Author’s response:

Dear Chris,

Thank you for taking care of the manuscript during the discussion process. We believe both reviewers’ comments were fair and helpful.

The following pages contain:

- Response to the 1st reviewer
- Response to the 2nd reviewer
- Track changes of the manuscript
- Track changes of the supplementary material

Thank you.

Authors.

Response to Dr. Renato R. Colucci (Reviewer #1) to manuscript TC-2020-82

Italic: Referee comments

Bold: Authors comments

Red: Selected changes in the manuscript (note, not all changes are shown here, but will be submitted as revised manuscript with track-changes)

SPECIFIC COMMENTS

Referee:

L26-27 When referring to the definition of glacieret a good reference is also the Unesco glossary of glacier mass balance and related terms by Cogley et al. available at this link https://unesdoc.unesco.org/ark:/48223/pf0000192525 Nevertheless, Serrano et al. 2011 gave a very interesting view of such minor ice bodies discussing their evolution from a disintegrating glacier or in areas where nival processes are dominant. To me, it would be important to add also this view in the introduction.

Authors:

The terminology is indeed vague when it comes to exact definition of the glacieret, so the definitions and discussions of Cogley et al. and Serrano et al. are now added in the text, and readers are referred to these two references for further reading.

…glacierets are defined as a type of miniature (typically less than 0.25 km^2) glaciers or ice masses of any shape persisting for at least two consecutive years (Cogley et al., 2011; Kumar, 2011). Serrano et al. (2011) differ them from ice patches in terms that glacierets are "the product of larger ancient glaciers, still showing motion or ice deformation, although both very low. They have a glacial origin, glacial ice and are never generated by new snow accumulation", whilst ice patches are "ice bodies without movement by flow or internal motion". Despite their small size, glacierets occupy a significant volume fraction at regional scales (Bahr and Radić, 2012), and can therefore be considered as an important target for palaeoclimate studies. Accordingly, many present-day glacierets are closely monitored and studied (Gądek and Kotyrba, 2003; Grunewald and Scheithauer, 2010; Gabrovec et al., 2014; Colucci and Žebre, 2016), but the peculiarity of current global climate change requires more evidence from different proxies and from further in the past when current ice patches and glacierets were still glaciers…

Referee:

L 29-30 Pay attention, reference Bahr and Radi´c, 2012 should be highlighted after the sentence "occupy a significant volume fraction at regional scales" and not after "and are thus an important target for palaeoclimate studies". . . they never stated this. Anyway, the sentence is overall questionable because the maximum size of the Triglav glacier during the Holocene was much larger than the size of a glacieret. I suggest rewriting the sentence in order to clarify this important aspect.

Authors:

We corrected the citation order, and also made it clearer that Triglav Glacier (Glacier with the capital as it is its official name) is now ice patch, but used to be glacier (and glacieret) in the past.

Referee:

Line 39-43 Subglacial carbonate crusts are also reported in the European Julian Alps by Colucci, 2016 (ESPL page 1232, Geomorphic influence on small glacier response to post-Little Ice Age climate warming: Julian Alps, Europe).

Authors:

The reference was added to the text.

Referee:

Line 51 You should be consistent with the given definition of glacieret, representing the actual state of this ice body. Honestly, as mentioned above, I would prefer the definition given by Serrano et al., 2011 and classify this ice body as a "glacial ice patch", meaning that it is actually an ice patch (no more than 2-3 m thick), residual ice body of a recently flowing glacier.

Authors:

We largely reworked the whole introduction chapter so it is clearly stated that Triglav Glacier is at present a "glacial ice patch" (and was also recently a "glacieret", and less recently a "glacier").

Referee:

Lines 84 and 94 Add space after "(sub)"

Authors:

Corrected.

Referee:

Line 127-133 I would suggest replacing here the term "glacieret" with "glacier" especially because when referring to the further chapter at line 135-138 is correctly stated that carbonate deposition resemble flow direction of the glacier and precipitation was strongly influenced by the mechanical force of the ice movement. Please, give clues about the location and number/name of such younger dated samples and of all the cited samples. It is important for the reader to understand where each dated sample is located in the surrounding s of the present ice patch which is a non-moving ice/firn mass. Nevertheless, after reading all the manuscript, I think this sub-chapter is rather unuseful and might be deleted because they are better presented and discussed in chapter 4.

Authors:

The term "glacieret" was replaced with "glacier". We also made it clearer in the Methodology chapter how many samples were collected and referred a reader to the location figures (Five subglacial carbonates were collected 50 m to 100 m from the current ice patch (Fig. 2).**). Since this chapter is strictly representing the results only (as the chapters before this), followed by a discussion chapter, we still left the chapter included in the manuscript.**

Referee:

Line 174-175 In that paper Resfinder et al. stressed the fact that carbonate crusts were preserved by very cold and dry Arctic climate, which is really not the case of the Triglav cirque in the last century or during any possible period of absence or almostcomplete- absence of an ice body. This is particularly true when looking at Mean Annual Precipitation (MAP) of 2600 mm w.e. recorded at Kredarica.

Authors:

This is a helpful additional argument for the continuously existing Triglav Glacier during the Holocene, and we added this part to the chapter 5.

…whilst Refsnider et al. (2012) discussed the preservation of the subglacial carbonates by very cold and dry Arctic climate, this cannot be the case of the cirque of Triglav Glacier in the last century or during any possible period of absence of an ice body, evident by mean annual precipitation at Kredarica hut (2515 m a.s.l.) (Slovenian Environment Agency, 2020) (see Fig. 2 for location)….

Referee:

Line 182 I'm wondering if this could be entirely correct. At the LGM peak, Kuhleman et al2008 suggested a lowering of summer temperature of about 9-11°C in the southeastern Alps. This roughly means that at Kredarica (2514 m), where the present summer temperature (1981âˇAˇ T2010) is around +6.0 ° C (http://meteo.arso.gov.si/uploads/probase/www/climate/table/sl/by_location/kredarica/climatenormals_81-10_Kredarica.pdf) and considering the recent warming in the area calculated in the southeastern Alps in +1.7 C since the end of the Little Ice Age by Colucci & Guglielmin 2015, should have been roughly between -4.7 and -6.7. These characteristics lead to the existence at that location of a cold base glacier, instead of a temperate glacier. Nevertheless, given dates at 23.62 ka, 18.45 ka, and 12.72 ka suggest some interesting speculation. As stated by Monegato et al., 2017 in the paper "The Alpine LGM in the boreal ice-sheets game" published in Scientific Reports (https://www.nature.com/articles/s41598-017-02148-7), the LGM seems to be characterized by 2 main peaks with a withdrawal phase between 23.9 and 23.0 ka when tha Garda glacier retreated, which fit rather well with the 23-62 ka date given in this work. The final collapse of the Garda glacier occurred around 17.7-17.3 ka but soon before there was a progressive stacking of moraines related to the retreat and lowering of the ice surface which seems to fit well with the 18.45 ka dating. Both events could represent the occurrence of "some" subglacial water at the glacier-bed. Finally, I have no problem considering that during the Younger Dryas phase there was certainly a large amount of free water flowing at the glacier-bed. Small scale Detailed paleoclimate conditions in the Alps are still an open question, and uncertainties are evident especially in the eastern Alps when looking at bias between the modeled MIS2 stage ice extent (Seguinot et al., 2018) and geomorphological reconstruction (Ehlers et al., 2011), but the discussion could be expanded in such a way.

Authors:

This discussion was avoided in the first draft due to the greater focus into preservation of subglacial carbonates and the lack of high-number/resolution dates to constrain the individual withdrawal periods during the LGM. Nevertheless, the retreat of the Garda Glacier indeed points out rather interesting correlations to the single ages of the subglacial carbonates of the Triglav Glacier, so we added the proposed discussion in the text.

…the cold Alpine environment during the glacial period with low biological respiration rates could be indicated in the relatively high δ13C signal, also reported by others (Lemmens et al., 1982; Fairchild and Spiro, 1990; Lyons et al., in press), but the (re)freezing of the subglacial water causes supersaturation with respect to carbonate and the non-equilibrium conditions produced by this process can affect the stable isotopic composition of the subglacial carbonate, usually leading to isotopic enrichment in the carbonate minerals (Clark and Lauriol, 1992; Courty et al., 1994; Lacelle, 2007). In any case, the climate during the precipitation of subglacial carbonate had to be "warm" enough to produce subglacial water at the glacier-bed. Kuhlemann et al. (2008) suggested a lowering of summer temperature of about 9-11°C at the LGM peak, meaning that the summer temperatures at Triglav Glacier should have been around -4.7 to -6.7°C (based on the present summer temperatures at around +6°C (Slovenian Environment Agency, 2020) and additional considering the recent warming of +1.7°C in the area calculated in the southeastern Alps since the end of the Little Ice Age by Colucci and Guglielmin (2015)), which would have been conditions for the cold base glacier and the absence of subglacial water flow. Whilst small scale detailed palaeoclimate conditions in the southeastern Alps are still uncertain, the current U-Th ages of subglacial carbonates within this research fit with the temporary Garda Glacier withdrawal phases reported by Monegato et al. (2017); 23.62 ka age of subglacial carbonate relates to the withdrawal phase between 23.9 and 23.0 ka, and 18.45 ka could relate to the glacier retreat from around 19.7 to 18.6 ka or even the final collapse of the glacier around 17.7 to 17.3 ka; both time periods could relate to commencement of subglacial water flow also at the Triglav Glacier and consequently the precipitation of subglacial carbonates. In addition, the 12.72 ka age of Younger Dryas would predate the period of maximum cooling between ca. 11-10 ka (Mathewes, 1993; Renssen and Isarin, 1997)…

Referee:

Lines 195-200 this is too speculative in my opinion. There is no evidence at present of cave ice older than roughly 10 ka at least in Europe, on my best knowledge. I would be more cautious in this manuscript deleting "perhaps even Last Glacial Maximum times".

Authors:

We deleted this part.

Referee:

Line 236 I would prefer "ablation" instead of "melting".

Authors:

We changed the words accordingly.

Referee:

Line 241 I might agree with what it is here stated, but as a possible cause I would also cite the important work of Painter et al., 2013 (https://www.pnas.org/content/110/38/15216).

Authors:

We included this work (and also added it in the chapter 7).

Referee:

Line 242-248 This part is too hasty, although crucial in the discussion, and should be more deeply investigated and discussed. For instance, has been shown as the retreat of Triglav glacier since the LIA in the last century has been more evident than in other sectors of the Julian Alps where other glaciers existed. This is the case of Canin-Kanin or Montasio West glaciers which are lower in elevation than the Triglav glacier. The Montasio West is still classified as a moving glacier with dynamics due to internal deformation. The reason why Canin-Kanin and Zeleni Sneg (the largest LIA glaciers in the Julian Alps) had different fates in terms of shrinking velocity and a 200 m difference in the Equilibrium Line Altitude (ELA) has been justified by Colucci 2016 to a large difference in Mean Annual Precipitation (in the Triglav area precipitation are roughly 60% of that in Canin-Kanin) and potential annual solar radiation for the glaciers differed by about 7%. In this view Triglav glacier generally has higher sensitivity to summer temperature while Canin-Kanin lies in a more "maritime" environment and is more sensitive in changes of winter precipitation. I guess a discussion in terms of variability of these two parameters during the Holocene and/or in the Lateglacial period would improve this part of the manuscript. The literature is quite abundant on this topic.

Authors:

We emphasised now the geomorphological peculiarity of small glaciers which influence their dynamics and included the Canin example. Nevertheless, the aim of the paper is to demonstrate the value of subglacial carbonates which offer possible indications of on-going persistence of the Triglav Glacier since the LGM, which based on geomorphological predispositions would be

amongst the first ones to disappear, despite its higher altitude, and therefore the most appropriate one to relate this to other small glaciers. However, as stated in the paper, high-resolution analyses of subglacial carbonates need to follow to justify further environmental discussions.

…on the other hand, further comparable research on various small glaciers is needed to generalise the palaeoclimatic data due to geomorphological peculiarity of glacier regions; for example, even though the resilience of the Triglav Glacier until present can be emphasised due to the above described regional components, the retreat of the Triglav Glacier has been more evident than the retreat of the Canin Glacier (Italy), Montasio West Glacier (Italy) and Skuta Glacier (Slovenia) (all in southeastern Alps), which are all lower in elevation than the Triglav Glacier, but large difference in mean annual precipitation (e.g., in the Triglav area water equivalent precipitation (2071 mm) is 62% of that in Canin area (3335 mm)) and potential annual solar radiation play a major role for differences in glaciers' dynamics (Colucci, 2016)…

FIGURES

Referee:

Figure 3 Is not adding anything crucial to the study area or the manuscript itself. It Maybe could be deleted and glacier outlines drawn in figure 2. Instead, Figure S2 could be added in the main article as Figure 3, maybe highlighting with arrows and numbers the location of the samples because in the main manuscript a picture of the study area with a view of the present state of the ice patch is missing.

Authors:

Figure 3 was deleted. We added the locations of samples in Figure 1 B, which is showing the area of the present state of the ice patch. Figure S2 and S3 are therefore also not needed as they are similar to Figure 1 B and were therefore deleted. The ice outline from previous Figure 3 was added (only 1946 year) to the Figure 2, whilst additional outlines can still be traced in supplementary material. All of the figures have now text changed into Times New Roman and in places enlarged to be more visible.

Fig. 1

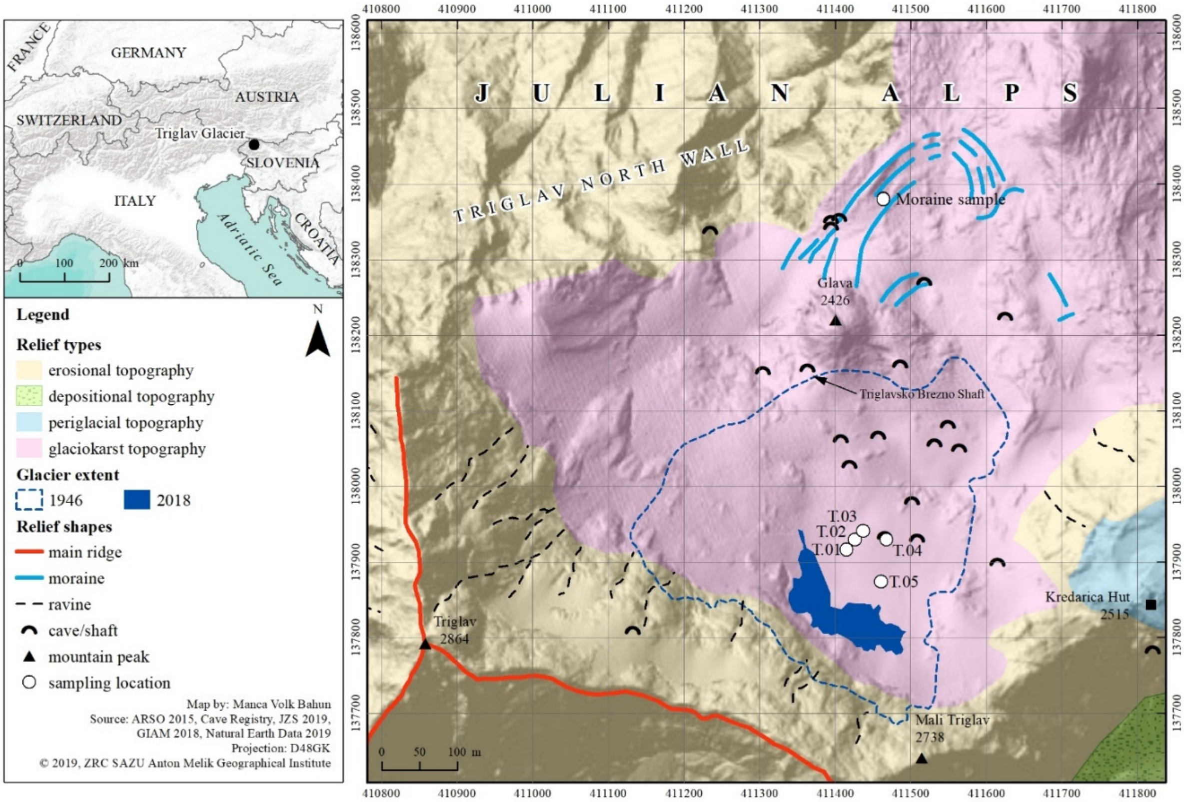


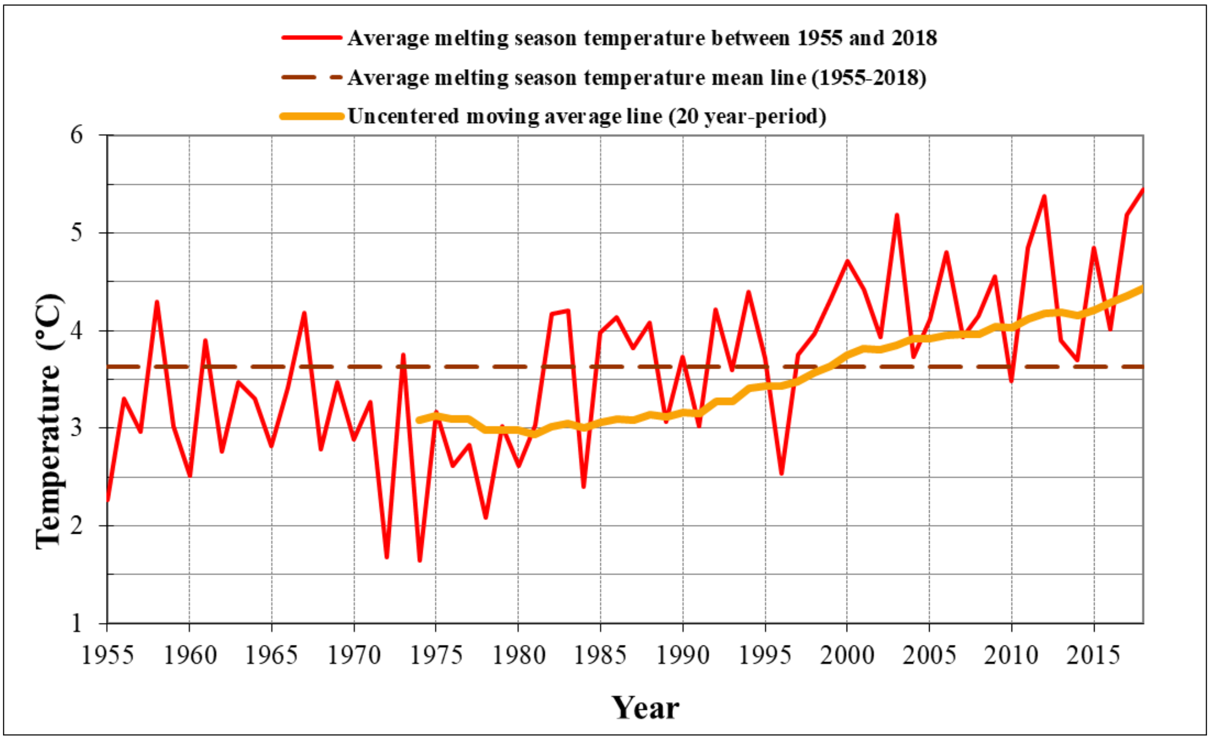
Fig. 2

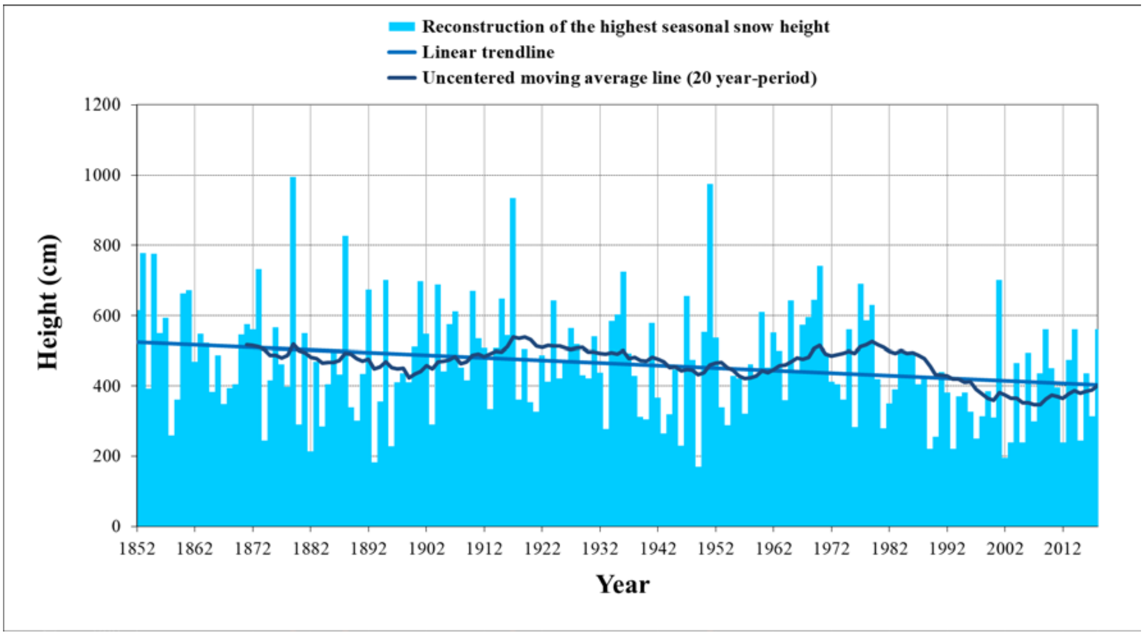
Referee:

Suppl. Material Figure S3 . . . it would be useful to add a number of samples together with arrows Figure S5 . . . not clear which of the 3 caves is the Tiglavski Brezno Shaft. . . Fonts and size are not the best, please improve the size and the visibility of the text Figure S6 . . . I would change "melting season" with "ablation season". More, please give clues about the moving average used (how many years ?! It is centered ?) Figure S7 . . . Besides linear regression, I would also add a moving average which probably better highlights variability along about the last 170 years. These are indeed very interesting data, I'm asking my self if they are available in some repository to the scientific community.

Authors:

We made on all the figure maps clear now which is the Triglavski Brezno Shaft, and also improved fonts and size. Figure S6 is updated, also Figure S7; we included now the 20-year uncentered moving average for both graphs. The raw data of Figure S6 is available through Slovenian Environment Agency site (https://www.arso.gov.si/en/), and a number of additional raw data of the Triglav Glacier are accessible on the dedicated page of the Slovenian Environment Agency (http://kazalci.arso.gov.si/en/content/triglav-glacier). The original reconstruction data of Figure S7 was primarily published in Gabrovec et al. (2014) and the reader is referred to this reference (as the caption states as well); the reconstruction of the highest seasonal snow height is not the main topic of the manuscript, however, due to its recognition as a valuable data, the process has been started to build a repository upon the referenced (Gabrovec et al., 2014) work.





Again, we thank dr. Colucci for the fair and constructive review.

Authors.

Response to Dr. Bernard Hallet (Reviewer #2) to manuscript TC-2020-82

Italic: Referee comments

Bold: Authors comments

Referee:

This is a fine paper, clearly presented and well illustrated, but only with skeletal captions that do not do justice to the figures…

Authors:

Incorporating also all the following comments, the figure captions have now been updated.

Referee:

One important improvement would be to add credibility to the ages reported by providing more explicit details about the impact on the calculated age of the initial content of Thorium 230 in the precipitate. One effective way of doing this is in table form much as that shown below from Fitzpatrick, J. J., Muhs, D. R., & Jull, A. J. T. (1990). (Saline minerals in the Lewis Cliff ice tongue, Buckley Island quadrangle, Antarctica. Contributions to Antarctic Research I, 50, 57-69). In particular, for 230/232 values of 4, for example, the age could be as much as 40% younger than the age calculated that does not assume there is any 230 initially. Also, the text should reflect as accurately as possible the corresponding large uncertainties.

