An updated seabed bathymetry beneath Larsen C Ice Shelf, west Antarctica" by Alex Brisbourne et al.

Response to reviewers - February 2020

We are grateful to the four reviewers for their careful analysis of the manuscript. We have endeavoured to address all the issues raised and outline our responses below with reference to the updated manuscript. Our responses are in blue.

General response

We recognise that some of the reviewers found the manuscript to be light on detail. We acknowledge that this was due to drawing on previous comprehensive studies with more exhaustive data sets. To this end, we have added more detail for the new data to make this paper a more robust standalone piece of work. However, we have resisted the need to provide too much background detail such that this remains most fundamentally a "Data description paper" and we envisage this being its primary purpose to the oceanographic community. For background to what we originally conceived as the purpose of the article we would refer to the aims of ESSD, outlined here: https://www.earth-system-science-data.net/about/aims_and_scope.html. In particular "Articles in the data section may pertain to the planning, instrumentation, and execution of experiments or collection of data. Any interpretation of data is outside the scope of regular articles. ... Any comparison to other methods is beyond the scope of regular articles."

The reviewers raised a number of issues with the gridding methodology. Our experience of collaborating with the oceanographic community is that invariably oceanographers will create bathymetric grids using their preferred method, specific to their preferred model and resolution. As such, they are unlikely to use gridded products directly in their models. The gridded product presented here is simply an aid to discussion and to highlight the value of these new data. However, we have added extra detail to the manuscript to ensure we are entirely clear with our methods and that the grid can be reproduced. We do not however go any further with the evaluation of the gridding method or interpolation as this will be specific to the data users' preferred gridding method and model parameterisation. We do now ensure that we clearly highlight the gridded product as a demonstration of the value of the data points rather than a tool for use directly.

This then leads in to comments about what the new data points introduce to the bathymetry map. In this sense the reviewers are ignoring the value of data where previously there were no measurements. Even if a data point in a previously unmeasured location matches depths previously derived by interpolation, this data point now confirms the validity of the interpolation at that site and users can have confidence in any results for that site. Without this confirmatory data point, interpretations would always be subject to caveats regarding the interpolation method.

Reviewer #1 Emma Smith

General Comments:

This study presents a new gridded bathymetry of the ice-shelf cavity beneath Larsen C Ice Shelf, complied from new and existing seismic data sets and some existing drill-site measurements. The article is concise and well written covering all relevant aspects of data processing. This data set presents a significant improvement on previously available cavity bathymetry. As identified by the authors, this data set will be of use in improving predictive models of the future evolution of the potentially vulnerable Larsen C Ice Shelf. All data sets are present at the links given.

My only major comment is easily remedied and of a technical nature: The labelling of the data sets used is somewhat confusing. It isn't clear to me how the new data described in Section 3.1 is related to Figure 1 and Table 1, I have gone back and forth between them a few times and tried to cross-check, but I am still not entirely sure. My suggestions would be:

- Adjust the labelling of Figure 1, so it is clear and consistent with Table 1. Add to the legend in Figure 1 to indicate which data sets (e.g. BAS reflection, MIDAS, RACE etc...) are indicated by the different coloured points. For example, I am not clear if the yellow points are referring to just the dedicated bathymetry measurements described at the start of Section 3.1, or also some of the other supplementary data sets (some of which are reflection and some refraction experiments)?
 Done
- 2. Add references in the text of Section 3.1 to Figure 1 Done

3. Add references in the text of Section 3.1 to the different survey names/campaigns given in Table 1 - I have made some suggestions in the specific comments as to where I think this would be useful. Done as per details below.

4. Add a row to Table 1 to give the reference to the paper/doi where data can be found. As only the BAS data have found their way into a publication previously (hence this paper) this is seen as excessive.

Minor/Specific Comments:

Pg1, L21 – State that "new water column thickness measurements" are from seismic data. Done

Pg2, L10 – step or steep increase? Step – it was a rapid event, hence step increase.

Pg2, L21 – Additional references:

Goldberg, D. N., Gourmelen, N., Kimura, S., Millan, R., & Snow, K. (2019). How Accurately Should We Model Ice Shelf Melt Rates? Geophys. Res. Lett., 46 (1), 189{199. doi: 10.1029/2018GL080383 Pattyn, F., Favier, L., Sun, S., & Durand, G. (2017). Progress in Numerical Modeling of Antarctic Ice-Sheet Dynamics. Current Climate Change Reports, 3 (3), 174{184. doi: 10.1007/s40641-017-0069-7 Done

Pg2, L31 – Rephrase sentence starting "The geometry of LCIS...". I had to read it twice as it sounds like the specific locations were measured by inverting gravity data, rather than the gravity inversions being used to help choose targets for the specific measurements. Done

Pg3, L5 – Reference to Figure 1 (blue dots) Done

Pg3, L6 – Add Reference to Nicholls et al., 2012 when boreholes are mentioned. Done

Pg3, L11 – Consider changing title to "New Data Acquisition for clarity. Done

Pg3, L12 – Reference to Figure 1 (yellow dots?) – see general comments. Done

Pg3, L14 – Does digging the plate in "improve source consistency" or coupling? It sounds odd to use "consistency" here, as you have described two different methods of placing the source.

We have clarified this point. We improve consistency between shots at that location for stacking.

Pg4, L15 – Explain the 30 m offset is between the source and the first geophone. Consider moving this a few sentences later, where you introduce the source, rather than here where you are talking about receivers. We have clarified this.

Pg3, L18 – "using a geophone trigger adjacent to the hammer plate" add "to start the recording" or something similar. Done

"A stack on 10 hammer blow were also..." – I'm not quite clear on what this means? Were 10 of the 20 hammer blows stacked to evaluate reflection strength, or were an additional 10 blows made and stacked on site for evaluation? A little re-phasing needed here, as the sentence seems a bit lost.

Done. The 10-blow stack is additional, to allow on-site evaluation of signal quality. Ice base reflections may not be immediately obvious in single-shot data.

Pg3, L22 – See general comments above, I am not clear on where the "supplementary surveys" are on Figure 1. Done

Pg3, L30 – "constrain arrivals" – I think "identify" would be a better word to use here, as you state that travel times were measured on the raw gathers so semblance and AGC wasn't actually used to constrain them? Good point. Done, thanks.

Pg4, L1 – Nice idea to use the multiples in these cases! Thanks!

Pg4, L10 – Are these the "BAS refraction sites" in Figure 1 or all refraction measurements? If so, reference here. As above, some confusions with which data set is which. This has been clarified in the text and referenced to Table 1.

Pg4, L26 – Add reference to Table 2, after "At site PRHB4" Done

Pg5, L29 – "We interpolated all available" change to "We gridded all available" or "We interpolated between all available" Done

Pg6, L6 – Errors on the gridded product is potentially much larger that the errors quoted in Section 3.3 - a comment to that effect here would be good. We have added a comment to this effect.

Figure 1: As mentioned above. I am confused with the labelling of survey data here, compared to the text in Section 3.1 and Table 1: Are blue points those from Brisbourne et al., 2014? Are the yellow points a combination of MIDAS, SOLIS and RACE and new reflection surveys? What are the red points, just BAS refraction or ALL refraction surveys? Please clarify. Figure 1 has been modified to allow discrimination of the surveys with additional references in the body of the manuscript.

Figure 2: Add labels (e.g. P1, M1, P2, M2) next to diagrams on right hand side to signify which are multiples and which primaries – something similar to Brisbourne et al., (2014). It might not be clear to those without a seismic background what they are are looking at. Done

Table 1: Add column for reference to paper where data is presented, where relevant. This is seen as unnecessary as the only data which were published previously are the BAS refraction data (Brisbourne, 2014) but which are included here as they form part of the new analysis.

Anonymous reviewer #2

General comments

The authors present new point seismic data collected beneath the Larsen C Ice Shelf in West Antarctica. These new data are used to produce a bathymetric grid of the seabed beneath the ice shelf and some of the main implications of features revealed in this new grid are discussed. This data set is crucial to improving modelling efforts in an important and rapidly changing region, however I find the paper to be very light on important details and I have some concerns about the bathymetric grid that is presented. These major issues are listed below and are followed by more minor technical corrections.

Specific comments

• The paper is very light on details and this is a particular weakness in terms of the error estimates and gridding as detailed below, but also throughout the paper in general.

We acknowledge that Reviewers 2 and 3 found the manuscript to be light on detail and recognise that this was due to building on previous comprehensive studies with more exhaustive data sets. To this end, we have added more detail to make this paper a more robust standalone work. Details below.

For example, I think a section discussing the problems with other estimates of sub-shelf cavity and the difficulties in obtaining these measurements is worthwhile.

We have added a paragraph at the end of the introduction to discuss the alternative methods.

