universidade de aveiro theoria poiesis praxis

February 18th, 2015

RE: Response to the referee comments and re-submission of The Cryosphere manuscript TC-2014-149

Dear Dr. Stokes,

After we addressed all comments from the referees, we have uploaded a revision of our paper "**Configuration of the Northern Antarctic Peninsula Ice Sheet at LGM based upon a new synthesis of seabed imagery**" by Lavoie et al. to be accepted for publication in The Cryosphere. The re-submission includes an abstract in pdf format, a complete manuscript (with abstract, text, 3 tables, 8 figures) in pdf, and supplementary documents (figure and video) in zip format.

As requested, from the next page, we provide a detailed point-by-point response to all referee comments structured as (1) comments from Referees, (2) author's response, (3) author's changes in manuscript. In addition a marked-up manuscript version showing the changes made.

We hope that this new version will meet the high quality standards of TC.

Yours sincerely,

Caroline Lavoie on behalf of the contributing authors
Email (preferred contact): clavoie@ua.pt

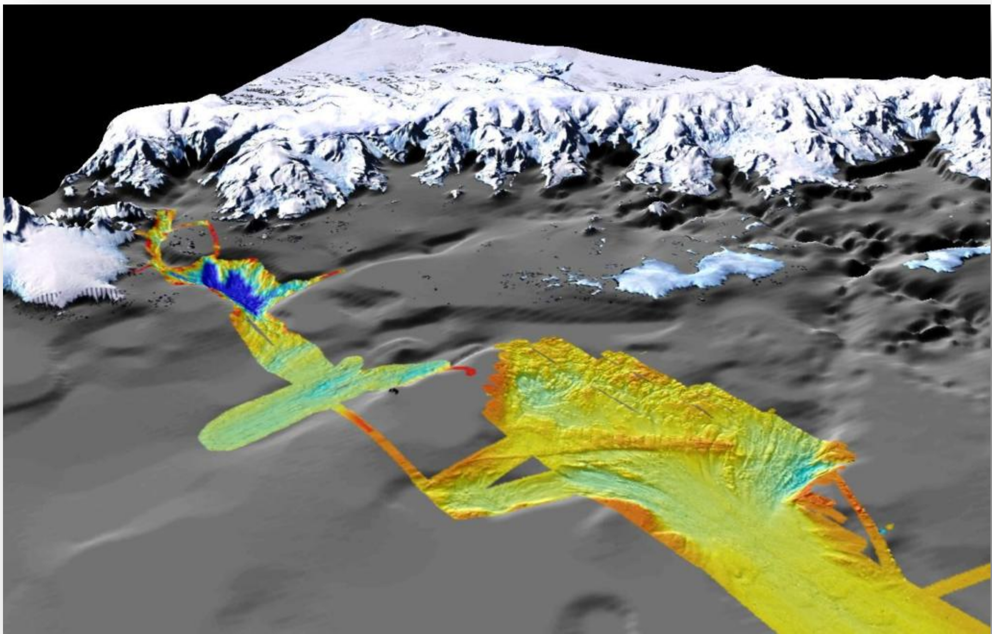
RE: Response to the M. Bentley referee interactive comments

Reviewer's comments:

Domes

The reasoning behind and evidence for the inter-stream areas being domes is not well presented. This is a critical part of the paper but it is split into several parts of the paper (e.g. 5333, line 19-20; but also a whole section (Sec 4.3) much later on 5337; and seems to be a mix of results and assumptions). Although the key elements of the logical argument may all be there and the interpretation of former ice domes in these areas may be one reasonable explanation for some of the observations the inference needs to be explained more clearly, and other explanations discussed (e.g. explain why there was not sheet flow between the streams). For example on 5337 – line 13 it says they (ice domes) 'must' have been centred without fully explaining why. Why were these areas not composed of other thicker (higher) parts of slow-moving ice without them being domes ?

First of all there is good, but admittedly limited, evidence for separate ice domes on the outer shelf banks. The swath data from the perimeter of the Biscoe Trough for instance is illustrated below. Here one can clearly see flow emanating from the bank and joining off-shelf flow from a coastal fed ice stream. This flow pattern could only be explained by an elevated ice dome located out on the outer shelf, at the same time as the paleo ice streams were flowing toward the shelf break. The dome model is the most reasonable explanation for this. Admittedly the other domes we propose do not have nearly the same set of data by which to examine flow patterns, we use this Hugo Dome example as analogy to the others.



Why do they have to be domes instead of sloping slowly moving ice accumulation? It is possible that at their maximum, they were ridges of slow moving ice, but if

a. their existence is due to a difference in basal drag, then they would still have been elevated above the surrounding ice streams because in order to overcome their high basal drag, they need to be thicker and have higher surface slopes. If there were no domes, then the surface slope and ice thickness would be limited by the max at the spine of the peninsula to the minimum at the ice edge - domes allow locally higher thickness and surface slopes.

b. their existence is due to a local high (shoal) in the bed topography, then they would flow more slowly due to thinner ice, this naturally would lead to a local thickening, and diversion of the ice into the surrounding streams.

So, in the end yes, a small change in the basal drag or a small change in the bed topography would not create a dome, it would create differing ice speeds and maybe a subtle long sloping ice ridge, but the strong difference in geological evidence for ice flow between the streaming areas and the non streaming areas suggests to us that the difference in velocity between the two was too great to only be a subtle shift in the basal drag or topography.

We added a definition of an ice divide and ice dome in text to be more specific:
(Introduction) ***In this paper, we examine and interpret the paleo-ice flow directions of the APIS based upon a new synthesis of single and swath bathymetry data, and provide a comprehensive assessment of the flow paths, ice divides and ice domes pertaining to the glacial history of the northern APIS at the LGM time interval. These ice divides can either be ice ridges or local ice domes with their own accumulation centers, which are ice divides with a local topographic high in the ice surface and flow emanating in all directions (although not necessarily equally). The shape of an ice dome may range from circular to elongated; elongated ridge-like ice domes are common between the present day ice streams of West Antarctica.***

It is notable that there are not major domes in other reconstructions, whether they are field-based (Davies et al 2012; O'Cofaigh et al, 2014) or models (Golledge, 2014, Antarctic Science – I accept that this is a new paper but the resultant ice sheet is similar to other models) so it is particularly important to explain why ths reconstruction does now include domes.

We are using in our paper a more detailed data set than in previous papers. This data set allows us proposing the existence of domes, of which one is proven (Hugo Dome) and others are hypothesized based on firm ground. Although we do not wish to be overly critical of the reconstructions of Davies and O'Cofaigh we should point out that these schemes utilize only one flow arrow to illustrate the drainage direction of only a single or even only a partial trough and/or paleo ice stream. As such there is no accounting for the divergence around the banks, contribution of flow along the ice stream path or the degree of flow convergence captured by the single large troughs. It is an evolving picture and simply reflects a difference in detail. I should say also that I was involved in the earlier drafts of the O'Cofiagh effort and was surprised to see the change in flow arrow direction in the Larsen B system that was apparent from the penultimate version(s) to the one that was finally published in 2014.

We are not sure that Golledge actually examined any detailed multibeam images from the areas he reconstructed the ice mass across. If he had, he would or should have included some time variant model in his reconstruction. It's almost as if he assumed an "East Antarctic Profile" from the spine of the Peninsula out across the shelf to both sides. But if you look closely at the flow lines of Golledge 2014, we can observe some ridges that almost look like domes where a small variation in basal conditions or more detailed topography would turn his ridges into actual domes. Our reconstruction is based heavily on the data and assumptions going into them, providing strong evidence of inter-stream areas being domes (We are reworking this part of the next to present better the reasoning behind the domes).

5338 – 10: Alexander Island is not an ice rise or ice dome in the same way as the domes grounded on continental shelf you are discussing.
This comment is totally correct, the Alexander Island (AI) system clearly was a center of accumulation separated from the AP because of its relief and elevation, similar to the South Sheltand Islands. What we are defining out on the shelf are indeed different kinds of dome systems. We see no conflict or contradiction in including the AI system.

Place names

There are several place names that are not on maps, or incorrect orientations given (some examples: Dyer plateau (5332, 11): I think this is mostly S of your study area so not sure why its mentioned Correct. Our mistake;, *Hugo Island Trough (5332, 20)* Added; *Biscoe Trough (5333-5)* Added; *Graham Land coast (5332, 24 and 26) is a huge area stretching several degrees of latitude so usage here seems inconsistent with mention of individual bays)* We constrained the area and deleted the individual bays... the text has been modified: '.... from the Graham Land Coast between 65ºS and 66ºS and ice which..'.; *5330 – 1: I think this is SE not SSW.* See comments below (Tables and Figures Section).

Age of features

It would be helpful to see a discussion of the potential for, or real, over-print of the LGM flow features by younger (deglacial) flow patterns. How do you know the patterns are all GM relicts ? You are right when pointing out the age of the flow lines, LGM or younger. We added new text to be more specific:

While it is possible that some portion of the preserved flow line features we examine are representative of the "death mask" state of the APIS (i.e., Wellner et al., 2006) rather than the mature LGM stage of the system, we suggest that this in general is not the case. We base this hypothesis upon specific observations and assumptions that include:
only slight modification of flow trajectory as preserved along recessional grounding zones (i.e., Evans et al., 2005, Fig. 7), and such flow relationships are easily resolved;
a general shelf slope gradiant that does not, except very locally, provide significant reversal in relief to have influenced evolving flow paths as ice would have thinned (drawn-down) and receded toward the coast;
clear association of converging flow paths from areas that would have provided divergent flow during stages of retreat (i.e., as from shelf ice domes).

Major reorganizations of flow during an ice mass recession are well documented from the southern margins of the Laurentide Ice Sheet (LIS) and elsewhere. But these nearly-90 degree re-orientations are when a large ice mass is thinning across mountains and deep valleys, such as the SE margin of the LIS across the Adirondack Mtns. and Mohawk Valley. The general relief of the continental shelf does not provide the same topography that would have allowed such major flow reorientations. This is because the major source of ice was the AP whose elevation and proximity did not provide a low profile ice sheet derived from distant sources and subject to changes in emergent relief (as was the case for the large ice sheets of the past). We do recognize that some flow lines may be altered slightly and we have pointed out in the literature where this might be the case. We also recognize that overprinting can take place, but we see no major evidence for this in our data. Rather it seems the "death mask" of the system was pretty much representative of the mature or vital extent and character of the APIS.