Authors:

We added extra data to the text, stating that we assumed an initial 230Th/232Th ratio of 0.825 ± 50 % (the bulk-Earth value, which is the most commonly used for initial/detrital 230Th corrections). In addition, the reader is referred to the Supplementary table showing the detailed data and including the detailed analysis procedures, which are furthermore referenced. For example, the 230Th/238U and 234U/238U activity ratios of the samples were calculated using the decay constants given in (Cheng et al., 2000). The non-radiogenic 230Th was corrected using an assumed bulk-Earth atomic 230Th/232Th ratio of 4.4±2.2×10-6. U-Th ages were calculated using the Isoplot/Ex 3.75 Program (Ludwig, 2012).

Referee:

The authors may also wish to consider leveraging the limelight of Ötzi, the Iceage Man, and its climate implications, as referenced by Solomina et al (2015) in their supplementary material.

Authors:

A helpful suggestion, which we included now in the text with appropriate referencing.

Referee:

29. …significant volume fraction of what?

Authors

It is a significant ice volume fraction. We corrected this in the text.

Referee:

41. Also reported from the southern tip of S. America (Tierra del Fuego, Personal communication, Rabassa), New Guinea (Peterson and Moresby, 1979), and from sites where they formed under LGM ice.

Authors:

We added New Guinea to the text, but, for now, left S. America out as it can only be cited as 'personal communication'. Nevertheless, we consider the reviewer's suggestion of S. America as very important, because it is assumed that the lack of available 'published material' is a likely cause that subglacial carbonates in S. America are 'missing'.

Referee:

56-57. The units, $kg/m^2/yr$, seem unusual. Why not report ice thinning rate in m/yr, or the rate of increase of exposed bedrock, m^2/yr? This rate must be averaged over a certain area, but what is it? This reference, Gabrovec et al., 2014, does not help; it is incomplete and insufficient.

Authors:

We changed the units and used and cited the newly published data about the Triglav Glacier retreat (…around 0.6 m/yr (1952-2016) (Triglav-Čekada and Zorn, 2020)).

Referee:

Fig. 1 caption should be more informative, explaining to unfamiliar readers

- *what is what (bedrock vs. precipitate)?*
- *the orientation of surface imaged relative to horizontal and to the former sliding direction*
- *the morphology of the precipitates*

Authors:

We updated the figure caption.

Referee:

Fig. 2. What are is the pink areas? Replace these terms in legend; in English they are incorrect or awkward.

From:

Relief types

Erosional topography

Depositional topography

Periglacial topography

Relief Shapes

Main ridge

To:

Terrain types

Erosional surfaces

Depositional surfaces

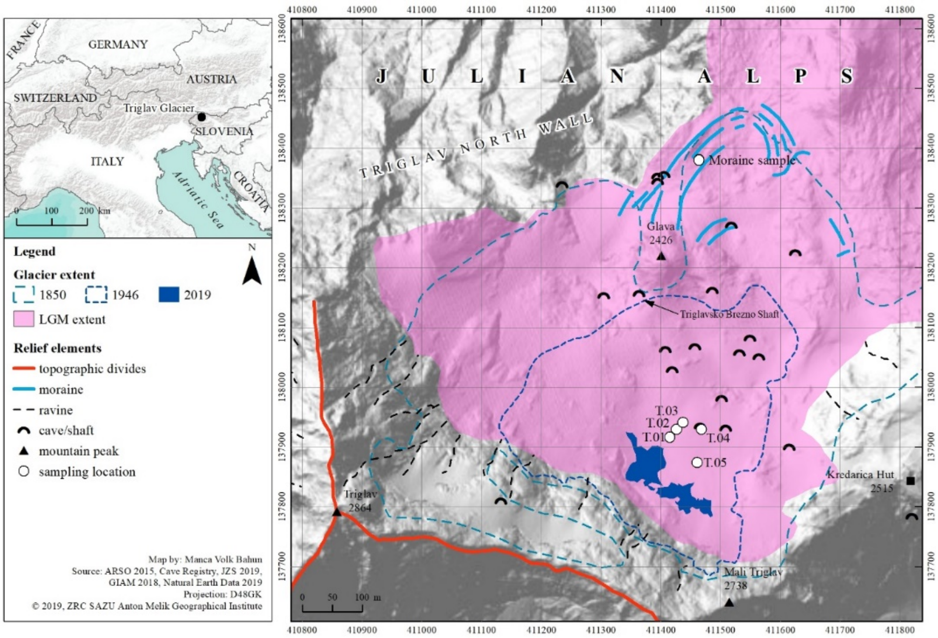
Periglacial terrain

Relief Elements

Topographic divides

Authors:

The terms have been corrected accordingly – note that the whole Figure 2 has been extensively edited, and eventually joined with the Figure S2, which makes the message of the figure itself more condensed and clearer. We omitted the topography types as their boundaries cannot be strictly defined (in places they are coinciding), and rather made the glacier extents throughout the history clearer.



Referee:

60. Replace "…the recently exposed subglacial carbonate deposits due to glacier retreat." by "…the subglacial carbonate deposits recently exposed by glacier retreat."

Authors:

Corrected.

Referee:

78. (…targeting carbonate) cement ought to be replaced by the more appropriate word, precipitate

Authors:

Corrected.

Referee:

103. Replace "They are fluted and furrowed crust-like deposits characterized by brownish, greyish or yellowish colour." by "The fluted and furrowed crust-like deposits are brownish, greyish or yellowish in colour."

Authors:

Corrected.

Referee:

115-6. "Depending on the angle of the lee side of bedrock protuberances, columnar calcite crystals grow either perpendicularly to the host rock (Fig. 5a) or with a lower angle, generally oriented downslope…" Replace "angle" by "inclination" or "slope". It would be good to explain how the crystal orientation varies with bedrock surface inclination less ambiguously. For example, do vertical crystals grow perpendicular to the rock when bedrock surface is near vertical or near horizontal? Is there a relation between the crystal orientation and the former glacier sliding direction?

Authors:

To avoid ambiguity, we have changed the cited sentence to the following "Calcite crystals grow perpendicularly to the substrate on the steeper, nearly vertical areas of the bedrock (Fig. 4a) while in the less steep, nearly horizontal areas, crystals grow inclined, oriented downslope, presumably in the sliding direction of the forming glacier (Supp. Fig. S6)."

Referee:

124. Replace is by are.

Authors:

Corrected.

Referee:

127. For the isotopic ratios, the ranges should be included in the text, as well as averages. The reader should not have to look up the supplement for this basic information.

Authors:

Corrected.

Referee:

129-134. Briefly explain what ages you expected. Weere the "two U-Th ages of stratigraphically younger cement" obtained from the same sample? If any of the thin sections are from this sample, you should mention it in the text, and help understand the stratigraphic setting of these younger deposits. Why would the former glacier be thick, and what do you mean by thick?

Authors:

The expected ages were of Little Ice Age, as it was assumed that glacier was completely melted during the Holocene Climactic Optimum – we added this in the text. We also referred readers to Figure 3 for more details where sample were obtained from (drilling locations), which also explains 'stratigraphically younger/older' situations. In the main text, we changed "of stratigraphically younger cement of the thickest …" to "corresponding to samples drilled in more surficial calcite layers of the thickest". By 'thick -glacier-' we mean 'of sufficient thickness to cause regelation', which is now clarified in the text.

Referee:

147. I'd replace low supersaturated solutions by slightly supersaturated solutions

Authors:

Corrected.

Referee:

148-9. Replace "high Mg/Ca ratio in the water partially could be the trigger for the precipitation of aragonite" by "high Mg/Ca ratios in the water partially be responsible for the precipitation of aragonite".

Authors:

Here we have rewritten the sentence to make it clearer. The new sentence is: "In some freshwater systems like spring deposits (Jones, 2017), and specially in speleothems, Mg/Ca ratios seem to be the main factor controlling aragonite vs calcite precipitation (Frisia et al. 2002; Wassenburg et al. 2012; Rossi and Lozano, 2016)".

Referee:

150-1. Recast sentence to avoid circular logic.

Authors:

Corrected.

Referee:

152. I suggest replacing "pose a challenge to determine" by "raise the difficult question of"

Authors:

Corrected.

Referee:

159-160. What is it about the moment that matters in the following "… factors such as the percentage of initial aragonite and the moment of the aragonite to calcite transformation…the possible additional redistribution of Th …. or the degree of opening of the system"? How about this rewording: "… factors such as the initial relative amount of aragonite and the timing of its transformation to calcite …the possible additional redistribution of Th …. and the extent of chemical exchange with widespread subglacial meltwater"?

Authors:

Corrected.

Referee:

162-4. Suggested edit from:

"Based on the U concentration in samples within this study (in ppm; Supp. Table S2), it is notable that the youngest sample (2ka; T.03_b1) has 1.77 ppm of U concentration, whilst two of the old samples (LGM and YD; T.01_a1 and T.03_a1) have around 0.41 and 0.46 ppm of U concentration, respectively"

To

"It is notable that the U concentration (in ppm; Supp. Table S2) in the youngest sample (2ka; T.03_b1) within this study is 1.77 ppm, whereas it is around 0.41 and 0.46 ppm in two of the old samples, T.01_a1 and T.03_a1, respectively LGM and YD."

Authors:

Corrected.

Referee:

165. Replace contrary by to the contrary

Authors:

Corrected.

Referee:

166 & 168. Replace In case of the first possibility…by Assuming the first possibility…The same goes for line 168.

Authors:

Corrected.

Referee:

Figure 4:

An informative caption is needed for this important figure. The labels are ambiguous. I assume, but am uncertain, that upper and lower "sides" refers to the surface (facing open air before being collected) and underside of the carbonate samples. In any case, how is depth measured? Is it relative to the surface or to the underside? For T.03, does the "lower side" include limestone bedrock as well as subglacial precipitate? It would be helpful for the reader to indicate clearly in words or graphics how the ages vary with stratigraphy. Perhaps, this could be dome easily by providing the ages that correspond to the depths written on figure. Is this the only sample for which several dates have been obtained?

Authors:

Upper and lower sides refer to the surface (facing open air before being collected) and underside of the carbonate samples, respectively (the most appropriate side was chosen for drilling and consequently for visual presentation within this figure). The depths were measured relative to the starting drilling point of each sample as they are shown in this figure (lower side perspective for sample T.03 and upper side perspective for all the other samples); only the T.03 sample had precipitates thick enough that allowed to obtain several dates in three different depths. We also made the figure clearer in terms of differentiating what is subglacial carbonate and what is limestone bedrock.

Referee:

192. $\delta^{18}O$ differences of a few per mill in the carbonate precipitate can also arise due to variations in subglacial hydrology shifting from closed to open geochemical systems (see Hanshaw & Hallet)

Authors:

Corrected.

Referee:

197. Replace "lighter in deuterium compared to the Triglav…" by "lighter in deuterium than those from Triglav…"

Authors:

Corrected/

Referee:

199. The last clause (constraining the implications that the Triglav Glacier was constant during *the Holocene.) does not follow logically from the preceding text. Clarify or delete it.*

Authors:

Corrected.

Referee:

203. I am unsure of your intent with the leading sentence of this section. If it is consistent with the heading, I would suggest this revision: The LGM and YD ages are the first physical evidence that Triglav Glacier persisted through the Holocene to the present day (Solomina et al., 2015). If your intent is different, describe it clearly.

Authors:

We made the leading sentence of this section clearer.

Referee:

210. I suggest replacing "not being documented in the literature" by "not having been reported in the literature"

Authors:

Corrected.

Referee:

214. This paragraph ought to be updated in view of more recent work reporting even slower denudation (e.g. Steinemann et al., 2020), but still supports the contention that the 5mm crust would have weathered off during the HCO if exposed to the elements.

Authors:

The recent work of Steinemann et al. (2020) has been incorporated into the text.

Referee:

221. Delete the last 3 words because once exposed the subglacial carbonate deposits they cannot be glacially abraded. Moreover, I would not expect them to be abraded even under the glacier because they form in lee positions where I would expect abrasion to vanish as abrading rock fragments diverge from the bed at sites of subglacial precipitation due to regelation ice growth.

Authors:

Corrected.

Referee:

228. Delete "assessment of"

Authors:

Corrected.

Referee:

240. Replace "quick rate of 21st" by "rapid 21st"

Authors:

Corrected.

Referee:

243. Replace "show a lower sensitivity to climate fluctuations" by "are less sensitive to climate fluctuations"

Authors:

Corrected.

Referee:

245. This remark about bright limestone substrate reminds me of the photographs, which begs the question: what is responsible for the color difference (greys vs. beige & brown on the more recently exposed bedrock surfaces)?

Authors:

To our knowledge, this has not been studied on that particular location. In general terms, the discolouration of the limestone is usually due to microbial (and lichen) activity (e.g. Dias et al., 2018). The more recently exposed bedrock surfaces have, assumingly, been affected less (for the shorter time) by microbials than the long-exposed bedrock in further surroundings. We inserted this remark in the Figure 1 caption.

Referee:

250. What do you mean here? The preliminary data shows a high possibility that subglacial carbonate deposits may endue unprecedented retreat… Might you mean the following? The preliminary data suggest that subglacial carbonate deposits can archive valuable datable records of glacial retreat, including hints that the current and ongoing retreat is unprecedented.

Authors:

Yes. We paraphrased the sentence to make the statement clearer.

Referee:

255. Replace observe by determine.

Authors:

We replaced 'observe' by 'detect'.

Referee:

260. Replace considerably fast by relatively high. This section should also leverage, and be updated by, recent work (Steinemann et al., 2020).

Authors:

Corrected. We also referred the reader to the Section discussion limestone denudation and glacial erosion on limestone substrate, which includes recent work by Steinemann et al., 2020.

Referee:

264-5. Replace "particulates on the present remnants of ice (and possible ice cores, if a glacier has not disappeared completely)" by "material on the small remaining ice masses and, if possible, ice cores)

Authors:

Corrected.

Referee:

274. The conclusion would be stronger and clearer without the first sentence. I would replace it as follows:

Subglacial carbonate deposits recently exposed by the retreating Triglav Glacier contain the first direct evidence of the existence and extent of Triglav Glacier since the Last Glacial Maximum and Younger Dryas.

The deleted sentences should be incorporated in the previous section and clearly explained:"U-Th ages of subglacial carbonate with the combination of aragonite and calcite are regarded as maximum ages as aragonite-to-calcite transformation, evident in fabrics, might have occurred in calcite crystals that could have been falsely considered as primary.

Authors:

We re-arranged the conclusion, especially the first sentence. The previous message of the sentence is a part of Section 4.

Referee:

Missing refs

Hanshaw, B. B. and B. Hallet. 1978. Oxygen isotope composition of subglacially precipitated calcite: possible paleoclimatic implications. Science, 200,1267-1270.

Peterson, J. A., and Moresby J.F. 1979 Subglacial travertine and associated deposits in the Carstensz area, Irian Jaya, Republic of InCorrectedsia. Zeitschrift fur Gletscherkunde und Glazialgeologie. 15(1), 23-29

Steinemann, O., Ivy-Ochs, S., Grazioli, S., Luetscher, M., Fischer, U. H., Vockenhuber, C., & Synal, H. A. 2020. Quantifying glacial erosion on a limestone bed and the relevance for landscape development in the Alps. Earth Surface Processes and Landforms, 45(6), 1401-1417.

Authors:

All these references are now included and cited in appropriate places within the text.

Referee:

Figure S2:

The caption states "The recently exposed surface with shafts and subglacial carbonate deposits" but does not address the distinct colors, ranging from greys to rusty brown. Do the color boundaries correspond to, or parallel outlines of glacial extent in Figure S4? The figure should also show where the subglacial deposits or shafts are. In fact, what do you mean by shafts?

Authors:

Figure S2 has been deleted as very similar photograph with more detail is shown in Figure 1. Colour boundaries generally correspond to the glacial extent in the 19th century, but note that deposition of graviclastic material (which is of brighter colour as well) took place in some areas, which correspond to the glacial extent coincidentally. However, in general it matches to the oldest extent documented, and we included the observation to the caption.

By shafts we mean vertical caves, which we added now in the text where the word 'shaft' first appear.

Referee:

Figure S8: XRD graphs. A short caption is needed to explain what these samples are, how they differ from one another, and which are bedrock (if any).

Authors:

We have improved the caption: "XRD diagrams of all the studied samples (for precise location, see Figure 3 in the main manuscript). Samples TRG-01 C and TRG-03 D correspond to the bed rock. Green lines mark the reflections corresponding to calcite and red lines, those corresponding to aragonite.".

Referee:

Comments and questions in italics. Figure S9: a) Short columnar calcite crystals alternating with brown micritic bands constitute the first phase of calcite precipitation on the bedrock. Plane polarised light (PPL); b) columnar calcite crystals predominantly oriented towards the right (downslope) .[what is the orientation of the thin section relative to the former sliding direction? Same question for Fig S10]. The growth of the crystal on the center crosscut the direction of growth of previous crystals.[what is the center crosscut?] Crossed polarised light (XPL)

Authors:

The figure captions have been modified according to the suggestions. The sentence referring to how some crystals crosscut the previous has been deleted and we have added information on the orientation of thin sections. "Thin sections orientation is parallel to the former glacier sliding direction.".

Referee:

Figure S11- caption needs a brief explanation of what the figure shows. What are the various curves?

Authors:

Figure S11 represented a location photo and a graph of ^{14}C results of dated moraine organic matter by Karsten Grunewald and his team in the laboratory in Erlangen. We initially included it in the paper as these results have not been published elsewhere. However, since the focus on the paper is on U-Th dates of subglacial carbonates and discussion about their preservation, and since discussion of dating techniques of moraines are not included, we feel that this figure rather confuses readers. We deleted this figure now.

Subglacial carbonate deposits as a potential proxy for a glacier's former ~~existence~~presence

Matej Lipar[1], Andrea Martín~~Andrea M.~~-Pérez[2], Jure Tičar[1], Miha Pavšek[1], Matej Gabrovec[1], Mauro Hrvatin[1], Blaž Komac[1], Matija Zorn[1], Nadja Zupan Hajna[3], Jian-Xin Zhao[4], Russell N. Drysdale[5,6], Mateja Ferk[1]

[1]Anton Melik Geographical Institute, Research Centre of the Slovenian Academy of Sciences and Arts, Ljubljana, 1000, Slovenia
[2]Ivan Rakovec Institute of Palaeontology, Research Centre of the Slovenian Academy of Sciences and Arts, Ljubljana, 1000, Slovenia
[3]Karst Research Institute, Research Centre of the Slovenian Academy of Sciences and Arts, Postojna, 6230, Slovenia
[4]School of Earth and Environmental Sciences, The University of Queensland, Brisbane, QLD 4072, Australia
[5]School of Geography, The University of Melbourne, Melbourne, VIC 3053, Australia
[6]EDYTEM, UMR CNRS 5204, Université de Savoie-Mont Blanc, 73376 Le Bourget Du Lac-Cedex, France

Correspondence to: Matej Lipar (matej.lipar@zrc-sazu.si)

Abstract. The retreat of ice shelves and glaciers over the last century provides unequivocal evidence of recent global warming. Glacierets (miniature glaciers) and ice patches are ~~an~~ important components of the cryosphere that highlight~~s~~ the global retreat of glaciers, but knowledge of their behaviour prior to the Little Ice Age is lacking. Here, we ~~present~~ report the u~~t~~ranium-thorium age ~~i~~of subglacial carbonate deposits from a recently exposed surface previously occupied by the disappearing Triglav Glacier (southeastern European Alps) that may elucidate the glacier's ~~existence~~ presence throughout the entire Holocene. The ages ~~since their maximum uranium-thorium (U-Th) ages~~ suggest their possible preservation since the Last Glacial Maximum and Younger Dryas. These thin deposits, formed by regelation, are easily eroded if exposed during previous Holocene climatic optima. The age data indicate the glacier's present unprecedented level of retreat since the Last Glacial Maximum, and the potential of subglacial carbonates as additional proxies to highlight the extraordinary nature of the current global climatic changes.

1 Introduction

Glaciers respond to climatic changes making them valuable archives with which to study the effects of past and current climatic changes (Benn and Evans, 2010). Their worldwide retreat ~~globally~~ over the last century provides evidence in support of current global climate change even though the decrease of summer insolation in the Northern Hemisphere favours climate cooling (Solomina et al., 2015; IPCC, 2018). The uniqueness of this trend can only be understood when compared to past retreats and advances of different types of glaciers throughout the entire Holocene.

~~A type of miniature (typically less than 0.25 km^2) glaciers or ice masses of any shape persisting for at least two consecutive years, and with little or no movement, are defined as 'glacierets' (Cogley et al., 2011; Kumar, 2011). Serrano et al. (2011) differ them from ice patches in terms that "the product of larger ancient glaciers, still showing motion or ice deformation, although both very low. They have a glacial origin, glacial ice and are never generated by new snow accumulation. Despite their small size, 'glacierets', defined as miniature glaciers or ice masses with little or no movement for at least two consecutive years (Kumar, 2011), occupy a significant volume fraction at regional scales (Bahr and Radić, 2012), and are can thus therefore be considered as an important target for palaeoclimate studies (Bahr and Radić, 2012). Accordingly, many glacierets are closely monitored and studied~~ (Gądek and Kotyrba, 2003; Grunewald and Scheithauer, 2010; Gabrovec et al., 2014; Colucci and Žebre, 2016)~~, but the peculiarity of current global climate change requires more evidence from different proxies and from further in the past.~~

The data that informs a glacier's dynamics in the past can be provided by subglacial carbonate deposits (Hallet, 1976; Sharp et al., 1990). These are thin carbonate crusts formed ~~in a microscopic space~~ between the ice and bedrock ~~due to~~ by regelation at the glacier base on the lee side of a bedrock protuberance (Hallet, 1976; Lemmens et al., 1982; Souchez and Lemmens, 1985), and can provide information on chemical and physical processes present at the time of their formation (Hallet, 1976). Unlike other ~~remnants of~~ glacial deposits (e.g., moraines), subglacial carbonates may be eroded in a ~~few~~ matter of decades (Ford et al., 1970), suggesting their exposure can be recent. ~~which is also evident in literature where generally 'recently exposed' subglacial carbonates are studied.~~ They have been reported from deglaciated areas of northern North America (Ford et al., 1970; Hallet, 1976; Refsnider et al., 2012), northern Europe and the European Alps (Lemmens et al., 1982; Souchez and Lemmens, 1985; Sharp et al., 1990; Lacelle, 2007; Gabrovec et al., 2014; Colucci, 2016; Thomazo et al., 2017), Tibet ~~in Asia~~ (Risheng et al., 2003), New Guinea (Peterson and Moresby, 1979) and Antarctica (Aharon, 1988; Frisia et al., 2017). The u~~U~~ranium-~~T~~thorium (U-Th)~~–~~ ~~isotope analyses~~method remains the main dating technique for these carbonates, whilst the ^{14}C technique is invalidated by modern carbon contamination (Aharon, 1988) and possible dead carbon effect.

The deposits recently exposed by the ~~drastic~~ rapid retreat of the Triglav Glacier (Fig. 1) ~~over the last 100 years, from ca. 46 ha (extending between 2280 and 2600 m.a.s.l.) to ca. 0.5 ha (between 2439 and 2501 m.a.s.l.)~~ (Gabrovec et al., 2014)~~,~~ offer a unique opportunity to gain additional knowledge of this glacier's behaviour in the past. The Triglav Glacier extends from the northeastern side of Mount Triglav (2864 m a.s.l.) in the Julian Alps (Fig. 2, Supp. Fig. S2), Slovenia's highest mountain and consisting of Upper Triassic limestone and dolostone (Ramovš, 2000; Pleničar et al., 2009). This region's montane climate is characterised by precipitation from moisture-bearing air masses from Mediterranean cyclones, ~~which are most frequent~~ typically in autumn and late spring, and by frequent ~~temperature change from below freezing to above freezing~~freeze-thaw cycles (Komac et al., 2020).