Section 5 is very brief and could greatly benefit from more careful analysis and discussion, particularly in the context of future ice-shelf stability. Furthermore I think there should be more care to emphasise the weaknesses of the grid and the interpretation that follows from it in areas where only one or two data points are available.

We regard detailed discussions of the implications of the results on future ice shelf stability as speculation without a significant amount of work to model ocean circulation beneath the ice shelf and therefore do not go into any more detail.

Finally, many parts of the paper are completely missing references.

We have updated the paper with a number of additional references.

• Section 3.3 seems to rely entirely on analysis made in previous studies and makes no attempt that I can see to constrain uncertainties using the newly collected data.

Indeed, uncertainties are discussed in detail in Brisbourne at el. (2014) upon which this paper builds. We have augmented discussions here with individual uncertainties for each new measurement and included these in Table 2.

How are the picking errors estimated?

We have added this to the text and included a lot more detail on uncertainties (S3.3).

The assumption of a linear variation in ice temperature from 100m below the surface to the base of the ice shelf is almost certainly flawed when you consider a typical ice shelf temperature profile.

A linear temperature profile is a reasonable fit to the measured temperature profile in the ice column (ice column temperature data acquired by Nicholls et al. 2012 - unpublished). In addition, at this northerly latitude the temperature range, and therefore velocity range, is low and therefore this assumption is insignificant. Text has been added to the manuscript to explain this (P4L33).

Why is a comparison not made between ice thicknesses obtained through surface and seismic measurements, surely this is easily done and worthwhile since in some cases the former is used rather than the latter.

A comparison of ice thickness determined using elevation and seismic methods was carried out previously and presented in Brisbourne et al. (2014). Due to the smaller number of new data points presented here we do not repeat this analysis, which has already proven this approach. How is the GPS error determined?

As stated in the original manuscript this is the measurement error calculated from the raw GPS data (P6L5).

• My main concern is with the bathymetric grid itself. The paper in its current form presents this grid, rather than individual point measurements, as the main result. Section 4 that describes the gridding does not go into sufficient detail. What grounded-ice-depth measurements are added into the grid, those from Bedmap2? So the gridded grounding line position is consistent with that dataset? The authors state that the ice draft in Bedmap2 is better constrained, do they mean the draft as calculated from floatation in regions far away from their own measurements? If so the last sentence is wrong since these thickness values in Bedmap2 are not measurements and therefore not 'known'.

We regard the seismic measurements as the fundamental product which is being presented here and these form the bulk of the data in the repository. The gridded product is included to put these data into context and highlight their value as without this the data would have little meaning or value to the reader. We have added detail of which Bedmap2 data are used (essentially outside of the cavity) and the gridding algorithm. It is correct to state that ice thickness is not "known" but comes from altimetry and floatation calculations. This has been corrected. (S4).

I find the choice of natural neighbour interpolation very puzzling and I think this choice will dramatically affect the resulting grid. I don't think the authors' justification is sufficient, but if there is a very good reason for this choice I would like a discussion and appropriate references. Many deep bathymetric points near the grounding line end up as bullseyes in the grid whereas they are almost certainly located in the troughs of paleo-ice-streams.

This argument arises repeatedly in internal discussions regarding gridding algorithms. Indeed, one method to grid the data would be to use palaeo ice stream routes to delineate troughs. However, by employing such methods one is prescribing geometry using assumptions which may not be valid. We can see how this may be a preferred method for some practitioners and anticipate that some users of

the data may prefer this method. However, our preferred method uses only the data available and does not prescribe geometry using theories or models. In our opinion the natural neighbour method remains true to the observations, where they are available and we regard this as the most appropriate method for the presentation of these data.

Deepening the seabed to ensure an open cavity in some cases is clearly a necessary evil but how extensively is this done? If this is going to be used by ice sheet modellers then I would strongly suggest a much greater minimum thickness than 10m, since even small transient dhdt values during the start of a simulation will cause the ice shelf to ground and completely change ice flow in the region. An uncertainty estimate would be useful but presumably would be difficult to produce without using a more advanced gridding algorithm (which I strongly feel should be done, or at least a comparison made to justify the choice made here).

We agree. Quantifying the uncertainty in a grid is extremely difficult and we have tried with this and other data sets without success. We also agree that using a minimum cavity thickness is a necessary evil and appreciate that the reviewer recognises this. As we do not intend, nor expect, the gridded product to be used directly by the oceanographic community, we used 10 m as this most closely resembles the original interpolated grid in form. The specific minimum depth used is determined by the type and resolution of oceanographic model used and there is therefore no correct value. We now do however include an additional figure (Figure 4) to highlight where this update has been done and to what degree. This is a useful addition and helps to highlight weaknesses in the interpolation and data coverage.

Also given that many of these data are already published elsewhere and lead to the generation of a previous grid, I think a direct comparison is essential to be able to ascertain which features are genuinely new discoveries resulting from the data presented here.

Overall, more detailed discussion is needed. I realise a perfect grid is impossible with limited data, but I do not feel that sufficient care has been taken with grid generation and I think the resulting discussion skips over these issues, particularly given that it is presented as the main result of the paper.

We do not think it necessary to focus on highlighting new features. As mentioned above, data points in previously unmeasured areas which confirm previous interpolations are just as valid as data points which contradict previous results as without confirmation, neither model can be deemed 100% reliable. We therefore discuss the main features and simply highlight whether these are confirmatory or not. Without oceanographic modelling, the importance of individual features cannot be ascertained, and therefore lies beyond the scope of this paper.

Technical corrections

Throughout the paper: Hyphenation rules inconsistently applied

We've tried hard to ensure consistency. A consequence of 14 authors I suspect.

p. 1 l. 21: Capitalise West (also in title)

LCIS is in west Antarctica but it is not in West Antarctica, as in the West Antarctic Ice Sheet. It is the Antarctic Peninsula Ice Sheet, hence west with the lower case.

p. 1 l. 28-30 Repeat of earlier parts of the abstract

This sentence specifically describes the data set, the earlier part of the abstract describes the study. We have changed the paragraph structure to reflect this.

p.2 l. 3: Missing references for buttressing e.g. Rott 2002, Furst 2016, Reese 2018

Rott and Furst added but we don't see Reese (2018) as appropriate.

p.2 l. 14: Missing references for Antarctic Peninsula warming

Good point. Vaughan et al. (2003) added.

p. 2l. 26: accurately predict This just depends on whether we split the infinitive.

p. 3 l. 9: here and elsewhere should be bathymetric when used as adjective and bathymetry when a noun. Good point but not necessarily always the case. In some cases we use the compound noun, such as "bathymetry map" where this is a specific entity.

p. 3 l. 16 Ensure that units are in-line with numbers We will make sure this is resolved at the typesetting stage.

p. 5 l. 1: How were picking errors determined, was a repeat of each pick done?

Correct, consistent with previous studies. Text has been added to clarify.

p. 5 l. 22: What is the vertical GPS accuracy based on, why were some surface elevation measurements not available?

As stated, this is the measurement uncertainty (calculated from the raw data). Not all field campaigns used dual frequency GPS to measure surface elevation. This is one of the complexities of integrating data from different field campaigns made by different groups and Table 1 presents this fact.

p.5 I. 26: Based on all of the above uncertainty sources, we arrive at a cumulative overall uncertainty... Done

p. 6 ;. 12: Surely another crucial aspect of the bathymetry around this ice rise is whether slight thickening could lead to extensive re-grounding.

Correct, although thickening in this area is not seen as particularly likely in the near future, words have been added to this effect.

p. 6 l. 16-17: I don't see this path of Jason trough north of Bawden Ice Rise since the bathymetry there is shallower than the route south.

Whether this is actually a route for oceanographic circulation is beyond the scope of this paper and an aspect to be addressed by the oceanographic community. We are merely stating that we can confirm that no barrier exists to this deeper water previously modelled in say Nicholls et al. (2012).

p.6 l. 17-19: This is based on one data point and the gridding here has just created a presumably unrealistic bullseye around that point. Presumably the reality is that there is a trough here leading towards the grounding line that is missed in the grid and this should be discussed.

This is of course the ultimate limitation of sparse data coverage and the reason why we present the grid with data points overlain to highlight coverage. Any interpretation of oceanographic models using these data will need to be fully aware of these limitations and discuss them in context. We have added a sentence at the start of this section to highlight this fact.

p. 6 l. 21: References needed.

Done

Fig. 3: Given that this is the main figure of the paper I think it needs a lot more work. Firstly the resolution is far too low for publication. The background MODIS imagery is either completely missing or not discernible. Please highlight the grounding line by making it a bolder contour. What do the black arrows indicate? Add label for Mobiloil inlet and Cole Peninsula which are discussed in the discussion text.