Links to regional geology

There is a discussion of geological control for one of the ice streams discussed but less so for the whole study area. It would be interesting to discuss what controls the gross location of the major ice streams – are they along major geological faults or across geological boundaries ?
This is an excellent point and reminded the authors about likely relations between deep basins, ice streams, and ice bed deformation. This is now added to the text and we are thankful for this constructive comment.

Section 4.4 - ***It should also be kept in mind that the ice stream catchments include deep basins (i.e., Palmer Deep) that serve as deposystems for thick interglacial mud and ooze deposits. For instance, typical thicknesses for Holocene mud within the Palmer Deep are about 100 m while across the broader shelf the interglacial muds are no more than 6-8 m thick. This mud could serve as basal lubrication as ice systems advance out across the shelf and eventually ground within the deep inner shelf, thus enhancing streaming flow within the trough trajectory via bed deformation. Once ice streaming was initiated in areas where interglacial sediments provided lubrication, the interglacial sediment would be completely removed by ice; streaming would continue, having been established through regional flow patterns, by eroding the underlying bedrock for more lubricating material and thus enhancing the focus of the trough through multiple cycles.***

Technical corrections

5324 – 18-25 – this is a result of this work rather than background (unless it can be independently referenced) It's a result.

24 – believed by whom ?

In general it is quite apparent that the AP would have this aspect, given the breadth of the shelf on both sides and the narrow modern center of accumulation. All the other embayments are fed by large ice sheets today. General knowledge does not need citation.

5325 – 1 – but AP ice sheet glacier change is at least partly driven by oceanographic change. Probably. Rebesco et al. (2014) demonstrated that the surface processes drove the ablation of Larsen-B make it most closely tied to surface driven ablation and accumulation changes than driven by oceanographic change such as in WAIS; *8 – 'enhance our knowledge' – I believe this paper does more than that and this phrasing sounds rather 'incremental'* We agree. The text has been modified.
16 – We highlight the geomorphic features: : :.. The text has been modified.
16-20 – split sentence into two The text has been modified.
24 - ..acquired from several regions including those recently: : :. The text has been modified.

5326- 18 – NGDC – in full The text has been modified.
21 – flow line reconstructions The text has been modified.
22 – interval and that The text has been modified.

5327- 25 – what values of A were used We used values of A based on the table presented in Cuffey and Paterson (Physics of Glacier, 2010) that is based on a summary of the existing research. The specific values we used were Warm ice: 6.8e-15 s^{-1} kPa^{-3} and Cold Ice 4.9e-16 s^{-1} kPa^{-3}. The text has been modified.

5328 – 3 – min and max what (b-dot ?) Min and Max bdot for each dome are shown as the end points of the major axes of the red ellipses in Fig. 8. The text has been modified to avoid confusion. In 5328-3 "We based the minimum and maximum dome volumes (table 2) on a low-end and high-end approximation of the accumulation rates,"
6 – accumulation rate The text has been modified.
7 – resulting in The text has been modified.
11 – IBCSO – in full The text has been modified.
20 – what is 'it' ? Slope ? Yes "it" refers to the "surface slope" The text has been modified.
22 – would lead to a slightly The text has been modified.

5329 – 18 – Hektoria – ambiguous which way it goes on basis of Fig 2 From the shelf bathymetry (showing a connection between Hektoria and Cold Seep basins) probably S-SE.
20 – from the southern edge of SCAR Inlet The text has been modified.
25 – Our flowline bedform The text has been modified.
26 – in the southern part of the Larsen-B embayment The text has been modified.

5330 – 2 – they're in a similar orientation but not parallel The text has been modified.
11 –evidence of what ? The evidence is for the establishment of two major outlets:.....

5331 – 2 – may have been developed The text has been modified.
9 – un-named channel is called Active Sound – see http://apc.antarctica.ac.uk/ Thanks, the text has been modified.
21 – Fig 6 implies this is ice shelf but text suggests grounded ice The Figure has been modified to avoid confusion.
22 – should be Fig 6 The text has been modified.
23 – what fans ? We mean trough-mouth fans (grounding zone fans) (defined by Simms el a. 2011). The text has been modified.... surface of the grounding zone fans (i.e. mouths of both Maxwell and Admiralty fjords)....
24 – How is a trough named after a snowfield? The text has been modified.

5332 – 7 – use NNW to be consistent The text has been modified.
14 – odd phrasing – 'are added' The text has been modified.
20 – there are more than three – do you mean it has 3 tributaries? No. it is one of the three major tributary systems
25 – NE not NW The text has been modified.
26 – Along the Graham Land Coast The text has been modified.

5333-1 – directed flow to The text has been modified.
4 – around the N end of Anvers The text has been modified.
8 – SW and NE direction – where ? In the main branch of the Biscoe Trough. The text has been modified.
13 – ice divide between what and what ? .... a distinct flow divide between the Biscoe Trough and Palmer Deep and Hugo Island Trough systems, and south along the trend defined by Hugo Island. The text has been modified.

5334 – 18 – followed what ? We deleted those 2 words that were part of an older sentence.

5335 – 2 – these topographic highs could have divided the glacial flow The text has been modified.
16 – The two mechanisms could have The text has been modified.
19 – has been observed The text has been modified.
24 – I think the topo obstacle might be an island/nunatak rather than ice ? The topo obstacle in Knight (1994) paper is about ice overtopping the obstacle, not a nunatak. The author is discussing what is happening at the bottom of the Greenland Ice Sheet. To avoid any confusion we added the following text at the end of the section 4.1

In addition to these real-world examples, modeling has shown that either a relative topographic high or a relative increase in the basal drag can lead to divergence of ice flow and formation of an elongated ice dome between them. A number of researchers have modeled the surface expression of variability in bed topography or bed properties; a comprehensive analysis is provided by Gudmundsson (2003).

5336 – reword this section. Need to explain the reasoning by which you define ice divides. We define ice divides based on: : :: : :.x and y We agree, we reworded the first sentences of this section (4.2 Evidence of ice divides).

We define an ice divide as a boundary separating divergent ice flow directions, i.e., the line that separates neighbouring drainage systems, analogous to a water divide. The separation of the West and East AP along the Bruce Plateau and Detroit Plateau on the Trinity Peninsula and the Graham Land Coast formed the primary ice divide for the AP during LGM. Our results, based on the details of the ice flow directions and the modern subaerial and submarine topography, suggest that secondary ice divides split off from the primary ice divide creating several large draining basins (Fig. 5). ...

5339 – 1-20 – this looks like methods We agree, part of this section has been moved to the methodology.

5340 – 17 – Need to clarify here that the ice volume that matters in this context is that above buoyancy so actually thin ice couldn't harbour very much, whether there was large areal extent or not. The text has been modified
26 – different number to table The text has been modified

5342 – 15-18 – cite Livingstone et al 2012 (Earth Sci. Rev.) here as this paper considers many of these factors and how they differentially affect individual ice streams. Cited. The text has been modified
20 – be more specific about what purpose GIA modelling might serve Ok

Text modified - ***The identification of ice domes, ice divides, and diverging/converging flows help us to understand ice-sheet evolution and processes. While considerable effort has been put forward recently toward understanding the character and timing of the retreat of the APIS, more work needs to focus upon the reconstruction and detailed vitality of the APIS during the last glacial cycle. The features we recognize have important implications for this effort and the future siting of ice cores and marine drilling sites. Finally, they provide important constraints for glaciohydrology, past and future ice-sheet modeling used, for instance, to look at sediment***

fluxes (Golledge et al., 2013) or provide more realistic predictions, ice-sheet modeling in response to changing environments, and sea level modeling. The existing challenge includes arranging models of ice flow and geological data so that they resemble each other, especially when geological features are small compared to the grid scale of ice flow paths....

Title – would be helpful to insert' LGM' or 'at LGM' in title to make study focus clearer The title has been modified..... to include not only the paleo-ice flow directions and also LGM. "Configuration of the Northern Antarctic Peninsula Ice Sheet at LGM based upon a new synthesis of seabed imagery"

Grammar – *The paper needs a close read – there are many instances of plurals/singular not matching and tense changes repeatedly including within sentences (e.g. 5329, 13-15). I have included examples for the first few pages but have not corrected after 5330.* The reviewed version of the paper was closely read for the grammar.

Tables and Figures

*Table 3: Not clear how 'systems' are defined – do they include the central parts of the AP (and therefore is underlying topography subtracted ?)*They do not include the central parts of the AP, only the path along the continental shelf. Text has been modified to avoid confusion.

Fig 1 – see comments on place names. We reviewed the text carefully to add the place names missing (Biscoe Trough, Trinity Peninsula, Maxwell and Admiralty fjords, Lafond, Laclavere and Mott Snowfield troughs, Hugo Island Trough) and put the labelling larger not only in Fig. 1, but also Figs. 2, 6 and 7.

Fig 3- 25m here, 30m in text: It's correct. The images in Fig 3. were plotted in a resolution of 25 m x 25 m and the maps (Figs. 1 and 2) at 30 m x 30 m. To avoid confusion we have included the following text in the Sect. 2.1 .... The data set was gridded at a cell size of 30 m x 30 m and analyzed with illumination at variable azimuths. The seabed morphology close-up were gridded at a cell size of 25 m x 25 m. ....

Fig 4- SSW direction doesn't make sense based on these images and orientation arrows. This is a typo in the text corrected to ESE. *Also, not sure if the bedrock flutes might in fact be meltwater features* These are not meltwater features, they are bedrock whalbacks or linear bedrock ridges.

Fig 7 – images and their annotation are far too small to be readable. We agree and put the labelling and the map larger.

Fig 8 - : : :domes with ice temperature averaging: : : The text has modified.

RE: Response to the P. O'Brien referee interactive comments

Reviewer's comments:

There are several points of discussion that should be considered: Page 6 Lines 22-24. The authors assume that the flow lines and the lineations on hard substrates are LGM or older. It would be good for there to be some discussion given to potential changes in flow during deglaciation or inheritance of older features. E.g. Was deglaciation so rapid that the ice pattern of features most likely reflects LGM flows? You are right when pointing out the importance to assume that the flow lines and the lineations on hard substrates are LGM or older. Modification already addressed (See above).