At present, the Triglav ~~glacier~~ Glacier is one of only two remaining ice masses in Slovenia since the last extensive Pleistocene glaciation (Bavec and Verbič, 2011; Ferk et al., 2017; Triglav-Čekada et al., 2020). The ~~extensive~~ retreat of the glacier has exposed a glaciokarst environment (Fig. 2, Supp. Fig. S2~~ and Supp. Fig. S2~~) comprising a range of erosional (shafts (i.e., vertical caves), karrens, polished surfaces and roches moutonnées) and depositional (moraines, boulders, till, carbonate deposits) features (Colucci, 2016; Tičar et al., 2018; Tóth and Veress, 2019). The known extent and behaviour of the Triglav Glacier spans from the present to the Little Ice Age (LIA) (Colucci, 2016; Colucci and Žebre, 2016), the cool-climate anomaly between the Late Middle Ages and the mid-19th century (Grove, 2004; Nussbaumer et al., 2011), and is based on geomorphological remnants, historical records and systematic monitoring since 1946 (Gabrovec et al., 2014). ~~o~~Over the last 100 years, the ~~Triglav Glacier~~glacier retreated from ca. 46 ha (extending between 2280 and 2600 m.a.s.l.) to ca. 0.5 ha (between 2439 and 2501 m.a.s.l.) (Supp. Fig. S1), with a downwasting rate ~~of retreat at~~of around ~~580 kg/m^2/yr~~0.6 m/yr (19~~92~~52-20~~08~~16) (Triglav-Čekada and Zorn, 2020).~~,~~ The glaci~~al~~er has thus evolved ~~Together, t~~T~~his information reveals its on-going retreat~~~~definition~~ from the plateau-type ~~glacier to the~~ through ~~present~~ ~~recent~~ glacieret~~-type and~~ to the present ice~~-~~-patch ~~-~~-type. ~~(Colucci, 2016; Colucci and Žebre, 2016) (see also Supp. Fig. S1 & S2), with a rate of retreat at around 580 kg/m^2/yr (1992-2008) (Gabrovec et al., 2014).~~

Glacierets are defined as a type of miniature (typically less than 0.25 km^2) glacier~~s~~ or ice mass~~es~~ of any shape persisting for at least two consecutive years (Cogley et al., 2011; Kumar, 2011). Serrano et al. (2011) ~~differ~~ discriminate them from ice patches, arguing ~~in terms~~ that glacierets are "the product of larger ancient glaciers, still showing motion or ice deformation, although both very low. They have a glacial origin, glacial ice and are never generated by new snow accumulation";~~, whilst~~ ice patches on the other hand are "ice bodies without movement by flow or internal motion". Despite their small size, glacierets occupy a significant ice volume fraction at regional scales (Bahr and Radić, 2012), and can therefore be considered as an important target for palaeoclimate studies. Accordingly, many present-day glacierets are closely monitored and studied (Gądek and Kotyrba, 2003; Grunewald and Scheithauer, 2010; Gabrovec et al., 2014; Colucci and Žebre, 2016), but the peculiarity of current global climate change requires more evidence from different proxies and from ~~further in~~ the past when current ice patches and glacierets were still glaciers.

~~The extensive retreat of the glacier has exposed a glaciokarst environment (Fig. 2 and Supp. Fig. S2) comprising a range of erosional (shafts, karrens, polished surfaces and roches moutonnées) and depositional (moraines, boulders, till, carbonate deposits) features (!!! INVALID CITATION !!! (Colucci, 2016; Tičar et al., 2018; Tóth and Veress, 2019)).~~

Here, we present preliminary geochemical and petrological data of ~~the~~ subglacial carbonate deposits recently exposed by the ~~glacier~~ retreat ~~the recently exposed subglacial carbonate deposits due to glacier the retreat~~ of the Triglav Glacier. The aim is to highlight the occurrence of deposits in terms of their possible preservation since the Last Glacial Maximum (LGM), discuss the complexity of the deposit and validate the results in the context~~. This relates to~~ of the present climate regime of rising temperatures and global retreat of glaciers.

~~6~~ 2 Methods

The extent of the Triglav Glacier has been measured annually since 1946 and systematically photographed since 1976 (Meze, 1955; Verbič and Gabrovec, 2002; Triglav Čekada and Gabrovec, 2008; Triglav-Čekada et al., 2011; Triglav-Čekada and Gabrovec, 2013; Gabrovec et al., 2014; Del Gobbo et al., 2016), using a panoramic non-metric Horizont camera. The photos were transformed from a panoramic to a central projection in order to allow the calculation of the area and estimation of the volume (Triglav-Čekada et al., 2011; Triglav-Čekada and Gabrovec, 2013; Triglav-Čekada and Zorn, 2020). The early measurement technique ~~included~~ was by measuring tape and compass, which enabled ~~to~~ measurement of the glacier's retreat from coloured marks on the rocks around the glacier (Meze, 1955). Accurate and continuous geodetic measurements began in the 1990s: standard geodesic tachymetric measurements, UAV photogrammetric measurements (from both the ground and air), GPS measurements, and LIDAR (Triglav Čekada and Gabrovec, 2008; Gabrovec et al., 2014). In addition, several extensive field campaigns were conducted throughout ~~the year~~ 2018 with the focus on the central part of Triglav Plateau at the side of the present and former glacier (Fig. 1, 2). During this time~~,~~ ~~and~~ five subglacial carbonate ~~deposit~~ samples (Fig. 3) were collected at multiple localities (Fig. 1, 2; Supp. Fig. S2~~Fig. 1~~) for ~~further~~ laboratory analyses.

~~Five subglacial carbonates t~~These were collected 50 m to 100 m from the current ice patch. A hand drill was used ~~in order~~ to obtain powdered samples for geochemical analysis;~~,~~ sampling was restricted to ~~performed in~~ areas ~~of the deposit~~ consisting of the densest and thickest ~~and thick enough crystals~~sections. Prior to and after each drilling, the surface was cleaned with deionized water and dried under clean air. Drilling was performed with a 0.6 mm drill bit in a clean environment~~, targeting carbonate cement~~precipitate. A stainless steel spatula and ~~a~~ weighing paper were used to harvest the drilled powder and transfer it into ~~a~~ clean 0.5 ml sterile vials.

Five thin sections (30 ~~-~~– 50 µm) were examined using an Olympus BX51 polarising microscope equipped with an Olympus SC-50 digital camera. Due to the fragility of the samples, they were embedded in Epoxy resin under vacuum before being cut and polished.

The mineralogy of twelve (sub) samples was determined by X-ray diffraction (XRD) using a Bruker D2PHASER diffractometer equipped with an energy dispersive LYNXEYE XE-T detector, located at the ZRC SAZU Karst Research Institute~~ ZRC SAZU~~, Slovenia. Powdered samples were scanned from 5 to 70° 2θ at a 0.02° 2θ/0.57 s scan speed. The diffractograms were interpreted using EVA software by Bruker (DIFFRACPlus 2006 version).

Five (sub) samples were dated by the ~~uranium-thorium (~~U-Th~~)~~ method at the University of Queensland, Australia. To ~~assure~~ ensure that samples ~~had sufficiently~~ were suitable for ~~high~~ U/Th ~~ratios for dating~~analysis, they were first measured by ICP-MS for their trace element concentrations. U-Th age dating was carried out using a Nu Plasma multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) in the Radiogenic Isotope Facility (RIF) at the School of Earth and Environmental Sciences, The University of Queensland~~ (UQ)~~. Ages were corrected for non-radiogenic ^{230}Th incorporated at the time of deposition assuming an initial ^{230}Th/^{232}Th ratio of 0.825 ± 50 % (the bulk-Earth value, which is the most commonly used for initial/detrital 230Th corrections.~~XXXX~~. Age errors are reported as 2σ uncertainties. Full details of the method are provided in the supplementary material ~~-~~– Table ~~S2~~S1.

The stable-isotope composition (δ^{13}C and δ^{18}O) of five (sub)samples was measured at ~~The stable isotope laboratory at~~ the School of Geography, University of Melbourne, Australia~~, was used to analyse five (sub)samples for both δ^{13}C and δ^{18}O isotopes~~. Analyses were performed on CO_2 produced by the reaction of the sample with 100% H_3PO_4 at 70°C using continuous-flow isotope~~-~~ratio mass spectrometry~~ (CF-IRMS)~~, following the method previously described in ~~Drysdale et al.~~ Drysdale et al. (2009) and employing an Analytical Precision AP2003 instrument. Results are reported using the standard δ notation (per mille ‰) relative to the Vienna PeeDee Belemnite (V-PDB scale). The uncertainty based on a working standard of Cararra Marble (NEW1) is 0.05‰ for $\delta^{13}C$ and 0.07‰ for $\delta^{18}O$.

3 Results

The s~~S~~ubglacial carbonate deposits occur on the lee sides of small protuberances on a bare polished and striated limestone bedrock surface ~~in the immediate vicinity of~~near the Triglav Glacier~~et~~. They are most abundant on the bedrock recently uncovered by the retreating ice, and their occurrence rapidly decreases with the distance from the edge of the present glacieret ~~termination~~margin. The fluted and furrowed crust-like deposits are brownish, greyish or yellowish in colour~~They are fluted and furrowed crust-like deposits characterized by brownish, greyish or yellowish colour~~. The deposits do not exceed 0.5 cm in thickness and ~~in some cases~~ are occasionally internally laminated.

3.1 Mineralogical and petrographic data

X-ray diffraction (XRD) analysis shows that the carbonate deposits mostly consist of calcite,~~;~~ and mixtures of calcite with small amounts of aragonite. XRD ~~has~~ also confirm~~s~~ed the calcite composition of the host rock (Supp. Fig. S~~8~~5). The ~~Petrographic~~ petrographic study has allowed the identification of different fabrics (Fig. 4). Due to the similarities of subglacial carbonate textures to those of speleothem deposits, we have used, whe~~re~~n possible, the formal terminology of ~~Frisia and Borsato (2010)~~ Frisia and Borsato (2010):

Primary calcite fabrics are composed of transparent crystals with uniform extinction. The first crystals to form directly over the bedrock are short columnar (length to width ratios < 6:1) crystals from 50 to 200 µm long (Supp. Fig. ~~S9~~ S6 and ~~S10~~S7). Columnar (L/W ratios ~ 6:1) and elongated columnar (L/W ratios > 6:1) crystals up to 2 mm long and 0.5 mm wide constitute the most abundant fabric. Calcite crystals grow perpendicularly to the substrate on the steeper, nearly vertical areas of the bedrock (Fig. 4a) while in the less steep, nearly horizontal areas, crystals grow inclined, oriented downslope, presumably in the sliding direction of the forming glacier~~Depending on the angle of the lee side of bedrock protuberances, columnar calcite crystals grow either perpendicularly to the host rock (Fig. 4a) or with a lower angleinclination, generally oriented downslope~~ (Supp. Fig. ~~S9~~S6). In some areas, the younger crystals crosscut the main direction of the crystal growth of the previous layer, resulting in crystal boundaries resembling unconformities (Supp. Fig. ~~S9~~S6).

Primary aragonite fabrics consist of acicular crystals (L/W ratio >>6:1) generally growing outwards from a common point in the shape of fans. In some areas of the crusts, these fans are aligned in bands interlayered with very dark, dense micrite and transparent equidimensional calcite crystals, forming layered textures (Fig. 4b, Supp. Fig. ~~S9d~~S6d).

Aragonite-to-calcite replacement fabrics are characterised by calcite crystals of variable size and patchy extinction patterns. They contain abundant fibrous inclusions interpreted as aragonite relicts that are either ~~are~~ aligned in layers or unevenly distributed throughout, which results in very irregular textures (Supp. Fig. ~~S9def~~S6d, e and f). Micrite and microsparite ~~is~~ are often associated with aragonite relicts.

3.2 Geochemical data and ages

Stable carbon and oxygen isotope ratios ($\delta^{13}C$ and $\delta^{18}O$) of the subglacial carbonate yielded average values of 1.35 ± 0.05 ‰ for $\delta^{13}C$ and ~~–~~-4.32 ± 0.07 ‰ for $\delta^{18}O$ (relative to the V-PDB; ~~Supp. Table S1~~Fig. 3). Whilst the expected ages of subglacial carbonates were of the LIA, ~~The~~ the U-Th ages yielded considerably older ages ~~than expected~~: 23.62 ka ± 0.78 ka, 18.45 ka ± 0.70 ka and 12.72 ka ± 0.28 ka, respectively (Supp. Table ~~S2~~S1). The results indicate that these subglacial carbonate dates fall within the ~~Last Glacial Maximum~~LGM and the Younger Dryas (YD). In addition, two U-Th ages corresponding to samples drilled in more surficial calcite layers of the thickest ~~of stratigraphically younger cement of the thickest~~ obtained sample -yielded 3.85 ka ± 0.09 ka and 1.96 ka ± 0.04 ka, indicating the presence of a glacier of sufficient thickness ~~thick enough glacieret~~ to cause regelation also during these periods~~, or recrystallisation~~. For details where the samples were obtained from, the reader is referred to Figure 3.

4 Subglacial carbonate deposits

The fluted and furrowed morphology of carbonate deposition parallel to the apparent former ice-flow direction, some of the crystal textures, the location of the samples and the age data imply a subglacial origin of the carbonate crusts. The presence of ice-flow oriented calcite crystals suggests that precipitation was strongly influenced by the mechanical force of the ice movement. Similar fabrics occur in different types of tectonic veins, ~~as~~ for instance, slickensides, where crystals grow obliquely to the sheets in shear veins, indicating the general shear direction (Bons et al., 2012). Previous studies on subglacial carbonates have considered the orientation of calcite parallel to the ice flow as ~~an~~ evidence of its growth in a thin water film confined by sliding regelation ice (Hallet, 1976), and deformation structures such as folds and fractures, the result of glacially imposed stress (Sharp et al., 1990).

The variability of fabrics of the studied crusts and, especially, the presence of aragonite coexisting with calcite indicate spatial and/or temporal variability in local subglacial water chemistry. The most important parameters controlling the precipitation of aragonite versus calcite appears to be the $CaCO_3$ saturation state, the Mg/Ca ratio in the waters (De Choudens-Sánchez and González, 2009) and/or rapid CO_2 degassing rates (Fernández-Díaz et al., 1996; Jones, 2017). In freshwater systems like spring deposits (Jones, 2017), and specially in speleothems, Mg/Ca ratios seem to be the main factor controlling aragonite vs calcite precipitation (Frisia et al., 2002; Wassenburg et al., 2012; Rossi and Lozano, 2016)~~, with aragonite precipitation favoured by high Mg/Ca ratios (Rossi and Lozano, 2016) in low~~ ~~slightly~~ ~~supersaturated solutions~~. The studied deposits grow over carbonate bedrock with prevailing limestone and some dolostone (Jurovšek, 1987; Ramovš, 2000), so high Mg/Ca ratios in the water may be partially ~~could be~~ responsible ~~the trigger~~ for the precipitation of aragonite. Similarly, precipitation of aragonite in subglacial deposits at Vestfold Hills, Antarctica, seems to have been favoured by the presence of Mg^{2+} in the waters, mobilised from the pyroxenes of the gneiss bedrock (Aharon, 1988).

The U-Th ages of LGM and YD are in good accordance with the glacier's history when it was expected to be thick enough to cause regelation~~ which additionally strengthens the argument for carbonate's subglacial origin~~. However, aragonite-to-calcite replacement fabrics ~~pose a challenge to determine~~raise the difficult question of whether all subglacial carbonate crystals were primarily aragonite and were subjected to complete recrystallisation to calcite ~~in places left no~~ without leaving traces of replacement fabrics, which may provide a false identification of calcite fabrics as primary. This, in turn, may lead to inaccurate interpretation of the U-Th ages (Bajo et al., 2016). Previous studies ~~i~~on corals and speleothems have shown that the diagenetic transformation of aragonite into calcite can affect the accuracy of U-Th dating (Ortega et al., 2005; Scholz and Hoffmann, 2008; Lachniet et al., 2012; Bajo et al., 2016; Martín-García et al., 2019)~~. This is mostly~~ due to ~~the~~ uranium loss~~ associated with the process~~ (Lachniet et al., 2012; Bajo et al., 2016), which usually leads to older-than-true U-Th ages. However, the extent of uncertainty can be ~~very~~ highly variable depending on several factors such as the ~~percentage of~~ initial ~~relative~~ amount of aragonite and the ~~moment of the aragonite~~timing of its transformation to calcite~~ transformation~~ (Bajo et al., 2016), the possible additional redistribution of Th (Ortega et al., 2005; Lachniet et al., 2012) ~~or~~ and the extent of chemical exchange with ~~widespread~~ younger subglacial meltwaters ~~degree of opening of the system during diagenesis~~ (Ortega et al., 2005; Martín-García et al., 2019).

~~It is notable that~~Notably, the U concentration ~~-~~(in ppm; Supp. Table S~~2~~1) in the youngest sample (2ka; T.03_b1) within this study is 1.77 ppm, whereas it is around 0.41 and 0.46 ppm in two of the old samples, ~~-~~T.01_a1 and T.03_a1, respectively LGM and YD~~Based on the U concentration in samples within this study (in ppm; Supp. Table S2), it is notable that the youngest sample (2 ka; T.03_b1) has 1.77 ppm of U concentration, whilst two of the old samples (LGM and YD; T.01_a1 and T.03_a1) have around 0.41 and 0.46 ppm of U concentration, respectively~~. This could indicate U-loss during aragonite-to-calcite recrystallisation and consequently provide older-than-true ages, or to the contrary, that these two samples represent primary calcite with non-preferential incorporation of U in calcite with respect to aragonite and thus prov~~id~~ing to be the most reliable. Assuming the first possibility~~In case of the first possibility~~, the oldest sample (24 ka; T.05) has relatively high U concentration (1.33 ppm), which would indicate less loss of U but still provide data that subglacial carbonates may date back to the last glacial period. ~~In case of~~Assuming the second possibility, the ages of T.03_a1 and T.03_a2 in correct stratigraphic order would strengthen the reliability of the results. Aharon (1988) used U-Th method for dating two samples with a combination of aragonite and calcite fabrics with high but also variable U content (23.2 and 41.4 ppm), however, the indistinguishable dates compared to the ~~ones~~ those from ~~of~~ pure aragonite led to the conclusion that they ~~the dates are reasonably good~~ provide the reliable age estimates. Nevertheless, due to the external Th incorporated into the samples, he regarded the dates as "maximum ages", which~~, in this case,~~ is the appropriate approach also with the dates discussed in this study. Similar U-Th ages (19 – 21 ka) were reported also from northern Canada (Refsnider et al., 2012), however, the carbonate fabrics were not ~~identified and discussed~~described. The U-Th dates from Antarctica by Frisia et al. (2017) and radiocarbon dates from the French Alps by Thomazo et al. (2017) were performed on calcites. More studies should therefore be done in this direction to positively confirm the LGM and YD ages of carbonates, and especially to gain the high-resolution dates to construct the whole timeline of subglacial carbonate precipitation. Nevertheless, since three of our dates fall in the period of 12 ~~–~~- 24 ka, we will proceed with the discussion of their susceptibility to weathering and its implication to glacier's existence.

The cold Alpine environment during the glacial period with low biological respiration rates ~~is evident~~could be indicated in the relatively high $\delta^{13}C$ signal, also reported by others (Lemmens et al., 1982; Fairchild and Spiro, 1990; Lyons et al., 2020), but~~.~~ ~~In addition,~~ the (re)freezing of the subglacial water causes supersaturation with respect to carbonate and the non-equilibrium conditions produced by this process can affect the stable isotopic composition of the subglacial carbonate, usually leading to isotopic enrichment in the carbonate minerals (Clark and Lauriol, 1992; Courty et al., 1994; Lacelle, 2007). In any case, the climate during the precipitation of subglacial carbonate had to be "warm" enough to produce subglacial water at the glacier-bed. Kuhlemann et al. (2008) suggested a lowering of summer temperature of about 9 - 11°C at the LGM peak, meaning that the summer temperatures at Triglav Glacier should have been around -4.7 to -6.7°C (based on the present summer temperatures at around +6°C (Slovenian Environment Agency, 2020) and ~~additional~~~~also~~considering the recent warming of up to +2.03°C in the area (Colucci and Guglielmin, 2015; Hrvatin and Zorn, in press)), which would have been conditions for the cold base glacier and the absence of subglacial water flow. Whilst small scale detailed palaeoclimate conditions in the southeastern Alps are still uncertain, ~~(Seguinot et al., 2018)~~the current U-Th ages of subglacial carbonates within this research fit with the temporary Garda Glacier (Italy) withdrawal phases reported by Monegato et al. (2017):~~;~~ 23.62 ka age of subglacial carbonate relates to the withdrawal phase between 23.9 and 23.0 ka, and 18.45 ka could relate to the glacier retreat from around 19.7 to 18.6 ka or even the final collapse of the glacier around 17.7 to 17.3 ka.~~;~~ ~~b~~Both time periods could relate to commencement of subglacial water flow also at the Triglav Glacier and consequently the precipitation of subglacial carbonates. In addition, the 12.72 ka age marks the early phase of YD cooling (12.9-11.5 ka ago) (Renssen and Isarin, 1997; Alley, 2000; Broecker et al., 2010).

The $\delta^{18}O_{PDB}$ of subglacial carbonate can be transformed into $\delta^{18}O_{SMOW}$ using the equation $\delta_{SMOW} = 1.03037\ \delta_{PDB} + 30.37$ (Faure, 1977). The mean values of subglacial carbonate $\delta^{18}O_{SMOW}$ would therefore be 25.92‰, ranging from 27.44 to 24.75‰. Using the fractionation factor of 1.0347 for calcite and water at 0°C (Clayton and Jones, 1968) and the δ_{SMOW} values of subglacial carbonate, we obtain $\delta^{18}O_{SMOW}$ values ranging from ~~–~~-7.02‰ to ~~–~~-9.62‰. On the other hand, if assuming calcite crystals could have all originated primarily as aragonite crystals, we can use the fractionation factor of 1.0349 for aragonite and water at 0°C (Kim et al., 2007) and obtain relatively similar $\delta^{18}O_{SMOW}$ values ranging from ~~–~~-7.21‰ to ~~–~~-9.81‰.~~–~~ This relates to the average Triglav Glacier ice meltwater values ($\delta^{18}O_{SMOW}$ = ~~–~~-9.3‰) measured in the summer 2018 (Carey et al., 2020). However, it is slightly heavier when compared to ~~the~~ glacier ice samples, which ~~that~~ range~~d~~ between ~~–~~-10.0‰ and ~~–~~-12.7‰. The reason could be that water in equilibrium with the growing ice is progressively impoverished in heavy isotopes (Jouzel and Souchez, 1982), or simply that the remnants of ~~present remaining~~ residual ice has a different isotopic ratio than the basal ice at the time of carbonate precipitation, ~~for~~ which ~~is also known that~~ itself could represent~~s~~ a large range ~~of isotopic composition~~ in values (Lemmens et al., 1982). In addition, $\delta^{18}O$ differences of a few per mills in the carbonate precipitate can also arise due to variations in subglacial hydrology shifting from closed to open geochemical systems (Hanshaw and Hallet, 1978). However, ~~the~~ a geochemical study of the present Triglav ~~area~~ ice area (Carey et al., 2020) ~~showed~~ shows that ice samples ~~found~~ within the cave of Triglavsko Brezno Shaft (see Fig. 1 for location) are much lighter in deuterium ~~compared to the~~than those from the Triglav Glacier, which suggests that they were deposited during colder~~, perhaps even Last Glacial Maximum,~~ times, indicating ~~possible remains of the~~ they are ~~old~~ remnants of ~~the~~ older ~~Triglav Glacier~~glacier ice~~, constraining the implications that the Triglav Glacier was constant during the Holocene~~.

5 Implications for continuously existing glacier during the Holocene

~~The LGM age is the first physical evidence to prove the LGM Triglav Glacier, whilst the YD age is related to the end of the Alpine Late Glacial, when glaciers advanced markedly (Ivy-Ochs et al., 2009) and persisted until the earliest Holocene (Solomina et al., 2015).~~

The LGM and YD ages o~~n~~f the Triglav subglacial carbonates provide ~~are~~ the first physical evidence that the Triglav Glacier persisted through the Holocene to the present day. Glacierets of southern Europe, including the Triglav Glacier, have generally been viewed as relicts of the LIA, ~~with~~ suggesting a discontinuous presence ~~due~~ following ~~to~~ the Holocene Climatic Optimum (HCO) (Grunewald and Scheithauer, 2010), a period of high insolation and generally warmer climate between 11,000 and 5,000 years ago (Renssen et al., 2009; Solomina et al., 2015).

