This borehole has been realized with a hand-auger (Edelman combination type, EjikelkampTM); this equipment allows to obtain a semi-disturbed sequence of fine sediments, with the limitation that the maximum grain size of the sediments that can be
30 sampled is coarse sand to fine gravel.

3.3 Sand petrography

Ten samples were collected from the two long cores for provenance analysis. The ~~entire sandsandy~~ fraction ~~(0.0625-2 mm)~~ was isolated and impregnated in an epoxy resin according to Gazzi et al. (1973) methodology, ~~in order~~ to obtain samples for thin-section analysis ~~comparable with river endmembers after Garzanti et al. (2006) and Monegato et al. (2010).~~ These were subsequently stained with alizarine-red solution for the determination of the carbonate phases. ~~Following the~~ Gazzi-Dickinson ~~methodprocedures (Ingersoll et al., 1984) was adopted for counting and~~ 400 points ~~per thin section~~ were ~~countedechecked,~~ using a 0.5 mm grid spacing ~~(Ingersoll et al., 1984).~~ ~~for each section.~~ Data and parameters were reported in Table 2 ~~and,~~ plotted in ternary diagrams. ~~Petrofacies of modern rivers (Garzanti et al., 2006; Monegato et al., 2010) and local late-Pleistocene deposits (Monegato et al., 2011; Rossato et al., 2013) were considered for comparison to assess the provenance of~~ the different stratigraphic intervals. ~~The statistical spreadsheet by Vezzoli and Garzanti (2009) was adopted to assess the contribution of each river system.~~

~~Principal component analysis (PCA) was performed using CoDaPack (Comas and Henestrosa, 2011) using the compositional biplot (Aitchinson and Greenacre, 2002) for better visualizing the dataset and the variables . The ternary diagrams with the most representative variables are proposed to discuss the data structure. The centering (e.g., Buccianti et al., 1999; von Eynatten et al., 2002) was used for avoiding disturbances related to the dominance of one or two components. In the statistical analysis, petrofacies of modern rivers (Garzanti et al., 2006; Monegato et al., 2010) were included for comparison in order to assess the sediment provenance in the different stratigraphic intervals.~~

~~In addition, the statistical technique by Vezzoli and Garzanti (2009) was also adopted to assess the contribution of major drainage systems of the area related to the Brenta, Cismon and Piave rivers (Fig. 1) as endmembers. The parameters were compared to evaluate the possible matching with these catchments and results with $R^2 > 0.7$ were considered robust. Except for one sample (RB1-8), all the samples show a good interpretation confidence (Tab. 2).~~

3.4 X-ray diffraction (XRD)

In order to minimize preferred orientation, samples were pulverized and backloaded. A Philips X'Pert Pro diffractometer (Cu tube and secondary monochromator) was adopted. The mineral constituents were quantified using HighScore plus software following Rietveld refinement (Young, 1993); zincite (ZnO) was added as an internal standard (sample:standard = 10:1 weight ratio). It allows also to estimate the amorphous components (labelled Am.XRD, in Stab. 1).

To check the reliability of mineral quantification, the chemical composition of samples was calculated using stoichiometric mineral composition (for quartz, calcite, dolomite, feldspars, illite and kaolinite); a Fe-rich, Mg-poor dolomite was also included in the calculation (according to the XRD evidences of non-stoichiometric dolomite in almost all the samples), two Al-chlorites (Fe- or Mg-enriched) and organic matter. The comparison between calculated and measured chemical composition was considered satisfactory (total least square within 10 for 29 samples over 32).

3.5 Chemical composition

The major elements, some trace elements (including N) and the organic carbon (C_{org}) were determined as reported by Carraro et al. (2015). Samples were digested with concentrated $HNO_3 + HCl + HF$ at $140\text{ }^\circ\text{C}$ for 90 minutes, then rinsed with H_3BO_3 and heated at $140\text{ }^\circ\text{C}$ for 60 minutes. Afterwards, the solutions were analyzed by inductively coupled plasma (ICP-OES) and atomic absorption spectroscopy (AAS). The loss on ignition (LOI) was measured after heating the sample to $860\text{ }^\circ\text{C}$ for 20 minutes and to $980\text{ }^\circ\text{C}$ for 2 hours.

An automatic elemental analyzer was used to obtain C_{org} and total N for the carbonate-free residues. The measures were repeated at least twice using Ag sample containers.

All the mineralogical and chemical data were used for hierarchical cluster analysis (SPSS), in order to point out sample similarities and/or anomalies. Five dark sediments were grouped in the same cluster; this group is characterized by a percentage of organic matter higher than 12 %. This threshold value was used for peat identification (see Carraro et al., 2015 for analytical details). Macroscopic features (black color and fine-grained) were used for peat identification when chemical data were not available.

3.6 Remote sensing

Aerial photographs and satellite images of public use (Google Earth and Bing databases) were processed and analyzed for the mapping of relict landforms. Panoramic and detail photos were acquired during field surveys and subsequently used in conjunction with the other images.

A Digital Elevation Model (DEM) provided by the Veneto Region, based on topographic data derived from 1:5000 topographic maps (5 m cell-size; XY accuracy: 2 m - <http://idt.regione.veneto.it/app/metacatalog/>) was used. It covers the entire study area, assuring a uniform accuracy of investigation. The various DEM tiles were assembled with ArcGis (10.4.1 version) to better process them and to obtain a uniform visualization. All topographic profiles here presented were based on this DEM.

4 Results

4.1 Field survey

The field survey allowed to identify some key stratigraphic sections and outcrops that were regarded to be representative of specific sectors of the study area (see Fig. 2 for location). Their descriptions are presented here in geographical order, from eEast to wWest and from nNorth to sSouth.

4.1.1 “Seren valley” and “Roncon” outcrops

In the Seren valley bottom (390 m a.s.l.), widespread outcrops of matrix-supported diamicton can be found (Fig. 2). These deposits are overconsolidated and characterized by centimetric clasts with sparse boulders, sub-rounded to angular in shape,

embedded in abundant silty-~~sandy~~ matrix. In the thalweg of the Stizzone Creek that runs along the valley, ~~silty overconsolidated~~, matrix-supported diamicton crops out, with striated clasts. Different sedimentary, volcanic and metamorphic lithologies are present in the deposit, all showing no evident weathering. ~~The Seren valley~~ These deposits can be ascribed to ~~lodgment and~~ melt-out tills, whilst those located along the thalweg are lodgment till, both belonging to the Piave glacier. In the nearby Roncon section (Fig. 2), a ~~deposit~~ similar to these melt-out tills ~~deposit~~ could be observed in few, decametric outcrops at an elevation of about 450 m a.s.l.

4.1.2 “Monache” ridges

In the Monache plateau a series of ridges, more than 0.5 km long, is present, ~~at an~~ elevation ranging from 750 to 650 m a.s.l. (Fig. 2). These ridges are elongated and asymmetric in shape, as they, present a very steep, 3 to 20 m high downhill flank, ~~3 to 20 m high~~, whilst the uphill side is lower ~~shorter~~ and ~~locally~~ consists of a low-angle slope that rests on the bedrock. These landforms consist mainly of matrix-supported diamicton characterized by white/grey limestone clasts, up to 50 cm large, with dark flint nodules (black and brown). All observed clasts are made of “Maiolica” limestone, a Lower Cretaceous formation that crops out extensively on the whole Grappa Massif (Dal Piaz et al., 1946; Carraro et al. 1989), where the ridges are located. These ridges are interpreted as lateral moraines of the Piave glacier fed by local ~~debris of~~ limestones debris.

15 4.1.3 “Guarda” ridge and core

The Guarda ridge ~~is located~~ ~~can be found~~ on the northern ~~left~~ side of the Canal La Menor valley, in the Casere alla Guarda locality, at an elevation ranging from 700 to 660 m a.s.l. (Fig. 2). It is about 400 m long, up to 30 m high and has very steep flanks. This ridge consists of a polygenic diamicton with clasts of porphyry, limestone and siltstone, up to 50 cm in size, sub-rounded to angular in shape. Weathering of clasts is minimal, and the material is not overconsolidated. It is interpreted as a lateral moraine of the tongue of the Brenta glacier that was flowing through the Canal La Menor valley.

A 4.7-m long core (Guarda1 core) was drilled manually in the Guarda locality, at an elevation of 664 m a.s.l., on a wide valley bottom that is closed downstream by the Guarda moraine (Fig. 3 and 6). The cored sequence consists of ~~is constituted by~~ clayey silt layers, grey brown in color, with sporadic presence of centimetric sandy intervals. A single 30-cm-thick gravelly layer ~~(clasts are 3-4 cm in size)~~ is present between 3.2 and 3.5 m b.s., with sparse angular gravel clasts (3-4 mm in size) immersed in sandy matrix. The Guarda1 core testifies a phase of low-energy sedimentation in a confined environment, with a single high-energy event, ~~that deposited 30 cm of gravel~~. According to the lack of deep weathering of the deposit and the presence of a poorly-developed soil on top of the succession, the whole sequence is likely to have deposited in a fluvio-lacustrine basin during the late stages of LGM and/or during the Lateglacial and early Holocene, when the Guarda moraine was blocking the runoff from this lateral valley to the main Canal La Menor valley.

4.1.4 “Novegno” and “Col del Gallo” deposits

The top of the Novegno plateau is characterized by a low-gradient plateau at elevations ranging from about 720 to 600 m a.s.l.. In this area, many elongated ridges were found, locally merging one into the other, with a general SW-NE direction (Fig. 2). They are up to 2-km long, 50-m wide and 40-m high, usually with steep slopes. The observed outcrops show that these ridges have polygenic clast composition, being constituted by matrix-supported diamicton with clasts of porphyry, limestone and siltstone, up to 40 cm in size, sub-rounded to angular in shape (Fig. 4b). Between the ridges, as well as on the northern and southern sides of Col del Gallo (780-600 m a.s.l.), scattered patches of similar deposits can be found, characterized by a slightly ~~higher~~ ~~more abundant content in~~ matrix ~~content~~ (Fig. 2, 4c). The deposit is not over-consolidated and the weathering, ~~even of the limestones,~~ is minimal. Locally, some big boulders, up to 1.5-m large, were found; these are mainly of porphyry (Fig. 4a) and granite. ~~These sediments can be classified as glacial in origin, more specifically melt-out and flow tills.~~ On top of Col del Gallo (870 m a.s.l.), no ~~prope~~ ~~lear~~ outcrops are present, but centimetric clasts of volcanic and metamorphic phyllites were found ~~in the~~ ~~at~~ surface ~~soil~~. All ~~evidence show~~ ~~evidences show~~ that the Novegno plateau is occupied by many lateral moraines formed by a glacier which was collecting material from ~~an area located~~ at least 25 km ~~to the~~ north, where the nearest outcrops of porphyry can be found (Fig. 1). Similar glacial sediments are found on the northern and southern sides of Col del Gallo (Fig. 4c). It is likely that they relate to the same glacier. The deposits located on top of Col del Gallo are about 100 m higher than the others and may possibly be related to a previous glacial advance.

4.1.5 “Sorist” ridges

In the Sorist mount area a series of at least three ridges, more than 0.8 km long, is present, at an elevation ranging from 760 to 650 m a.s.l. (Fig. 2). These ridges are elongated and present steep flanks, up to 10 m high. Locally the deposits forming these landforms crop out, ~~showing a~~ ~~allowing to determine their~~ polygenic nature, with clasts of porphyry, limestone and siltstone, up to 60 cm in size, sub-rounded to angular in shape, embedded in abundant matrix (Fig. 4d). ~~Weathering~~ ~~Alteration~~ of clasts is minimal, and the material is not overconsolidated. Some ~~large~~ ~~big~~ porphyry boulders, ~~are~~ up to 1 m ~~size,~~ ~~are found~~ ~~large~~. These ridges are interpreted as left moraines of the LGM Brenta glacier, which was flowing ~~through~~ ~~in~~ the ~~underlying~~ Valsugana valley.

4.1.6 “Enego” ridge

This 1-km long and more than 70-m high ridge is located on the ~~western~~ ~~right~~ side of the Brenta valley, at elevation 790-760 m a.s.l., where the Enego village lies (Fig. 2). This ridge is a lateral moraine of the Brenta glacier, already described by former scholars (Trevisan, 1939; Dal Piaz et al., 1946) and considered to have formed during the LGM. These deposits are the southernmost ~~known~~ ~~ones directly connected to the~~ Brenta glacier ~~deposits~~. During our survey, no large boulders (>1 m) were discovered, but a second, smaller ridge was found at lower elevation (~650 m a.s.l.).

These ridges are interpreted as the right-lateral moraines of the Brenta glacier during the LGM.

4.1.7 “Coste” and “Valstagna” sections

In the Coste area, at the bottom of the Valsugana valley on its western side, about 600 m south of the Enego ridge, a stratigraphic section was observed at the excavation front of a gravel pit (Fig. 5), with the base at about 210 m a.s.l. (~10 m above the present valley bottom) (Fig. 2). The section is about 50 m high, 100 m long and it is composed by two main units, here described:

Lower unit: ~~extending vertically for about 10-15 m~~, this unit consists of a 10-15 m thick gravel body rich in sandy matrix, presenting cross-to-planar stratification. Clasts are centimetric in size (maximum diameter is about 30 cm), sub-rounded to sub-angular and consist mainly of carbonate rocks (limestones/marlstones), with abundant siltstones and some granites and porphyries. The lower boundary of this unit is not visible due to the covering by loose debris. The upper boundary with the “upper unit” shows the interfingering of the two units in the western part of the section, near the foot of the rock wall that constitutes the valley side.

Upper unit: from the top of the lower unit up to the topographic surface there is a sedimentary body made of angular clasts, centimetric-to-decimetric in size, with sandy matrix and scattered boulders (maximum diameter is about 1 m). This unit is crudely stratified, with bedding dipping 25° – 30° degrees towards the valley axis. Clasts are lithologically homogeneous, consisting only of the local carbonate rocks of the overlying rock walls.

The lower unit is ~~attributed ascribable~~ to fluvial deposition by the Brenta River, interfingering and superimposed by scree deposits ~~falling coming~~ from the overlying rock walls.

~~A similar succession was~~~~An analog sequence has been~~ found on the eastern side of the Brenta valley, in front of the town of Valstagna, about 9 km south of Coste section. Here, a 15-m-high outcrop has been exposed by quarry activity and testify the occurrence of Brenta River fluvial deposits at elevation ~(-165 to 170 m a.s.l.), covered by 10 m of slope deposits.

4.1.8 “Rocca” deposits

About 1 km north~~wards~~ of the village of Rocca, two 20-m-high ridges are present, the top being at 310 m a.s.l. (Fig. 2). The northernmost one is made of sub-rounded polygenic matrix-supported diamicton with clasts up to 20 cm, sub-rounded to angular in shape. These ridges are interpreted as frontal ~~moraines~~~~morainic areas~~ of a glacier tongue flowing into the Canal La Menor valley.

The town of Rocca is built upon carbonate bedrock, but a small patch of sediments crops out next to the local graveyard (Fig. 2). This deposit is made of a matrix-supported diamicton with sub-rounded clasts, up to 30 cm large, sub-rounded to angular in shape. Clasts are minimally weathered and mainly carbonate, but porphyry clasts are present as well. The abundant matrix is mainly constituted by sandy particles.

These deposits are interpreted as LGM till ~~deposited by~~~~belonging to~~ a glacier tongue flowing into the Corlo valley, where the artificial lake is currently located.

4.2 Remote sensing

Whilst investigation of aerial and satellite images was not very profitable, due to the dense vegetation coverage, the DEM provided very valuable data. The DEM allowed to trace laterally those landforms already recognized in the field in few scattered spots, as in the case of the Enego moraine, and to map other new landforms, basing on morphological similarity. In particular, many moraines belonging to the Novegno group have been mapped using this approach. In the geomorphological sketch (Fig. 2), landforms recognized directly on the field are mapped with bright colors, whilst those mapped on the DEM have fainter shades.

