Responses to the reviewer's and editor's comments

First, we would like to thank the two anonymous reviewers and the editor for their comments, which helped to improve our manuscript.

Reviewer 1:

The manuscript presents the evolution of the Frébouge polygenetic cone in the Ferret Valley based on geomorphological mapping, 10Be surface exposure ages, and simulations of the rock avalanche. In general, I really like the comprehensive interdisciplinary look at the cone´s evolution, also the writing style is clear, without grammar issues. Some minor typos corrections and modifications are suggested in the attached pdf file.

Here I point out some of them:

How did you distinguish the RA and debris flow deposits? Only by the geomorphic context? How looked the RA deposit in detail? Was there any outcrop of the RA sediment? How was the inner fabrics?

The RA and the debris flow deposits were distinguished based on their geomorphology but also based on their sedimentology. The debris flow deposits are characterised by sub-rounded to rounded boulders with a maximum size of ca. 2 m. Furthermore, levees and the debris flow noses in the cone represent a distinct morphology. The RA deposits consists of angular to sub-angular clasts deposited in an open-framework fabric. The maximum boulder height is 10 m. There are no natural outcrops of the RA deposits, whereas Philip Deline (2009) opened a trench and investigated the contact between the RA deposits and the underlying sediments (till and earth flow deposits).

We included this information into the manuscript:

"*The southwestern and northeastern part of the Frébouge cone is characterized by hummocky deposits consisting of a complex network of channels, levees, and debris flow noses (Figure 4). The longest channel is about 500 m in length and 15 m in width. These channels were formed by incision of the debris flow into the ~~surface~~ cone. Levees are elongated landforms lying on the side of the channels. The debris flow noses can be up to 60 m long, 25 m wide, and 10 m high (Figure 5). These noses are structures with a blocky terminus. On the Frébouge cone, the levees and the debris flow noses are difficult to distinguish. Therefore, all landforms with a clear blocky end were classified as debris flow noses regardless of their length. Elongated geomorphic features on the other hand were classified as levees. The sediment of the levees and the debris flow noses are mostly well-sorted, and their grain size is between cobbles and blocks. The clasts are sub-rounded. Within unweathered deposits, sand and finer-grained sediments were observed.*

In addition, the area with the hummocky deposits is strongly vegetated and forested. In the northeastern part, many levees and debris flow noses are up to 2 m high, whereas they are less than 1 m in the southwestern part. In the area of the debris flow noses the forest is less dense. The channels and levees show a complex interaction. Older levees and channels are cut by younger ones and towards the center of the cone they tend to be longer than at the sides, where they are stronger segmented. The main orientation of the channels and levees in the southwestern part is NE-SW and NNW-SSE in the north-eastern part.

Rock avalanche deposits dominate the lower part of the cone, where debris forms a chaotic deposit (Figure 4). We distinguished the deposits of the rock avalanche from the debris flow deposits based on their geomorphology and their sedimentology. The rock avalanche consists of, on the contrary to the debris flows, weathered, unsorted, and angular to sub-angular clasts with a grain size between sand and blocks deposited in an open framework fabric. Two dense accumulations of granite boulders and an accumulation of boulders larger than 2.5 m in diameter are located at the distal zone of the cone. The largest boulder reaches a height of 10 m (Figure 6). In the dense accumulation of granite boulders, smaller blocks are also observed. A 2 m high rim marks the extent of the rock avalanche deposit on the sides of the cone, whereas the southeastern limit of the rock avalanche deposit is not determined by a clear rim. Therefore, this limit was reconstructed based on the frequency of granitic boulders along the slope. In this part, the deposit has a thickness of 0.5 m. The RA deposits overly till and earth flow deposits Philip Deline (2009)."

L. 243: "The south-eastern side of the valley could be affected by a deep-seated gravitational slope deformation..."

So it was affected or was not? What do you mean by "could be"? In the future? I would suggest rephrasing this sentence.

We thank the reviewer for this comment. To make our statement clearer we rephrased the sentence as follows:

"*In the south-eastern side of the valley bent trees are observed, which indicate deep-seated gravitational slope deformation (DGSD) and creep.*"

Figure 1: For completeness and reader´s fast orientation, here I miss presentation of the entire source area of the material incorporated in the fan, i.e. the rock avalanche scarp, glacial cirque, etc. Can you please slightly enlarge the area of the detailed terrain map and to label the most important features?

We would like to thank both reviewers for pointing this out. We enlarged the area and included the source area of the rock avalanche as well as some geological information to the inset. Furthermore, we increased the size of the coordinates in the inset.