Being prone to fast weathering (Ford et al., 1970), subglacial carbonate deposits are generally found only on recently deglaciated areas (Ford et al., 1970; Sharpe and Shaw, 1989). The Triglav Glacier area is no exception.~~,~~ The fact that they have not been reported previously in the literature ~~and the relatively recent exposure of the deposits is also evidenced by not being documentedhaving been reported in the literature~~ (Meze, 1955; Šifrer, 1963, 1976, 1987) until the year 2005 (Hrvatin et al., 2005; Gabrovec et al., 2014) reinforces their likely recent exposure. Whilst Refsnider et al. (2012) discussed the preservation of the subglacial carbonates by very cold and dry Arctic climate, this is unlikely to be the case ~~cannot be the case of in~~ of the plateau of the Triglav Glacier, either in the last century or during any possible period of absence of an ice body, ~~evident by~~ because of the large mean annual precipitation at the site (2038 mm; re~~d~~corded at Kredarica hut, ~~(~~2515 m a.s.l.) (Slovenian Environment Agency, 2020) (see Fig. 2 for location).

~~To provide the~~ This is supported by theoretical numerical data ~~of~~ for the chemical denudation of the subglacial carbonate, ~~we can~~ which is based on ~~summarise selected chemical~~ denudation~~al~~ rates of limestones (Table ~~1~~21).

Chemical denudation rates on carbonate rocks can vary from ca. 0.009 to 0.14 mm/year (Gabrovšek, 2009). Taking the low and high extreme values for, e.g., 6 ka during the HCO, ~~the denudation~~ surface lowering would be between 54 and 840 mm, so the exposed 5 mm thick subglacial carbonate would have been denuded ~~in~~ by this time.

In addition, carbonate surfaces in periglacial areas are exposed not only to chemical weathering but also to intensive frost weathering, promoting physical disintegration of minerals ~~of depositional features~~ (Matsuoka and Murton, 2008). Therefore, had the subglacial carbonate been exposed in the past, it would be expected to be eroded by dissolution or frost weathering. This indicates, that subglacial carbonate was constantly covered with glacier ice, and, as Steinemann et al. (2020) has demonstrated, that glacial abrasion on carbonate bedrock~~s~~ is minimal compared to the abrasion on crystalline bedrock. This ~~s, aiming at~~ would promote the preservation of subglacial carbonates on limestone plateaus in the Alps. Moreover, ~~as~~ since the subglacial carbonates form in lee positions of bedrock protuberances, it is ~~expect~~ likely that abrasion would vanish as abrading rock fragments diverge from the bed at sites of subglacial precipitation due to regelation ice growth.~~In case of a glacier retreat beyond the subglacial carbonates, the re-advance of the glacier would abrade the deposits with material eroded from surrounding mountain face. Therefore, had the subglacial carbonate been exposed in the past, it would be expected to be eroded by dissolution, frost weathering, or by abrasion.~~ Organic matter (charc~~h~~oal/wood) from a non-vegetated, scree-covered moraine ca. 300 m below the main ice patch of the Triglav Glacier (as it stood in the year 2006) was analysed in the radiocarbon (^{14}C) laboratory in Erlangen, Germany. The ^{14}C result yielded 5604-5446 BP age, which provides additional evidence of pre-LIA, and post-LGM and post-YD ice cover (unpublished analysis by Karsten Grunewald and his team~~; Supp. Fig. S11~~). Similarly, the two younger U-Th ages obtained within this study (3.85 ka and 1.96 ka) also provide evidence of a pre-LIA ice cover.

6 Glacier variations and palaeoclimatic implications

The ~~assessment of~~ complex global pattern~~s~~ ~~in~~ of Holocene glacier fluctuations ~~shows that they are~~ indicates the influence~~d~~ ~~by~~ of multiple climatic mechanisms and that individual glaciers may not respond uniformly to a particular set of climate forcings (Kirkbride and Winkler, 2012; Solomina et al., 2015). In addition, glaciers are also influenced by topographic conditions (DeBeer and Sharp, 2017), as well as their size and flow dynamics (Sugden and John, 1976; Nussbaumer et al., 2011). The Alps has experienced several glacial ~~expansions~~ advances and ~~recessions~~ retreats during the Holocene (Nussbaumer et al., 2011), with reports that some glaciers were even smaller than today or ~~entirely~~ absent (Leemann and Niessen, 1994; Hormes et al., 2001; Ivy-Ochs et al., 2009; Solomina et al., 2015). On the other hand, certain regions show evidence of unprecedented modern retreat of glaciers beyond their previous Holocene minima (Koerner and Fisher, 2002; Antoniades et al., 2011; Miller et al., 2013).

Current climate near the Triglav Glacier is characterised by rising temperatures in the ~~melting~~ ablation season from May to October (Supp. Fig. S~~6~~3) and a descending trend of the highest seasonal snow elevation (Supp. Fig. S4~~7~~). If subglacial deposits ~~would~~ indicate its ongoing existence throughout the Holocene, the ~~present~~ recent retreat of the Triglav Glacier ~~would indicate~~ suggests ~~cold enough~~ regional climate during previous Holocene optima was cool enough to sustain the glacier, ~~or~~ unless an additional (presently unknown) forcing component prevailed which ~~would have not been~~ was not important in the past. Exceptionally ~~quick rate of~~rapid ~~21st~~ 21st-century melting, for example, has been reported also from Barnes Ice Cap in northern Canada (Gilbert et al., 2017), in the ~~European~~ Alps, where the exceptional retreat has been ~~contributed~~ attributed to deposition of ~~the~~ industrially sourced -black carbon (Painter et al., 2013), and is also evident by a large number of recently melt-out archaeological and paleontological finds (Mol et al., 2001; Basilyan et al., 2011), including the famous “Ice Man” Ötzi in the Tyrolean Alps (Baroni and Orombelli, 1996; Solomina et al., 2015).

Local physiographic influences can insulate small glaciers from the warming effects of regional and global climate (Grunewald and Scheithauer, 2010); it has been shown that some small glaciers ~~show a lower sensitivity~~are less sensitive to climate fluctuations than previously thought (Colucci and Žebre, 2016). The natural resilience of the Triglav Glacier is due to its relatively high elevation, bright limestone substrate with higher albedo,~~ and~~ the vertical water drainage through karstified rocks and the consequent lack of subglacial lakes as heat collectors, and avalanche~~-~~ feeding (Grunewald and Scheithauer, 2010; Gabrovec et al., 2014). Assuming these factors were relatively constant throughout the Holocene, the possible unprecedented retreat may highlight the consequences of direct anthropogenic forcing (Solomina et al., 2015). On the other hand, further comparative research on ~~various~~ other small glaciers is needed to ~~generalise~~ test ~~the~~ palaeoclimatic data due to the geomorphological peculiarity of glacier regions.~~;~~ ~~f~~For example, ~~even though in spite~~despite of the apparent resilience of the Triglav Glacier until the ~~present~~recently~~ can be emphasised due to the above described regional components~~, ~~the~~ its retreat ~~of the Triglav Glacier~~ has been more evident than ~~the retreat~~ that of the glacierets/ice patches of Canin ~~Glacier~~ (Italy), Montasio West ~~Glacier~~ (Italy) and Skuta~~s~~ (Slovenia) (all in the southeastern Alps), which are all lower in elevation than the Triglav Glacier, but with large differences in mean annual precipitation (e.g., in the Triglav area water equivalent precipitation (2038 mm) is 62% of that in Canin area (3335 mm)); ~~and~~ potential annual solar radiation also plays a major role in controlling for differences in glaciers' dynamics (Colucci, 2016).

7 ~~Further research~~Conclusion

Three U-Th ages of subglacial carbonate exposed by the retreating Triglav Glacier fall within the LGM and YD, providing the first direct evidence of the Triglav Glacier at that time. The high erodibility of these deposits, once exposed, strongly suggests a continuous glacier cover since their deposition throughout all but the most recent part of the Holocene, including the HCO. This defines the subglacial carbonates as a complex, but an important palaeoenvironmental proxy and a research subject for further analyses with great potential that may further highlight the extraordinary nature of the current global warming in the context of the Holocene.

~~The preliminary data presented here shows a high possibility suggest that subglacial carbonate deposits may endue record unprecedented retreat of the Triglav Glacier in the southeastern Alps, and are thus constitute a potentiallyn important proxy worthy of for further research.~~ Several separate lines of additional evidence ~~are worth studying to~~ could strengthen this assertion~~e hypothesis~~:

A ~~–~~- ~~High resolution U-Th dating targeting primary calcite. Additionally, isolation i~~Identification and geochemical analyses of primary aragonite would contribute ~~the~~ data on primary U concentration in samples (~~in case~~ where there is evidence ~~all the crystals were primarily~~ of primary aragonite), which can be used to ~~observe~~ detect U loss~~ in recrystallised crystals~~. In situ U-series dating by laser-ablation would represent the best approach as the samples (and laminae) are small and the aim is to target different crystal fabrics, but this is challenging due to low U concentrations.

B ~~–~~- ~~u~~Use ^{36}Cl nuclide dating method on the limestone hosting the subglacial carbonate deposits to extract the exposure time of the limestone surfaces ~~where those~~ hosting the carbonate crusts ~~occur~~ (i.e., no glacier cover) and provide additional data as to whether or not those areas have ~~not~~ experienced ~~additional~~ multiple episodes of exposure~~s~~ during the H~~olocene~~ C~~limatic~~ O~~ptimum~~. The production rate at 2500 m a.s.l. (the mean altitude of the upper part of the present Triglav Glacier) is relatively high~~considerably fast~~, which is ~~i~~an advantage for dating young exposures. In addition, calcite and limestone are one of the best mineral/rock systems for ^{36}Cl because they often have low ^{35}Cl abundances, so there is less ~~of~~ uncertainty regarding contributions~~ed~~ ~~to the~~ from factors that affect thermal neutron production of ^{36}Cl, such as water or snow shielding (Fabel and Harbor, 1999; Marrero et al., 2016).

C ~~–~~- The analyses of material on the small remaining ice masses and, if possible, ice cores~~particulates on the present remnants of ice (and possible ice cores, if a glacier has not disappeared completely)~~ can highlight the existence of a present-day input to accelerate melting. For example, black carbon and other mineral dust particles in glaciated regions, which accumulate on the ice, can accelerate the melt of glaciers by reducing ~~the~~ albedo (Ramanathan and Carmichael, 2008; Ming et al., 2013; Painter et al., 2013; Gabbi et al., 2015).~~. Despite various published examples of such additional contributions (e.g.?), small glaciers would be the most affected due to their larger surface-to-volume ratios.~~

D ~~–~~- ~~the n~~Numerical data ~~of~~ on frost weathering. There is a relatively extensive literature concerning the chemical denudation and glacial erosion of the limestone, but scarce numerical data ~~of~~ for frost weathering, and no direct measurements concerning subglacial carbonates. This can be experimentally studied by direct freezing-thawing ~~method~~ experiments with controlled humidity and additional ~~measurements~~ control for ~~of~~ the type of porosity and pressure gradient (Ducman et al., 2011).

~~8 Conclusion~~

~~Three U-Th ages of subglacial carbonate with the combination of aragonite and calcite are regarded as maximum ages as aragonite-to-calcite transformation, evident in fabrics, might have occurred in calcite crystals that could have been falsely considered as primary. Nevertheless, three ages of subglacial carbonate deposits exposed by the retreating Triglav Glacier fall within the Last Glacial Maximum and Younger Dryas, which could be providing the first direct evidence of the Triglav Glacier at that time. The fragility high erodibility of these deposits once exposed strongly suggests the a continuous glacier- cover since their deposition throughout all but the most recent part of the Holocene, including the Holocene cClimatic opOptimum. This defines the subglacial carbonates as a complex, but an important palaeoenvironmental proxy and a research subject for further analyses with great potentials, which that may further highlight the extraordinary nature of the current global warming in the context of the Holocene.~~

Data availability

The live and recent-archive photos of Triglav Glacier observation: http://ktl.zrc-sazu.si/

The climate data are available through the Slovenian Environment Agency web page: https://www.arso.gov.si/en/ and http://meteo.arso.gov.si/met/sl/archive/

Additional Triglav Glacier measurement data are available on the dedicated Slovenian Environment Agency web page: http://kazalci.arso.gov.si/en/content/triglav-glacier

All visual computer data are included in Supplementary files.~~s, raw data will be available on the ZRC SAZU repository after the acceptance of the paper.~~

Author contributions

ML designed the research, led the study, drafted the manuscript and generated figures. AMP performed petrographic analysis, generated the petrographic figures, contributed the writing and editing of the manuscript. JT, MG, MH, BK, MZ contributed the writing and editing of the manuscript. MP contributed the writing and editing of the manuscript and compiled the monitoring data. NZH performed XRD analysis. J-XZ performed U-Th analysis and wrote the U-Th methods section of the manuscript. RND performed stable isotope analysis, edited and reviewed the manuscript. MF contributed the writing and editing of the manuscript, overall editing and internal review.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgement

We thank Kata Cvetko-Barić from the ZRC SAZU Institute of Palaeontology ~~ZRC SAZU~~ for preparation of the geological thin sections, Manca Volk Bahun from the ZRC SAZU Anton Melik Geographical Institute ~~ZRC SAZU~~ for producing the map of the sampling areas~~, and Russell N. Drysdale from the University of Melbourne for performing C and O isotopic analysis~~. We also thank peer-reviewers Renato R. Colucci and Bernard Hallet, and editor Chris R. Stokes for improving the manuscript.

Financial support

The work of ML was supported by the European Regional Development Fund: European Union & Republic of Slovenia, Ministry of Education, Science and Sport (2017-2020; research programme OP20.01261) and, including the work of JT, MG, MH, BK, MZ and MP, by the Slovenian Research Agency research core funding Geography of Slovenia (P6-0101) and Infrastructure Programme (I0-0031). The work of AMP was supported by the Slovenian Research Agency project J1-9185 and research core funding Paleontology and Sedimentary Geology (P1-0008).~~programme P1-0008 (B).~~

References

, !!! INVALID CITATION !!! (Colucci, 2016; Tičar et al., 2018; Tóth and Veress, 2019).

Aharon, P.: Oxygen, carbon and U-series isotopes of aragonites from Vestfold Hills, Antarctica: Clues to geochemical processes in subglacial environments, Geochimica et Cosmochimica Acta, 52, 2321-2331, doi:10.1016/0016-7037(88)90134-2, 1988.

Alley, R. B.: The Younger Dryas cold interval as viewed from central Greenland, Quaternary Science Reviews, 19, 213-226, doi:10.1016/s0277-3791(99)00062-1, 2000.

Antoniades, D., Francus, P., Pienitz, R., St-Onge, G., and Vincent, W. F.: Holocene dynamics of the Arctic's largest ice shelf, Proceedings of the National Academy of Sciences of the United States of America, 108, 18899-18904, doi:10.1073/pnas.1106378108, 2011.

Bahr, D. B. and Radić, V.: Significant contribution to total mass from very small glaciers, The Cryosphere, 6, 763-770, doi:10.5194/tc-6-763-2012, 2012.

Bajo, P., Hellstrom, J., Frisia, S., Drysdale, R., Black, J., Woodhead, J., Borsato, A., Zanchetta, G., Wallace, M. W., Regattieri, E., and Haese, R.: “Cryptic” diagenesis and its implications for speleothem geochronologies, Quaternary Science Reviews, 148, 17-28, doi:10.1016/j.quascirev.2016.06.020, 2016.

Baroni, C. and Orombelli, G.: The Alpine “Iceman” and Holocene Climatic Change, Quaternary Research, 46, 78-83, doi:10.1006/qres.1996.0046, 1996.

Basilyan, A. E., Anisimov, M. A., Nikolskiy, P. A., and Pitulko, V. V.: Wooly mammoth mass accumulation next to the Paleolithic Yana RHS site, Arctic Siberia: its geology, age, and relation to past human activity, Journal of Archaeological Science, 38, 2461-2474, doi:10.1016/j.jas.2011.05.017, 2011.

Bauer, F.: Kalkabtragungsmessungen in den österreichischen Kalkhochalpen, Erdkunde, 18, 95-102, doi:10.3112/erdkunde.1964.02.04, 1964.

Bavec, M. and Verbič, T.: Glacial History of Slovenia. In: Quaternary Glaciations - Extent and Chronology - A Closer Look, Developments in Quaternary Sciences, doi:10.1016/b978-0-444-53447-7.00029-5, 2011.

Benn, D. I. and Evans, D. J. A.: Glaciers & Glaciation (2nd Ed.), Routledge, London, 2010.

Bons, P. D., Elburg, M. A., and Gomez-Rivas, E.: A review of the formation of tectonic veins and their microstructures, Journal of Structural Geology, 43, 33-62, doi:10.1016/j.jsg.2012.07.005, 2012.

Broecker, W. S., Denton, G. H., Edwards, R. L., Cheng, H., Alley, R. B., and Putnam, A. E.: Putting the Younger Dryas cold event into context, Quaternary Science Reviews, 29, 1078-1081, doi:10.1016/j.quascirev.2010.02.019, 2010.

Carey, A. E., Smith, D. F., Welch, S. A., Zorn, M., Tičar, J., Lipar, M., Komac, B., and Lyons, W. B.: The Geochemistry of Ice in the Triglav Area, Slovenia, Acta Geographica Slovenica, 60, doi:10.3986/AGS.7420, 2020.

Clark, I. D. and Lauriol, B.: Kinetic enrichment of stable isotopes in cryogenic calcites, Chemical Geology, 102, 217-228, doi:10.1016/0009-2541(92)90157-z, 1992.

Clayton, R. N. and Jones, B. F.: Isotope studies of dolomite formation under sedimentary conditions, Geochimica et Cosmochimica Acta, 32, 415-432, doi:10.1016/0016-7037(68)90076-8, 1968.

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., Jansson, P., Kaser, G., Möller, M., L., N., and Zemp, M.: Glossary of Glacier Mass Balance and Related Terms, UNESCO-IHP, Paris, 2011.

Colucci, R. R.: Geomorphic influence on small glacier response to post-Little Ice Age climate warming: Julian Alps, Europe, Earth Surface Processes and Landforms, 41, 1227-1240, doi:10.1002/esp.3908, 2016.

Colucci, R. R. and Guglielmin, M.: Precipitation-temperature changes and evolution of a small glacier in the southeastern European Alps during the last 90 years, International Journal of Climatology, 35, 2783-2797, doi:10.1002/joc.4172, 2015.

Colucci, R. R. and Žebre, M.: Late Holocene evolution of glaciers in the southeastern Alps, Journal of Maps, 12, 289-299, doi:10.1080/17445647.2016.1203216, 2016.

Courty, M. A., Marlin, C., Dever, L., Tremblay, P., and Vachier, P.: The properties, genesis and environmental significance of calcitic pendents from the High Arctic (Spitsbergen), Geoderma, 61, 71-102, doi:10.1016/0016-7061(94)90012-4, 1994.

De Choudens-Sánchez, V. and González, L. A.: Calcite and Aragonite Precipitation Under Controlled Instantaneous Supersaturation: Elucidating the Role of CaCO3 Saturation State and Mg/Ca Ratio on Calcium Carbonate Polymorphism, Journal of Sedimentary Research, 79, 363-376, doi:10.2110/jsr.2009.043, 2009.

DeBeer, C. M. and Sharp, M. J.: Topographic influences on recent changes of very small glaciers in the Monashee Mountains, British Columbia, Canada, Journal of Glaciology, 55, 691-700, doi:10.3189/002214309789470851, 2017.

Del Gobbo, C., Colucci, R. R., Forte, E., Triglav Čekada, M., and Zorn, M.: The Triglav Glacier (South-Eastern Alps, Slovenia): Volume Estimation, Internal Characterization and 2000–2013 Temporal Evolution by Means of Ground Penetrating Radar Measurements, Pure and Applied Geophysics, 173, 2753-2766, doi:10.1007/s00024-016-1348-2, 2016.

Dias, L., Rosado, T., Coelho, A., Barrulas, P., Lopes, L., Moita, P., Candeias, A., Mirao, J., and Caldeira, A. T.: Natural limestone discolouration triggered by microbial activity-a contribution, AIMS Microbiol, 4, 594-607, doi:10.3934/microbiol.2018.4.594, 2018.

Drysdale, R. N., Hellstrom, J. C., Zanchetta, G., Fallick, A. E., Sanchez Goni, M. F., Couchoud, I., McDonald, J., Maas, R., Lohmann, G., and Isola, I.: Evidence for obliquity forcing of glacial Termination II, Science, 325, 1527-1531, doi:10.1126/science.1170371, 2009.

Ducman, V., Škapin, A. S., Radeka, M., and Ranogajec, J.: Frost resistance of clay roofing tiles: Case study, Ceramics International, 37, 85-91, doi:10.1016/j.ceramint.2010.08.012, 2011.
Fabel, D. and Harbor, J.: The use of in-situ produced cosmogenic radionuclides in glaciology and glacial geomorphology, Annals of Glaciology, 28, 103-110, doi:10.3189/172756499781821968, 1999.
Fairchild, I. J. and Spiro, B.: Carbonate minerals in glacial sediments: geochemical clues to palaeoenvironment, Geological Society, London, Special Publications, 53, 201-216, doi:10.1144/gsl.Sp.1990.053.01.11, 1990.
Faure, G.: Principles of isotopic geology, John Wiley and Sons, New York, 1977.
Ferk, M., Gabrovec, M., Komac, B., Zorn, M., and Stepišnik, U.: Pleistocene glaciation in Mediterranean Slovenia, Geological Society, London, Special Publications, 433, 179-191, doi:10.1144/sp433.2, 2017.
Fernández-Díaz, L., Putnis, A., Prieto, M., and Putnis, C. V.: The Role of Magnesium in the Crystallization of Calcite and Aragonite in a Porous Medium, Journal of Sedimentary Research, 66, 482-491, doi:10.1306/d4268388-2b26-11d7-8648000102c1865d, 1996.
Ford, D. C., Fuller, P. G., and Drake, J. J.: Calcite precipitates at the soles of temperate glaciers, Nature, 226, 441-442, doi:10.1038/226441a0, 1970.
Frisia, S. and Borsato, A.: Karst. In: Carbonates in Continental Settings: Facies, Environments and Processes. Developments in Sedimentology, Alonso Zarza, A. M. and Tanner, L. H. (Eds.), Elsevier, Amsterdam, doi:10.1016/S0070-4571(09)06106-8, 2010.
Frisia, S., Borsato, A., Fairchild, I. J., McDermott, F., and Selmo, E. M.: Aragonite-Calcite Relationships in Speleothems (Grotte De Clamouse, France): Environment, Fabrics, and Carbonate Geochemistry, Journal of Sedimentary Research, 72, 687-699, doi:10.1306/020702720687, 2002.
Frisia, S., Weyrich, L. S., Hellstrom, J., Borsato, A., Golledge, N. R., Anesio, A. M., Bajo, P., Drysdale, R. N., Augustinus, P. C., Rivard, C., and Cooper, A.: The influence of Antarctic subglacial volcanism on the global iron cycle during the Last Glacial Maximum, Nature Communications, 8, 15425, doi:10.1038/ncomms15425, 2017.
Furlani, S., Cucchi, F., Forti, F., and Rossi, A.: Comparison between coastal and inland Karst limestone lowering rates in the northeastern Adriatic Region (Italy and Croatia), Geomorphology, 104, 73-81, doi:10.1016/j.geomorph.2008.05.015, 2009.
Gabbi, J., Huss, M., Bauder, A., Cao, F., and Schwikowski, M.: The impact of Saharan dust and black carbon on albedo and long-term mass balance of an Alpine glacier, The Cryosphere, 9, 1385-1400, doi:10.5194/tc-9-1385-2015, 2015.
Gabrovec, M., Hrvatin, M., Komac, B., Ortar, J., Pavšek, M., Topole, M., Triglav Čekada, M., and Zorn, M.: Triglavski ledenik [Triglav Glacier], Založba ZRC, Ljubljana, 2014.
Gabrovšek, F.: On concepts and methods for the estimation of dissolutional denudation rates in karst areas, Geomorphology, 106, 9-14, doi:10.1016/j.geomorph.2008.09.008, 2009.
Gądek, B. and Kotyrba, A.: Struktura wewnętrzna Lodowczyka Mięguszowieckiego (Tatry) w świetle wyników badań georadarowych (Internal structure of Mięguszowiecki Glacieret (Tatra Mountains, southern Poland) in the light of results of georadar investigations), Przegląd Geologiczny, 51, 1044–1047, 2003.
Gams, I.: Kras v Sloveniji - v prostoru in času [Karst in Slovenia - in Space and Time], Založba ZRC, Ljubljana, 2004.
Gilbert, A., Flowers, G. E., Miller, G. H., Refsnider, K. A., Young, N. E., and Radić, V.: The projected demise of Barnes Ice Cap: Evidence of an unusually warm 21st century Arctic, Geophysical Research Letters, 44, 2810-2816, doi:10.1002/2016gl072394, 2017.
Grove, J. M.: Little Ice Ages: Anciend and Modern, 2nd edn., Routledge, London, 2004.
Grunewald, K. and Scheithauer, J.: Europe's southernmost glaciers: response and adaptation to climate change, Journal of Glaciology, 56, 129-142, doi:10.3189/002214310791190947, 2010.
Hallet, B.: Deposits formed by subglacial precipitation of CaCO3, Geological Society of America Bulletin, 87, 1003, doi:10.1130/0016-7606(1976)87<1003:dfbspo>2.0.co;2, 1976.
Hanshaw, B. B. and Hallet, B.: Oxygen isotope composition of subglacially precipitated calcite: possible paleoclimatic implications, Science, 200, 1267-1270, doi:10.1126/science.200.4347.1267, 1978.
Hormes, A., Müller, B. U., and Schlüchter, C.: The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps, The Holocene, 11, 255-265, doi:10.1191/095968301675275728, 2001.
Hrvatin, M., Komac, B., and Zorn, M.: Geomorfološke značilnosti okolice Triglava [Geomorphological characteristics around Mt. Triglav]. Elaborate, Anton Melik Geographical Institute ZRC SAZU, Ljubljana, 2005.
Hrvatin, M. and Zorn, M.: Climate and hydrological changes in Slovenia's mountain regions between 1961 and 2018, Economic- and ecohistory, 16, in press.
IPCC: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. , 2018.
Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W., and Schlüchter, C.: Latest Pleistocene and Holocene glacier variations in the European Alps, Quaternary Science Reviews, 28, 2137-2149, doi:10.1016/j.quascirev.2009.03.009, 2009.