Major reorganizations of flow during an ice mass recession are well documented from the southern margins of the Laurentide Ice Sheet (LIS) and elsewhere. But these nearly-90 degree re-orientations are when a large ice mass is thinning across mountains and deep valleys, such as the SE margin of the LIS across the Adirondack Mtns. and Mohawk Valley. The general relief of the continental shelf does not provide the same topography that would have allowed such major flow reorientations. This is because the major source of ice was the AP whose elevation and proximity did not provide a low profile ice sheet derived from distant sources and subject to changes in emergent relief (as was the case for the large ice sheets of the past). We do recognize that some flow lines may be altered slightly and we have pointed out in the literature where this might be the case. We also recognize that overprinting can take place, but we see no major evidence for this in our data. Rather it seems the “death mask” of the system was pretty much representative of the mature or vital extent and character of the APIS.

What likely was truly fast was degrounding, rather than deglaciation (deglaciation is a generic concept, often lacking precision (i.e. Does it refer to volume, areal extent, retreat,...?)). Ice retreat took longer and was not uniform, as some published reconstruction have shown (e.g. Willmott et al.).

Figure 6: The figure shows NE flow along Bransfield Strait then major divergence of flow to the Powell Basin and between King George and Elephant Island yet still major palaeoflow lines continue NE well past Elephant Island. This looks strange to me. Given the bathymetry, would it not be more likely that there was a small ice dome on Elephant Island? To have definite flow direction as shown there must be some evidence from the sea floor though the area is off the NE corner of figures 1 and 5. It doesn't detract from the main part thrust of the paper but it would be good to tidy up this end of the region. We also believe that it is likely that there was a small accumulation center on Elephant Island providing a plug to the NE flowing Bransfield Ice Shelf system. The text and Fig. 6 have been clarified. On the figure we deleted the flow line NE past Elephant Island to avoid any confusion.

Presentation: The descriptions and arguments rely heavily on place names in the Antarctic Peninsula. Therefore, all place names need to be present on figures and large enough to be read easily. As someone who has never worked in the Peninsula, I regularly found myself lost in the geography, making it harder to evaluate details of the discussion: We agree and to answer your comment, we reviewed the text carefully to add the place names missing (Biscoe Trough, Trinity Peninsula, Maxwell and Admiralty fjords, Lafond, Laclavere and Mott

Snowfield troughs, Hugo Island Trough) and put the labelling larger in Figures 1, 2, 6 and 7 adding 2 pt (size).

The paper is quite well written but has some minor issues in places, particularly in clarity of expression. I list them below.
Page 9, Line 7: "more a more" needs rewording: The text has been modified... By using a more detailed analysis...

What do you mean by flow indices? Do you mean flow indicators? Indices would suggest a derived numerical parameter of some sort. Indices is plural of index, not indicators. Yes, we mean flow indicators. The text has been modified..... of flow indicators available...... Also Page 10, Line 2.

Page 9, Line 14: "an indistinct tributary confluence" I'm not really sure what this means, even after looking closely at the maps. We mean fed by small tributary confluence not clearly identifiable today. The text has been modified..... and was probably fed by small tributary confluence.

Page 9, line 27: do you mean "offshore of"? Yes, the text has been modified.

Page 10, Line 2: What are marine flow indices? Do you mean flow indicators in which case you are saying flow of marine currents? Alternatively, do you mean ice flow indicators further offshore (delete "marine"). Yes, we mean flow indicators. The text has been modified....... that parallel flow indicators found directly further offshore.

Page 10, line 6: What does "and inward the shipboard surveys" mean? Do you mean "adjacent to the areas surveyed by ship"? No, our mistake. We rephrased for .... Recent seismic reflection soundings close to the northern ice shelf front and inward show a uniform....

Page 10, Line 11: Do you mean "the evidence is for the establishment: : :"? Yes, the text has been modified.

Page 11, Line 1: Should not this be in past tense? Do you mean Crossed rather than crosses? "May only have" rather than "may only be": : :? Yes, the text has been modified.

Page 11, Line 23: What do you mean by "fans"? This the first a fan has been mentioned. What sort of fan? Alluvial, submarine????? Please explain. We mean trough-mouth fans (grounding zone fans) (see Simms el a. 2011). The text has been modified.... surface of the grounding zone fans (i.e. mouths of both Maxwell and Admiralty fjords)....

Page 12, line 7: "structure 100 km long" is correct, delete "of". The text has been modified.

Page 15, line 22: "flows into the northern outlet glaciers: : :." The text has been modified.

Page 15, line 24: "a topographic obstacle about 400 m high": : :Don't need "of". The text has been modified.

Page 17, line 5: "conditions change: : :" The text has been modified.

The reviewed version of the paper will be closely read for the grammar (also suggested by Dr. Bentley).

Configuration of the Northern Antarctic Peninsula Ice Sheet at LGM based upon a new synthesis of seabed imagery

C. Lavoie[1,2], E.W. Domack[3], E.C. Pettit[4], T.A. Scambos[5], R.D. Larter[6], H.-W. Schenke[7], K.C. Yoo[8], J. Gutt[7], J. Wellner[9], M. Canals[10], J.B. Anderson[11], D. Amblas[10]

[1]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante, Sgonico, 34010, Italy

[2]Department of Geosciences/CESAM, University of Aveiro, Aveiro, 3810-193, Portugal

[3]College of Marine Science, University of South Florida, St. Petersburg, Florida, 33701, USA

[4]Department of Geosciences, University of Alaska Fairbanks, Fairbanks, Alaska, 99775, USA

[5]National Snow and Ice Data Center, University of Colorado, Boulder, Colorado, 80309, USA

[6]British Antarctic Survey, Cambridge, Cambridgeshire, CB3 0ET, United Kingdom

[7]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, 27568, Germany

[8]Korean Polar Research Institute, Incheon, 406-840, South Korea

[9]Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas, 77204, USA

Eliminado: ~~Paleo-ice flow directions of the Northern Antarctic Peninsula Ice Sheet based upon a new synthesis of seabed imagery~~ ¶

[10]Departament d'Estratigrafia, Paleontologia i Geociències Marines/GRR Marine Geosciences, Universitat de Barcelona, Barcelona, 08028, Spain

[11]Department of Earth Science, Rice University, Houston, Texas, 77251, USA

Correspondance to: C. Lavoie (clavoie@ua.pt) or E.W. Domack (edomack@usf.edu)

Abstract

We present a new seafloor map for the northern Antarctic Peninsula (AP), including swath multibeam data sets from five national programs. Our map allows for the examination and interpretation of Last Glacial Maximum (LGM) paleo-ice flow paths developed upon the seafloor from the preservation of: mega-scale glacial lineations, drumlinized features, and selective linear erosion. We combine this with terrestrial observations of flow direction to place constraints on ice divides and ice domes on the AP continental shelf during the LGM time interval. The results show a flow bifurcation as ice exits the Larsen-B embayment. Flow emanating off the Seal Nunataks (including Robertson Island) is directed toward the southeast, then eastward as the flow transits toward the Robertson Trough. A second, stronger "streaming flow" is directed toward the southeast then southward, as ice overflowed the tip of the Jason Peninsula to reach the southern perimeter of the embayment. Our reconstruction also refines the extent of at least five other distinct paleo-ice stream systems that, in turn, serve to delineate seven broad regions where contemporaneous ice domes must have been centered on the continental shelf at LGM. Our reconstruction is more detailed than other recent compilations because we followed specific ice flow indicators and have kept tributary flow paths parallel.

Eliminado: sheet/stream

Eliminado: directions

Eliminado:

Eliminado: accumulation centers (

Eliminado:)

Eliminado: which

Eliminado: during the

Eliminado: time interval

1 Introduction

The reconstruction of paleo-ice sheets/stream flow directions depends first upon an accurate assessment of ice domes, ice divides, and outlet flow paths (Andrews, 1982). Studies of the configuration of the Antarctic Peninsula Ice Sheet (APIS) during the Last Glacial Maximum (LGM; time interval ~23-19 kyr BP) suggest that the grounded ice reached the continental shelf break (e.g., Larter and Barker, 1989; Banfield and

Eliminado: accumulation centers

Eliminado: (outlets)

Eliminado: e.g.

Anderson, 1995; Larter and Vanneste, 1995; Wellner et al., 2001; Canals et al., 2002; Evans et al., 2005; Heroy and Anderson, 2005; Amblas et al., 2006; Wellner et al., 2006; Simms et al., 2011). The seafloor of the Antarctic Peninsula (AP) continental shelf is characterized by over-deepened troughs and basins where mega-scale glacial lineations (MSGLs) (Clark, 1993; Clark et al., 2003) and large-scale flowlined bedforms such as glacial flutes, mega-flutes, grooves, drumlins and crag-and-tails provide geomorphic evidence for former regional corridors of fast-flowing ice and drainage directions of the APIS on the continental shelf. Also of importance is their synchroneity as the ice flows change during the ice sheet evolution, from ice sheet to ice stream to ice shelf (Gilbert et al., 2003; Dowdeswell et al., 2008).

Our capability to image specific flow directions and styles on the Antarctic continental shelf is critical to any glacial reconstruction in so much as they help us to understand the present and future ice sheet's behavior. Recently, Livingstone et al. (2012) published an inventory of evidence for paleo-ice streams on the continental shelf of Antarctica at LGM. Their reviews are in agreement with previous studies and highlight that the West (Pacific) AP continental shelf is characterized by preferred regional ice flow pathways on the middle shelf through cross-shelf troughs connected to major flow paths on the outer shelf (e.g., Evans et al., 2004; Heroy and Anderson, 2005). On the other side, the East (Weddell Sea) AP continental shelf is less well defined but characterized by multiple deep tributaries on the inner shelf that converge in shallow troughs on the mid to outer shelf (e.g., Evans et al., 2005). Nevertheless, our knowledge on the APIS configuration at the LGM time interval, such as paleo-flow paths in the Larsen-B embayment, is limited and particularly relevant to the ice sheet reconstruction, where the broad continental shelf served as a platform for extension of the glacial systems that spilled off the Detroit and Bruce Plateau ice caps. In fact, the AP is

Eliminado: e.g.