Some good points here. We have updated and improved this image and added additional annotation for clarity as well as the Bedmap2 grounding line. Unfortunately, the resolution is limited by the 5MB limit imposed by the publisher for images. The MODIS imagery was used to highlight the new ice front only and so we have replaced this with a solid line to improve the clarity of the rest of the figure.

Anonymous Referee #3

This study presents new bathymetric information derived from seismic shots beneath the Larsen-C lce cover. The Significance of new information has no doubt concerning ocean circulation and global climatological issues. However, it is not very clear to me up to which level your new data improve previous datasets. The main global comment that I may have from reading the paper several time is that further care should be taken on making the difference on the contribution of the existing data and the motivation/input from the new data.

As stated in the general response, even if new data do not delineate new features, the very fact that they can be used to confirm the existence of previously "assumed" features is a valuable result when modelling sub-shelf bathymetry. We are therefore not particularly concerned about highlighting lots of new features which may only be marginally different from the previously assumed features.

Specific comments -

Location of previous work: I believe that a table giving summary statistics of the previous dataset would be valuable (columns could be like: survey name, survey date, type/sensor, number of measurements, estimated vertical accuracy, estimated horizontal accuracy. - Using the table proposed above you can detail the new dataset –

The data we feel are required are already presented in Table 1 (P13). More detail is provided in the metadata of each archived data set.

It is not very clear to me how the gridding methodology is done. I understand you've used natural neighbour interpolation. You should provide a schema of your procedure in which we could see the data flow, the different steps (data preparation, gridding process, corrections) and the parameters used. –

Details and discussion added in Section 4.

Your gridding correction steps (line 2-5, p6) is not clear. It looks to me as some sort of data tweaking. Please see reviewers #2 on this point. –

As reviewer #2 accepts this "tweak" is a necessary evil of transforming the grid where data are sparse a form that can be used by the oceanographic community. We have outlined our procedure to ensure this is understood by end users of the gridded product. We have added an additional figure (Figure 4) to highlight areas where the mismatch between the interpolated grid and ice draft is most prevalent, mostly along the grounding line.

Concerning the two last points I believe that the minimal aim of your paper and more specifically section 4 is to enable any readers/data user to be able to reconstruct the bathymetric grid. Therefore I suggest being more explicit in your gridding methodology. Algorithm, implementation, software, parameters

As described above, the main aim of our paper is to present the data and discuss its potential significance. The gridded product is not seen as an essential output for the community. We have however added enough detail to allow the reader to reproduce the gridded product but also highlighted that we do not see it as a final product.

I do not pretend to be able to comment on the English or the style; however I would suggest limiting the vagueness to its minimum. You should be more explicit and limit yourself from using terms like "relatively", "more reliable", "where required", "consistent", "much lower", "further uncertainty", We have removed a number of these issues where we feel they are not essential. We would argue that the term "relative" is in certain instances valid, for example.

Reviewer #4 Coen Hofstede (Referee)

General comments: The paper presents addition of seismic point measurements to existing ice column–water column thickness measurements at Larsen C Ice Shelf (LCIS). By measuring the travel times of the ice shelf base and seabed, the ice shelf thickness and water column are calculated. In addition to existing data points and bedmap2, a sub-shelf bathymetric map of LCIS is created. The paper is well written, clearly built-up, and easy to follow. The method to calculate ice thickness and water column is straightforward and well explained, but certain parts are described vaguely, making it hard to judge the quality of the presented data, such as the p-wave velocity of the ice column and the gridding process.

The bathymetric sub-shelf map of LCIS is a valuable addition to the gap in bathymetric data under Antarctic ice shelves. The data points better constrain the sub-shelf bathymetry such as their key findings show, and improve the modeling of the oceanshelf interaction. LCIS is probably next in line to disintegrate.

Specific Comments:

3.2/3.3 Seismic velocities/Uncertainties The velocity analysis of the firn/ice column is well explained but a number (or range) for the ice velocity(ies) would be nice. Indirectly this is mentioned at the uncertainty of the ice column thickness, being 3.8m at 1 ms uncertainty, which suggests the ice velocity is 3800m/s. If that is the case I come to half of the suggested uncertainty as the times of reflections are TWTs. To understand the uncertainty of the ice column, velocities of the ice column are essential.

The range of maximum velocities is now included in Section 3.2. Uncertainties are now presented and discussed in more detail and individual uncertainties presented in Table 2 for each new seabed depth measurement.

It is not clear if the measurements are corrected for tides, I suspect not. This is important for those shots that do not show no ice base return. With a tidal range of 2 m, I would come to approximately 20m inaccuracy. How many shots do not have this ice base return, one at PRHB4 or more?

As already outlined at P5-L23 in the original submission, no correction for tides is made, consistent with Brisbourne et al. (2014). This is included in the uncertainty estimate. It is not clear to us how a 2 m tide will result in 20 m inaccuracy. Indeed, as stated in the original manuscript, only PRHB04 lacks an ice base reflection in the seismic data.

Although the error analysis is clearly described and the order of magnitude is correct, the choice of 10m accuracy seems somewhat arbitrary to me. Why not 9m or 13m I wonder? We now provide uncertainties calculated for each site separately (Table 2).

Bathymetric gridding I think it is important here to be clear about the gridding method is used rather then "which is well suited to a dataset with an uneven distribution of data point". It is important to know how you get from data points to the gridded bathymetry map. A reference possibly? Additional text has been added to Section 4 to provide this detail.

I find the phrasing about the gridding problem at places where the "calculated seabed is shallower than : : :..the ice draft of the Bedmap2 dataset" unclear. Are these calculations ignored or overruled by a deeper seabed? If so it would make sense to mark these data points in map 3 so that we know exactly what data points have been used in the gridding

We have replaced the word "calculated" with "interpolated" to help clarify this issue. The problem arises where the interpolated values are contradicted by the measured ice thickness data, not where we have direct measurements of sea bed depth.

Figure 1: The text (3.1) and Table 2 mention 30 measurements (14 seismic bathymetry measurements and 16 seismic refraction and reflection surveys). In the figure I see 28 yellow dots (new measurements) and 3 red dots. - How do these 28+3=31 dots relate to the 30 measurements from Table 2? Please explain in the caption or adjust the figure.

Figure 1 has been updated to make this clearer. Two MIDAS sites are collocated and one was mislabelled as it is a repeat of an existing site.

Figure 3: Please use another color for the contour lines. They can hardly be made out. Done

Technical corrections:

Table 1, receiver spacing MIDAS: Why an asterisk? Well spotted! These are the data referred to in the caption where the acquisition geometry varies and as such is detailed in the data repository.

An updated seabed bathymetry beneath Larsen C Ice Shelf, west Antarctica

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Abstract. In recent decades, rapid ice-shelf disintegration along the Antarctic Peninsula has had a global impact through enhancing outlet_glacier flow, and hence sea level risesea-level rise, and the freshening of Antarctic Bottom Water. Ice_-shelf

- 20 thinning due to basal melting results from the circulation of relatively warm water in the underlying ocean cavity. However, the effect of sub-shelf circulation on future ice-shelf stability cannot be predicted accurately with computer simulations if the geometry of the ice-shelf cavity is unknown. To address this deficit for Larsen C Ice Shelf, west Antarctica, we integrate new water-column thickness measurements from recent seismic campaigns with existing observations. We present these new data here along with an updated bathymetry grid of the ocean cavity. Key findings include relatively deep seabed to the south-east
- of the Kenyon Peninsula, along the grounding line and around the key ice shelfice-shelf pinning-point of Bawden Ice Rise. In addition, we can confirm that the cavity's southern trough stretches from Mobiloil Inlet to the open ocean. These areas of deep seabed will influence ocean circulation and tidal mixing, and will therefore affect the basal-melt distribution. These results will help constrain models of ice-shelf cavity circulation with the aim of improving our understanding of sub-shelf processes and their potential influence on ice shelfice-shelf stability.
- 30

The data sets comprises all <u>the new point</u> measurements of seabed depth<u>and a gridded data product</u>, derived using additional measurements of both offshore seabed depth and the thickness of grounded ice. _We present <u>present</u><u>all</u><u>the</u> new depth measurements here as well as a compilation of previously published measurements<u>used in the gridding process</u>. <u>To</u> demonstrate the improvements to the sub-shelf bathymetry map which these new data provide we include a gridded data

product in the supplementary material of this manuscript, derived using the additional measurements of both offshore seabed depth and the thickness of grounded ice. The gridded data product is included in the supplementary material.

