Interactive comment on "Brief communication: 4 Mm3 collapse of a cirque glacier in the Central Andes of Argentina" by Daniel Falaschi et al.
Anonymous Referee #1

General comments: This study deals with the collapse of an unnamed glacier in the central Andes of Argentina in March 2007 (between 5 March and 14 March 2007). This glacier, named by the authors, ' Lenas glacier ', is located in the very remote area. The collapse and the avalanche have not been observed directly and it seems to remain unnoticed during several years. Very few data are available about this collapse. Most of data come from satellite images. This study aims at reconstructing the conditions of the collapse (Volume, slope, meteorological conditions, sismic events) in order to understand the possible causes of this breaking off. The authors claim that this event, very rare, can be compared with the very large collapses of Kolka in 2002 and Aru glaciers in 2016, given that the volume size is huge and the slope of the glacier is low. Unfortunately, the analysis and the conclusions remain qualitative and speculative due to the lack of data. This study contains vagueness, large assumptions, and lack of rigour for the following reasons:

We thank the referee for the in-depth review. In regards to his/her main comments, we agree that the data available is limited and probable causes of the event are difficult to assess In our view, the chosen format of a Brief Communication, is perfectly suited to present and report this Leñas update and to make the community aware of the event. We cannot expect to get an answer for every open question from image time-series analysis and geomorphometric interpretation of surface characteristics (in the field and using DEMs / satellite data) for an event discovered with many years delay. The kind of event described in our study is rare enough that knowledge about every single event is important.
Also, brief communications do not normally require lengthy accounts of theoretical background and methodology principles, and thus we had not extensively elaborated on i.e. DEM accuracies and limitations of the DEM difference method, which can be nevertheless found in the literature.

1) First, the uncertainty relative to the collapse volume can be questioned. The volume changes have been assessed from satellite images (Spot 5 12 February 2007, Landsat 5 March 2007, Spot 5 14 March 2007, Quickbird 19 April 2007). The failed glacier area and thickness have been estimated from images 12 February 2007 and 19 April 2007. The accuracy of each DEM is not mentioned. The authors wrote that ' the average thickness at the scarp was roughly 35 m as estimated from scarp shadows and solar angles at the time of acquisitions . Thus assuming a linear decrease of the glacier thickness from the scarp to the former glacier front . . .. . .a rough estimate of 4.5 106 m3 ' (l. 108-111) . No detailed information is given about the method and the uncertainty of thickness. In the following lines (l.112), the authors mentioned a ' conservative 15% error from uncertainty in detached area and thickness estimate' without providing any details about this uncertainty. Another ' independent ' estimate has been done from the difference between SRTM DEM (February 2000) and ALOS PRISM DEM AW3D obtained between 2007 and 2011. Again, the uncertainty of these DEM is not given. The uncertainty related to SRTM penetration is not mentioned. The authors mentioned only that the assumption of no radar penetration is confirmed by the comparison between C Band and X Band SRTM which show no significant difference.

The authors did not provide any detail or reference. In addition, the authors used the ' average DEMS' of ALOS PRISM DEM (2007-2011) with an ' average year' of 2009. They assume that there is no change between March 2007 and 2009 (l. 125-126). It is very confusing. The uncertainties relative to this assumption are not explained. Nothing is said about the elevation differences between these 2007-2011 DEMs. The uncertainty of 2.3 m (l. 128) on elevation difference seems to be very optimistic. Moreover, from Figure 2a, one can see surprising elevation changes of 25- 50 m in several areas of the upper part of the glacier between 2000 and 2009 far from the detached zone. These values are similar to the elevation changes of the collapse area. However, no explanation is given about that. Due to the lack of information, it seems very difficult to assess the uncertainty on the volume of the collapse.

We have now partially recalculated our volume estimates, and largely rewritten, extended and rearranged the related description. We use now SRTM, ALOS PRISM, and (new) the TanDEM-X DEMs as main source of our volume estimate, and use the scarp height only as rough check. Note that we don't need to estimate the DEM accuracies but only the accuracies of elevation differences to arrive at an accuracy estimate for the volume. A detailed assessment of the DEMs used is out of scope for our brief communication. The gross uncertainties seen in the figure are situated on the steep headwall of the glacier, whereas the detachment happened from the flatter part for which the elevation differences to the left and right of the detachment are more representative. Most importantly, we believe the exact number of the volume is not crucial as we are only interested in the ballpark of the volume, i.e. around 4 Mm3, which we hope to demonstrate sufficiently now.

2) The discussion about the mean slope' is confusing. The authors make a difference between hanging glaciers with steep slopes (>30◦) and glaciers with low slope (lines 26-27). They wrote that ' the detachment of large portions of low-angle glaciers is much less frequent ' (l. 34-35). The manuscript is confusing because the authors mentioned both the low angle of reach (5◦) (lines 22 and 106), the average slope of glacier (24.6◦) (line 97) and the slope of the detachment part to discuss the stability/instability of the glacier. These slopes are mentioned in different sections of the manuscript which creates confusion.
The low angle reach is not relevant to study the stability of hanging part of the glacier. More specifically, the ' suprisingly low angle of reach (5◦) ' (Abstract, l. 22) seems to be irrelevant as an indicator of stability of glacier. The slope of ' detached glacier', which seems to be the relevant value to assess the stability, is mentioned in Discussion only in line 186 (15.6◦). We do not have any information about the method used to calculate this slope. Is the surface slope before the collapse ? calculated on which distance ? is the surface slope after the collapse ? Which images have been used to obtain this value ? What is the accuracy of this calculated value ? The analysis of slope change reveals also a lack of rigour. In line 142, the authors wrote : Ân´ the glacier slope decreased from 24 .6 to 20.4◦ from before to after collapse Âz. The ˙ distance on which this slope is calculated is not specified. One can assume that the slope change is mainly due to the length changes of the glacier and the size of the avalanche. In this way, is the slope change a relevant information?

In order to clarify the different angles mentioned in the manuscript and avoid confusion, we have now differentiated only 2 of them.

-The angle of reach is measured from the scarp head to the avalanche terminus. While this is not specifically relevant to the stability of the glacier, it does tell about the fahrboshung mobility index and we have therefore included it.
-The angle of the detached part of the glacier before collapse (15.6◦) was measured from the SRTM DEM over the failed glacier area measured from the Quickbird 2007 scene (mentioned in the text). SRTM has been tested in a large number of scientific studies in glacier areas and has been fully accepted to derive glacier topographic parameters (such as slope) with adequate results (e.g. Racoviteanu et al, 2009 in Annals of Glaciology, Frey and Paul, 2011 in International Journal of Applied Earth Observation and Geoinformation). Also, SRTM accuracies can be found in Farr et al. 2007 in reviews of Geophysics.
We agree that the overall glacier slope change is not relevant information and have removed the previous analysis. Incidentally, as opposed to the referee's understanding, there was no hanging part of the glacier before collapse).

