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## Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic Peninsula): Regional and global implications

David Palacios, Jesus Ruiz-Fernández, Marc Oliva, Nuria Andrés, José M. Fernández-Fernández, Irene Schimmelpfennig, Laetitia Léanni, Benjamín González-Díaz, Team Aster

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## Manuscript Details

**Manuscript number** JQSR\_2019\_856\_R1

**Title** Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic Peninsula): regional and global implications

**Article type** Research Paper

### Abstract

The timing of neoglacial advances in the Antarctic Peninsula (AP) is not yet well constrained. Accurate temporal reconstruction of Neoglaciation in the AP is needed to better understand past glacial responses and regional and global teleconnections during the Holocene. Here, we examine all available information about neoglacial advances in the South Shetland Islands (SSI) as well as in the broader geographical context of the AP region and Antarctic continent. In order to shed light on the contrasting chronologies existing for neoglacial advances in these regions, we focused on a case study where a detailed picture of the Holocene deglaciation was already available. Lake sediments revealed that Byers Peninsula, west of Livingston Island (SSI), was fully deglaciated during the Holocene Thermal Maximum. To complement this approach, we identified glacially polished bedrock surfaces, erratic boulders and a moraine ridge near the present front of the glacier in the SE corner. We applied cosmogenic ray exposure (CRE) dating using in situ  $^{36}\text{Cl}$  for basalt rocks and  $^{10}\text{Be}$  for granitic rocks in: (i) 8 samples from glacial erratic and ice-rafted boulders, (ii) 2 samples from moraine boulders, (iii) 2 samples from polished bedrock surfaces, and (iv) 1 sample from an erratic boulder deposited on one of these surfaces. The CRE dates indicate that the onset of deglaciation started around  $9.9 \pm 1.2$  ka, with two phases of glacier expansion during the Mid-Late Holocene forming moraines at  $\sim 4.1 \pm 0.5$  and  $\sim 1.0 \pm 0.2$  ka, respectively. The main neoglacial advances in the AP and the SSI were mostly synchronous and coincided with cold periods, as shown by other records (e.g. glacio-isostatic marine terraces, marine and lake sediments). In addition, these periods of glacial expansion show a similar timing to those recorded in the Arctic. These results suggest that Neoglaciation was driven by global climate forcing in both polar areas despite temporal variations at regional and local scale.

**Keywords** Antarctic Peninsula; Byers Peninsula; Neoglaciation; surface exposure dating;

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**Suggested reviewers** Stephen Roberts, Daniel Nývlt, vincent Jomelli, Brenda Hall, Michael Bentley



## Submission Files Included in this PDF

### File Name [File Type]

Cover\_letter.docx [Cover Letter]  
ANSWER TO REFEREES-3.docx [Response to Reviewers]  
Highlights.docx [Highlights]  
MANUSCRIPT NEOGL SSI-9.docx [Manuscript File]  
Fig-1R.jpg [Figure]  
Fig-2R.jpg [Figure]  
Fig 3.jpg [Figure]  
Fig-4.jpg [Figure]  
Fig-5.jpg [Figure]  
Fig-6.jpg [Figure]  
Fig 7R byers.jpg [Figure]  
Fig 8R byers.jpg [Figure]  
Fig 9R byers.jpg [Figure]  
Fig\_10R.jpg [Figure]  
Fig-11R byers.jpg [Figure]  
Table 1-R.docx [Table]  
Table 2 F.docx [Table]  
Table 3 F.docx [Table]  
Table 4 F.doc [Table]  
Table 5 F.docx [Table]  
Table 6 F.docx [Table]  
Table 7-R.docx [Table]  
declaration-of-competing-interests.docx [Conflict of Interest]  
CRedit author statement.docx [Author Statement]

## Submission Files Not Included in this PDF

### File Name [File Type]

Byers\_samples.kmz [Interactive Map Data (.kml, .kmz)]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

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Madrid, February 18, 2020

Dear Editors,

We present an unpublished work entitled "*Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic Peninsula): regional and global implications*", which focused on the Neoglacial landforms in the Antarctic Peninsula. The work makes an exhaustive bibliographical revision of the dating of Neoglacial landforms in this region and chooses an area of ideal experimentation, in the Byers Peninsula and finds multiple possibilities in the cosmogenic method to apply in the future. We think that the research and its relevance fits well with the scope of the journal **Quaternary Science Research**.

In addition to our analysis, our manuscript presents a dataset of 12 samples, important and a novel revision on the state of knowledge of the Neoglaciation in the Antarctica. In this sense, the limited number of samples is compensated with a detailed previous study, analyzing the degree of stability of the sampled boulders, by combining other methods, which is a completely new strategy.

The work deals with the problem of Neoglacial landforms, using Cosmic-Ray Exposure (CRE) dating, which is still in its initial phase, and analyzes all the problems that can be encountered, such as inheritance, reception of cosmic radiation during boulder transport, etc. On the other hand, it addresses the geomorphological and climatic significance that the formation of Neoglacial advances in the context of Holocene climate tendency. It should be noted that this is the first time that these methods are applied to Neoglacial landforms in this area.

We believe that the manuscript provides a strong bibliographic review and opens new paths to research on climatic and geomorphological evolution in Neoglacial landforms.

All the authors have worked with intensity in the investigation, whose results are presented:

1. David Palacios, coordination of the whole phases of the research and draft of a first manuscript, sampling and intense geomorphological fieldwork and data processing and collaboration in the writing
2. Jesus Ruiz-Fernández. sampling and intense geomorphological fieldwork and data processing and collaboration in the writing
3. Marc Oliva, sampling and intense geomorphological fieldwork and data processing and collaboration in the writing
4. Nuria Andrés, data processing and geomorphological cartography and collaboration in the writing.
5. José M. Fernández-Fernández. Work in the laboratory and data processing and geomorphological cartography and collaboration in the writing.
6. Irene Schimmelpfennig. Supervision of the whole process of analysis of the samples and interpretation of the results. Exhaustive correction of the manuscript
7. Laetitia Leanni. Work in the laboratory and treatment of cosmogenic data, correction of the manuscript.

8. Benjamín González-Díaz. Work in the laboratory and treatment of cosmogenic data, correction of the manuscript.
9. ASTER Team. Team Analysis of the cosmogenic samples and correction of the manuscript.

We have carefully studied the observations made by the referees and have made entirety them, changing the wording of different parts of the manuscript and incorporating the new suggested figures. We believe that thanks to these corrections, the manuscript has improved in quality.

Thank you very much for your attention.

Kind regards,

A handwritten signature in blue ink, appearing to read 'David Palacios', is written over a light blue grid background. The signature is fluid and cursive, with a long horizontal stroke extending to the right.

David Palacios, on behalf of the co-authors.

Ref: JQSR\_2019\_856

Title: Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic Peninsula): regional and global implications

Journal: Quaternary Science Reviews

Dear Dr. David,

Thank you for submitting your manuscript to Quaternary Science Reviews. I have completed the review of your manuscript and a summary is appended below. The reviewers recommend reconsideration of your paper following major revision. I invite you to resubmit your manuscript after addressing all reviewer comments.

When resubmitting your manuscript, please carefully consider all issues mentioned in the reviewers' comments, outline every change made point by point, and provide suitable rebuttals for any comments not addressed.

Professor. Yang  
Editor  
Quaternary Science Reviews

#### **Comments from the editors and reviewers:**

##### **-Reviewer 1 (Vincent Jomelli)**

Dear David, dear All

I made some comments directly on the PDF. As you will see most of them concern the review section in the introduction. I have specific questions about the method and results easy to solve. I also believe that it would be easier for the reader if you put the location of the samples on figure 4. It would help to follow the discussion. I hope my comments will help, all the best

Vincent

We greatly appreciate the indications suggested by Prof. Jomelli. He has pointed out the most confusing parts and has helped us greatly to improve the orientation and clarity of the manuscript.

Line 44-46 in my opinion this is still difficult to claim such differences as there are no strict synchrony in the chronologies even in the southern hemisphere

We have changed the sentence leaving the statement as a simple suggestion in the new lines 28-40.

Line 31-35 I'm not sure these info are necessary in the abstract

Yes, we agree. Besides, this suggestion coincides with that of Prof. May. We have eliminated the unnecessary information for the summary. See lines 28-40.

Line 64 There are some differences between regions so please specify.

We have already specified that we are talking about the Antarctic Peninsula in the new lines 52-54.

Line 85 what sort please specify and 86 based on what sort of proxies. Several improvements on ice core records have been published this last decade.

We have indicated the type of records in the new lines 98-105.

Line 90. Please update, Bentley, et al (2014). A community based reconstruction of Antarctic Ice sheet deglaciation since the Last Glacial Maximum. Quat. Sci. Rev. 100, 1-9.

Done in line 84-85 and in the references.

Line 93-94 strange sentence

Yes, we agree and have changed it. See lines 98-105.

Line 106 it is not exactly what you propose afterwards.

We have eliminated this phrase and we have improved the objective of the work in the following paragraph.

Line 112 what do you mean exactly. Please specify. This generic term is too vague at this step of the manuscript in my opinion.

This sentence was really badly worded, but now it has been rewritten to show much clearer in the new lines 116-125.

Line 116 I do not really like these two points. In my opinion presenting a review could be viewed as a description of the context of your study and not the main real objective of this paper. To clarify either you propose a review or a research paper including a full description of the data in the intro and in the discussion (as a classical paper)

This sentence was really badly worded, but now it has been rewritten to show much clearer in the new lines 116-125.

Line 119 again specify

Done in line 120-125.

Line 132 I would suggest another organisation of this paragraph. I think that for your purpose it would be more relevant to emphasise climate conditions that we can summarize from the different proxies rather a list of events identified in each of them.

We have followed the reviewer's advice and have changed the wording of this section, focusing the new text about the climatic conditions of the PA.

Line 137 Ok so why not mention this conclusion in the introduction

We agree and we have changed this sentence to the introduction. See Lines: 116-125.

Line 142 I agree so why not including this in the introduction

We have included this sentence in the introduction. See Lines: 116-125.

Line 148 climate conditions are totally different so I'm not sure it is really relevant for your purpose. If then you should mention other and numerous ice core records in east antarctica.

We have partly followed the reviewer's advice, and we have focused fundamentally on eastern Antarctica, although we also cite study cases where the impact of the LIA has been detected, as we consider it important in the discussion. See Lines: from 136.

Line 157 strange

Clarified now in the text. See Lines: 149-168.

Line 158 Then how reconcile these two cold periods with the previous one. I do not understand

Clarified now in the text. See Lines: 149-168.

Line 170. In the end i'm a bit lost why these data show distinct things. A summary would be necessary.

We have fully changed the wording of this section. Now the conclusions show better the results, it is no longer a simple exposition. See Lines: 149-168.

Line 196 based on what

Clarified now in the text and we have eliminated not necessary information. See Lines: 191-217.

Line 201 please specify

Clarified now in the text. See Lines: 191-217..

Line 212 what

Clarified now in the text. See Lines: 191-217.

Line 215 please remove this is out of your area which increases the confusion

Yes, we agree and had removed more of this information. See Lines: 191-217.

Line 220 i do not understand the organisation of these paragraphs why not to include the previous sentences in this section?

Yes, we agree and we have join both sections. See Lines: from 218.

Line 280 These paragraphs are informative. I would suggest to include information related in the previous pages here. This would clarify the introduction and would give a clear picture of previous work.

We agree and we have included it. See Lines: 228-235.

Line 312 would delete this but the paragraph is very helpful.

Yes, we did. See Lines: 228-235.

Line 508. Maybe it would be nice to use another scaling to get an identical approach with  $^{10}\text{Be}$  (you used LSD instead).

*Yes, we agree with this observation as it improve the comparisons between  $^{10}\text{Be}$  and  $^{36}\text{Cl}$  ages in equal conditions. We have re-calculated the  $^{36}\text{Cl}$  exposure ages through the LSD elevation latitude scaling scheme, and added this new ages in a new column in the Table 7. Consequently, we have included an explanation of the exposure age calculation with this scaling scheme (see the new text in the 'Methods' section; current lines from 535-551 and Table 7).*

Line 532. What about the snow effect and the erosion

We do not have any information on the snow cover of the area, since it is not inhabited throughout the winter, until the disappearance of the snow. Therefore, we have sampling the areas most exposed to the wind. With regard to erosion, we have followed the criteria of the latest publications. Now everything is explained in the 576-586 lines

Line 596 It would be nice to put the sample location on fig 4 because it is no easy to understand the geomorphological context

We have done it and also we have included it in the new geomorphological map. See new figures 4, 5 and 6.

Line 655. So I do not understand how you combine these two informations.

We have improved the wording and added a new phrase that clarifies our reasoning. See Lines: from 793.

Line 752. I agree with you but the fact that Patagonia and NZ show another pattern of glacier evolution suggest complexes drivers even at a millienia timescale

We agree with this affirmation. Therefore, we have limited our comparison between regions with the same latitude. Extending the comparison to other temperate latitudes would really mean facing a new large work, with a much more detailed analysis. Anyway, it would be interesting to afford that comparison in the future to try to solve important gaps in the knowledge of the global glacier dynamics.

**-Reviewer 2-**

In their paper, "Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic Peninsula): regional and global implications", Palacios et al. present a study of neoglacial landforms and related chronology, by means of cosmogenic ray exposure, of a sector of the Livingstone Island. The presented information, mainly the chronology, is of particular interest, however the manuscript fails in some respects.

We appreciate the suggestions made by reviewer 2, which we have tried to follow in all cases and believe that they have helped to improve the manuscript.

Firstly, the text has a poor grammatical writing, several sentences show grammatical mistakes, redundancies and/or are not comprehensible

We have reviewed and improved the entire wording of the text, with the help of professional, expert in English and with expertise in geosciences.

(Just some examples: lines 41-44,

We have changed and improved the wording of these sentences. See lines 28-40.

120-122,

We have eliminated this sentence, as it was too general and obvious.

237-240,

We have now explained it better in the new text. Lines: 222-235.

249-252,

We have now explained it better in the new text. Lines: 250-253.

261-262,

We have corrected the mistakes.

280-282,

We have eliminated this sentence as it was confusing.

333-337,

We have now explained it better in the new text. Lines: 330.

678-679,

We have now explained it better in the new text. Lines: from 662.

734-736,

We have improved the writing. See Lines: from 793.

758-761,

We have improved the writing. See Lines: from 793.

"characterized the Antarctic during ..." at line 63, study case (?) at line 117 and 422 (case study in Abstract and other sections),

We have reviewed and corrected this erratum throughout the text.

line 678: using "proposed" 4 times in one paragraph (9 lines), among others.

We have changed the text with more variety of synonym verbs. See Lines: from 793.

It is not clear the sentence (the last one of the abstract) "These results support the idea that Neoglaciation is driven by global climate forcing, unlike other Holocene glacial advances that are

specific to each hemisphere.” What do they refer with “other Holocene glacial advances”? Not Neoglaciation?

We agree with the reviewer, who also makes the same observations of Prof. Jomelli. We have changed this sentence and eliminated the general and confusing statements. See lines 840-857.

When few lines after they quote “the term Neoglaciation to refer to the glacial advances that occurred after the Holocene Thermal Maximum (HTM: 11-5 ka, Renssen et al., 2009) until the end of the Little Ice Age (LIA).” ??? Moreover, in the abstract the authors indicate their research “These results support the idea that Neoglaciation is driven by global climate forcing ...” but they do not describe, discuss, assess nothing of their results in relation to that topic in any part of the text.

We only wanted to delimit what is called Neoglaciation period according to the scientific literature.

The result of our contrast between the glacial advances along the Late Holocene in the Antarctic Peninsula and in the Arctic confirm that these processes occur simultaneously in the high latitudes of both hemispheres. The causes of climatic mechanisms driving this synchronicity in glacial advances in both polar areas are out of our expertise, and should be responded by paleoclimatologists. However, we have included now the most outstanding paleoclimatic findings about this subject at the end of the discussion. See lines 840-957.

The manuscript is untidy in some aspect, for example there is not section 3, it passes from section 2 (line 124) to section 4 (line 352), and in between there is subsection 3.3 (!).

Yes, it was a mistake and it is already corrected.

In general, the text of the Introduction is confused.

The other reviewers think also the same. We have changed and rewritten the most confusing sections of the introduction and we believe that now the objectives of the work and their context are now well understood. See lines 98-110.

The Methodology section only explains the laboratory aspect of the dating by cosmogenic ray exposure, but it lacks information about the geomorphological survey and a general description of how the sampling strategy was designed and what this strategy represents.

We agree with the reviewer and have added a new section to the methodology, where the geomorphological strategy is clearly exposed. See lines from 423.

Other significant weakness is the lack of a geomorphological map. Considering the authors are using glacial landforms to find evidences and reconstruct neoglacial advances, and they sample boulders and surfaces of these glacial landforms, it is essential to elaborate a map with the detailed geomorphology of the study area and location of samples in that map to allow the readers to understand and evaluate the obtained information.

We agree with the reviewer and have included a new figure with the geomorphological map, where you can see all the landforms cited in the text and help to understand the results. See lines from 589 and new figures 5 and 6.

Besides, when one read the section of results “6.1 Geomorphological setting of neoglacial landforms” it is not clear what results are own from the authors and which ones are from other authors. In the first sentence they say “Outside the moraine system next to Rotch Dome glacier, there are no clear moraine formations that would correspond to Late Holocene advances” but it is not clearly explained the basis for that assumption.

Again, we agree with the reviewer and have left only our results in that section. See lines from 589.

In some sentences the authors describe results using comparative adjectives but without including with what other element they are comparing. In line 595 it is not clear what “the last surface” means.



We have improved the writing and we have located the samples on the geomorphological map and in figure 4, 5 and 6, as requested by the reviewer 1, so that now the explanation is much better understood.

Finally, I consider the author can find a briefer and more comprehensible way to synthesize the state of knowledge on the Neoglaciation. The section "2. State of knowledge of the Neoglaciation chronology in South Shetland Islands in the context of the Antarctic Peninsula" is very long and confused. The previously published data is already in the tables, then I suggest producing a shorter text about this topic and to produce some kind of figure or table to summarize the conclusions.

We have summarized and improved the wording throughout that section. We have also included the requested figure, which helps to compare our results. See lines from 134.

Figures: I do not see the necessity of including the figure 1, it is enough the maps of figure 2 to put in context the case study. But I highly recommend including a detailed geomorphological map of the study area, with the sample dots. In figure 3 it is recommend adding more information of each sample besides the lab code.

According to reviewer 3, we keep Figure 1, with the location of all the place-names cited in the text. But we have simplified Figure 2 and it is no longer repetitive with Figure 1. We have also expanded the information requested in Figure 3.

### **-Reviewer 3 (Jan-Hendrik May)**

The manuscript „Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic Peninsula): regional and global implications" presents a comprehensive review of studies investigating climatic and landscape changes around Antarctica with focus on the Antarctic Peninsula. It also presents a new dataset of cosmogenic surface exposure dates from the South Shetland Islands and discusses the results within the framework of the existing literature. The topic and approach are well in line with the scope of QSR. The paper is of very reasonable length and I have very much enjoyed reading it – it is well written and presented and follows a clear and logical structure. In addition, all figures are of top quality and contribute in providing a context for the new dataset. Therefore, I believe that the paper deserves publication after addressing a few general and more specific minor issues and suggestions that I will list in the following:

We are very grateful to Prof. May for each and every one of his indications. We have corrected all the errors indicated and have followed the majority of his advices, improving considerably the manuscript.

#### **Some general issues and suggestions:**

1. Could you discuss the local-scale controls on glaciers and glacial advances (e.g. temp vs precipitation) a bit more somewhere – this may help to highlight the scope of your study and research. Are you interested in glaciers as a temperature proxy – or are you interested in the evolution of Antarctic landscapes?

Unfortunately, there are not many quantitative or qualitative climate records from the Antarctic Peninsula for the last millennia. Several researchers are working now to provide quantitative reconstructions of past temperature conditions using lake (e.g. BAS researchers, Dr. Hodgson, Dr. Roberts) and marine records (Dr. Etorneau) to produce such reconstructions. We have included in the discussion some references related to the Neoglacial period to support the text. See lines from 791.

2. The paper presents a relatively small dataset of new results but compensates by constructing a detailed framework for interpretation by reviewing a large amount of available literature. I am aware that – as indicated by the title, and re-emphasized in lines 794-795 – you are trying to avoid an in-depth discussion of climatic drivers for glacial advances. However, in my personal opinion if you compare your and other existing data from Antarctic to the Arctic, I would think that you need to provide (at least a short, i.e. a few sentences) discussion of reasons and mechanisms for these global scale controls. How does this work? What are the mechanisms? Is this related to global insolation changes over millennial scales, and thereby global air temperature? How does this relate to the atmospheric and oceanic circulations? And what are the implications with regard to the RRW (i.e. can you come back to your introduction)?

We have really followed the reviewer's advice, and we have cited the latest reflections of paleoclimatologists on this topic at the end of the discussion. We consider that is important to take these ideas into consideration to correctly frame our results. See lines 848-056.

3. The geomorphological setting of neoglacial landforms is part of the results but there is no methodology section corresponding to these results – add some info on how the mapping / field work was done...

We agree with the reviewer (reviewer 2 mentioned the same), and have added a new section to the methodology, where the geomorphological strategy is exposed. See lines from 423.

4. In your literature review provide errors for cited ages where possible or indicate the uncertainties by adding “~”

We have followed this suggestion whenever we have been able to agree with the information provided by the publications.

5. Literature review and Fig. 1 – The literature review seems solid and rather complete but – due to the large number of cited studies – can be somewhat difficult to keep track of while reading. Could you include the localities of these studies into your overview figures 1 and 2 (and providing reference in the figure captions)? This would graphically add to the review, and help the reader to assess the relevance of the individual records with regard to your results.

We have completed the Figure 1 with the location of all the place-names cited in the text. But we have simplified Figure 2 and it is no longer repetitive with Figure 1.

6. I agree with the subdivision of the review into archives (i.e. ice cores, marine sediments etc). For many of these cited studies and their results, however, it might make sense to add some info on which proxies these study use (e.g. are the results based on isotopes, or sedimentation rates, or ...) to avoid comparing "apples with oranges"? And, what do the proxies us and how do they inform on past climate?

We have followed the instructions of the reviewer and at the beginning of each paleoclimatic source we have made a minimum summary. Obviously each method is very complicated to explain and a lot of text would be necessary. In the new version of the text, we believe that with the small introduction the reader can assess the meaning of the ages proposed by each proxy. See lines from 137.

#### **Specific minor comments:**

The abstract is well written but includes some detailed place names (e.g. line 25-29 – Livingston Island, Rotch Dome, Clark Nunatak) and detailed information (e.g. lines 32-38 – is it necessary

to provide sample numbers and specific elevations here?) that – at least in my opinion – are distracting from the main idea and results of the paper. Consider summarizing these details and thereby shortening the abstract.

This suggestion coincides with that from Prof. Jomelli. We have deleted unnecessary information for the summary, shortening it. See lines 28-40

Line 30 – basalt rocks

Done.

Lines 45 – you refer to the hemispheric scale here, but from my understanding some glacial advances are also specific to even more regional or local scales... Consider adding: “specific to a region or hemisphere”

We have changed this whole sentence and have included your idea. You can see a much clearer wording in the new sentence. Lines: 28-40.

Line 59 – cyclonic conditions? Not quite clear what you mean... low pressure systems and increased precipitation?

Yes, this was a bad expression indeed and now it is already corrected. Line 51-54.

Line 59 – , “exhibiting” a more intense trend...

Included in Line 51-54.

Line 63 – general, longer-term tendency to cooling...

Included. Line 56-58.

Line 77 – replace “begin” with “onset”

Done. Line 78-81

Line 84 – According to the available records...

We changed the entire sentence and included it. Lines 78-81.

Line 90 – replace “aimed” with “reported” or “interpreted”...

Done. Line 98-105

Line 94 – delete “...?”

It was a mistake and now we write a new sentence. Lines 98-105.

Line 99 – these new data “also” introduce new...

Done. Line 98-105

Line 105 – PA? Do you mean AP? Otherwise explain what PA means...

It was a mistake and now it is corrected. Line 98-105.

Line 110 – replace “reconstruction pattern” with “framework”

Done. Line 107-110.

Lines 109-112 – Would this be a good place to add a sentence on your hypothesis (based on the existing literature and available data – what is expected/tested) before you state your aims in the next paragraph?

We agree and we have added it in the lines: 116-125.

Line 117 – study case? Sounds strange, use “case study”

Done in Line: 116-125.

Line 118 – “representative”? Why do you suspect that this case study is representative for the entire AP? Either explain or delete...