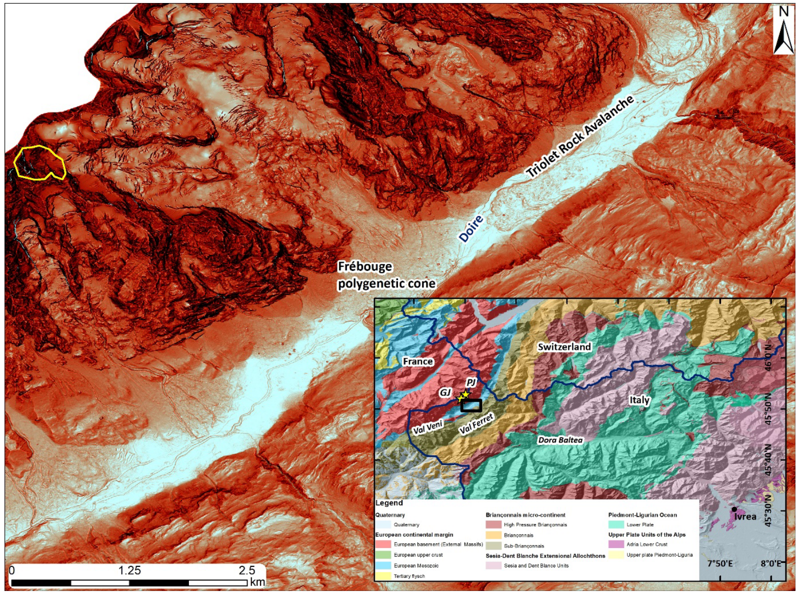
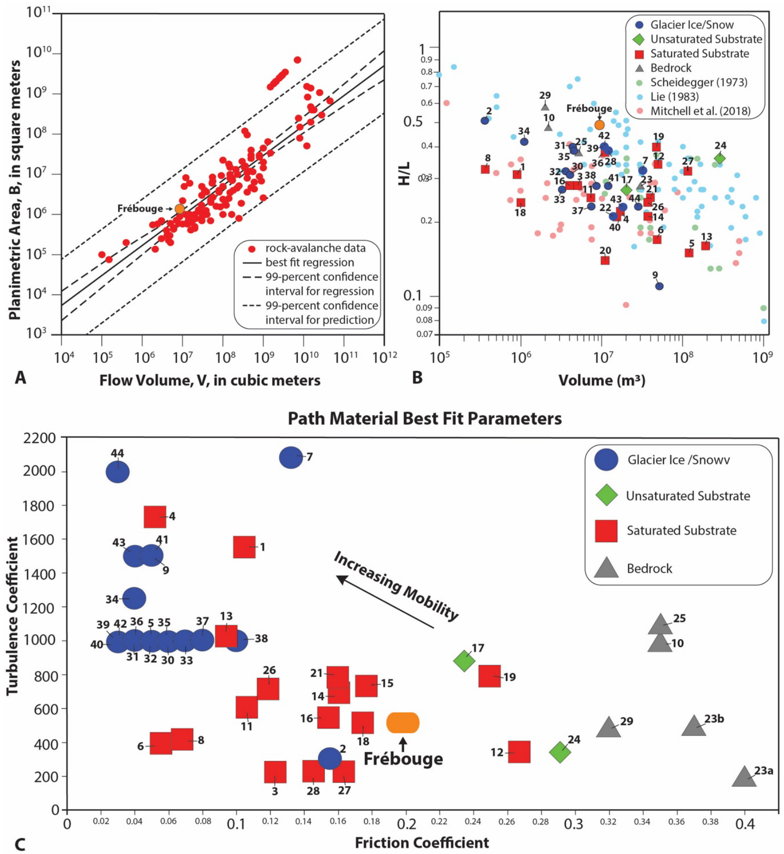


Figure 1: The Red Relief Image Map (RRIM) of the Ferret Valley showing the Frébouge polygenetic cone and the 1717AD Triolet rock avalanche. The yellow line indicates the source area of the Frébouge Rock avalanche. The inset shows a simplified tectonic map and the location of the study within the Alpine realm (after Schmid et al., 2017) **© European Union, Copernicus Land Monitoring Service 2023, European Environment Agency (EEA). PJ = Petites Jorasses and GJ = Grandes Jorasses.**

Figure 9: some labels are too small and difficult to be read correctly.

We are grateful for this comment. We increased the size of the labels to enhance the readability. Furthermore, we harmonised the three panels, so that they have the same style.



Concluding figure is missing, I would suggest to the authors to prepare a conceptual model schematically presenting the cone´s evolution and main contributing processes.

We are grateful for this remark. We added a conclusive figure at the end.