3) As mentionned by the authors in Conclusions, due to the limited data, this study is not able to identify the causes of the Lenas event. Many assertions are highly speculative. For example ' the thin glacier front could have been frozen to the bed and a change in this polythermal regime may have caused changes in stability' (l. 202-204) or ' we suggest that the soft glacier bed material could have played an important role in the collapse. . ..' (l. 206-207), or ' we hypothesize a mixed origin for the debris layer observed on the ice avalanche deposit. . .' or ' . . .may indicate that a large glacier collapse has not happened in 2007 for the first time. This speculation relies on. . .. . .. '. The Discussion is a list of assumptions and questions and does not shed light on the causes of this collapse.
We agree that the discussion section includes speculative statements that partly go beyond the empirical evidence. Although we think this is allowed when speculations are clearly marked as such (e.g. to stimulate further research) we have removed most of them and focused on statements with at least some evidence.

In summary, the authors claim that the Lenas collapse deviates from typical ice avalanches from steep glacier and can be compared to the rare low-angle glaciers collapses similar to Aru glaciers and Kolka glaciers avalanches.
We agree that a direct comparison of the event observed here to the collapses at Kolka and Aru should not be made and have revised the text accordingly. However, we think when talking about detachments of glacier sections with comparably low surface angles, and about glacier avalanches travelling large distances over comparably flat surfaces it is appropriate to at least mention the Kolka and Aru collapses.

Given the lack of information given in this study, the uncertainty on collapse volume can be questioned.
We actually think that the derived collapse volume is a comparably robust part of the study and has higher certainty than several other numbers. We however revised the volume estimate parts significantly (see response to above comment).

In addition, the data provided by this study are poor and do not allow to identify the possible causes of the collapse.

We agree that the data available are limited and possible causes of the event are difficult to derive from it. However, we also think that sufficient information is around to make the community aware of the event. This is why we have chosen the format of Brief Communication, which is to our best understanding among others meant for such types of updates.

This study points out the low detachment slope (15.6◦) although the determination of the slope has not been explained and the uncertainty on this slope is unknown. 'No significant change in glacier geometry could be identified due to the lack of data' as mentioned in Conclusions (l. 267-268).

We have now added how the slope has been calculated and revised the text sections about the angles involved (see response to above comment).

The authors suggest that soft bed characteristics play a crucial role on the collapse trigger. I do not think that this study provides sufficient quantitative information for understanding complex processes in glacier instabilities and collapses.

We agree that there is very limited evidence for this speculation and briefly mention the idea in the discussion section.

I do not think this study shed new light on the triggers and factors responsible for this event. Given the paucity of data, I am not sure that this event can be compared to Aru glaciers and Kolka glaciers avalanches as claimed by the authors.

We agree that this direct comparison is based on very limited evidence and have rewritten this section (see above).

Interactive comment on "Brief communication: 4 Mm3 collapse of a cirque glacier in the Central Andes of Argentina" by Daniel Falaschi et al.

This submission documents the catastrophic collapse of a glacier tongue in the Central Andes. The volume can be considered small compared to the well known 2016 twin collapse of Tibetan glaciers (around an order of magnitude smaller) but large compared to ice avalanches typically encountered in Alpine terrain. The described event dates back to 2007 and occurred in a remote area, consequently little evidence is available and the analysis evolves around satellite-derived digital elevation models and images.

The study cannot provide much physical insights into the processes leading up to the collapse, but this should not be expected given the relatively sparse catalog of observations. On the other hand, the 2016 glacier collapses in Tibet vividly illustrated that catastrophic runaway surges of low-angle glacier tongues can occur and may be related to climate, a matter that previously had been largely overlooked by the glaciological community. So I agree with the authors that this short note contribution is of interest to the glaciological community and well suited the Cryosphere journal.

To my mind the manuscript requires a considerable amount of modifications, however. In particular, several figures are poorly presented, annotated and referred to in the text, which obscures some important information on the collapse event. Some of my points of criticism may be misunderstandings on my side but I nevertheless urge the authors to consider and clarify them and make the necessary adjustments to convey their message in this short note. Below I detail these points and provide further minor questions and comments. Fabian Walter.

We thank Fabien Walter for the critical and constructive comments to improve the paper and have modified and corrected the manuscript accordingly. Also the misunderstandings served to clarify concepts in the manuscript (e.g. the glacier and ice avalanche deposit separation) and were useful to prepare better figures. The figures have also been re-arranged and further improved. Because parts of the manuscript have been rewritten, some of the comments are now obsolete (e.g. specific comment in line 229).

MAJOR COMMENTS FIGURES I have to admit I was puzzled when looking at the details of Figures 1-3. It may sound picky, but I was confused because I did not understand the authors' conception of the glacier outlines. Usually I think of avalanche debris as not being part of the glacier, i.e. a calving event (dry or wet calving) causes the glacier to retreat. If I understand the outlines in Figure 1 correctly, then the authors consider the avalanche debris as lying within the glacier extent. Whatever the case is, this should be clarified and my personal suggestion is to define the glacier outlines by the ice that has NOT detached from the glacier in the form of avalanches.

This is actually fully correct but would be unnoticed in a glacier inventory when not checking back the time series of high resolution images. In a 10 to 30 m satellite image (Landsat, ASTER, Sentinel 2) the collapsed (clean ice) part would very likely be mapped as a part of the glacier and the entire feature classified as a valley glacier. As regenerated glacier parts are typically included in glacier inventories and the discussion if this makes sense or not can be endless, the inclusion of the collapsed part is maybe not that wrong. However, as we are presenting a collapse event here, the collapsed part has been marked separately in the revised figures.

Moreover, in Figure 1, there are several grades of red lines, which are difficult to distinguish on the image. It would be better to use different colors or line symbols. The figure would also benefit greatly from two panels, one showing the glacier before and one showing the glacier after the collapse. Within the figure I would also label the avalanche debris as well as the LIA moraine, which is discussed in the text. Once this is clarified, it will be easier to understand Figure 2.

Here I was wondering for a long time why the Leñas Glacier tongue had thickened. Is this a result of surging behavior? Then I noticed that what I thought was the tongue was actually the avalanche debris. It would help to see the extent of the glacier tongue before the break-off in addition to the shown scarp head (note also that some of the text in this figure is likely too small). Similarly, in the different panels of Figure 3 I suggest drawing the glacier outlines. Finally, the photographs in Figure 3 are not self explanatory but do seem to contain important information. I suggest annotating the photographs extensively (e.g. glacier terminus, LIA moraine, avalanche debris, outwash planes, etc.).
We have prepared a new set of figures paying attention to the referee's comments and suggestions. Figure 1 contains three panels, showing the Leñas glacier before and after collapse, and the DEM differencing-elevation change map. 100m contour lines have been included. We have followed the referee's suggestion and clearly separated the glacier extent and the ice avalanche deposit. This is valid not only for the figure but for the area calculations in the main manuscript as well (the avalanched area is only 0.63 km^2 instead of 0.7 km^2 now). The glacier outlines for the years 1955, 1970, 2011 and 2018, as requested, have been removed from figure 1 to avoid confusion and transferred to figure 2, which effectively follows the glacier and avalanche deposit's evolution through time. Also, the LIA moraines can now to be seen more clearly in the figure.
We have eliminated the figure showing Tinguiririca glacier, as we have taken the decision to strictly stick to the event described in the introduction (see response to the Tinguiririca glacier comment below).
Figure 2 includes the 1955, 1970, 2011 and 2018 glacier and avalanche debris outlines, and has been annotated with (LIA) moraines, rock glaciers, glacier forefield, crevasses, avalanche scarp. We note that some of the avalanche features (thermoklarst ponds, hummocks, etc.) are too small to be annotated in this figure and have been marked in figure 3a instead.