4.3 Alluvial plain cores

Cores are here described as lithofacies assemblages, from the bottom up. The depth of the various layers is referred to the top of the core and indicated with the acronym “b.s.” (below surface). Detailed logs are presented in Fig. 6. Data concerning the samples collected for radiocarbon dating are summarized in Table 1; see the specific core description for details on the position of the samples in the stratigraphy.

4.3.1 RB1 core

This borehole was drilled in the Brenta megafan near the town of Carturo, about 5 km north of Piazzola sul Brenta (see Fig. 3 for location, Fig. 6 for stratigraphic log), at a topographic elevation of 30 m a.s.l..

The basal part of the core is made of an alternation of sand bodies and silty and clayey layers with varying sand content. The sand is normally well sorted, being constituted at maximum by grains 0.5 mm wide. Six thin (6-18 cm thick) very fine-grained intervals characterized by high organic content are present. Three of them, almost equally spaced (27.5, 21.8 and 9.3 m b.s.) were radiocarbon dated to 26.6-27.3, 25.7-26.1 and 22.6-23.2 ka cal BP, respectively.

At about 9 m b.s. a clear erosional surface is present, marked by an abrupt transition from clayey silt to a coarsening-upward sequence from medium sand to coarse gravel, sub-angular to sub-rounded (largest clasts are about 2 cm). A single, 15 cm-thick silty layer interrupts this succession at 7.85 m b.s.. The uppermost 2.5 m of the core are constituted by a fining upward sequence of sandy and silty layers. No clear evidence of the modern soil has been found at the top.

The core is interpreted as sandy proximal overbank deposits, intercalated with more distal overbank fines indicative of low-energy floodplain deposition. Locally, some intra-ridges swampy areas developed, inducing the formation of peat layers where organic deposition prevailed over minerogenic contribution, as it was common in the south-eastern alpine piedmont during LGM (Miola et al., 2006; Rossato and Mozzi, 2016). The coarsening-upward sequence is ascribable to sandy-gravelly channel sediments that eroded the older deposits at the end of the LGM forming fluvial incised valleys through the whole Brenta megafan (Mozzi et al., 2013). Finally, the top of the core consists of lower-energy channel deposits or proximal overbank sandy and silty fines.

4.3.2 PM1 core

This core was drilled near the town of Piazzola sul Brenta, about 1 km to the west, at an elevation of 27 m a.s.l. (see Fig. 3 for location, Fig. 6 for stratigraphic log).

5 The entire core is quite homogeneous, being composed by an alternation of silty layers, with a variable content in clay and sand, interbedded with fine sand intervals. The sand is normally well sorted, being constituted at maximum by grains 0.5 mm large. Two layers of medium sand located at 19-20 and 16.3-17.2 m b.s. are the only exception to this rather monotonous sequence. Three thin (10 cm maximum) layers with a very high organic content are present in the uppermost 15 m of the succession, two of which have been radiocarbon dated to 23.2-23.7 (13.45 m b.s.) and 19.9-20.4 (9 m b.s.) ka cal BP, respectively. The topmost 2 m of the core show evidence of a well-developed soil, constituted by pedogenic horizons C, Bk
10 and Bw, from the bottom up. The entire sequence is topped by a 0.5-m thick anthropogenic landfill made of gravels with silty matrix.

As in the core RB1, the whole sequence can be interpreted as sandy proximal overbank sediments intercalated with finer floodplain deposits. Locally, peat deposition took place when minerogenic contribution was very low, as it occurred also in RB1 core. The topmost soil has characteristic calcic horizons (Calcisol after FAO, 1998), that allow its correlation to the
15 “caranto paleosol”, that developed on top of the LGM deposits in the whole Venetian area (Mozzi et al., 2003; ARPAV, 2005; Donnici et al., 2011).

4.4 Sand petrography

The results of the petrographic analysis of the sand fraction, and related statistic, of ~~in~~ the two cores RB1 and PM1 are reported in Table 2 and Figure 7. According to the distribution in the biplot diagram (Fig. 7a) samples clustered in 6) shows three
20 different sectors allow to distinguish two groups of petrofacies (A and B), with a single sample (RB1-8) clearly separating towards a carbonaticlastic composition.

distinguishable both in the main component (Q+F, L, CE) and lithics (Lm, Lv, Ls) ternary diagrams (Fig. 7). Samples related to petrofacies A belong to the RB1 core ~~1~~ below the peat layer at 27.5 m b.s.. Sandy grains are mainly, in the RB1 core show high content in quartz, feldspar, felsic volcanic and lithic low grade metamorphic rock fragments (>30 % of which volcanic);
25 whereas the carbonate fragments are scarce and around 10 % (Fig. 7b). No sediments belonging to this petrofacies have been found in the PM1 core%. Above the peat, the sample RB1-27 shows dolostone clasts to about 25 %, while the felsic volcanic fragments remain high.

Petrofacies B is clustered towards the center of the biplot. Although the spectrum of lithic fragments contained ~~2~~ have a general content in this petrofacies is similar to that of petrofacies A, petrofacies B contains more carbonate clasts (Fig. 7c), generally
30 above 35%, and sedimentary lithic fragments (Fig. 7d). Micritic % compared to those of petrofacies 1, in particular limestone fragments are particularly common. Petrofacies B in RB1 core starts above the 27.5 m b.s. peat; the other parameters are always abundant, even if with the lower percentage.

The single sample RB1-27 (Fig. 6). All samples from PM1 core belong to petrofacies B.

The outlier sample was ascribed to petrofacies C. This shows a completely different composition towards, with carbonate (>60 % of the total amount) and fragments, especially micritic limestones, up to 55 % and high content in cherts (10 %), which are normally embedded in the micritic limestones as nodules (Barbieri and Grandesso, 2007); on the other hand, this sample

5 has the lowest amount of quartz (10 %) and all the other parameters, which are below 10 %.

These results were compared with the present-day sands of the Brenta, and Cison and Piave rivers (Garzanti et al., 2006; Monegato et al., 2010) show that petrofacies A (RB1-29 and 30) is shifted towards the felsic volcanic component. No modern river shows such a petrofacies. On the other hand, petrofacies B has a good match with the modern Brenta River, which includes the Cison catchment. Ternary diagrams show a slight shift of petrofacies B towards carbonate components (Fig. 7).

10 Using the mixing technique after (Fig. 7) through the spreadsheet from Vezzoli and Garzanti (2009), petrofacies A confirms to be). Petrofacies 1 is the most similar to the Brenta River sediments upstream the junction with the Cison River, except

for the sample at 27.3 m b.s. in which dolostones are common (24.3 %): as no main tributaries exist in the lower sector of the Brenta valley, this latter suggests the contribution of a tributary in the piedmont plain, like the Astico River. Petrofacies B2 is

15 quite similar to the present Brenta River, with an enrichment of carbonate rock fragments parameters that suggests the contribution of a catchment rich in these components. This input could be from the Piave drainage basin, whereas an input

from the Astico-Bacchiglione system in the lowlands can be discarded because during the LGM the river was pushed to the west by the development of the Brenta megafan (Rossato et al., 2013; Fontana et al., 2014), which also managed to dam the

Lake Fimon south of Vicenza (Monegato et al., 2011). Finally, petrofacies C shows 3 is remarkable for the high values content in carbonate and chert parameters (Tab. 2) with no clustering with endmembers (Fig. 7); the mixing technique rules out any

20 possible scenario involving modern endmembers ($R^2 < 0.7$; Tab. 2). Petrofacies C belongs, more similar to the filling present Piave catchment. However, a direct supply of sediments from such system can be ruled out, as petrofacies 3 is related to a

unit sedimented within the post-glacial incision of the Brenta megafan (Mozzi et al., 2013), when only Brenta and Cison catchments were contributing, the Piave glacier had already collapsed and the Piave River was flowing along its present valley

to the East (Pellegrini et al., 2005; Carton et al., 2009). Most of the carbonate clasts are micritic limestones that, coupled with

25 the abundance of cherts, suggest an erosion event/phase in the lower Cison (Corlo) valley north of Rocca (Fig. 1, 3) or where these rocks are dominant, or an erosion in the upper Cison valley close to Lamon, where these rocks are dominant (Tessari, 1973).

4.53 Mineralogy and geochemistry

Mineralogical analyses of the bulk sediments related to the petrofacies sedimentary units of the cores (Fig. 6) are reported in

30 terms of main minerals, such as phyllosilicates (mainly micas and chlorites), dolomites (two different crystal chemical terms) and feldspars (plagioclase and k-feldspar), as shown in Fig. 8a. The complete dataset, including mineralogical and geochemical data, Unit 1 is enriched in feldspars in the diagram reported in the supplementary material (STab. 1).

Basal sediments in Fig. 8, but in its uppermost parts (RB1 core (i.e., three deepest samples and a peat sample) are characterized by an enrichment in feldspars and correspond to petrofacies A. The overhead sediments, below and PM1 cores) the main erosional surface along the core, are characterized by a distinguishing feature in respect to Unit 2 is the abundance of phyllosilicates, whereas dolomites are depleted. This mineralogical association is very different from that of Unit 3 (very rich in dolomites) and samples of Unit 2 plot in intermediate position are depleted in feldspars. Such features also agree with chemical data (STab. 1), in particular considering MgO, Na₂O and Fe₂O₃ (SFig. 2), because of their stratigraphic position corresponds to petrofacies B. Two topmost samples (above the erosional surface), are distinctive affinity for their higher dolomite content, plagioclases and correspond to petrofacies C.

Samples from PM1 core mainly plot as those recognized for petrofacies B in RB1 core, without significant stratigraphic differences along the PM1 core. Although calcite is one of the main fine-grained minerals observed in the cores, it (clay minerals, oxides and hydroxides). Calcite is not considered as a discriminating variable because it is strongly depleted or even absent in peat sediments (i.e., > 12 wt % organic matter), making this mineral mainly influenced by the depositional environment and, therefore, poorly indicative of the sediment provenance. Due to this reason, peat samples show higher Al₂O₃/CaO ratio respect to other samples of the same Unit. This chemical ratio for non peat sediments is a reliable marker of Unit 1, 2 and 3 (SFig. 1). Unit 1 can be also distinguished according to the feldspars/quartz ratio in RB1 core, which is sandier than PM1 core.

The distinctive mineralogical features of samples corresponding to petrofacies A, B and C are also evidenced by sediment chemistry, as reported in Fig. 8b in terms of MgO, Na₂O and Fe₂O₃, because of their affinity for dolomite, plagioclases and fine-grained minerals (clay minerals, oxides and hydroxides). In this case, petrofacies A, B and C are even more clearly discriminated for both cores.

A more detailed evaluation of the bulk mineralogical composition along the RB1 core enables to highlight that both samples corresponding to petrofacies A, B and C are characterized by a peculiar feldspar/quartz ratio (SFig. 1) and that the transition between each group is rather sharp. On the contrary, the feldspar/quartz ratio throughout the PM1 core does not show abrupt variations.

4.4 Alluvial plain cores

Cores are here subdivided into informal units based on lithofacies assemblages and petrography, described from the bottom up. The depth of the various layers is referred to the top of the core and indicated with the acronym "b.s." (below surface). Detailed logs are presented in Fig. 6.

Data concerning the samples collected for radiocarbon dating are summarized in Table 1; see the specific core description for details on the position of the samples in the stratigraphy.

4.4.1 RB1 core

~~This borehole was drilled in the Brenta megafan near the town of Carturo, about 5 km north of Piazzola sul Brenta (see Fig. 3 for location, Fig. 6 for stratigraphic log), at a topographic elevation of 30 m a.s.l.~~

Unit 1: ~~spanning from the bottom of the core up to 27 m b.s., this unit is constituted by sand bodies interbedded with silty layers and two thin (10 cm maximum), fine grained intervals that are characterized by high organic content. The uppermost organic layer (27.5 m b.s.) was radiocarbon dated to 26.6–27.3 ka cal BP. The sand is normally well sorted, being constituted at maximum by grains 0.5 mm wide. Sandy grains are mainly Quartz, Feldspar and lithic fragments (>30 % of which volcanic) (Fig. 7), with high Feldspar/Quartz (0.6–0.7) and Al_2O_3/CaO (1.3–1.9) ratios in the bulk sediments (SFig. 1).~~

Unit 2: ~~from 27 to 9 m b.s. there is an alternation of silty and clayey layers with varying sand content. Four very fine grained organic intervals are present, 6 to 18 cm thick, and two of them has been dated 25.7–26.1 (21.8 m b.s.) and 22.6–23.2 (9.3 m b.s.) ka cal BP, respectively. The base of this unit was placed in correspondence of a sand layer that shows evidence of a change in the petrographic signature. More precisely, in respect to the lower one, this unit shows a remarkable enrichment in carbonates and sedimentary lithic fragments (Fig. 7). Mineralogical and geochemical analyses (bulk) show that the Feldspar/Quartz and Al_2O_3/CaO ratios reduce too (0.25–0.43 and 0.3–1.2, respectively).~~

Unit 3: ~~the topmost 9 m of RB1 core consists of two different sub intervals. The bottom one, from 9 up to 2.6 m b.s., has an erosional base and is composed of a coarsening upward sequence from medium sand to coarse gravel, sub angular to sub rounded (largest clasts are about 2 cm). A single, 15 cm thick silty layer is present at 7.85 m b.s.. The upper sub interval is remarkably finer, being constituted by a fining upward sequence of sandy and silty layers. No clear evidence of the modern soil has been found at the top.~~ This unit has a clear erosive base, with sand superimposed on clayey silt, which also marks a clear shift in the petrographic, mineralogic and chemical signatures (Fig. 7, 8). This uppermost unit is characterized by the highest content in carbonate (>60 % of the total amount) and sedimentary lithic fragments (Fig. 7). Whilst Feldspar/Quartz and Al_2O_3/CaO ratio values (bulk) are similar to those of Unit 2 (~0.4 and 0.1–0.3, respectively), the dolomite content shows a significant increase (Fig. 8).

Unit 1 is interpreted as sandy proximal overbank deposits, intercalated with more distal overbank fines and intra-ridges peat layers. The fine dominated succession of Unit 2 indicates low energy floodplain deposition, with the development of some swampy areas, where organic deposition prevailed over minerogenic contribution, as it was common in the south eastern alpine piedmont during LGM (Miola et al., 2006; Rossato and Mozzi, 2016). Unit 3 is ascribable to sandy gravelly channel sediments that eroded the older deposits at the end of the LGM forming fluvial incised valleys through the whole Brenta megafan (Mozzi et al., 2013). The upper part of the unit consists of lower energy channel deposits or proximal overbank sandy and silty fines.