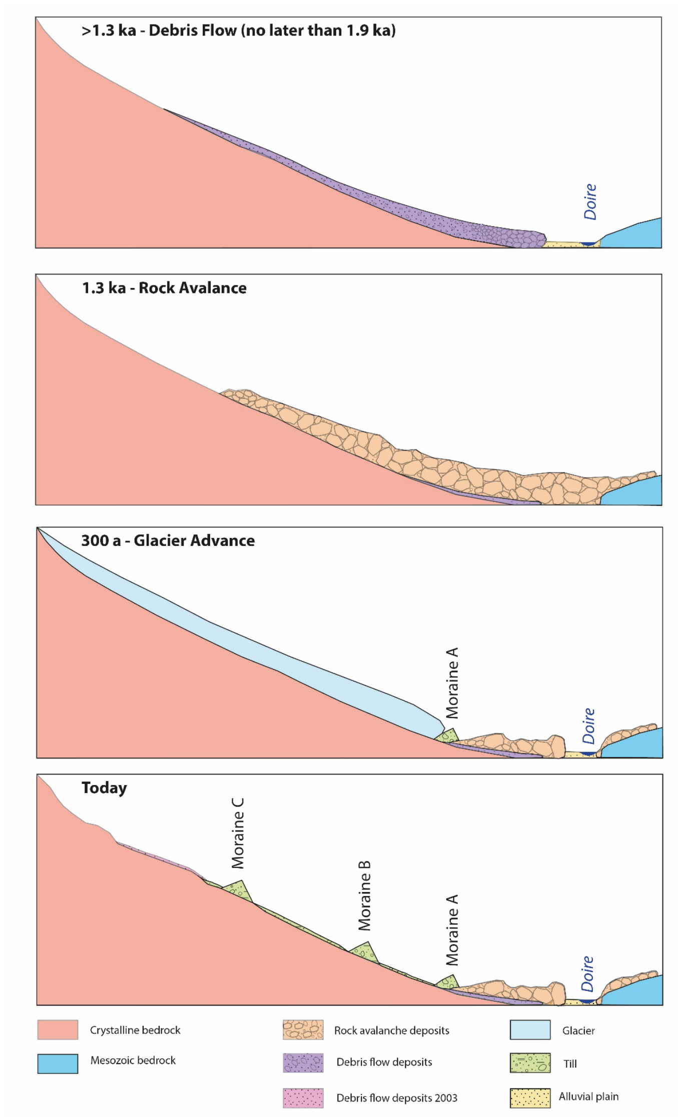


Figure 12: Schematic cross-section through the Frébouge polygenetic cone showing the evolution through time.

I propose accepting the manuscript to be published after a minor revision.

Reviewer 2:

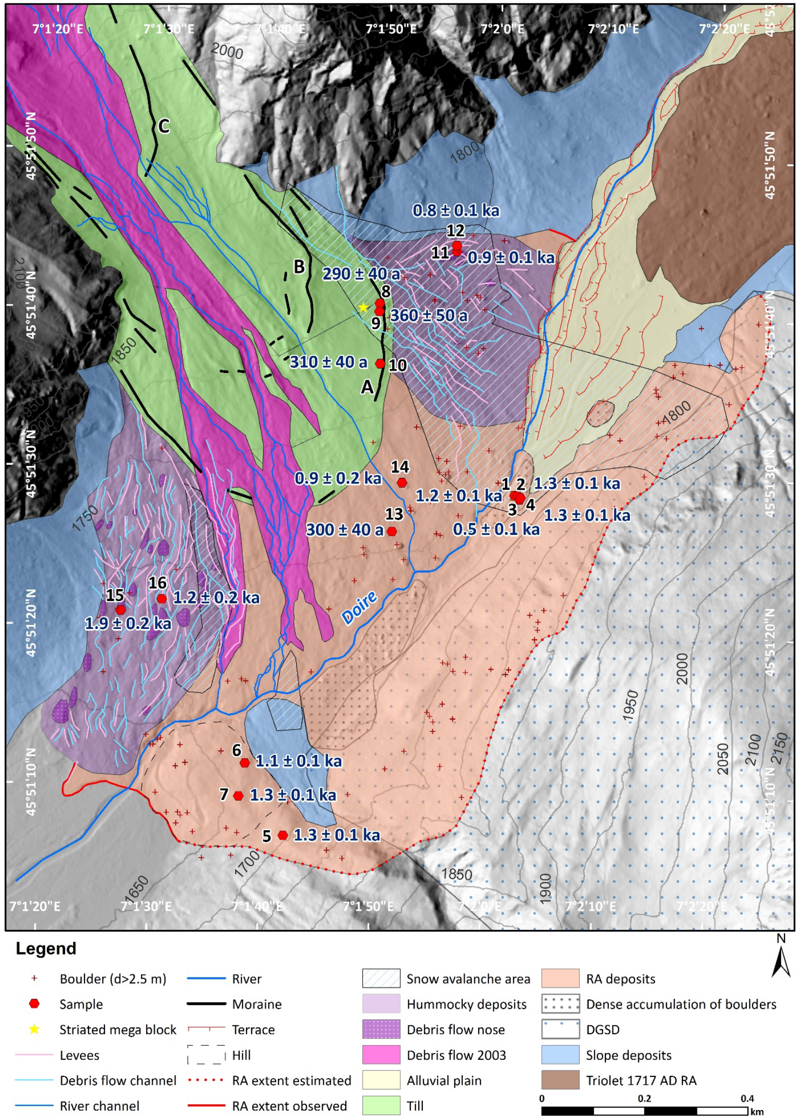
This is a scientifically sound and well written paper that I think may be suitable for publication in EGUsphere after the following minor revisons:

- I suggest improving the inset of Fig. 1 in order to include some elements of geology.

Please see previous comment to Fig. 1.

- In the legend of Fig. 3, the text is too small and the boxes should have a black outline.

We are grateful for this comment, we increased the size of the text, added black lines to the boxes and adjusted the legend according to the editor's suggestion.



- A final conceptual figure is required to summarize your findings.

Please see comment above.

Editor:

Dear authors,

first of all, I would like to apologize for the long time it has taken us to evaluate your submission.

I'm happy to see that both reviewers find your manuscript interesting and a valuable contribution to Earth Surface Dynamics. Their comments provide you some guidance to improve your manuscript for submitting a revised version. Both reviewers suggested a final conceptual figure to summarize your findings and I agree with them. I think that such a figure should be accompanied with an additional section in which you try to draw some conclusions regarding the bigger picture. What have you learned from this particular case study, which is relevant for the larger research question of how mountainous landscapes respond to ice retreat and climate change. You should try to pick up some of the topics and questions you raised in the first two paragraphs of your introduction. That helps the reader to place your research in a wider context.