We have changed the wording of this sentence and now the justification for this case study is clear See Lines: 116-125.

Line 126-129 – you seem to suggest that mass loss during the early/mid-Holocene is mainly driven by ocean temperatures, but isn't there some contribution of internal and threshold-driven dynamics (that are independent of larger-scale climatic drivers) as well? Check and potentially add

We have not found any clear reference on this threshold in relation to Neoglaciation.

Line 136 – “on” average

Eliminated in the new wording

Line 147 – “colder than present”

Changed. See Lines: from 137.

Line 151 – close ice cores?? Closed? Or close-by?

Eliminated in the new wording

Line 171 – “is” also important

Eliminated in the new wording

Line 179 – “records” instead of “approaches”

Eliminated in the new wording

Line 190 – “some” direct dating

Eliminated in the new wording

Line 192 – you refer to radiocarbon dating here. Could you briefly add the type of dated material as readers may not expect this method to be applicable to the largely vegetation free Antarctic environments

Indicated now in the text. See Lines: from 191.

Line 194 – dated beaches “and” indicated

Changed. See Lines: from 191.

Line 206 – replace “set the age of” with “date”

Changed. See Lines: from 191.

Line 209 and following – I would suggest providing the info on the type of chronology (i.e.  $^{10}\text{Be}$  ages) in brackets and not in the main text

Changed. See Lines: from 191.

Line 222 – “In” the first geomorphological studies...

Changed. See Lines: from 191.

Line 228 – Could you briefly provide an explanation on the relationship between moraines and raised beaches (i.e. why would these be related, and what does this imply for the reconstruction of glacial advances that early studies focused on?).

We have provide this explanation. See Lines: 229-235.

Line 251 – “related LIA advances”

Changed. See Lines: 251-253.

Line 262 – “indicates”

Changed. See Lines: 262.

Line 271-273 – dated by radiocarbon, ok, but what were the dates?

Clarified in the text. See Lines: 271.

Line 273 – add ) after last reference

Done. See Lines: 273.

Line 299 – Maxwell Bay

Changed. See Lines: 296.

Line 312 – very long title for subchapter 3.3

Eliminated

Line 368 – “onto” which protruded...

Changed. See Lines: 364.

Line 371 – “on” this plateau

Changed. See Lines: 366.

Line 383 – is annual precipitation only snow?

No, now is clarified in the text See Lines: 379-380.

Line 422 – delete “applied to the study case”

Done

Line 423-435 – did you check for boulder instability before sampling, and if yes, what did you look for? Briefly include into the paragraph...

We have done it, including a paragraph about this strategy. See Lines: from 424.

Line 448-450 – How was the compositional analysis done? XRF? ICMPS? Specify somewhere

The analysis performed is specified in the following paragraphs. See Lines: from 483-487.

Line 466-468 – is the final step of oven drying also resulting in targets (similar to the 10Be approach)?

NO. We have clarified it in the text with a new sentence. See lines 503-505.

Line 492 – could you briefly add a comment as to why the  $^{35}\text{Cl}/^{37}\text{Cl}$  ratio is important to consider for this method!?

We have now rewritten the earlier sentence to clarify this aspect. See new wording from lines from 535

Line 504 – Schimmelpfennig et al.

Changed. See new wording from lines from 535

Line 533 – “analytical error”

Changed. See new wording from lines from 535

Line 537 – ice-cored moraine ridges / an ice-cored moraine ridge

Changed. Line 589

Line 541 – .... stability “over annual to decadal timescales”

Changed.

Line 544 – “and” are formed by blocks...

Changed.

Line 553 – “exposure” instead of “exposition”

Changed. Line 598

Line 555 – “overrides”

Changed. See Lines: Line 599.

Line 560 – next to? Be more specific

It is now clarified in the text. See line 603.

Line 580 – so, these boulders are (partly?) embedded in sediment, and you interpret them to be ice-rafted? Could you provide some brief explanation how this process works – mainly to justify the boulders’ use for exposure dating...

The position of these boulders with respect to the beaches is defined in the previous paragraphs. We have added a phrase where, at the request of the reviewer, we present our hypothesis about the meaning that the results of their dating by cosmogenic methods can mean, since there is no previous experience.

Line 596 – what kind of average was taken, weighted mean?

Clarified now in the text, see line 645 and following.

Line 603 – mean “of”

Changed. See Lines: 645.

You could show the sample points on a map/figure

Yes, we have included already in figure 4.

Line 614 - .... Rish Point. These samples are indicative...

Changed. See Lines: 664.

Line 616 – were dated at 7.4 cal ka BP on this peninsula

Changed. See Lines: 667.

Line 635 – where were the whale bones found, nearby? Specify

We have now specified in the text. See Lines: 687.

Line 645 – do not “necessarily”...

Changed. See Lines: 697.

Line 644-645 – Ok, I agree that beaches of similar altitude do not necessarily need to be of same age, but please provide a brief explanation for your statement. Which processes would enable to ridges of different ages at the same elevation?

We have explained it now in the text, according to the cited publications. See Lines: 697-698.

Line 647 – “boulders”

Changed. See Lines: 700.

Line 655-659 – close to their present-day position, could you specify how close approximately? Within meters? Or hundreds of meters?

We have improved the wording and added a new phrase that clarifies our reasoning in relation to glacier fronts. See Lines: 714-716.

Line 672 – delete “trying” and replace with “advancing around”

Changed. See Lines: 729.

Line 675 – confirmed “during this” time

Changed. See Lines: 732.

Line 687 – “old periods”? Specify or delete

It was a mistake and we deleted it

Line 694 – replace (older) and (younger) with ages.

Changed. See Lines: 751-752.

Line 705 – some results? Specify

Clarified now in the text.. See Lines: 763-764.

Line 706 – the author... do you mean Hall 2007?

Yes, clarified now in the text. Line 764

Line 710 – delete “as”

Changed. See Lines: 768.

Line 708-713 – are all ridges dated by radiocarbon, or are there additional uncertainties introduced by the application of other dating methods (e.g. luminescence)?

It is only by radiocarbon, as we specify in the text. See Lines: 767.

Line 718 – replace “extended” with “expanded”

Changed. See Lines: 776.

Line 722 – the 1.3 ka is your result? Then add “based on our results”

Changed. See Lines: 780.

Line 728 – “started”

Changed. See new wording in Lines: from 792.

Line 729 – with new “and previously undated” neoglacial advances

Changed. See new wording in Lines: from 792.

Line 731 – nature of the records and dating methods. Yes, I agree, but I think these statements need some more commenting and discussion somewhere.

We agree with reviewer’s comments. Due to limited space in this work, we have included a limited explanation and given some examples of the progress that is being made recently to homogenize the results of each method and make them comparable. See new wording in Lines: from 792.

Line 725-770 – ok to relate your results to the existing results around the AP, but before discussing the global significance and comparing with Arctic records, wouldn’t it make sense to compare it against the wider context of the entire Antarctic continent?

Yes, we agree. In fact, we have included the most important references about Neoglaciation from the rest of Antarctica. In any case, the comparative sectors of the Arctic have a greater climatic similarity (temperate and humid) and similar glacial variability with the Antarctic Peninsula than the rest of most continental Antarctica.

Line 736 – what’s greater? The difference?

Yes, now is clarified in the text. See Lines: 811-812.

Line 750 – a common “global” pattern

Changed. See Lines: 828.

Line 760 – “and are” attributed to

Changed. See Lines: 836.

Line 762 – (AMOC; Baker et al....)

Changed. See Lines: 840.

Line 773 – terrestrial ecosystem dynamics? This appears here for the first time and is not in line with the introduction... Which aspects of the terrestrial ecosystem? Be more specific and clarify...!

We agree with reviewer's observation. That is why we have added several phrases that clarify it in the introduction, in the study area and we have adapted the aforementioned text to the problem previously described. See Lines: See Line: 860.

Line 777- the evolution.. of what? Mid-Late Holocene

Now it is clarified in the text. See Lines: See Line: 864.

Line 790-791 – add a brief comment on potential reasons for this regional diversity and discrepancies here

The explanation of the causes of this diversity in the Arctic is a very complex and debatable problem, which would require a much more detailed analysis of the literature, which exceeds the objectives of this work. In any case, we have followed the reviewer's suggestion and summarized it in one sentence the basic and obvious fact of that diversity. See Lines: 879-800.

References list – check Lifton reference!!

We have corrected the reference. See Line: 1200.



## **Highlights**

1. The timing of neoglacial advances in the Antarctic Peninsula.
2. Study case: Byers Peninsula, Livingston Island, South Shetland Islands.
3. We applied cosmogenic ray exposure using  $^{36}\text{Cl}$  and  $^{10}\text{Be}$  isotopes.
4. Deglaciation started around  $9.9 \pm 1.2$  ka.
5. Glacier expansion at  $\sim 4.1 \pm 0.5$  and  $\sim 1.0 \pm 0.2$  ka.

1 **Timing of formation of neoglacial landforms in the South Shetland Islands (Antarctic**  
2 **Peninsula): regional and global implications**

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13  
14 **Key words:** Antarctic Peninsula, Byers Peninsula, Neoglaciation, surface exposure  
15 dating.

16 **Abstract**

17 The timing of neoglacial advances in the Antarctic Peninsula (AP) is not yet well  
18 constrained. Accurate temporal reconstruction of Neoglaciation in the AP is needed to  
19 better understand past glacial responses and regional and global teleconnections during  
20 the Holocene. Here, we examine all available information about neoglacial advances in  
21 the South Shetland Islands (SSI) as well as in the broader geographical context of the AP  
22 region and Antarctic continent. In order to shed light on the contrasting chronologies  
23 existing for neoglacial advances in these regions, we focused on a case study where a  
24 detailed picture of the Holocene deglaciation was already available. Lake sediments  
25 revealed that Byers Peninsula, west of Livingston Island (SSI), was fully deglaciated  
26 during the Holocene Thermal Maximum. To complement this approach, we identified  
27 glacially polished bedrock surfaces, erratic boulders and a moraine ridge near the present  
28 front of the glacier in the SE corner. We applied cosmogenic ray exposure (CRE) dating  
29 using in situ <sup>36</sup>Cl for basalt rocks and <sup>10</sup>Be for granitic rocks in: (i) 8 samples from glacial  
30 erratic and ice-rafted boulders, (ii) 2 samples from moraine boulders, (iii) 2 samples from  
31 polished bedrock surfaces, and (iv) 1 sample from an erratic boulder deposited on one of

32 these surfaces. The CRE dates indicate that the onset of deglaciation started around  $9.9 \pm$   
33  $1.2$  ka, with two phases of glacier expansion during the Mid-Late Holocene forming  
34 moraines at  $\sim 4.1 \pm 0.5$  and  $\sim 1.0 \pm 0.2$  ka, respectively. The main neoglacial advances in  
35 the AP and the SSI were mostly synchronous and coincided with cold periods, as shown  
36 by other records (e.g. glacio-isostatic marine terraces, marine and lake sediments). In  
37 addition, these periods of glacial expansion show a similar timing to those recorded in the  
38 Arctic. These results suggest that Neoglaciation was driven by global climate forcing in  
39 both polar areas despite temporal variations at regional and local scale.

40

## 41 **1. Introduction**

42 The Antarctic Peninsula (AP; Fig. 1) is affected by intense warming, which is recorded  
43 through reliable meteorological measurements since approximately 1950. This most  
44 recent period has been called Recent Rapid Warming (RRW), and is characterized by an  
45 accelerated temperature increase being four times greater in the AP region than the  
46 Earth's average (Vaughan et al., 2003; Turner et al., 2005). This dramatic temperature  
47 rise caused fast melting of glaciers and a generalized retreat of glacier fronts (Vaughan  
48 and Doake, 1996; Cook et al., 2005; Kunz et al., 2012; Pritchard et al., 2012). However,  
49 since 1998 a tendency towards cooling in the AP and a return to positive mass glacial  
50 balances has been detected (Navarro et al. 2013; Engel et al., 2018). This shift is  
51 associated with an increase in the frequency of low pressure systems that has led higher  
52 precipitation and lower summer temperatures in the region, particularly in the N and NE  
53 AP region, including the South Shetland Islands (SSI) (Turner et al., 2016; Sancho et al.,  
54 2017; Oliva et al., 2017a) (Fig. 2). Therefore, the question arises whether RRW is the  
55 beginning of a trend towards deglaciation in the AP, or a brief warming within the long-  
56 term cooling trend affecting this region over the last millennia, continuation of the long-  
57 term cooling started since the Neoglaciation (Vaughan et al., 2003; Bentley et al., 2009).  
58 However, the timing, distribution, evolution and origin of the neoglacial advances in the  
59 AP region is still poorly understood because of: (i) the lack of historical information on  
60 this continent, (ii) the limited number of terrestrial natural archives as sources of  
61 palaeoenvironmental information, and (iii) the difficulties of dating these glacial  
62 advances in Antarctica (Davies et al., 2012).

63 Porter and Denton (1967) proposed the generalization of the term Neoglaciation to refer  
64 to the glacial advances that occurred after the Holocene Thermal Maximum (HTM: 11-5

65 ka, [Renssen et al., 2009](#)) until the end of the Little Ice Age (LIA). Evidence of Late  
66 Holocene glacial advances has been found in a great variety of latitudes and continents  
67 ([Solomina et al., 2015](#)), widespread also in mountains of the Southern Hemisphere  
68 ([Clapperton and Sugden, 1988](#); [Porter, 2000](#)) and Antarctica ([Clapperton and Sugden,](#)  
69 [1988](#); [Clapperton et al., 1989](#); [Ingólfsson et al., 1998](#)). However, delimiting the end of the  
70 HTM and the onset of the neoglacial chronology in the Polar Regions is a matter of great  
71 complexity ([Kaufman et al., 2004](#); [Renssen et al., 2009, 2012](#)). Similarly, the concept of  
72 Neoglaciation in the Arctic has been proposed as a tendency to climate cooling ([McKay](#)  
73 [et al., 2018](#)). However, phases of glacial advances in the Arctic during Neoglaciation  
74 alternated with warm periods and glacial retreat, occurring asynchronously across the  
75 region without a clear regional pattern ([McKay et al., 2018](#)).

76 As in the Arctic, the chronology of Neoglaciation varied significantly within the AP and  
77 throughout the Antarctic continent ([Bentley and Hodgson, 2009](#)). According to the  
78 available glacio-marine sedimentary records, cold phases during Neoglaciation in the AP  
79 region were short, not exceeding 0.5 ka ([Yoon et al., 2010](#)), and alternated with longer  
80 warm periods ([Davies et al., 2012](#)). The first synthesis on climatic and glacial evolution  
81 in the AP during the Holocene was carried out by [Ingólfsson et al. \(1998\)](#) who suggested  
82 the first neoglacial advances after 5 ka. [Ingólfsson et al. \(2003\)](#) proposed several other  
83 neoglacial advances between 3 and 1 cal ka BP. [Bentley et al. \(2009, 2014\)](#) reported a  
84 generalized warm period in the AP between 4.5 and 2.8 cal ka BP followed by a relatively  
85 widespread cold period between 2.5 and 1.2 cal ka BP. [Bentley and Hodgson \(2009\)](#)  
86 highlighted that Late Holocene cold phases in different sites across the AP were not  
87 synchronous, even in close regions. [Hall \(2009\)](#) provided a synthesis of Holocene glacial  
88 evolution for the entire Antarctic continent, including the AP, with many references to  
89 neoglacial landforms. Subsequent studies provided new glacial evidence of neoglacial  
90 landforms in other regions, thus confirming the occurrence of the Neoglaciation as a  
91 widespread pattern of glacial advance in the AP ([Davies et al., 2012, 2013](#); [Carrivick et](#)  
92 [al., 2012](#); [Cofaigh et al., 2014](#)). However, these new data also introduce new uncertainties  
93 about the time range of neoglacial phases in different areas across this region ([Allen et](#)  
94 [al., 2010](#); [Davies et al., 2012](#); [Barnard et al., 2014](#); [Cofaigh et al., 2014](#)). The spatio-  
95 temporal variations of glacial oscillations over the last centuries are also a consequence  
96 of climate variability in the region ([Mosley-Thompson et al., 1990](#); [Guglielmin et al.,](#)  
97 [2016](#); [Brightley, 2017](#)). Recently, [Čejka et al. \(2019\)](#) examined the neoglacial onset in

108 the AP region through the revision of 22 studies focused on ice cores and marine and lake  
109 sediments. They concluded that the beginning of neoglacial cooling occurred, in average,  
110 at  $2.6 \pm 0.8$  cal ka BP, with large spatio-temporal differences within the AP region ranging  
111 between 4.8 ka and 1.2 cal ka BP. However, a review on glacier oscillations during  
112 Neoglaciatioin is still missing. [Kaplan et al. \(2020\)](#) provided new information about the  
113 Neoglaciatioin chronology in the AP and compared it with the neoglacial advances in  
114 Patagonia.

115 The Byers Peninsula, on the western end of Livingston Island, is the largest deglaciated  
116 terrestrial area in the SSI (Fig. 2). In this area, lake records suggest that the retreat of the  
117 Rotch Dome Glacier occurred throughout the Holocene ([Toro et al., 2013](#); [Oliva et al.,](#)  
118 [2016](#); [Ruiz-Fernández and Oliva, 2016](#)), although the existence of neoglacial landforms,  
119 such as moraines, is not yet evidenced. The application of cosmogenic radiation exposure  
120 (CRE) methods – that have not been applied yet to neoglacial landforms in the SSI –  
121 offers new possibilities to obtain a detailed chronology for the development of these  
122 neoglacial landforms. The knowledge of the age of moraines formed in neoglacial  
123 advances in the Byers Peninsula can provide important information on the possible  
124 synchrony of these advances within the context of the AP.

125 The aim of this paper is to map and date neoglacial landforms in the SSI as well as explore  
126 their paleoclimatic implications in the context of the Antarctic continent. Firstly, we  
127 review the current state of knowledge of Neoglaciatioin in Antarctica, focusing mainly in  
128 the AP. In order to provide the most detailed picture on the paleoclimatic evolution in this  
129 region, we examined all available records from ice cores, deep marine sediment cores,  
lake sediments and glacial landforms. Subsequently, we focused on an area of the AP  
region where information about Holocene glacial advances is still absent: the Byers  
Peninsula. In this peninsula, we have mapped the spatial distribution of possible  
neoglacial moraines, analyzed the geomorphological setting, and applied CRE dating to  
these landforms.

125

## 126 **2. The Neoglaciatioin in the Antarctic Peninsula and South Shetland Islands**

127 A recent synthesis of the evolution of the West and East Antarctic Ice Sheets shows that  
128 glacial mass loss was intense from 9 until 7-6 ka in both areas ([Mackintosh et al., 2011,](#)  
129 [2014](#)), mainly due to ocean warming, although the long-term glacial shrinking had

130 already begun before 10 ka (Larter et al., 2014). (Fig. 1, Table 1). A wide range of climatic  
131 proxies provides data on the occurrence of various cold periods in the AP for the last  
132 millennia.

133 In order to constrain the magnitude and the chronology of neoglacial advances and  
134 retreats in the SSI, we first review the climatic evolution over the Mid- and Late Holocene  
135 in the AP region based on different environmental sources:

136 (i) *Neoglaciation from ice cores in the AP.* Polar ice cores preserve and provide  
137 information on climatic changes and their causes, mainly from comparison of the  $\delta^{18}\text{O}$ ,  
138 deuterium and  $\text{CO}_2$  concentration variations in different layers, as well as on the climate  
139 and chronology from the impurities of the ice (Lorius et al., 1990). The most accurate  
140 reconstruction from ice core records in the AP comes from James Ross Island, NE AP,  
141 which revealed a cold phase between 2.5 and 0.6 cal ka BP, and a peak of cold climate  
142 that occurred roughly at 1.4 cal ka BP (Mulvaney et al., 2012; Abram et al., 2013). The  
143 last phase of intense cooling was recorded during the LIA at around AD ~1410-1460  
144 (Abram et al., 2013), as also detected in ice cores from other areas in Antarctica, e.g. Ross  
145 Sea, with a temperature ca. 2° C colder than present (Bertler et al., 2011), or in Princess  
146 Elizabeth Land, East Antarctica, with a significant cooling at AD 1450–1850 (Li et al.,  
147 2009) (Fig. 1 and Table 1).

148 (ii) *Neoglaciation from marine sediments in the AP.* Deep marine sediment cores can  
149 reveal climatic changes based on the proportion of foraminifera and microfossils that are  
150 highly sensitive to sea surface temperatures. The ratio of the oxygen isotopes from the  
151 calcium carbonate shells of foraminifera and coccoliths, and from the silicon dioxide  
152 shells of radiolarians and diatoms, is indicative of the temperature of the ocean during the  
153 build-up of every shell layer (Rothwell and Rack, 2006). Several sedimentary records  
154 were collected from areas adjacent to the AP region. As in ice core records, most records  
155 show changes in sedimentation patterns during neoglacial cold periods, with notable  
156 chronological differences. Records obtained in the Bransfield Strait reported abrupt cold  
157 conditions at 4.5 and 2.5 cal ka BP (Shevenell et al., 2011), at 3.5 and 1.2 cal ka BP (Khim  
158 et al., 2002; Heroy et al., 2008; Barnard et al., 2014) and during the LIA (Khim et al.,  
159 2002; Barnard et al., 2014). In other records from the western side of the AP, similar  
160 patterns were observed, including long-term cooling trends from 3.3 to 0.1 cal ka BP in  
161 Palmer Deep (Domack et al., 2001), from 2.8 to 0.2 cal ka BP in Marguerite Bay (Allen  
162 et al., 2010), and during the LIA in Müller Ice Shelf (Domack et al., 1995) and in Barilari

163 Bay, Graham Land (Christ et al., 2015; Reilly et al., 2016). Neoglacial cooling was also  
164 reported in the NE of the AP, as in the Firth of Tay, where marine sediment cores revealed  
165 a minor glacial advance between 6.0 and 4.5 cal ka BP, retreat between 4.5 and 3.5 cal ka  
166 BP, and glacial readvance from 3.5 cal ka BP to recent times (Michalchuk et al., 2009)  
167 (Fig. 1 and Table 1).

168 *(iii) Neoglaciation from lake sediments in the AP.* Paleolimnological studies can reveal  
169 climatic changes from a wide range of proxies including the analysis of magnetic  
170 susceptibility, grain-size distribution, geochemistry, diatoms studies, and geochronology  
171 (Zale and Karlén, 1989; Čejka et al., 2019). Čejka et al. (2019) examined the onset of  
172 Neoglaciation in the AP region from lacustrine sediments suggesting that it occurred at 2  
173 cal ka BP, with significant regional variations. Conversely, in our study, we analyzed  
174 periods during the Neoglaciation that led to glacial advances. Evidences of neoglacial  
175 advances in the AP from lacustrine sediments suggest a phase of glacial expansion at 1.2  
176 cal ka BP in James Ross Island, (Björck et al., 1996a), at around 5 ka and during the LIA  
177 in Hope Bay (Zale and Karlén, 1989) and from 2.6 until 1.1 cal ka BP in Marguerite Bay  
178 (Hodgson et al., 2013) (Fig. 1 and Table 1).

179 *(iv) Neoglaciation from raised beaches in the AP.* Rates of glacio-isostatic uplift inferred  
180 from the elevation of raised beaches are indicative of the intensity of the deglaciation  
181 (Simkins et al., 2013). Hall and Denton (1999) determined that these rates were especially  
182 high between 8 and 5 cal ka BP in the Ross Sea, suggesting that glacial shrinking  
183 decreased during the Mid Holocene. However, decreasing uplift rates can be also  
184 indicative of glacial advances (Simkins et al., 2013). In Beak Island, NE AP, the relative  
185 sea level fell from a maximum uplift rate of 3.91 mm yr<sup>-1</sup> at around 8 cal ka BP to 2.11  
186 mm yr<sup>-1</sup> between 6.9 and 2.9 cal ka BP, 1.63 mm yr<sup>-1</sup> between 2.9 and 1.8 cal ka BP, and  
187 finally to 0.29 mm yr<sup>-1</sup> during the last 1.8 ka BP. This reveals a trend towards more glacial  
188 stability and/or glacial readvances during the neoglacial period (Roberts et al., 2011) (Fig.  
189 1 and Table 1).