Eliminado: e.g.

Eliminado: accumulation centers, ice divides and flow paths

Eliminado: APIS

believed to have experienced the largest percentage change in areal extent of glacial cover of any sector of the Antarctic margin through the last glacial cycle (i.e., MIS stage 2 to 1). For instance our reconstruction shows that the current APIS covers ~ 23 % of the total area of grounded ice coverage at LGM. The APIS system in particular is a significant bellwether system in the evolution of the Antarctic Ice Sheet because it is:

1) the one system today that is most closely tied to surface driven ablation and accumulation change (Rebesco et al., 2014) rather than driven mainly by oceanographic change such as in West Antarctic Ice Sheet, having equilibrium lines above sea level (a.s.l.) as a consequence of significantly warm summer temperatures;
2) exposed to a contrasting oceanographic regime of cold and warm water on the eastern and western sides, respectively, and
3) the most northern of the ice sheet systems and it is exposed to southward excursions in westerly winds and the Antarctic Circumpolar Current.

In this paper, we examine and interpret the paleo-ice flow directions of the APIS based upon a new synthesis of single and swath bathymetry data, and provide a comprehensive assessment of the flow paths, ice divides and ice domes pertaining to the glacial history of the northern APIS at the LGM time interval. These ice divides can either be ice ridges or local ice domes with their own accumulation centers, which are ice divides with a local topographic high in the ice surface and flow emanating in all directions (although not necessarily equally). The shape of an ice dome may range from circular to elongated; elongated ridge-like ice domes are common between the present day ice streams of West Antarctica. The spatial coverage of the bathymetric data is extensive (Fig. 1) and for this and the above reasons we focus upon regional systems by dividing it into seven sectors. These include the (1) Larsen-B embayment, (2) Larsen-A

Eliminado: i.e.

Eliminado: s

Eliminado: above sea level

Eliminado: enhance our knowledge on

Eliminado:

Eliminado: sheet/stream

Eliminado: drainage

Eliminado: accumulation centers

and James Ross Island, (3) Joinville Archipelago Platform, (4) Bransfield Strait, (5) Gerlache-Croker-Boyd Straits, (6) Palmer Deep and Hugo Island Trough, and (7) Biscoe Trough. First, we highlight the geomorphic features that define the specific flow paths at LGM and glacial tributaries across the inner to outer shelf. We combine this with terrestrial observations of flow direction to place constraints on ice divides and ice domes that controlled the APIS flow drainage and subsequent retreat history. Finally, we discuss the characteristics of the reconstructed northern APIS and its regional significance for ice sheet modeling.

2 Methods

2.1 Data sets

Extensive multibeam swath bathymetry data have been acquired from several regions including those recently uncovered by the collapse of the Larsen Ice Shelf system. Ice-flow directions within the Larsen-B embayment are indicated by a series of interconnected (1) multibeam surveys beginning with a USAP program in 2000 and followed by the British Antarctic Survey (2002), additional USAP surveys (2001 and 2006), Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research surveys (2007 and 2011) and Korea Polar Research Institute survey (KOPRI, 2013) under the LARISSA project, and (2) single beam sonar data from USAP in 2005. Detailed observations of the seafloor morphology in the Larsen-A embayment, the area surrounding James Ross Island and offshore from Joinville Archipelago were collected by the USAP program between 2000-2002, 2005-2007, in 2010 and 2012 including work by the British Antarctic Survey (2002) and United Kingdom Hydrographic Office (2006-2008). The Bransfield Strait has been covered by the Spanish Antarctic program between 1991 and 1997, USAP program (1995-1997, 1999-2002, and 2005-2011) and

Eliminado: W

Eliminado: draw upon our compiled seabed map the

Eliminado: to infer the flow paths,

Eliminado: and the accumulation centers that controlled the APIS flow drainage and subsequent retreat history.

Eliminado: ¶

Eliminado: including work

Eliminado: 2009

United Kingdom Hydrographic Office (2006-2008, 2010 and 2012). The multibeam swath bathymetry data from the Gerlache-Croker-Boyd Strait, Palmer Deep and Hugo Island Trough, and Biscoe Trough are from the USAP program (1995-1997, 1999-2002, and 2005-2012), the Spanish Antarctic program in 1996-1997 and 2001-2002, and KOPRI (2013). The data set was gridded at a cell size of 30 m x 30 m and analyzed with illumination at variable azimuths. The high-resolution seabed images were gridded at a cell size of 25 m x 25 m. Additional single beam sonar data from NOAA National Geophysical Data Center (NGDC) Marine Trackline Geophysical database (http://ngdc.noaa.gov/mgg/geodas/trackline.html) were used to support the delineation of the continental shelf ice domes.

2.2 Bedform mapping

We assume that our flow line reconstructions over sedimentary deposits are contemporaneous to the LGM time interval and that observed seafloor lineations over resistant substrate were carved last by the APIS at LGM, although formation of the latter may derive from time-integrated glacial processes (e.g., Nývlt et al., 2011). While it is possible that some portion of the preserved flow line features we examine are representative of the "death mask" state of the APIS (*i.e.*, Wellner et al., 2006) rather than the mature LGM stage of the system, we suggest that this in general is not the case. We base this hypothesis upon specific observations and assumptions that include:

1) only slight modification of flow trajectory as preserved along recessional grounding zones (i.e., Evans et al., 2005, Fig. 7), and such flow relationships are easily resolved;

Eliminado: the USAP program (1995-1997, 1999-2002, and 2005-2012)

Eliminado: morphology close-up

Eliminado:

Eliminado: Furthermore,

Eliminado: delimitation

Eliminado: s

Eliminado: considering

Eliminado: our

Eliminado: their

Eliminado: previous over

Eliminado: *i.e.*

Eliminado: Anderson et al.,

Eliminado:

Eliminado: our ......

Eliminado:

Eliminado: ;

Eliminado: , pg. 752

2) a general shelf slope gradiant that does not, except very locally, provide significant reversal in relief to have influenced evolving flow paths as ice would have thinned (drawn-down) and receded toward the coast;

3) clear association of converging flow paths from areas that would have provided divergent flow during stages of retreat (i.e., as from shelf ice domes).

From the observed seafloor lineations, we establish a central flow line at the root of each tributary glacier adjacent to areas of reasonable coverage in the multibeam data. We preserved these central flow lines by forcing tributary contributions to remain parallel and consistent with observed seafloor lineations. In this way converging flow can be evaluated more easily than by using "idealized" single-line flow arrows (as has been done on previous reconstructions). The number of lines in a given flow path is defined by the number of tributaries, and is only a visual approximation of the ice discharge for that flow path. In some cases, ice flow across the seafloor diverged around obstacles but remained parallel within the larger confining troughs or fjords. Small-scale basal-flow divergence patterns such as these were not preserved in our reconstruction.

The orientation of the bedrock striations at Cape Framnes and Foyn Point (Larsen-B embayment; Fig. 2) were measured with a Brunton Compass, corrected for regional declination, and compared to visual data of large-scale bedrock fluting from overflights during 2010 (USAP-ship based helicopters during LARISSA NBP10-01 cruise).

2.3 Ice volume estimation and assumptions

We utilize two different algorithms to estimate volumes of the ice sheet, depending upon the type of system, streaming flow or ice domes. The average depths along the flow paths are estimated from our swath bathymetry map and the International

Eliminado: ¶

Eliminado: s were established

Eliminado: all major glacier tributaries

Eliminado: These central flow lines were preserved

Eliminado: along the path by

Eliminado: ie domes or

Eliminado: To estimate the ice volume of the convergent flow paths we use less established assumptions.

Bathymetric Chart of the Southern Ocean (IBCSO) map gridded at 500 m (Arndt et al., 2013). For the minimum volumes, we assume that the ice streams were lightly grounded until the shelf break or to the end of the defined flow path (except for Larsen-B/Jason Trough) where the ice thickness must be about 10 % more than the average depth to prevent flotation (allowing the deepest areas to be subglacial lakes, rather than full of ice). We assume a minimal surface slope (0.001) similar to the lowest sloping modern ice streams. For the maximum volumes, we assume that the ice was grounded to the continental shelf break (except for Larsen-B/Jason Trough). We assume the surface slope of the ice was steeper (0.005), but not too steep to exceed the nearby ice divide elevations. The real slope will depend on the geology. A softer more malleable bed would favor a lower profile ice stream, a stiffer bed would lead to a slightly steeper profile. For the ice domes in this reconstruction, we use a radially symmetric Bodvarsson–Vialov model as presented in Bueler et al. (2005). This model assumes the shallow-ice approximation (no sliding bed) and Glen-type ice flow with a softness that depends on the average temperature. The model can directly predict the thickness as a function of distance from the dome center (r = 0) as:

$$H(r) = \left(2^{(n-1)}\frac{\dot{b}}{\Gamma}\right)^{1/(2n+2)} \left(L^{1+1/n} - r^{1-1/n}\right)^{n/(2n+2)} \qquad (1)$$

$$\Gamma = \frac{2A(\rho g)^n}{n+2} \qquad (2)$$

where H is the ice thickness, $\dot{b}$ is the accumulation rate, L is the lateral extent of the ice dome, assuming it is circular, and n = 3 for typical Glen-type ice flow. Γ is a parameter that depends on the ice softness, A, which is temperature dependent, the density (ρ) of ice, and gravity (g). The specific values of A used are for warm ice 6.8^{e-15} s^{-1} kPa^{-3} and

Eliminado:
Eliminado: to
Eliminado: out
Con formato: Color de fuente: Automático
Eliminado: In both estimations, it
Eliminado: have
Eliminado: (but it still needs to be thick enough to be grounded)
Eliminado: require
Eliminado: ¶
Eliminado: simple,
Eliminado: ,
Eliminado:

cold ice 4.9^{e-16} s^{-1} kPa^{-3} (Cuffey and Paterson, 2010). Because we lack specific data for LGM accumulation rate and ice temperature, we use our best guesses to bound the ice thicknesses and volumes as follows. We assume that the same strongly orographic precipitation occurred during LGM interval as today, and the ice temperature was around 0 ºC (mostly temperate) for the West AP domes and averaging -20 ºC for the domes located on the East side. For the modern AP, the western side has higher average temperatures than the eastern side suggesting that in the past, the ice domes on the western side were warmer on average than the eastern side. We based the minimum and maximum dome volumes (Table 2) on a low-end and high-end approximation of the accumulation rates, respectively. In these accumulation rate assumptions, we took into account that some domes are more exposed to the prevailing storm direction and some will be in the lee, resulting in higher or lower accumulation rates. Also, we take the geologically defined aerial dome extent and assume a dome base of circular area that has the same area as the geologically defined dome. The approximation of a circular dome with the same average radius as the estimated bathymetric features will introduce additional source of uncertainty into the volume estimates. This circular dome assumption may overestimate volume if the real feature is a oval ridge shape, but it may underestimate the volume if the dome is bounded by thick ice streams. Without more constraints, we feel the uncertainties due to the circular dome assumption are small compared to the uncertainties due to the accumulation rate and temperature assumptions.