TINGUIRIRICA GLACIER Compared to Leñas glacier, Tinguiririca Glacier receives less attention in the text. It is only illustrated in two panels of Figure 2. The reader needs a map view equivalent to Figure 1 to get a feel for the glacier extent and geometry (for both glaciers it would be helpful to see a few contour lines which helps identifying steep parts and planes) and more explanations, otherwise it seems that Tinguiririca Glacier was half-heartedly added to the study.
We agree that this extra example is difficult to integrate in the research context without providing further details. The available remote sensing data (high resolution images, and DEMs) for Tinguiririca was even scarcer than for the Leñas glacier, which did not allow for a fuller and more comprehensive description. We have taken the decision, based also on another referee's judgment, to discuss and compare the Tinguiririca event only very briefly in

terms of the avalanche volume and runout distance. This means that we have also eliminated the figures showing the Tinguiririca glacier.

SURGE HISTORY The topic of glacier surging receives little attention in the manuscript. Do the satellite DEM's provide some hints for surge behavior? In any case, it would be good to write 1-2 sentences on this subject to put the collapse into context of the Aru Co and Kolka events. This could be built into the second paragraph of the Discussion section. Currently, there is some mentioning of a thermal regime change, but no specific evidence or context is provided.
We thank the referee for the suggestion. We have added a few sentences about surges in the region. In a recent review of glacier surges in the Central Andes, Falaschi et al (2018, Progress in Physical Geography) found evidences of glacier surges at nearby glaciers, but not for the Leñas glacier specifically. We re-examined the material from Falaschi et al. and our own dataset and concluded that no evidence of a Leñas surge could be identified.
For clarification, the text referred to the overall thermal regime beneath the glacier but not specifically to the possibility of a thermally triggered Svalbard-type surge.

MINOR COMMENTS Figure references: At several parts of the manuscript it is not clear what the autor's assertions are based on. For example, in the first paragraph of Section 3 no references to figures are made, but if I understand correctly the described observations are based on information shown in the figures.
We agree that the figures could be better referenced in the main text and have inserted further links to them.

Line 68: It would help to give a rough estimate of avalanche volumes for the 16 events of the WGMS.
This is a good idea! Now included in the text.

Line 134: "(e.g. due to decrease in glacier slope)" is unclear.
We meant that the new debris cover might have developed in a now flatter glacier. We have clarified this in the text.

Line 140-141: Do detachment scarp and crevasses really disappear or were they simply covered by debris?
The scarp and crevasses were swept away in the avalanche, as they formed its head. No evidence of them being filled with debris was observed in the field.

Near Line 150: How was the absence of bedrock beneath the glacier confirmed? Using boreholes? Could exposed bedrock be concealed by deposited sediments? Please mark/annotate figures accordingly.
The absence of a hard bed beneath the glacier was visually evaluated in situ. No rock outcrops were to be found in the failed area whatsoever. The area is steep and subjected to rockfall, hence boreholes were not considered. From the thick sediment layer in the failed glacier area (visible in incised gullies seen in figures 3a and b) we believe the hard bed lies well beneath the glacier bed. We now mention this characteristic in the caption of Figure 3.

Line 152: Reference to Figure 4a is unclear. Please mark/annotate figure accordingly.

See previous comment. This has now been clarified (annotated).

Line 156-157: The smoother hammocks and thermocarst should be highlighted in the respective figures.
We have marked thermokarst ponds and hummocks in Figure 3a.

Section 4: It would help to show parts of the meteorological analysis in a plot. Also, some specifics on the acceleration criteria would be of interest.
We have chosen not to include a graph showing the meteorological data as this does not reveal a strong link with the collapse event. With 3 multipanel figures, we are already in the maximum length advised for a brief communication in TC journal.

Line 183 (and elsewhere): It would help the non-expert to specify what is mean by "ordinary“ ice avalanches.
We agree and have changed this to "from steep fronts and hanging glaciers steeper than 30º.

Discussion: It may be worth considering the possibility that the event happened as a series of small break-offs rather than a single rupture. Such cases are known to exist and it is not clear which conditions favor one scenario over the other. https://www.geopraevent.ch/project/weissmies-glacier-velocities/?lang=en
Indeed, we can not be 100% sure if the event was due to a single rupture or several smaller ones. However, the field evidence and the relatively large blocks of massive ice point in the direction of an avalanche composed of large blocks (see Fig. 3b). We mention the possibility of small events now in the revised manuscript. We assume that numerical modelling could help in identifying this, but this is beyond the scope of the current study.

Line 229 and following paragraph: When discussing the permafrost conditions it seems that the authors present arguments for and against permafrost. It was not clear to me what the actual conditions are believed to be. Also, it is not clear what the implication of the last sentence is (reference to Kolka).
Confirming the presence/absence of permafrost in the plateau (i.e away from the headwall) would need proper, in-situ temperature logging. Alternatively, an approximation of the thermal conditions could be investigated by building a potential incoming solar radiation model. Again, we consider that any of them would be beyond the scope of the current study, and would not help in elucidating a collapse trigger per se. Due to the lack of convincing evidence for permafrost presence/absence in the plateau where the ice avalanche deposit sits up to this point, we have removed the discussion on the role of permafrost in the preservation of the ice avalanche deposit.

Line 244: Specify "same method“.
Checked and corrected. By 'same method' we referred to SRTM and ALOS PRISM differencing.

Line 262: "time difference“ → time lag.
Changed to time lag.

Interactive comment on "Brief communication: 4 Mm3 collapse of a cirque glacier in the Central Andes of Argentina" by Daniel Falaschi et al.
Anonymous Referee #3

Summary

Falaschi and coauthors describe an apparent sudden collapse of a small cirque glacier in the central Andes, Argentina. They describe this event largely through the use of remote sensing and limited field surveys. Although largely documentary in nature, this brief report provides additional evidence for sudden failure of alpine glaciers – these events present an unusual type of mountain hazard that may occur with greater frequently in the years ahead. Overall, I found the evidence for the failure convincing, and the manuscript's organization made their arguments mostly easy to follow. The paper will require moderate revisions to bring it up to the level required for publication in The Cryosphere, however. Below, I outline major points I have with the manuscript. I also include a marked up copy of the manuscript to help the coauthors revise their paper.

We thank the referee for the constructive comments. We have modified and corrected the manuscript following the comments and suggestions.

2. Major Points A) Remove or substantially trim speculative material - This manuscript represents a short note (Brief Communications) in The Cryosphere, and simply providing sound documentation for the event is sufficient for publication (largely because of the hazard implications associated with these events). In many places, however, the authors tend to go a bit too far in the interpretation of their data that leads to too much speculation (mostly about whether event was enhanced by fine-grained bed or whether events happened before). The authors point out, for example, that they have limited field observations, but then they go on to make claims that really require additional field observations or require modeling data that they currently to do not have in hand (or report in the paper). I think a proper documentation of the event is enough. Simply state factors that caused the event to happen are currently uncertain. The logic of several statements are flawed at least in the way they are written. (e.g. towards the end of the paper '. . .no strong evidence, but can't rule out past events. . .')