The underlying seismic data sets which were used to determine bed depth and ice thickness are available at https://doi.org/10.5285/315740B1-A7B9-4CF0-9521-86F046E33E9A (Brisbourne 5 et al., 2019), https://doi.org/10.5285/5D63777D-B375-4791-918F-9A5527093298 (Booth, 2019), https://doi.org/10.5285/FFF8AFEE-4978-495E-9210-120872983A8D

(Kulessa and Bevan, 2019) and https://doi.org/10.5285/147BAF64-B9AF-4A97-8091-26AEC0D3C0BB (Booth et al., 2019).

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1 Introduction

The loss of Antarctic ice shelves is of global significance for two reasons. First, ice shelves provide a buttressing force – controlled by the geometry and stress regime of the ice shelf - to the glaciers or ice streams that feed them. Although loss of the floating ice shelf ice shelf makes only a small direct contribution to sea level rise sea-level rise, the removal of buttressing results in acceleration of the tributary glaciers, enhancing their current contribution to sea level risesea-level rise (Rignot et al.,

- 2004; Scambos et al., 2004; Rott et al., 2002; Fürst et al., 2016). Secondly, basal melting of ice shelves produces cold and lowsalinity water that influences Antarctic Bottom Water (AABW) formation, which in turn affects the properties of the global oceans (Jacobs, 2004).
- 20 Over recent decades, there has been a southwards progression of ice shelf loss along the eastern Antarctic Peninsula. The disintegration of the Larsen A Ice Shelf in 1995, and the Larsen B in 2002, resulted in a step increase in flow of the grounded glaciers that formerly fed these ice shelves (e.g., Khazendar et al., 2015). This increase in glacier flow resulted in accelerated sea level risesea-level rise and increased freshening of dense AABW (Jullion et al., 2013). In a number of cases, ice shelf retreat has been attributed to atmospheric warming (Vaughan and Doake, 1996; Rott et al., 1998; Skvarca et 25 al., 1999). With the Antarctic Peninsula exhibiting one of Earth's highest rates of atmospheric warming during the late twentieth century_(Vaughan et al., 2003), the long-term viability of the Larsen C Ice Shelf (LCIS) is in question. However, Holland et al. (2015) demonstrated that the thinning of LCIS over the last decade is a result of both atmospheric and oceanic influence in almost equal measure. For the remaining ice shelves on the Antarctic Peninsula, the relative contribution to their future stability by basal melt from incursions of relatively warm ocean water, and increased surface melting by a warmer 30
- atmosphere, is still unknown.

To improve projections of the effects of basal melt on ice shelves, knowledge of the geometry of the ocean cavity beneath is vital (Mueller et al., 2012; Jenkins et al., 2010; Grosfeld et al., 1997; Goldberg et al., 2019; Pattyn et al., 2017). Models of subshelf circulation are critically dependent on cavity geometry, particularly in regions where the influence of strong tides is topographically constrained (e.g., Mueller et al., 2012). Ongoing efforts to model ocean processes beneath LCIS suffer from

- 5 inadequate knowledge of cavity geometry because seabed depth is very poorly sampled_-(Brisbourne et al., 2014)₁. Improving knowledge of cavity geometry is crucial for LCIS because the sparse existing data suggest the presence of large-scale seabed features capable of guiding ocean currents and inducing significant tidal mixing. It is impossible for computer simulations to predict accurately the future influence of the ocean on LCIS without knowledge of the geometry of such features.
- 10 Although labour intensive, seismic methods remain the most reliable method for determining sub-shelf cavity geometry. Airborne and ground-based radar are used extensively to map ice thickness but cannot penetrate the sub-shelf cavity. Autonomous underwater vehicles (AUV) provide another direct measurement of sub-shelf bathymetry but with limited coverage at present (e.g., Jenkins et al., 2010). Inversion for water column thickness using airborne gravity measurements is sensitive to assumptions about local density variations such as sediment infill and may lead to inaccurate results (Brisbourne
- et al., 2014). Recent studies using gravity inversion combine data from multiple methods to address these assumptions (e.g., Muto et al., 2016).

2 Location and previous work

LCIS, the largest ice shelf on the Antarctic Peninsula at around 44 000 km² (Cook and Vaughan, 2010), lies just south of the recently collapsed Larsen A and B ice shelves (Fig. 1). The geometry of LCIS's sub-shelf cavity has previously been measured
in detail at specific locations only (Brisbourne et al., 2014): this campaign was designed to target locations where an existing where an inversion of gravity measurements indicated areas of significant control over sub-shelf circulation (Cochran and Bell, 2012). However, uncertainties associated with such-gravity inversions for bathymetry result in large areas of unknown geometry, specifically beneath LCIS (i) away from the western grounding line, (ii) away from the ice front, and (iii) in the south.

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We build on a number of published sources of <u>bathymetrybathymetric</u> data with new observations from four recent field campaigns. The existing <u>bathymetrybathymetric</u> data used in the gridding process here <u>(Figure 1, blue dots)</u> are derived from a targeted seismic bathymetry survey, seismic refraction experiments and drill site measurements (Brisbourne et al., 2014; Nicholls et al., 2012). The depth to grounded ice and known offshore bathymetry of Bedmap2 is included in the gridding process (Fretwell et al., 2013). Surface elevation and ice thickness measurements at Bawden Ice Rise <u>(BIR)</u> are also included

30 process (Fretwell et al., 2013). Surface elevation and ice thickness measurements at Bawden Ice Rise <u>(BIR)</u> are also included (Holland et al., 2015). Here, we integrate these existing data with the new measurements of seabed depth. All data are then gridded to obtain a new bathymetry map of LCIS.

3 Data acquisition and processing of new observations

3.1 Data Acquisition

In December 2016, 14 seismic bathymetry measurements were made across LCIS, targeting areas of sparse data coverage (Figure 1, yellowmagenta dots). The seismic source consisted of a sledgehammer with a plate stamped into the snow surface,

- 5 or dug down to a shallow ice layer, to improve source consistency of the shots at that location for stacking purposes. Twenty-four Georod receivers (Voigt et al., 2013) were buried to 0.30 em depth, at 10 m spacing, and with a 30 m offset between the shot and to the first receiver. Burying sensors in this way ensures good coupling and provides protection from wind-induced noise. Georods consist of four geophone elements in series, which improves the signal to noise ratio. We recorded 2 s records at 0.125 ms sample interval with a 24-channel data logger. At each site, ~20 hammer blows were recorded using a geophone
- 10 trigger-adjacent to the hammer plate to initiate recording. An additional stack of 10 hammer blows was also recorded for onsite evaluation of the seismic reflection strength. To determine an accurate surface elevation a dual-frequency GPS system ran was deployed for the duration of the seismic acquisition at each site.

These data are supplemented by bathymetry measurements from an additional 16 seismic refraction and reflection surveys

- 15 across LCIS (Figure 1 orange, black and yellow dots). Although many of these experiments targeted depth profiles of the firn, the data are suitable for ice shelfice-shelf thickness and seabed d_depth measurement. The acquisition procedure is similar to that described above and therefore data quality and uncertainties are similar. Details of the acquisition parameters for each experiment are presented in Table 1 with further details in the metadata of each data archive.
- Figure 2 presents an example of a seismic gather formed of 10 hammer blows stacked during acquisition. Clear ice_base and seabed arrivals, as well as multiples thereof, are observed. Where necessary, to help identify reflections, a frequency-wavenumber filter was used to suppress groundroll that may mask the ice_base reflection. An automatic gain control filter and semblance analysis was also used as required to <u>constrain_identify</u> arrivals. However, ice_base and seabed reflection traveltimes were measured on raw seismic records, even if a filter was required to help identify arrivals. A relatively thin ice shelf will result in the ice_base reflection arriving within groundroll noise (see Figure 2). In these cases, surface multiples of the ice-base reflection were used to calculate the primary two-way traveltime through the ice column.

3.2 Seismic velocities in ice and water and thickness measurement

We follow the procedures outlined in Brisbourne et al. (2014) to convert from traveltime to thickness. Values of seismic 30 velocity are required to convert traveltimes to layer thickness or depth. A mean seismic velocity in the water column of 1445 $\pm 1 \text{ m s}^{-1}$ was derived during conductivity-temperature-depth (CTD) measurements made beneath northern and southern LCIS by Nicholls et al. (2012). The seismic velocity profile in the upper 100 m of the ice shelf, which includes the firn, was measured using the shallow refraction experiments presented here (see Table 1 – <u>SOLIS/MIDAS/RACE</u>), as well as those of Brisbourne et al. (2014) (see <u>Table 1 – BAS Refraction</u>). At each of the refraction sites, a series of surface shots was recorded with increasing receiver

- 5 spacing. The first arrivals were picked and converted to a velocity-depth profile using the method described by Kirchner and Bentley (1990). This method relies on a monotonic increase in velocity with depth, an assumption that is supported by observations of smoothly varying traveltimes. <u>Maximum velocities at 100 m depth calculated by inversion of the refraction</u> <u>measurements range from 3698 to 3916 m s⁻¹</u>. Below 100 m depth, we assume that ice density is constant and seismic velocity depends on ice temperature alone. CTD measurements of Nicholls et al. (2012) indicate an ice-base temperature of -2° C.
- 10 Temperature measurements within the ice column indicate an approximately linear temperature profile with a small range (-2° to -13° C; Nicholls, 2012, unpublished) and therefore using the relationship of Kohnen (1974), a small range of seismic velocities (3800-3827 m s⁻¹). Therefore, below 100 m we linearly interpolate between the velocity measured by seismic refraction at 100 m depth and an ice_-base velocity calculated from the temperature-velocity relationship of Kohnen (1974). Where a bathymetry measurement and seismic refraction experiment are not coincident, results from the closest seismic
- 15 refraction experiment are used to determine ice thickness.