Con formato: Sin Resaltar
Eliminado: are
Eliminado: ing
Eliminado: 10
Eliminado: (see Section 4.3)
Eliminado: s
Eliminado: s
Eliminado: ¶

Results

3.1 Larsen-B embayment

The major collapse of the Larsen-B Ice Shelf in 2002 (Scambos et al., 2003), unprecedented in the Holocene history of this glacial system (Domack et al., 2005; Curry and Pudsey, 2007), has provided a unique opportunity for seafloor mapping. This work reveals a far more detailed flow pattern in Larsen-B embayment than that inferred by general orientation of bathymetric troughs derived from sparse swath or single line bathymetric data. Such earlier approaches suggested that all Larsen-B ice flowed out toward the Robertson Trough (e.g., Evans et al., 2005; Davies et al., 2012; Livingstone et al., 2012).

By using a more detailed analysis of flow indicators available from the swath data, we now recognize two distinct flow trajectories that split the Larsen-B embayment into two outlets (Fig. 2). The first relates to the attenuated drumlinized bedforms and highly attenuated MSGLs observed in the northern perimeter of the Larsen-B embayment. The ice flow emanating off the Seal Nunataks and Robertson Island directed flow toward the southeast then eastward as the flow transits toward the Robertson Trough, a feature that connects Larsen-A and B (Evans et al., 2005). This flow pattern extends across relatively shallow depths of less than 500 m and was probably fed by small tributary confluence.

In contrast, the southern perimeter is marked by stronger "streaming flow" indicators fed by large tributaries draining the APIS, including the Crane Glacier and most likely the Evans, Green and Hektoria Glaciers. The well-defined drumlinized bedforms with crescentric scour and MSGLs indicate that ice flow was funneled into the Cold Seep Basin (Fig. 3a) and moved toward the southeast from the interior. From the southern edge of Scar Inlet (Larsen-B Ice Shelf), the swath bathymetric map shows evidence of a northeastward flow (Fig. 3b) that shifted in a downstream direction toward the southeast, thus convergent with the flow streaming from the Cold Seep Basin corridor.

Eliminado: e.g.
Eliminado: a more
Eliminado: indicies
Eliminado:
Eliminado: indistinct
Eliminado:
Eliminado: the
Eliminado: CAR
Eliminado: downstream

The Scar Inlet ice stream system was fed by the tributaries of the Starbuck, Flask, and Leppard Glaciers. Our flowline bedform compilation suggests that the southeastward flow in the southern part of the Larsen-B embayment changed to a southward direction with ice overflowing the tip of the Jason Peninsula, offshore of the northern region of the Larsen-C Ice Shelf (Figs. 2 and 3c), to reach the Jason Trough. This southward flow orientation is supported by bedrock striations and flute orientations east southeast at Cape Framnes, Jason Peninsula (Fig. 4) that are in similar orientation to the flow indicators found directly offshore.

Eliminado: SCAR
Eliminado: d
Eliminado: perimeter
Eliminado: SSW
Eliminado: east
Eliminado: parallel
Eliminado: marine
Eliminado: indicies
Eliminado: further

Finally, the southernmost swath bathymetry data at the edge of the northern Larsen-C Ice Shelf indicates a southeastward ice flow orientation on a seafloor deeper than 400 m. Recent seismic reflection soundings close to the northern ice shelf front and inward show a uniform water cavity thickness beneath the ice shelf of around 220 to 240 m (Brisbourne et al., 2014).

Eliminado: the shipboard surveys

3.2 Larsen-A and James Ross Island

Our mapped flow pattern of the Larsen-A and James Ross Island sector differs only in fine detail to those of earlier reconstructions (e.g., Evans et al., 2005; Johnson et al., 2011; Davies et al., 2012). The data show the establishment of two major outlets: the Robertson Trough system and the Erebus-Terror system (Fig. 5). The Robertson Trough system collected flow out of the Larsen-A, southern Prince Gustav Channel, and portions of Admiralty Sound. The ice flowed from the Larsen-A, derived mainly from the Detroit Plateau (AP), toward the south, then east. It then coalesced with the southern Prince Gustav Channel flow across the shelf toward the southeast and finally directly east (Pudsey et al., 2001; Gilbert et al., 2003; Evans et al., 2005). On the outer shelf the

Eliminado: e.g.
Eliminado: evidence is

ice flow coalesced with the northern perimeter of the Larsen-B flow to form a major ice flow trend in the Robertson Trough.

The Erebus-Terror system captured flow out of the northern Prince Gustav Channel, Antarctic Sound, and Admiralty Sound. The northern Prince Gustav Channel, shows evidence of a main eastern flow direction, fed by tributaries from ice caps on Trinity Peninsula and James Ross Island before coalescing with the Antarctic Sound and the Admiralty Sound flows into the Erebus and Terror Gulf to reach the shelf break. Flow within the Prince Gustav Channel was separated from the south Larsen-A system by an ice divide that extended from the Detroit Plateau across to James Ross Island (Camerlenghi et al., 2001). Recent observations and cosmogenic isotope exposure-age dating on erratic boulders on James Ross Island by Glasser et al. (2014) suggest that the ice divide that crossed the central Prince Gustav Channel may only have been developed during the post-LGM recession.

Eliminado: , as a consequence of an ice saddle (divide)

Eliminado: the

Eliminado: crosses

Eliminado: be

3.3 Joinville Archipelago Platform

The platform surrounding the northernmost extension of the AP terrain (D'Urville, Joinville, and Dundee Islands) has very limited multibeam coverage. Only two distinctive troughs have been imaged and flow lines are conjectural and defined (as in earlier approaches) by recognition of bathymetric troughs. Portions of the flow out of the Larsen Channel, between D'Urville Island and Joinville Island, and out of Active Sound between Joinville Island and Dundee Island ran in a southwestern direction coalescing with the Antarctic Sound flow to the Erebus-Terror system. The other portion shows evidence of east and southeast flows. South of Joinville Island, the multibeam data imaged drumlin-like features indicating that ice was grounded on the

Eliminado: ~~the~~ unnamed channel

Joinville Plateau, indicating that the APIS extended across the shelf (Smith and Anderson, 2011; their Fig. 6).

3.4 Bransfield Strait

The continental shelves off the Trinity Peninsula (e.g., Lawver et al., 1996; Canals et al., 2002) and the South Shetland Islands (Simms et al., 2011) reveal paths of paleo-ice streams that drained into the Bransfield Strait. This narrow and deep (greater than 1000 m) strait was formed by rifting, actively spreading since the past four million years ago in response to subduction in the South Shetland Trench (Barker, 1982). Base on seafloor evidence, the grounded ice flow along the Bransfield basin's perimeter transitioned to an ice shelf in a deeper water (floating glacier ice that was not in contact with the seafloor). This system must have been confined to the Bransfield basin between tributary flow out of the Orleans Strait, off the Trinity Peninsula, and the South Shetland Islands (Figs. 5 and 6). As indicated by the curvature of bedforms on the surface of the grounding zone fans (i.e., mouths of both Maxwell and Admiralty bays) and major troughs (i.e., Lafond, Laclavere and Mott Snowfield Trough) that extend into Bransfield Strait, flow of the ice shelf was conjectured to involve a northeastern direction more or less parallel to the trend of the basin (Canals et al., 2002; Willmott et al., 2003). Outlets in the eastern portions of the basin are even less well defined but must have involved partitioned grounded flow out across the northern end of the South Shetland Platform (just northeast of King George Island), out beyond Elephant Island, and into the Powell Basin (Fig. 6). According to the swath bathymetry data it is likely that there was a small ice dome on Elephant Island providing a plug to the northeast flowing Bransfield Ice Shelf system.

Eliminado: e.g.

Eliminado: The depth of the Bransfield Strait (greater than 1000 m) necessitates that

Eliminado: in inner shelf

Eliminado: i.e.

Eliminado: Maxwell Bay and Admiralty Bay

Eliminado: i.e.

Eliminado: ;

Eliminado: Heroy et al., 2008

3.5 Gerlache-Croker-Boyd Straits

In the Gerlache-Croker-Boyd Straits, the streaming ice flow is confined in a spectacular bundle structure 100 km long and flowing to the north-northwest (Canals et al., 2000). Almost the entire ice drainage out of the Gerlache Strait was funneled through the Croker Passage that included glaciers draining the eastern side of Anvers and Brabant islands and the western flank of the Bruce Plateau (Domack et al., 2004; Evans et al., 2004). These tributary systems converged at various depths (submarine hanging valleys) where fjord valleys joined the Gerlache Strait and the Croker Passage. This along with the large number of tributaries requires considerable constriction of parallel arrangement of flow lines within the Croker Passage and Boyd Strait outlet path (Fig. 5). However, near the shelf break the grounding line system shows a spread of flow trajectories out toward the shelf break (Canals et al., 2003; their Fig. 2b).