Jones, B.: Review of calcium carbonate polymorph precipitation in spring systems, Sedimentary Geology, 353, 64-75, doi:10.1016/j.sedgeo.2017.03.006, 2017.

Jouzel, J. and Souchez, R. A.: Melting–Refreezing at the Glacier Sole and the Isotopic Composition of the Ice, Journal of Glaciology, 28, 35-42, doi:10.3189/s0022143000011771, 1982.

Jurovšek, B.: General Geological Map SFRJ 1:100,000, Villach section, National Geological Survey, Belgrade, 1987.

Kim, S.-T., O'Neil, J. R., Hillaire-Marcel, C., and Mucci, A.: Oxygen isotope fractionation between synthetic aragonite and water: Influence of temperature and Mg2+ concentration, Geochimica et Cosmochimica Acta, 71, 4704-4715, doi:10.1016/j.gca.2007.04.019, 2007.

Kirkbride, M. P. and Winkler, S.: Correlation of Late Quaternary moraines: impact of climate variability, glacier response, and chronological resolution, Quaternary Science Reviews, 46, 1-29, doi:10.1016/j.quascirev.2012.04.002, 2012.

Koerner, R. M. and Fisher, D. A.: Ice-core evidence for widespread Arctic glacier retreat in the Last Interglacial and the early Holocene, Annals of Glaciology, 35, 19-24, doi:10.3189/172756402781817338, 2002.

Komac, B., Pavšek, M., and Topole, M.: Climate and Weather of Slovenia. In: The Geography of Slovenia, Perko, D., Ciglič, R., and Zorn, M. (Eds.), Springer, Ljubljana, doi:10.1007/978-3-030-14066-3_5, 2020.

Krklec, K., Domínguez-Villar, D., Carrasco, R. M., and Pedraza, J.: Current denudation rates in dolostone karst from central Spain: Implications for the formation of unroofed caves, Geomorphology, 264, 1-11, doi:10.1016/j.geomorph.2016.04.007, 2016.

Kuhlemann, J., Rohling, E. J., Krumrei, I., Kubik, P., Ivy-Ochs, S., and Kucera, M.: Regional synthesis of Mediterranean atmospheric circulation during the Last Glacial Maximum, Science, 321, 1338-1340, doi:10.1126/science.1157638, 2008.

Kumar, R.: Glacieret. In: Encyclopedia of Snow, Ice and Glaciers, Singh, V. P., Singh, P., and Haritashya, U. K. (Eds.), Encyclopedia of Earth Sciences Series, Springer Netherlands, doi:10.1007/978-90-481-2642-2_203, 2011.

Kunaver, J.: Intenzivnost zakrasevanja in njegovi učinki v Zahodnih Julijskih Alpah – Kaninsko pogorje [The intensity of karst denudation in the Western Julian Alps and the measruing of it], Geografski Vestnik, 50, 33-50, 1978.

Lacelle, D.: Environmental setting, (micro)morphologies and stable C–O isotope composition of cold climate carbonate precipitates—a review and evaluation of their potential as paleoclimatic proxies, Quaternary Science Reviews, 26, 1670-1689, doi:10.1016/j.quascirev.2007.03.011, 2007.

Lachniet, M. S., Bernal, J. P., Asmerom, Y., and Polyak, V.: Uranium loss and aragonite–calcite age discordance in a calcitized aragonite stalagmite, Quaternary Geochronology, 14, 26-37, doi:10.1016/j.quageo.2012.08.003, 2012.

Leemann, A. and Niessen, F.: Holocene glacial activity and climatic variations in the Swiss Alps: reconstructing a continuous record from proglacial lake sediments, The Holocene, 4, 259-268, doi:10.1177/095968369400400305, 1994.

Lemmens, M., Lorrain, R., and Haren, J.: Isotopic composition of ice and subglacially precipitated calcite in an Alpine area, Zeitschrift für Gletscherkunde und Glazialgeologie, 18, 151-159, 1982.

Lyons, W. B., Foley, K. K., Carey, A. E., Diaz, M. A., Bowen, G. J., and Cerling, T.: The Isotopic Geochemistry of $CaCO_3$ Encrustations in Taylor Valley, Antarctica: Implications for Their Origin, Acta Geographica Slovenica, 60, doi:10.3986/AGS.7233, 2020.

Marrero, S. M., Phillips, F. M., Caffee, M. W., and Gosse, J. C.: CRONUS-Earth cosmogenic 36Cl calibration, Quaternary Geochronology, 31, 199-219, doi:10.1016/j.quageo.2015.10.002, 2016.

Martín-García, R., Alonso-Zarza, A. M., Frisia, S., Rodríguez-Berriguete, Á., Drysdale, R., and Hellstrom, J.: Effect of aragonite to calcite transformation on the geochemistry and dating accuracy of speleothems. An example from Castañar Cave, Spain, Sedimentary Geology, 383, 41-54, doi:10.1016/j.sedgeo.2019.01.014, 2019.

Matsuoka, N. and Murton, J.: Frost weathering: recent advances and future directions, Permafrost and Periglacial Processes, 19, 195-210, doi:10.1002/ppp.620, 2008.

Meze, D.: The Triglav and Skuta glaciers, Acta Geographica, 3, 10-114, 1955.

Miller, G. H., Lehman, S. J., Refsnider, K. A., Southon, J. R., and Zhong, Y.: Unprecedented recent summer warmth in Arctic Canada, Geophysical Research Letters, 40, 5745-5751, doi:10.1002/2013gl057188, 2013.

Ming, J., Xiao, C., Du, Z., and Yang, X.: An overview of black carbon deposition in High Asia glaciers and its impacts on radiation balance, Advances in Water Resources, 55, 80-87, doi:10.1016/j.advwatres.2012.05.015, 2013.

Mol, D., Coppens, Y., Tikhonov, A. N., Agenbroad, L. D., MacPhee, R. D. E., Flemming, C., Greenwood, A., Buigues, B., de Marliave, C., van Geel, B., van Reenen, G. B. A., Pals, J. P., Fisher, D. C., and Fox, D.: The Jarkov Mammoth: 20,000-Year-Old carcass of a Siberian woolly mammoth Mammuthus primigenius, 2001, 305-309, 2001.

Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., and Piccin, A.: The Alpine LGM in the boreal ice-sheets game, Nature Scientific Reports, 7, 2078, doi:10.1038/s41598-017-02148-7, 2017.

Nussbaumer, S. U., Steinhilber, F., Trachsel, M., Breitenmoser, P., Beer, J., Blass, A., Grosjean, M., Hafner, A., Holzhauser, H., Wanner, H., and Zumbühl, H. J.: Alpine climate during the Holocene: a comparison between records of glaciers, lake sediments and solar activity, Journal of Quaternary Science, 26, 703-713, doi:10.1002/jqs.1495, 2011.

Ortega, R., Maire, R., Devès, G., and Quinif, Y.: High-resolution mapping of uranium and other trace elements in recrystallized aragonite–calcite speleothems from caves in the Pyrenees (France): Implication for U-series dating, Earth and Planetary Science Letters, 237, 911-923, doi:10.1016/j.epsl.2005.06.045, 2005.

Painter, T. H., Flanner, M. G., Kaser, G., Marzeion, B., VanCuren, R. A., and Abdalati, W.: End of the Little Ice Age in the Alps forced by industrial black carbon, PNAS, 110, 15216-15221, doi:10.1073/pnas.1302570110, 2013.

Peterson, J. A. and Moresby, J. F.: Subglacial travertine and associated deposits in the Carstensz area, Irian Jaya, Republic of Indonesia, Zeitschrift fur Gletscherkunde und Glazialgeologie, 15, 23-29, 1979.

Plan, L.: Factors controlling carbonate dissolution rates quantified in a field test in the Austrian alps, Geomorphology, 68, 201-212, doi:10.1016/j.geomorph.2004.11.014, 2005.

Pleničar, M., Ogorelec, B., and Novak, M.: Geologija Slovenije [The Geology of Slovenia], Geološki zavod Slovenije, Ljubljana, 2009.

Ramanathan, V. and Carmichael, G.: Global and regional climate changes due to black carbon, Nature Geoscience, 1, 221-227, doi:10.1038/ngeo156, 2008.

Ramovš, A.: O Zlatenski plošči sensu Kossmat, 1913, Slatenskem pokrovu sensu Buser, 1986, Slatenskem narivu sensu Jurkovšek, 1987 in Triglavskem pokrovu sensu Ramovš, 1985 [About the Zlatna (Kossmat 1913), Slatna (Buser 1986; Jurkovšek 1987) or the Triglav Thrust (Ramovš 1985)], Geologija, 43, 109-113, doi:10.5474/geologija.2000.010, 2000.

Refsnider, K. A., Miller, G. H., Hillaire-Marcel, C., Fogel, M. L., Ghaleb, B., and Bowden, R.: Subglacial carbonates constrain basal conditions and oxygen isotopic composition of the Laurentide Ice Sheet over Arctic Canada, Geology, 40, 135-138, doi:10.1130/g32335.1, 2012.

Renssen, H. and Isarin, R. F. B.: Surface temperature in NW Europe during the Younger Dryas: AGCM simulation compared with temperature reconstructions, Climate Dynamics, 14, 33-44, doi:10.1007/s003820050206, 1997.

Renssen, H., Seppä, H., Heiri, O., Roche, D. M., Goosse, H., and Fichefet, T.: The spatial and temporal complexity of the Holocene thermal maximum, Nature Geoscience, 2, 411-414, doi:10.1038/ngeo513, 2009.

Risheng, L., Jun, C., Gengnian, L., and Zhijiu, C.: Characteristics of the subglacially-formed debris-rich chemical deposits and related subglacial processes of Qiangyong Glacier, Tibet, Journal of Geographical Sciences, 13, 455-462, doi:10.1007/bf02837884, 2003.

Rossi, C. and Lozano, R. P.: Hydrochemical controls on aragonite versus calcite precipitation in cave dripwaters, Geochimica et Cosmochimica Acta, 192, 70-96, doi:10.1016/j.gca.2016.07.021, 2016.

Scholz, D. and Hoffmann, D.: ^{230}Th/U-dating of fossil corals and speleothems, E&G Quaternary Science Journal, 57, 52-76, doi:10.3285/eg.57.1-2.3, 2008.

Seguinot, J., Ivy-Ochs, S., Jouvet, G., Huss, M., Funk, M., and Preusser, F.: Modelling last glacial cycle ice dynamics in the Alps, The Cryosphere, 12, 3265-3285, doi:10.5194/tc-12-3265-2018, 2018.

Serrano, E., González-trueba, J. J., Sanjosé, J. J., and Del río, L. M.: Ice patch origin, evolution and dynamics in a temperate high mountain environment: the Jopicou Negro, Picos de Europa (NW Spain), Geografiska Annaler: Series A, Physical Geography, 93, 57-70, doi:10.1111/j.1468-0459.2011.00006.x, 2011.

Sharp, M., Tison, J.-L., and Fierens, G.: Geochemistry of Subglacial Calcites: Implications for the Hydrology of the Basal Water Film, Arctic and Alpine Research, 22, 141-152, doi:10.1080/00040851.1990.12002776, 1990.

Sharpe, D. R. and Shaw, J.: Erosion of bedrock by subglacial meltwater, Cantley, Quebec, Geological Society of America Bulletin, 101, 1011-1020, doi:10.1130/0016-7606(1989)101<1011:Eobbsm>2.3.Co;2, 1989.

Šifrer, M.: The main findings concerning the Triglav Glacier in the years (1963—1973) Acta Geographica, 15, 213-240, 1976.

Šifrer, M.: New findings about the glaciation of Triglav - the Triglav glacier during the last 8 years (1954-1962), Acta Geographica, 8, 157-210, 1963.

Šifrer, M.: The Triglav Glacier in the years 1974-1985, Acta Geographica, 26, 97-137, 1987.

Slovenian Environment Agency: Kredarica Climate Diagram, 2020.

Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., Nesje, A., Owen, L. A., Wanner, H., Wiles, G. C., and Young, N. E.: Holocene glacier fluctuations, Quaternary Science Reviews, 111, 9-34, doi:10.1016/j.quascirev.2014.11.018, 2015.

Souchez, R. A. and Lemmens, M.: Subglacial carbonate deposition: An isotopic study of a present-day case, Palaeogeography, Palaeoclimatology, Palaeoecology, 51, 357-364, doi:10.1016/0031-0182(85)90093-8, 1985.

Steinemann, O., Ivy-Ochs, S., Grazioli, S., Luetscher, M., Fischer, U. H., Vockenhuber, C., and Synal, H. A.: Quantifying glacial erosion on a limestone bed and the relevance for landscape development in the Alps, Earth Surface Processes and Landforms, 45, 1401-1417, doi:10.1002/esp.4812, 2020.

Sugden, D. E. and John, B. S.: Glaciers and landscape: a geomorphological approach., Arnold, London, 1976.

Sweeting, M. M.: Some factors in the absolute denudation of limestone terrains, Erdkunde, 18, 92-95, 1964.

Thomazo, C., Buoncristiani, J.-F., Vennin, E., Pellenard, P., Cocquerez, T., Mugnier, J. L., and Gérard, E.: Geochemical Processes Leading to the Precipitation of Subglacial Carbonate Crusts at Bossons Glacier, Mont Blanc Massif (French Alps), Frontiers in Earth Science, 5, doi:10.3389/feart.2017.00070, 2017.

Tičar, J., Lipar, M., Zorn, M., and Kozamernik, E.: Triglavsko podzemlje [The underground world of Triglav Plateau]. In: Triglav 240, Zorn, M., Mikša, P., Lačen Benedičič, I., Ogrin, M., and Kunstelj, A. M. (Eds.), Založba ZRC, Ljubljana, doi:10.3986/9789610500841, 2018.

Tóth, G. and Veress, M.: Examination of karren surfaces in the foreland of the glacier below Triglav. In: Glaciokarsts, Veress, M., Telbisz, T., Tóth, G., Lóczy, D., Ruban, D. A., and Gutak, J. M. (Eds.), Springer, Cham, Switzerland, doi:10.1007/978-3-319-97292-3_8, 2019.

Triglav-Čekada, M., Barbo, P., Pavšek, M., and Zorn, M.: Monitoring the Skuta Glacier (SE Alps) using non-metric images, Acta Geographica Slovenica, 60, doi:10.3986/AGS.7674, 2020.

Triglav-Čekada, M. and Gabrovec, M.: Documentation of Triglav glacier, Slovenia, using non-metric panoramic images, Annals of Glaciology, 54, 80-86, doi:10.3189/2013AoG62A095, 2013.

Triglav-Čekada, M., Radovan, D., Gabrovec, M., and Kosmatin-Fras, M.: Acquisition of the 3D boundary of the Triglav glacier from archived non-metric panoramic images, The Photogrammetric Record, 26, 111-129, doi:10.1111/j.1477-9730.2011.00622.x, 2011.

Triglav-Čekada, M. and Zorn, M.: Thickness and geodetic mass balance changes of the Triglav Glacier (SE Alps) in the period 1952–2016, Acta Geographica Slovenica, 60, doi:10.3986/AGS.7673, 2020.

Triglav Čekada, M. and Gabrovec, M.: Zgodovina geodetskih meritev na Triglavskem ledeniku [The History of Geodetic Surveys on Triglav Glacier], Geodetski Vestnik, 52, 508-519, 2008.

Verbič, T. and Gabrovec, M.: Georadarske meritve na Triglavskem ledeniku [The ground-penetrating-radar measurements of the Triglav Glacier], Geografski Vestnik, 74, 25-42, 2002.

Wassenburg, J. A., Immenhauser, A., Richter, D. K., Jochum, K. P., Fietzke, J., Deininger, M., Goos, M., Scholz, D., and Sabaoui, A.: Climate and cave control on Pleistocene/Holocene calcite-to-aragonite transitions in speleothems from Morocco: Elemental and isotopic evidence, Geochimica et Cosmochimica Acta, 92, 23-47, doi:10.1016/j.gca.2012.06.002, 2012.

Figure 1: Mount Triglav, the Triglav Glacier and the sampling location of subglacial carbonates relative to the years 1932 (A; arrows) and 2017 (B; dots). Close up of ~~an~~ the exposure of subglacial carbonate (C); arrows point to fluted subglacial carbonate,

attached to the lee side of the Upper Triassic limestone. Note the colour-change between the bedrock surfaces: greys (longer exposure) versus beige & brown on the recently exposed surfaces. This has often been explained by microbial activity (Dias et al., 2018). Photo courtesy of (A) Janko Skerlep (© ZRC SAZU Anton Melik Geographical Institute archive), (B) Miha Pavšek and (C) Matej Lipar.

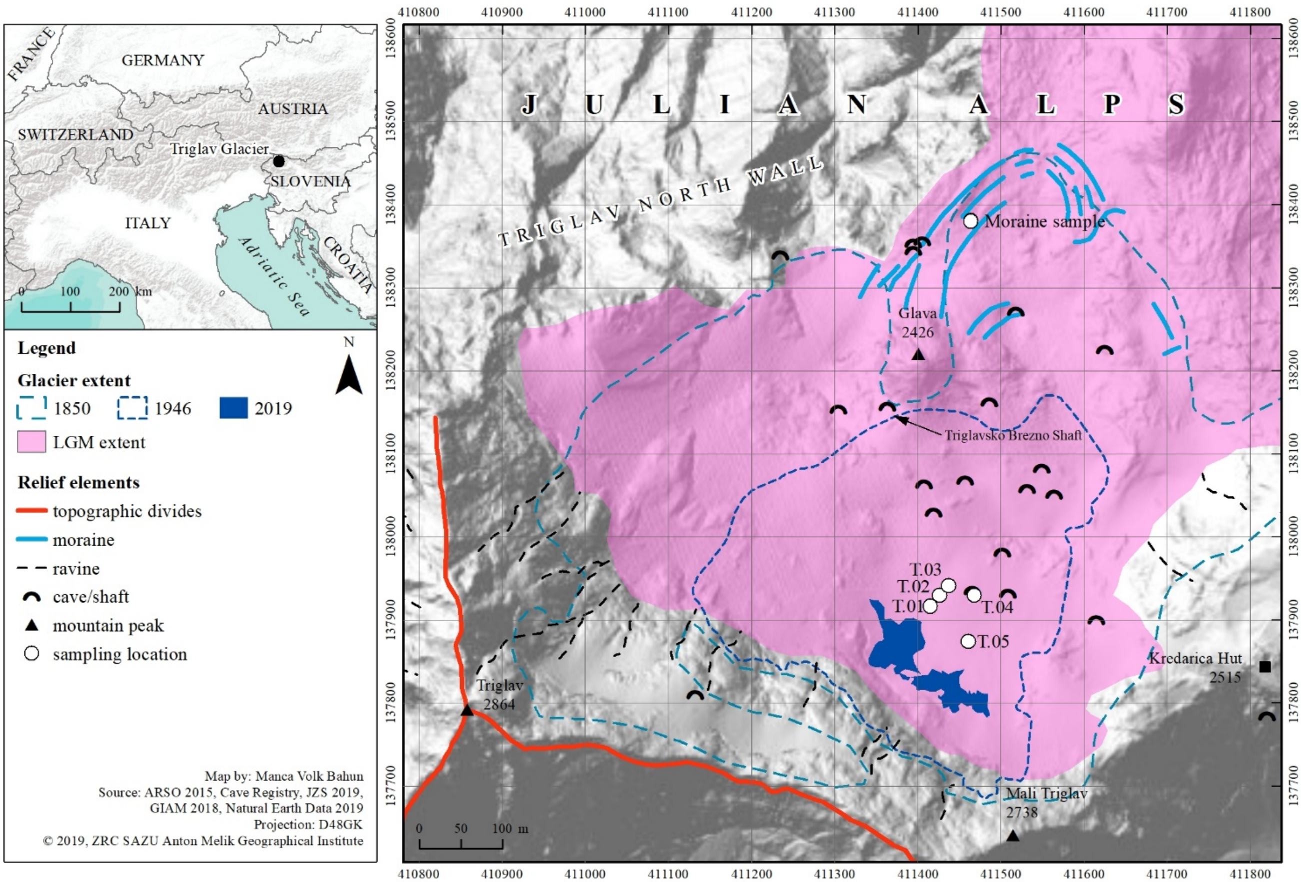
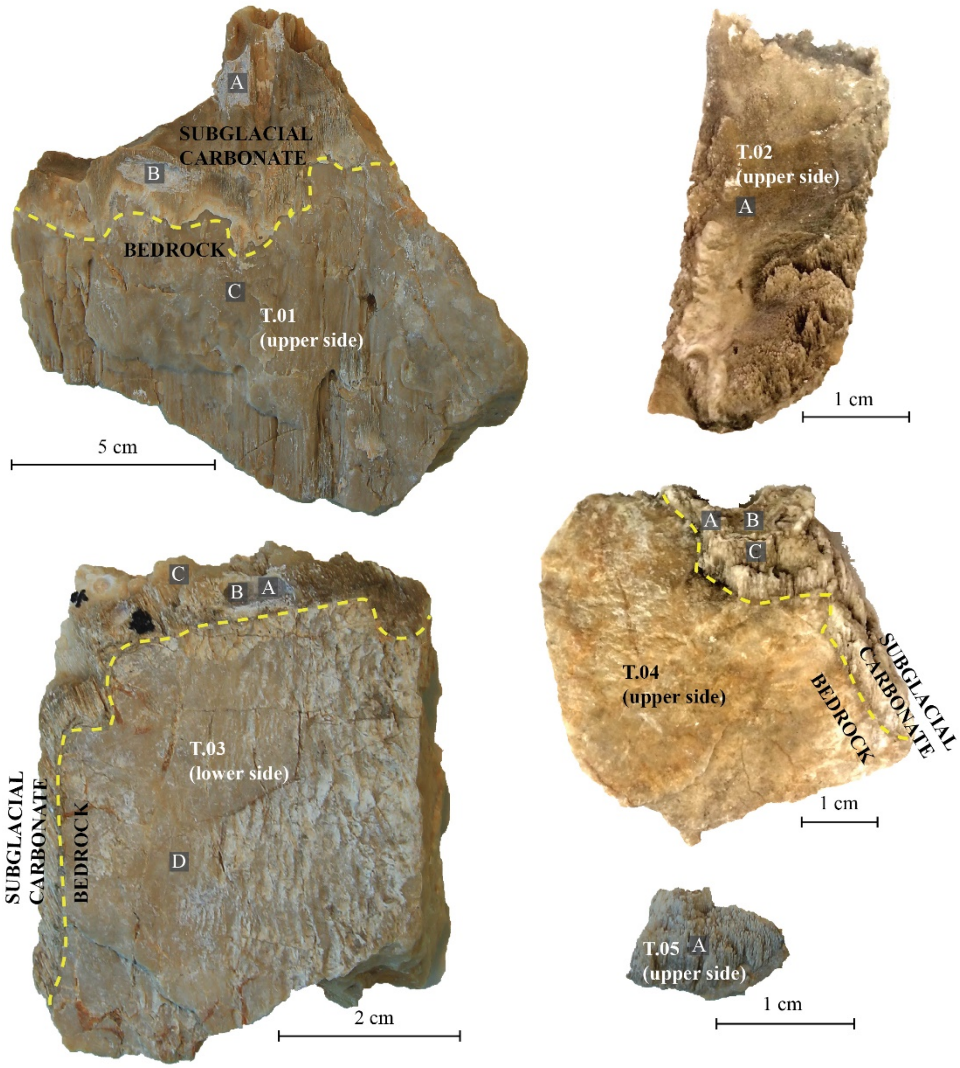


Figure 2: Locality map of the Triglav Glacier, the sampling sites discussed in the text, and general geomorphology.