Find below a few additional points to please consider when preparing a revised version:

At the end of the introduction, it would be useful to provide a motivation for the research, ideally a research question, which helps the reader to understand the goal of the research and what difference it makes when you reach this goal. Please try to keep the broader picture in mind, beyond the question of how this particular cone was formed. It would also help if you could provide reasons why geomorphic mapping, surface exposure dating and runout modelling are needed to reach the goal.

We thank the editor for pointing this out. We revised the following paragraphs as follows:

"*In proglacial environments, the combination of different processes leads to high sediment production, which often exceeds the sediment discharge (e.g., Hallet et al., 1996). This imbalance between the sediment production and transport causes accumulation, which is driven in part by sudden failures such as debris flows (Kamp and Owen, 2013; Carrivick et al., 2013), while rock, ice, and snow avalanches can get detached from the steep valley flanks (e.g., Akçar et al., 2012; Deline et al., 2015). As glaciers retreat due to global warming, proglacial areas expand, altering the landscape and potentially increasing the frequency and magnitude of natural hazard events. The interplay between mass movement processes (like landslides, rockfalls, and debris flows) and climatic changes, including global warming, is indeed complex and not yet fully understood. Therefore, studying how changes in climate and the growth of areas in front of glaciers affect natural disasters, water supply, ecosystems, infrastructure, and climate patterns helps us better understand and respond to environmental changes and risks. Consequently, the investigation of the mechanisms governing the occurrence and behaviour of past failures, as well as their magnitudes and frequencies is critical for improving hazard and risk assessments of alpine settlements and infrastructure, and in hazard mitigation (Prager et al., 2008; Ivy-Ochs and Schaller, 2009 among others).*

The Ferret Valley is not only influenced by glaciations but also by mass movement processes. Rock avalanches and large rock falls with volumes from 10'000 m^3 to 10 Mm^3 were identified as occurring between 2.5 ka and 2007 (Deline, 2009; Deline and Kirkbride, 2009; Deline et al., 2012). In the upper part of the Ferret valley, the 1717 AD Triolet rock avalanche was studied in detail (Figure 1). Deposits of this landslide were dated to 1742 AD by applying dendrochronology (Porter and Orombelli, 1980) and between 1717 AD and 1727 AD by lichenometry (Porter and Orombelli, 1980), which was later confirmed by surface exposure dating with cosmogenic ^{10}Be (Akçar et al., 2012, 2014). Another rock avalanche event in the Ferret Valley was observed at the toe of the Frébouge Glacier, which has taken place around 350 years ago (Porter and Orombelli, 1981), representing a part of the Frébouge *polygenetic cone (Deline 2009). Finally, the Frébouge polygenetic cone was partially covered by the Frébouge Glacier during the LIA (Deline, 2009). Frequent snow avalanches and debris flows fed by glacial runoff have been recorded over the past decades (Deline et al., 2004).*

Glacier fluctuations and mass movement processes in the Val Ferret and their timing have been studied at various places (Porter and Orombelli, 1980, 1981; Deline et al. 2004; Deline 2009; Akçar et al. 2012, 2014). Despite this, the frequency of these processes within the complex environment of a polygenetic cone has not been investigated. The Frébouge polygenetic cone thus provides a unique record of complex natural hazards such as rock avalanches, debris flows, and snow and ice avalanches, the future occurrence of which can constitute a danger for the inhabitants of this area. This raises the question of what the recurrence intervals are for these different processes. Hitherto, the processes on the Frébouge polygenetic cone have been considered independently, and their interactions have not been studied in detail. In this paper, we aim at deciphering the geomorphic processes and their interactions by exploring all processes at once. This allows us to understand the evolution of the Frébouge polygenetic cone and gather information on the climatic conditions that could trigger these events. To achieve this, field mapping and remote sensing tools were applied. These methods enable us to distinguish between the processes responsible for the valley's diverse geomorphological features. The chronology of this polygenetic cone was established by applying cosmogenic ^{10}Be surface exposure dating on moraines, debris flow deposits, and rock avalanche deposits. This chronology not only reveals the frequency of these events but also indirectly suggests climatic conditions that may have influenced them. The dynamics of the Frébouge rock avalanche were investigated using the semi-empirical numerical model DAN3D, which offers insights into the parameters that influence the motion of the rock avalanche."

Section 3.1: You mention a very high-resolution DEM. What is the resolution and do you show it somewhere in a figure? It was not clear to me how it was useful for the geomorphic mapping. Or was it more the orthoimage that helped you in the geomorphic mapping?

We are grateful for this comment. The resolution of the high-resolution DEM is ca. 5 cm. This DEM is used as a background of figure 3 (surficial geology map). For the remote digital mapping the combination of the high-resolution DEM and orthoimages helped to identify the different geomorphologic features.