4.4.2 PM1 core

~~This core was drilled near the town of Piazzola sul Brenta, about 1 km to the west, at an elevation of 27 m a.s.l. (see Fig. 3 for location, Fig. 6 for stratigraphic log).~~

Unit 1: spanning from the bottom of the core up to 24 m b.s., this unit is constituted by fine grained sand with silty layers. ~~The sand is normally well sorted, being constituted at maximum by grains 0.5 mm large. Sandy grains are mainly Quartz and lithic fragments with bulk Feldspar/Quartz ratio from 0.2 to 0.5 and high Al_2O_3/CaO (1.3–1.9) ratios, in respect to Unit 2, excluding peat sediments.~~

- 5 Unit 2: from 24 to the top of the core, this unit is composed by an alternation of silty layers, with a variable content in clay and sand. ~~Two layers of medium sand, located at 19 and 16.3 m b.s. are the only exception to this rather monotonous sequence. Three thin (10 cm maximum) layers with a very high organic content are present in the uppermost 15 m of the succession, two of which have been radiocarbon dated to 23.2–23.7 (13.45 m b.s.) and 19.9–20.4 (9 m b.s.) ka cal BP, respectively. The topmost 2 m of the core show evidence of a well developed soil, constituted by pedogenic horizons C, Bk and Bw, from the bottom~~
- 10 ~~up. The entire core is petrographically homogeneous, being mainly constituted by carbonate (35–40 % of total) and sedimentary lithic fragments (Fig. 7, 8). Bulk Al_2O_3/CaO is lower than 0.7, excluding peats which are depleted in carbonates (STab. 1). As in the core RB1, Unit 1 is interpreted as sandy proximal overbank deposits, while Unit 2 can be interpreted as a fine dominated succession of floodplain deposition, where more proximal sandy sediments alternate with distal silty layers. Locally, peat deposition took place when minerogenic contribution was very low, as it occurred also in Unit 2 of RB1 core. The topmost~~
- 15 ~~soil has characteristic calcic horizons (Calcisol after FAO, 1998), that allow its correlation to the “earanto paleosol”, that developed on top of the LGM deposits in the whole Venetian area (Mozzi et al., 2003; ARPAV, 2005; Donnici et al., 2011).~~

4.5 Remote sensing

- ~~Whilst image analysis was not very profitable, due to the high vegetation coverage, the DEM provided very valuable data. The DEM allowed to trace laterally those landforms already recognized in the field, where few scattered spots were available, as~~
- 20 ~~is the case of the Enege moraine, and to map other new landforms, basing on morphological similarity. In particular, many morainic arcs belonging to the Novegno group have been mapped using this approach. In the geomorphological sketch (Fig. 2), landforms recognized directly on the field are mapped with bright colors, whilst those mapped with remote sensing have fainter shades.~~

5 Discussion

- 25 Data gathered in the mountain area and in the piedmont megafan are here discussed in order to reconstruct the evolution of the LGM Brenta glacier and tributary glacial systems.

5.1 Glaciers in the mountain area

- While all the major LGM valley glaciers of the south-eastern Alps preserved all or parts of their end-moraine systems in the terminal valley tracts and/or in the piedmont plain (Venzo et al., 1977; Monegato et al., 2007; Carton et al., 2009; Rossato et
- 30 al., 2013), in the Brenta valley there is no evidence of the LGM (nor older) terminal moraines (Castiglioni, 2004). The Brenta

glacier that used to flow through the Valsugana during the LGM was mainly fed by the Adige glacier, the largest on the southern side of the Alps (Bassetti and Borsato, 2005; Monegato et al., 2017) and some local tributary glaciers from the ~~eastern~~ ~~left~~ valley side. The transfluence of Adige glacier into the Valsugana was through the Fersina saddle (550 m a.s.l.) and the Vigolo Vattaro windgap (lowermost altitude: 680 m a.s.l.); more significantly, above the Calisio plateau (ca 1000 m a.s.l.) during the maximum glacier expansion. Flowing for about 50 km along the Valsugana, the glacier reached the Primolano sector where the Valsugana narrows from about 1 km to 100 m and the Canal La Menor windgap opens eastwards at about 350 m a.s.l. (Fig. 2).

Based on ~~the location of marginal glacial deposits~~ ~~our data~~, the sudden narrowing of the Brenta valley ~~may have~~ caused the ~~bulging of the~~ glacier front stabilization, as happened in the northwestern Himalaya during the Late Pleistocene, when narrow steep-walled canyons constituted an effective barrier to glaciers advance (Burbank and Fort, 1985). The subsequent growth of the glacier forced ~~inducing~~ it to ~~rise~~ ~~reach higher elevations~~ up to the Canal La Menor windgap and, thus, to split in two lobes (Fig. 2). The eastern lobe flowing across the windgap formed the Sorist (760 to 650 m a.s.l.), Novegno (720 to 600 m a.s.l.) and Guarda (700 to 660 m a.s.l.) lateral moraines; the western lobe built the Enego and Col del Gallo (both ~780 m a.s.l.) lateral moraines. The abundance of porphyry clasts and boulders in the deposits related to both eastern and western lobes indicates sediment provenance from the upper Valsugana and the Adige valley. ~~The differences in elevation of the various moraines suggest that the western lobe grew more than the eastern one, possibly bulging due to the narrowing of the Valsugana.~~ A secondary effect of the glacier bulging would have been the formation of transverse crevasses, producing the fall of supraglacial debris into the ice mass, both hindering the transport of sediments to the glacier front and increasing the hydraulic conductivity of ~~the~~ otherwise effectively impermeable glacier ice (Gulley and Benn, 2007). At the end of the gorge the Valsugana valley widens again, ~~a morphology that~~ likely induced ~~the~~ formation of splaying/radial crevasses and icefalls in the frontal glacier mass (Nye, 1952; Harper et al., 1998; Colgan et al., 2016).

The large stratigraphic section in the Coste quarry, and the minor Valstagna one, display ~~s~~ no evidence of glacial deposits while ~~they~~ it indicates the presence of important LGM glaciofluvial aggradation in front of the western glacier's fronts. Henceforth, the front of the Brenta glacier flowing in the main valley (western lobe) should have been located between the ~~southernmost end of the Enego and Col del Gallo moraines and the Coste quarry. Glacier confined in narrow valleys normally experience rapid advances under positive mass balance condition: the narrower the valley, the faster the glacier's speed (e.g., Egholm et al., 2011). However, it has been proved that during Late Pleistocene valleys narrowing promoted glaciers blockage in the Himalaya (Burbank and Fort, 1985). This latter is probably the case of this Brenta tongue, the Coste section being only about 250 m downstream of the Enego moraine.~~ ~~Coste quarry and the southernmost end of the Enego and Col del Gallo moraines.~~

The presence of the high-elevation lateral moraines hanging above the valley (the Enego moraine is about 550 m higher than the ~~present~~ valley floor) ~~at such a short distance from proglacial sediments~~ suggest that ~~when the glacier was at its maximum size its~~ glacier's front probably consisted ~~of~~ ~~in~~ an icefall ~~that hampered the formation of a terminal moraine~~. This tongue of the Brenta glacier, being a debris-free glacier, has been characterized by a more effective ablation due to solar energy compared to glaciers covered by several centimeters ~~or more~~ of debris (Lardeux et al., 2015; Wei et al., 2010). The resulting abundant

meltwaters fed a well-developed proglacial stream, inducing aggradation along the whole Brenta valley, as testified by the Coste and Valstagna sections. ~~The~~ However, the development of a subglacial/englacial drainage system related to debris-filled crevasses ~~probably controlled~~ hindered the formation of supraglacial lakes and the seasonal variation of ~~the glacier's~~ glacier's velocity, thus resulting in ~~less fluctuations at the~~ higher resistance to glacier's front (~~fluctuation~~ (Basnett et al., 2013; van der Veen, 2007). Such stability would result in the growing of the Enego and Col del Gallo lateral moraines. This Brenta glacier tongue may have brought debris at its front both during stability, through supra- and/or englacial transport (Barr and Lovell, 2014 and reference therein), and while advancing, bulldozing preexisting valley-floor sediments (e.g., Winkler and Matthews, 2010). Such debris may have formed end moraines, later eroded by post-glacial fluvial and slope processes. However, considering the narrow gorge that hosted the glacier front, it seems more probable that high-discharge proglacial streams were occupying the entire gorge, continuously removing the incoming debris and precluding the formation of terminal moraines.

When the Brenta glacier reached the elevation of the Canal La Menor windgap, the eastern path became an effective glacial flux, ~~as it happens when stabilized valley glaciers can extend laterally (Barr and Lovell, 2014).~~ The higher the glacier, the more effective would have been the glacial flux through the eastern path, overtopping also the western side of the Novegno plateau. As glacial sediment transport is likely to follow the main glacial flux, ~~so~~ the eastern flow probably subtracted increasingly higher portions of the glacially-transported debris to the western one, depleting the sedimentary flux through the Valsugana gorge ~~and further hindering the formation of an end moraine at the western front.~~ The eastern glacial lobe flowed along the Canal La Menor windgap down to the confluence with the Corlo valley. Here, it merged with the glacier coming from the north-east, ~~formed by~~ related to the contribution of both the Cismon glacier and the westernmost lobe of the Piave glacier, as testified by the Roncon till. This latter deposit is polygenic, with pebbles of dolostones and Triassic volcanic rocks belonging to the Piave catchment. This latter till crops out extensively also in the nearby Seren valley, into which a lateral tongue of the Piave glacier was flowing. Geomorphic evidence of the westward flow of Piave glacier is provided by the lateral moraines at Monache (750 to 650 m a.s.l.), even though they are made mostly of limestone clasts, thus reflecting a local glacial sedimentary input.

The glacier deriving from the merging of the eastern Brenta lobe and the Cismon/Piave glaciers, at the confluence of Canal La Menor and the Corlo valley, left no traces of frontal moraines. Glacial till crops out close to Rocca (Fig. 2) and till patches were described about 0.5 km southwards (Dal Piaz et al., 1946), suggesting that the front of this glacier was located at the beginning of the narrow gorge now occupied by the southern end of the artificial Lake Corlo. The geomorphological setting is very similar to the ~~western tongue~~ Valsugana one, suggesting that also here ~~the glacier's front~~ it may have ~~consisted in~~ informed an icefall with deep crevasses ~~without terminal moraines, at the glaciers' front.~~

The Valsugana glacier left a remarkably small amount of erratics. During our survey, a total amount of 7 boulders made of porphyry and granite, up to 1 m large, have been found (Novegno and Sorist areas). Other authors mentioned erratics on top of the Novegno plateau (up to 2 m large and made of crystalline rocks), next to the Enego moraine ("very large" boulders made of carbonate rocks; Secco, 1883; Venzo, 1940) and on the Canal La Menor valley bottom ("extremely large" porphyry boulders; Taramelli, 1882). No erratics have been found, nor mentioned, downstream along the Valsugana valley bottom.

5.2 The fluvial record of glaciers' changes

The fluvial sediments cropping out in the Coste and Valstagna quarries are the only remnants of the LGM glaciofluvial aggradation that took place downstream of both eastern and western glaciers' fronts. This glaciofluvial sedimentation led to the infilling of the Valsugana valley bottom up to some tens of meters above the present Brenta river. The elevation of the top of the LGM valley fill at Coste (about 225 m a.s.l.) is consistent with ~~the~~ one of the Valstagna section (about 175 m a.s.l.) as well as with the top LGM surface of the Brenta megafan SE of Bassano del Grappa (about 130 m a.s.l.). This allows the correlation of these depositional top surfaces and the related sediments, as well as the reconstruction of the longitudinal profile of the LGM Brenta valley bottom (Fig. 9). The LGM fluvial aggradation was followed by the incision of the valley bottom and the piedmont megafan at around 17.5 ka cal BP, as the fluvial system reacted to the downwasting of the glacial system (Mozzi, 2005; Fontana et al., 2014; Rossato and Mozzi, 2016).

The growth/collapse of glacial tongues and modifications in the fluvial networks can be detected from changes in the mountain catchments and in the alluvial plain. Sedimentary systems developing at the mouth of major valleys are highly valuable databases of sedimentary, climatic and tectonic data (e.g., Mozzi et al., 2005; Carton et al., 2009; Pini et al., 2009; Piovan et al., 2012; Rossato and Mozzi, 2016). The paucity of radiocarbon datable material usually available in glacial deposits can be balanced with the abundant organic samples that can be collected in fluvial sedimentary sequences of this area. In our investigation, the petrographic, mineralogical and geochemical analyses of RB1 and PM1 cores in the glaciofluvially-fed Brenta megafan, chronologically framed through radiocarbon dating, integrate the evidence obtained in the mountain area. This allowed to distinguish specific evolutionary phases in the drainage network feeding the Brenta megafan (Fig. 10), described as follows from the oldest one:

- The first phase, ~~is testified by Unit 1, both in the RB1 core, corresponds to petrofacies A and lasted up to PM1 cores. In the former, the top of this unit dates back~~ straight after 27 ka cal BP. ~~At that time, when~~ glaciers were growing at the onset of LGM (Monegato et al., 2007; 2017; Ivy-Ochs et al., 2008; Preusser et al., 2011) and the mountain drainage systems began to modify. The Brenta megafan sedimentation rates were still comparable to pre-LGM ones (Rossato and Mozzi, 2016). Sediments indicate that this megafan was fed by a river with a drainage system limited to the Valsugana, ~~as shown by the petrographic samples (RB1-29 and 30). The Cismon drainage system, which is currently merging with the Brenta one, was not contributing, as it was probably flowing eastwards into the Piave one (Fig. 10), with a minor contribution from the Astico system as shown by the petrographic sample RB1-27. The Cismon drainage system was not merging with the Brenta one at the beginning (petrographic sample RB1-30), probably flowing eastwards into the Piave one (Fig. 10a). Afterwards, the Cismon river started to flow into the Corlo valley, contributing to the Brenta megafan aggradation (petrographic sample RB1-29), before 27 ka cal BP. The trigger responsible for this shift can be looked to, alternatively: i) the rapid and remarkable growth of the Stizzone fan, that pushed the Cismon river to the North until the southern path to the Corlo valley was favored, compared to the previous eastern one; ii) the arrival of the Cismon glacier at the junction between southern and eastern path that may have~~

perturbed the equilibrium in favor of the Corlo valley path. The first hypothesis seems more reasonable, since it is likely that this shift occurred when glaciers were not grown enough to reach the terminal tracts of the valleys, but an early spread of the Cison glacier cannot be ruled out.

- The beginning of the second phase coincided to a gradually increasing Unit 2 is marked by a change in the drainage system, as testified by mineralogical and petrographic analyses of petrofacies B (samples RB1-27, 24, 21 and 16 and PM1-19, 17 and 12) (Figs. 7-8) in both cores and spans for the whole LGM. Radiocarbon dates in Piazzola sul Brenta cores indicate that this phase unit started straight after 27 ka cal BP and continued after 20.1 ka cal BP (Fig. 6). The lack of major unconformities in the succession of PM1 core suggests that the sedimentary top of this phase Unit 2 in PM1 corresponds to the LGM surface of the Brenta megafan, implying suggesting that sedimentation lasted until 17.5 ka cal BP (Rossato and Mozzi, 2016). Soon after in between 27 and 25.9 ka cal BP, the Piave and Cison systems glacier began to contribute to the Brenta one through the Corlo valley. Whilst the Cison river diversion do not require a direct connection with glacier dynamics, alluvial plain (mineralogic sample RB1-13 - 26.5 m b.s. and petrographic sample RB1-24 - 24.45 - 24.5 m b.s.; Fig. 6, 10b). This event required the Piave glacier must to have grown enough to overcome the Seren saddle (~330 m a.s.l.; Figs. 1, 10), about 100 m above the current Piave valley bottom. At the acme of LGM, the contribution of these systems is likely to have blown up the sedimentation rates in the Brenta megafan, that nearly doubled in the 26.7-23.8 ka cal BP period (Rossato and Mozzi, 2016; Fig. 10). The Piave Such advanced position of the Piave glacier tongue overcoming the Seren saddle probably survived the ~19.5 ka cal BP glacial retreat, as the main Piave glacier was still being about 500 m thick near Belluno ("Val Piana" stage: 16.210 ± 50 years BP, Pellegrini et al., 2005, recalibrated to 19,386 - 19,772 years cal BP with IntCal13 calibration curve, Reimer et al., 2013), recalibrated basing on Pellegrini et al., 2005; Fig. 10c). The Piave system contribution is likely to have blown up the sedimentation rates in the Brenta megafan, that nearly doubled in the 26.7-23.8 ka cal BP period (Rossato and Mozzi, 2016).
- The youngest phase is recorded only in the topmost sediments Unit 3 of RB1 core, constituting petrofacies C. It is ascribable to the infilling of a fluvial entrenchment (Fig. 2) developed during late stages of deglaciation (Mozzi et al., 2013), as occurred elsewhere in the whole Central and Eastern Po Plain (Fontana et al., 2014b). Mineralogy confirms the present configuration of the drainage system, with the Cison River flowing into the Brenta River one through the Corlo valley and when the Piave River was already flowing along its into the modern valley. However, a remarkable enrichment in carbonates (micritic limestones) in respect to of modern Brenta sediments, testified by petrography, mineralogy and geochemistry, highlights pinpoints to an anomalous setting. Two possible scenarios may be proposed to explain such signal: i) a significant bedrock remarkable erosion of these such lithologies in the mountain area (i.e. especially in the Cison catchment), or ii) a connection with the dismantling of the postulated landslide Lamon terraces and/or of the obstacle that induced their aggradation of the Lamon terraces (if the "landslide scenario" is assumed; see the Setting chapter for details). The first hypothesis can relate to with the carving of the Corlo valley by Cison River during the Lateglacial when high meltwater discharges could easily induce such. Such

enhanced erosion stages, ~~are likely to occur when meltwater amount is high (Herman et al., 2011)~~, as normally occurs ~~it is~~ during glacier recessional phases (Herman et al., 2011).