Sample	Bedrock / subglacial carbonate	XRD mineralogy	δ^{13}C (‰ PDB)	δ^{18}O (‰ PDB)	U-Th ages (ka)
T.01 A	subglacial carbonate	calcite	2.41	-2.84	18.45
T.01 B	subglacial carbonate	calcite, aragonite			
T.01 C	bedrock	calcite			
T.02 A	subglacial carbonate	calcite			
T.03 A	subglacial carbonate	calcite, aragonite	1.35	-4.71	12.72
T.03 B	subglacial carbonate	calcite, aragonite	0.51	-5.45	3.85
T.03 C	subglacial carbonate	calcite			1.96
T.03 D	bedrock	calcite			
T.04 A	subglacial carbonate	calcite	1.50	-3.96	
T.04 B	subglacial carbonate	calcite, aragonite			
T.04 C	subglacial carbonate	calcite			
T.05 A	subglacial carbonate	calcite	0.98	-4.63	23.62
Average			1.35	-4.32	

Figure 3: Subglacial carbonate samples used for this study. Upper and lower sides refer to the surface (facing open air before being collected) and underside of the carbonate samples, respectively. The depths were measured relative to the starting drilling point of each sample as they are shown in this figure (lower side perspective for sample T.03 and upper side perspective for all the other samples); only the T.03 sample had precipitates thick enough that allowed to obtain several dates in three different depths.

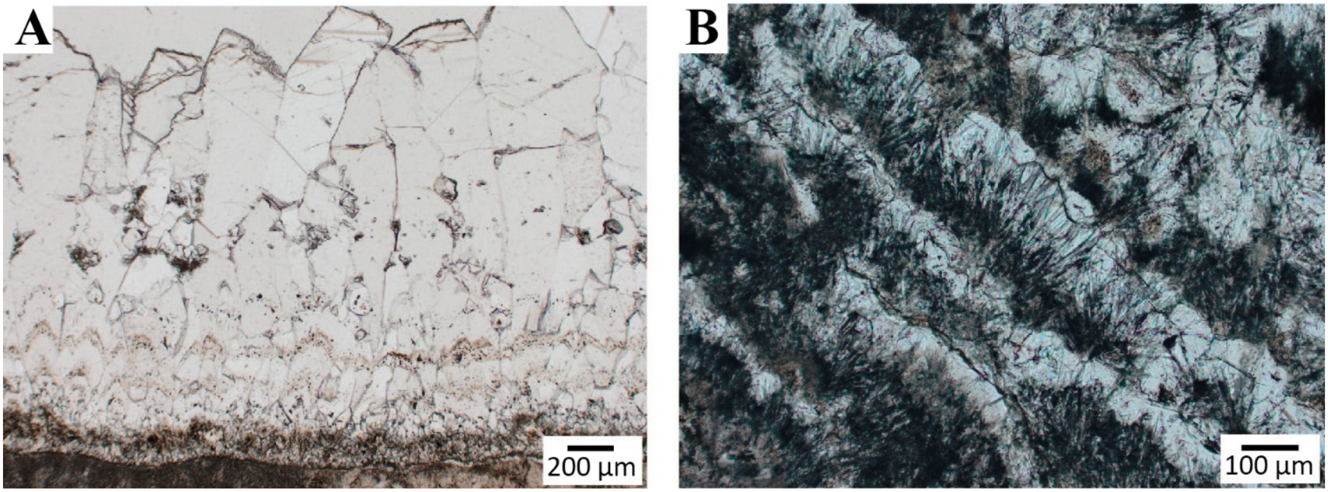


Figure 4: Petrography of the carbonate crusts. a) Primary columnar calcite crystals growing perpendicularly to the substrate on the ~~lee~~ steeper side of the bedrock irregularity.; b) alternation of aragonite (fibrous) and calcite crystals forming layered textures. The base of the aragonite fans of crystals nucleates in dark micritic aggregates. Both images were taken under plane polarised light.

~~Table 1: $\delta^{13}C$ and $\delta^{18}O$ stable isotope ratios.~~

Surface denudation in karst areas (mm/a)			
Location / Source	**From**	**To**	**Precipitation (mm)**
Dachstein, Austria, 1700 – 1800 m a.s.l. (Bauer, 1964)	0.015	0.020	1500
Malham area, NW England, 400 – 500 m a.s.l. (Sweeting, 1964)	0.040	/	1500
Western Julian Alps, 2000 – 2100 m a.s.l. (Kunaver, 1978)	0.094	/	3500
Average for Slovenia, 0 – 2864 m a.s.l. (Gams, 2004)	0.020	0.100	< 900 – > 3200
Northern Calcareous Alps, Austria, 1500 – 2277 m a.s.l. (Plan, 2005)	0.011	0.048	1377
Classical Karst area and Istrian Karst, 0 – 440 m a.s.l. (Furlani et al., 2009)	0.009	0.140	1015 - 1341
Tietar Valley, central Spain, 427 m a.s. l. (Krklec et al., 2016)	0.018	0.025	797
			Average (rounded)
Min	0.009	0.020	**0.01**
Avg	0.0296	0.0666	**0.05**
Max	0.094	0.140	**0.1**

Calculation of subglacial carbonate ~~existance~~existence

Thickness (mm)	Existence - max (years)	Existence - avg (years)	Existence - min (years)
0.1	10	2	1
0.2	20	4	2

0.3	30	6	3			
0.4	40	8	4			
0.5	50	10	5			
1	100	20	10			
1.5	150	30	15			
2	200	40	20			
2.5	250	50	25			
3	300	60	30			
4	400	80	40			
5	500	100	50			

Table ~~1~~21: Calculation of subglacial carbonate existence under meteoric environment based on its thickness, years of exposure and denudation rate.

Subglacial carbonate deposits as a potential proxy for a glacier's former ~~existence~~presence

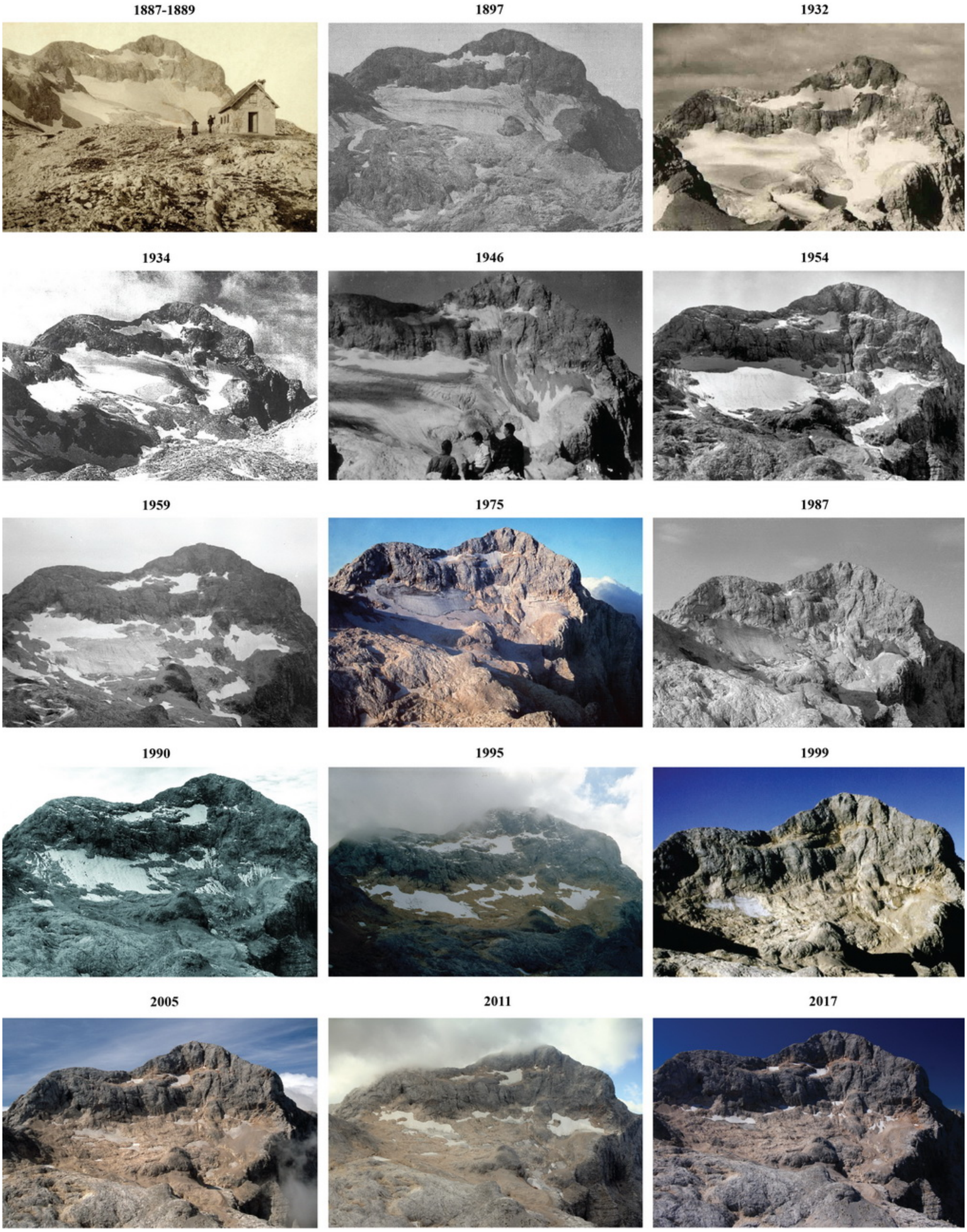
Authors: Matej Lipar[1]*, Andrea Martín-Pérez[2], Jure Tičar[1], Miha Pavšek[1], Matej Gabrovec[1], Mauro Hrvatin[1], Blaž Komac[1], Matija Zorn[1], Nadja Zupan Hajna[3], Jian-Xin Zhao[4], Russell N. Drysdale[5,6], Mateja Ferk[1]

[1]Anton Melik Geographical Institute, Research Centre of the Slovenian Academy of Sciences and Arts, Ljubljana, 1000, Slovenia
[2]Ivan Rakovec Institute of Palaeontology, Research Centre of the Slovenian Academy of Sciences and Arts, Ljubljana, 1000, Slovenia
[3]Karst Research Institute, Research Centre of the Slovenian Academy of Sciences and Arts, Postojna, 6230, Slovenia
[4]School of Earth and Environmental Sciences, The University of Queensland, Brisbane, QLD 4072, Australia
[5]School of Geography, The University of Melbourne, Melbourne, VIC 3053, Australia
[6]EDYTEM, UMR CNRS 5204, Université de Savoie-Mont Blanc, 73376 Le Bourget Du Lac-Cedex, France

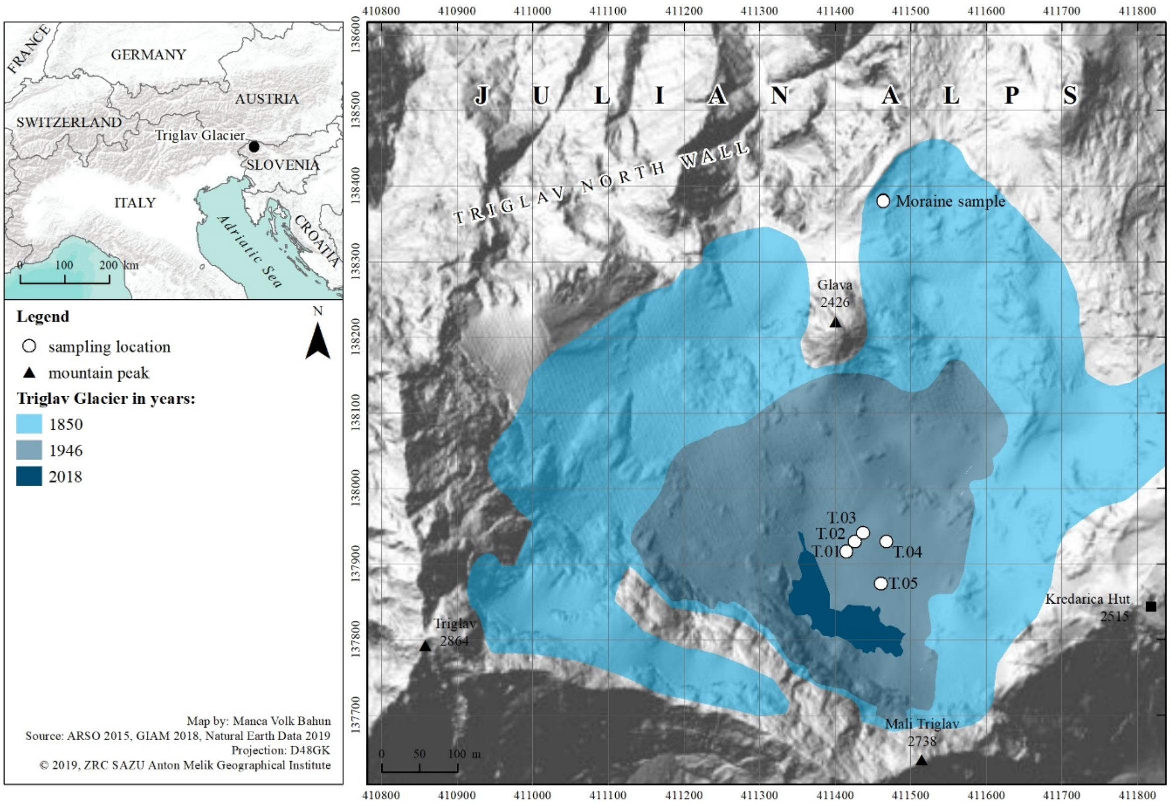
Correspondence to: Matej Lipar (matej.lipar@zrc-sazu.si)

Supplementary Information

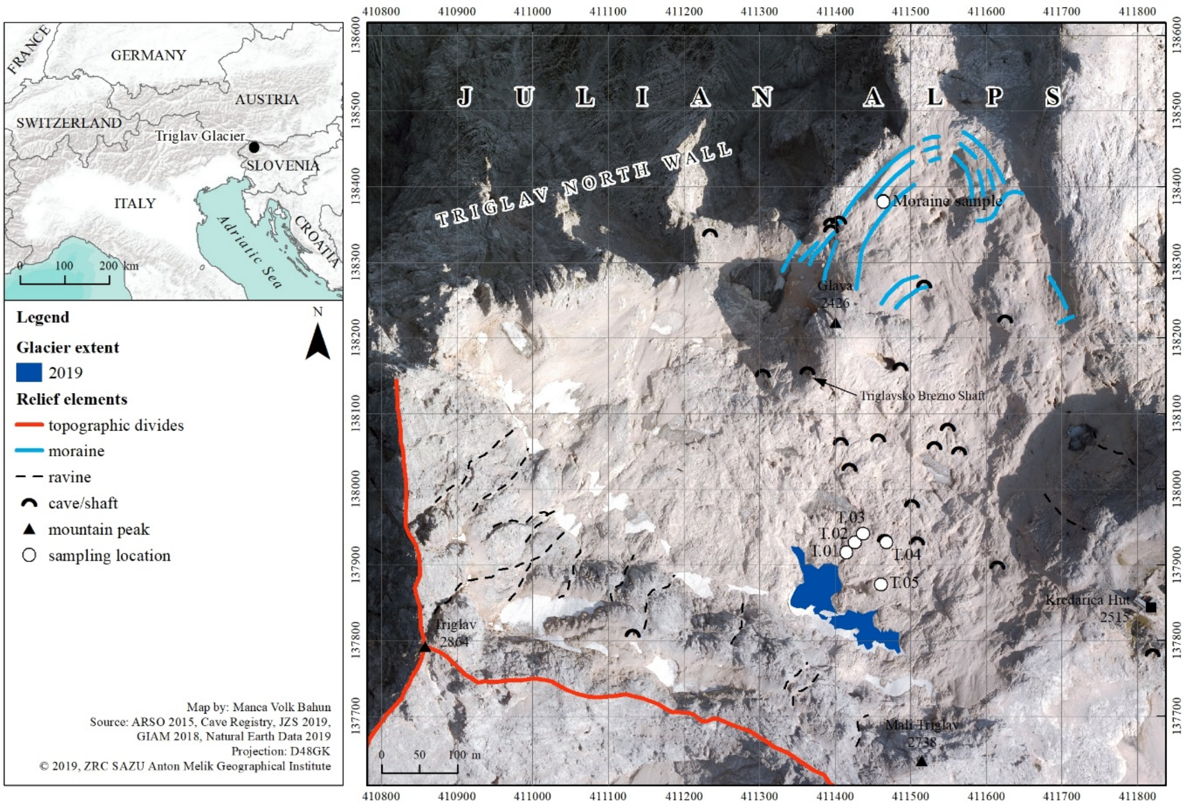
Supplementary Figure S1: Photographic material of the retreating Triglav Glacier (© ZRC SAZU Anton Melik Geographical Institute archive).



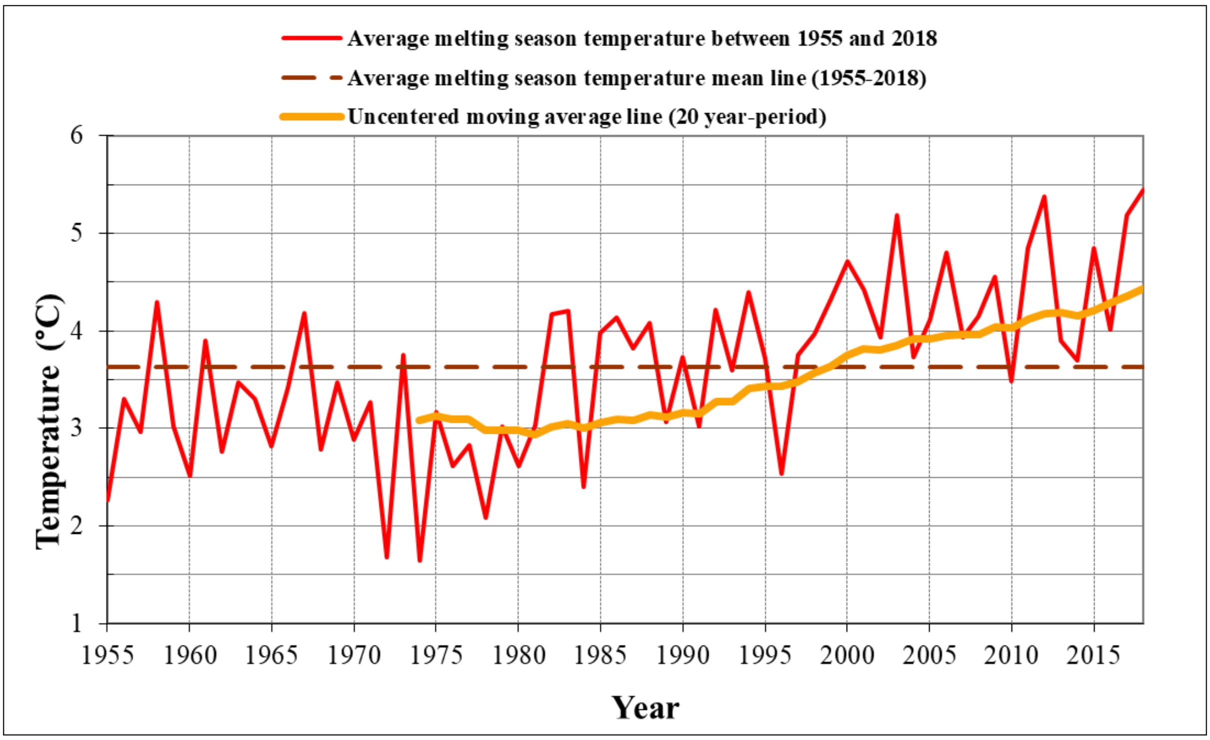
~~Supplementary Figure S2: Locality LiDAR DTM map of the Triglav Glacier extent and the sampling sites discussed in the text.~~



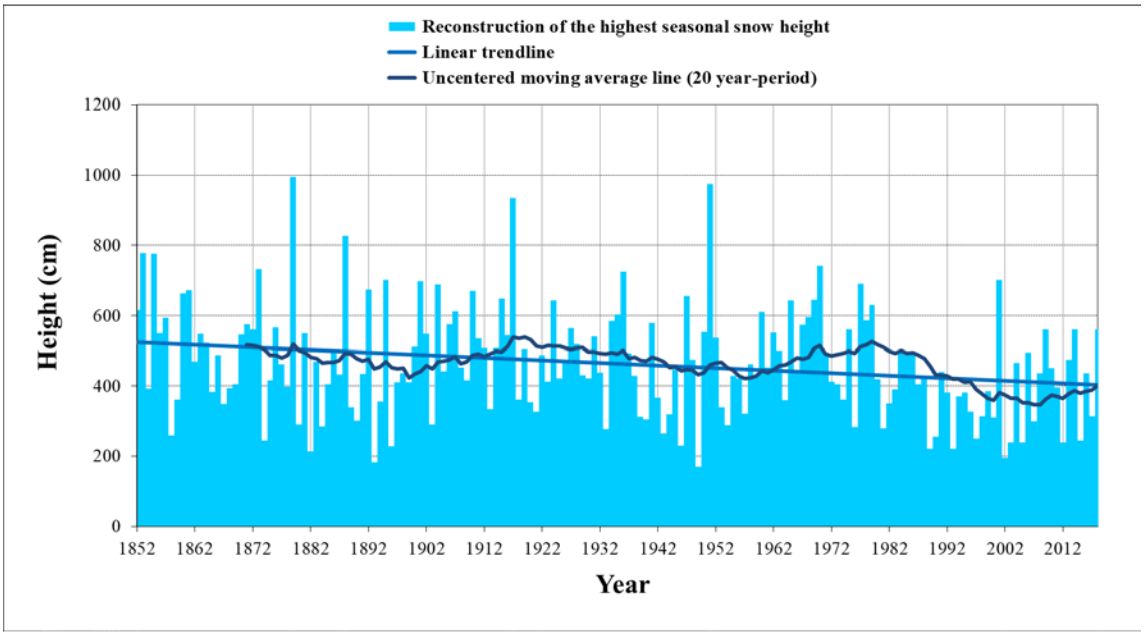
Supplementary Figure S2~~3~~: Locality aerial map of the Triglav Glacier, the sampling sites discussed in the text, and general geomorphology.