We incorporated this information in the manuscript:

"*For remote digital mapping, high-resolution aerial photographs, which were taken with an unmanned aerial vehicle, were then used to create a digital elevation model (DEM) with a resolution of 5 cm and orthophotograph of the study area. The combination of high-resolution DEM and the orthophotograph allowed us identifying and distinguishing the different geomorphic landforms. The corresponding flight missions were planned in Litchi Mission Hub® (flylitchi.com/hub)."*

Section 3.3: I found the description of how you evaluated the volume of the deposit a bit short. As this seems to be a key input for the modelling, I suggest to provide more details here. For example, how did you constrain the lower boundary of the deposit? Was it exposed somewhere? If so where and how does it look like? Is it sufficient to constrain the thickness of the deposit across the entire area? Perhaps an additional figure that details the volumetric reconstruction would help the reader, also for the results section. Finally, I can see that adding uncertainties to a volumetric reconstruction is not trivial, but it would help the reader to assess the modelling results if you can provide an estimate of uncertainties. Note that these do not have to be measured uncertainties, but they could be guessed based on some of the assumptions you made in the reconstruction. I've seen that you address the uncertainties in the discussion section 5.2, but I think you can provide some percentages, based on your approach and the available data.

The determination of the RA's volume is based on the mapped extent of the RA deposit and its thickness. To determine the thickness of the rock avalanche deposit, we subtracted the volume of younger events than the RA. As there are no drill cores available, the lower boundary of the RA deposit was estimated by combining field observations, descriptions of the deposits in previous studies (e.g. Deline 2009), and cross-sections drawn across the Frébouge cone. We added a figure to the manuscript, which shows the cross-sections through the cone to estimate the thickness of the deposit. We included more details on the volume reconstruction in the manuscript:

"*To estimate the source volume, we first estimated the deposit volume and then reduced it by 25% to account for bulking (Hungr and Evans, 2004). The volume of the deposit was estimated according to the mapped extent of the RA deposits as well as their thickness. The thickness was reconstructed based on field observations and mapping, geomorphic analyses of the deposit, descriptions of the Frébouge Rock Avalanche deposits in Deline (2009), and cross-sections through the cone as no drill cores are available in this area (Figure 3). Based on these estimations we manually modified a recent DEM to calculate the volume (after Grämiger et al., 2016). A small hill in the southwestern part of the Frébouge cone was due to its small volume included in the volume estimate (Figure 4). Subtracting the present-day DEM from the reconstructed pre-failure topography yielded the landslide deposit volume.* "

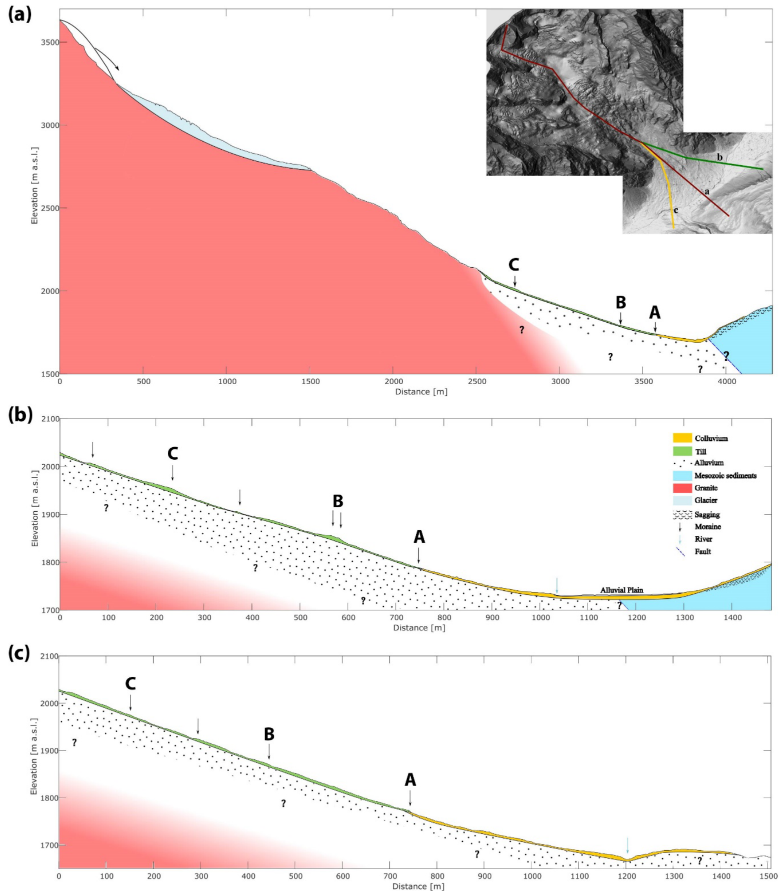


Figure 3: Cross sections through the Frébouge cone: a) from the Petites Jorasses release area through the centre of the cone, b) through the northeastern part of the deposition area, c) through the southwestern side of the debris cone.

For the volumetric reconstruction we estimate an uncertainty of about 10%. We implemented this uncertainty also to the text:

"*The runout analysis allowed us to verify our geomorphic interpretation and place the mobility of the Frébouge rock avalanche into a broader context. The runout analysis is based on a volume reconstruction (Figure 8), which resulted in a deposit volume of 12 Mm3, and a source volume of 9.5 Mm3 (assuming 25% bulking). The volumetric uncertainty is about 10%. This volume was then used in the runout analysis, and the most relevant output parameters of the runout modeling are shown in Table 4, and final simulation results are given in Figure 8.*"

Figure 1: Please add a color bar for the main map. The coordinates in the inset figure are very difficult to read.