Eliminado: of
Eliminado: -
Eliminado:
Eliminado: which
Eliminado: and Dyer
Eliminado: p
Eliminado: x
Eliminado:
Eliminado: Some tributaries are added as the system flows out toward the shelf break, beyond Smith Island and this maintains the tight, parallel arrangement of flow in the Boyd Strait.
Eliminado: at
Eliminado: clearly

3.6 Palmer Deep and Hugo Island Trough

The outflow from the Palmer Deep and Hugo Island Trough is one of the three major tributary systems that terminate as an outlet system along the western AP continental shelf edge (Fig. 5). These were delineated first by Pudsey et al. (1994), Vanneste and Larter (1995) and later outlined in detail by Domack et al., (2006). The systems include tributary glaciers from the Graham Land Coast between 65ºS and 66ºS and ice which flowed out of Dallmann Bay around the northeast corner of Anvers Island (Fig. 5). Along the Graham Land Coast the ice flow emanating from the fjords directed flow to the northeast coalescing with the Palmer Deep ice flow in Hugo Island Trough and crossed the mid-shelf in a northern direction to the outer shelf (Domack et al., 2006). On the outer shelf the ice flow coalesced with the Dallman Bay flow that runs out around the north end of Anvers and Brabant islands.

Eliminado: Antarctic Peninsula
Eliminado:
Eliminado: Graham Land Coast
Eliminado: , the Flandres Bay and Bismark Strait
Eliminado: northwest
Eliminado: In
Eliminado: ed
Eliminado: from
Eliminado: Island
Eliminado: I

3.7 Biscoe Trough

The cross-shelf Biscoe Trough system consists of three flow branches with overdeepened troughs up to 800 m depth, a topographic ridge of 300 m high crosses the main branch of the Biscoe Trough system in a southwest and northeast direction, and a smoother surface toward the shelf edge at 400-500 m depth (Canals et al., 2003; Amblas et al., 2006). The flowlined bedforms show a general converging westward flow directions toward the shelf edge. Biscoe Trough system also shows a spread of flow trajectories out toward the shelf break. This system was fed by ice flow primarily off Renaud Island archipelago but notably, as well, contains indications of ice flow off mid to outer shelf banks with a distinct flow divide between the Biscoe Trough and Palmer Deep and Hugo Island Trough systems, and south along the trend defined by Hugo Island.

Eliminado: overdeepened troughs

Eliminado: up to

Eliminado: clear

Eliminado: out

3 Interpretation and discussion

Based upon the above observations we recognized six major outlets for paleo-ice stream drainage off the APIS during the LGM and refined the locations of their ice divides (Fig. 5). In addition, the patterns revealed by our flow direction reconstruction indicate the locations and areal dimensions of at least seven major ice domes centered on the middle to outer AP continental shelf. Below we focus on a comprehensive interpretation of the new seabed morphology and discuss the regional implications regarding flow paths, ice divides and ice domes.

Eliminado: s

Eliminado: s

Eliminado: ir

Eliminado: centers of accumulation

4.1 Flow bifurcation in Larsen-B embayment

Our observations of streamed bedforms in the Larsen-B embayment indicate that the modern glaciers (i.e., Crane, Leppard, and Flask Glaciers) were not tributaries of the Robertson mid-outer shelf paleo-ice stream as previously interpreted by Evans et al. (2005) and highlighted in previous reviews (e.g., Davies et al., 2012; Livingstone et al., 2012). Keeping in mind that there are no surface expressions of seismic stratigraphic boundaries on the shelf interpreted as a LGM ice stream bifurcation (Smith and Anderson, 2009) we provide two possible explanations to explain the flow divergence we observe in the Larsen-B embayment. The first explanation is based on the hypothesis of a non-uniform geological framework. The diverging flow could be explained by the southeastward extension of the Seal Nunatak and Robertson Island post-Miocene volcanic sequence, in contact with Mesozoic rocks in the Larsen embayment. We infer from some seismic data (Rebesco, personal communication; 2014) the presence of Mesozoic mudrocks similar to the Nordensköld Formation (Jurassic black shale; Reinardy et al., 2011) and Cretaceous sedimentary sequences of Robertson Island within the Larsen-B embayment. These are known to have influenced bed deformation within tills derived from them (Reinardy et al., 2011). One hypothesis, therefore, would suggest that the divergence of flow was related to faster flow and was funneled out of the inner Larsen-B embayment by a bed that was more easily deformed (mud base) than the higher friction of the sandy volcaniclastic palagonite units that comprise the Seal Nunatak massif. Detailed petrographic analysis of the respective tills could test this hypothesis.

We also consider the pre-determined topography and glacial dynamics that could have split the flow direction on the mid-shelf. The existence of a slightly elevated seabed over the middle shelf could have acted as a prow between the Robertson Trough and Jason Trough thus causing diverging flow. This hypothesis cannot be fully tested at this

Eliminado: i.e.
Eliminado: e.g.
Eliminado: ;
Eliminado: Ó Cofaigh et al., in press
Eliminado: We provide two possible explanations to explain the flow divergence we observe in the Larsen-B embayment. Although,
Eliminado: ,
Eliminado: t
Eliminado: scanty
Eliminado: st
Eliminado:
Eliminado: that followed
Eliminado: -
Eliminado: The second hypothesis to take into consideration relates to
Eliminado: barrier
Eliminado: Unfortunately,
Eliminado: t
Eliminado: reliably

time because heavy ice cover in this particular region makes navigation and acquisition of key swath bathymetry very difficult. However, some bathymetric data and seismic profiles from shipboard surveys south of Jason Peninsula do exist (Sloan et al., 1995) and these show evidence of shallow shelf banks at less than 300 m water depth. - Such topographic highs could have divided the glacial flow (Fig. 5). The examination of a time-series of MODerate-resolution Imaging Spectroradiometer (MODIS) images from the northeastern AP also shows unequivocal evidence of several previously unknown reef and shoal areas, based on their influence on sea ice drift and grounding of small icebergs (Table 1, Figs. 7 and S1, and video S2; see also http://nsidc.org/data/iceshelves_images/index_modis.html). Luckman et al. (2010) demonstrated the reliability of using satellite remote-sensing tools to identify western Weddell Sea grounded tabular icebergs and to estimate their draft, which they interpreted as maximum water depth. In the 12-year series of images, shoal areas appear as frequent stranding areas of small icebergs, particularly during heavy winter sea ice periods. Larger icebergs (having 200-350 m keels) show drift paths strongly controlled by the shoals. Stranding of icebergs (especially for the informally named Bawden, Roberston, and Jason shoal or reef areas, see Table 1) indicates the shallowest areas of the region. These high areas could have served as centers of glacial nucleation similar to the model proposed for shallows across the Bellingshausen Sea continental shelf (Domack et al., 2006).

The two mechanisms described above could have interacted to cause the divergence of the flow observed from the Larsen-B embayment; a processes combination of a deformation of weak bed material and a bifurcation of the ice around a topographic high. Divergence of flow lines has been observed at the margin of the Greenland Ice Sheet and Antarctica. A modern example that shows fast flowing ice bifurcation can be

Eliminado: during the austral summer

Eliminado: —

Eliminado: these

Eliminado: could have acted as a topographic prow dividing the acting on glacial flow

Eliminado: Antarctic Peninsula

Eliminado: sea ice and

Eliminado: pack

Eliminado: above explanations

Eliminado: within

Eliminado: two processes:

Eliminado: have

Eliminado: already

observed on the flow velocity field map of the northeast Greenland Ice Stream, where the southern flow feeds Storstrømmrn and flows into the northern outlet glaciers of Zachariæ Isstrøm and Nioghalvfjerdsfjorden (Joughin et al., 2001; Joughin et al., 2010). Modern analogs such as Siple Dome show diverging flow of marine-based ice streams (bed 600 to 700 m b.s.l. - below sea level) around a topographic high only 300 to 400 m b.s.l. (Fretwell et al., 2013). In the Siple Coast region, only 200 to 300 m topographic different is sufficient to create diverging flow separated by ice domes. In addition to these real-world examples, modeling has shown that either a relative topographic high or a relative increase in the basal drag can lead to divergence of ice flow and formation of an elongated ice dome between them. A number of researchers have modeled the surface expression of variability in bed topography or bed properties; a comprehensive analysis is provided by Gudmundsson (2003).

4.2 Evidence of ice divides

We define an ice divide as a boundary separating divergent ice flow directions, i.e., the line that separates neighbouring drainage systems, analogous to a water divide. The separation of the West and East AP along the Bruce Plateau and Detroit Plateau on the Trinity Peninsula and the Graham Land Coast formed the primary ice divide for the AP during LGM. Our results, based on the details of the ice flow directions and the modern subaerial and submarine topography, suggest that secondary ice divides split off from the primary ice divide creating several large draining basins (Fig. 5). On the eastern side of the peninsula, we define four major ice divides:

(1) from the AP across the Seal Nunatak and Robertson Island to divide the ice flow between the northeast Larsen-B embayment and the western area of Larsen-A;

Eliminado: the northern

Eliminado: the

Eliminado: According to Knight et al. (1994) a topographic obstacle of about 400 m high is sufficient to impose a pattern of ice divergence.

Eliminado: below sea level

Eliminado: below sea level

Eliminado:

Eliminado: An ice divide is the

Eliminado: at greatest altitude

Eliminado: opposite

Eliminado: which defines ice drainage systems

Eliminado: major center of radial flow in the northern AP at LGM was the

Eliminado: x

Eliminado: the northern AP was bounded by

Eliminado: interconnected with the main center

Eliminado: In order to explain our East AP flow line reconstruction, ice divides must have included the following

Con formato: Sangría: Izquierda: 0.5 cm

Eliminado: NE

Eliminado: ,

(2) from the Bruce Plateau (AP) to Cape Longing to divide flows between Larsen-A and southern Prince Gustav Channel;

(3) from the Detroit Plateau (AP) southeast across the Prince Gustav Channel and up across the center of James Ross Island (Camerlenghi et al., 2001) before continuing across Admiralty Sound and Seymour Island to split the ice flow between the southern and northern Prince Gustav Channel, dividing the ice flow on James Ross Island and Admiralty Sound, and

(4) from the Trinity Peninsula to the Joinville Island Group, and along the axis of D'Urville Island, across the Larsen Channel, Joinville Island and Dundee Island according to the seabed morphology in the Antarctic Sound.