Supplementary Figure S~~4~~3: Average ~~melting~~ ablation season temperature (May – October) on meteorological station Kredarica (Fig. 1) between 1955 and 2018. Data ~~Source~~source: Slovenian Environment Agency.

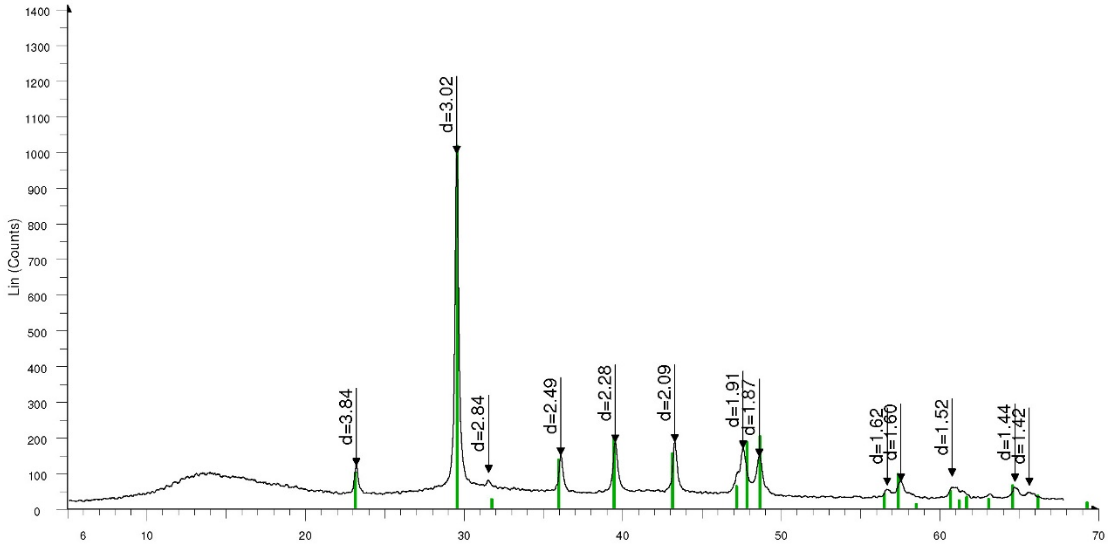


Supplementary Figure S~~5~~4: Reconstruction of the highest seasonal snow height on the edge of the Triglav Glacier between 1852 and 2018~~. U~~ updated from Gabrovec et al. (2014) ~~(Gabrovec et al. 2014(Gabrovec et al., 2014). S~~source: Slovenian Environment Agency (from 1955 on), reconstruction/reanalysis before 1955 done by Jaka Ortar).



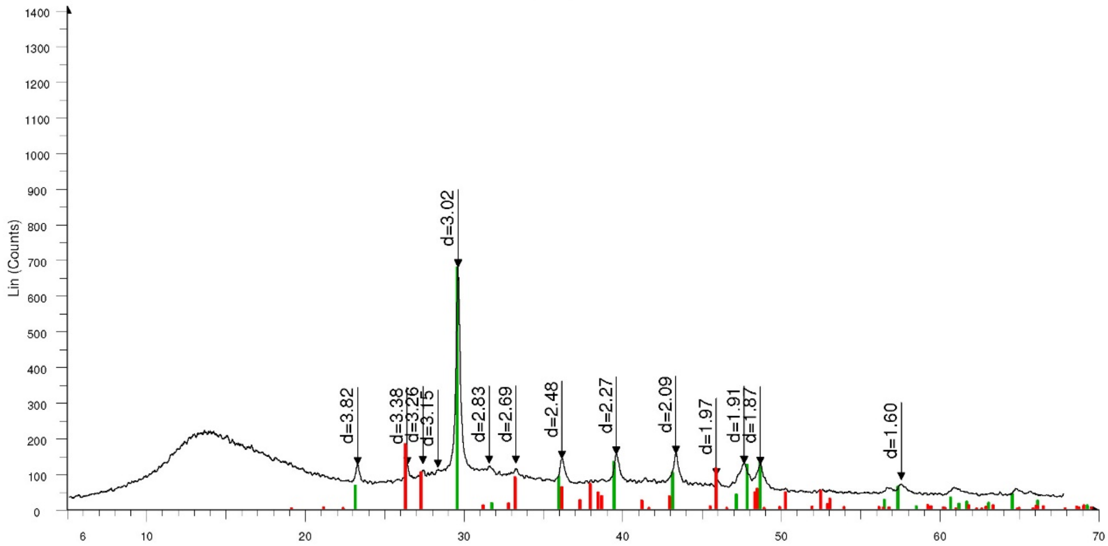
Supplementary Figure S~~6~~5: XRD diagrams of all the studied samples (for precise location, see Figure 3 in the main manuscript). Samples TRG-01 C and TRG-03 D correspond to the bed rock. Green lines mark the reflections corresponding to calcite, and red lines mark the reflections of those corresponding to aragonite.~~XRD graphs~~

TRG-01 A



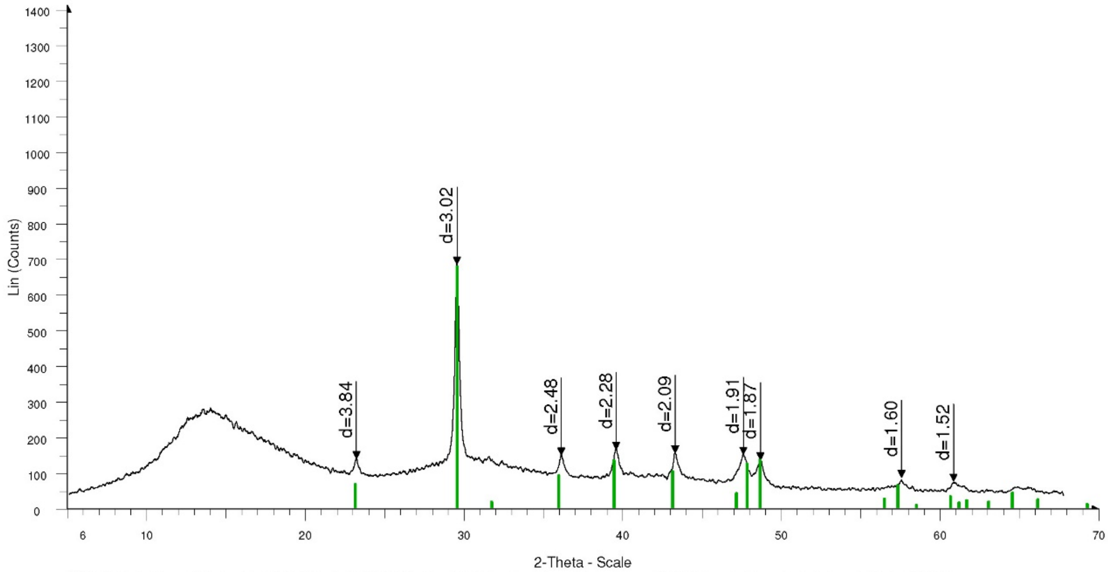
TRG-01 A - Type: 2Theta - Start: 5.002 ° - End: 67.859 ° - Step: 0.010 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-072-1650 (C) - Calcite

TRG-01 B



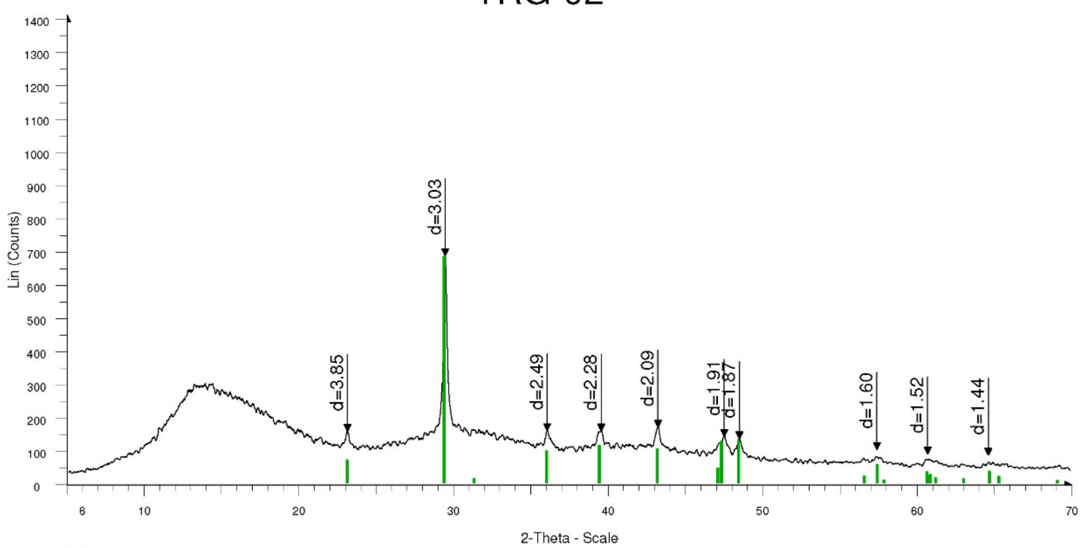
TRG-01 B - Type: 2Theta - Start: 5.002 ° - End: 67.859 ° - Step: 0.010 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-076-0606 (C) - Aragonite
01-072-1650 (C) - Calcite

TRG-01 C



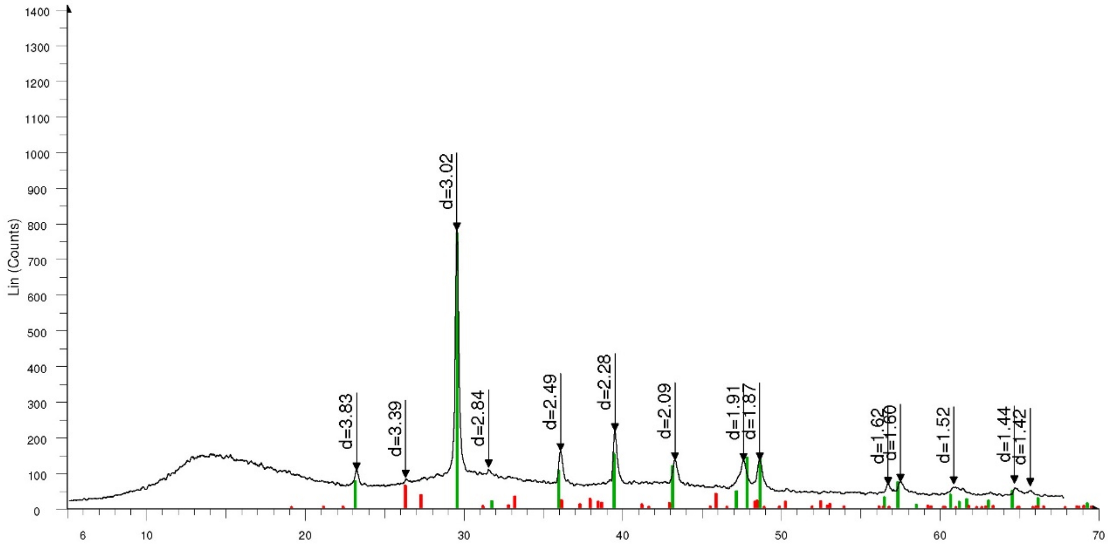
TRG-01 C - Type: 2Theta - Start: 5.002 ° - End: 67.859 ° - Step: 0.010 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-072-1650 (C) - Calcite

TRG-02



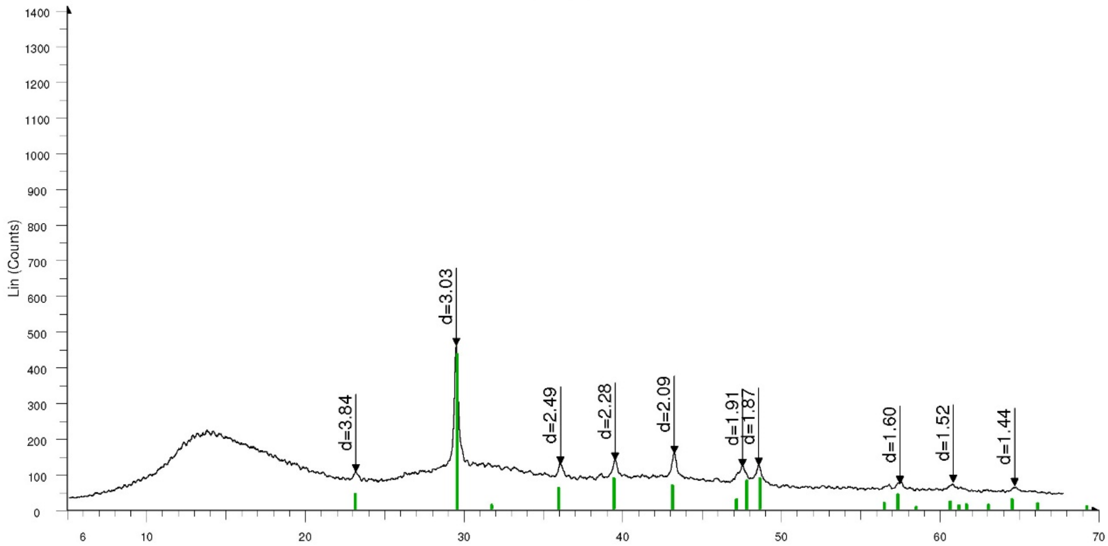
Commander Sample ID - Type: 2Theta - Start: 5.002 ° - End: 69.994 ° - Step: 0.020 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-086-2339 (C) - Calcite

TRG-03 A

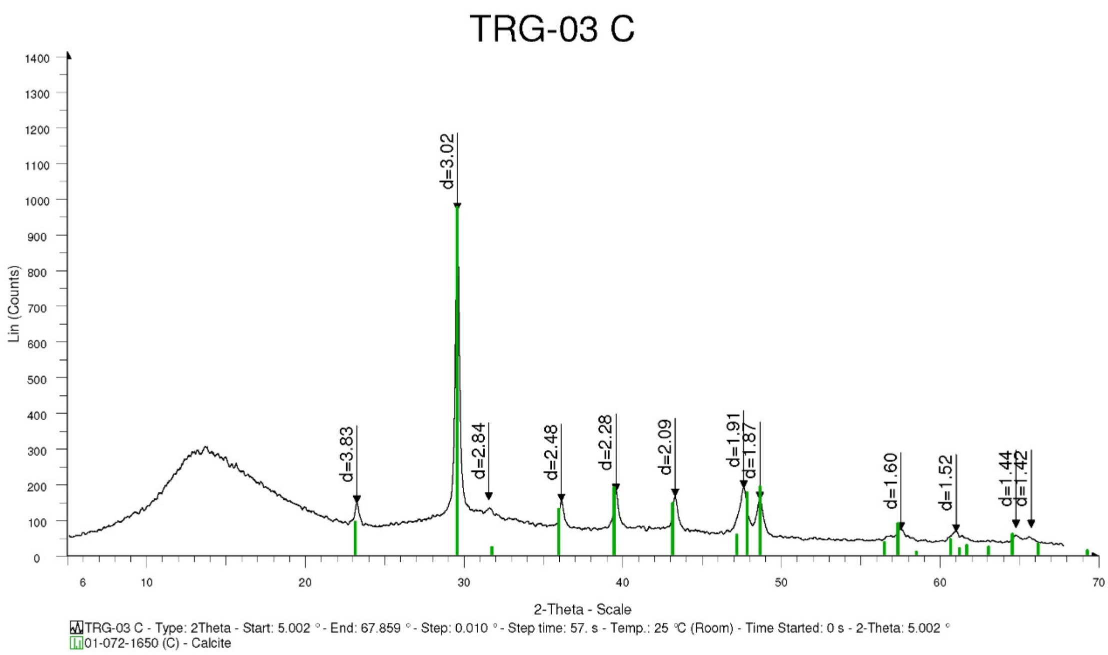


TRG-03 A - Type: 2Theta - Start: 5.002 ° - End: 67.859 ° - Step: 0.010 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-076-0606 (C) - Aragonite
01-072-1650 (C) - Calcite

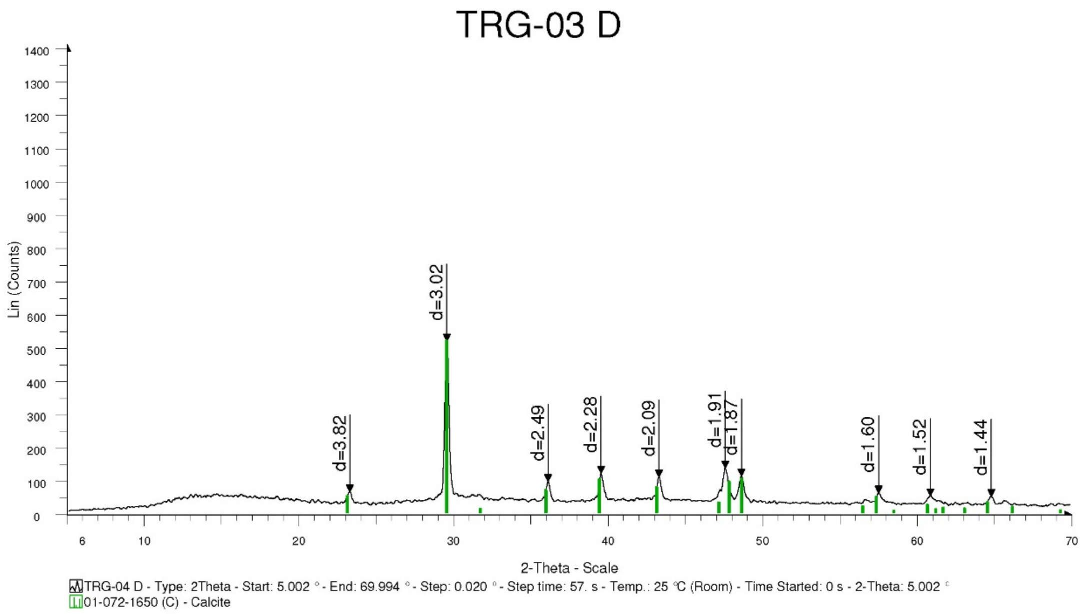
TRG-03 B



TRG-03 B - Type: 2Theta - Start: 5.002 ° - End: 67.859 ° - Step: 0.010 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-072-1650 (C) - Calcite

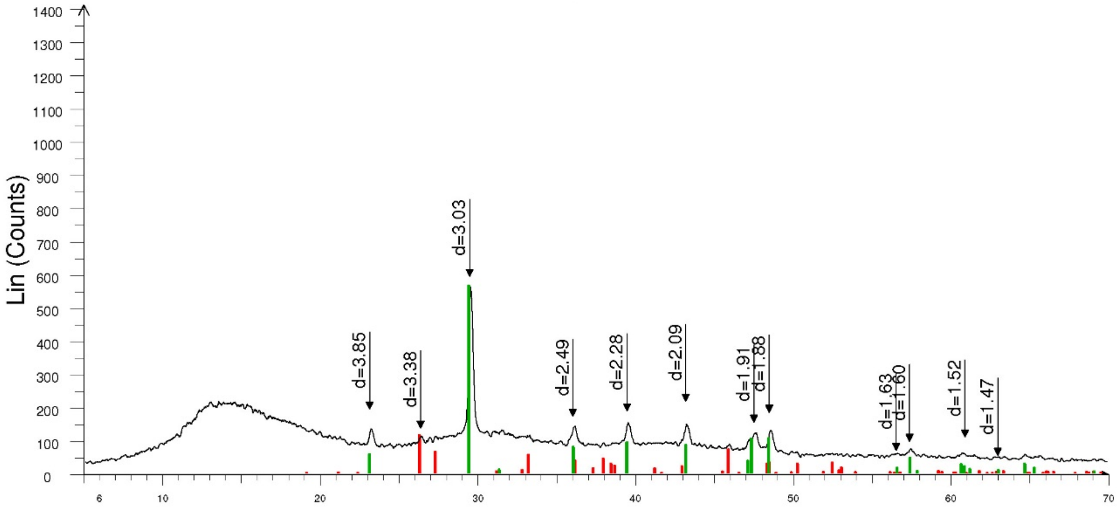


TRG-03 C
Lin (Counts)
2-Theta - Scale
d=3.02
d=3.83
d=2.84
d=2.48
d=2.28
d=2.09
d=1.91
d=1.87
d=1.60
d=1.52
d=1.44
d=1.42
TRG-03 C - Type: 2Theta - Start: 5.002 ° - End: 67.859 ° - Step: 0.010 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-072-1650 (C) - Calcite



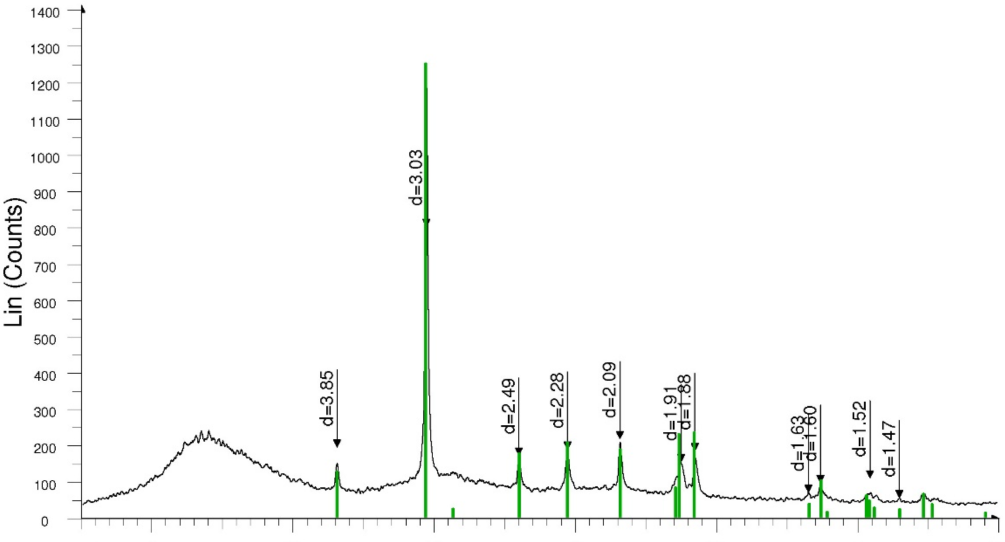
TRG-03 D
Lin (Counts)
2-Theta - Scale
d=3.02
d=3.82
d=2.49
d=2.28
d=2.09
d=1.91
d=1.87
d=1.60
d=1.52
d=1.44
TRG-04 D - Type: 2Theta - Start: 5.002 ° - End: 69.994 ° - Step: 0.020 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-072-1650 (C) - Calcite