6 Conclusions

The acquired dataset casts new light on the dynamics of the LGM glaciers in the canyon-like, middle tract of a major Alpine valley, the Valsugana. The knot of the Valsugana glacier has been disentangled for the first time, indicating a singular configuration of the glacier snouts crossing narrow and deep valley reaches.

Our data indicates that at the LGM acme the Brenta glacier split at Primolano. One tongue used to flow southwards along the Valsugana valley through a narrow gorge which prevented an effective glacier flux and caused the glacier's bulging. The bulging forced the right side of the glacial tongue to reach high elevation at Enego, while its front was probably constituted by an icefall located just upstream of Coste. Meltwaters were flowing in subglacial and englacial streams removing debris from the glacier front and filling the Valsugana valley bottom. The other tongue collected most of the glacial and debris fluxes, flowing eastwards along the Canal Lata Menor valley and joining the Cison/Piave glacier near Rocca. ~~The front of this glacier probably was an icefall as well, with deep crevasses at its back, located in the Corlo valley.~~

The coupling of data gathered in the mountain area with those collected in the piedmont alluvial plain allows a coherent reconstruction of the dynamics of the LGM glacier tongues. Prior to the arrival of the glacier fronts in the study area, the Brenta megafan received sediments only from the upper Valsugana catchment. A major alteration of the drainage system occurred just ~~soon~~ before 27 ka cal BP, when the Cison and River abandoned the Piave systems catchment and joined the Brenta River in the Valsugana valley. ~~It was followed soon after by another major change, directly related to the glacier's dynamics: the arrival of the westernmost tongue of the Piave glacier~~ through the Seren saddle and the Corlo valley. Between ~27 and, at least, ~19.5 ka cal BP, the Brenta, Cison and Piave glaciers were merging in the surroundings of the Novegno mount. Their meltwaters were building up the largest alluvial landform of the whole Po Plain ~~Venetian Friulian plain~~ at that time: the Brenta megafan. At the end of the LGM, the waning of glaciers induced the fluvial incision of the Brenta megafan. The abundance of micritic carbonates in the sedimentary fill of such incisions near Piazzola sul Brenta suggests a concomitant remarkable bedrock erosion in the Corlo valley and/or the reworking of sediments from the upper Cison catchment at Lamon.

As general conclusive remarks, this study highlights that:

- the narrowing of a main glaciated valley may result in the blockage/slowing of the glacier flux. A larger lateral valley may easily represent an alternative path for the glacier, even if its bottom lies at higher elevation, subtracting large part of the glacial and debris flux from the main valley;
- valley glaciers flowing across narrow gorges may be subject to bulging and likely have icefalls at their front, while proglacial meltwater streams ~~which may~~ prevent the formation of end ~~terminal~~ moraines;
- in rugged Alpine terrains, glacial catchments may significantly vary over time during a single glaciation. Such changes affect both the glacial and glaciofluvial systems and can be recognized in the alluvial stratigraphic record far

downstream from the glacier front. Sand petrography and chemical/mineralogical composition of sediments are good tracers of glacial catchment variations.

Acknowledgements

5 We sincerely thank S. Winkler and L. Stutenbecker for thorough critical reviews that greatly improved the quality of the manuscript.

Author contributions

All authors contributed to interpreting results and improving the text, that has been written mostly by S. Rossato. Each author contributed to different parts, here listed: field survey: S. Rossato, G. Monegato, P. Mozzi; sand petrography: G. Monegato; X-ray diffraction: A. Carraro, F. Tateo; chemical composition: A. Carraro, F. Tateo; core description: S. Rossato, P. Mozzi; 10 remote sensing: S. Rossato.

Competing interests

The authors declare that they have no conflict of interest.

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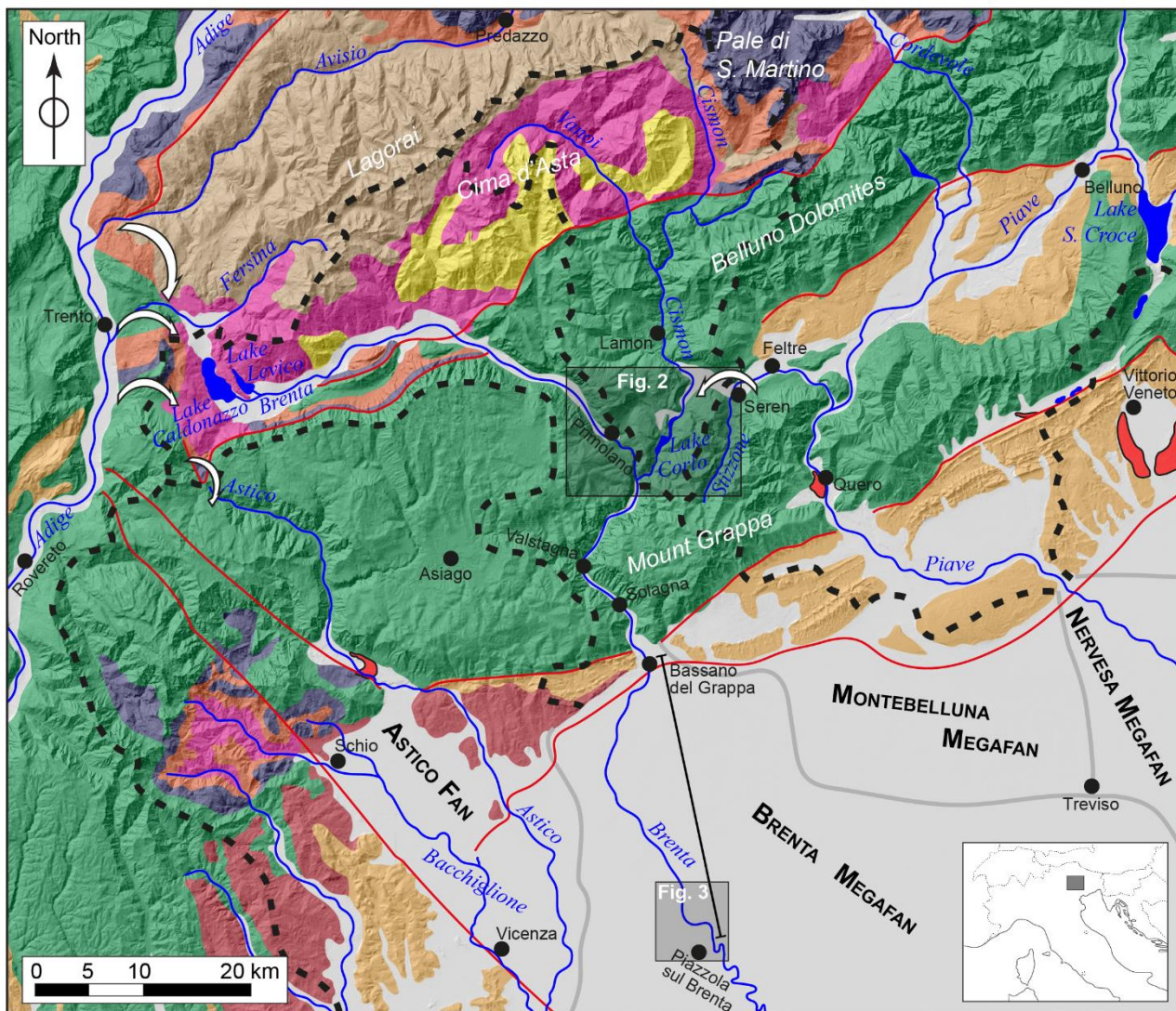
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Topographic profile - Fig. 9

Watershed

LGM glacier transfluence

LGM terminal moraine

Fault / thrust

Loose sediments and conglomerates
QUATERNARY

Conglomerates, marls, glauconitic arenites
OLIGOCENE-PLIOCENE

Volcanic and subvolcanic rocks
PALEOCENE

Dolostones and limestones
TRIASSIC-CRETACEOUS

Sandstones, dolostones, limestones and volcanic rocks
UPPER PERMIAN-MIDDLE TRIASSIC

Sandstones and evaporites, dolostones, limestones
UPPER PERMIAN

Volcanic rocks
PERMIAN

Plutonic rocks
LOWER PERMIAN

Variscan basement
PRE-PERMIAN

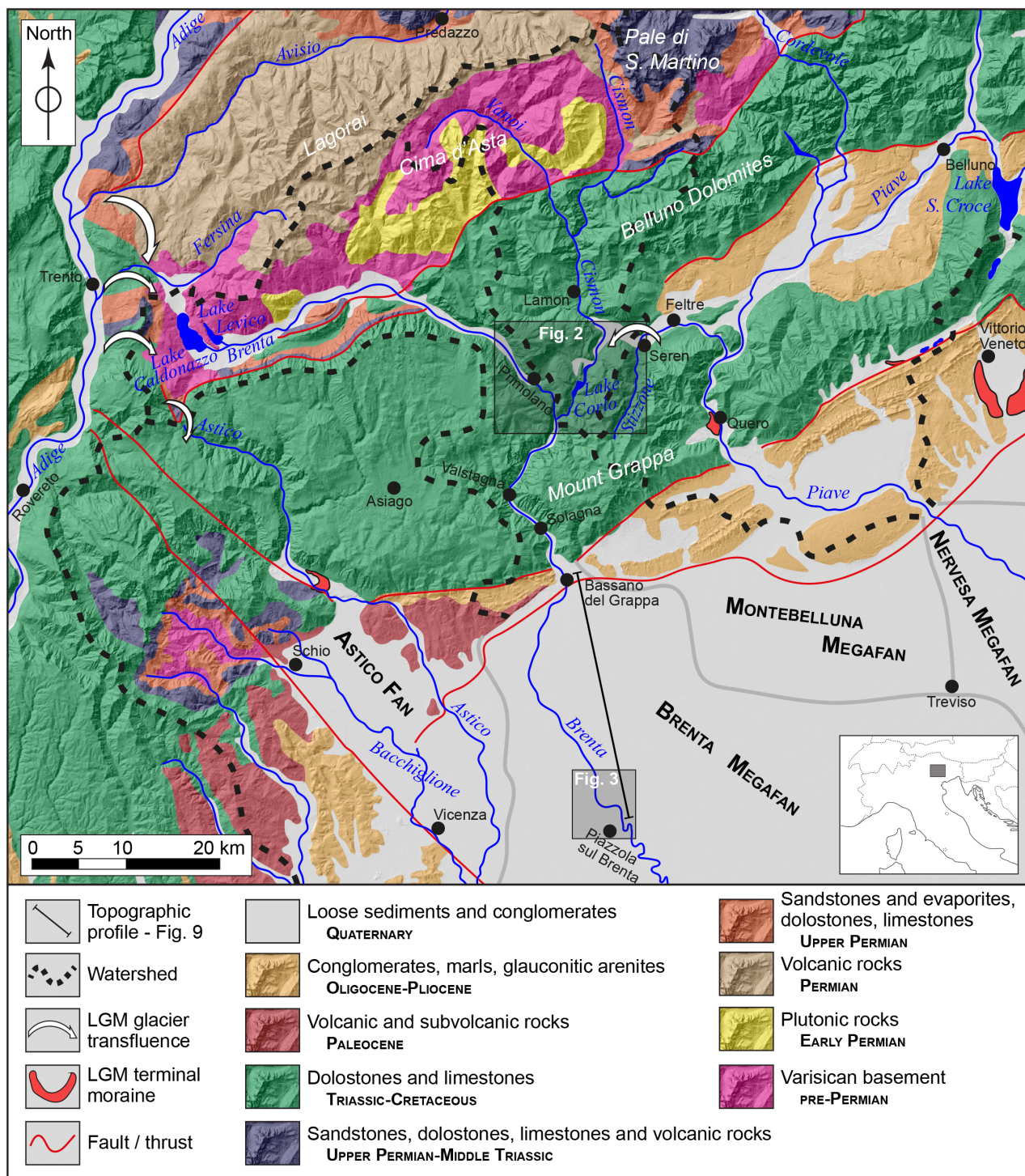
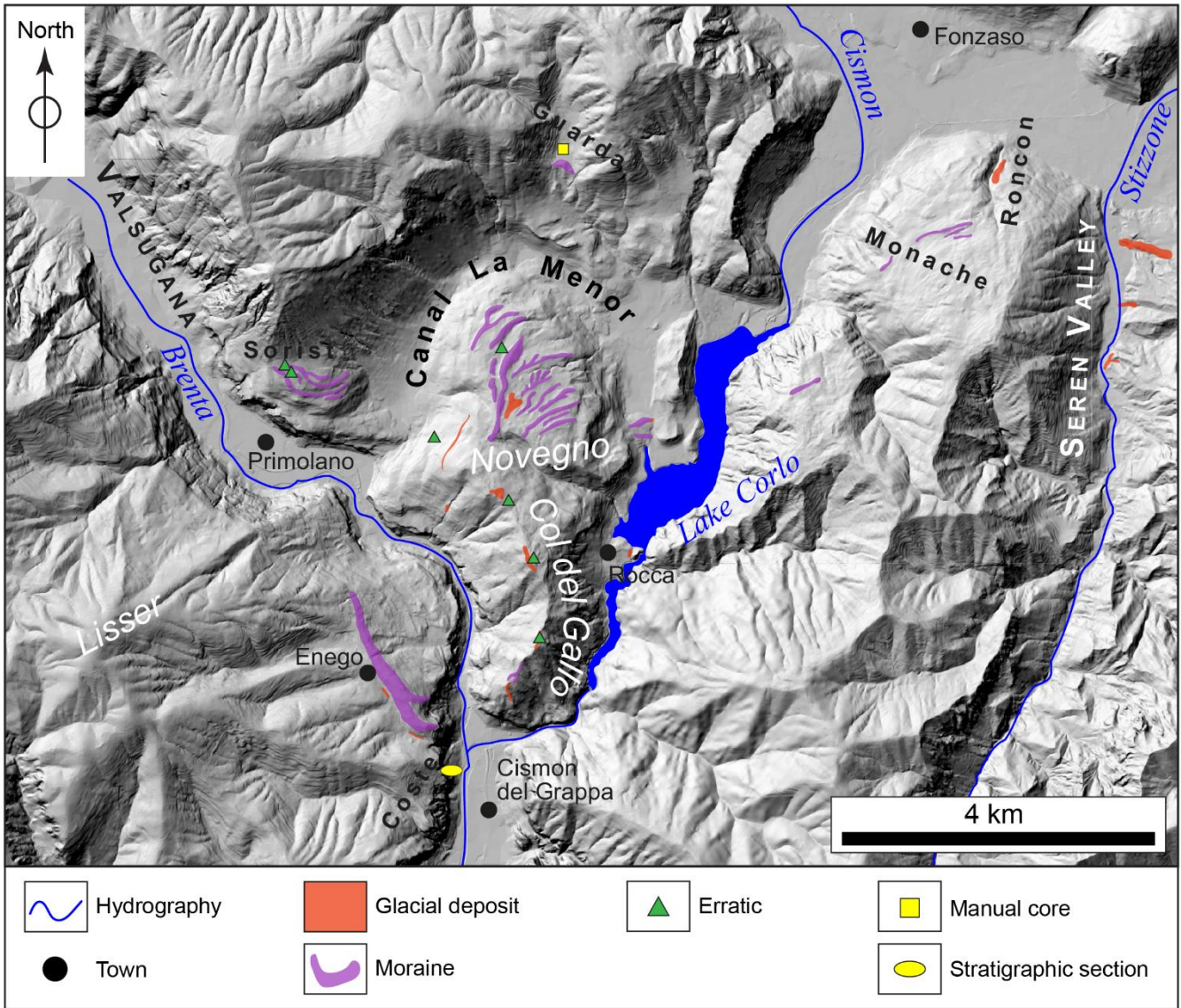


Figure 1: Geological sketch of the study area. The map is based on the Structural Model of Italy (Bigi et al., 1990) and local geological maps (Bartolomei et al., 1969; Dal Piaz et al., 1946; Barbieri and Grandesso, 2007; Avanzini et al., 2010) and it overlies a SRTM-derived Digital Elevation Model (30-m large cells) [source: <http://viewfinderpanoramas.org/>].