On the West AP, the boundary of major ice divides runs:

(1) along the South Shetland archipelago;

(2) from the AP across the Orleans Strait, Trinity Island and along a series of shelf banks at the western end of the Bransfield Strait that divide the ice flow between the Bransfield Strait and Gerlache-Boyd Strait;

(3) from the Bruce Plateau (AP) across Gerlache Strait, Wiencke Island, southern edge of Anvers Island, Schollaert Channel and up along the crest of Brabant Island to explain the constriction of flow lines in the Gerlache Strait, and

(4) flow divides must have been present on the Anvers Island and Renaud Island to explain the Palmer Deep and Hugo Island Trough ice flow system and its separation from the Biscoe Trough.

Ice divides typically evolve into elongated ice domes, with topographic highs that influence the spatial pattern of accumulation rate and the ice flow directions. These divides are not stationary and can evolve under variations in climate or boundary condition (e.g., Nereson et al., 1998; Marshall and Cuffey, 2000). Indeed, an entire ice

Eliminado: ,

Eliminado: SE

Eliminado: .

Eliminado: Moreover, a flow divide must have

Eliminado: bridged

Eliminado: run

Eliminado: (4)

Eliminado: , the flow divides are defined by

Con formato: Sangría: Izquierda: 0.5 cm

Eliminado: ,

Eliminado: a boundary that runs

Eliminado: ,

Eliminado: a line running

Eliminado: , and

Eliminado: Once ice becomes thick enough to overtop a bedrock divide, the divide will be determined by the accumulation rate pattern and the dynamics of ice flow.

Eliminado: e.g.

dome can change shape as climate conditions change on a timescale of a few hundred to thousands of years, depending on the accumulation rate and size of the divide (Nereson et al., 1998, Marshall and Cuffey, 2000).

4.3 Inferred ice domes on the continental shelf

The existence of two separate shelf ice domes at LGM, one covering the northern AP and the other upon the South Shetland Islands was suggested by early work that recognized centers of ice accumulation over the highest exisisting bedrock topography (Banfield and Anderson, 1995; Bentley and Anderson, 1998). Our LGM ice flow reconstruction of at least six distinct systems across the northern AP continental shelf and evidence of ice divides serve to delineate at least seven broad regions where additional ice domes may have been centered out on the continental shelf. The presence of the domes is required to constraint lateral spreading of each of the paleo-ice stream outlets and also to explain the observation of radial flow that, in part, converges with flow within several of the paleo ice stream trajectories. We define each of these features here by assigning names associated with the nearest prominent headland for each ice dome, headlands which likely provided some axial orientation to the ice dome. These include: Hugo Dome, Marr Dome, Brabant Dome, Livingston Dome, Snow Hill Dome, Robertson Dome, and Hektoria Dome (Fig. 5).

The exact dimensions and character of each of these domes is difficult to define because these areas of the continental shelf are generally devoid of multibeam coverage. Further, extensive iceberg scouring across these banks has largely obscured original glacial flow indicators, which might have provided some sense of paleo-ice flow direction. Nevertheless, some small troughs and lineated features do exist, for at least three of the inferred domes. For the Marr, Brabant and Livingston Domes, some radial flow

Eliminado: Pioneering studies shown
Eliminado: t
Eliminado: (Banfield and Anderson, 1995; Bentley and Anderson, 1998)
Eliminado:
Eliminado: ere
Eliminado: paleo-
Eliminado: indicates the extent
Eliminado: paleo-ice stream
Eliminado: and these must
Eliminado: also
Eliminado: must
Eliminado: ,
Eliminado: (see below)
Eliminado: cap
Eliminado: cap divide
Eliminado: , and these do contain flow indicators

indicators can be seen in small troughs that drain the mid-point divides in about the middle of the continental shelf (Fig. 5). Further, the Hugo Dome can be seen to have directed flow into the Biscoe Trough from a position considerably out on the continental shelf. Hence, this evidence does indicate that the mid-shelf hosted ice domes as centers of ice accumulation which contributed ice drainage contemporaneous with the large paleo ice streams (Fig. 5). In this hypothesis, the continental shelf ice domes do not necessarily require excessive elevation, only sufficient height to have grounded the system and allowed each dome to constrain the surrounding paleo-ice streams. Our hypothesis for these ice domes is not without precedent as some work on the East Antarctic margin has postulated a similar situation, where major divides were diverted and constrained by large ice domes that rested upon shelf banks (Eittreim et al., 1995). Also, an independent ice dome centered over the west of the Alexander Island, western AP, persisted through the LGM and deglaciation (Graham and Smith, 2012). Furthermore, there are existing modern ice domes that separate fast flowing, marine-based ice in West Antarctica, including Siple Dome (surface elevation 600 m a.s.l. and an ice thickness of 1000 m; Gades et al., 2000; Conway et al., 2002).

The seaward extent of each of the shelf ice domes would seem to correspond to the outer continental shelf, as outlet systems are uniformly constrained out to the grounding line position (the outer shelf) in each of the systems we examined. The exception to this is the broad apron of the grounding line associated with the Gerlache-Croker-Boyd Strait and Biscoe ice streams. In those cases diverging flow is clearly imaged out across the continental shelf break, indicating spreading flow toward the grounding line. Indeed, the extensive relief of Smith Island (maximum elevation 2100 m a.s.l.) would likely have blocked any ice flow associated with the Brabant Dome from reaching the outermost shelf (Fig. 5). This spreading flow is similar to that observed for unrestricted

Eliminado: s

Eliminado: the orientations found in

Eliminado: ,

Eliminado: Here the flow lines actually flow back toward the Peninsula for a distance (Amblas et al., 2006; their Fig. 5).

Eliminado: limited

Eliminado: -

Eliminado: cap

Eliminado: persisted on

Eliminado: Antarctic Peninsula

Eliminado: above sea level

Eliminado: se

Eliminado:

paleo-ice stream fans such as in the Kveithola Trough off Svalbard (Rebesco et al., 2011).

While the areal dimensions of the ice domes are fairly certain, their thickness is less well defined. We can assume that these features were thick enough to have served as effective lateral constraints to ice stream outlets and to have allowed the dome to have been grounded across a bathymetry of approximately 350 m, on average. The thickness of an ice dome in steady state depends on the regional accumulation rate average, the temperature of the ice, and the aerial extent of the dome outlined in section 2.3 (Bueler et al., 2005). Figure 8 shows the results of our model with red ellipses defining the range of possible ice thickness values for each dome. We assume that the western-side domes (Marr, Livingston, Brabant, and Hugo) have an average ice temperature of 0 ºC (Fig. 8a), while the eastern-side domes have an average ice temperature of -20 ºC (Fig. 8b). The colder ice is stiffer, this can result in thicker domes if all other parameters are the same. The minor axis of the red ellipses shows a possible range of error in the ice radius associated due to the irregular aerial extent of the real ice dome.

For accumulation rates, we base our assumptions on the modern AP, which has a strong orographic precipitation gradient that ranges from 4 m yr^{-1} on the western side to less than 0.1 m yr^{-1} on the eastern side. High accumulation sites will result in thicker ice domes if all other parameters are equal. In the LGM case, the distribution of domes will create multiple precipitation highs and lows as each dome creates its own pattern of orographic precipitation (Roe and Lindzen, 2001). Therefore we predict the highest accumulation rates for Brabant, Livingston, and Hugo Domes. Marr Dome will likely be shielded somewhat from the highest accumulation. On the eastern side, Hektoria and Snow Hill Domes are likely to have slightly higher accumulation than Robertson Dome, as they may receive some precipitation from the Weddell Sea. We have selected a broad

Eliminado: ¶

Eliminado: 10

Eliminado: larger

Eliminado: to a slight over estimation effect

Eliminado: /

Con formato: Superíndice

Eliminado: /

range of accumulation rates because we have only general atmospheric patterns from which to draw our assumptions. Despite this large range of input values, we can bracket the ice thicknesses for each dome as presented in Figure 8, and estimate volumes, as shown in Table 2.

4.4. Regional implications

We have presented a compilation of paleo-ice flow indicators for the northern AP and used the resulting map to infer ice-flow patterns, ice divides, and ice domes. This allows an integrated view over the full extent of the APIS at the LGM. This mapping effort suggests that the seabed topography and the complex geology influenced the ice flow route and regime at the LGM. The bifurcation of the flow lines in the Larsen-B embayment affected the character of the basal ice erosion mechanisms. In general, diverging ice flow is associated with an area of decelerating flow (e.g., Stokes and Clark, 2003). Moreover, the increased flux of ice and debris flowing around a topographic high could provide a powerful feed-back where an ice stream could deepen existing depressions (Knight et al., 1994). On the other hand, the flow convergences (strongest near the mid-shelf in the northern AP) led to an increase in flow speed at the mid- and upper end of the ice streams, promoting high basal shear stress and significant basal sediment transport (e.g., Boulton, 1990).

It should also be kept in mind that the ice stream catchments include deep basins (i.e., Palmer Deep) that serve as deposystems for thick interglacial mud and ooze deposits. For instance, typical thicknesses for Holocene mud within the Palmer Deep are about 100 m while across the broader shelf the interglacial muds are no more than 6-8 m thick. This mud could serve as basal lubrication as ice systems advance out across the shelf and eventually ground within the deep inner shelf, thus enhancing streaming flow

Eliminado: ir
Eliminado: ping
Eliminado:
Eliminado: accumulation ce
Eliminado: nters
Eliminado: to show
Eliminado: e.g.
Eliminado: e.g.
Eliminado: i.e.
Eliminado: PD
Eliminado: acorss

within the trough trajectory via bed deformation. Once ice streaming was initiated in areas where interglacial sediments provided lubrication, the interglacial sediment would be completely removed by ice; streaming would continue, having been established through regional flow patterns, by eroding the underlying bedrock for more lubricating material and thus enhancing the focus of the trough through multiple cycles.

The presence of multiple APIS ice domes centered on the mid-shelf implies that ice thickness was not uniform on the northern AP continental shelf during the maximum extension of the APIS at LGM. These domes may have harbored significant ice volume above buoyancy, even under minimal scenarios of ice thickness due to their large areal extent. Comparing the estimated total area of the ice domes with the one estimated for the flow paths (Tables 2 and 3) shows that the ice domes were at least as important if not more so than the paleo-ice streams, in terms of areal coverage. The minimum estimate for total ice volume of the domes and the paleo-ice streams are similar. However, because the convergent flow paths have significantly deeper beds (as they flow in troughs) the ice streams contains 43% more maximum ice than the domes.