Measurement of the surface elevation allows for the estimation of ice thickness assuming freely floating ice. These estimates can guide the identification of ice_base reflections in the data. The EIGEN-GL04C geoid level (Forste et al., 2008) is removed from the elevation and an empirical relationship determined by Brisbourne et al. (2014) used to calculate ice thickness: geoid-

20 corrected height, $h = (0.113 \pm 0.005)H + (5.003 \pm 1.525)$, where H is ice column thickness in metres. This relationship accounts for firn thickness, which affects mean density. The absence of a clear ice_-base reflection is not necessarily a result of poor data-quality data. Under certain conditions, particularly in ice_-shelf suture_-zones, poorly consolidated marine_-ice at the base of the ice shelf may result in a weak or absent seismic reflection. At site PRHB04 (see Table 2), in the absence of a clear ice_ base reflection, we calculate the ice thickness and its uncertainty from the surface elevation using the empirical relationship 25 described above.

3.3 Uncertainties

Errors in picking reflections, seismic velocities and seabed topography all contribute to uncertainties in ice and water-column thickness calculations.

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Picking of ice and seabed reflections was repeated three times for each site in order to quantify the error, indicating a maximum pPicking errors in the seismic reflections data of are < 10.5 ms, equivalent to thickness uncertainties of 1.4 and 3.8 m for water

and ice, respectively. Ice column thickness is determined by the difference in seabed and ice-base arrival times and therefore has an uncertainty of 1.0 ms. We assume

A a conservative estimate of the uncertainties in seismic velocity in the ice column of 30 m s⁻¹ (Kirchner and Bentley, 1990;

- 5 Rosier et al., 2018)-is equivalent to an uncertainty of 2 m in ice column thickness. However, <u>T</u>the presence of marine ice in suture zones (Kulessa et al., 2019) or significant warm refrozen ice within the firn column (Hubbard et al., 2016; Ashmore et al., 2017) may result in seismic velocities which deviate from the standard model and introduce greater uncertainty in measured velocities. However, a previous study highlighted the consistency between seismic<u>ally</u>-derived ice_-thickness measurements and those from surface_-elevation measurements (Brisbourne et al., 2014). Importantly, <u>where an ice-base reflection can be</u>
- 10 <u>identified</u> the <u>calculated</u> thickness of the <u>derived</u>-water column is independent of the ice velocity-depth profile used. Direct measurements of seismic velocity in the water column (Nicholls et al., 2012) result in a much lower uncertainty in water column thickness than that of ice thickness or seabed depth.

Ice_-base and seabed topography can introduce additional uncertainty to thickness measurements (Nost, 2004). Calculations of ice and water_-column thickness from traveltimes assumes that reflectors are planar and horizontal. Such a geometry results in a characteristic curvature, or moveout, of traveltimes with increasing receiver offset. Assuming an isotropic seismic velocity structure, any deviation from standard moveout is indicative of dip at the reflecting interface. Brisbourne et al. (2014) used observed deviations from standard moveout to demonstrate that topography across LCIS causes a maximum error in seabed depth of <10 m. However, a full assessment of the error introduced by bed topography would require multiple measurements at each site at different angles across the slope and this uncertainty is therefore not included here.</p>

We calculate seabed depth by removing ice and water_-cavity_thickness from measured_surface_-elevation data. Elevation \underline{U} ncertainties in dual-frequency GPS <u>elevation</u> measurements are <u>up to</u> ±40 mm. Where direct surface_elevation measurements are not available (dual-frequency GPS measurements not made, see Table 1) the REMA surface DEM of 2017

at 8 m resolution is used (Howat et al., 2019), resulting in an absolute elevation uncertainty in these areas of \pm 2 m. No tidal correction is made to surface elevations, resulting in a further additional uncertainty in surface elevation of \pm 2 m (Brisbourne et al., 2014).

We therefore Based on the above uncertainty sources, but excluding the unknown seabed slope, we assign a maximum overall
 uncertainty of ±10 m to the ccalculated uncertainties in -seabed depths at each site and present these with the seabed depths in Table 1. -Uncertainty at site PRHB04, where no ice-base reflection was observed, has been calculated using the range of ice thickness values indicated by the empirical surface elevation relationship of Brisbourne et al. (2014) and the resultant uncertainty in water column thickness.

4 Bathymetry gridding and results

We include a one-kilometre horizontal resolution bathymetry grid of LCIS's cavity in the supplementary material. To produce this grid_Wwe interpolated between all available existing and new seabed_depth measurements._, along with gWe augmented these data with the grounding line position, grounded-ice bed depths and offshore bathymetry derived from Bedmap2 (Fretwell

- 5 et al., 2013). The measured bed geometry of Bawden Ice Rise was derived from Holland et al. (2015) (see Table A1). to create a map of the seabed geometry directly under the ice shelf. We present a 1.3 km horizontal resolution bathymetry map of LCIS's cavity created using a composite of the data outlined above and previously published depth measurements (Table A1). We use a natural neighbour interpolation implemented in the griddata function of MATLAB (Release 2019a), which is well-suited to a dataset with an uneven distribution of data points (Sibson, 1981). Importantly, the fit to these points does not
- 10 'overshoot', which would result in interpolated values that are higher or lower than known values. <u>A weakness of this method</u> is that where seabed topography changes rapidly with respect to data coverage the seabed may not be well constrained. This results in a discrepancy where the interpolated seabed depth is shallower than the ice draft as reported in Bedmap2. Therefore, in the gridded product we deepen the seabed where this discrepancy occurs and assign a seabed depth to be equivalent to the Bedmap2 ice draft plus a minimum water column thickness of 10 m. This ensures that all interpolated seabed depths are
- 15 consistent with the Bedmap2 ice thickness.

Figure 3 presents a map of seabed elevation in the LCIS region, resulting from gridding of all available data as described above and with a minimum cavity thickness of 10 m when compared to Bedmap2 ice draft. The analysis and application of such grids is of course dependent on the limitations of data coverage and the gridding method used. Our method does not superimpose any additional constraints on the resultant bathymetry, as highlighted by the bullseye deepening around the single data point

20 any additional constraints on the resultant bathymetry, as highlighted by the bullseye deepening around the single data point to the south of the Kenyon Peninsula that in reality may form a linear trough. However, the sparse data coverage in that area precludes any definitive knowledge of bed geometry and any gridded product will require -careful interpretation.

Figure 4 presents the difference between the grid corrected for Bedmap2 ice draft and the original interpolated grid,
highlighting the areas of the cavity where the data coverage and interpolation method are least reliable. In general, this discrepancy occurs where topography is changing rapidly with respect to data coverage, such as along the grounding line. To avoid issues such as this, other methods of interpolation may be preferred. For example, knowledge of past ice flow may be used to prescribe channels around isolated data points, or onshore slopes may be continued into the cavity. Similarly, the prescribed minimum cavity thickness of 10 m may be adapted to the resolution and type of oceanographic model used. This
gridded product is therefore not viewed as a definitive bathymetry for use by the oceanographic community but is used here

to highlight the value of these new data. No matter what method is applied, there are intrinsic weakness of gridding with interpolation in regions of sparse data coverage, and by their nature, uncertainties cannot be quantified readily.

Locations where the calculated seabed depth is shallower than the better constrained ice draft of the Bedmap2 dataset (Fretwell et al., 2013) highlight the limitations of the data and gridding process. This issue is most noticeable along the grounding line, where bed topography changes rapidly but data coverage remains sparse. Therefore, in the gridded product we deepen the seabed where required to ensure that its depth is greater than the Bedmap2 ice draft plus an arbitrary minimum water column

5 thickness of 10 m. This ensures that all interpolated seabed depths are at least consistent with known ice thickness measurements, which are regarded as far more reliable.