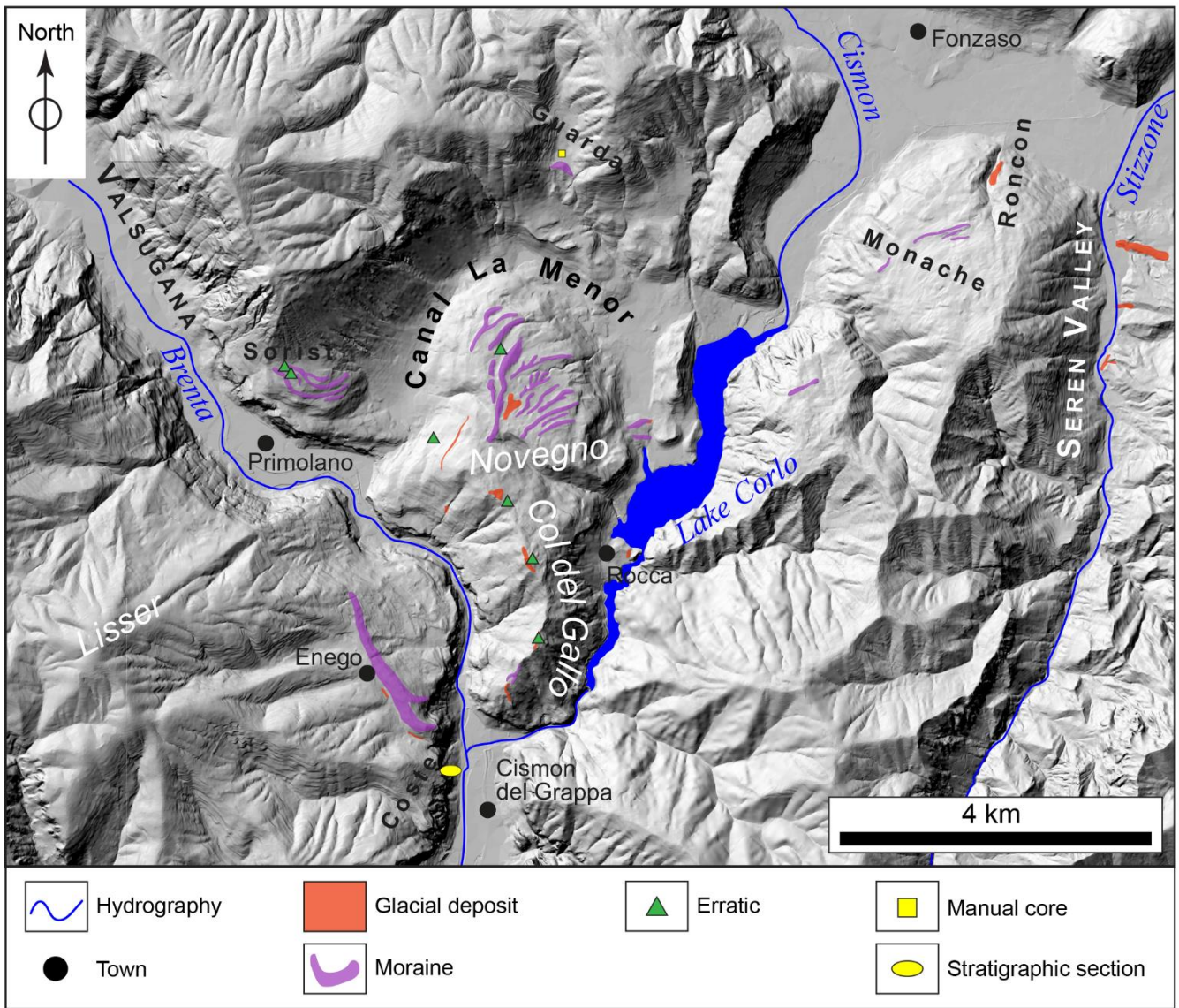


Figure 2: Outcrops map of the middle Valsugana sector derived from field surveys and remote sensing data. Polygons/symbols overlies a 5-m cell DTM (modified from data provided by Regione Veneto, 2011).

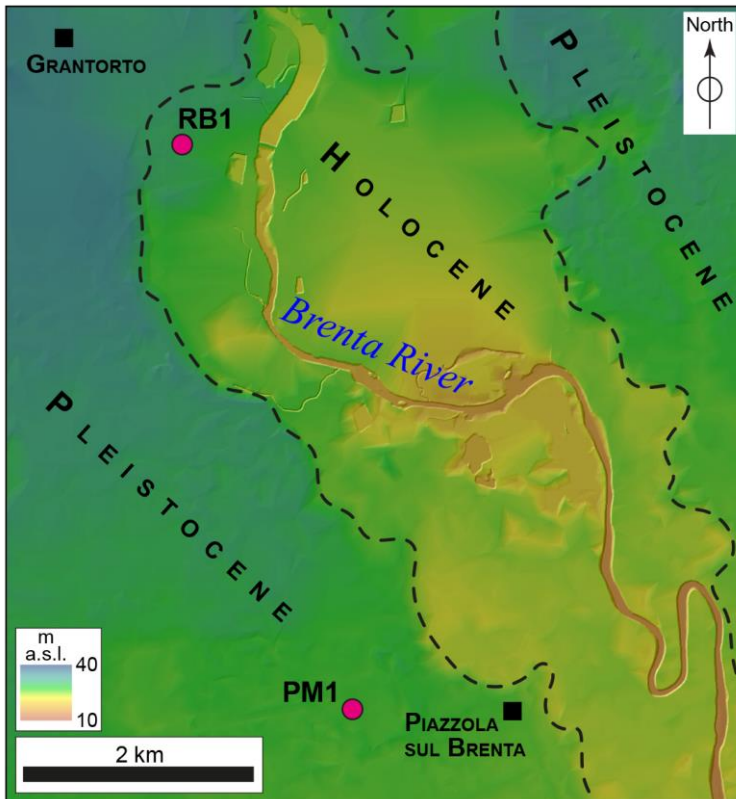


Figure 3: Location of the PM1 and RB1 cores (purple circles). The background is a 5-m cell DTM (modified from data provided by Regione Veneto, 2011), stretched to highlight elevation changes. Scarps bounding the post-glacial incision of the Brenta megafan are evidenced with black dashed lines.

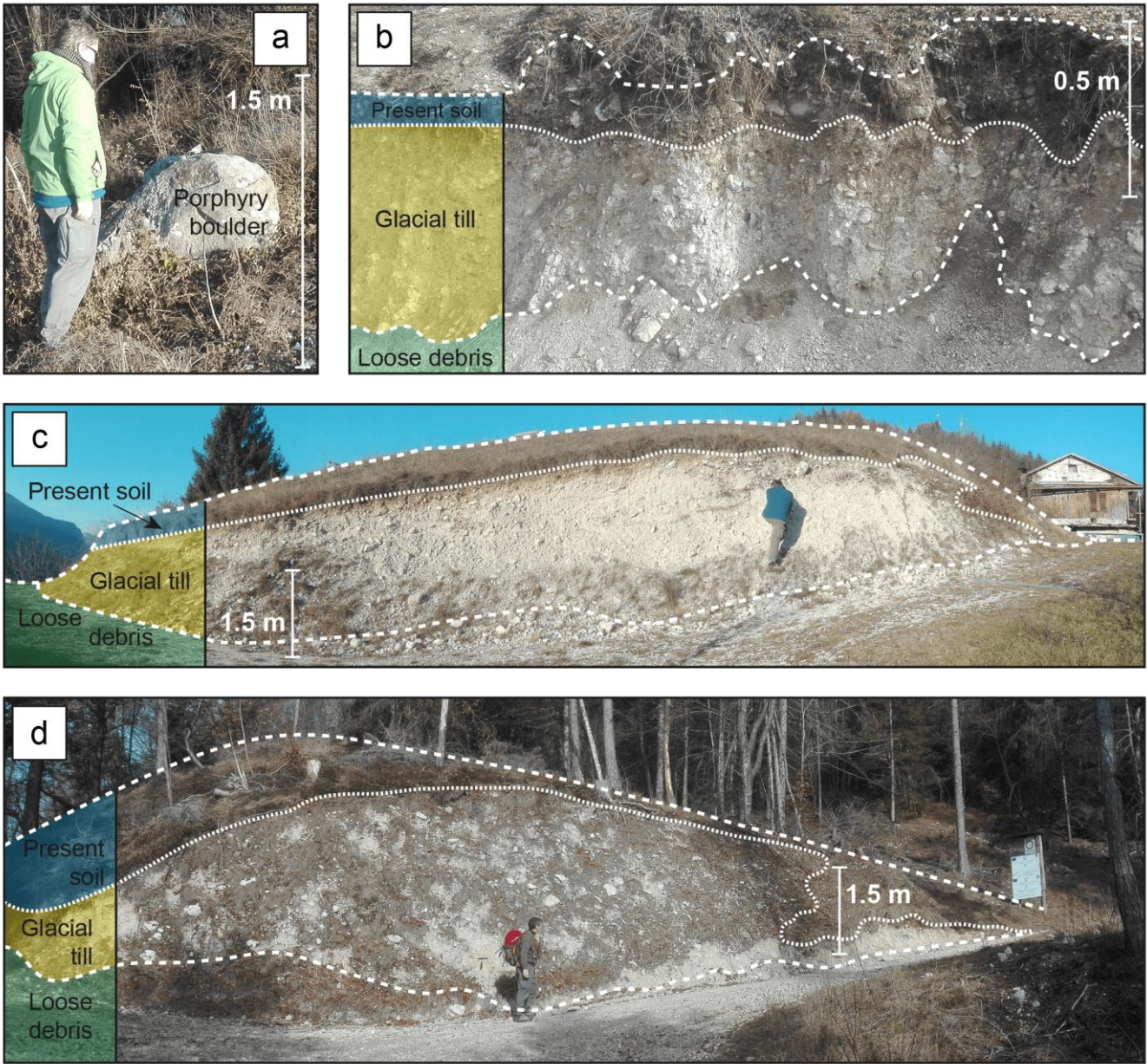


Figure 4: Photos taken in the middle sector of the Valsugana valley. When present, stratigraphic layers are separated by dotted/dashed white lines. a) porphyry boulder, located on top of Col del Gallo mount; b) section of a lateral moraine of the Brenta glacier, located on top of the Novegno mount; c) moraine, located on the southern sides of Col del Gallo mount; d) moraine, located in the Sorist area.

5

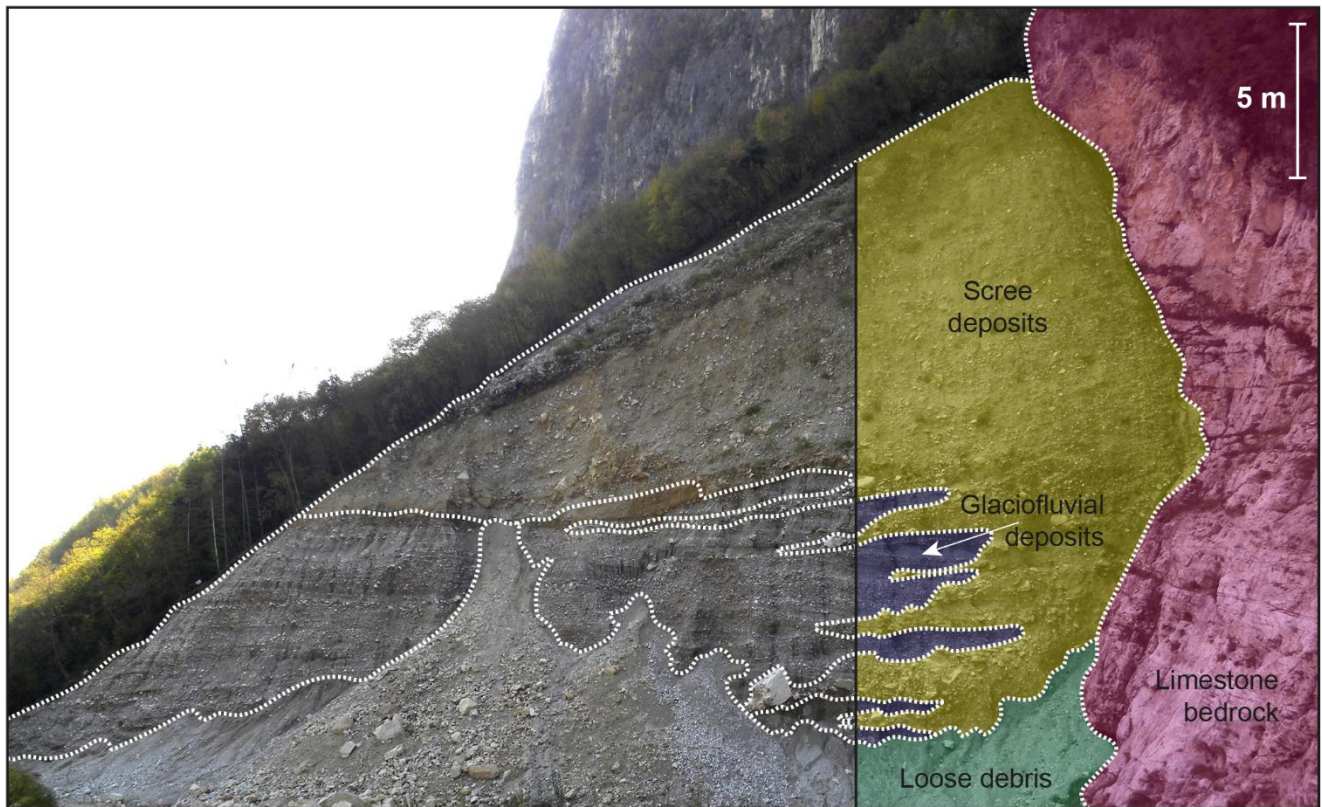
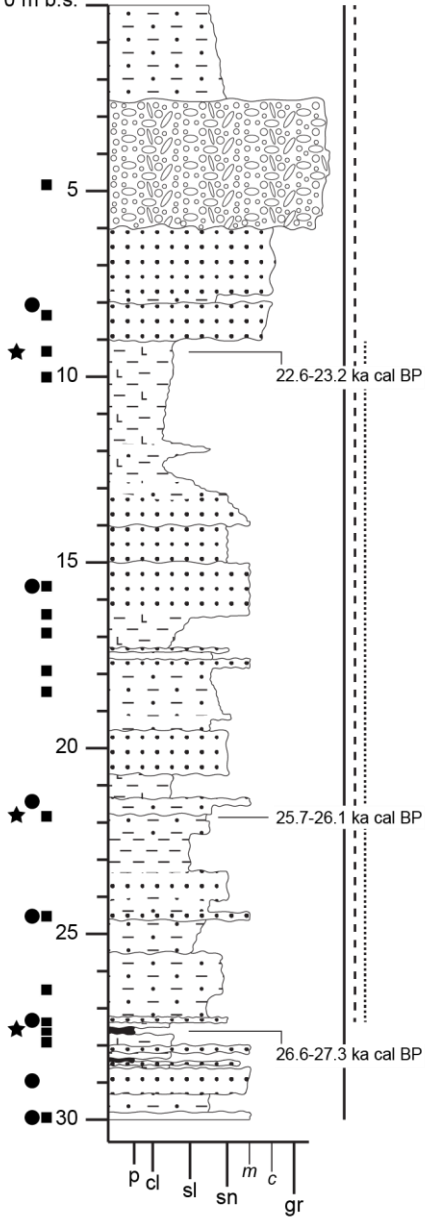


Figure 5: Coste section. It is possible to appreciate how inclined-bedding scree deposits overlie and interfinger with horizontal-bedding glaciofluvial sediments.