190 *(v) Neoglaciation from glacial landforms in the AP.* Together with these proxies, some  
191 studies have focused on the direct dating of neoglacial landforms in the AP. Radiocarbon  
192 dating of unconsolidated glacial sediments demonstrated the occurrence of six neoglacial  
193 advances at 6.5, 4.6, 3.9 cal ka BP, two around 2.6 cal ka BP, as well as glacial expansion  
194 during the LIA in James Ross Island (Strelin et al., 2006). This LIA glacial advance has  
195 been also detected in the western AP, namely in Rothera Point, Marguerite Bay

196 (Guglielmin et al., 2016) as well as in Anvers Island, where the glacier front was at or  
197 behind its present position at 0.7-0.9 cal ka BP (Hall et al., 2010) (Fig. 1 and Table 1).  
198 Outside the AP, in the Scott Coast, in Ross Sea, Late Holocene moraines are distributed  
199 on dated raised beaches indicating a neoglacial advance that occurred between 3.5 ka and  
200 the LIA (Hall and Denton, 2002).

201 However, the most reliable approach to date Neoglaciation in the AP is based on the  
202 dating of glacial landforms using CRE methods. In James Ross Island, one of the areas  
203 with most CRE dates available, deglaciation was intense until 6 ka (Hodgson et al., 2011;  
204 Glasser et al., 2014) and neoglacial advances occurred at ~4.8 ka and from 1.5 to 0.3 ka  
205 ( $^{10}\text{Be}$  ages) (Davies et al., 2014). Close to James Ross Island, in Solari Bay, the Sjögren,  
206 Boydell and Drygalski glaciers advanced at 1.4 ka ( $^{10}\text{Be}$  ages) (Balco et al., 2013).  
207 Recently, a work focusing on James Ross Island area reported 49  $^{10}\text{Be}$  ages of Holocene  
208 glacial landforms (Kaplan et al., 2020). These results suggest that the major glacial  
209 advance following the HTM occurred at ~7-4 ka, with subsequent phases of glacier  
210 expansion between 3.9 and 3.6 ka, just after 3 ka, between ~2.4 and ~1 ka, and from  
211 ~0.3 to ~0.1 ka (Kaplan et al., 2020).

212 Using CRE dating, neoglacial advances were also detected in the western AP region, as  
213 in Alexander Island, Marguerite Bay, where a period of glacial expansion took place at  
214  $4.4 \pm 0.7$  and 1 ka ( $^{10}\text{Be}$  ages) (Davies et al., 2017). Neoglacial advances have been  
215 reported in other areas in Antarctica, such as in the Darwin Mountains between 3 and 0.5  
216 ka ( $^{10}\text{Be}$  ages) (Storey et al., 2010) (Fig. 1 and Table 1).

217 *(vi) Neoglaciation in the South Shetland Islands.* The SSI archipelago, located NW of  
218 the AP, lies at 120 km from the AP. The existence of neoglacial landforms in the SSI is  
219 known since the last third of the 20th century (Fig. 2 and Table 2). In the first  
220 geomorphological studies, at the end of the 1960s and early 1970s, researchers focused  
221 on the existence of moraines distributed a few hundred meters away from the present-day  
222 glacier fronts, which transgressed and overlapped recent raised beaches (Araya and  
223 Hervé, 1966; Everett, 1971; John and Sugden, 1971; John, 1972; Sugden and John, 1973).

224 This geomorphological pattern was first described in several deglaciated areas of the SSI,  
225 such as Byers and Hurd peninsulas (Livingston Island) and Fildes peninsula (King George  
226 Island). Since then, attention has been paid to inferring the age of deglaciation of these  
227 raised beaches and their relationship with moraines which transgressed them. Previous



228 works considered that the raised beaches formed as a result of glacio-isostatic rebound  
229 due to the partial deglaciation of these islands. The existence of moraines distributed on  
230 some of these raised beaches suggest that the moraines are chronologically younger than  
231 the raised beaches. Radiocarbon dating of organic fragments interbedded in the raised  
232 beach provide a minimum age for the formation of the moraine resting on this beach. In  
233 Hurd Peninsula, [Everett \(1971\)](#) inferred a phase of glacial expansion that advanced on a  
234 raised beach at 10-12 m a.s.l. and a subsequent glacier advance that left a moraine on a  
235 raised beach at 4-6 m a.s.l., which was known as the "False Bay event" ([Everett, 1971](#)).  
236 The application of radiocarbon dating to raised beaches at 4-6 m a.s.l. in Fildes Peninsula  
237 yielded an age of 0.4-0.7 cal ka BP. As this level of the raised beach (4-6 m a.s.l.) is  
238 frequently occupied by the youngest moraines existing in the SSI, geomorphologists  
239 deduced that these moraines were of LIA age ([John and Sugden, 1971](#); [John, 1972](#);  
240 [Sugden and John, 1973](#)). Subsequently, further radiocarbon dates differentiate between  
241 two levels of raised beaches in the SSI that were covered by the last neoglacial advances:  
242 (i) the first one at 6 m a.s.l., (varying locally between 5 and 7.5 m a.s.l.) associated with  
243 a 2-3 km glacier readvance dated at the 13th to early 16th centuries A.D., and (ii) another  
244 one at 2-3 m a.s.l. associated with a 0.25-1 km glacier readvance at approximately the 15-  
245 17th centuries A.D, that in some areas overlapped the previous ([Curl, 1980](#); [Sugden and](#)  
246 [Clapperton, 1986](#); [Clapperton, and Sugden, 1988](#)). Further radiocarbon dates of raised  
247 beaches also suggest, at least, two neoglacial advances between 3 and 1 cal ka BP ([Barsch](#)  
248 [and Mäusbacher, 1986](#)). The application of lichenometric dating to the moraines  
249 distributed on the lowest raised beaches in the SSI confirmed that these landforms  
250 developed during LIA glacial advances ([Birkenmajer, 1981, 1995; 1998](#)) (Fig. 2 and  
251 Table 2).

252 To better understand the relationship between glacial advances and raised beaches  
253 transgressed by moraines, a more accurate geomorphological mapping was conducted to  
254 determine the altitude and extent of raised beaches in the Byers Peninsula ([Arche et al.,](#)  
255 [1996](#)) and their correlation with those existing in other ice-free areas in this archipelago  
256 ([Fretwell et al., 2010](#)). The abundance of ice rafted debris of allochthonous lithology on  
257 raised beaches dated between 0.25 and 1.7 cal ka BP suggest that these beaches were  
258 related to cold periods of increased glacial extent and greater iceberg delivery ([Hall and](#)  
259 [Perry, 2004](#)). In addition, the dating of the highest raised beaches (located at about 16-20  
260 m a.s.l.) indicates that the most massive deglaciation phase in this peninsula occurred

261 between 9 and 6 cal ka BP, with glaciers close to their current position by 5.5 cal ka BP  
262 (Barsch and Mäusbacher, 1986; Mäusbacher, 1991; Del Valle et al., 2002; Hall, 2003;  
263 Bentley et al., 2005; Hall, 2010; Watcham et al., 2011).

264 New records obtained during the early 21st century have improved our knowledge on the  
265 age of moraines in the SSI (Fig. 2 and Table 2). The oldest moraines in Livingston Island  
266 identified by Everett (1971) were dated at >7.3 ka, predating the formation of the oldest  
267 raised beaches (Sugden and John, 1973; Curl, 1980; López-Martínez et al., 1992; Hall  
268 and Perry, 2004; Bentley et al., 2005; Hall, 2009; Fretwell et al., 2010). Hall (2007) dated  
269 by radiocarbon the youngest moraines previously studied in Fildes and Hurd Peninsulas  
270 (Everett, 1971, John and Sugden, 1971; John, 1972; Sugden and John, 1973). However,  
271 Hall (2007) considers the possibility that there could have been previous advances as old  
272 as 2.8 cal ka BP. Radiocarbon ages from a 4-6 m raised beach related to these moraines  
273 support glacial advance and transgression during the LIA. The application of Optically  
274 Stimulated Luminescence (OSL) dating methods to these younger beaches at 4-6 m in the  
275 Fildes Peninsula confirmed an age of the 16-18th centuries AD, which coincided with the  
276 LIA (Simms et al., 2011a, 2012).

277 On the one hand, at the end of the 80s and beginning of the 90s, sediment cores collected  
278 from several lakes in Livingston and King George Islands reported radiocarbon minimum  
279 ages of 4-5 cal ka BP for deglaciation (Mäusbacher et al., 1989; Björck et al., 1991, 1993,  
280 1996b). The analysis of lake sediments from a number of lakes in the western part of the  
281 Byers Peninsula suggested the occurrence of a warm period occurring between 3.2 and  
282 2.7 cal ka BP (Björck et al., 1993) and a remarkable cooling between 1.5 and 0.5 cal ka  
283 BP (Björck et al., 1991). More recent studies suggest that the onset of the deglaciation of  
284 the Byers Peninsula occurred at 8.3 cal ka BP (Toro et al., 2013), with the deglaciation of  
285 the central plateau taking place between 8.3 and 5.9 cal ka BP and ice-free exposure of  
286 the easternmost fringe, close to the present-day glacier front, around 1.8 cal ka BP (Oliva  
287 et al., 2016).

288 CRE dating methods were applied to polished bedrock surfaces in the Barton Peninsula  
289 (King George Island) along a transect from the highest peaks to the coast. These data  
290 showed that deglaciation of this small peninsula had begun earlier than inferred from lake  
291 sediments and raised beaches, between 17 and 14 ka, and had finished 1 ka ago (Seong et  
292 al., 2009). Hall (2009) CRE dated moraines from Hurd Peninsula and Marion Cove (King  
293 George Island) at 1.5-1.0 ka (Hall and Stone, personal communication).

294 Finally, the analysis of marine sediments in Maxwell Bay (King George Island)  
295 determined that there was rapid glacial retreat from 10.1 to 8.2 cal ka BP and a period of  
296 gradual cooling and more extensive sea-ice cover in the bay from 5.9 cal ka BP onwards,  
297 with no evidence of LIA glacial advance (Milliken et al., 2009). However, a more recent  
298 study of marine sediments in Maxwell Bay confirmed that the deglaciation began as soon  
299 as 14 cal ka BP – as was proposed by CRE dating in the nearby Barton Peninsula (Seong  
300 et al., 2009) – and that deglaciation was completed by 5.9 cal ka BP, with a neoglacial  
301 advance into the bay ending at approximately 1.7 ka (Simms et al., 2011a). Recent coastal  
302 sediment analysis in Fildes Peninsula showed a cold period from 5.8 to 4.8 cal ka BP, a  
303 mid-Holocene climatic optimum between 4.4 and 2.7 cal ka BP, and the onset of  
304 Neoglaciation at 2.7 cal ka BP (Chu et al., 2017). Sediment cores obtained from the  
305 continental shelf of the northern SSI pointed to the existence of a cold period around 0.33  
306 cal ka BP, which must have corresponded to the LIA (Yoo et al., 2009).

307 To sum up, despite varied results, a common pattern can be deduced in studies of  
308 neoglacial phases in the SSI in the context of AP region. The glaciers were similar to or  
309 smaller than present-day in the AP, as in the SSI, around 6 ka.

310 Before the warmer period detected in the AP between 4.5 and 2.8 cal ka BP (Bentley et  
311 al., 2009), a cold period with the first neoglacial advances occurred around 5 ka in many  
312 places of the AP and the rest of the continent (Zale and Karlén, 1989; Mosley-Thompson,  
313 1996; Khim et al., 2002; Strelin et al., 2006; Heroy et al., 2008; Bentley et al., 2009;  
314 Michalchuk et al., 2009; Davies et al., 2012; Shevenell et al., 2011; Carrivick et al., 2012;  
315 Cofaigh et al., 2014; Barnard et al., 2014; Davies et al., 2017; Kaplan et al., 2020). So far,  
316 there is no evidence of this neoglacial advance in the SSI, except perhaps for the  
317 references made by Everett (1971) in the Hurd Peninsula about moraines in relation to  
318 the raised beaches at 10-12 m a.s.l.

319 Another period of widespread neoglacial advance took place in the AP between 2.8 and  
320 1.4 ka, with cooling intensifying between 1.8 and 1.4 cal ka BP. (Mosley-Thompson,  
321 1996; Björck et al., 1996; Khim et al., 2002; Heroy et al., 2008; Bentley et al., 2009; Yoon  
322 et al., 2010; Domack et al., 2001; Strelin et al., 2006; Michalchuk et al., 2009; Allen et  
323 al., 2010; Davies et al., 2012; Mulvaney et al., 2012; Shevenell et al., 2011; Mulvaney et  
324 al., 2012; Abram et al., 2013; Hodgson et al., 2013; Barnard et al., 2014; Davies et al.,  
325 2014; Čejka et al., 2019; Kaplan et al., 2020). To date, this glacial advance is also poorly  
326 represented in the SSI, with the only reference by Hall (2007, 2009). However, there is

327 some evidence of a cold period around 1.8 ka in the SSI from other paleoclimatic proxies,  
328 such as ice rafted debris on raised beaches (Hall and Perry, 2004), lake sediments (Björck  
329 et al., 1991, 1993; Oliva et al., 2016), and marine records (Chu et al., 2017).

330 The information available on glacial advances during the LIA is varied across the AP, as  
331 in the SSI. Similarly, there is clear evidence of advances in some areas (Strelin et al.,  
332 2006), but it is absent in archives such as lake and marine sediments (Shevenell et al.,  
333 2011; Hodgson et al., 2013) as well as in ice core records (Mulvaney et al., 2012;  
334 Brightley, 2017). In any case, it is important to note that in many areas a cooling period  
335 was observed from 1.5 ka to the first cooling events associated with the LIA (Zale and  
336 Karlén, 1989; Domack et al., 2001; Hall and Denton, 2002; Allen et al., 2010; Storey et  
337 al., 2010; Michalchuk et al., 2009; Balco et al., 2013; Davies et al., 2014; Davies et al.,  
338 2017). On the other hand, most of the studies carried out on the youngest moraines of the  
339 SSI, transgressing the 4-6 m raised beach, confirmed that they were formed during the  
340 LIA, between the 16th and 18th centuries AD, with minor age differences depending on  
341 dating methods.

342

### 343 **3. Geographical setting of the case study: the Byers Peninsula**

344 With the aim of resolving the discrepancies observed between the SSI and the rest of the  
345 AP on the timing of development of neoglacial landforms, this work explores the age of  
346 formation of several landforms in an area that is already known to have been deglaciated  
347 during the Mid-Late Holocene (Oliva et al., 2016), the Byers Peninsula, the largest ice-  
348 free area in the SSI (Fig. 2 and Table 3). The Byers Peninsula (62°34'35"–62°40'35"S,  
349 60°54'14"–61°13'07"W) is located on the western end of Livingston Island, the second  
350 largest island in the SSI, with an area of approximately 60 km<sup>2</sup>, and a maximum altitude  
351 of 265 m a.s.l.. The peninsula is part of a Jurassic-Quaternary magmatic forearc generated  
352 by Mesozoic and Cenozoic subduction processes along the South Shetland Trench  
353 (Smellie et al., 1980; Alfaro et al., 2010). This peninsula is composed of Upper Jurassic-  
354 Lower Cretaceous sedimentary deposits (mainly sandstones, mudstones and  
355 conglomerates) and volcanic and volcanoclastic rocks, with abundant intrusive igneous  
356 rocks of basalt-basaltic andesite composition (Smellie et al., 1980; Hathway and Lomas,  
357 1998; Parica et al., 2007; Alfaro et al., 2010). The geomorphology of the Byers Peninsula  
358 (Araya and Hervé, 1966; John and Sugden, 1971; López-Martínez et al., 1996) is formed  
359 by a high plateau (80-110 m), considered a marine platform, onto which protruded a series

360 of volcanic plugs such as Start Hill (265 m a.s.l.), Chester Cone (188 m), Cerro Negro  
361 (143 m), Tsamblak Hill (113 m) and Clark Nunatak (147 m). Many lakes are distributed  
362 on this plateau, such as the Limnopolar, Chester, Escondido, Cerro Negro and Domo lakes  
363 (Fig. 2, Table 3). This central plateau is encircled by an intermediate marine platform (50-  
364 80 m) that is surrounded by a lower platform above which Holocene raised beaches from  
365 2 to 15-16 m a.s.l have developed. The sequence of raised beaches is particularly well-  
366 preserved in the South beaches (S), the Robbery beaches (N), and the President beaches  
367 (W). The ice-free area of the Byers Peninsula is delimited in its eastern flank by the Dome  
368 Rotch Glacier, which covers the rest of the western part of Livingston Island reaching a  
369 maximum altitude of 360 m. Although there is no information about the recent evolution  
370 of Dome Rotch Glacier in the side of the Byers Peninsula, significant retreat has been  
371 observed in other neighbouring coastal fringes since the 1950s (Birkenmajer 2002) that  
372 seems to have decelerated in the last decade (Navarro et al., 2013; Oliva et al., 2017).

373 The mean annual temperature is around  $-2.8$  °C at 80 m and annual precipitation (rain  
374 and snowfall) reaches ca. 650 mm at this altitude (Bañón et al., 2013; De Pablo et al.,  
375 2014). Discontinuous permafrost patches have been detected in raised beaches (Correia  
376 et al., 2017) whereas permafrost is continuous at the central plateau (de Pablo et al., 2014).  
377 Abundant periglacial landforms distributed across the peninsula show evidence of active  
378 periglacial dynamics in the area, strongly conditioned by local topography and snow  
379 distribution (Serrano et al., 1996; López-Martínez et al., 2012; Hrbáček et al., 2016; Ruiz-  
380 Fernández et al., 2016; Oliva et al., 2017b). Most of the area is covered by bryophytes  
381 and lichens, including the two native Antarctic phanerogams on the raised beaches  
382 (Lindsay, 1971; Vera, 2013), which makes the Byers Peninsula a unique environment in  
383 terms of terrestrial biodiversity within Antarctica (Benayas et al., 2013; Almela et al.,  
384 2019). To protect this hotspot of biodiversity, the Byers Peninsula was designated an  
385 Antarctic Specially Protected Area (ASPA N° 126).

386 The Byers Peninsula was covered by an ice sheet distributed across the SSI during the  
387 last glacial cycle (Araya and Hervé, 1966; John and Sugden, 1971; López Martínez et al.,  
388 1996). This ice sheet was connected with the AP ice sheet during the maximum ice extent,  
389 though it became isolated as ice started thinning during the deglaciation (Cofaigh et al.,  
390 2014). Previous studies on lake sediments have determined that the deglaciation of the  
391 Byers Peninsula occurred from W to E, with a timing of 7.5 to 1.8 cal ka BP (Toro et al.,  
392 2013; Oliva et al., 2016; Ruiz-Fernández and Oliva, 2016). Domo Lake, located only at

393 350 m from the present glacier front, was deglaciated around 1.8 ka (Oliva et al., 2016).  
394 Several geomorphological landforms and deposits of glacial origin are distributed  
395 between the contemporary glacial front and the sea. This is the case of the large  
396 longitudinal ice-cored moraines located in front of the Rotch Dome Glacier (Martinez de  
397 Pisón et al., 1996; Ruiz-Fernández et al., 2016). John and Sugden (1971) observed how  
398 these moraines override all marine levels incorporating littoral deposits; they suggested  
399 that the most recent moraines were directly related to the 4-6 m beach and were  
400 contemporary in age, representing thus a recent glacial readvance. Hansom (1979)  
401 radiocarbon dated a 10 m a.s.l. raised beach at 1.8 cal ka BP, whereas Curl (1980) reported  
402 that the 6 m a.s.l. raised beach formed during the 15-17th centuries AD. Hall and Perry  
403 (2004) suggested that this beach and the 10 m a.s.l. unit formed during cold periods over  
404 the last 1.7 cal ka BP, as they are rich in ice rafted debris. Hall (2003, 2010) contributed  
405 numerous dates for all the sequences of raised beaches in the main complexes of the Byers  
406 Peninsula, concluding that the highest levels formed at 7.4 cal ka BP and confirming that  
407 the 6 m a.s.l. raised beach developed during the 15-17th centuries AD. The frontal ice-  
408 cored moraines in front of the Rotch Dome Glacier have been very stable over the last  
409 decades, as can be seen in photos and descriptions in old publications (John and Sugden,  
410 1971; López Martínez et al., 1996; Hall, 2010). The glacier has retreated from these  
411 moraines only in the vicinity of the northern coast and in the southern fringe, around Clark  
412 Nunatak (Martinez de Pisón et al., 1996). In the nearby peninsula of Elephant Point, only  
413 3 km SE of Clark Nunatak, a similar retreat occurred from 1956 to 2000 (Oliva and Ruiz-  
414 Fernández, 2015, 2017) (Fig. 2 and Table 3).

## 415 **5. Methodology**

### 416 *5.1 Geomorphological research and sampling strategy*

417 In the eastern fringe of the Byers Peninsula, next to Rotch Dome Glacier, an ice-cored  
418 moraine has been described to be in contact with the glacier front from 1966 to 1996  
419 (Araya and Hervé, 1966; John and Sugden, 1971; Martinez de Pisón et al., 1996) (Fig. 2).  
420 Over these thirty years, the limits, extent, and shape of the ice-cored moraine crests were  
421 identical to those described in earlier observations (Martinez de Pisón et al., 1996),  
422 showing evidence of the prevailing geomorphic stability at annual to decadal timescales  
423 (López Martínez et al., 1996; Hall, 2010). The ice-cored moraine system develops from  
424 a single polygenic ridge in the southern edge to a sequence of twelve ridges in its northern  
425 fringe next to Robbery beaches (Ruiz-Fernández et al., 2016). These ice-cored moraines



426 are similar to those described in other areas of the AP region (Hambrey et al., 2015). As  
427 for Hurd and Fildes peninsulas, Martínez de Pisón et al., (1996) proposed also a  
428 synchronicity between the timing of formation of raised beaches and moraines in the  
429 Byers Peninsula.

430 The objective of the geomorphological research was to explore the existence of moraines  
431 disconnected from the glacier front of the Roch Dome Glacier, which would suggest the  
432 occurrence of neoglacial advances. Roch Dome Glacier moraines include sediments  
433 transported by the glacier from the interior of the island, and, therefore, are mostly  
434 composed of basalts. We sampled some of these moraine boulders to apply CRE dating  
435 using *in situ*  $^{36}\text{Cl}$ . These moraines transgressed raised beaches whose age is already well  
436 constrained (Hall 2003 and 2010) and provide a minimum age for the development of the  
437 moraines that lay on them. In addition, researchers already identified the existence of ice-  
438 rafted granite boulders on these raised beaches (Hall and Perry, 2004). These boulders  
439 were sampled to be dated using the *in situ*-produced  $^{10}\text{Be}$  dating method to study their  
440 possible chronological relationship with the sampled moraine. Finally, we collected  
441 samples from glacially polished bedrock surfaces close to the present glacier front for  
442  $^{36}\text{Cl}$  dating in order to date the glacier retreated from this position.

### 443 3.2. CRE sampling and analytical procedures

444 During the fieldwork campaign, a total of 12 samples were taken from glacially polished  
445 outcrops and >1-m-diameter erratic/moraine boulders by means of hammer and chisel.  
446 We focused on flat gentle surfaces on the top of the boulders/outcrops and avoided steep  
447 surfaces and sharp crests in order to ensure the optimal cosmic-ray flux reception. We  
448 selected the most stable boulders, which were rooted in the moraines, with no signs of  
449 spalling or fracturing and that could not have been deposited through gravitational  
450 processes from rock walls. The thickness of the samples ranged from 1.8 to 4.5 cm (Table  
451 4). Following the sample collection, they were crushed and sieved to the 0.25-1 mm  
452 fraction at the “Physical Geography Laboratory” of the Complutense University of  
453 Madrid. Then the samples were physically and chemically processed at the “Laboratoire  
454 National des Nucléides Cosmogéniques” (LN2C) of the “Centre Européen de Recherche  
455 et d’Enseignement des Géosciences de l’Environnement” (CEREGE, Aix-en-Provence,  
456 France). As the sampled surfaces were constituted both by basaltic and granitic rocks  
457 (Table 4), samples were processed for measurement of the *in situ* cosmogenic nuclides  
458  $^{36}\text{Cl}$  (10 samples) and  $^{10}\text{Be}$  (2 samples) by accelerator mass spectrometry (AMS),

459 respectively.