5 Results Discussion and significance of the data set

Figure 3 presents a map of seabed elevation in the LCIS region, resulting from gridding of all available data as described above. A number of key features that will influence tidal and oceanic circulation through the sub-shelf cavity, and thus affect
basal melt rates and melt water circulation are apparent: (1) A relatively deep seabed surrounds Bawden Ice Rise-(BIR), a key pinning point of LCIS_a. Holland et al. (2015) highlighted that BIR is the pinning point-where LCIS is closest to floatation (Holland et al., 2015). The bathymetry of this area therefore plays a key role in the ice shelf's future stability. A deep seabed here may alter the strong tidal currents that are thought to induce melt in this region (Mueller et al., 2012) and also reduce the likelihood of re-grounding following any slight thickening. (2) The southern trough, to the north of the Kenyon Peninsula,

- 15 extends from Mobiloil Inlet to the ice front. Nicholls et al. (2012) highlighted this deepening in southern LCIS as a potential conduit for High Salinity Shelf Water (HSSW) that may access the deeper ice at the grounding line, providing vigorous melting. Similarly, the updated bathymetry also confirms that the Jason Trough in the north also continues through to the open ocean, to the north of Bawden Ice Rise. (3) The sub-shelf cavity to the southeast of the Kenyon Peninsula is relatively deep. Again, Nicholls et al. (2012) highlight this location as potentially important to the supply of HSSW that sustains melt at the grounding
- 20 line. (4) All additional point measurements confirm that the <u>where sampled the</u> sub-shelf cavity is particularly deep close to the grounding line between Mobiloil Inlet and the Cole Peninsula. Sub-shelf circulation models highlight that the grounding line, where shelf ice is thickest and therefore deepest, provides a key site for basal melt_(Mueller et al., 2012). <u>However, the inconsistency between the interpolated grid and Bedmap2 bathymetry at the grounding line (Figure 4) highlights the remaining shortcomings of the bathymetric data close to the grounding line.</u>

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These data provide a valuable product for the study of ice-ocean interaction beneath LCIS. The interaction of these newly determined cavity features with the sub-shelf circulation pattern requires detailed oceanic modelling to ascertain their importance. These data, along with the gridded bathymetry map, provide a valuable product for the study of ice ocean interaction beneath LCIS. The updated bathymetry is a prerequisite to estimating the contribution of sub-shelf melt to thinning of the ice shelf and the contribution of that melt to the global ocean system. Previous studies have highlighted the importance of accurate bathymetry beneath LCIS, but until now have lacked information on the major troughs delineated by our these data. The provision of the spot measurements will allow users to re-grid using other algorithms if required, and allow for rapid

assimilation of any new data points that become available in the future. This is of course not a definitive data set and additional data points that address gaps in the current coverage will always be of value to reduce uncertainty where interpolation has been necessary. As the resolution of ocean models improves, the requirement for greater certainty with regards small-scale features will also increase.

5 Data Availability

The underlying seismic data sets which were used to determine bed depth and ice thickness are available at https://doi.org/10.5285/315740B1-A7B9-4CF0-9521-86F046E33E9A (Brisbourne et al., 2019), https://doi.org/10.5285/5D63777D-B375-4791-918F-9A5527093298 (Booth, 2019), https://doi.org/10.5285/5D63777D-B375-4791-918F-9A5527093298 (Booth, 2019), https://doi.org/10.5285/FFF8AFEE-4978-495E-9210-120872983A8D

10 (Kulessa and Bevan, 2019) and <u>https://doi.org/10.5285/147BAF64-B9AF-4A97-8091-26AEC0D3C0BB</u> (Booth et al., 2019).

-Author contribution

PRH and AMB led the NERC BAS bathymetry experiment. BK, AJL and ADB respectively led NERC projects SOLIS, MIDAS and RACE. TH, BK, SB, DA, BH, AJL, ADB, EP and JW were involved in field data acquisition. AMB and BK wrote the manuscript with contributions from others. LH and AMB gridded the final bathymetry product.

Competing interests

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The authors declare no competing interests.

Acknowledgements

- 20 We acknowledge support by UK Natural Environment Research Council (NERC), the British Antarctic Survey Polar Science for Planet Earth Programme and NERC grants NE/E012914/1 (SOLIS), NE/L005409/1 (MIDAS) and NE/R012334/1 (RACE) and. We thank BAS Operations for support of all data acquisition presented here. NERC Geophysical Equipment Facility supplied instruments for the fieldwork under loans 863, 864, 865, 1028 and 1060. The MODIS image from 2018 was retrieved on 2019_10_01 from Earth Science Data and Information System (ESDIS) Project, Earth Science Projects Division (ESPD),
- 25 Flight Projects Directorate, Goddard Space Flight Center (GSFC) National Aeronautics and Space Administration (NASA) 2019. We are grateful to Emma Smith, Coen Hofstede and two anonymous reviewers for their constructive comments which helped improve this manuscript.

Figures





Figure 1 Map of seismic points used in the gridded bathymetry product of this study. The approximate path of the ice-shelf rift which resulted in the calving of iceberg A68 is highlighted (Jansen et al., 2015). The background is MODIS imagery (Scambos et al., 2007), pre-dating the break-off of iceberg A68 along the rift.





Figure 2 Example hammer and plate seismic shot gather with readily identified primary seismic reflections and multiples. <u>The</u> primary ice-base reflection at 190 ms is masked by groundroll signal at far offsets.





Figure 3 Updated bathymetry map of Larsen C Ice Shelf with large-scale features highlighted. For clarity, elevations above 0 m are unscaled and we label only the -400 and -600 m contours. The brown line represents the Bedmap2 grounding line (GL) (Fretwell et al., 2013). The background is MODIS imagery from orange line represents the ice front on 20th December 2018 highlighting the new ice shelf-front following the calving of iceberg A68 determined from MODIS imagery (Vermote and Wolfe, 2015). MOI – Mobiloil Inlet. The black arrows highlight likely oceanographic conduits as discussed in the text.



Figure 4

Difference between the grid corrected for the Bedmap2 ice draft mismatch and the original natural neighbour interpolation grid in metres, highlighting areas where the cavity has been forced to 10 m.

References

Ashmore, D. W., Hubbard, B., Luckman, A., Kulessa, B., Bevan, S., Booth, A., Munneke, P. K., O'Leary, M., Sevestre, H.,
and Holland, P. R.: Ice and firn heterogeneity within Larsen C Ice Shelf from borehole optical televiewing, 122, 1139-1153, 10.1002/2016jf004047, 2017.

Booth, A.: Seismic refraction data, Antarctic Peninsula, Larsen C Ice Shelf, Whirlwind Inlet, November-December 2015 [Data set], UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation, 10.5285/5D63777D-B375-4791-918F-9A5527093298, 2019.

10 Booth, A., White, J., Pearce, E., Cornford, S., Brisbourne, A., Luckman, A., and Kulessa, B.: Seismic refraction data from two sites on Antarctica's Larsen C Ice Shelf, Nov 2017, following the calving of Iceberg A68 [Data set], UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation, 10.5285/147BAF64-B9AF-4A97-8091-26AEC0D3C0BB, 2019.

Brisbourne, A., Hudson, T., and Holland, P.: Seismic bathymetry data, Antarctic Peninsula, Larsen C Ice Shelf, 2016 [Data
set], UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation, 10.5285/315740B1-A7B9-4CF0-9521-86F046E33E9A, 2019.

Brisbourne, A. M., Smith, A. M., King, E. C., Nicholls, K. W., Holland, P. R., and Makinson, K.: Seabed topography beneath Larsen C Ice Shelf from seismic soundings, The Cryosphere, 8, 1-13, 10.5194/tc-8-1-2014, 2014.

Cochran, J. R., and Bell, R. E.: Inversion of IceBridge gravity data for continental shelf bathymetry beneath the Larsen Ice Shelf, Antarctica, J. Glaciol., 58, 540-552, 10.3189/2012JoG11J033, 2012.

Cook, A. J., and Vaughan, D. G.: Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years, Cryosphere, 4, 77-98, 10.5194/tc-4-77-2010, 2010.