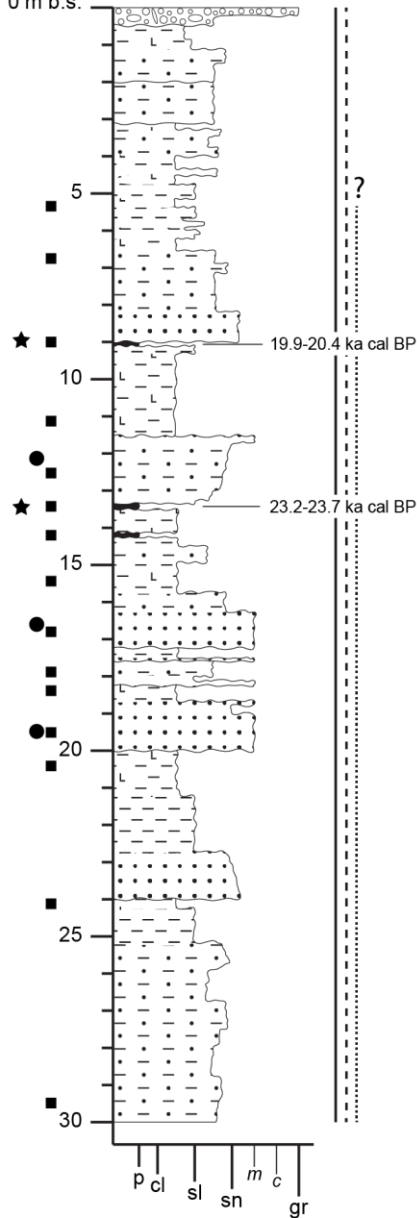
30 m a.s.l.
0 m b.s.

RB1



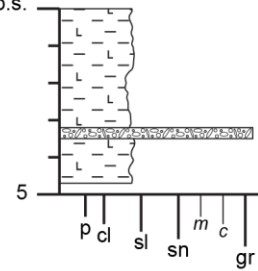
27 m a.s.l.
0 m b.s.

PM1



664 m a.s.l.
0 m b.s.

GUARDA1



LYTHOLOGY

- Peat
- Clay
- Silt
- Sand
- Gravel

SAMPLES

- Mineralogy & geochemistry
- Petrography
- ¹⁴C date

CONTRIBUTING SYSTEM

- Brenta
- Cisonon
- Piave

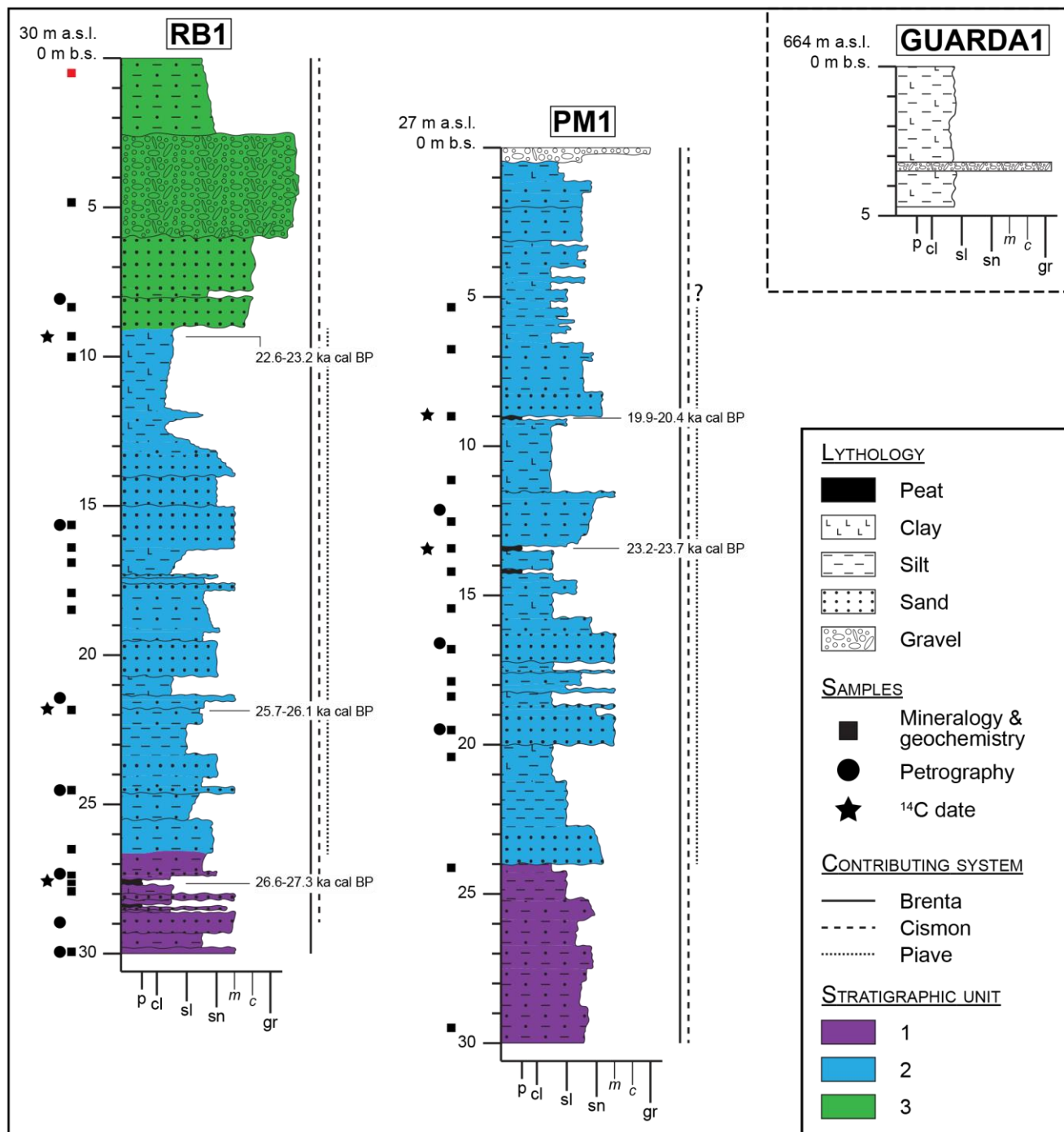
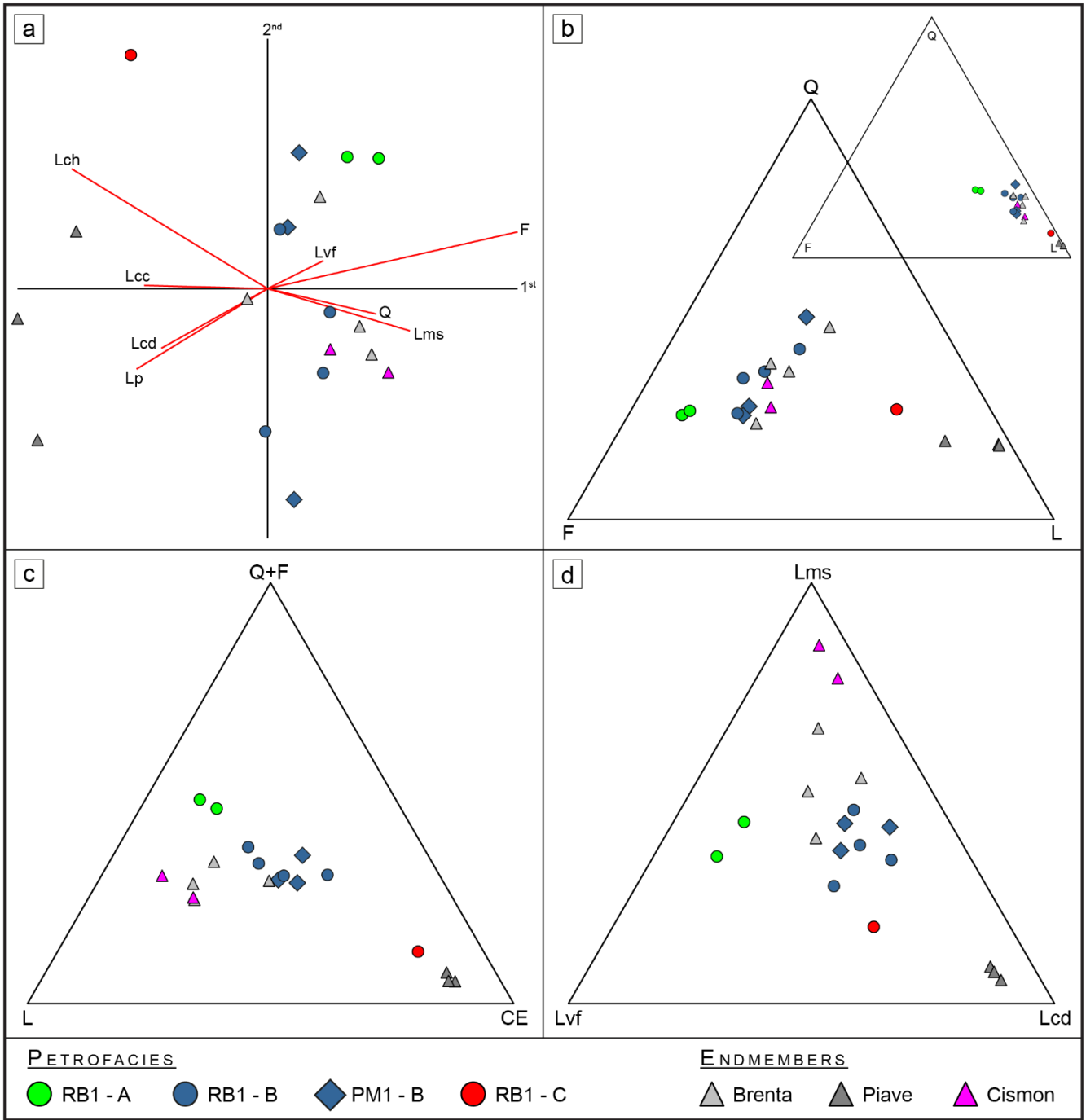
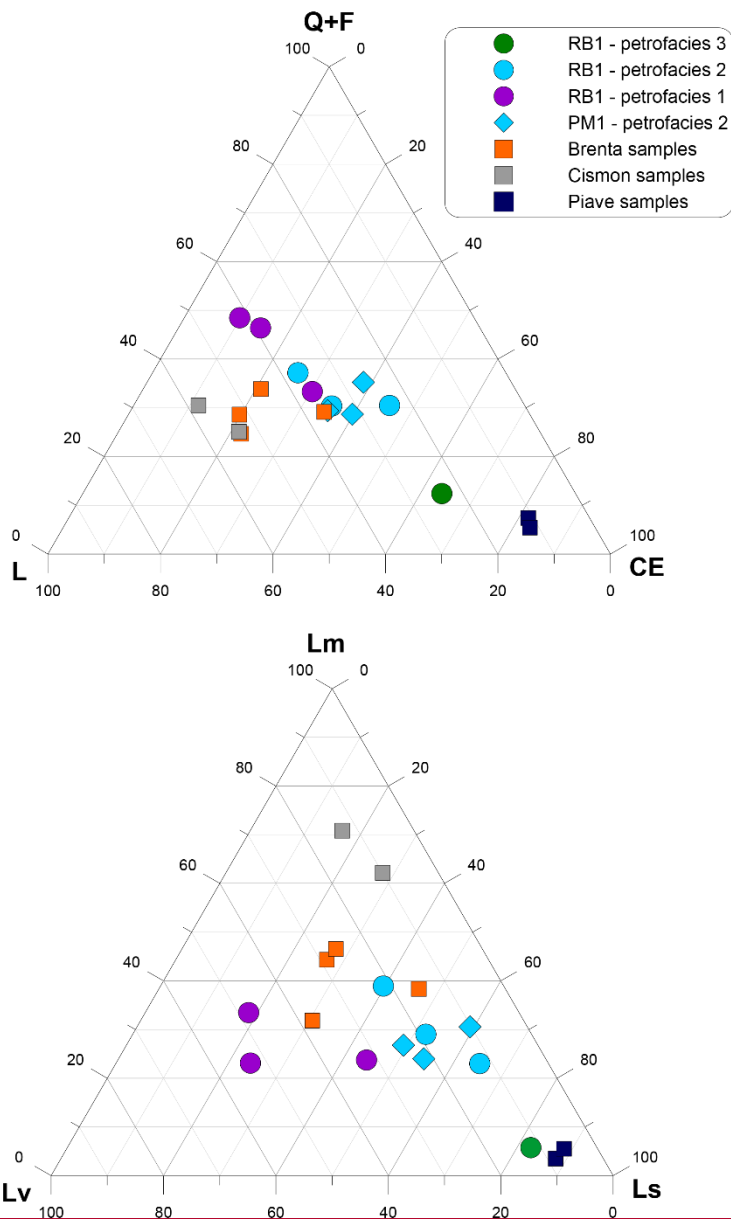


Figure 6: Stratigraphic logs of the RB1, PM1 and Guardia1 cores. **Different Stratigraphic units described in the text are evidenced with different colours, while different** catchments contributing to the sedimentation are marked by lateral solid/dashed lines. Samples are shown with different symbols according to the adopted technique.





5 **Figure 7: (a) Compositional biplot of the principal components; (b) original (small) and centred (large) QFL diagrams; (c) Q+F, L (non-carbonate lithic) and CE (carbonate lithic and cherts) and (d) Lms, Lvf and Lcd ternary diagrams with the results of the sand petrography analysis performed in RB1 and PM1 cores. Endmembers after Garzanti et al. (2006) and Monegato et al. (2010). See Table 2 for component acronyms. The compositions of the sediments transported by the present Cison and Brenta rivers are included.**