460 In the case of the  $^{36}\text{Cl}$ , the sample preparation procedures were similar to those described  
461 in [Schimmelpfennig et al. \(2011\)](#). Magnetic separation was performed on one sample  
462 (BYC-10) to isolate the abundant feldspar minerals for  $^{36}\text{Cl}$  extraction by discarding the  
463 magnetic minerals with a magnetic separator “Frantz LB-1”.  $^{36}\text{Cl}$  extraction from whole  
464 rock was conducted for the other 9 samples, which had insufficient amounts of feldspar  
465 minerals. In both cases, aliquots of untreated bulk sample were taken to determine the  
466 sample composition (major and trace elements; Table 5). Samples with initial weights of  
467 120 g were rinsed and shaken with ultrapure water for 3 hours to remove dust and fines.  
468 After that, between 40 and 50% of the initial weight was dissolved with a mixture of  
469 diluted nitric acid (10%  $\text{HNO}_3$ ) and concentrated hydrofluoric acid (48% HF) in order to  
470 remove atmospheric  $^{36}\text{Cl}$  and potentially Cl-rich groundmass. After this partial  
471 dissolution, the remaining etched sample mass was rinsed and dried, and 2-g aliquots  
472 were taken to determine the major element concentrations (Table 6). Compositional  
473 analyses of all aliquots were performed at the “Service d’Analyse des Roches et des  
474 Minéraux” (SARM, CRPG, Nancy, France). Before total dissolution,  $\sim 260\ \mu\text{L}$  of a  $^{35}\text{Cl}$   
475 carrier (spike: 010813(4),  $6.92\ \text{mg Cl g}^{-1}$ ,  $^{35}\text{Cl}/^{37}\text{Cl}$  ratio 917.75) manufactured in-house  
476 were added to the samples for isotopic dilution ([Ivy-Ochs et al., 2004](#)), allowing for  
477 simultaneous determination of the  $^{36}\text{Cl}$  and Cl concentrations from the  $^{36}\text{Cl}/^{35}\text{Cl}$  and  
478  $^{35}\text{Cl}/^{37}\text{Cl}$  measurements. For the total dissolution of the rock samples, a mixture of 9 mL  
479 of 10%  $\text{HNO}_3$  per gram of sample and 4.5 mL of 48% HF per gram of sample was used.  
480 After the total dissolution, the samples were centrifuged to discard the undissolved  
481 residues and gel (fluoride complexes,  $\text{CaF}_2$ ). Then, the chlorine in the liquid solution was  
482 precipitated to silver chloride ( $\text{AgCl}$ ) by adding 2 ml of a silver nitrate ( $\text{AgNO}_3$ ) solution  
483 at 10%. To achieve this, samples were stored for 2 days in a dark place to allow the  $\text{AgCl}$   
484 to settle down on the bottom of the bottles. This enabled the extraction of the supernatant  
485 solution (excess HF and  $\text{HNO}_3$ ) by a peristaltic pump avoiding the disturbance of the  
486  $\text{AgCl}$  precipitate. In the next step, aiming to reduce the isobaric interferences of  $^{36}\text{S}$   
487 throughout the  $^{36}\text{Cl}$  measurements in the Accelerator Mass Spectrometer (AMS) sulphur  
488 was removed in the form of barium sulphate ( $\text{BaSO}_4$ ) obtained after the re-dissolution of  
489 this first  $\text{AgCl}$  precipitate and the addition of 1 mL of a saturated solution of barium  
490 nitrate ( $\text{Ba}(\text{NO}_3)_2$ ).  $\text{BaSO}_4$  was discarded by centrifuging and filtering the supernatant  
491 with a syringe and an acrodisc filter. Then,  $\text{AgCl}$  was precipitated again with 3-4 mL of



492 diluted HNO<sub>3</sub> (1:1 vol.). The precipitate was collected after centrifuging, and was rinsed  
493 and finally dried in the oven at 80 °C for 2 days. Once the AgCl precipitate was  
494 completely dried, it was loaded in cathodes. Subsequently, targets were stored in the oven  
495 in order to protect them from atmospheric humidity until they were measured by AMS.

496 For the <sup>10</sup>Be extraction, the processing started with the quartz isolation from the bulk rock.  
497 Magnetic minerals were discarded by using the magnetic separator “Frantz LB-1”. After  
498 that, the non-magnetic fraction was chemically attacked at successive rounds with a  
499 mixture of concentrated hydrochloric (1/3 HCl) and hexafluorosilicic (2/3 H<sub>2</sub>SiF<sub>6</sub>) acids  
500 aiming to dissolve non-quartz minerals. Then, the remaining minerals were  
501 decontaminated from meteoric <sup>10</sup>Be by means of three successive partial dissolutions with  
502 concentrated HF, which also dissolved the remaining impurities from the previous step.  
503 The samples yielded 60-80 g of purified quartz (Table 7). Before the total dissolution,  
504 150 µL of a <sup>9</sup>Be carrier solution (concentration: 3025 ± 9 µg g<sup>-1</sup>; [Merchel et al., 2008](#))  
505 manufactured in-house from a phenakite crystal were added to the samples. Quartz was  
506 totally dissolved in 48 % HF (3.6 mL per g of quartz + 30 mL in excess). The resulting  
507 solutions were evaporated until dryness and samples were recovered with hydrochloric  
508 acid. Subsequently samples were precipitated with ammonia before successive  
509 separations through an anion exchange column (Dowex 1X8) to remove iron and a cation  
510 exchange column (Dowex 50WX8) to discard boron (isobar) and recover Be (Merchel  
511 and Herpers, 1999). Finally, the eluted Be was precipitated to Be(OH)<sub>2</sub> with ammonia and  
512 oxidized to BeO at 700 °C. The targets were prepared by mixing Niobium powder with  
513 the BeO oxide for AMS measurements.

514 The final AgCl and BeO targets were analysed at the AMS facility ASTER “Accélérateur  
515 pour les Sciences de la Terre, Environnement et Risques” at CEREGE to measure the  
516 specific isotope ratios for <sup>36</sup>Cl (<sup>35</sup>Cl/<sup>37</sup>Cl and <sup>36</sup>Cl/<sup>35</sup>Cl) and <sup>10</sup>Be (<sup>10</sup>Be/<sup>9</sup>Be) dating. The  
517 <sup>36</sup>Cl measurements were normalized to the in-house standard SM-CL-12 with an assigned  
518 <sup>36</sup>Cl/<sup>35</sup>Cl ratio value of (1.428 ± 0.021) × 10<sup>-12</sup> ([Merchel et al., 2011](#)) and assuming a  
519 natural <sup>35</sup>Cl/<sup>37</sup>Cl ratio of 3.127. The <sup>10</sup>Be measurements were calibrated against the in-  
520 house standard STD-11, using an assigned <sup>10</sup>Be/<sup>9</sup>Be ratio of (1.191 ± 0.013) × 10<sup>-11</sup>  
521 ([Braucher et al., 2015](#)). Analytical 1σ uncertainties include uncertainties in AMS counting  
522 statistics, the standard <sup>10</sup>Be/<sup>9</sup>Be ratio, an external AMS error of 0.5% (Arnold et al., 2010)  
523 and a chemical blank measurement. A <sup>10</sup>Be half-life of (1.387 ± 0.0012) × 10<sup>6</sup> years was  
524 used ([Chmeleff et al., 2010](#); [Korschinek et al., 2010](#)).

525 We calculated  $^{36}\text{Cl}$  ages using two different procedures. On the one hand, the Excel™  
526 spreadsheet for *in situ*  $^{36}\text{Cl}$  exposure age calculations designed by Schimmelpfennig et al.  
527 (2009), as it allows using different  $^{36}\text{Cl}$  production rates from spallation. In this case, the  
528 elevation-latitude scaling factors were based on the time invariant “St” scheme (Stone,  
529 2000). The production rate of epithermal neutrons for fast neutrons in the atmosphere at  
530 the land/atmosphere interface was  $696\pm 185$  neutrons  $(\text{g air})^{-1} \text{yr}^{-1}$  (Marrero et al., 2016).  
531 The high-energy neutron attenuation length value applied was  $160 \text{ g cm}^{-2}$ . We used the  
532 following  $^{36}\text{Cl}$  production rates –references to sea-level and high latitude (SLHL)– from  
533 spallation of different elements:  $42.2\pm 4.8$  atoms  $^{36}\text{Cl} (\text{g Ca})^{-1} \text{yr}^{-1}$  for Ca spallation  
534 (Schimmelpfennig et al., 2011),  $148.1\pm 7.8$  atoms  $^{36}\text{Cl} (\text{g K})^{-1} \text{yr}^{-1}$  for K spallation  
535 (Schimmelpfennig et al., 2014),  $13\pm 3$  atoms  $^{36}\text{Cl} (\text{g Ti})^{-1} \text{yr}^{-1}$  for Ti spallation (Fink et al.,  
536 2000),  $1.9\pm 0.2$  atoms  $^{36}\text{Cl} (\text{g Fe})^{-1} \text{yr}^{-1}$  for Fe spallation (Stone et al., 2005). On the other  
537 hand, we calculated the  $^{36}\text{Cl}$  exposure ages using the trial version of the online calculator  
538 CREP for  $^{36}\text{Cl}$  (Schimmelpfennig et al., 2019), where the “LSD” (Lifton-Sato-Dunai)  
539 elevation latitude scaling scheme was implemented, together with the LSD geomagnetic  
540 database framework (Lifton et al., 2014) and the same production rates from the spallation  
541 of the abovementioned elements. As Ca spallation is the most dominant  $^{36}\text{Cl}$  production  
542 reaction and the Schimmelpfennig et al. (2011) production rate was calibrated at the Etna  
543 volcano (i.e. an area with a different atmospheric setting from the Antarctica sampling  
544 sites), we corrected the atmospheric pressure of the sampling sites. South Shetland Islands  
545 are affected by permanent subpolar low-pressure systems, which affect the cosmic-ray  
546 particle flux so that it influences (i.e. increases) the local cosmogenic nuclide production  
547 rate. Consequently, this atmospheric pressure anomaly has to be taken into account when  
548 scaling the SLHL production rates. In fact, Dunai (2010) advises including any long-term  
549 atmospheric pressure anomaly at least for Holocene exposure periods. Thus, the  
550 atmospheric pressure value was corrected for the elevation of each sampling site by  
551 implementing the ERA40 (Uppala et al., 2005) atmosphere model using the MATLAB  
552 function “ERA40.mat” (Lifton et al., 2014). The specific Antarctica atmosphere model  
553 (Stone, 2000) was not used as the atmosphere in continental Antarctic is affected by the  
554 air flow over the ice-sheet, which impacts the elevation/air pressure relationship in the  
555 opposite way (thermal high pressure at surface level). The  $^{36}\text{Cl}$  ages that will be presented  
556 and discussed throughout this work are those obtained from the “LSD” scaling scheme  
557 so that they are comparable to the  $^{10}\text{Be}$  ages.

558 Finally,  $^{10}\text{Be}$  exposure ages were calculated by using the online calculator “CREp”  
559 (Martin et al., 2017; available online at: <http://crep.crpq.cnrs-nancy.fr/#/>). In this  
560 calculator, we applied again the “LSD” elevation latitude scaling scheme (Lifton et al.,  
561 2014), the ERA40 atmospheric model (Uppala et al., 2005) and the geomagnetic database  
562 based on the LSD framework (Lifton et al., 2014). These parameters yield a SLHL  $^{10}\text{Be}$   
563 production rate from Be spallation of  $3.98\pm 0.22$  atoms  $\text{g}^{-1} \text{yr}^{-1}$ .

564 We include the results, with total error and analytical errors in Table 7 and Fig. 3. In the  
565 text and in the figures we show the results with the total error. We do not have any  
566 quantitative information on the snow cover during the surface exposure duration.  
567 Therefore, samples were taken from surfaces that are exposed to strong winds, in order  
568 to limit the potential effects of prolonged snow cover on the cosmogenic nuclide  
569 production. We also avoided surfaces that showed signs of significant erosion or spalling.  
570 In addition, denudation rates in Antarctica are reported to be extremely low (0-1 m/Ma;  
571 e.g. Schäfer et al., 1999, Balco et al., 2014), thus having no significant effect on the  
572 Holocene exposure ages. Hence, no corrections for potential effects of snow cover or  
573 denudation were applied to the ages, in consistency with other studies from this region  
574 (e.g. Ciner et al., 2019).

575

## 576 **6. Results of the timing of neoglacial advance in the Byers Peninsula**

### 577 *6.1 Geomorphological setting of neoglacial landforms*

578 The ice-cored moraine system in the present front of the Roch Dome Glacier is formed  
579 by sharp-crested ridges standing 50 to 70 m above the adjacent bedrock surface, with  
580 blocks  $>1$  m in diameter (Fig. 4, 5 and 6). The extensive debris cover has a very high ice  
581 proportion, exceeding 60% of the total volume, according to field observations. The  
582 sediments are distributed in the direction of the glacier’s foliation and its lithology reflects  
583 that of the basalt bedrock, which indicates that the moraine results from basal and  
584 englacial debris. From the moraine crests, a steep ramp of ice ( $40^\circ$  slope) descends to the  
585 southern side of the peninsula. The unconsolidated sediments of the moraines are  
586 currently being intensely reworked by mass wasting processes, and are thus not  
587 appropriate for surface exposure dating methods (lichenometry or CRE).

588 This ice-cored moraine ridge overrides all raised beaches from the central plateau to the  
589 6 m a.s.l. raised beach in the N and S coastal fringes (Fig. 4). Our research focuses on the

590 southern sector of the moraine system, where it overlaps the raised beaches until the Clark  
591 Nunatak. Just SW of this nunatak, a small peninsula – called Rish Point – formed by a  
592 series of volcanic plugs stands only at 60 m from the coast line (Fig. 4, 5 and 6).

593 Next to the highest volcanic plug of the area (Ritli Hill, 45 m) (Fig. 4, 5, 6 and 7), we  
594 observed a glacial polished surface at an elevation of 28 m, and a distance of 600 m  
595 southwards of the present moraine ridge. Here, we collected the bedrock sample BYC-1.  
596 On another volcanic plug, only 350 m from the moraine ridge and at elevation of 47 m,  
597 another polished surface was observed with an erratic on it. Samples were taken from  
598 bedrock surface BYC-2 and from the erratic boulder BYC-3.

599 On the western side of the Clark Nunatak, the ice ramp descending from the external part  
600 of the ice-core moraine ridge does not connect with the bedrock surface but to thick layers  
601 of till, which rest on the 10-12 m a.s.l. raised beach. At the connection between the till  
602 deposits and the raised beach, there is a group of large, stable erratic glacial boulders,  
603 aligned parallel to the limit of the glacier. This line of erratic boulders is located about  
604 200 m to the S of the present glacier front and lies on the 10-12 m a.s.l. beach. These  
605 boulders are basalts and we assume that were deposited by Dome Rotch glacier during a  
606 small advance, when it trespassed the 10-12 m a.s.l. beach. The five largest and most  
607 stable basaltic boulders were selected from this line to take samples for <sup>36</sup>Cl dating (BYC-  
608 9, 10, 11, 13 and 14) (Fig. 5, 6, 8). In addition to the erratic basaltic boulders that rest on  
609 the 10-12 m a.s.l. raised beach, there are some granite boulders that were embedded in the  
610 sediments of this raised beach protruding around a meter above the beach sand level. We  
611 assume that these granitic boulders were transported by icebergs from the AP during the  
612 beach formation, as there are no granitic rocks in Byers bedrock (Hall and Perry, 2004).  
613 We sampled two of the ice rafted granitic boulders (BYB-10 and BYC-12) (Fig. 4, 5, 6,  
614 8 and 9). We assume that the ice-rafted boulders have been stable since they were  
615 deposited on the beach, and therefore CRE ages of these boulders must coincide with the  
616 age of formation of the beach where they are distributed.

617 On the other hand, there is a moraine ridge surrounding the W side of Clark Nunatak and  
618 with the eastern extreme of Rish Point, which trespassed the 4-6 m a.s.l. raised beach.  
619 This is one of the few sites in the Byers Peninsula where the current front of the glacier  
620 is separated from the ice-core moraine crest (distance of ca. 500 m). This moraine is  
621 formed by several crests and arcs that overlap one another. The youngest arcs constitute  
622 ice-cored moraine ridges and are very unstable and subject to mass movements and

623 intense remobilization. The outer most crests are stable. Two boulders from this stable  
624 older sector of the moraine were selected for CRE samples (BYC-4 and 5), located at  
625 elevation of 35 m (Fig. 4, 5, 6, and 10).

## 626 *6.2 CRE results*

627 CRE results show a complex spatio-temporal pattern with regards to the glacial evolution  
628 during the Mid-Late Holocene in the Byers Peninsula.

629 The oldest ages correspond to the deglaciation of the Rish Point. Samples BYC-1 and 2  
630 on the two polished surfaces located on the summit of volcanic plugs reported the same  
631  $^{36}\text{Cl}$  age of  $10.4 \pm 1.2$  and  $10.3 \pm 1.3$  ka. The erratic boulder BYC-3 deposited on the same  
632 polished surface as BYC-2 yielded a slightly younger  $^{36}\text{Cl}$  age of  $9.1 \pm 1.1$  ka. The  
633 arithmetic mean of these three samples is  $9.9 \pm 1.2$  ka ( $n=3$ ) (Fig. 3, 4, 5, 6 and Table 7).

634 The samples taken from the erratic boulders lying on the 10-12 m a.s.l. raised beach  
635 (BYC-9, 10, 11, 13 and 14) yielded the following  $^{36}\text{Cl}$  ages:  $3.0 \pm 0.7$ ,  $4.2 \pm 0.6$ ,  $3.6 \pm 0.6$ ,  
636  $4.7 \pm 0.6$  and  $3.6 \pm 0.7$  ka, respectively. The arithmetic mean is  $3.8 \pm 0.6$  ka ( $n=5$ ). The  
637 ages of the granitic boulders embedded in the 10-12 m a.s.l. raised beach (BYB-10) and  
638 on the littoral platform (BYC-12) give  $^{10}\text{Be}$  ages of  $3.5 \pm 0.4$  ka and  $5.5 \pm 0.4$  ka,  
639 respectively, with an arithmetic mean of  $4.4 \pm 0.4$  ka ( $n=2$ ). In fact all this ages are  
640 indistinguishable from each other with an average of  $4.1 \pm 0.5$  ka ( $n=7$ ) (Fig. 3, 4, 5, 6 and  
641 Table 7).

642 The two boulders distributed on the moraine from the eastern flank of the Clark Nunatak  
643 where the front of the glacier has significantly retreated over the last decades (BYC-4 and  
644 5) showed similar  $\text{Cl}^{36}$  ages of  $1.1 \pm 0.3$  and  $0.8 \pm 0.2$  ka, respectively. The mean is  $1.0 \pm$   
645  $0.2$  ka ( $n=2$ ) (Fig. 3, 4, 5, 6 and Table 7).

## 646 **7. Discussion**

### 647 *7.1 Analysis of the results in the context of the SSI and the AP*

648 The here presented first CRE dates from the Byers Peninsula indicate the existence of  
649 three different periods concerning glacier evolution in the area. The first group of  
650 landforms correspond to the polished surfaces and the erratic boulder located in Rish  
651 Point. These samples are indicative of the northwards retreat of Rotch Dome Glacier,  
652 which occurred at around 11-9 ka ( $9.9 \pm 1.2$  ka;  $n=3$ ). This ice-free corner was deglaciated  
653 prior to the oldest raised beaches distributed at 15-16 m a.s.l. that were dated at 7.4 cal ka

654 BP in the Byers Peninsula (Hall 2003; 2010). The age of these landforms fits also with  
655 the chronological framework of deglaciation inferred from lake records in this peninsula,  
656 suggesting that the initial deglaciation of the central plateau took place at 8.3 cal ka BP  
657 (Toro et al., 2013; Oliva et al., 2016). The Early Holocene deglaciation of coastal  
658 environments also occurred between 9 and 6 ka in the rest of the SSI (Barsch and  
659 Mäusbacher, 1986; Mäusbacher, 1991; Del Valle et al., 2002; Hall, 2003; Bentley et al.,  
660 2005; Hall, 2010; Watcham et al., 2011), or even before 9 ka (Milliken et al., 2009; Seong  
661 et al., 2009; Simms et al., 2011). This timing also coincides with data from other records  
662 from the AP, such as marine sediments, which show a clear warming trend beginning 12  
663 ka ago (Shevenell et al., 2011), as well as from CRE dating of glacial landforms in this  
664 peninsula (White et al., 2011; Glasser et al., 2014; Anderson et al., 2017) (Fig. 11).

665 A second group of landforms includes glacial basaltic boulders distributed on the beach  
666 and littoral platform at 10-12 m a.s.l (BYC 9, 10, 11, 13 and 14) and the two ice rafted  
667 granitic boulders embedded in the sediments of this raised beach (BYB 10) or located on  
668 the same littoral platform (BYC 12). The results obtained show very similar ages for all  
669 types of boulders, both basalts and granites, with an average of  $4.1 \pm 0.5$  ka ( $n=7$ ).  
670 Therefore, the ages of the stabilization of these boulders transported by the Rotch Dome  
671 Glacier should correspond to the age of this beach level, where ice rafted granitic boulders  
672 are embedded. Radiocarbon dating from whale bones of similar altitude raised beach in  
673 the South Beaches, suggested younger ages, between 2.6 and 2 cal ka BP (Hansom, 1979;  
674 Hall and Perry, 2004; Hall, 2003, 2010). These data coincide with OSL dates of this level  
675 of raised beaches from other islands in this archipelago, between 2.3 and 2.1 ka (Simms  
676 et al., 2011a and 2012). Our results from the ice-drafted granitic boulders indicated older  
677 ages for this raised beach,  $4.4 \pm 0.4$  ka ( $n=2$ ), which are synchronous with the glacial  
678 boulders that are distributed on it. There is a lack of correspondence between the older  
679 ages of the erratic and ice-rafted boulders and the former much younger radiocarbon dates  
680 attributed to this raised beach. To understand this apparent contradiction, it is important  
681 to highlight that there is no direct dating of the raised beach in the area. Landforms at  
682 similar altitudes within the same region do not necessarily have identical chronologies,  
683 as glacio-isostatic uplift rates enhanced also by neotectonic activity vary throughout the  
684 archipelago (Bentley et al., 2005; Fretwell et al., 2010; Simms et al., 2018). In fact, it  
685 seems reasonable that the raised beach at +10-12 m a.s.l where the erratic boulders are  
686 distributed may constitute an intermediate level between the raised beach dated at 2.6 and

687 2 cal ka BP in other sectors of the SSI and the highest raised beach of +15-17 m a.s.l.,  
688 which was dated at 7.4 cal ka BP in different areas of this archipelago (Fig. 11).

689 The ages of glacial boulders prove the existence of a neoglacial advance in the Byers  
690 Peninsula occurred ~4 ka. Until now, no such advance had been proposed, although [Hall  
691 and Perry \(2004\)](#) related the 10 m raised beach to a cold period with abundant rich ice-  
692 rafted debris, and [Everett \(1971\)](#) proposed the same for the 10-12 m a.s.l. raised beach  
693 existing in the Hurd Peninsula. Previous studies proposed that the glacier fronts in the  
694 Byers Peninsula, as well as in the rest of the SSI, were approximately at their present-day  
695 position by 5.5 ka ([Barsch and Mäusbacher, 1986](#); [Mäusbacher et al., 1989](#); [Björck et al.,  
696 1991, 1993, 1996b](#); [Mäusbacher, 1991](#); [Del Valle et al., 2002](#); [Hall, 2003, 2010](#); [Bentley  
697 et al., 2005](#); [Watcham et al., 2011](#); [Simms et al., 2011a and 2012](#); [Toro et al., 2013](#); [Oliva  
698 et al., 2016](#)). Our results highlight the occurrence of a limited neoglacial advance at ~4  
699 ka not exceeding 200 m from the present-day glacier front. Consequently, due to the small  
700 extent of this neoglacial expansion, it may have not been detected yet in other areas. There  
701 is evidence of a cold period in the SSI before 4 ka according to the analysis of lake ([Björck  
702 et al., 1991](#)) and marine sediments ([Milliken et al., 2009](#); [Chu et al., 2017](#)). In the context  
703 of the entire AP area and the rest of the continent, as discussed above, there is robust  
704 paleoenvironmental evidence that colder conditions with neoglacial associated advances  
705 occurred around 5 ka and were interrupted by the thermal maximum around 4-3 ka ([Zale  
706 and Karlén, 1989](#); [Mosley-Thompson, 1996](#); [Ingólfsson et al., 1998, 2003](#); [Khim et al.,  
707 2002](#); [Strelin et al., 2006](#); [Heroy et al., 2008](#); [Bentley et al., 2009](#); [Hall, 2009](#); [Michalchuk  
708 et al., 2009](#); [Davies et al., 2012](#); [Shevenell et al., 2011](#); [Carrivick et al., 2012](#); [Cofaigh et  
709 al., 2014](#), [Barnard et al., 2014](#); [Davies et al., 2017](#); [Kaplan et al., 2020](#)) (Fig. 11).