We agree that the nature of some statements is speculative when considering the available evidence and have thus shortened or removed them (e.g. the Tinguiririca avalanche). However, we think that it is allowed in the discussion section - if properly marked - to add some interpretation that is more speculative in nature. This should not only make clear that we have indeed recognized the geomorphological evidence of a probably larger previous collapse (to give one example), but should also identify open issues and point to interesting further studies. By presenting them here, there is a possibility to link potential future research proposals to such open issues and investigate them further. A pure observational report without reflecting about the lessons learned and open issues (i.e. the more speculative elements) would likely not warrant publication in The Cryosphere.

Most importantly, we have considerably shorten/fully removed most of the speculative ideas that were originally included in the discussion chapter (namely the influence of the fine grained material of the glacier bed, the presence/absence of permafrost conditions below the avalanche deposit and the possibility of previous collapses), trying to stick to the main event (Leñas collapse). As far as the latter is concerned, we have also limited the discussion *regarding the Tinguiririca avalanche due to the even lesser amount of available remote sensing data, removing the corresponding figure as well.*

B) Stick to the event described in the methods/study area – In the discussion section the authors (line 240+) describe methods used to study another glacier collapse, but this site really wasn't described except primarily in the introduction of the paper. A reader can't really evaluate the evidence for that event as it now stands since it's only briefly described in the introduction of the paper. I would recommend the paper be revised to either describe both events or simply to refer to the other one in passing (in the present version of the paper the authors start to tell us about their DEM differencing and uncertainties in the discussion section of the paper).
We agree with the referee that the Tinguiririca avalanche was half-heartedly discussed in the study, and that there is even less remote sensing data available (high resolution satellite imagery, DEMs) for this event. Hence, we have removed the Tinguiririca event more or less completely (incl. the figures). It is now only briefly presented in terms of avalanche volume and runout distance.

C) Check co-registration/uncertainty analysis – The authors co-registered their DEMs prior to differencing, but I would request that they check the quality of that coregistration (see artifacts near top of cirque in Figure 2a). It may simply be as good as they can get, but some explanation for this offset over steep terrain would be useful.
In steep terrain it is indeed possible that DEMs have artifacts that are much larger than the real changes. However, they have no impact on the general pattern of the elevation trends observed here. Moreover, the causes and problems of such artefacts have been discussed widely in the literature and we have thus only added a short explanation and some further references.

D) English needs to be improved –The paper includes many statements that are unclear or overly vague. I would suggest that the second and third authors spend some time with the text to improve the English. There are also many topographical errors in the manuscript. These errors really should have been cleaned up prior to submission.
We apologize for these errors (assuming you mean typographical?) and will give the ms a proper English check before re-submitting it. Also, all TC papers undergo language editing by the publisher after acceptance.

3. Figures and Tables Figure 1. Latitude/longitude (even two) needed so one can locate this glacier. Also, please state which bands (spectral range) were used for the color composite.
Figures 2 and 3. I found the order of these figures to be reversed. I would first report on Figure 2 as this shows when the event happened. Figure 3 really is a derivative product of stereo imagery, so DEM make more sense to show after you introduce Figure 2.
Figures 1 and 2 have been reorganized according to another reviewer's suggestion and are now including coordinates. Figures 1 and 2, show the Leñas glacier (February 12, 2007 and April 19 2007) before and after collapse and the DEM differencing-elevation change map. We thought that looking at the glaciers before/after collapse together with the elevation difference map would help the reader to better interpret the event. We have included a latitude/longitude grid in figures 1, and have added to the text the RGB composites used.

4. References I did not check the references for consistency, but this should be done on the revised paper.

Thank you for noting. We have double-checked and added some more reference to the revised manuscript.

5. Title – It’s always awkward to start a title (or sentence) with a number. Why not just, ‘Sudden collapse of

We agree and have now written: “Collapse of 4 Mm3 ice from a cirque glacier in the Central Andes of Argentina”.

Brief communication: Collapse of 4 Mm^3 ice from a cirque glacier in the Central Andes of Argentina

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Abstract. Among glacier instabilities, collapses of large parts of low-angle glaciers are a striking, exceptional phenomenon. So far, merely the 2002 collapse of Kolka Glacier in the Caucasus Mountains and the 2016 twin detachments of the Aru glaciers in western Tibet have been well documented. Here we report on the previously unnoticed collapse of an unnamed cirque glacier in the Central Andes of Argentina in March 2007. Although of much smaller ice volume, this 4.2 ±0.6 × 10^6 m^3 collapse in the Andes is similar to the Caucasus and Tibet ones in that the resulting ice avalanche travelled a total distance of ~2 km over a surprisingly low angle of reach (~5°).

1 Introduction

On steep glacier fronts, icefalls, and hanging glaciers (usually >30° steep), glacier instabilities in the form of ice break-offs and avalanches of varying size and magnitude are common and have been noted everywhere around the globe (Faillettaz et al., 2015). The current WGMS '*special events*' database lists in fact a total of 110 ice avalanche events worldwide (WGMS, 2017). Such gravitational ice failures can be a normal process of ablation of steep glaciers, but extraordinary events can be triggered by seismic events and changes in the ice thermal regime or in topographic or atmospheric conditions (Faillettaz et al., 2015). Typical volumes of ice avalanches from steep glaciers are in the order of up to several 10^5 m^3, with extraordinary event volumes of up to several 10^6 m^3. Yet the detachment of large portions of low-angle glaciers is a much less frequent process, and has so far only been documented in detail for the 130 × 10^6 m^3 avalanche released from the Kolka Glacier in the Russian Caucasus in 2002 (Evans et al., 2009), and the recent 68 ±2 × 10^6 m^3 and 83 ±2 × 10^6 m^3 collapses of two adjacent glaciers in the Aru range in the Tibetan Plateau (Tian et al., 2017; Gilbert et al., 2018; Kääb et al., 2018).
The massive, sudden detachments of both the Kolka and Aru glaciers caused the loss of human lives (Evans et al., 2009; Tian et al., 2017). These two extreme events have been critical in posing relevant questions on the origin and dynamics of massive glacier collapses of low-angle glaciers and their implication for glacier-related hazards over other mountain areas worldwide (Kääb et al., 2005). The recent Caucasus and Tibet events also showed that glacier instabilities of catastrophic nature with no historical precedents can happen under specific circumstances. Previously known catastrophic glacier instabilities should be re-evaluated in the light of the new findings in order to investigate their relation to processes involved in the massive Caucasus and Tibet glacier collapses, or ice avalanching from steep glaciers, respectively (Kääb et al., 2018).
In this contribution we present the collapse of a cirque glacier in the Central Andes of Argentina in March 2007, which we informally named Leñas glacier. Owed to the isolated location of the glacier and the lack of human activity affected, the event had remained unnoticed until recently (Falaschi et al., 2018a). Based on the analysis of aerial photos, high resolution satellite imagery, and field observations, we follow the evolution of the Leñas glacier from the 1950´s through present day, describe the collapse event and later changes of the avalanche ice deposits, and discuss the possible triggering factors for the collapse. It should be noted that the remoteness of the study site, and the fact that the event remained unnoticed for a decade, limit the data base available to interpret the event. We consider it nonetheless important to report about this unusual glacier collapse in order to contribute to the discussion about glacier instabilities.