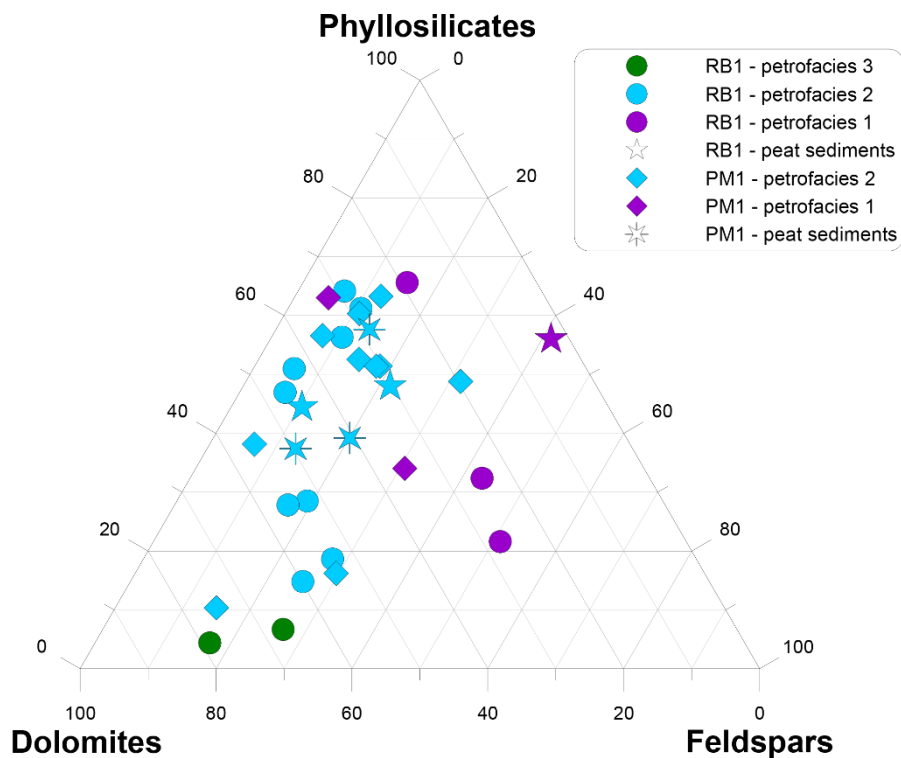
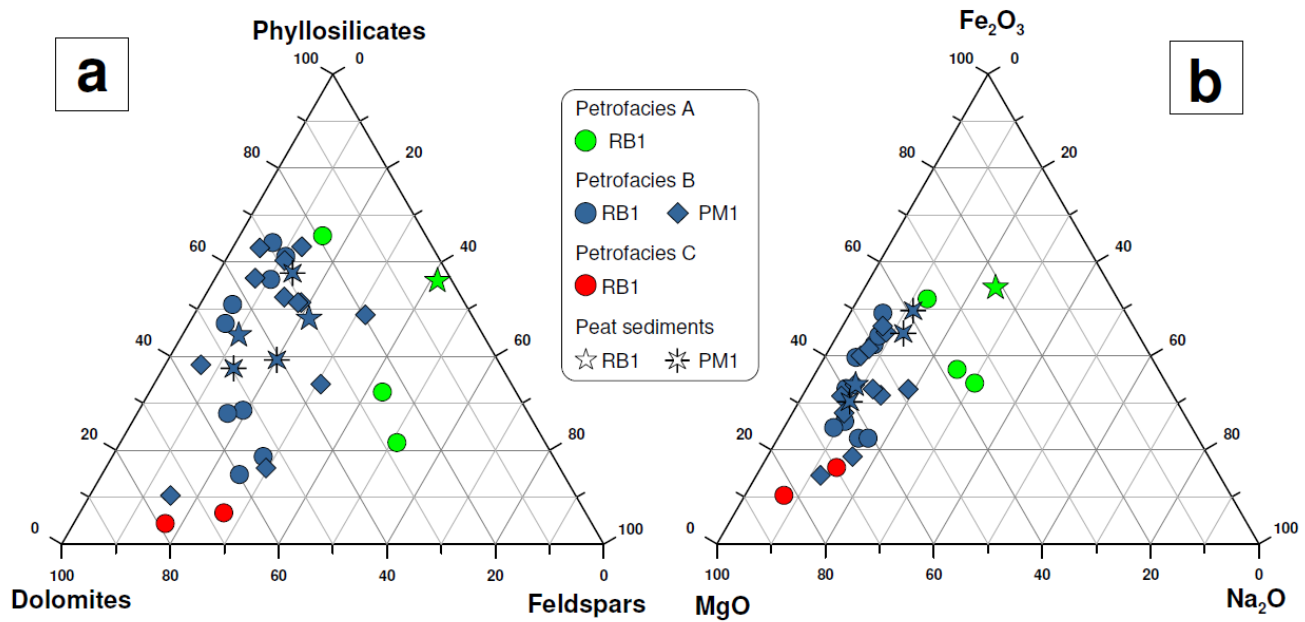


Figure 8: Ternary diagram reporting main selected mineral components **(a)** and geochemical components **(b)** of bulk sediments in RB1 and PM1 cores. Peat samples are evidenced with different symbols.

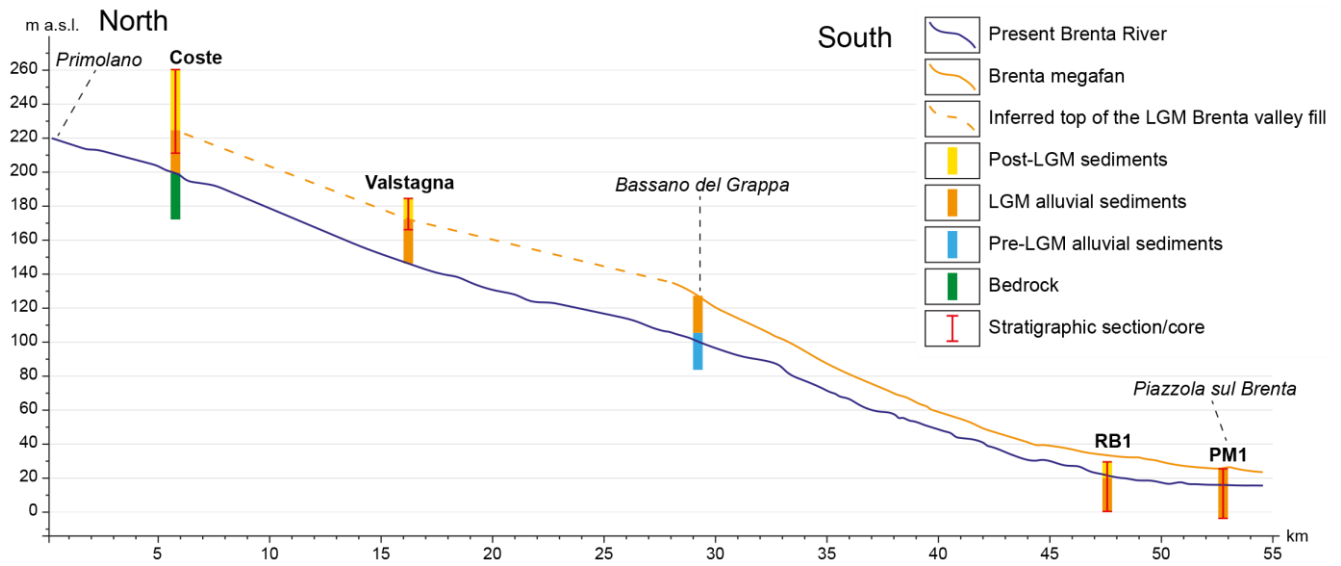
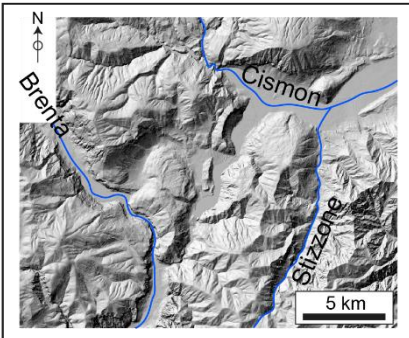
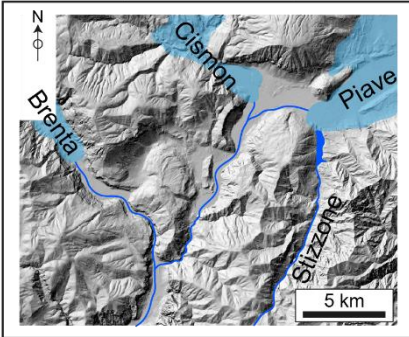
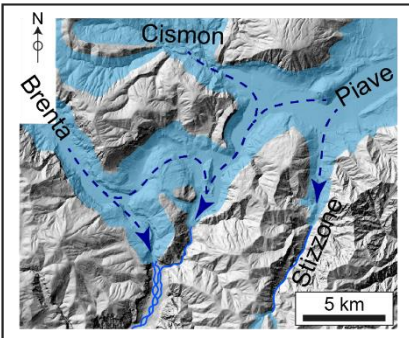


Figure 9: Longitudinal profiles of the present Brenta river (blue solid line), from Primolano to Piazzola sul Brenta, the Brenta megafan (orange solid line), from the apex to Piazzola sul Brenta, and the possible profile of the Brenta valley bottom during LGM (orange dashed line), inferred from stratigraphic sections. The age of sediments/bedrock is shown with different colours.

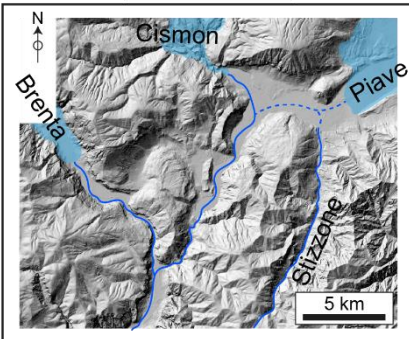


----- 27.0 ka BP -----

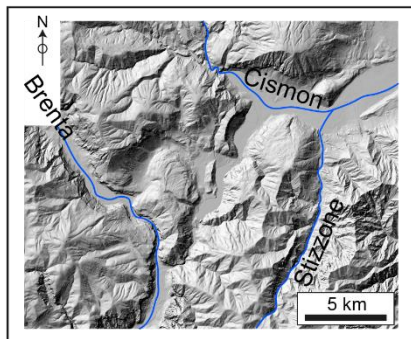




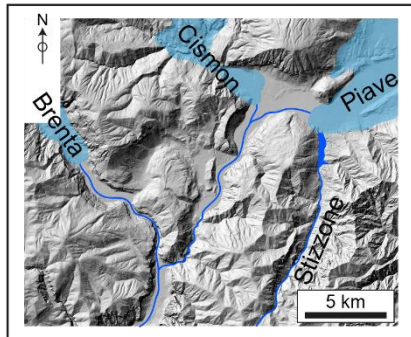
----- 19.5 ka BP -----



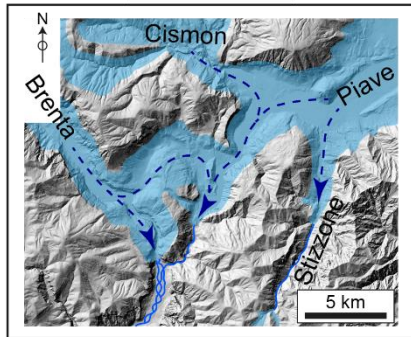
----- 17.5 ka BP -----



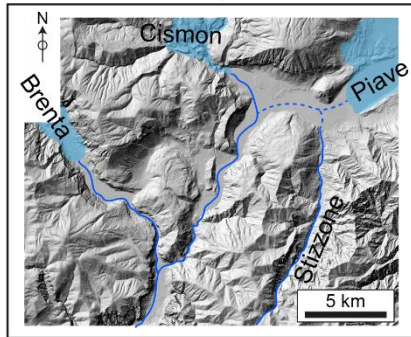
----- 27.0 ka BP -----



----- 26.0 ka BP -----



----- 19.5 ka BP -----



----- 17.5 ka BP -----

Figure 10: Evolution of the middle sector of the Valsugana valley since the onset of LGM; see text for details.

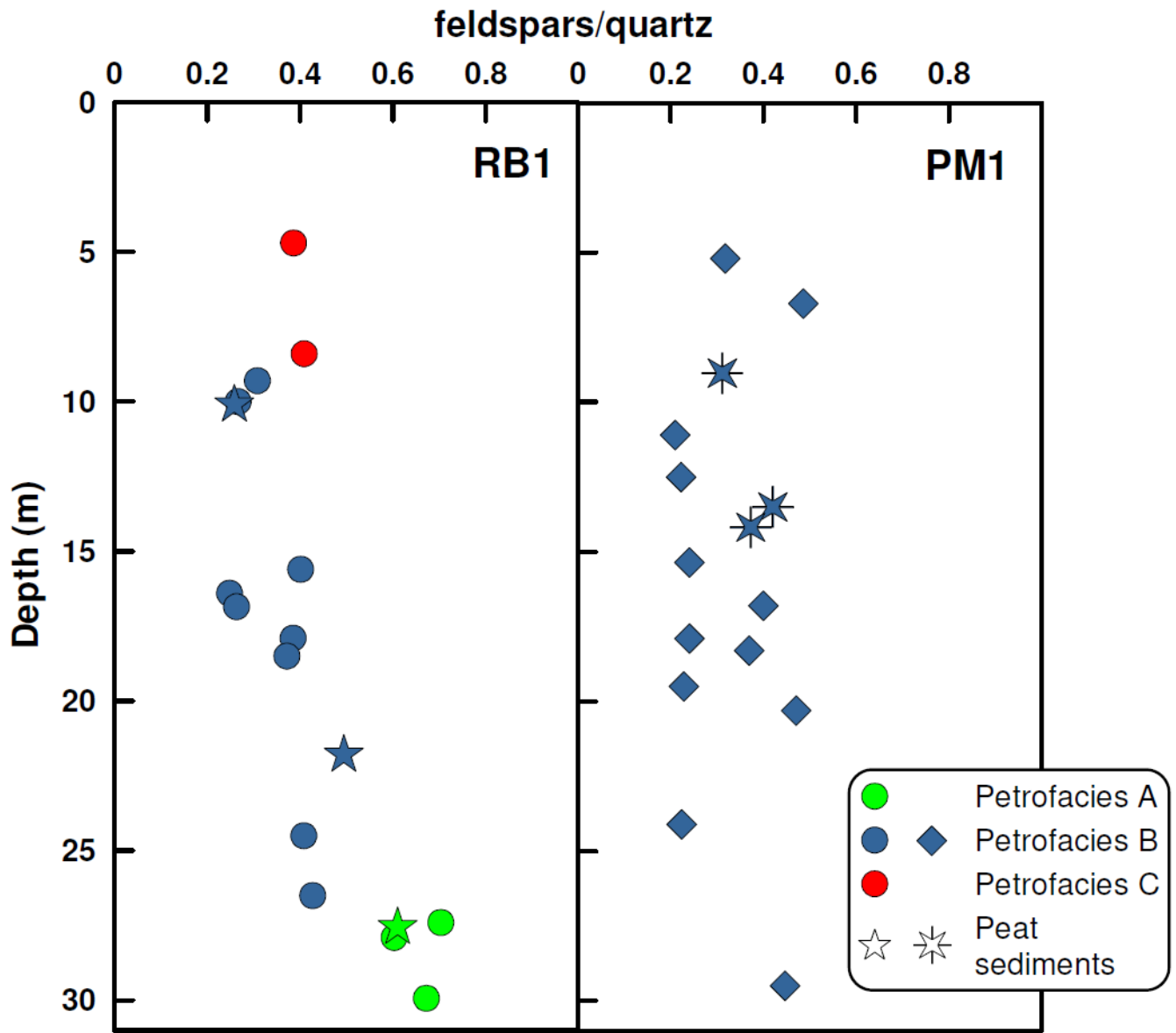
Sample name	Lab. code	Material	Depth [m]	Thickness [cm]	Uncalibrated age [years BP]		Calibrated age (IntCal 13 - 2 σ) [years BP]		
					Lab. age	Uncertainty (\pm)	Min	Max	Median prob.
PM1-1	UZ-6073	Peat	9.00	1.5	16,700	60	19,945	20,362	20,147
PM1-2	UZ-6074	Peat	13.45	1	19,500	75	23,167	23,754	23,495
RB1-1	UZ-6075	Peat	9.30	1.5	19,050	70	22,648	23,221	22,938
RB1-2	UZ-6076	Peat	21.80	1	21,610	90	25,715	26,058	25,888
RB1-3	UZ-6077	Peat	27.50	1	22,660	90	26,634	27,296	27,013

Table 1: Conventional, calibrated and median probability ^{14}C ages obtained from samples collected on RB1 and PM1 cores. Calibration was made with OxCal (version 4.2, Bronk Ramsey, 2009), based on the IntCal13 calibration curve (Reimer et al., 2013).