Forste, C., Schmidt, R., Stubenvoll, R., Flechtner, F., Meyer, U., Konig, R., Neumayer, H., Biancale, R., Lemoine, J. M., Bruinsma, S., Loyer, S., Barthelmes, F., and Esselborn, S.: The GeoForschungsZentrum Potsdam/Groupe de Recherche de
Geodesie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1 and EIGEN-GL04C, Journal of Geodesy,

- 82, 331-346, 10.1007/s00190-007-0183-8, 2008.
 Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W.,
- 30 Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 375-393, 10.5194/tc-7-375-2013, 2013.
- Fürst, J. J., Durand, G., Gillet-Chaulet, F., Tavard, L., Rankl, M., Braun, M., and Gagliardini, O.: The safety band of Antarctic ice shelves, Nature Climate Change, 6, 479-482, 10.1038/nclimate2912, 2016.
 Goldberg, D. N., Gourmelen, N., Kimura, S., Millan, R., and Snow, K.: How Accurately Should We Model Ice Shelf Melt Rates?, Geophysical Research Letters, 46, 189-199, 10.1029/2018gl080383, 2019.
 Grosfeld, K., Gerdes, R., and Determann, J.: Thermohaline circulation and interaction between ice shelf cavities and the
- 40 adjacent open ocean, J. Geophys. Res.-Oceans, 102, 15595-15610, 10.1029/97jc00891, 1997.
 Holland, P. R., Brisbourne, A., Corr, H. F. J., McGrath, D., Purdon, K., Paden, J., Fricker, H. A., Paolo, F. S., and Fleming, A. H.: Oceanic and atmospheric forcing of Larsen C Ice-Shelf thinning, The Cryosphere, 9, 1005-1024, 10.5194/tc-9-1005-2015, 2015.

Howat, I. M., Porter, C., Smith, B. E., Noh, M. J., and Morin, P.: The Reference Elevation Model of Antarctica, The Cryosphere, 13, 665-674, 10.5194/tc-13-665-2019, 2019.

Hubbard, B., Luckman, A., Ashmore, D. W., Bevan, S., Kulessa, B., Kuipers Munneke, P., Philippe, M., Jansen, D., Booth, A., Sevestre, H., Tison, J.-L., O'Leary, M., and Rutt, I.: Massive subsurface ice formed by refreezing of ice-shelf melt ponds, Nature Communications, 7, 11897, 10.1038/ncomms11897, 2016.

Jacobs, S. S.: Bottom water production and its links with the thermohaline circulation, Ant. Sci., 16, 427-437, 2004.

Jansen, D., Luckman, A. J., Cook, A., Bevan, S., Kulessa, B., Hubbard, B., and Holland, P. R.: Brief Communication: Newly developing rift in Larsen C Ice Shelf presents significant risk to stability, The Cryosphere, 9, 1223-1227, 10.5194/tc-9-1223-2015, 2015.

Jenkins, A., Dutrieux, P., Jacobs, S. S., McPhail, S. D., Perrett, J. R., Webb, A. T., and White, D.: Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat, Nat. Geosci., 3, 468-472, 10.1038/ngeo890, 2010.

- Jullion, L., Garabato, A. C. N., Meredith, M. P., Holland, P. R., Courtois, P., and King, B. A.: Decadal Freshening of the Antarctic Bottom Water Exported from the Weddell Sea, J. Clim., 26, 8111-8125, 10.1175/Jcli-D-12-00765.1, 2013.
- Khazendar, A., Borstad, C. P., Scheuchl, B., Rignot, E., and Seroussi, H.: The evolving instability of the remnant Larsen B Ice Shelf and its tributary glaciers, Ear. Planet. Sci. Let., 419, 199-210, 10.1016/j.eps1.2015.03.014, 2015.
- Kirchner, J. F., and Bentley, C. R.: RIGGS III: Seismic short-refraction studies using an analytical curve-fitting technique, Ant. Res. Series, 42, 109-126, 1990.
 Kohnen, H.: The temperature dependence of seismic waves in ice, J. Glaciol., 13, 144-147, 1974.
 Kulessa, B., and Bevan, S.: Seismic refraction data, Antarctic Peninsula, Larsen C Ice Shelf, Cabinet Inlet, November-December 2014 [Data set], UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation,
- 15 10.5285/FFF8AFEE-4978-495E-9210-120872983A8D, 2019. Kulessa, B., Booth, A. D., O'Leary, M., McGrath, D., King, E. C., Luckman, A. J., Holland, P. R., Jansen, D., Bevan, S. L., Thompson, S. S., and Hubbard, B.: Seawater softening of suture zones inhibits fracture propagation in Antarctic ice shelves, Nat Commun, 10, 5491, 10.1038/s41467-019-13539-x, 2019.

Mueller, R. D., Padman, L., Dinniman, M. S., Erofeeva, S. Y., Fricker, H. A., and King, M. A.: Impact of tide-topography interactions on basal melting of Larsen C Ice Shelf, Antarctica, J. Geophys. Res.-Oceans, 117, 10.1029/2011jc007263, 2012.

Muto, A., Peters, L. E., Gohl, K., Sasgen, I., Alley, R. B., Anandakrishnan, S., and Riverman, K. L.: Subglacial bathymetry and sediment distribution beneath Pine Island Glacier ice shelf modeled using aerogravity and in situ geophysical data: New results, Ear. Planet. Sci. Let., 433, 63-75, 2016.

Nost, O. A.: Measurements of ice thickness and seabed topography under the Fimbul Ice Shelf, Dronning Maud Land, Antarctica, J. Geophys. Res.-Oceans, 109, 10.1029/2004jc002277, 2004. Pattyn, F., Favier, L., Sun, S., and Durand, G.: Progress in Numerical Modeling of Antarctic Ice-Sheet Dynamics, Current

Pattyn, F., Favier, L., Sun, S., and Durand, G.: Progress in Numerical Modeling of Antarctic Ice-Sheet Dynamics, Current Climate Change Reports, 3, 174-184, 10.1007/s40641-017-0069-7, 2017.

- 30 Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., and Thomas, R.: Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, Geophysical Research Letters, 31, 10.1029/2004gl020697, 2004. Rosier, S. H. R., Hofstede, C., Brisbourne, A. M., Hattermann, T., Nicholls, K. W., Davis, P. E. D., Anker, P. G. D., Hillenbrand, C. D., Smith, A. M., and Corr, H. F. J.: A New Bathymetry for the Southeastern Filchner-Ronne Ice Shelf: Implications for Modern Oceanographic Processes and Glacial History, Journal of Geophysical Research: Oceans, 123, 4610-
- 4623, 10.1029/2018JC013982, 2018.
 Rott, H., Rack, W., Nagler, T., and Skvarca, P.: Climatically induced retreat and collapse of northern Larsen Ice Shelf, Antarctic Peninsula, Ann. Glaciol., 27, 86-92, 1998.
 Rott, H., Rack, W., Skvarca, P., and de Angelis, H.: Northern Larsen Ice Shelf, Antarctica: further retreat after collapse, Ann. Glaciol., 34, 277-282, 2002.
- 40 Scambos, T. A., Bohlander, J. A., Shuman, C. A., and Skvarca, P.: Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, Geophysical Research Letters, 31, L18402, 10.1029/2004gl020670, 2004. Scambos, T. A., Haran, T. M., Fahnestock, M. A., Painter, T. H., and Bohlander, J.: MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size, Remote Sens. Environ., 111, 242-257, 10.1016/j.rse.2006.12.020, 2007.
- Sibson, R.: A brief description of natural neighbor interpolation, in: Interpolating Multivariate Data, edited by: Barnett, V., Wiley, Chichester, 21-36, 1981.
 Skvarca, P., Rack, W., Rott, H., and Donangelo, T. I. Y.: Climatic trend and the retreat and disintegration of ice shelves on the Antarctic Peninsula: an overview, Polar Res., 18, 151-157, 1999.
 Vaughen, D. G. and Doake, C. S. M.: Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula.

Vaughan, D. G., and Doake, C. S. M.: Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula,
Nature, 379, 328-331, 10.1038/379328a0, 1996.

Nicholls, K. W., Makinson, K., and Venables, E. J.: Ocean circulation beneath Larsen C Ice Shelf, Antarctica from in situ observations, Geophysical Research Letters, 39, 10.1029/2012gl053187, 2012.

Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C., Mulvaney, R., Hodgson, D. A., King, J. C., Pudsey, C. J., and Turner, J.: Recent rapid regional climate warming on the Antarctic Peninsula, Clim. Change, 60, 243-274, 2003. Voigt, D. E., Peters, L. E., and Anandakrishnan, S.: 'Georods': the development of a four-element geophone for improved seismic imaging of glaciers and ice sheets, Ann. Glaciol., 54, 142-148, 10.3189/2013AoG64A432, 2013.

Table 1 Field acquisition parameters for new data presented here. <u>(*) Note:</u> Due to the use of a range of acquisition geometries,

 the specific geometry used at every refraction experiment site is included in the data repository. <u>BAS Refraction data were</u>

 published previously in Brisbourne et al. (2014) but are again presented here as they form part of the analysis of new data.