2 Study area

The Leñas glacier (34º 28' S – 70º 3' W; lower limit ca. 3450 m asl.; Fig. 1a) is located at the headwaters of the Atuel river, in the Argentinean province of Mendoza. The climate in this portion of the Andes of Argentina and Chile has been described as a Mediterranean regime. Snowfall maxima occur during the austral cold season (April-October), as the westerly flow drives frontal systems eastwards from the Pacific Ocean over the Andes. Glaciers in the Central Andes have retreated significantly since the second half of the 20th century (Malmros et al., 2016). Specifically in the Atuel catchment, Falaschi et al. (2018a) reported a moderate (though highly variable) glacier thinning rate of 0.24 ±0.31 m a^{-1} overall for the 2000-2011 period.

Regarding glacier instability processes, there is a total of 16 glacier avalanches in the Tropical Andes of Peru and Colombia contained in the WGMS database, involving avalanche volumes of 0.2-100 × 10^6 m^3 (WGMS, 2017). In the classic work of Lliboutry (1956) on the glaciers of the Southern Andes, a number of ice break-offs in icefalls in the Central Andes of Chile are reported, though none of them were out of the ordinary in order to have raised particular consideration. More recently, at least two glaciers in Central Chile have lost a significant portion of their mass in sudden collapses (Iribarren Anacona et al., 2014), namely, the 7.2 × 10^6 m^3 detachment of a debris-covered glacier just south of Cerro Aparejo (33°34'S–70°00'W) in March 1980 (Marangunic, 1997), and the 1994 ice avalanche in the southern flank of Volcán Tinguiririca (34°48'S–70°21'W), merely 50 km southwest of the Leñas glacier (Iribarren Anacona et al., 2014). A second, 10-14 × 10^6 m^3 ice-rock avalanche originating from Tinguiririca glacier occurred in January 2007 (Iribarren Anacona and Bodin, 2010; Schneider et al., 2011), only two months before the Leñas event.

The abundance of rock glaciers and perennial snow patches in the Leñas glacier surrounding (Fig. 1a) indicates that permafrost is widespread in the area. Brenning (2005) indicated for the region that the minimum elevation of rock glacier fronts is indicative of negative levels of mean annual air temperature (MAAT) and of the altitudinal lower limit of discontinuous mountain permafrost, and set its extent at 3200 m in the nearby Cerro Moño range (34º 45' S; see also Brenning and Trombotto, 2006; Brenning and Azócar, 2010; Azócar and Brenning, 2010). This value is comparatively higher than the ~2800 m elevation established for the whole Atuel catchment by IANIGLA (2015). The rough global permafrost zonation index map (Gruber, 2012) also indicates probable permafrost around the Leñas glacier.

Lithology in the glacier surroundings is chiefly composed of pre and post-glacial volcanics (basalts, andesites and dacites) of Pliocene and Holocene age. Glacial, fluvial and mass removal processes have eroded and transported these rocks, which form the glacier forefields and outwash plains.

3 Satellite imagery and field observations

During the five decades prior to the 2007 collapse, Leñas glacier occupied a small glacier cirque, south below the rockwall of the Morro del Atravieso peak (4590 m) and had a short debris-covered tongue in the flatter terrain underneath (Figs.1a 2 a-c). The analysis of available aerial photos shows that the glacier had an area of ~2.24 km^2 in 1955, and had shrunk to ~2.15 km^2 by 1970. There was no further area decrease until 2007. Concomitantly, the front retreated some 200 m between 1955-2007. Before the collapse, the elevation range of the glacier spanned between 4555-3441 m.

Sometime between 5 March (Landsat image showing an intact glacier) and 14 March 2007 (SPOT5 image showing the collapse), the lowermost part (3630-3441 m) of the glacier detached from the main glacier and produced an ice avalanche that ran down the valley for ~2 km, measured from the uppermost part of the scarp to the most distant point of the fragmented ice mass (Fig. 1). Immediately after collapse, the ice avalanche had an area of 0.63 km^2 (Figs. 1, 2d). The orographic right (western) portion of the glacier subsided, but the break-off was restrained by a lateral moraine (Fig. 2a). The altitude difference between the scarp head and the avalanche terminus of only 190 m results in a low angle of reach of only 5º (i.e. the avalanche horizontal distance and its vertical path, the so-called 'Fahrböschung'). The failed glacier portion had an average surface slope of 15.6º (derived from the SRTM DEM) and an area of about 250,000 m^2 as measured from Quickbird imagery of 19 April 2007.

To estimate the avalanche volume we difference the February 2000 1-arcsecond C-band SRTM DEM and the ALOS PRISM World DEM AW3D (Fig. 1c). For the SRTM DEM we assume no penetration of the radar pulse into the snowpack and ice as February 2000 falls in austral summer with melting conditions likely. The assumption of no to little radar penetration is confirmed by the fact that the C-band and the X-band SRTMs show no significant vertical difference over the Leñas and other glaciers in the area (cf. Gardelle et al. 2012) and that the SRTM image product shows for these glaciers low backscatter, a sign for surface melt (Kääb et al. 2018). The AW3D DEM is stacked from individual DEMs from ALOS PRISM optical stereo triplets. Exploration of the PRISM archive shows that the first suitable scene of the study site is from 18 April 2007 (i.e. after the collapse), and there are good scenes for every year over 2007–2011. In the averaged DEM product AW3D the elevations should thus roughly represent the average year 2009. The differences between the 2000 SRTM and the ~2009 AW3D DEMs (Fig. 1c) reveal a volume loss over the collapse detachment area of 4.0 10^6 m^3. We also compute differences between the SRTM DEM and the TanDEM-X WorldDEM, the raw data of which were acquired between January 2011 and September 2014, giving an average date of ~2013. The volume change over the glacier detachment estimated from these DEMs is around 3.5 10^6 m^3. Our DEM-based estimates include, though, not only glacier elevation changes between 2000 and the collapse date in March 2007, but also changes between the 2007 collapse date and the date represented by the AW3D DEM, or the TanDEM-X DEM, respectively. Correcting for linear elevation loss between 2007 and ~2013 suggests thus a 2007 detachment volume of around 4.2 10^6 m^3. A volume error of ±0.3 10^6 m^3 was calculated according to Wang and Kääb (2015) using an off-glacier standard deviation of elevation differences found to be 2.3 m and a conservative autocorrelation length of 400 m. Assuming instead complete correlation of the elevation differences (i.e. assuming the number of observations n to be 1) gives a pessimistic volume uncertainty of ±0.6 10^6 m^3 or around 15% of the volume estimated. Incidentally, the positive elevation changes seen in the upper part of the glacier are most probably the result of DEM artifacts on steep terrain and due to different details included in the SRTM and AW3D DEMs (as becomes clear from visually comparing their hillshades), but have nevertheless no impact on the general pattern of the elevation trends observed here (see e.g. Le Bris and Paul, 2015).