We appreciate this remark. Please see previous comment to figure 1.

Figure 2: A scalebar would help those unfamiliar with the setting to better assess the size of the cone on this picture.

We are grateful for this comment. We added a scale bar to the picture.

Figure 3: It is uncommon to have individual rivers (Doire) get their own signature in a legend. You can use the same signature as for "river channel" and simply make it a bit thicker to indicate that it's a bigger river. Add the name in the map directly.

We thank the editor for this comment. Please see remark above.

Figures 4&5: I can hardly see the panel labels. Please make them bigger and better place them in the upper left corner of your panels.

We are thankful for this input. We increased the size of the panel labels and placed them in the upper left corner.

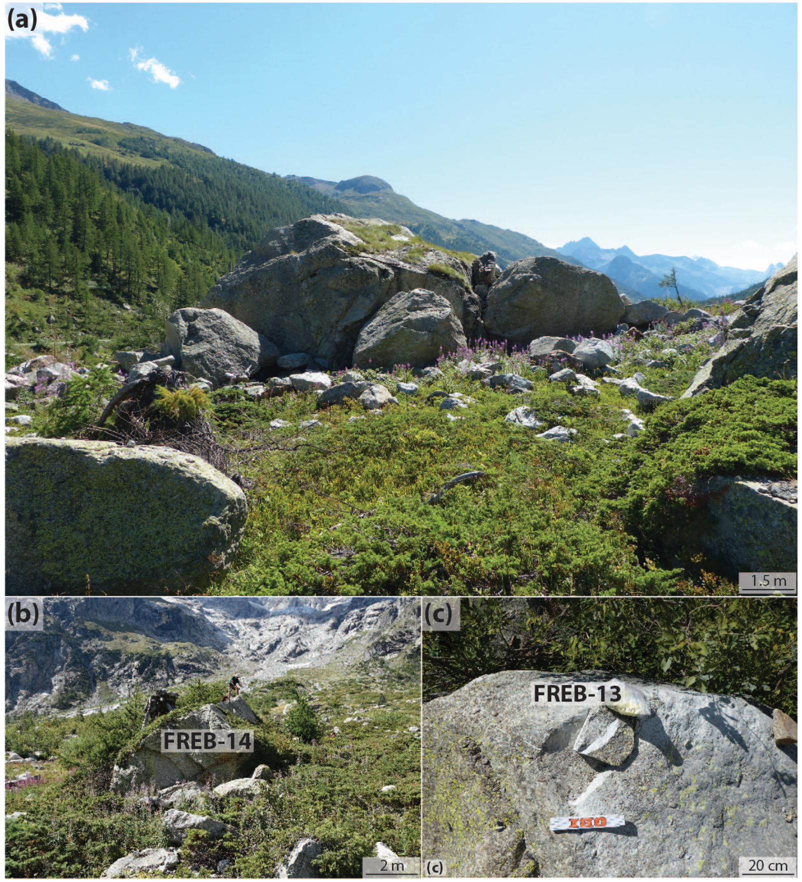
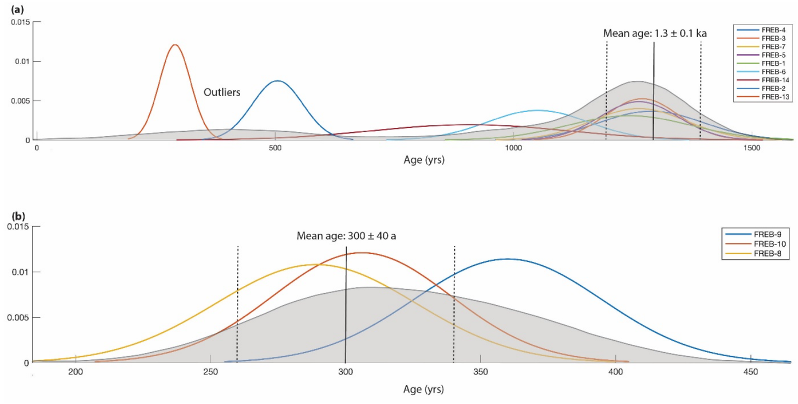


Table 3: Did you deliberately round many of the ages to hundreds of years? As you also have ages <100 years, I think it is better to keep the decades for all ages.

Thank you for this remark. We decided to indicate ages older than 500 years in ka. Therefore, we deliberately rounded the ages > than 0.5 ka to the hundreds as keeping the decades would convey the impression that we are able to date older deposits in a very precise way.

Figure 6: Better place the subplot labels in the upper left corner of the panels. It would help the readers to somehow indicate how the samples belong to a geomorphic unit, perhaps by combining different line colors and styles.

We thank the editor for this input. We moved the labels to the upper left corner. Regarding the samples: we already separated the different geomorphic units in subplots. Subplot (a) represents all the samples that were collected from boulders of the RA and subplot (b) shows the samples taken on moraine A.