710 The last set of glacial landforms corresponds to the moraine ridges of the Rotch Dome  
711 Glacier on the southern flank of Clark Nunatak. This is the only area where the glacier is  
712 now spatially disconnected from the moraine and includes evidence of a Late Holocene  
713 advance of the glacier around the nunatak. Till and disperse erratic boulders are  
714 distributed on the 4-6 m a.s.l. raised beach. The BYC-4 and 5 samples were taken from  
715 the highest and most stable sector of the moraine showing an average age of ~1. ka.  
716 Although, to date, a similar advance has not been confirmed during this time in the SSI,  
717 there is some sedimentological evidence pointing to that fact. [Barsch and Mäusbacher  
718 \(1986\)](#) suggested two neoglacial advances at 3 and 1 cal ka BP in the SSI. [Björck et al.  
719 \(1991\)](#) proposed a cold period in the Byers Peninsula between 1.5 and 0.5 cal ka BP. [Hall](#)



720 and Perry (2004) delimited two cold periods at 0.25 and 1.7 cal ka BP. Hall (2009) used  
721 the CRE <sup>10</sup>Be methodology to date moraines in the Hurd Peninsula and Marion Cove to  
722 1.5–1.0 ka (Hall and Stone, personal communications). Simms et al. (2011a) indicated a  
723 neoglacial advance that ended at approximately 1.7 cal ka BP in Maxwell Bay (King  
724 George Island). Lake Domo, which is very close to the study area and located only 350  
725 m from the present-day glacier front, was deglaciated around 1.8 cal ka BP, probably after  
726 a neoglacial advance (Oliva et al., 2016). Chu et al. (2017) proposed the onset of  
727 neoglacial advances in the Fildes Peninsula at 2.7 cal ka BP. As discussed before, plentiful  
728 evidence from the AP confirm the occurrence of glacial advances between 2.8 and 1.4 ka  
729 (Mosley-Thompson, 1996; Björck et al., 1996; Khim et al., 2002; Heroy et al., 2008;  
730 Bentley et al., 2009; Yoon et al., 2010; Domack et al., 2001; Strelin et al., 2006;  
731 Michalchuk et al., 2009; Allen et al., 2010; Davies et al., 2012; Mulvaney et al., 2012;  
732 Shevenell et al., 2011; Mulvaney et al., 2012; Abram et al., 2013; Hodgson et al., 2013;  
733 Barnard et al., 2014; Davies et al., 2014; Čejka et al., 2019 and Kaplan et al., 2020) (Fig.  
734 11).

735 As in previous glacial landforms, the ages of the moraine boulder (~1.0 ka) contradict the  
736 age of the raised beach where they rest (LIA). In fact, this raised beach at about 6 m a.s.l.  
737 has been dated in the Byers Peninsula and other islands as belonging to the LIA, between  
738 approximately the 13 and 17th centuries AD (Everett, 1971; John and Sugden, 1971;  
739 John, 1972; Sugden and John, 1973; Curl, 1980; Sugden and Clapperton, 1986;  
740 Clapperton and Sugden, 1988; Hall, 2007; Hall, 2010; Simms et al., 2011a and 2012)  
741 (Fig. 11).

742 The only place where a moraine similar to the one studied in this work has been directly  
743 dated in the SSI was the Collins Glacier moraine in the Fildes Peninsula by Hall (2007),  
744 according to radiocarbon ages of mosses incorporated into the interior of the moraine. As  
745 in our study area, this sector of moraine was almost the only area where the moraine was  
746 separated from the present Collins Glacier front, and was also at a distance of about 500  
747 m. The first results of this work indicated that the most external advance was 2.8 to 1 cal  
748 ka BP, although Hall (2007) discards this possibility, precisely because the moraine rests  
749 on the 6 m a.s.l. beach.

750 The discordance between the ages of the moraines dated by CRE ages and the ages of  
751 raised beaches provided by radiocarbon dating of organic fragments present in their sands  
752 will remain a topic of debate until we directly date the studied raised beaches instead of



753 basing their age on a simple correlation of altitudes. This approach could lead to important  
754 errors related to the regional variability and local neo-tectonics (Bentley et al., 2005;  
755 Fretwell et al., 2010; Simms et al., 2018).

756 The results suggest that these younger moraines may be somewhat older than the LIA, as  
757 previously thought (Everett, 1971; John and Sugden, 1971; John, 1972; Sugden and John,  
758 1973; Curl, 1980; Sugden and Clapperton, 1986; Clapperton, and Sugden, 1988; Hall,  
759 2007; Hall, 2010). Our proposal is that they are polygenic moraines formed by several  
760 neoglacial advances driven by cold periods that may have expanded from 2 ka to the LIA,  
761 as has been proposed in many other areas of the AP (Zale and Karlén, 1989; Domack et  
762 al., 2001; Hall and Denton, 2002; Allen et al., 2010; Storey et al., 2010; Michalchuk et  
763 al., 2009; Balco et al., 2013; Davies et al., 2014; Davies et al., 2017). In fact, although the  
764 outermost crest of the moraine dates back to ~1.0 ka, based on our results (Fig. 4), the  
765 glacier must have retreated from the moraine limits very recently, probably after 1950, as  
766 occurred in the nearby peninsula of Elephant Point (Oliva and Ruiz-Fernández, 2015,  
767 2017) (Fig. 11).

768 The available proxy data for the Mid and Late Holocene does not yet allow to constrain  
769 which climate parameters are responsible for such glacial oscillations. Bentley et al.  
770 (2009) provided evidence of the occurrence of relative warmth from 4.5 to 2 cal. ka BP  
771 in the AP region, which is also confirmed by ice core records from the NE corner of the  
772 AP reporting relative stable temperature until 2.5 ka BP when climate cooled (Mulvaney  
773 et al., 2012). Past surface air temperature changes are similar to those inferred from  
774 several sites across the AP from moss banks (Charman et al., 2018).

## 775 *7.2 The Neoglaciation of the SSI and the AP in a global context*

776 Despite significant regional variations in the timing of Neoglaciation in the AP, there are  
777 some common patterns in all records: the end of maximum deglaciation occurred at  
778 around 7-6 ka and the first neoglacial started at 5 ka, with new and previously undated  
779 neoglacial advances between 2.7 and 1 ka, and even up to the LIA, before the RRW. Most  
780 records in the SSI are not concurrent with neoglacial timing in the AP. This can be related  
781 to the different nature of the records and dating methods used in each study. In fact, each  
782 of the proxies examined in this work (ice core, marine and lake sediments, raised beaches  
783 and glacial landforms) as well as the dating methods have been substantially refined over  
784 the last years and inter-comparisons between areas and methods are needed to  
785 homogenize and compare results (e.g. Simonsen et al., 2019; Singer et al., 2019; Sadatzki

786 [et al., 2019](#); [Čejka et al., 2019](#)). However, our data show that the chronology inferred  
787 directly from glacial landforms shows a similar timing for neoglacial advances in the SSI  
788 and the AP. Recently, [Kaplan et al. \(2020\)](#) highlighted synchronous millennial-scale  
789 neoglacial oscillations in the NE edge of the AP and in Patagonia. These authors proposed  
790 that these neoglacial advances coincided with negative phases of the Southern Annular  
791 Mode (SAM), when the westerly winds expanded towards the equator. In line with this,  
792 the current RRW coincides with a positive phase of the SAM that is favoring widespread  
793 glacial retreat in both regions ([Abram et al., 2014](#)).

794 The comparison of Neoglaciation in the AP with the Arctic records may reveal whether  
795 neoglacial advances follow interhemispheric connection between polar regions.  
796 However, neoglacial advances within the Arctic show a very different pattern, even more  
797 divergent than within the AP ([Solomina et al., 2015](#); [McKay, et al., 2018](#)). Throughout  
798 the Arctic, the end of deglaciation varied from 11 to 5 ka depending on the region  
799 ([Renssen et al., 2012](#)). The first phases of neoglacial advances were detected between 9  
800 to 7 ka in Scandinavia and 4 ka in Greenland ([Solomina et al., 2015](#); [McKay, et al., 2018](#)).  
801 In any case, there are also some common patterns for the entire Arctic, which are quite  
802 similar to those observed in the AP. According to the most recent synthesis, glaciers  
803 retreated throughout the Arctic from 8.6 to 5 ka ([Marcott et al., 2013](#); [Solomina et al.,](#)  
804 [2015](#); [Kaufman et al., 2016](#); [Sejrup et al., 2016](#); [Briner et al., 2016](#); [McKay, et al., 2018](#);  
805 [Geirsdóttir et al., 2019](#)), similarly to what happened in the SSI and the AP. After this  
806 widespread retreat, there are two main phases of generalized neoglacial expansion in  
807 (almost) all regions across the Arctic, one beginning at 4.5 ka and another from 2 ka to  
808 the LIA ([Solomina et al., 2015](#); [Miller et al., 2013](#); [Miller et al., 2017](#); [McKay, et al.,](#)  
809 [2018](#); [Geirsdóttir et al., 2019](#)). A similar timing for glacial advances was also identified  
810 in the SSI and the AP.

811 Therefore, there is a common global pattern at a millennia timescale with regards to the  
812 Neoglaciation dynamics in glaciers of the AP and in the Arctic. These patterns are similar  
813 to those found in the Byers Peninsula: intensive deglaciation around 8.6 to 5 ka, followed  
814 by the first neoglacial advances around 4.5 ka and new, intensive neoglacial advances  
815 around 2 ka. This Late Holocene glacier behavior in the high latitudes of both  
816 hemispheres is very different from the evolution of temperatures that occurred in the two  
817 regions during Termination I, when temperature changes were simultaneous but inverse  
818 in the two hemispheres, the pattern known as “bipolar seesaw” ([Broecker and Denton,](#)

1990; Barker et al., 2009, 2010). The opposite temperature trends recorded in Antarctica and Greenland during Termination I (seesaw pattern) have been confirmed by ice cores (Severinghaus and Brook, 1999; Brook and Buizert, 2018; Stolper et al., 2016) and are attributed to changes in the intensity of the Atlantic Meridional Overturning Circulation (AMOC, Baker et al., 2009, 2010). The cooling of the Northern Hemisphere reduces the strength of the AMOC (Deaney et al., 2017; Muschitiello et al., 2019), which, in turn, causes the ventilation of the Southern Hemisphere oceans and the emission of a large amount of CO<sub>2</sub> into the atmosphere, significantly warming Antarctica (Ahn et al., 2012; Beeman et al., 2019; Clementi and Sikes, 2019). Inverse temperatures between the two hemispheres during Termination I resulted in opposite behavior of the glaciers in each hemisphere (Jomelli et al., 2014; Darvill et al., 2016; Koffman et al., 2017; Shulmeister et al., 2019). However, this was not the case during the Holocene, mainly during Neoglaciation. The orbitally-forced changes in insolation are likely to be the main driver of Neoglaciation. In fact, negative Total Solar Irradiance anomalies are proposed as one of the main triggers of neoglacial advances into the large scale climatic transformations (Renssen 2006; Solomina et al., 2012), together with volcanic activity, which also played an important role in some of the neoglacial events (Miller et al., 2012, 2013). Both the HTM and the Neoglaciation are global-scale patterns, despite recording notable regional variability. This could be the critical difference with the current warm period (RRW), where the response of glaciers is almost global and synchronous (Renssen 2012; Solomina et al., 2012).

840

## 841 **7. Conclusions**

842 Establishing the chronology of deglaciation of ice-free areas in the AP region is of key  
843 importance in a changing climate scenario. To that purpose, we have reconstructed the  
844 calendar of the most recent glacial oscillations in the largest ice-free area in the SSI, the  
845 Byers Peninsula. Here, previous knowledge on the deglaciation was based on only a few  
846 radiocarbon dates from lake sediments that did not offer an accurate picture of the glacial  
847 evolution of the Mid-Late Holocene. We used CRE dating to examine the timing of  
848 neoglacial advances of Rotch Dome Glacier and compare it with other areas across the  
849 AP region.

850 Deglaciation of today's main ice-free areas in the SSI and the rest of the AP occurred  
851 between 9 and 6 ka, according to previous studies. After 6 ka, glaciers were similar or

852 smaller than their present-day size in most of the AP. The first neoglacial advance in this  
853 area took place from ~5.5 ka, followed by a warm period between 4 and 2.8 ka.  
854 Subsequently until 1.0 ka, there was another period of generalized neoglacial advance in  
855 the AP. In the SSI, there was evidence of cold periods from 5.8 to 5.6, and from 2.7 cal  
856 ka BP from some paleoclimatic proxies, but the glacial response to those climate shifts  
857 was still unknown. This study confirms that, as in other areas of the AP, glacial advances  
858 also occurred in the SSI during these Neoglaciation cold periods in ~4.1 and 1.0 ka.

859 The recent synthesis of glacial evolution in the Arctic since the Mid-Holocene shows that  
860 there was even larger regional diversity with regards to the chronology of neoglacial  
861 advances. In the Arctic, the regional climate forcings determine climate trends that can  
862 lead to glacial advance within a global tendency to warming. However, millennial-scale  
863 patterns between the Arctic and the AP region seem to follow common trends. This timing  
864 revealed by the neoglacial landforms should be taken into account when looking for the  
865 origin of climate changes that caused Neoglaciation, which was practically synchronous  
866 in both polar areas. Consequently, although the objective of this work was not to examine  
867 the origin and causes of Neoglaciation, we provide new evidence supporting a global  
868 background for neoglacial advances beyond hemispheric-scale factors, which would have  
869 favored neoglacial advances with different time ranges in both Polar Regions.

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888 **References**

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1442 **Figure captions**

1443 Figure 1. Location of areas cited in the text related to Antarctica. A) Antarctic Ice Sheet;  
1444 B) Ross Ice Shelf; C) Antarctic Peninsula; D) Graham Land. This figure is available in  
1445 colour in the online version.

1446 Figure 2. Location of the areas cited in the text. A) South Shetland Islands; B) Hurd  
1447 Peninsula; C) Fildes and Barton peninsulas; D) Byers Peninsula. This figure is available  
1448 in colour in the online version.

1449 Figure 3. Probability density plots of CRE ages for differentiated chronostratigraphical  
1450 units: A) Deglaciation, b) First Neoglacial advance and c) Second Neoglacial advance.  
1451 This figure is available in colour in the online version.

1452 Figure 4. Location of the study area, with the main geomorphological features, CRE  
1453 samples and their ages plotted in a Google Earth satellite image. This figure is available  
1454 in colour in the online version.

1455 Figure 5. Geomorphological sketch with CRE arithmetic mean ages for each  
1456 geomorphological unit. This figure is available in colour in the online version.

1457 Figure 6. Geomorphological transect of the main features with arithmetic mean of the  
1458 CRE ages in each unit. This figure is available in colour in the online version.

1459 Figure 7. BYC-1 and -2 samples and CRE ages in Rish Point, Byers Peninsula. This  
1460 figure is available in colour in the online version.

1461 Figure 8. BYC-11 and -12 and BYB-10 samples and CRE ages on South Beaches area,  
1462 Byers Peninsula. This figure is available in colour in the online version.

1463 Figure 9. BYC-12 and -13 samples and CRE ages in front of Rish Point, Byers Peninsula.  
1464 This figure is available in colour in the online version.

1465 Figure 10. BYC-4 and -5 samples and CRE ages in the moraine between Rish Point and  
1466 Clark Nunatak, Byers Peninsula. This figure is available in colour in the online version.

1467 Figure 11. Summary table comparing the timing of neoglacial expansion in the AP region  
1468 and the results of this work. This figure is available in colour in the online version.

1469 **Table captions**

1470 Table 1. Timing of Neoglacial advances in the AP region.

1471 Table 2. Timing of the end of deglaciation and geomorphic evidence of Neoglacial  
1472 advances in the SSI.

1473 Table 3. End of deglaciation, Neoglacial evidence and related features in the Byers  
1474 Peninsula.

1475 Table 4. Geographic location of samples, topographic shielding factor, sample thickness  
1476 and distance from terminus.

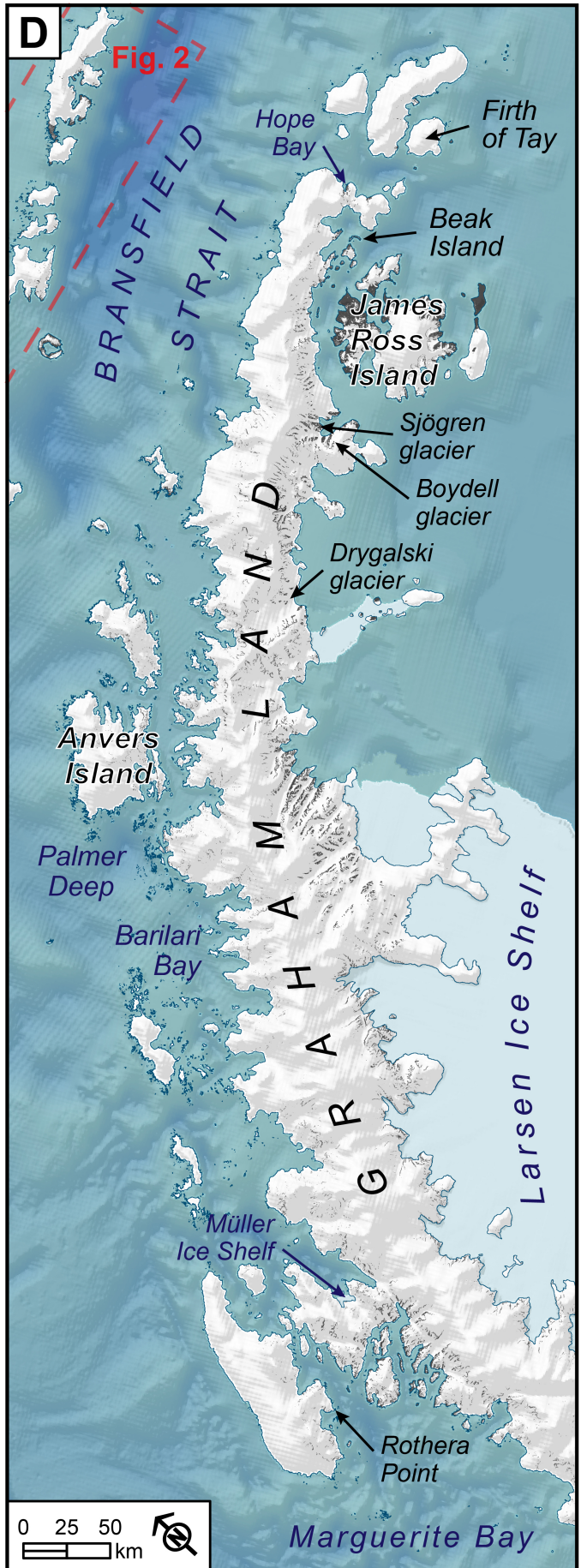
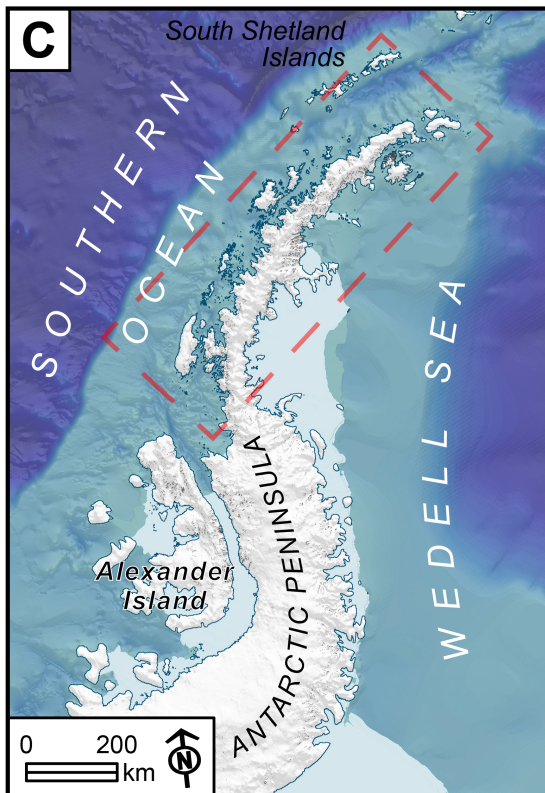
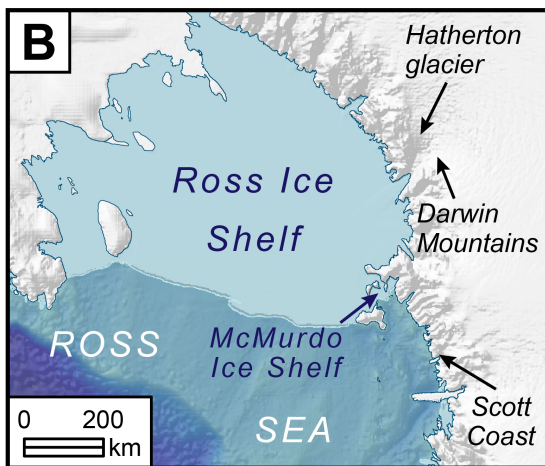
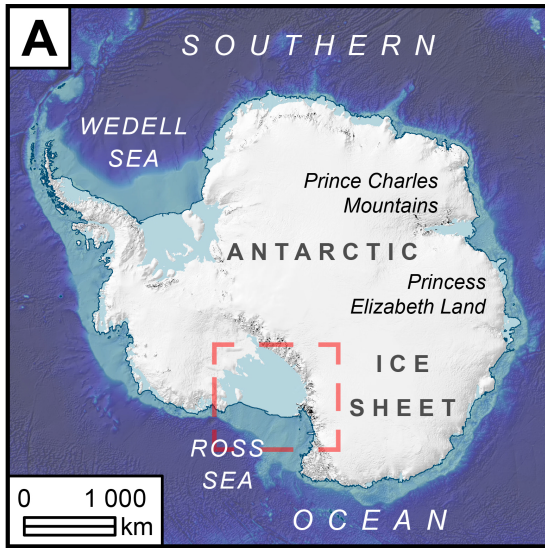
1477 Table 5. Chemical composition of the bulk rock samples before chemical treatment. The  
1478 data in italics correspond to the average values of the element concentrations of the  
1479 samples BYC-2, BYC-4, BYC-11 (included in this studio) and others of similar lithology  
1480 collected in nearby areas, but not included in this study. These average values have been  
1481 used for the age-exposure calculations of those samples without bulk chemical  
1482 composition analysis.