Sample	Depth [(m)]	Q	F	Lvf	Lvi	Lvp	Lcc	Lcd	Lp	Lch	Lms	Lmi	tot	<u>Contribution of endmembers (R²)</u>
PM1-12	12.1	30.5	4.7	6		0.5	14.4	20.8	3.5	0.2	19.4		100	50% Brenta, 20% Cisonon, 30% Piave (0.76)886
PM1-17	16.6	18.2	10.6	9.1	0.3	2.6	23.9	14.8	1.4	1.1	17.9	0.3	100	30% Brenta, 20% Cisonon, 50% Piave (0.80)892
PM1-19	19.4	19.5	9.9	13.1		2.1	15.5	19.3	0.6	1.6	18.4		100	50% Brenta, 20% Cisonon, 30% Piave (0.93)955
RB1-8	7.9	10.3	2.1	8		0.3	47.3	15.3	1.6	10.1	5.2		100	All combinations (<0.7) Not representative
RB1-16	15.7	25.1	5.5	7.5			18.9	22.5	4.6	0.5	15.5		100	40% Brenta, 10% Cisonon, 50% Piave (0.79)897
RB1-21	21.4	26.8	10.4	9.7		1.7	5.6	18.9	1.6	0.7	24.4	0.2	100	5060% Brenta, 3020% Cisonon, 20% Piave (0.88)953
RB1-24	24.45	19.3	11.1	11.1		1.1	12	21.6	2.2	1.8	19.7	0.2	100	5040% Brenta, 20% Cisonon, 3040% Piave (0.93)956
RB1-27	27.3	25.1	8.3	18.8	0.3		3.3	24.3	2.8	0.5	16		100	8070% Brenta, 10% Cisonon, 10% Piave (20% Astico 0.94)957
RB1-29	28.95	28.3	20.2	19.2		1.5	2.5	6.6	1.1	1	19.2		100	10090% Brenta (10% Cisonon 0.83)906
RB1-30	29.95	27.9	18.5	21.1		2.6	7.8	5.3	0.3	1	14.1		100	100% Brenta (0.83)914

Table 2: Detrital modes of the sand fraction collected on RB1 and PM1 cores. List of acronyms: Q: quartz; F: feldspars; Lvf: felsic volcanic and subvolcanic lithic fragments; Lvi: intermediate and mafic lithic fragments; Lvp: plutonic lithic fragments; Lcc: limestone grains; Lcd: dolostone grains; Lp: shale, siltstone lithic fragments; Lch: chert grains; Lms: low-grade metamorphic lithic fragments; Lmi: medium-grade metamorphic lithic fragments.

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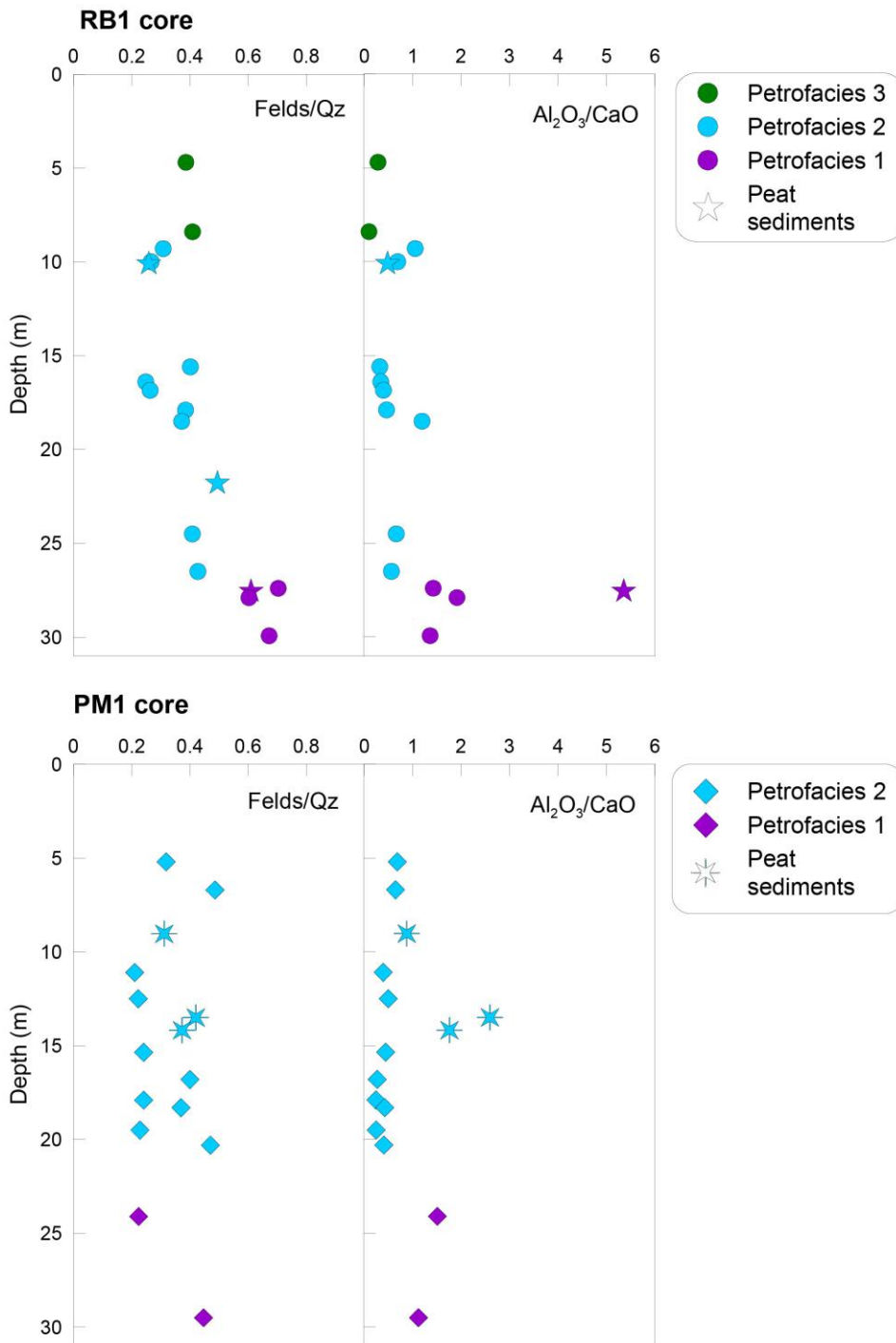


Figure 1: Mineralogical and geochemical parameters (Feldspars/quartz/Quartz and Al_2O_3/CaO ratio in RB1 and PM1 cores (bulk sediments). This mineralogical parameter is, respectively) useful to highlight peculiar compositional features of petrofacies A, B and C, Units 1, 2 and 3 from cores RB1 and PM1 (bulk sediments).

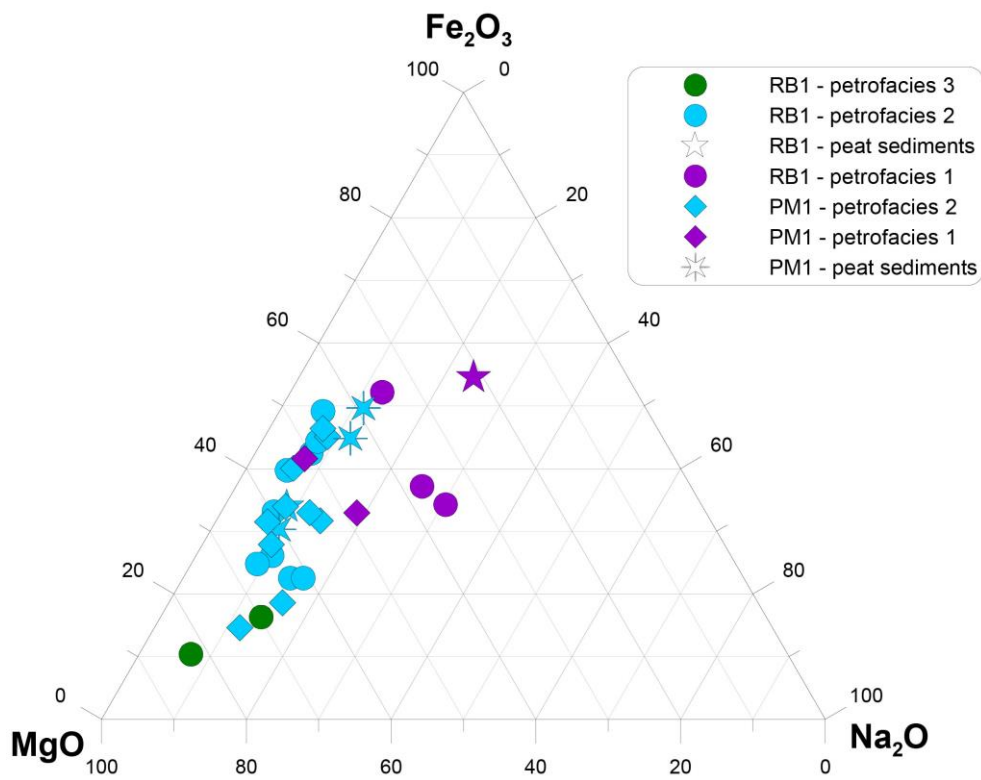


Figure 2: Ternary diagram reporting main selected geochemical components of bulk sediments in RB1 and PM1 cores.

RB1 core																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	A
Depth (m)	0.5	4.7	8.4	9.3	10.0	10.1	15.6	16.4	16.9	17.9	18.5	24.5	26.5	27.4	27.6	27.9	29.9	21.85
Mineralogical analyses (wt%)																		
Quartz	21	35	17	19	14	18	33	14	12	37	19	28	26	15	25	41	39	27
Calcite	6	15	37	12	25	20	15	31	30	12	6	5	5	10	1	2	5	3
Dolomites	21	34	32	15	16	19	31	25	22	27	22	31	37	13	1	14	14	19
Plagioclase	6	10	5	4	3	4	11	3	2	12	6	9	10	10	13	20	19	10
K-feldspar	1	4	2	1	1	<1	2	1	1	3	1	3	2	1	3	5	7	3
Phyllosilicates	33	3	2	33	36	18	8	25	26	10	38	17	19	45	21	19	11	29
Am.XRD	14	<1	5	16	4	20	<1	1	7	<1	8	7	2	6	36	<1	4	9
Chemical analyses (wt%)																		
SiO2	40.65	45.17	23.97	37.94	32.77	30.81	44.13	28.88	27.34	49.21	39.58	43.50	39.15	42.14	45.90	59.94	61.30	
TiO2	0.64	0.14	0.10	0.39	0.39	0.30	0.23	0.23	0.31	0.21	0.30	0.29	0.26	0.41	0.45	0.53	0.28	
Al2O3	14.00	5.62	3.29	13.19	12.96	8.96	6.23	8.33	9.64	7.25	14.62	9.13	8.95	16.18	11.84	12.40	10.94	
Fe2O3 tot	5.03	1.25	0.75	4.17	4.72	2.82	1.90	2.92	3.99	1.82	5.36	2.95	2.93	5.67	3.45	3.13	2.43	
MnO	0.13	0.02	0.02	0.06	0.09	0.04	0.04	0.06	0.08	0.03	0.08	0.04	0.05	0.11	0.04	0.04	0.03	
MgO	5.30	5.36	5.97	4.90	4.31	4.79	5.29	5.26	5.48	4.92	5.81	7.17	7.82	3.82	1.35	3.13	2.51	
CaO	10.79	19.54	32.44	12.50	18.70	18.48	19.22	24.23	24.18	15.62	12.22	13.74	15.83	11.34	2.21	6.47	8.03	
Na2O	0.92	1.07	0.52	0.76	0.58	0.72	1.25	0.64	0.58	1.34	0.93	1.19	1.08	1.38	1.53	2.17	2.16	
K2O	2.73	1.47	0.71	2.92	2.87	1.94	1.45	1.82	2.16	1.88	3.50	2.21	2.14	3.55	2.49	2.95	2.85	
P2O5	0.17	0.05	0.04	0.11	0.10	0.11	0.07	0.11	0.11	0.07	0.13	0.09	0.09	0.15	0.16	0.10	0.09	
L.O.I.	19.04	20.51	31.89	22.63	22.15	31.27	20.23	27.35	26.51	17.45	17.35	19.55	21.32	15.16	30.42	8.68	9.49	
Tot	99.40	100.20	99.70	99.58	99.64	100.24	100.04	99.83	100.38	99.80	99.88	99.86	99.62	99.91	99.84	99.53	100.11	
N (%)	0.15			0.14		0.33			0.03						0.76			
Corg (%)	1.28			3.18		5.62			0.40						14.70			
ppm																		
As	32	20	1	55	23	84	18	19	11	0	<1	12	2	20	103	20	4.6	
Cd	2.9	0	0	0	0	1	0	<1	0	0	1	0	0	2	2	0	0	
Cr	80	19	8	47	28	72	8	38	34	11	82	23	37	79	61	51	20	
Cu	34	6	1	21	6	30	5	19	9	2	29	5	19	33	25	10	7	
Ni	35	3	3	44	14	31	4	22	15	9	25	6	17	29	17	40	18	
Sr	92	138	155	144	159	160	82	139	123	68	100	71	69	83	69	96	82	
Zn	114	127	18	84	78	227	44	67	57	28	121	37	2	132	51	77	58	
PM1 core																		
	A	B	C	D	E	F	G	H	I	L	M	N	O	P	Q			
Depth (m)	5.2	6.7	9.0	11.1	12.5	13.5	14.2	15.4	16.8	17.9	18.3	19.5	20.3	24.1	29.5			
Mineralogical analyses (wt%)																		
Quartz	17	28	22	15	29	14	18	12	31	17	15	33	13	15	35			
Calcite	19	11	1	22	17	0	0	27	16	35	31	15	30	1	2			
Dolomites	14	8	26	26	11	12	13	14	23	9	10	38	25	21	18			
Plagioclase	5	12	6	3	5	5	5	2	9	3	5	7	2	3	11			
K-feldspar	0	2	1	0	2	1	1	1	3	1	0	1	0	0	5			
Phyllosilicates	29	21	20	18	18	25	13	22	7	15	27	5	18	42	17			
Am.XRD	15	19	25	16	18	43	49	22	11	20	12	1	12	17	12			
Chemical analyses (wt%)																		
SiO2	37.84	47.85	36.44	30.89	42.21	35.91	29.75	29.15	44.75	27.94	30.04	42.39	29.12	39.09	54.13			
TiO2	0.29	0.24	0.26	0.23	0.24	0.35	0.27	0.26	0.18	0.22	0.25	0.17	0.26	0.30	0.36			
Al2O3	11.63	9.43	9.38	8.88	8.83	12.86	8.90	10.59	5.27	6.27	9.83	4.84	9.77	15.42	11.23			
Fe2O3 tot	4.05	2.79	2.78	2.88	3.01	4.15	2.81	3.94	1.29	1.93	3.01	1.21	3.57	4.91	3.03			
MnO	0.07	0.05	0.03	0.05	0.06	0.04	0.03	0.07	0.03	0.04	0.06	0.03	0.06	0.07	0.05			
MgO	4.16	4.76	5.54	5.61	5.00	3.26	2.71	3.93	4.56	4.34	5.11	6.11	4.77	6.04	4.44			
CaO	16.95	14.48	10.65	22.42	17.65	4.95	5.05	23.73	19.51	25.48	22.95	19.35	23.98	10.20	9.99			
Na2O	0.78	1.27	0.86	0.66	1.12	0.95	0.75	0.63	1.09	0.66	0.75	0.98	0.58	0.86	1.73			
K2O	2.66	2.08	1.85	1.91	1.79	2.56	1.54	2.29	1.37	1.33	2.16	1.18	2.08	3.43	2.39			
P2O5	0.15	0.18	0.24	0.23	0.21	0.18	0.30	0.36	0.19	0.28	0.20	0.22	0.20	0.18	0.09			
L.O.I.	21.02	16.77	31.94	26.11	19.91	34.39	47.59	24.81	21.31	31.11	25.35	23.34	25.65	19.49	12.47			
Tot	99.60	99.90	99.97	99.87	100.03	99.60	99.70	99.76	99.55	99.60	99.71	99.82	100.04	99.99	99.91			
N (%)			0.38			0.64	1.13			0.24				0.14				
Corg (%)			7.25			14.46	21.90			3.04				1.75				
ppm																		
As	4	35	87	15	6	181	220	15	23	27	19	31	20	60	13			
Cd	6	3	5	5	6	10	12	7	13	8	3	8	14	11	10			
Cr	54	29	39	44	33	55	69	66	16	34	46	22	58	69	53			
Cu	30	24	26	22	23	27	32	25	31	21	22	12	20	37	24			
Ni	25	33	24	21	28	18	18	15	16	12	13	8	9	6	2			
Sr	194	119	80	170	174	82	80	241	130	206	199	109	264	89	132			
Zn	228	135	132	130	268	142	164	153	143	127	180	111	133	267	263			

STable 1: Results of mineralogical and geochemical analyses of RB1 and PM1 cores.