For an independent check of the collapse volume, we estimate the average glacier thickness at the scarp to have been roughly 35 m as derived from scarp shadows and solar angles at the time of image acquisitions. Thus, assuming arbitrarily linear decrease of the glacier thickness from the scarp to the former glacier front, an average glacier thickness of 18 m yields a rough estimate of 4.5 10^6 m^3 of ice detached in the avalanche. This collapse volume agrees well with the above more quantitative estimate based on DEM differences.

The large crevasses that would later delineate the collapse scarp were clearly visible 3 weeks before the collapse (Fig. 2c) but strong crevassing at approximately the same location is also evident in the 1970 aerial photos (Fig. 2b). This indicates a potential break in slope of the glacier bed at this location. Interestingly, the upper, steeper part of the glacier that had been mainly devoid of rock debris before the collapse, gradually became debris covered after the break off (Fig. 2e,f). It is however unclear if this development is related to the collapse (e.g., due to debris concentration on a now flatter glacier), or coincidental (e.g., related to overall glacier shrinkage in the area, or increased rock fall activity from the steep mountain flank above the glacier).

The ice avalanche deposit transformed from a mostly clean-ice surface directly after the collapse in 2007 (Fig. 2d) to a debris-covered one later on (Fig. 2e-f, 3a). Ice interspersed with rocks is featured at the avalanche terminus in the 19 April 2007 Quickbird image (Fig. 2d) and by 2011, the full ice debris (as most of the upper portion of the glacier) had been sheltered by scree. Also, the detachment scarp and crevasses have disappeared, and large thermokarst ponds have formed within the avalanche deposit. Currently, the avalanche terminus lies ~450 m horizontally up the valley with respect to the maximum avalanche extent in 2007.

The ice deposits of the Leñas collapse sit on a flat leveled plateau consisting of volcanic rocks, reworked by glacial erosion, rockfall and maybe previous collapses. As stated above, the ice avalanche is meanwhile fully debris covered, though massive ice is visible on the walls of thermokarst ponds and ice cliffs. Within the avalanche deposit, which has now mostly a subdued and concave topography, at least two small outwash plains are forming, one at the abrupt slope change just above the uppermost reaches of the avalanche deposit, the other in front of the avalanche terminus (Fig. 3a).

Recent field observations of the detachment area done in March 2018 confirmed the absence of a hard bedrock underneath the glacier, as already suggested by the high-resolution satellite images. The sediment layer beneath the failed glacier area is deeply incised with gullies showing no hard bedrock (Fig. 3a,b) Also, the terrain under the former avalanche scarp is steep and not too rough (see Fig. 3a). Further down, debris in the ice avalanche deposit is composed of fragments of volcanic rock (<0.5 m in size) contained in a finer (pelitic to sandy) matrix, and very few large boulders (Fig. 2a,c). We assume this material to be further evidence of the soft bed upon which the glacier rested before collapse. Between the outer limit of the ice avalanche and the LIA moraines (Fig. 1a, 3d), the terrain is made up of a chaotic arrangement of hummocks and thermokarst ponds that appear similar (though smoother) to the complex topography of the actual avalanche deposit (Fig. 3a). From the 2018 terrain inspection, and the 1955 and 1970 aerial photographs from before the collapse, it appears that the ice avalanche flowed over a seemingly bumpy, rough surface.

4 Meteorological and seismic data

We used the CHIRPS daily precipitation data (Funk et al., 2015), with a spatial resolution of 0.05° to identify unusually high rainfall occurrences. During the period 4-15 March 2007, no precipitation was recorded in the CHIRPS pixel where the Leñas collapse occurred and its surrounding pixels. These results were further verified with data from in-situ observations from the Laguna Atuel meteorological station. In addition, daily temperature reanalysis fields from ERA-Interim (Dee et al., 2011) were analyzed, considering the anomalies over the study area based on the 1981-2010 standard period. Results show that temperature anomalies close to 3°C above normal were recorded during 11 and 12 March 2007.

Using data from the USGS earthquake catalogue (http://earthquake.usgs.gov) and applying the ground acceleration criteria discussed in Kääb et al. (2018) we find no earthquake between 4 and 15 March 2007 that could have triggered the Leñas collapse. The strongest earthquake found during the period of concern and within a radius of 1000 km had a magnitude of 5.0 and distance of about 200 km from Leñas (depth 35 km; 11 March). The closest earthquakes (20-30 km) had magnitudes of 2.5 (4 March, 8.3 km depth) and 3.2 (11 March, 128 km depth).

5 Discussion

In terms of volume, and glacier and runout slopes, the type of the 2007 Leñas glacier collapse (4.2 10^6 m^3) seems to range somehow in between the massive collapses 2002 in the Caucasus and 2016 in Tibet, and ice avalanches from steep fronts and hanging glaciers >30º steep. Compared to the Kolka (130 × 10^6 m^3; Evans et al., 2009) and Aru (68 ±2 × 10^6 m^3 and 83 ±2 × 10^6 m^3; Kääb et al., 2018) collapses, the Leñas event has a much smaller mass of ice sheared off due to a smaller and shallower glacier. On the other hand, despite the spatial and temporal proximity, the Leñas and Tinguiririca events are probably different in nature. In the first place, the Tinguiririca event involved a much larger volume (10-14 × 10^6 m^3 vs. 4.2 × 10^6 m^3 -Schneider et al., 2011) and secondly, the source slope is a bit higher (~20º vs. 15.6º). On another note, the 2007 Leñas event is also not typical for regular ice avalanches as the glacier was not very steep (15.6º) and the event volume is at the upper margin of more typical ice break-offs (Failletaz et al. 2015; Alean, 1985).

An important finding from field work is the abundance of fine sediments in and on the collapse deposits (Fig. 3). We suggest that a soft glacier bed material could have played an important role in the collapse enhancing avalanche mobility, as already noted for the Kolka and Aru collapses (Gilbert et al., 2018). Also, the rather large amount of debris on top of the collapse deposits has probably favored the rather good preservation of much collapse ice, even 11 years after the event took place. In comparison, the bare ice deposits of the Aru glacier collapses will have melted away to a large extent 2 years after collapse whereas the heavily debris-covered and up to more than 100 m thick deposits of the Kolka glacier collapse lasted many years despite their low elevation (Kääb et al., 2018),

As potential factors for large glacier collapses, a number of causes have been investigated so far, namely (i) high liquid water input into the glacier system from precipitation and melting, (ii) seismicity, (iii) changes in glacier geometry, and (iv) a shift in the thermal regime towards warmer conditions (Gilbert et al., 2018; Kääb et al., 2018). In the first place, our analyses of meteorological data showed no evidence of unusually strong increases in precipitation or temperature in the days immediately preceding the Leñas collapse that would directly destabilize the glacier. Neither do earthquake records reveal any strong seismic activity that could have triggered the collapse. Instability may be favored as a glacier recedes from a flatter foot back into a steeper part of the bed, loosing thus the fontal stabilization in a type of self-debuttressing process, as also found for some more typical ice break-off situations (Faillettaz et al., 2015). From the very slight glacier area decrease in the Leñas case (2.24 to 2.15 km^2) before collapse, we cannot identify a significant change in glacier geometry that would have changed its stress regime, but this finding could in parts be due to the limited availability of suitable DEMs. The Aru twin collapses in Tibet were preceded by geometry changes in the form of surge-like behavior (Kääb et al., 2018). Although surges in this region of the Andes and in close proximity to the Leñas glacier have been documented Falaschi et al. (2018b), we were unable to detect any evidence of a surge leading to collapse in the satellite imagery and DEMs. As for a change in thermal regime, from the rock glaciers in the area and the long preservation of the collapse deposits we conclude a potentially cold ground temperature regime for parts of the glacier and forefield. The thin glacier front could have been frozen to the bed, and we cannot exclude that a change in this polythermal regime may have caused changes in stability.