1483 Table 6. Concentrations of the major elements determined in splits taken after the

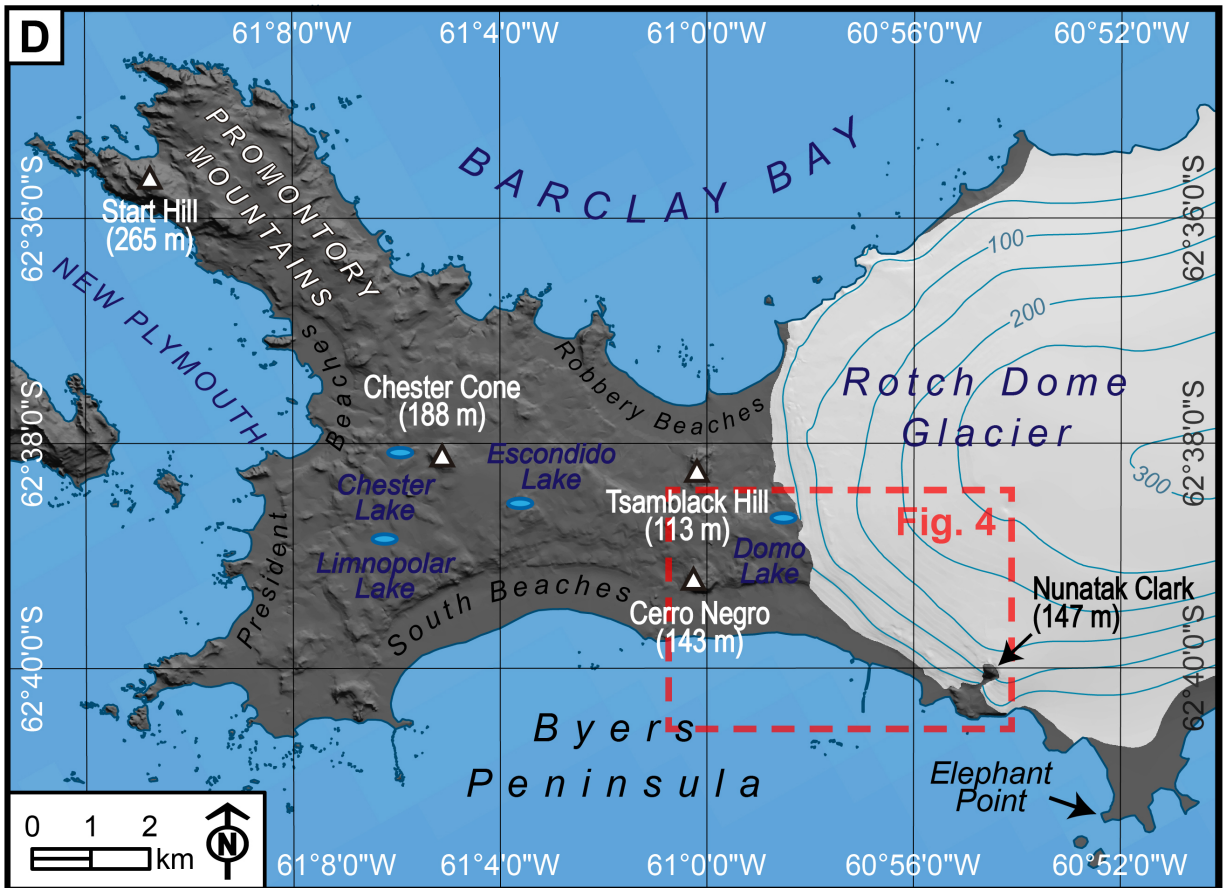
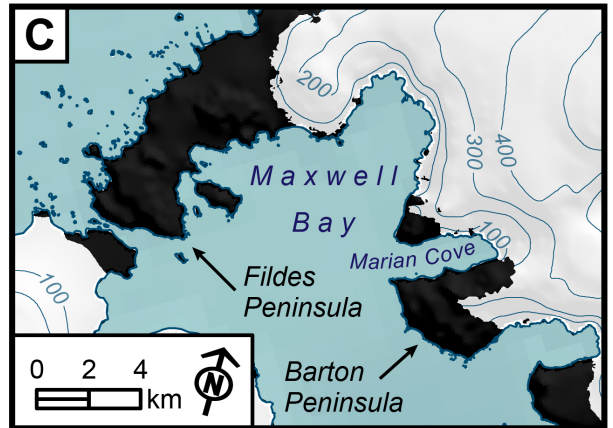
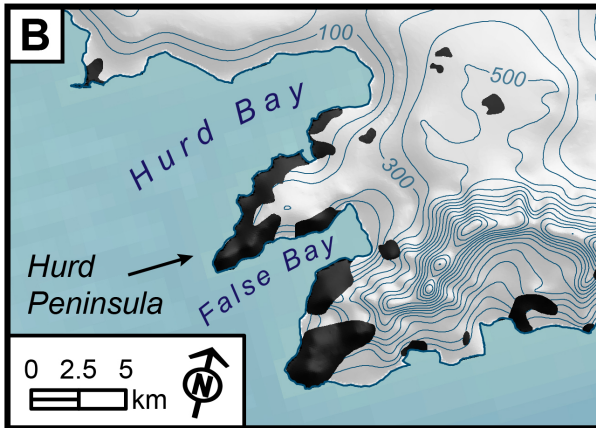
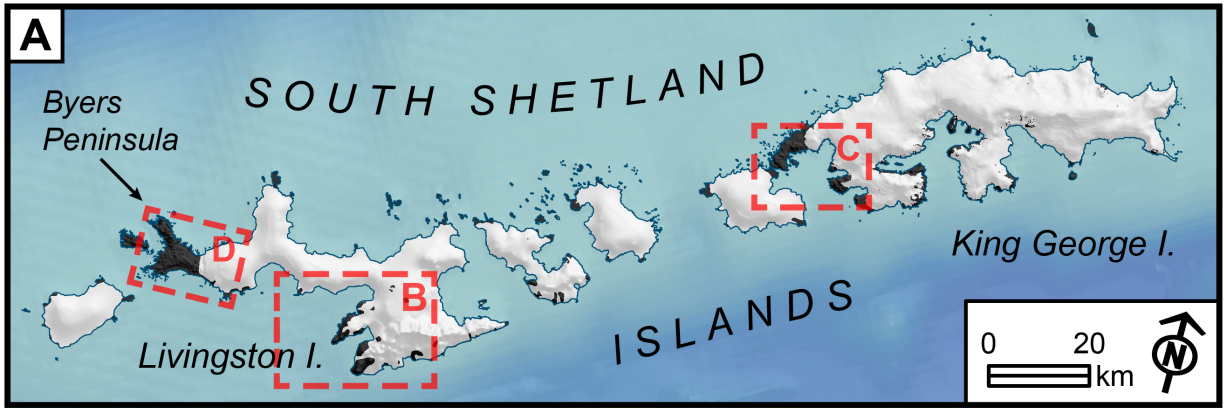


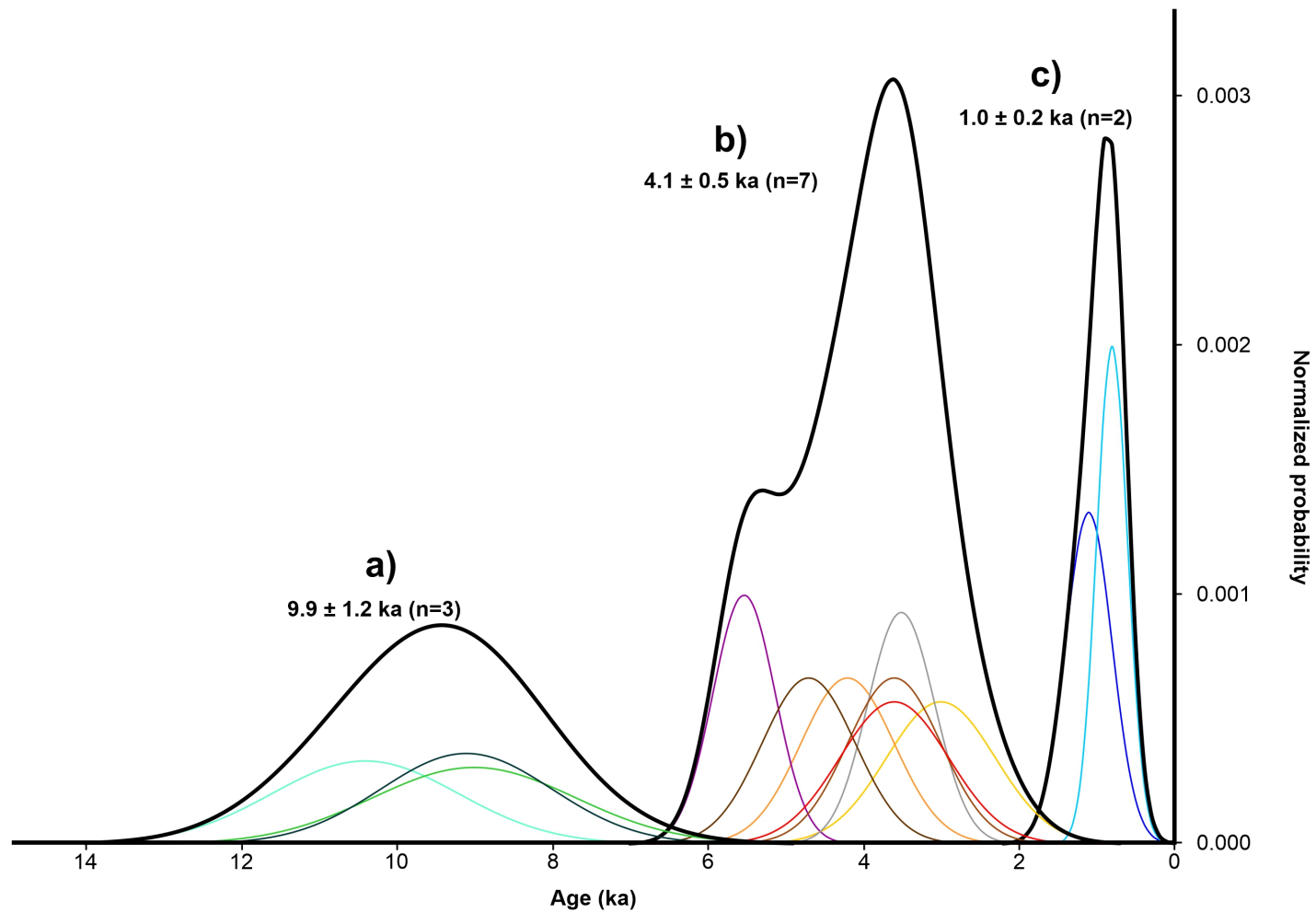
1484 chemical pre-treatment (acid etching).  $P_2O_5$  (%) concentrations are below detection limit  
1485 ( $0.10 \pm 0.015$ ).

1486 Table 7. AMS analytical data and calculated exposure ages.  $^{36}Cl/^{35}Cl$ ,  $^{35}Cl/^{37}Cl$  and  
1487  $^{10}Be/^9Be$  ratios were inferred from measurements at the ASTER AMS facility. The  
1488 numbers in italics correspond to the internal (analytical) uncertainty at one standard level.

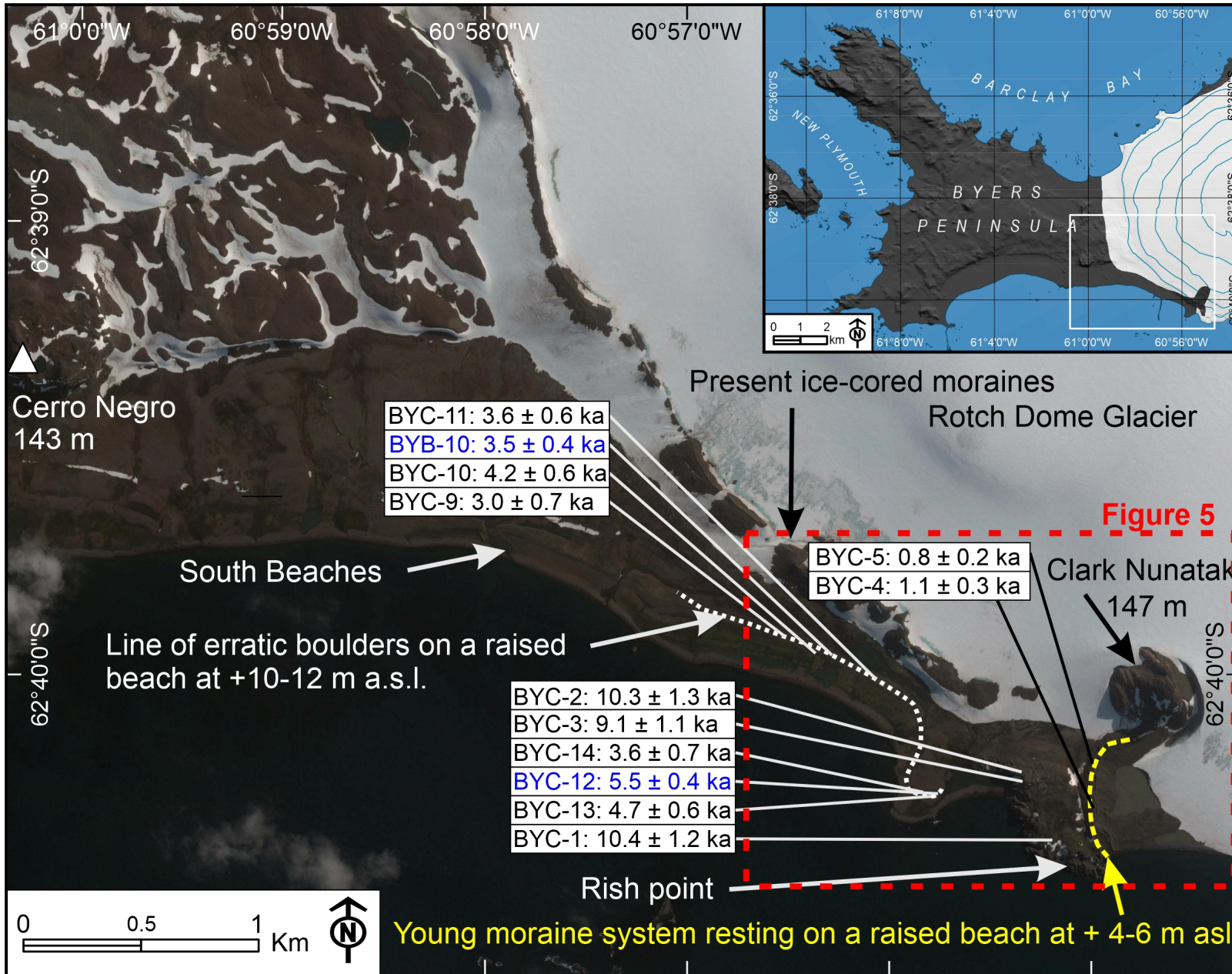




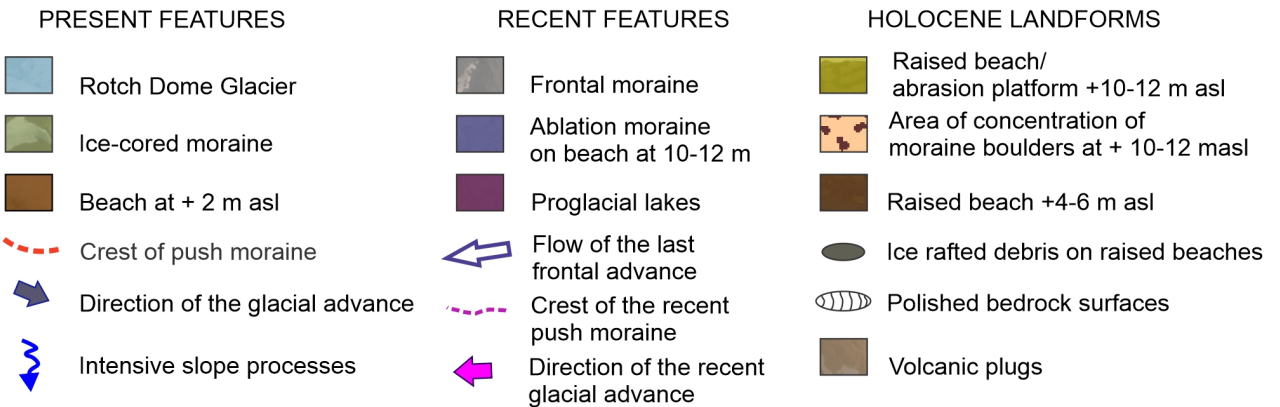
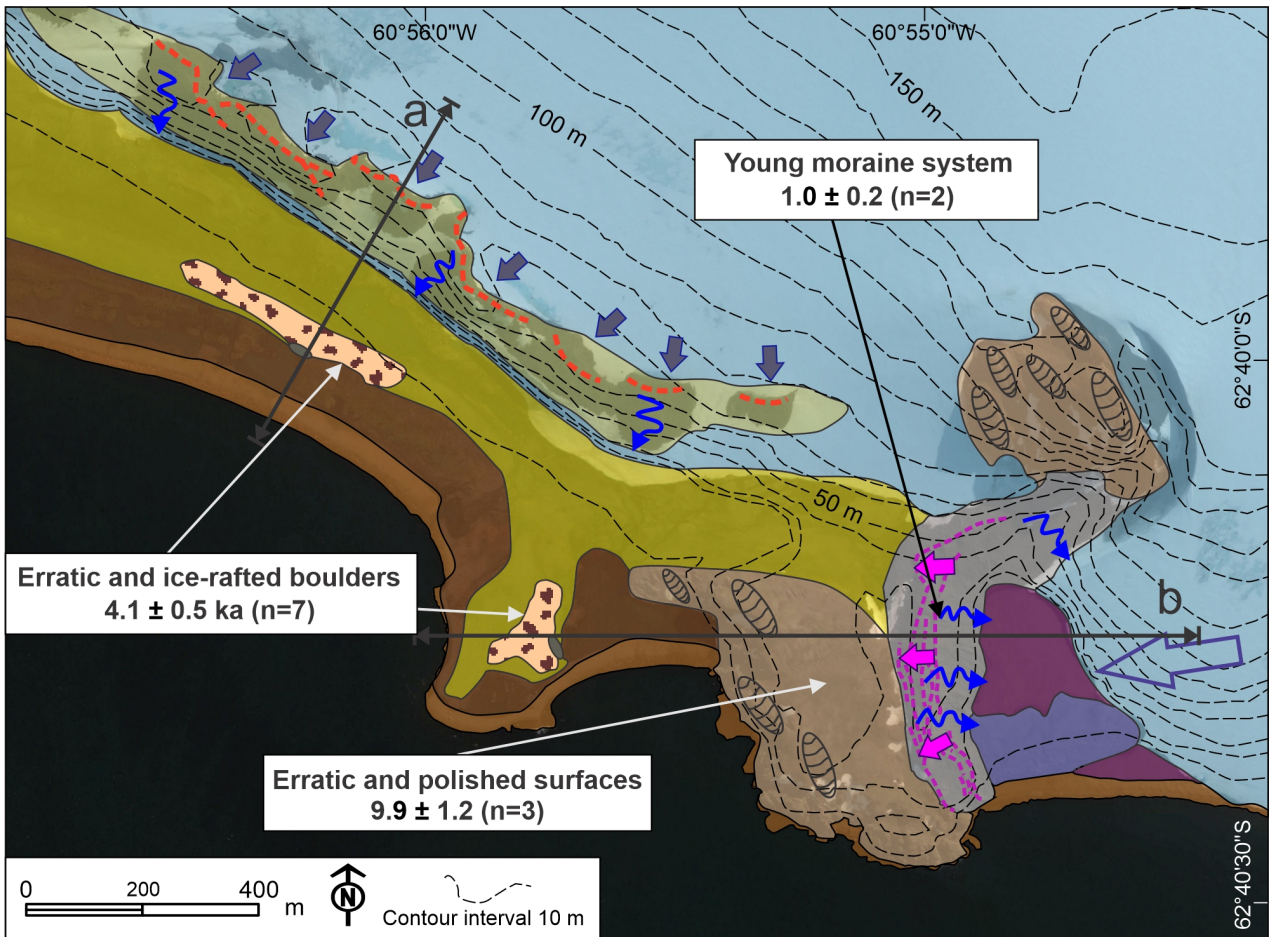


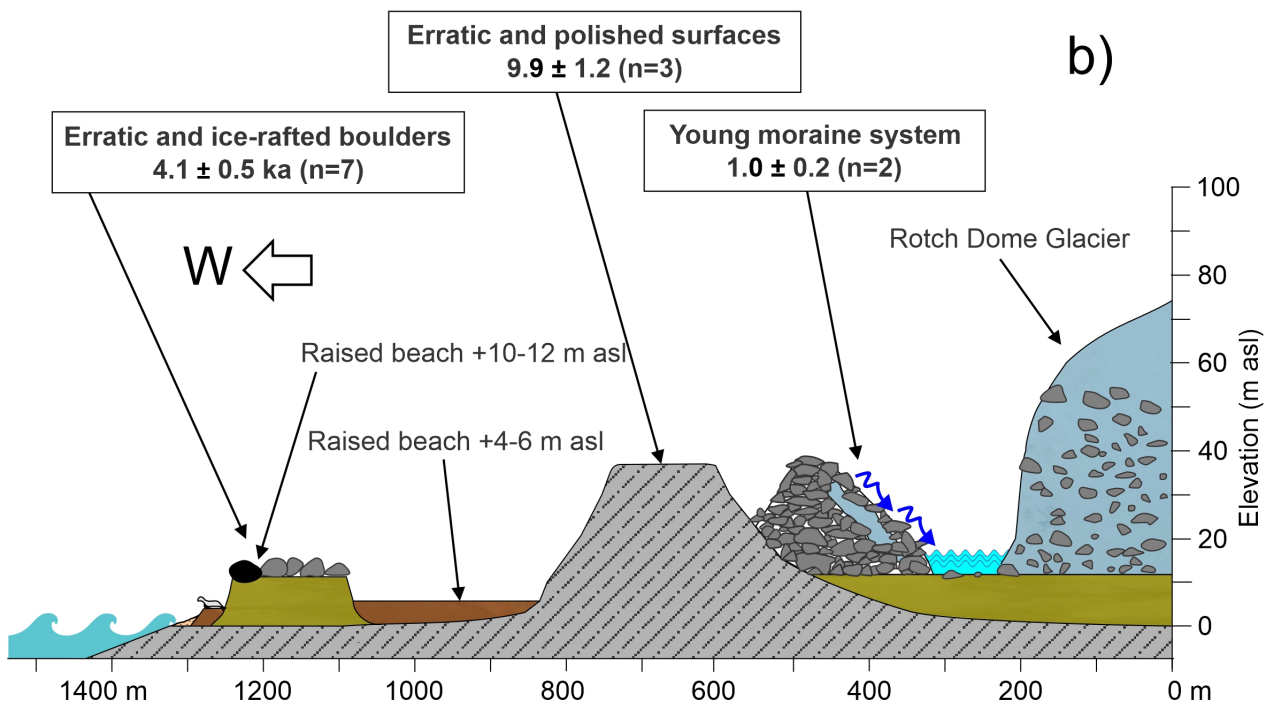
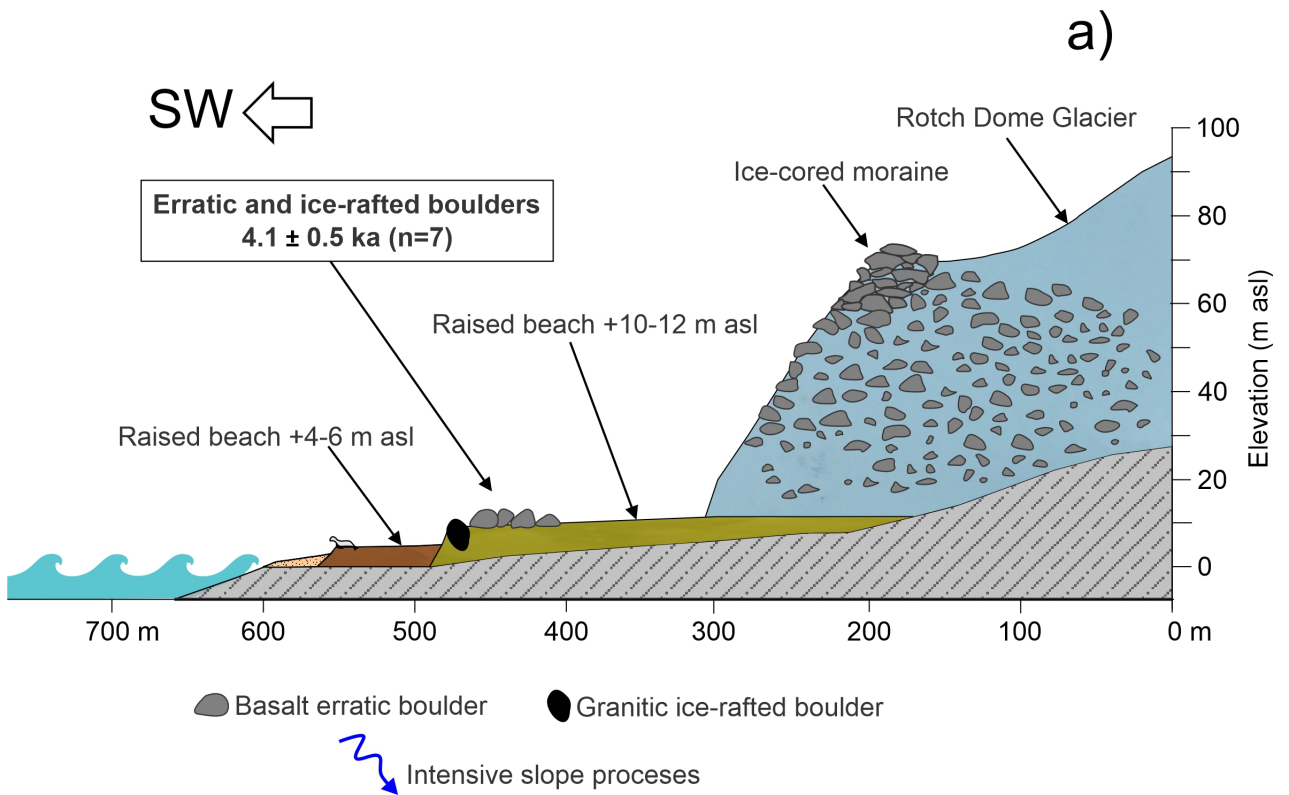


- |   |   |   |
|---|---|---|
| <b>a)</b>   | <b>b)</b>   | <b>c)</b>   |
| BYC-1: $10.4 \pm 1.2 \text{ ka}$ (Glacially-polished surface) | BYC-9: $3.0 \pm 0.7 \text{ ka}$ (Erratic boulder)     | BYC-5: $0.8 \pm 0.2 \text{ ka}$ (Moraine boulder) |
| BYC-2: $10.3 \pm 1.3 \text{ ka}$ (Glacially-polished surface) | BYB-10: $4.2 \pm 0.6 \text{ ka}$ (Ice-rafted boulder) | BYC-4: $1.1 \pm 0.3 \text{ ka}$ (Moraine boulder) |
| BYC-3: $9.1 \pm 1.1 \text{ ka}$ (Erratic boulder)             | BYC-11: $3.6 \pm 0.6 \text{ ka}$ (Erratic boulder)    |   |
|   | BYC-14: $3.6 \pm 0.7 \text{ ka}$ (Erratic boulder)    |   |
|   | BYC-10: $4.2 \pm 0.6 \text{ ka}$ (Erratic boulder)    |   |
|   | BYC-13: $4.7 \pm 0.6 \text{ ka}$ (Erratic boulder)    |   |
|   | BYC-12: $5.5 \pm 0.4 \text{ ka}$ (Ice-rafted boulder) |   |