Section 4.3: In addition to a more detailed description of the method on the volume reconstruction, more details on the results would also be beneficial. I would strongly suggest to provide a figure just on the volume reconstruction, where you could also show the pre-landslide topography and perhaps photos from outcrops you deem important for defining the base of the deposit.

We are thankful for this remark. More details on the method on the volume reconstruction we added to the methodology section. Since there are no outcrops showing the base of the rock avalanche deposits, except for a section of a trench provided by Deline (2009), we are unable to provide any photographs. We added the following figure to the manuscript, which shows the reconstructed pre-event topography including the thickness. More details on the results are embedded into section 4.3:

"The runout analysis is based on a volume reconstruction (Figure 8), which resulted in a deposit volume of 12 Mm^3, and a source volume of 9.5 Mm^3 (assuming 25% bulking). The volumetric uncertainty is about 10%. The rock avalanche deposit cover an area of 1.11 Mm^2 and the thickness ranges from ca. 1m to ca. 30 m (Figure 3 and 8). …"

Figure 7: Perhaps add a bigger gap between the PJ and GJ models to indicate their different setups? The V1 models seem to touch the edge of the model and spread laterally. To avoid edge effects, you probably have to make the model domain bigger.

We appreciate this remark. We increased the gap between the two model setups.

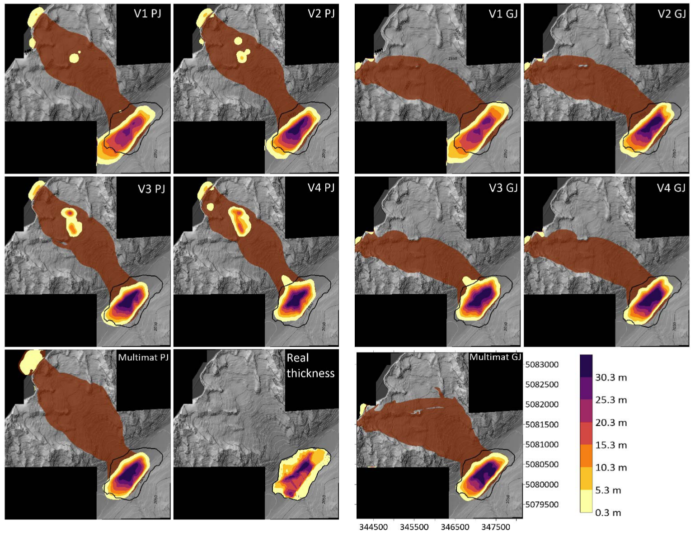


Table 4: "GJ" and "PJ" are only shown for "Multimat", but they apply to V1-V4, too, right?

We would like to thank the editor for pointing this out. The two release areas "GJ" and "PJ" apply also to V1-V4. The labels are now placed in the middle to make it clearer.

Release Area	Simulation	Max. Deposit Thickness (m)	Max. Velocity (m/s)	Travel distance (vert./horiz., m)	Max. Run-up SE (m a.s.l.)	Time to reach cone (s)
	V1	28	119	2200/4600	1885	40
	V2	37	100	2150/4400	1875	40
GJ	V3	43	99	2140/4200	1850	45
	V4	41	89	2125/4100	1825	50
	Multimat	40	120	2145/4300	1850	30
	V1	28	122	1950/4800	1850	45
	V2	36	106	1910/4450	1830	50
PJ	V3	40	82	1900/4200	1825	55
	V4	39	99	1875/4100	1775	60
	Multimat	41	113	1900/4200	1825	30

Section 5.1: When discussing your results with respect to Figure 8, you can point at specific panels of the figure to help the reader see the raised points.

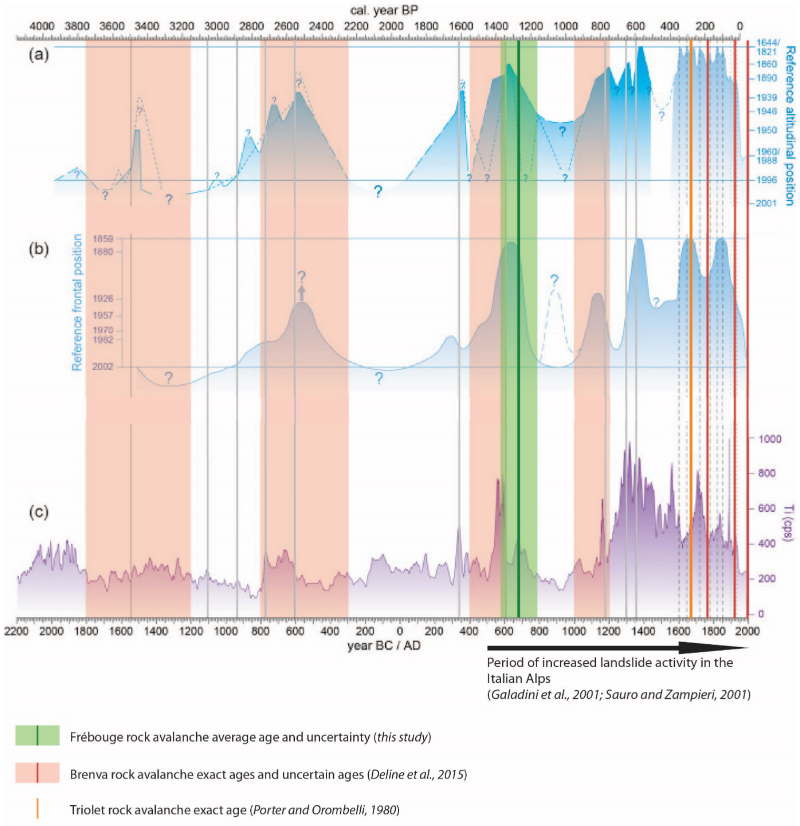
We are thankful for this remark. We implemented the references to the single panels of the figure into the text:

"*A rock avalanche with a volume possibly up to 12 Mm^3 occurred 1300 ± 100 years ago, overriding an already existing cone, which was most likely composed of polygenetic deposits (Figure 4, 7 10). We compared the timing of the Frébouge rock avalanche to glacier advances and rock avalanches reconstructed at Brenva and Triolet (Holzhauser et al., 2005; Nussbaumer et al., 2007; Arnaud et al. 2012; Deline et al. 2015; Le Roy et al. 2015; Figure 10). The Frébouge rock avalanche would have occurred when the glaciers started to retreat, after the glacier advance peak recorded around 1.4 ka at Mer de Glace (Le Roy et al., 2015; Figure 10a) or Aletsch (Holzhauser et al., 2005; Figure 10b), during the Göschenen Cold Phase II (ca. 1.8–1.1 ka). Titanium anomalies measured in Lake Le Bourget (Savoie, France), indicating the terrigenous silicate input are high between 1450-1300 cal. BP, suggest a larger contribution of the catchments located at high elevations, which is associated with climatic changes such as major glacier advances (Arnaud et al., 2012; Figure 10c). […] The Mer de Glace record shows stronger glacier fluctuations during the last 500 years and no clear correlation is recognizable between the rock avalanches and the glacier extent (Figure 10a).*

The chronology of Great Aletsch Glacier advances shows that the glacier reached a maximum around 1660 AD (Holzhauser et al. 2005; Figure 10b), while the Frébouge Glacier had its maximum at 1700 ± 20 AD. Moraine-B could correspond to the glacier advance at ca. 1820 or 1850 AD (e.g. Holzhauser et al. 2005; Ivy-Ochs et al. 2009; Schimmelpfennig et al. 2012; Braumann et al., 2020). While the Great Aletsch Glacier had a similar size during its advance in middle 19th century as during the 1660 AD advance (Figure 10b), the advance 320 ± 20 years ago at Frébouge was larger than the other LIA advances. Based on photographs, the uppermost moraine on the cone (Moraine-C) corresponds to a glacier advance in the early 20th century (Sacco, 1918; Gabinio, 1923)."

Figure 8: It would help the reader to see directly in the figure what the graphs are showing. Overall, I find the figure informative when it comes to the rock avalanches, but the moraine ages during the last ~400 years get a little crowded and it is hard to see how they compare to the reference altitudinal/frontal positions. What actually do the numbers on the y-axis represent? Absolute elevations in a and distances from the present-day glacier in b? And what do the horizontal lines indicate (a: 1996, b: 2002)?

We thank the editor for this remark. We removed the moraine ages from the plot to make the figure clearer.
The numbers on the y-axis represent the absolute elevation of the mean elevation of the ice surface in a. In b the numbers show the extent of the Great Aletsch Glacier (Switzerland) based on a dendro-chronology. The graphs in c indicate measured Titanium concentrations in sediments from Lake Bourget, which can be used as a proxy for glacier activity.
The lines a: 1996 and b: 2002 are the bottom and top boundary lines of the individual graphs. We increased the gap between the graphs to make it clearer.



Section 5.2: In your discussion of how the Frébouge rock avalanche compares to literature data, you are referring to Figure 9 without calling it. Please do so and point at specific panels. Note the “H7L” typo in line 397

We are grateful for this comment. We implemented the references to Figure 9 into the text:

… “To further explore the uncertainties in our reconstruction, we compared the reconstructed release volume of 9.5 Mm3 to empirical correlations provided between source volume and deposit area (Griswold and Iverson 2008; Figure 10a), as well as source volume and H/L glacier (Aaron and McDougall, 2019; Figure 10b). Our reconstruction fits well with the Griswold and Iverson (2008) data, however the H/L for the Frébouge rock avalanche suggests low mobility, despite the presence of both saturated substrate and glacial ice (Figure 10a and b).” …

… “During the modelling a constant turbulence coefficient of 500 was used, and the best fit friction coefficient was found to be 0.2. Compared to best fitting Voellmy parameters in other rock avalanches on saturated sediment, the friction coefficient is slightly higher but within the range found for other events (Aaron and McDougall, 2019; Figure 10c). This contrasts with the H/L correlation presented earlier, which suggests low mobility for this event. H/L can be confounded by geometric factors (e.g. Davies and McSaveney, 1999), and we consider the runout modelling results more reliable when placing the mobility of the Frébouge rock avalanche in the context of other case histories.” …

Figure 9: It is not required, but it would make your figure more appealing if you could harmonize the different panels. At present, the different panels all come with different styles. Please make sure to have the required copyright permissions from the original publishers if reusing figures previously published elsewhere.

We are grateful for this input. Please see comment above.

Best regards,

Dirk Scherler