TRG-04 A



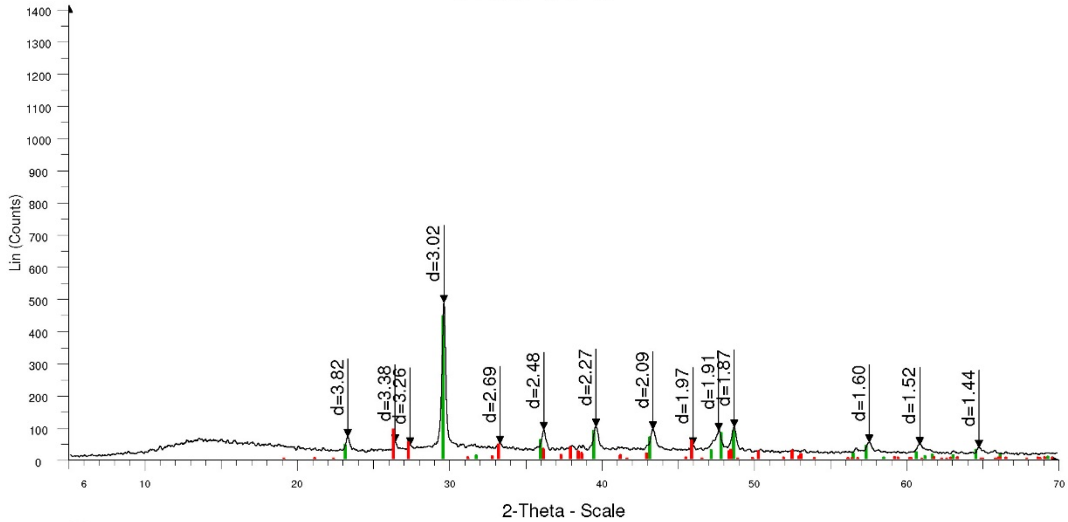
TRG-04 A - Type: 2Theta - Start: 5.002 ° - End: 69.994 ° - Step: 0.020 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-086-2339 (C) - Calcite
01-076-0606 (C) - Aragonite

TRG-04 B



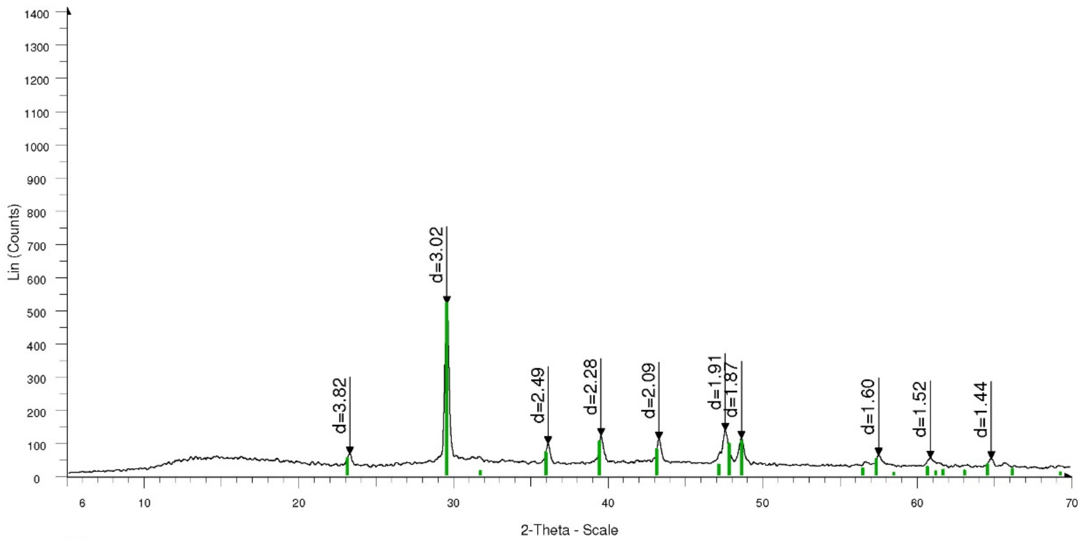
TRG-04 B - Type: 2Theta - Start: 5.002 ° - End: 69.994 ° - Step: 0.020 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
Operations: Smooth 0.150 | Import
01-086-2339 (C) - Calcite

TRG-04 C

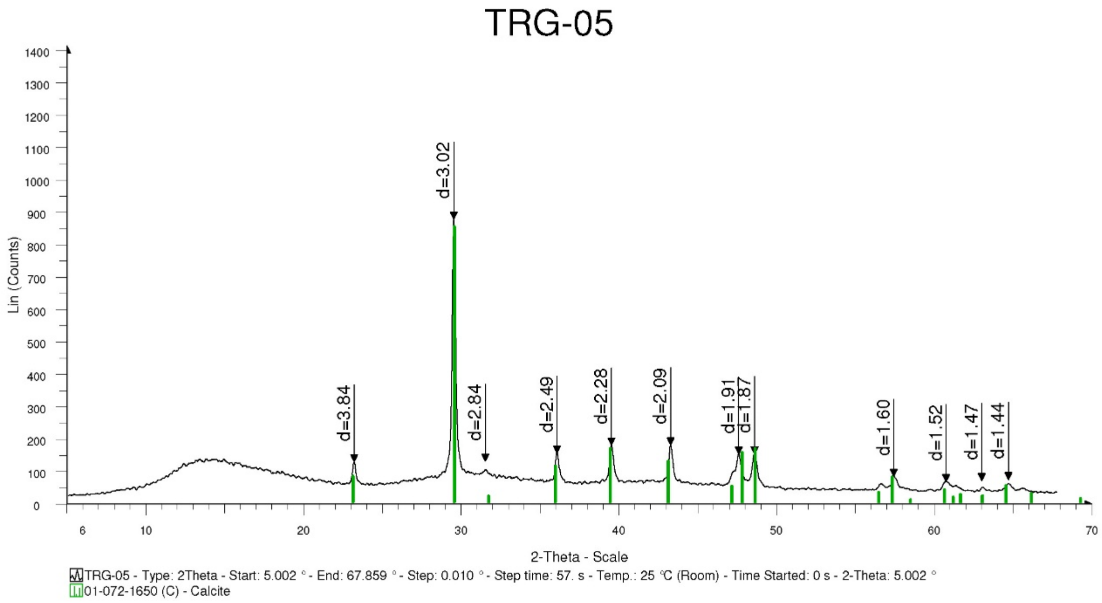


TRG-04 C - Type: 2Theta - Start: 5.002 ° - End: 69.994 ° - Step: 0.020 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-076-0606 (C) - Aragonite
01-072-1650 (C) - Calcite

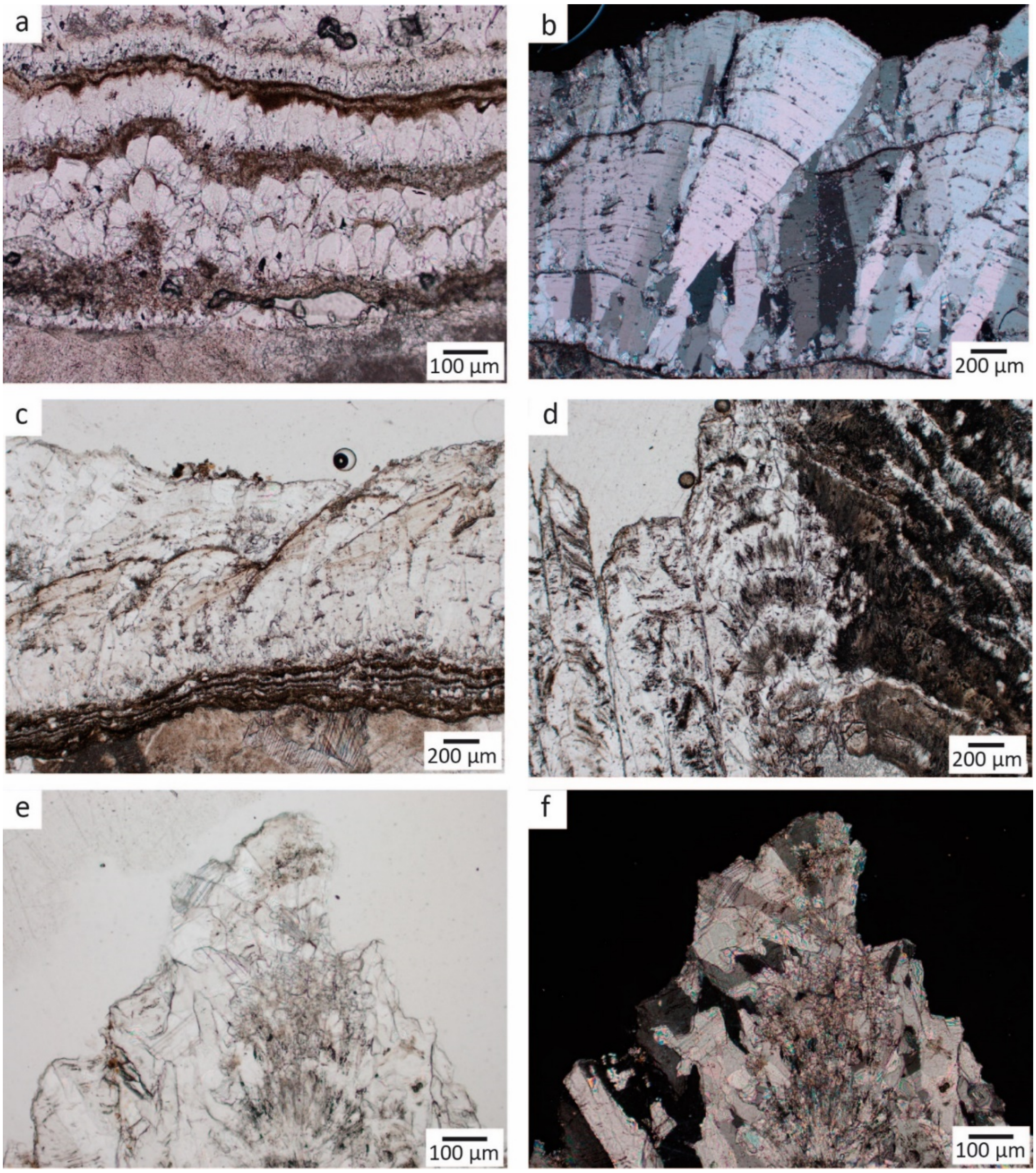
TRG-04 D



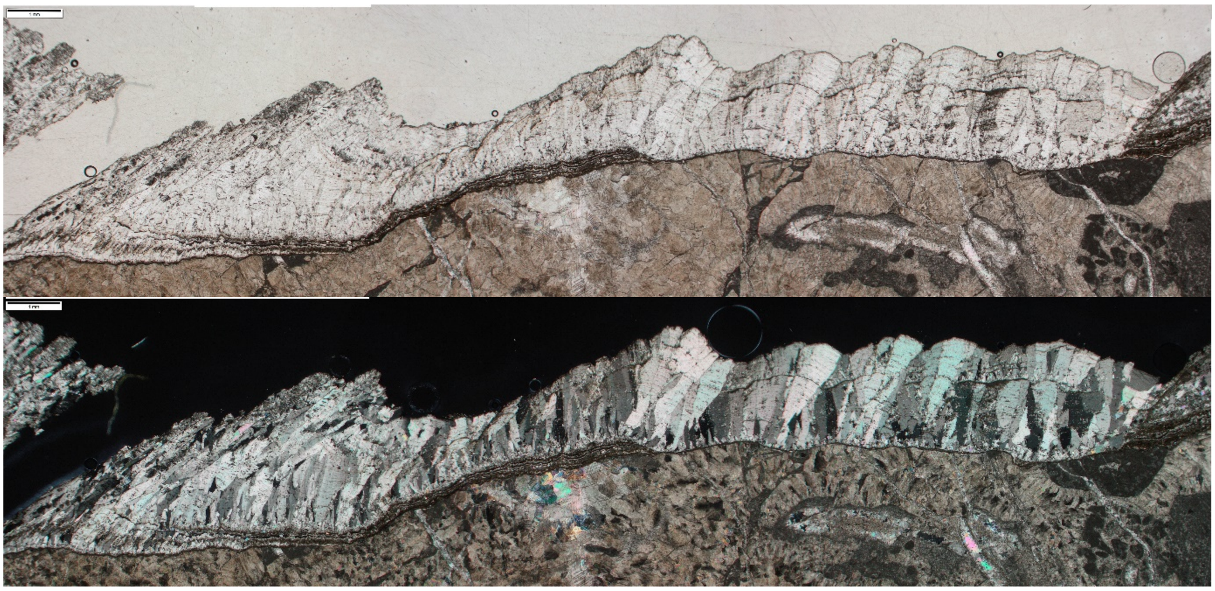
TRG-04 D - Type: 2Theta - Start: 5.002 ° - End: 69.994 ° - Step: 0.020 ° - Step time: 57. s - Temp.: 25 °C (Room) - Time Started: 0 s - 2-Theta: 5.002 °
01-072-1650 (C) - Calcite



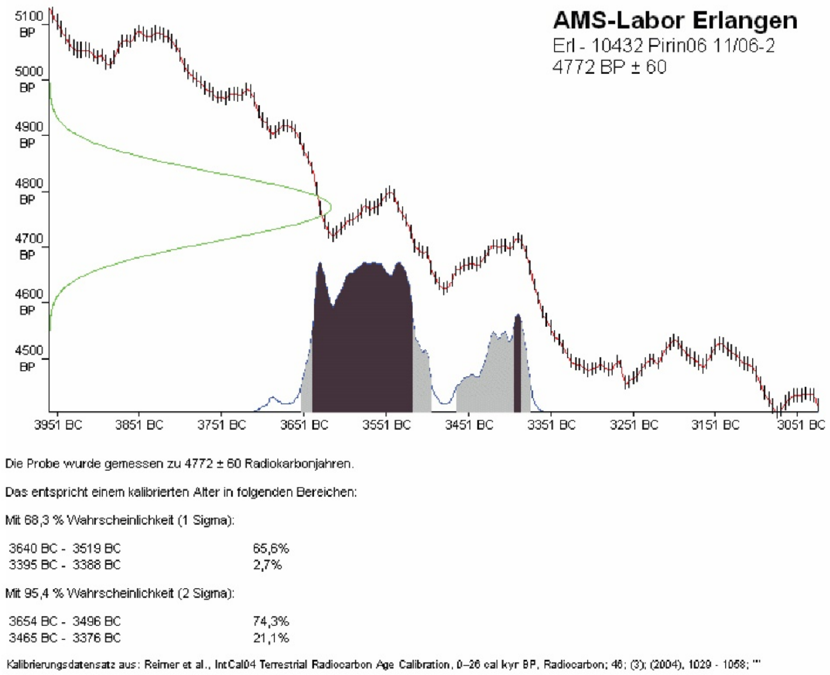
Supplementary Figure S~~7~~6: a) Short columnar calcite crystals alternating with brown micritic bands constitute the first calcite precipitates over the host rock. Plane polarised light (PPL); b) columnar calcite crystals predominantly oriented towards the right (downslope). ~~The growth of the crystal on the center crosscut the direction of growth of previous crystals.~~ Crossed polarised light (XPL); c) oriented columnar calcite crystals displaying signs of dissolution. Occasionally, both crystal layers are separated by a thin, wavy micritic layer possibly indicating dissolution processes (PPL); d) aragonite-calcite layered textures (right) and secondary calcite crystals with aragonite relicts, some of them arranged in fans aligned forming a band (PPL); e) secondary calcite showing abundant aragonite relicts and very anhedral textures (PPL); f) the same image as e, under crossed polarised light. Thin sections orientation is parallel to the former glacier sliding direction.



Supplementary Figure ~~S8~~S7: The columnar and elongated columnar calcite crystals~~s~~ oriented downslope (plane polarised light – above, and crossed polarised light – below). Thin section orientation is parallel to the former glacier sliding direction.



~~Supplementary Figure S9: The photograph and ^{14}C results of dated moraine organic matter by Karsten Grunewald and his team in the laboratory in Erlangen.~~



~~Supplementary Table S1: $\delta^{13}C$ and $\delta^{18}O$ stable isotope ratios.~~

~~Sample~~	~~$\delta^{13}C$ (‰ PDB)~~	~~$\delta^{18}O$ (‰ PDB)~~
~~T.01_a~~	~~2.41~~	~~-2.84~~
~~T.03_a~~	~~1.35~~	~~-4.71~~
~~T.03_b~~	~~0.51~~	~~-5.45~~
~~T.04_c~~	~~1.50~~	~~-3.96~~
~~T.05_a~~	~~0.98~~	~~-4.63~~

Supplementary Table ~~S2~~S1: U-Th data for the subglacial calcite. Note: Ratios in parentheses are activity ratios calculated from the atomic ratios. Errors are at 2δ level. The ages are calculated using the Isoplot 3.75 Program of ~~Ludwig (2012)~~Ludwig (2012) with decay constants from ~~Cheng et al. (2000)~~Cheng et al. (2000). Corrected Ages were calculated assuming initial/detrital $^{230}Th/^{232}Th$ activity ratio equal 0.825 ± 50 % (the bulk-Earth value, which is the most commonly used for initial/detrital ^{230}Th corrections).

U-Th dating was carried out using a Nu Plasma multi-collector inductively-coupled plasma mass spectrometer (MC-ICP-MS) in the Radiogenic Isotope Facility (RIF) at the School of Earth and Environmental Sciences, The University of Queensland (UQ) following chemical treatment procedures and MC-ICP-MS analytical protocols described elsewhere (Zhao et al., 2009; Clark et al., 2012; Clark et al., 2014). Powdered or chipped sub-samples weighing 16–78 mg were spiked with a mixed ^{229}Th-^{233}U tracer and then completely dissolved in concentrated HNO_3. After digestion, each sample was treated with H_2O_2 to decompose trace amounts of organic matters (if any) and to facilitate complete sample-tracer homogenisation. U and Th were separated using conventional anion-exchange column chemistry using Bio-Rad AG 1-X8 resin. After stripping off the matrix from the column using double-distilled 7N HNO as eluent, 3 ml of a 2% HNO_3 solution mixed with trace amount of HF was used to elute both U and Th into a 3.5-ml pre-cleaned test tube, ready for MC-ICP-MS analyses, without the need for further drying down and re-mixing. After column chemistry, the U-Th mixed solution was injected into the MC-ICP-MS through a DSN-100 desolvation nebuliser system with an uptake rate of around 0.07 ml per minute. U-Th isotopic ratio measurement was performed on the MC-ICP-MS using a detector configuration to allow simultaneous measurements of both U and Th isotopes (Zhou et al., 2011; Clark et al., 2014). The $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ activity ratios of the samples were calculated using the decay constants given in (Cheng et al., 2000). The non-radiogenic ^{230}Th was corrected using an assumed bulk-Earth atomic $^{230}Th/^{232}Th$ ratio of $4.4 \pm 2.2 \times 10^{-6}$. U-Th ages were calculated using the Isoplot/Ex 3.75 Program (Ludwig, 2012).

Sample Name	**Sample wt.(g)**	**U (ppm)**	**±2s**	**^{232}Th (ppb)**	**±2s**	**($^{230}Th/^{232}Th$)**	**±2s**	**($^{230}Th/^{238}U$)**	**±2s**	**($^{234}U/^{238}U$)**	**±2s**	**uncorr. ^{230}Th Age (ka)**	**±2s**	**corr. ^{230}Th Age (ka)**	**±2s**	**corr. Initial ($^{234}U/^{238}U$)**	**±2s**
T.01_a1	0,06022	0,45584	0,00019	20,522	0,019	10,945	0,047	0,1624	0,0007	0,9787	0,0012	19,83	0,10	**18,45**	**0,70**	0,9773	0,0013
T.03_a1	0,07823	0,41066	0,00017	7,454	0,012	19,219	0,103	0,1150	0,0006	1,0053	0,0005	13,26	0,07	**12,72**	**0,28**	1,0055	0,0006
T.03_a2	0,02380	0,8933	0,0003	4,929	0,005	19,99	0,23	0,0363	0,0004	1,0062	0,0011	4,012	0,047	**3,849**	**0,094**	1,0063	0,0011
T.03_b1	0,01620	1,7737	0,0005	4,080	0,005	24,49	0,23	0,0186	0,0002	1,0079	0,0008	2,027	0,019	**1,959**	**0,039**	1,0079	0,0008
T.05	0,02151	1,3305	0,0004	68,59	0,11	12,20	0,05	0,2072	0,0008	1,0060	0,0010	25,15	0,11	**23,62**	**0,78**	1,0065	0,0011
~~HU-1 standard~~	~~0,03057~~	~~0,7511~~	~~0,0003~~	~~0,0660~~	~~0,0006~~	~~34680~~	~~342~~	~~1,0036~~	~~0,0026~~	~~1,0013~~	~~0,0011~~	~~**Secular equilibrium**~~		-	-	-	-
~~HU-1 standard~~	~~0,03538~~	~~0,7542~~	~~0,0003~~	~~0,1994~~	~~0,0008~~	~~11439~~	~~53~~	~~0,9969~~	~~0,0024~~	~~1,0006~~	~~0,0009~~	~~**Secular equilibrium**~~		-	-	-	-
~~YB-1 standard~~	~~0,09094~~	~~0,1293~~	~~0,0001~~	~~0,5889~~	~~0,0012~~	~~291,3~~	~~1,3~~	~~0,4371~~	~~0,0018~~	~~1,7452~~	~~0,0018~~	~~30,79~~	~~0,15~~	~~**30,71**~~	~~**0,15**~~	~~1,8136~~	~~0,0020~~
~~YB-1 standard~~	~~0,10259~~	~~0,1292~~	~~0,0001~~	~~0,6118~~	~~0,0012~~	~~278,6~~	~~1,3~~	~~0,4348~~	~~0,0019~~	~~1,7445~~	~~0,0020~~	~~30,62~~	~~0,15~~	~~**30,54**~~	~~**0,16**~~	~~1,8126~~	~~0,0022~~

~~SRM-960 standard~~	~~0,10570~~	~~5,5396~~	~~0,0046~~	~~0,01~~	~~0,000~~	~~1485~~	~~28~~	~~0,00071~~	~~0,00001~~	~~0,9636~~	~~0,0007~~	~~0,0805~~	~~0,0009~~	**~~0,0805~~**	**~~0,0009~~**	~~0,9636~~	~~0,0007~~
~~YB-1 speleothem std~~	~~0,10214~~	~~0,1253~~	~~0,0000~~	~~0,49~~	~~0,001~~	~~339,8~~	~~1,2~~	~~0,4343~~	~~0,0015~~	~~1,7492~~	~~0,0013~~	~~30,53~~	~~0,12~~	**~~30,46~~**	**~~0,12~~**	~~1,8174~~	~~0,0014~~

~~REFERENCES~~References:

Cheng, H., Edwards, R. L., Hoff, J., Gallup, C. D., Richards, D. A., and Asmerom, Y.: The half-lives of uranium-234 and thorium-230, Chemical Geology, 169, 17-33, doi:10.1016/s0009-2541(99)00157-6, 2000.
Clark, T. R., Zhao, J.-x., Feng, Y.-x., Done, T. J., Jupiter, S., Lough, J., and Pandolfi, J. M.: Spatial variability of initial $^{230}Th/^{232}Th$ in modern Porites from the inshore region of the Great Barrier Reef, Geochimica et Cosmochimica Acta, 78, 99-118, doi:10.1016/j.gca.2011.11.032, 2012.
Clark, T. R., Zhao, J.-X., Roff, G., Feng, Y.-X., Done, T. J., Nothdurft, L. D., and Pandolfi, J. M.: Discerning the timing and cause of historical mortality events in modern Porites from the Great Barrier Reef, Geochimica et Cosmochimica Acta, 138, 57-80, doi:10.1016/j.gca.2014.04.022, 2014.
Gabrovec, M., Hrvatin, M., Komac, B., Ortar, J., Pavšek, M., Topole, M., Triglav Čekada, M., and Zorn, M.: Triglavski ledenik [Triglav Glacier], Založba ZRC, Ljubljana, 2014.
Ludwig, K. R.: User's manual for Isoplot version 3.75–4.15: a geochronological toolkit for Microsoft Excel, Berkeley Geochronological Center Special Publication, 5, 2012.
Zhao, J.-x., Yu, K.-f., and Feng, Y.-x.: High-precision ^{238}U–^{234}U–^{230}Th disequilibrium dating of the recent past: a review, Quaternary Geochronology, 4, 423-433, doi:10.1016/j.quageo.2009.01.012, 2009.
Zhou, H., Zhao, J., Qing, W., Feng, Y., and Tang, J.: Speleothem-derived Asian summer monsoon variations in Central China, 54-46 ka, Journal of Quaternary Science, 26, 781-790, doi:10.1002/jqs.1506, 2011.