Acquisition	BAS	BAS	MIDAS	SOLIS	RACE Reflection	
parameter	Bathymetry	Refraction	Refraction	Refraction		
Source type	Hammer	Pentolite	Hammer	Pentolite	Hammer	
		(surface)		(1 m deptn)		
Trigger type	Uphole	Blaster initiated	Impact-sensitive	Blaster	Impact-sensitive	
	geophone		switch	initiated	switch	
Receiver type	Georod	Georod	Geophone	Geophone	Geophone	
Receiver corner	40 Hz	40 Hz	100 Hz	100 Hz	10 Hz	
frequency						
Receiver spacing	10 m; 30 m	2.5m to 10m; 5m	48 channels	2.5m to 10m; 5m	10 m	
	offset to first	to 30m; 10m	increasing from	to 30m; 10m		
	receiver	thereafter	0.5 to 10m*	thereafter		
Maximum offset (m)	260	610	1110	1110	330	
Sample interval (ms)	0.125	0.125	0.0625	0.0625	0.0625	
Record length (s)	2	2	1	1	1	

Table 2 Location and seabed depth measurements and associated uncertainty of all new points used in this study.

SITE	Project	Latitude (°)	Longitude (°)	Elevation (m)	Ice shelf thickness (m)	Water column thickness (m)	Seabed elevation (m)	<u>Seabed depth</u> <u>uncertainty (m)</u>
SLGS	SOLIS	-68.005	-62.642	55.00	302.4	410.4	-657.8	<u>8.2</u>
SLGN	SOLIS	-67.954	-62.624	53.00	300.8	410.4	-658.1	<u>8.2</u>
CI-0-wet	MIDAS	-66.403	-63.376	76.87	559.3	176.5	-659.0	<u>16.8</u>
CI-0-dry	MIDAS	-66.402	-63.371	70.62	577.3	173.4	-680.1	<u>17.1</u>
CI-20	MIDAS	-66.571	-63.238	66.73	499.3	213.8	-646.4	<u>14.8</u>
CI-40	MIDAS	-66.746	-63.121	56.21	439.9	192.2	-575.9	<u>15.9</u>
CI-60	MIDAS	-66.885	-62.847	49.74	366.4	222.2	-538.9	<u>14.4</u>
CI-80	MIDAS	-66.948	-62.415	48.05	301.2	282.5	-535.6	<u>12.4</u>
CI-100	MIDAS	-66.984	-61.939	48.05	277.9	243.2	-473.0	<u>13.6</u>
CI-120	MIDAS	-67.000	-61.481	47.21	262.2	237.5	-452.5	<u>13.8</u>
WI-70	MIDAS	-67.500	-63.336	49.00	297.6	326.4	-575.0	<u>11.4</u>
WI-60	MIDAS	-67.500	-63.569	49.65	283.9	324.0	-558.2	<u>11.5</u>
WI-45	MIDAS	-67.500	-63.901	49.70	303.0	242.0	-495.3	<u>13.6</u>
WI-00	MIDAS	-67.444	-64.953	59.10	445.8	254.9	-641.6	<u>13.2</u>
PRHA01	BAS	-67.346	-62.803	52.44	282.5	317.7	-547.7	<u>9.6</u>
PRHA02	BAS	-67.662	-62.189	51.24	267.4	312.0	-528.2	<u>9.8</u>
PRHA03	BAS	-66.609	-60.884	46.00	211.3	262.2	-427.5	<u>11.0</u>
PRHA04	BAS	-66.705	-61.785	47.19	236.3	280.1	-469.2	<u>10.5</u>
PRHA05	BAS	-68.294	-62.048	48.15	236.5	269.7	-458.1	<u>10.8</u>
PRHA07	BAS	-66.860	-60.424	43.83	235.1	200.3	-391.5	<u>13.4</u>
PRHB01	BAS	-68.525	-64.761	78.08	547.9	382.4	-852.2	<u>8.6</u>
PRHB02	BAS	-68.088	-63.458	58.32	329.1	293.2	-564.0	<u>10.2</u>
PRHB03	BAS	-68.002	-61.634	48.95	266.8	417.0	-634.9	<u>8.1</u>
PRHB04	BAS	-68.582	-62.006	27.55	130.0	551.4	-653.8	<u>31.7</u>
PRHB05	BAS	-69.062	-61.864	38.87	146.2	224.0	-331.3	<u>12.3</u>
PRHB06	BAS	-67.034	-64.460	48.83	277.4	426.3	-654.9	<u>8.0</u>
PRHB12	BAS	-67.705	-61.156	47.72	228.1	338.2	-518.6	<u>9.2</u>
PRHB15	BAS	-66.400	-61.328	51.54	277.6	307.7	-533.7	<u>9.9</u>
RACE-S1	RACE	-67.783	-61.657	50.35	274.9	375.1	-599.7	<u>10.6</u>
RACE-S2	RACE	-68.005	-62.600	53.65	297.9	413.1	-657.3	<u>10.1</u>

Appendix A

Latitude (°)	Longitude (°)	Depth (m)	Latitude (°)	Longitude (°)	Depth (m)	Latitude (°)	Longitude (°)	Depth (m)
-67.500	-64.083	-615.9	-67.286	-64.508	-327.0	-68.102	-64.140	-758.8
-67.500	-63.366	-577.6	-66.947	-63.872	-334.3	-68.074	-64.049	-748.7
-67.017	-62.813	-479.2	-66.975	-63.869	-341.8	-68.104	-64.607	-428.7
-66.990	-62.816	-483.6	-67.002	-63.867	-341.2	-68.076	-64.515	-449.3
-66.962	-62.817	-481.3	-67.033	-63.863	-414.0	-68.048	-64.424	-572.7
-66.935	-62.818	-506.9	-67.058	-63.861	-420.8	-68.019	-64.332	-614.7
-66.907	-62.820	-523.4	-67.086	-63.858	-501.7	-67.991	-64.242	-703.6
-66.880	-62.821	-529.1	-67.114	-63.855	-530.6	-67.962	-64.151	-768.8
-66.853	-62.823	-493.5	-67.158	-63.849	-555.0	-68.109	-64.435	-639.6
-66.826	-62.824	-474.8	-67.265	-63.829	-528.3	-68.143	-64.360	-799.6
-66.798	-62.825	-494.2	-67.326	-63.830	-481.6	-68.177	-64.283	-794.3
-66.771	-62.827	-513.1	-67.642	-63.930	-620.6	-68.204	-64.206	-702.5
-66.960	-63.689	-382.6	-67.639	-64.041	-650.6	-68.246	-64.129	-621.2
-66.965	-63.570	-500.7	-67.637	-64.156	-534.9	-68.280	-64.053	-577.5
-66.971	-63.459	-546.1	-67.634	-64.273	-585.1	-66.894	-60.193	-124.8
-66.976	-63.346	-541.6	-67.631	-64.389	-477.5	-66.894	-60.194	-122.2
-66.980	-63.234	-522.7	-67.629	-64.505	-236.0	-66.894	-60.195	-129.7
-66.985	-63.122	-557.5	-67.857	-63.794	-641.0	-66.894	-60.196	-123.6
-66.990	-63.009	-498.8	-67.852	-64.023	-599.8	-66.894	-60.197	-124.7
-66.994	-62.897	-492.9	-67.849	-64.131	-586.2	-66.894	-60.198	-123.9
-66.847	-61.114	-479.7	-67.846	-64.249	-539.9	-66.895	-60.199	-119.2
-66.932	-61.116	-466.2	-67.843	-64.366	-540.1	-66.895	-60.200	-126.6
-67.018	-61.117	-454.0	-67.841	-64.484	-531.8	-66.895	-60.201	-126.7
-67.104	-61.119	-434.0	-67.838	-64.601	-547.7	-66.895	-60.202	-125.1
-67.190	-61.120	-434.0	-67.835	-64.718	-532.0	-66.895	-60.203	-123.9
-67.276	-61.121	-424.6	-67.737	-64.599	-448.5	-66.895	-60.204	-123.2
-67.362	-61.123	-432.7	-67.636	-65.229	-496.6	-66.895	-60.204	-122.5
-67.323	-64.012	-316.0	-67.638	-65.153	-481.5	-66.895	-60.205	-120.3
-67.320	-64.120	-321.3	-67.640	-65.075	-490.6	-66.895	-60.206	-128.1
-67.316	-64.235	-461.1	-67.823	-65.502	-392.3	-66.895	-60.207	-126.6
-67.238	-63.973	-413.1	-67.823	-65.431	-567.8	-66.895	-60.208	-127.2
-67.270	-64.120	-358.9	-67.823	-65.361	-625.6	-66.896	-60.209	-127.7
-67.275	-64.234	-328.2	-68.272	-64.692	-868.1	-66.896	-60.210	-130.7
-67.279	-64.348	-314.3	-68.216	-64.507	-856.2	-66.896	-60.211	-133.6
-67.284	-64.462	-306.3	-68.130	-64.231	-763.4	-66.896	-60.212	-136.7
						-66.896	-60.213	-137.5

Table A1 Previously published seabed depth measurements included in the gridding process (Holland et al., 2015; Br	risbourne et al., 2014)
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