We hypothesize a mixed origin for the debris layer observed on the ice avalanche deposit. On the glacier head, frost action and permafrost thaw are probably responsible for the production of fine grain deposits originating from rock fall off the steep and ice-free surrounding rock walls (Fig. 2, panels e and f). The compact pieces of ice with a small amount of debris on top of them (Fig. 3b) may be intact parts of the former debris-covered glacier front that detached as a whole (or in few large fragments) and formed the front of the collapsed ice mass (cf. Fig. 1b, 2d). The loss of the glacier front likely debuttressed higher (and not debris-covered) glacier parts that came down after the front, either in direct sequence or even with some delay, in the latter case suggesting the possibility for different phases of the collapse with different properties. The former glacier front might have also ploughed through the forefield and in parts have taken up debris there together with the original debris cover on the glacier front. Although from the data accessible to us we cannot tell if the Leñas 2007 avalanche happened as one or few larger events (as also the Kolka and the second Aru event -Evans et al., 2009; Kääb et al., 2018), the morphology of the deposits and the low Fahrböschung nevertheless seem to exclude that the deposits are the product of repeated small ice falls.

5 Conclusions

In the region of the Central Andes studied here, gravity-driven failures of steep glaciers have been observed previously. The volume of the Leñas collapse of ~4 10^6 m^3 and the detachment slope of 15.6º, however, deviate from the more typical ice avalanches from steep glaciers and place the event closer to low-angle glacier collapses. Due to the large time lag between the Leñas glacier collapse in 2007 and its discovery, and the remoteness of the site, only limited data are available to analyze the case. We are not able to identify a clear potential trigger of the Leñas event, as neither the meteorological or seismic data reveal unusual conditions or events that could have triggered the Leñas collapse, nor a significant change in glacier geometry before collapse could be identified. The event does not rule out the importance of soft bed characteristics as a factor in the (rare) collapses of low-angle glaciers (Kääb et al., 2018; Gilbert et al., 2018). Despite the knowledge deficiencies related, for instance, to the hydrological, hydraulic, or ground-thermal conditions under which the Leñas glacier collapse took place, the information presented here adds to the spectrum of environmental and glaciological circumstances under which glacier collapses can take place, including related implications for mountain hazard management.

Author contribution

DF led and designed the study, conducted the field work, analyzed data, and wrote the paper. AK and FP helped in designing the study, analyzed data, and wrote the paper. TT processed and orthorectified the ALOS PRISM imagery. JAR prepared and analyzed the meteorological station and reanalysis data. LL helped in designing the study.

Competing interests

The authors declare that they have no conflict of interest.

Data availability

Landsat data and the SRTM C-band DEM are available from http://earthexplorer.usgs.gov, SRTM images from https://earthdata.nasa.gov/. The SRTM X-band DEM is available from http://eoweb.dlr.de, the TanDEM-X WorldDEM from https://geoservice.dlr.de/web/ The ALOS AW3D is available from http://www.eorc.jaxa.jp/ALOS/en/aw3d30/. Earthquake data are available from http://earthquake.usgs.gov. Data from DigitalGlobe (Quickbird), Planet, and Airbus (SPOT) are commercial.

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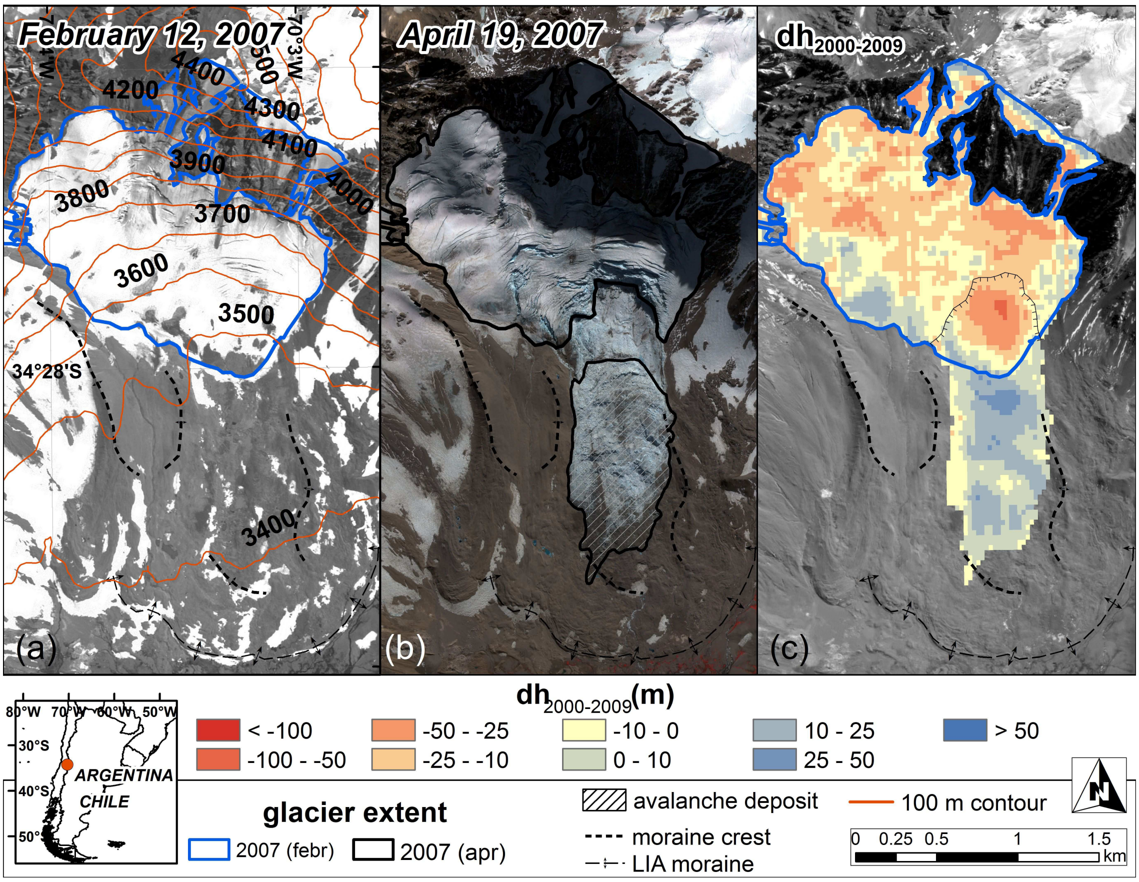

Figure 1: (a) The Leñas glacier before (SPOT 5, 12 February 2007) and (b) after collapse (Quickbird image - RGB 432- 19 April 2007). (c) 2000-2009 elevation differences (background image ALOS PRISM, 31 March 2011). Inset: Location of the Leñas glacier in the study area.