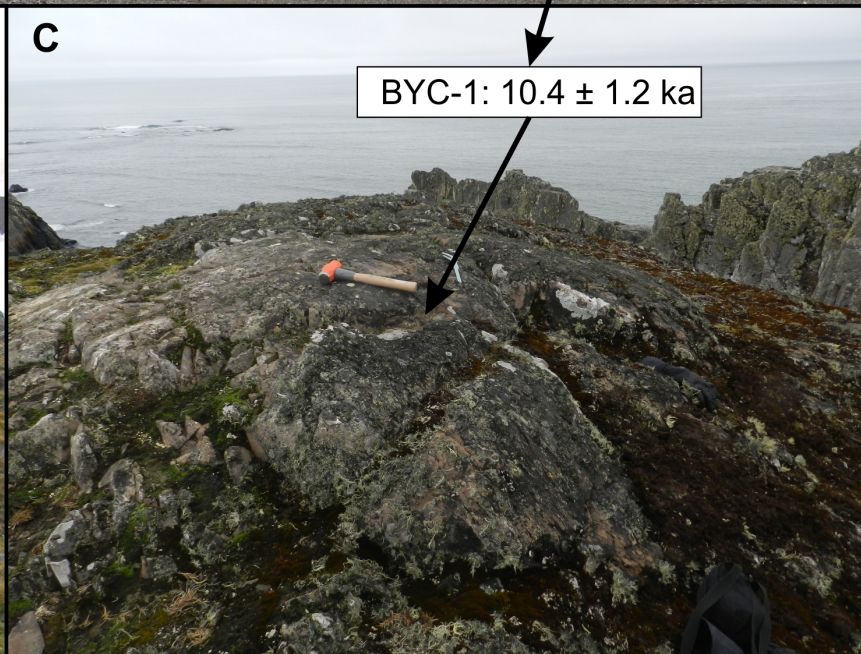
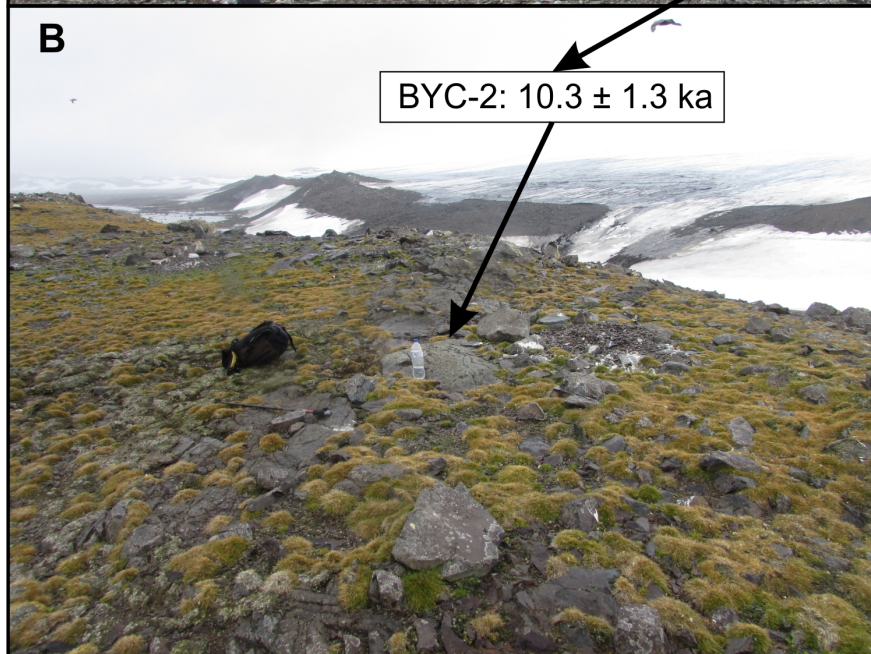
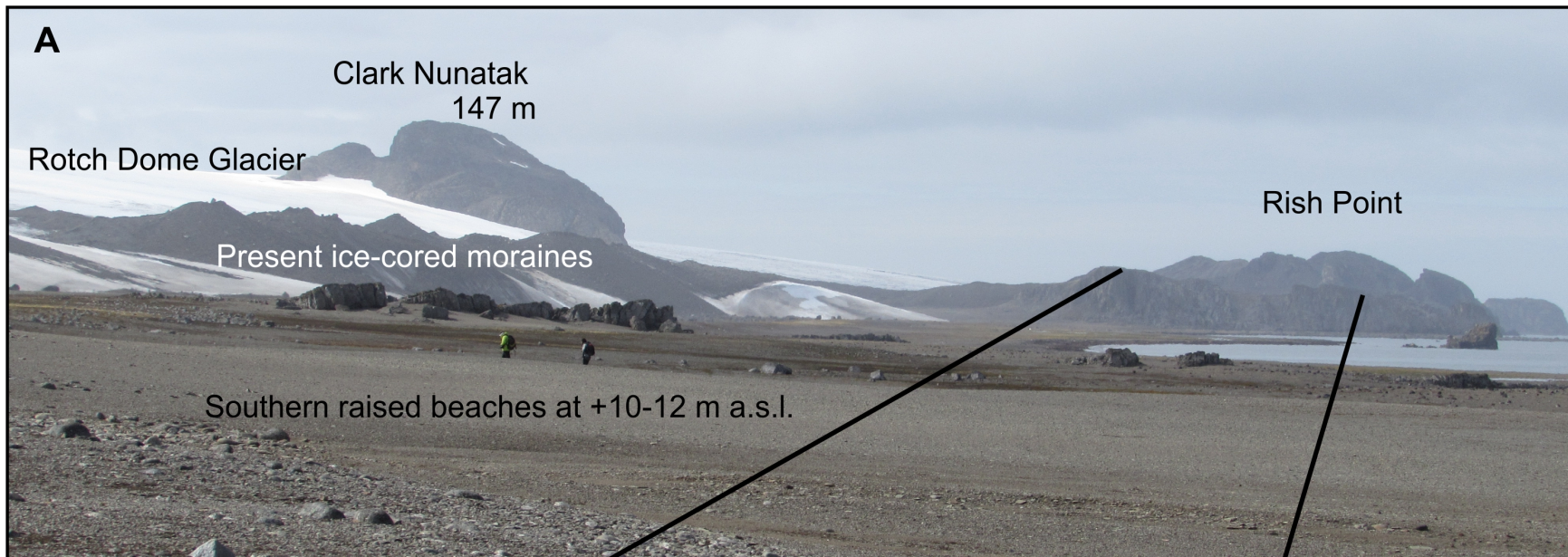




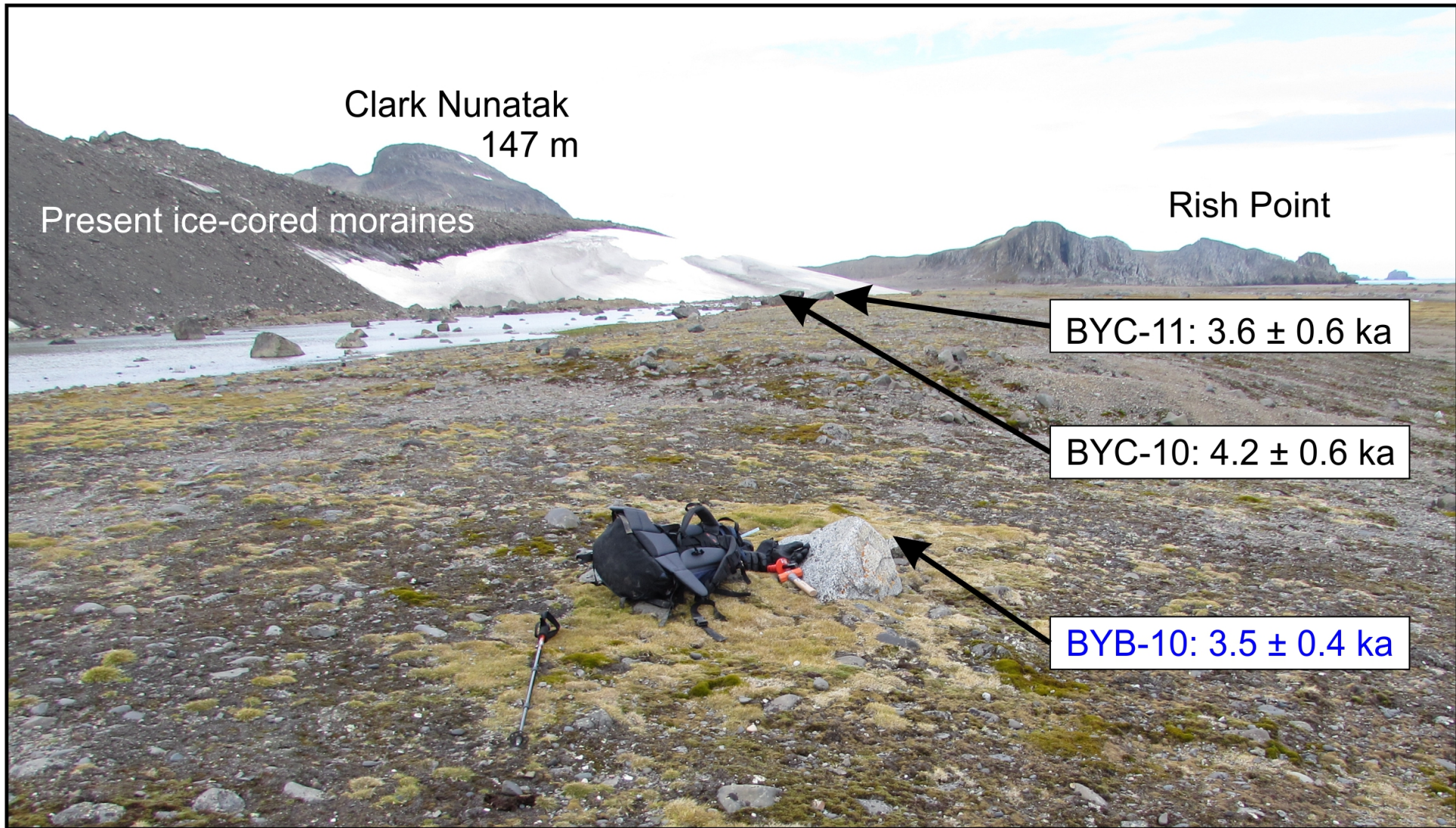












Clark Nunatak  
147 m

Present ice-cored moraines

Rish Point

BYC-11: 3.6 ± 0.6 ka

BYC-10: 4.2 ± 0.6 ka

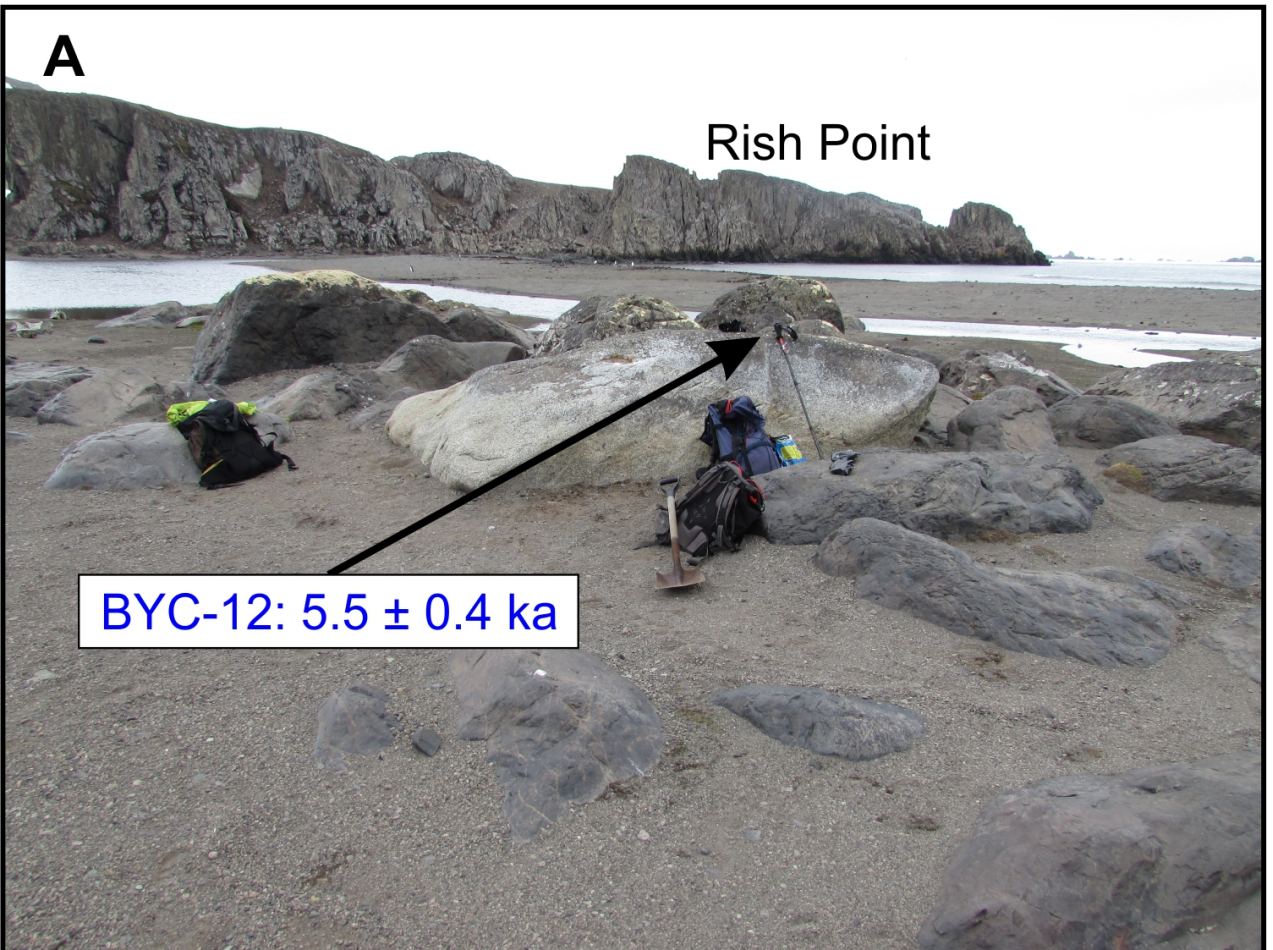
BYB-10: 3.5 ± 0.4 ka



**A**

Rish Point

BYC-12:  $5.5 \pm 0.4$  ka



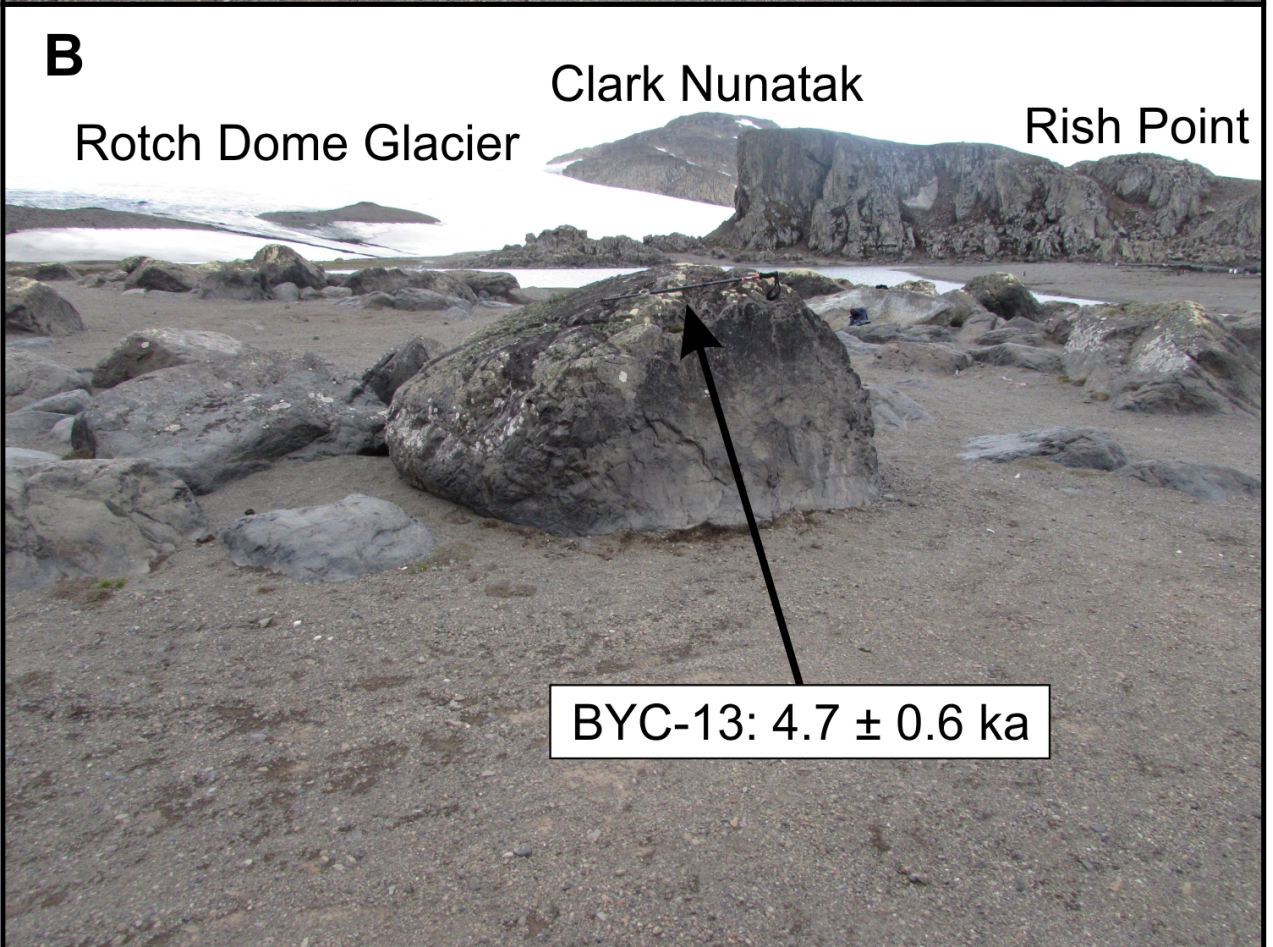
**B**

Clark Nunatak

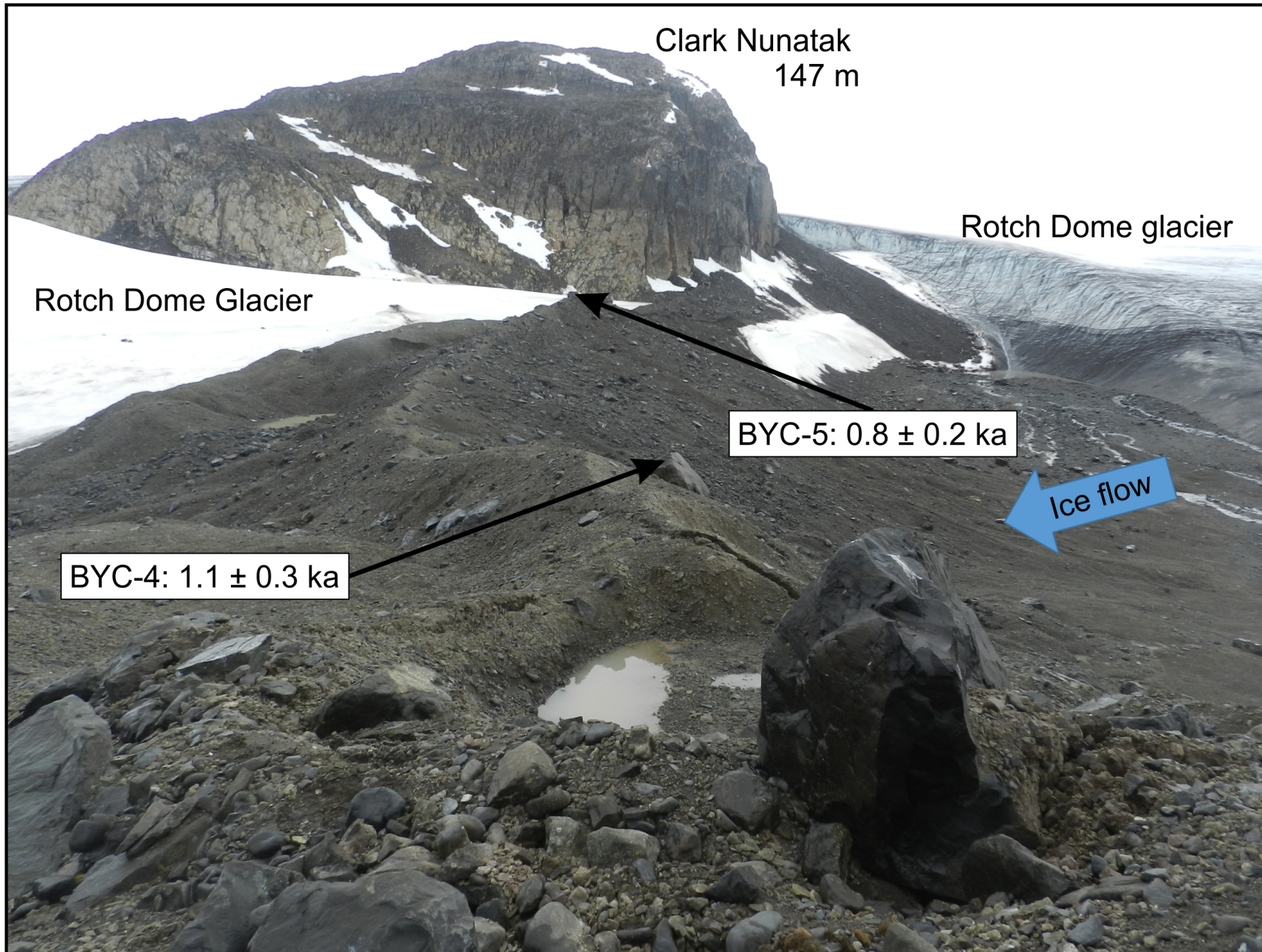
Rotch Dome Glacier

Rish Point

BYC-13:  $4.7 \pm 0.6$  ka







Clark Nunatak  
147 m

Rotch Dome glacier

Rotch Dome Glacier

BYC-5:  $0.8 \pm 0.2$  ka

BYC-4:  $1.1 \pm 0.3$  ka

Ice flow

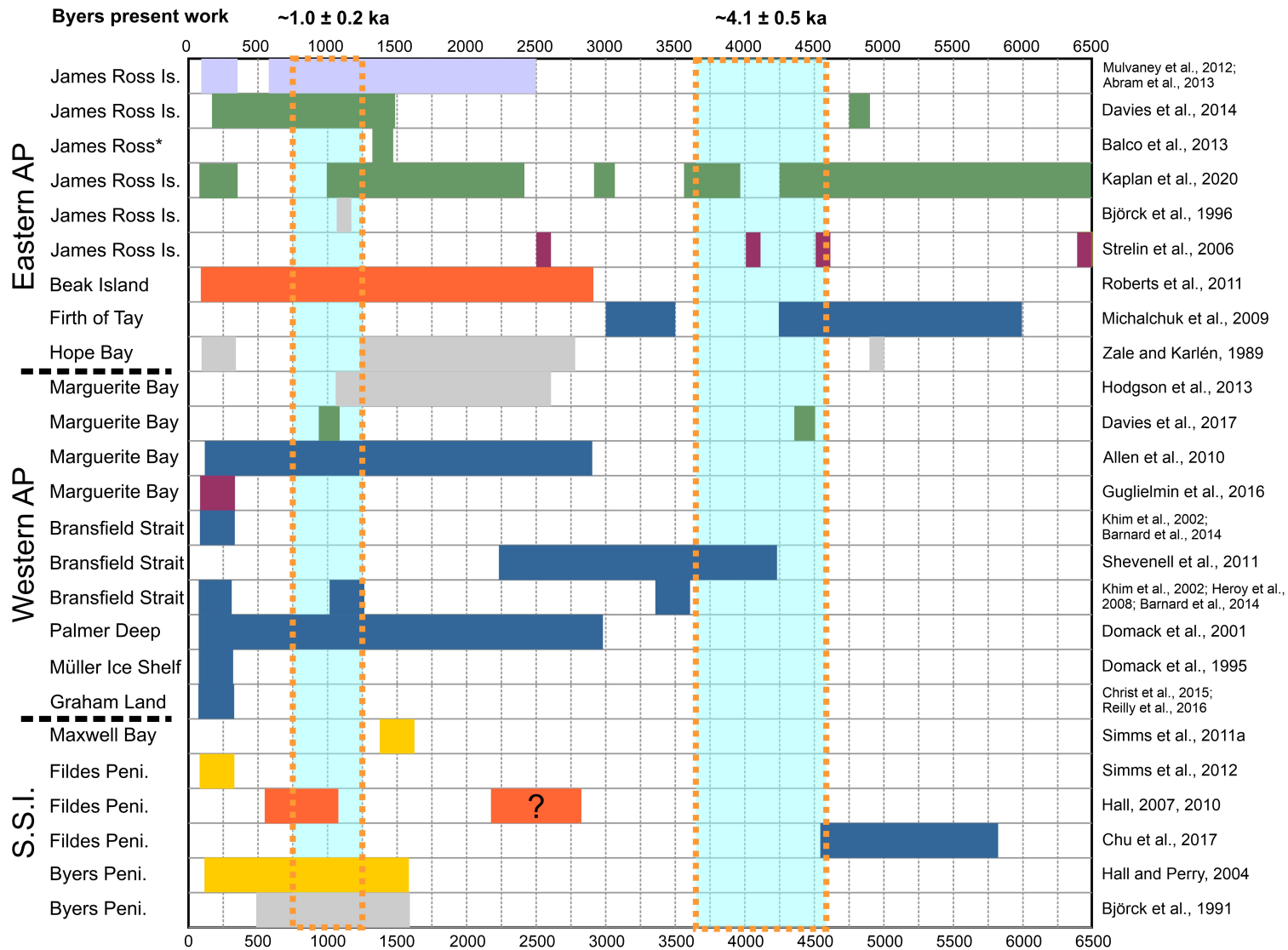


Table 1 Timing of neoglacial advances in the Antarctic Peninsula.