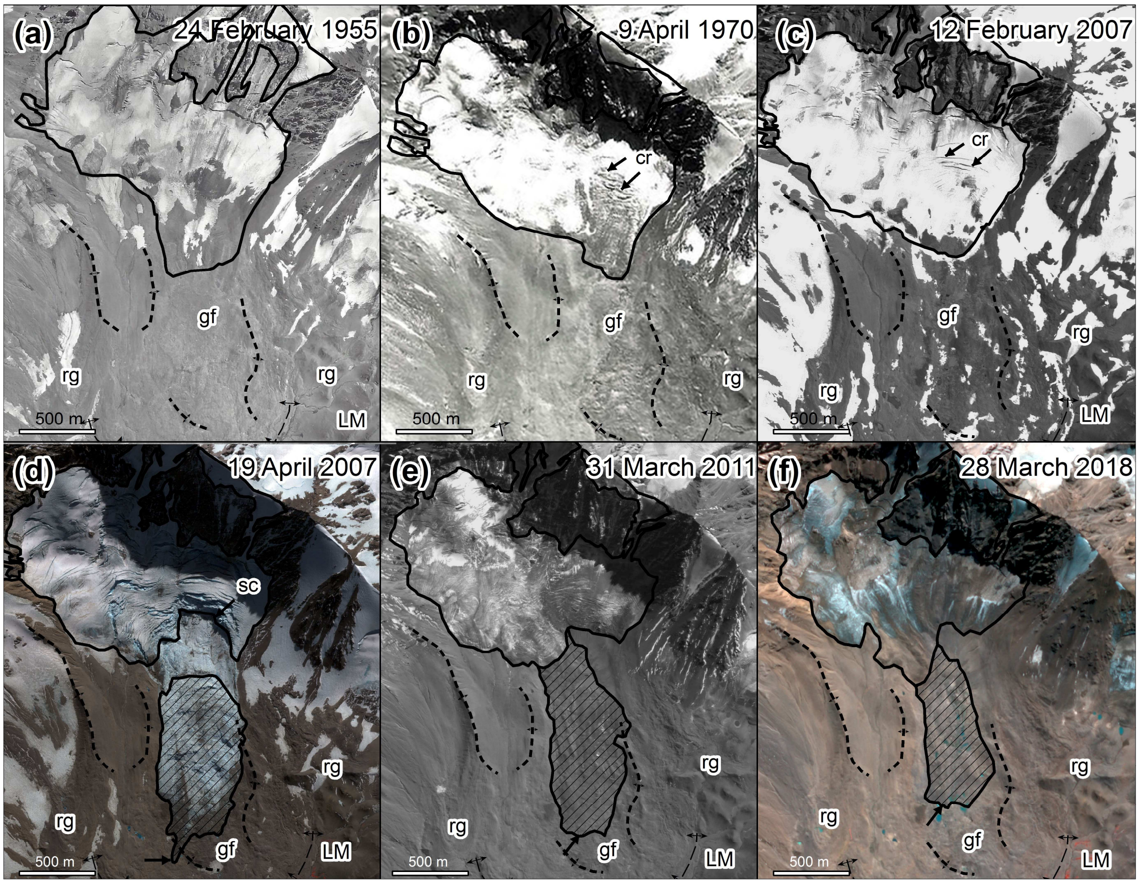

Figure 2: Evolution of the Leñas glacier (black line) and avalanche deposit extent through time. (a,b) –aerial photos- and (c) -SPOT 5- show the glacier's slight retreat before collapse. The large crevasses visible in the 1970 (b) and February 2007 (c) demark the location of the scarp head in the Quickbird scene of 19 April 2007 (d). (e) -ALOS PRISM) and (f) –Planet RGB 432- depict the growth of debris-covered portions on the glacier and the transformation of the collapse deposits. The black arrow shows the distal terminus of the avalanche deposit. gf: glacier forefield LM: LIA moraine rg: rock glacier cr: crevasse sc: avalanche scarp

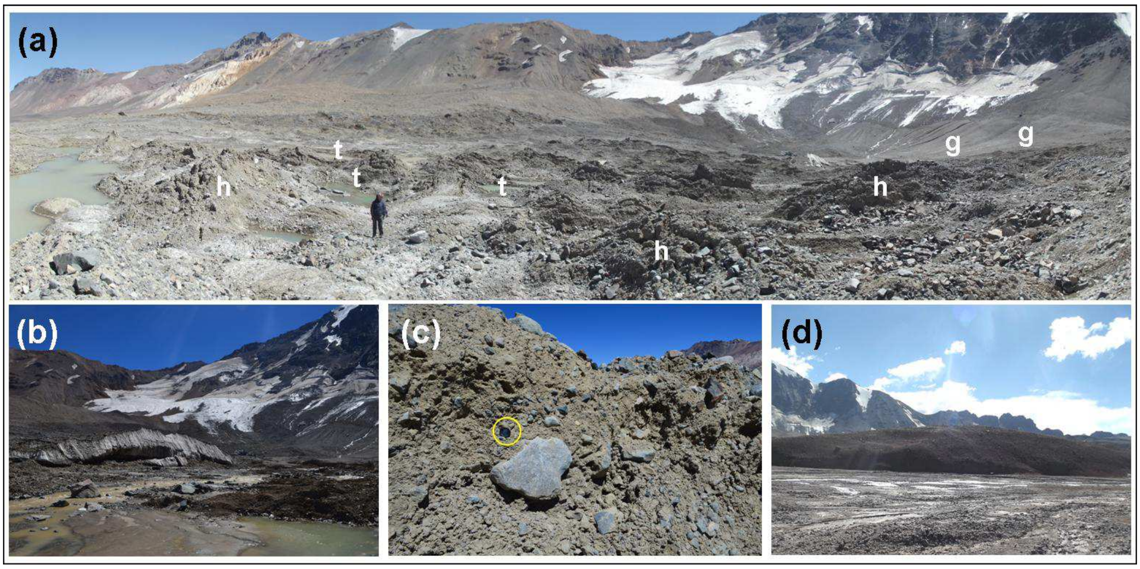

Figure 3: (a) Panoramic view of the Leñas glacier and avalanche deposit in March 2018, showing the chaotic arrangement of thermokarst ponds (t) and hummocks (h), and the glacier head on the far upper right. The failed glacier area lies below the debris-free ice. Note the absence of rock outcrops/hard bed in the failed glacier area and the deeply incised gullies (g) in the sediment layer. (b) Former glacier fragment at the base of the detachment area arrow in Fig. 3). (c) Detail of the debris cover on the avalanche deposit, showing the rock fragments and matrix (see the black camera objective cover inside the yellow circle for scale). (d) Presumably ice-cored LIA moraines. Photos (b) and (c) courtesy Mariana Correas.