<b>Location</b>	<b>Evidence</b>	<b>Chronology of related events</b>	<b>Neoglacial environments and landforms</b>	<b>References</b>
James Ross Island	Ice cores	From 2.5 to 0.6 cal ka BP, especially around 1.4 cal ka BP	Cold period	Mulvaney et al., 2012; Abram et al., 2013
James Ross Island	Lake sediments	At 1.2 cal ka BP	Glacial advance	Björck et al., 1996
James Ross Island	Glacial landforms	At 6.5, 4.6, 3.9, 2.6 cal ka BP	Glacial advances	Strelin et al., 2006
James Ross Island	Glacial landforms	At 4.8 ka Be <sup>10</sup>	Glacial advance	Davies et al., 2014
James Ross Island	Glacial landforms	From 1.5 to 0.3 ka Be <sup>10</sup>	Glacial advances	Davies et al., 2014
Bransfield Strait	Marine sediments	At 4.5 and 2.5 cal ka BP	Cold periods	Shevenell et al., 2011
Bransfield Strait	Marine sediments	At 3.5 and 1.2 cal ka BP	Cold periods	Khim et al., 2002; Heroy et al., 2008; Barnard et al., 2014
Marguerite Bay	Marine sediments	From 2.8 to 0.2 cal ka BP	Cold period	Allen et al., 2010
Marguerite Bay	Lake sediments	From 2.6 / 2.0 to 1.1 cal ka BP	Cold periods	Hodgson et al., 2013
Marguerite Bay	Glacial landforms	At 4.4 ± 0.7 ka Be <sup>10</sup>	Glacial advance	Davies et al., 2017
Marguerite Bay	Glacial landforms	At 1 ka Be <sup>10</sup>	Formation of ice-cored moraines	Davies et al., 2017
Palmer Deep	Marine sediments	From 3.3 to 0.1 cal ka BP	Cold period	Domack et al., 2001
Firth of Tay	Marine sediments	Between 6.0 and 4.5 cal ka BP	Minor glacial advance	Michalchuk et al., 2009
Firth of Tay	Marine sediments	From 3.5 cal ka BP	General neoglaciation	Michalchuk et al., 2009
Hope Bay	Lake sediments	Around 5 ka	Glacial advance	Zale and Karlén, 1989

Beak Island	Raised beaches	From 2.9 cal ka BP	Decreased rates of sea level rise associated with neoglacial events	Roberts et al., 2011
Scott Coast	Glacial landforms	From 3.5 ka to the LIA	Glacial advances	Hall and Denton, 2002
Anvers Island	Glacial landforms	Until 0.7-0.9 cal ka BP	Glacial advances followed by retreat	Hall et al., 2010
Sjögren, Boydell and Drygalski glaciers	Glacial landforms	After 1.4 ka	Glacial advances	Balco et al., 2013
Hatherton Glacier, Darwin Mountains	Glacial landforms	Between 3 and 0.5 ka Be <sup>10</sup>	Formation of moraines	White et al., 2011
Bransfield Strait	Marine sediments	LIA	Glacial advance	Khim et al., 2002; Barnard et al., 2014
Müller Ice Shelf	Marine sediments	LIA	Glacial advance	Domack et al., 1995
Palmer Deep One	Marine sediments	LIA	Glacial advance	Domack et al., 2001
Barilari Bay, Graham Land	Marine sediments	LIA	Glacial advance	Christ et al., 2015; Reilly et al., 2016
Hope Bay	Lake sediments	LIA	Glacial advance	Zale and Karlén, 1989
James Ross Island	Glacial landforms	LIA	Glacial advance	Strelin et al., 2006
Marguerite Bay	Glacial landforms	LIA	Glacial advance	Guglielmin et al., 2016



Table 2 Timing of the end of deglaciation and geomorphic evidence of neoglacial advances in the South Shetland Islands

Location	Chronology of related events	Neoglacial environments and landforms	References
Several raised beaches in Livingston and King George islands	At 5.5 cal ka BP	Raised beaches distributed at about 16-20 m a.s.l. indicate that the glaciers were close to their current position at that time	<a href="#">Barsch and Mäusbacher, 1986</a> ; <a href="#">Mäusbacher, 1991</a> ; <a href="#">Del Valle et al., 2002</a> ; <a href="#">Hall, 2003</a> ; <a href="#">Bentley et al., 2005</a> ; <a href="#">Hall, 2010</a> ; <a href="#">Watcham et al., 2011</a>
Several lakes in Livingston and King George islands	At 4-5 cal ka BP	Total deglaciation and glaciers close to their current position	<a href="#">Mäusbacher et al., 1989</a> ; <a href="#">Björck et al., 1991, 1993, 1996b</a>
Maxwell Bay (King George Island)	Around 5.9 cal ka BP	Deglaciation was completed	<a href="#">Simms et al., 2011a</a>
Maxwell Bay (King George Island)	From 5.9 cal ka BP	Gradual cooling and more extensive sea-ice cover in the bay	<a href="#">Milliken et al., 2009</a>
Maxwell Bay (King George Island)	Until 1.7 ka	Neoglacial advance	<a href="#">Simms et al., 2011a</a>
Several areas in King George Island	13-17th centuries	Occurrence of two glacial advances: (i) a 2-3 km long advance was dated at the 13th to early 15th CE related to the raised beach 6 m a.s.l., (ii) and another smaller glacial expansion of 0.25-1 km at the 16-17th CE related to raised beach 2-3 m a.s.l.	<a href="#">Curl, 1980</a> ; <a href="#">Sugden and Clapperton, 1986</a> ; <a href="#">Clapperton, and Sugden, 1988</a> ; <a href="#">Birkenmajer, 1981, 1995; 1998</a>
Fildes Peninsula (King George Island)	16-18th centuries AD, OSL ages	Moraine associated with the development of the raised beach 4-6 m a.s.l.	<a href="#">Simms et al., 2011a, 2012</a>
Fildes Peninsula (King George Island)	At 0.65 cal ka BP, but possible older advances occurred from 2.8 cal ka BP onwards	Moraine associated with the development of the raised beach 4-6 m a.s.l.	<a href="#">Hall, 2007</a> ; <a href="#">Hall, 2010</a>
Fildes Peninsula (King George Island)	From 5.8 to 4.8 cal ka BP	Cold period	<a href="#">Chu et al., 2017</a>
Fildes Peninsula (King George Island)	From 2.7 cal ka BP	Beginning of neoglacial advances	<a href="#">Chu et al., 2017</a>
Byers and Fildes peninsulas	From 3 to 1.5 ka cal ka BP	Two glacial advances	<a href="#">Barsch and Mäusbacher, 1986</a>

Byers and Fildes peninsulas	At 0.4-0.7 cal ka BP	Glacial advances associated with the development of the raised beach 4-6 m a.s.l.	<a href="#">John and Sugden, 1971</a> ; <a href="#">John, 1972</a> ; <a href="#">Sugden and John, 1973</a>
Hurd Peninsula (Livingston Island)	Middle and Late Holocene	Two glacial advances related to raised beach 10-12 m a.s.l. and 4-6 m a.s.l.	<a href="#">Everett, 1971</a>
Byers Peninsula (Livingston Island)	At 5.9 cal ka BP	Deglaciation of the central plateau	<a href="#">Toro et al., 2013</a> ; <a href="#">Oliva et al., 2016</a>
Byers Peninsula (Livingston Island)	From 1.7 to 0.25 cal ka BP	Cold periods of increased glacial extent and greater iceberg delivery	<a href="#">Hall and Perry, 2004</a>
Byers Peninsula (Livingston Island)	Between 1.5 and 0.5 cal ka BP	Cold period	<a href="#">Björck et al., 1991</a>
Byers Peninsula (Livingston Island)	Around 1.8 cal ka BP	Deglaciation of the area close to the present glacial front of Dome Roch glacier	<a href="#">Oliva et al., 2016</a>

Table 3 End of deglaciation, Neoglacial evidence and related features in the Byers Peninsula.

<b>Location</b>	<b>Evidence</b>	<b>Chronology of related events</b>	<b>Neoglacial environments and landforms</b>	<b>References</b>
From West to East	Lake sediments	From 8.3 to 1.8 cal ka BP	Deglaciation of the entire peninsula	<a href="#">Toro et al., 2013; Oliva et al., 2016</a>
Front of the Rotch Dome glacier	Geomorphic evidence	LIA?	Ice-cored moraines distributed on the raised beach 4-5 m a.s.l.	<a href="#">John and Sugden, 1971; López Martínez et al., 1996.</a>
Domo Lake	Lake sediments	Slightly younger than 1.8 cal ka BP	Deglaciation of the lake	<a href="#">Oliva et al., 2016</a>
Midge Lake	Lake sediments	Between 1.5 and 0.5 cal ka BP	Cold periods	<a href="#">Björck et al., 1991</a>
Southern Beaches	Raised beaches	1.8 cal ka BP	Raised beach 10 m a.s.l.	<a href="#">Hansom, 1979</a>
Southern Beaches	Raised beaches	15-17th centuries CE	Raised beach 6 m a.s.l.	<a href="#">Curl, 1980</a>
Southern Beaches	Raised beaches	1.7 cal ka BP	Raised beach 6 and 10 m a.s.l. with ice rafted debris	<a href="#">Hall and Perry, 2004</a>
Southern Beaches	Raised beaches	From 7.4 cal ka BP to 15-17th centuries CE	Raised beaches from 15 to 6 m a.s.l.	<a href="#">Hall, 2003, 2010</a>
West front of the Rotch Dome glacier	Aerial imagery	From 1971	Stable ice-cored moraines	<a href="#">John and Sugden, 1971; López Martínez et al., 1996; Hall, 2010</a>
South front of the Rotch Dome glacier	Aerial imagery	From 1956 to 2000	Retreat of ice-cored moraines	<a href="#">Oliva and Ruiz-Fernández, 2015, 2017</a>

Table 4. Geographic location of samples, topographic shielding factor, sample thickness and distance from terminus.

Sample name	Geomorphological unit	Landform	Latitude (DD)	Longitude (DD)	Elevation (m a.s.l.)	Topographic shielding factor	Thickness (cm)	Dist. from present moraine ridge	Isotope
BYC-1	Deglaciated bedrock	Glacially-polished surface	-62.6731	-60.9199	28	0.9961	1.8	600	<sup>36</sup> Cl
BYC-2	Deglaciated bedrock	Glacially-polished surface	-62.6705	-60.9223	47	0.9995	4.8	350	<sup>36</sup> Cl
BYC-3	Deglaciated bedrock	Erratic boulder	-62.6707	-60.9223	47	0.9912	4.0	350	<sup>36</sup> Cl
BYC-4	Moraine (nunatak Clark, W)	Moraine boulder	-62.6716	-60.9163	36	0.9963	4.5	-	<sup>36</sup> Cl
BYC-5	Moraine (nunatak Clark, W)	Moraine boulder	-62.6704	-60.9166	35	0.9956	3.5	-	<sup>36</sup> Cl
BYC-9	Raised beach (+10/12 m)	Erratic boulder	-62.6654	-60.9409	11	0.9992	3.0	200	<sup>36</sup> Cl
BYC-10	Raised beach (+10/12 m)	Erratic boulder	-62.6660	-60.9386	10	0.9992	2.0	200	<sup>36</sup> Cl
BYC-11	Raised beach (+10/12 m)	Erratic boulder	-62.6668	-60.9349	10	0.9992	3.1	200	<sup>36</sup> Cl
BYC-12	Raised beach (+10/12 m)	Ice-rafted boulder	-62.6714	-60.9293	4	0.9900	3.5	-	<sup>10</sup> Be
BYC-13	Raised beach (+10 m)	Erratic boulder	-62.6714	-60.9295	5	0.9900	3.2	-	<sup>36</sup> Cl
BYC-14	Raised beach (+10 m)	Erratic boulder	-62.6713	-60.9298	5	0.9900	1.8	-	<sup>36</sup> Cl
BYB-10	Raised beach (+10/12 m)	Ice-rafted boulder	-62.6663	-60.9380	8	0.9988	3.5	-	<sup>10</sup> Be

Table 5. Chemical composition of the bulk rock samples before chemical treatment. The data in italics correspond to the average values of the element concentrations of the samples BYC-2, BYC-4, BYC-11 (included in this study) and others of similar lithology collected in nearby areas, but not included in this study. These average values have been used for the age-exposure calculations of those samples without bulk chemical composition analysis.

<b>Sample name</b>	<b>CaO (%)</b>	<b>K<sub>2</sub>O (%)</b>	<b>TiO<sub>2</sub> (%)</b>	<b>Fe<sub>2</sub>O<sub>3</sub> (%)</b>	<b>Cl (ppm)</b>	<b>SiO<sub>2</sub> (%)</b>	<b>Na<sub>2</sub>O (%)</b>	<b>MgO (%)</b>	<b>Al<sub>2</sub>O<sub>3</sub> (%)</b>	<b>MnO (%)</b>	<b>P<sub>2</sub>O<sub>5</sub> (%)</b>	<b>Li (ppm)</b>	<b>B (ppm)</b>	<b>Sm (ppm)</b>	<b>Gd (ppm)</b>	<b>Th (ppm)</b>	<b>U (ppm)</b>
BYC-2	8.989	0.432	1.411	12.575	145	51.580	3.053	4.749	14.928	0.203	0.230	9.800	5.200	3.484	3.877	0.620	0.174
BYC-4	8.920	0.498	1.419	12.515	74	50.670	3.244	4.867	15.233	0.184	0.210	5.550	4.400	3.410	3.773	0.632	0.192
BYC-11	9.565	0.482	1.305	12.175	58	50.580	2.625	5.388	15.008	0.192	0.190	3.830	2.900	3.096	3.392	0.600	0.194
<i>Average</i>	<i>9.651</i>	<i>0.524</i>	<i>1.094</i>	<i>10.741</i>	<i>74</i>	<i>48.099</i>	<i>3.082</i>	<i>4.746</i>	<i>15.906</i>	<i>0.211</i>	<i>0.194</i>	<i>48.099</i>	<i>3.082</i>	<i>4.746</i>	<i>15.906</i>	<i>0.211</i>	<i>0.194</i>

Table 6. Concentrations of the major elements determined in splits taken after the chemical pre-treatment (acid etching). P<sub>2</sub>O<sub>5</sub> concentrations are below detection limit (0.015%).

Sample name	CaO (%)	K <sub>2</sub> O (%)	TiO <sub>2</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	MnO (%)	MgO (%)	Na <sub>2</sub> O (%)
BYC-1	8.99 ± 0.45	0.40 ± 0.10	0.78 ± 0.16	10.21 ± 0.20	55.49 ± 1.11	14.37 ± 0.29	0.19 ± 0.04	4.38 ± 0.44	8.99 ± 0.29
BYC-2	8.06 ± 0.40	0.39 ± 0.10	1.07 ± 0.11	10.71 ± 0.21	58.03 ± 1.16	13.45 ± 0.27	0.19 ± 0.04	3.86 ± 0.39	8.06 ± 0.30
BYC-3	8.15 ± 0.41	0.43 ± 0.11	1.40 ± 0.14	10.54 ± 0.21	57.13 ± 1.14	13.24 ± 0.26	0.18 ± 0.04	4.67 ± 0.47	8.15 ± 0.27
BYC-4	8.21 ± 0.41	0.49 ± 0.12	0.74 ± 0.15	9.30 ± 0.93	56.98 ± 1.14	14.41 ± 0.29	0.17 ± 0.03	4.01 ± 0.40	8.21 ± 0.33
BYC-5	8.20 ± 0.41	0.41 ± 0.04	0.87 ± 0.17	10.70 ± 0.21	57.04 ± 1.14	13.35 ± 0.27	0.20 ± 0.04	4.53 ± 0.45	8.20 ± 0.30
BYC-9	8.71 ± 0.44	0.29 ± 0.07	1.22 ± 0.12	11.03 ± 0.22	57.09 ± 1.14	11.31 ± 0.23	0.20 ± 0.04	5.75 ± 0.12	2.27 ± 0.23
BYC-10	7.51 ± 0.38	0.49 ± 0.12	1.19 ± 0.12	8.77 ± 0.88	61.48 ± 1.23	10.86 ± 0.22	0.16 ± 0.03	4.51 ± 0.45	2.00 ± 0.20
BYC-11	8.35 ± 0.42	0.35 ± 0.09	1.22 ± 0.12	10.00 ± 1.00	57.42 ± 1.15	11.45 ± 0.23	0.18 ± 0.04	5.46 ± 0.11	2.07 ± 0.21
BYC-13	8.22 ± 0.41	0.49 ± 0.12	1.04 ± 0.10	9.67 ± 0.97	57.94 ± 1.16	12.55 ± 0.25	0.18 ± 0.04	4.84 ± 0.48	2.39 ± 0.24
BYC-14	8.75 ± 0.44	0.32 ± 0.08	1.27 ± 0.13	10.70 ± 0.21	57.05 ± 1.14	11.84 ± 0.24	0.19 ± 0.04	5.58 ± 0.11	2.23 ± 0.22

Table 7. AMS analytical data and calculated exposure ages.  $^{36}\text{Cl}/^{35}\text{Cl}$ ,  $^{35}\text{Cl}/^{37}\text{Cl}$  and  $^{10}\text{Be}/^9\text{Be}$  ratios were inferred from measurements at the ASTER AMS facility. The numbers in italics correspond to the internal (analytical) uncertainty at one standard deviation. Note that the  $^{36}\text{Cl}$  ages reported for “St” scaling were calculated through the Excel™ spreadsheet by Schimmelpfennig et al. (2009) and those for “LSD” scaling were calculated through the trial version of the CREp online calculator (Schimmelpfennig et al., 2019).

<b><math>^{36}\text{Cl}</math> samples</b>								
Sample name	Sample weight (g)	mass of Cl in spike (mg)	$^{35}\text{Cl}/^{37}\text{Cl}$	$^{36}\text{Cl}/^{35}\text{Cl}$ ( $10^{-14}$ )	[Cl] in sample (ppm)	$[^{36}\text{Cl}]$ ( $10^4$ atoms $\text{g}^{-1}$ )	Age (ka) “St” scaling	Age (ka) “LSD” scaling
BYC-1	78.58	1.821	$13.808 \pm 0.231$	$11.015 \pm 0.702$	8.8	$5.54 \pm 0.37$	<b><math>11.0 \pm 1.4</math> (1.0)</b>	<b><math>10.4 \pm 1.2</math> (0.7)</b>
BYC-2	76.22	1.777	$7.833 \pm 0.138$	$8.731 \pm 0.681$	20.4	$5.70 \pm 0.47$	<b><math>11.0 \pm 1.5</math> (1.2)</b>	<b><math>10.3 \pm 1.3</math> (1.0)</b>
BYC-3	66.44	1.809	$13.201 \pm 0.220$	$8.028 \pm 0.575$	10.9	$4.79 \pm 0.36$	<b><math>9.7 \pm 1.2</math> (1.0)</b>	<b><math>9.1 \pm 1.1</math> (0.8)</b>
BYC-4	75.32	1.807	$8.490 \pm 0.142$	$1.207 \pm 0.197$	18.3	$0.68 \pm 0.13$	<b><math>1.2 \pm 0.3</math> (0.3)</b>	<b><math>1.1 \pm 0.3</math> (0.2)</b>
BYC-5	75.46	1.811	$10.409 \pm 0.171$	$1.093 \pm 0.176$	13.4	$0.53 \pm 0.11$	<b><math>1.0 \pm 0.2</math> (0.2)</b>	<b><math>0.8 \pm 0.2</math> (0.2)</b>
BYC-9	74.98	1.819	$3.962 \pm 0.066$	$1.927 \pm 0.263$	120.8	$3.69 \pm 0.59$	<b><math>3.4 \pm 0.8</math> (0.7)</b>	<b><math>3.0 \pm 0.7</math> (0.6)</b>
BYC-10	68.10	1.814	$25.547 \pm 0.495$	$3.983 \pm 0.390$	4.6	$1.95 \pm 0.21$	<b><math>4.4 \pm 0.7</math> (0.6)</b>	<b><math>4.2 \pm 0.6</math> (0.4)</b>
BYC-11	67.49	1.821	$6.966 \pm 0.121$	$2.753 \pm 0.330$	29.0	$2.19 \pm 0.29$	<b><math>3.9 \pm 0.7</math> (0.6)</b>	<b><math>3.6 \pm 0.6</math> (0.5)</b>
BYC-13	70.44	1.819	$19.341 \pm 0.347$	$4.606 \pm 0.422$	6.3	$2.32 \pm 0.23$	<b><math>5.0 \pm 0.7</math> (0.6)</b>	<b><math>4.7 \pm 0.6</math> (0.5)</b>
BYC-14	69.89	1.799	$5.217 \pm 0.088$	$2.623 \pm 0.335$	51.0	$2.77 \pm 0.39$	<b><math>4.0 \pm 0.8</math> (0.7)</b>	<b><math>3.6 \pm 0.7</math> (0.6)</b>
<i><math>^{36}\text{Cl}</math> Blanks</i>					<i>Total atoms Cl (<math>10^{17}</math>)</i>	<i>Total atoms <math>^{36}\text{Cl}</math> (<math>10^4</math>)</i>		
BL-1	-	1.805	$353.174 \pm 11.131$	$0.265 \pm 0.073$	$2.252 \pm 0.160$	$8.264 \pm 2.264$	-	-
BL-5	-	1.822	$362.525 \pm 8.014$	$0.290 \pm 0.075$	$2.177 \pm 0.133$	$9.133 \pm 2.377$	-	-
<b><math>^{10}\text{Be}</math> samples</b>								
Sample name	Quartz weight (g)	mass of carrier ( $^9\text{Be}$ mg)		$^{10}\text{Be}/^9\text{Be}$ ( $10^{-14}$ )		$[^{10}\text{Be}]$ ( $10^4$ atoms $\text{g}^{-1}$ )		Age (ka)
BYC-12	64.5799	152.29		$5.644 \pm 0.286$		$2.701 \pm 0.137$		<b><math>5.5 \pm 0.4</math> (0.3)</b>
BYB-10	82.2924	151.98		$4.719 \pm 0.496$		$1.762 \pm 0.185$		<b><math>3.5 \pm 0.4</math> (0.4)</b>
<i><math>^{10}\text{Be}</math> Blank</i>								
BYB-BK	-	151.29			-	-	-	-





## Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

## CRedit author statement

All the authors have worked with intensity in the investigation, whose results are presented:

1. David Palacios. Conceptualization. Formal analysis. Investigation. Investigation. Writing. Supervision. Funding acquisition. Methodology.
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