The presence of multiple ice domes on the shelf would have influenced the ice sheet dynamics (e.g., basal melting and sliding parameters) and the sediment transport to beyond the margin of the ice. The ice velocity would have been slower near the ice divides with lower sediment transport rates than at the peripheral regions where the domes fed out into fast flowing ice streams with high sediment transport rates. Because of feedbacks between ice dome formation and the orographic precipitation, all of these domes may not have reached their largest extent at the same time; the growth of one dome may "starve" another of its accumulation (e.g., Roe and Lindzen, 2001).

Finally, the delineation of ice domes and faster flowing outlets is important in that it would help to gauge the relative contribution of each system to post glacial eustatic rise

Eliminado: Our assumptions related to ice volumes estimates of the converging flow paths are not as strong as the ones we use for the ice domes. Because of this t

Eliminado: s

Eliminado: Because

Eliminado: the maximum total ice volume for the paleo ice streams is 27,085 km^3 more than the volume estimate for the ice dome system

Eliminado:

Eliminado: likely

Eliminado: controlled

Eliminado: e.g.

Eliminado: the ocean (shelf break)

Eliminado: e.g.

in sea level or conversely how each system might have responded to a eustatic or ocean-climate event. For instance, recent models for glacial recession within the Palmer Deep and along the East Antarctic margin suggest a calving bay re-entrant model, wherein ice streams retreat preferentially landward thus creating a linear “fjord-like” bay surrounded by slower flowing ice of the domes (Domack et al., 2006; Leventer et al., 2006). This model and others (*i.e.*,, Kilfeather et al., 2011) deserve consideration in that our reconstruction clearly outlines differences in the boundary conditions of flow, thickness, bed character, accumulation, and ice sourcing for the domes and converging flow systems. Thus the two systems would logically be expected to respond differently to any forcing factors involved in deglaciation.

The identification of ice domes, ice divides, and diverging/converging flows help us to understand ice-sheet evolution and processes. While considerable effort has been put forward recently toward understanding the character and timing of the retreat of the APIS, more work needs to focus upon the reconstruction and detailed vitality of the APIS during the last glacial cycle. The features we recognize have important implications for this effort and the future siting of ice cores and marine drilling sites. Finally, they provide important constraints for glaciohydrology, past and future ice-sheet modeling used, for instance, to look at sediment fluxes (Golledge et al., 2013) or provide more realistic predictions, ice-sheet modeling in response to changing environments, and sea level modeling. The existing challenge includes arranging models of ice flow and geological data so that they resemble each other, especially when geological features are small compared to the grid scale of ice flow paths. While the evidence for the ice domes out on the shelf is in large part circumstantial; there exists today likely remnants to these features as it is the case for the ice cap on Hugo Island, where it stands as a prominent feature in the middle of the AP continental shelf.

Eliminado: ”
Eliminado:
Eliminado: *i.e.*
Con formato: Fuente: Cursiva
Eliminado: s
Eliminado: -drainage
Eliminado: IP
Eliminado: IP
Eliminado: se
Eliminado: siting
Eliminado:
Eliminado: flow
Eliminado:
Eliminado: A challenging field
Eliminado: to get
Eliminado: to
Eliminado: Antarctic Peninsula

4 Conclusions

Our results provide considerable improvement in the assessment of ice flow and thereby the dynamics that may have governed expansion, stabilization and eventual demise of the ice mass which comprised the APIS. We now recognize not only six spatially defined paleo-ice streams but we can infer with some confidence the source areas and number of tributaries which fed them. In addition, our study highlights the need to understand the extent and behavior of seven large shelf ice domes that best explain the configuration of the ice flow directions and served as lateral constraints to the paleo-ice stream flow. These ice domes had slower flowing ice and were likely frozen to their beds, exhibiting somewhat different behavior to the paleo-ice streams which were fed almost exclusively from convergence of tributary glaciers draining the elevated spine of the AP and surrounding islands. Also, while the timing of paleo-ice stream recession is known in a general way from recent syntheses (Ó Cofaigh et al., 2014) the detailed rates and step backs are far from resolved. Our reconstruction allows focus upon the varying character of each ice stream and how this might have influenced differential response to the forcing factors (i.e., eustasy, atmospheric and ocean temperature) and accumulation rates which may have induced instability in the region (Livingstone et al., 2012).

Future research including strategic multibeam coverage, marine sediment cores and modeling considering the glacio-isostatic rebound are needed to confirm the existence of the ice domes, define their characteristics and constrain the timing of ice retreat from them. When combined with high resolution dating efforts, our flow reconstruction will help elucidate the retreat history of the ice sheet, and, therefore, those forces that acted to destabilize the system and initiate the most recent deglaciation of the APIS.

Eliminado: we now infer for the continental shelf where these ice masses were supported by local accumulation

Eliminado: may have been

Eliminado: in press

Eliminado:

Eliminado: i.e.

Eliminado: more

Eliminado: -

Acknowledgements

This work was funded by U.S. National Science Foundation grants OPP-0732467 to Eugene W. Domack, ANT-1340261 and ANT-0732921 to Ted Scambos, and OPP-0855265 to Erin C. Pettit, and the Korean Polar Research Institute (PP14010). In addition, we thank the captains and crews of the RVIB *Nathaniel B. Palmer*, *Polarstern*, RRS *James Clark Ross*, BIO *Hesperide*s, and *Aaron*, and support staffs and scientific parties who participated in cruises. This work contains public sector information, licensed under the Open Government Licence v2.0, from the United Kingdom Hydrographic Office for the data collected on HMS *Endurance*, HMS *Scot*t and HMS *Protector*. We thank all Principal investigator owners of the released swath multibeam data from the Marine Geoscience Data System portal hosted by Lamont-Doherty Earth Observatory of Columbia University (http://www.marine-geo.org/index.php). C.L. was supported by 'TALENTS' Marie Curie COFUND FP7 Programme and MARES programme and an individual Research Assistant contract within the project MARES-Sustainable Use of Marine Resources (CENTRO-07-ST24-FEDER-002033), co-financed by QREN, Mais Centro - Programa Operacional Regional do Centro e União Europeia/European Regional Development Fund (EU).

Eliminado:
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Con formato: Fuente: Cursiva
Eliminado: All
Eliminado: s
Eliminado:

References

Amblas, D., Urgeles, R., Canals, M., Calafat, A. M., Robesco, M., Camerlenghi, A., Estrada, F., De Batist, M., and Hughes-Clarke, J. E.: Relationship between continental rise development and palaeo-ice sheet dynamics, Northern Antarctic Peninsula Pacific margin, Quaternary Sci. Rev., 25, 933–944, 2006.

Andrews, J. T.: On the reconstruction of pleistocene ice sheets: a review, Quaternary Sci. Rev., 1, 1–30, 1982.

Arndt, J. E., Schenke, H. W., Jakobsson, M., Nitsche, F. O., Buys, G., Goleby, B., Rebesco, M., Bohoyo, F., Hong, J., Black, J., Greku, R., Udintsev, G., Barrios, F., Reynoso-Peralta, W., Taisei, M., and Wigley, R.: The International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0 – a new bathymetric compilation covering circum-Antarctic waters, Geophys. Res. Lett., 40, 3111–3117, 2013.

Barker, P.F.: The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: ridge crest-trench interactions, J. Geol. Soc., 139, 787-801, 1982.

Banfield, L. A. and Anderson, J. B.: Seismic facies investgation of the late Quaternary glacial history of Bransfield Basin, Antarctica, in: Geology and Seismic Stratigraphy of the Antarctic Margin, edited by: Cooper, A. K., Barker, P. F., and Brancolini, G., Antarct. Res. Ser. 68, American Geophysical Union, Washington, D.C., 123–140, 1995.

Bentley, M. J. and Anderson, J. B.: Glacial and marine geological evidence for the ice sheet configuration in the Weddell Sea-Antarctic Peninsula region during the Last Glacial Maximum, Antarct. Sci., 10, 309–325, 1998.

Boulton, G. S.: Sedimentary and sea level changes during glacial cycles and their control on glacimarine facies architecture. in: Glacimarine Environments: Processes and Sediments, edited by: Dowdeswell, J. A. and Scourse, J. D., Geological Society Special Publication 53, The Geological Society, London, 15–52, 1990.

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, doi:10.5194/tc-8-1-2014, 2014.

Bueler, E., Lingle, C. S., Kallen-Brown, J. A., Covey, D., and Bowman, L. N.: Exact solutions and verification of numerical models for isothermal ice sheets, J. Glaciol., 51, 291–306, 2005.

Eliminado: ¶

Camerlenghi, A., Domack, E. W., Rebesco, M., Gilbert, R., Ishman, S., Leventer, A., Brachfeld, S., and Drake, A.: Glacial morphology and post-glacial contourites in northern Prince Gustav Channel (NW Weddell Sea, Antarctica), Mar. Geophys. Res., 22, 417–443, 2001.

Canals, M., Urgeles, R., and Calafat, A. M.: Deep sea-floor evidence of past ice streams off the Antarctic Peninsula, Geology, 28, 31–34, 2000.

Canals, M., Casamor, J. L., Urgeles, R., Calafat, A. M., Domack, E. W., Baraza, J., Farran, M., and De Batist, M.: Seafloor evidence of a subglacial sedimentary system off the northern Antarctic Peninsula, Geology, 30, 603–606, 2002.

Canals, M., Calafat, A. M., Camerlenghi, A., De Batist, M., Urgeles, R., Farran, M., Geletti, R., Versteeg,W., Amblas, D., Rebesco, M., Casamor, J. L., Sànchez, A., Willmott, V., Lastras, G., and Imbo, Y.: Uncovering the footprint of former ice streams off Antarctica, EOS, 84, 97–108, 2003.

Clark, C. D.: Mega-sclae glacial lineations and cross-cutting ice-flow landforms, Earth Surf. Proc. Land., 18, 1–29, 1993.

Clark, C. D., Tulaczyk, S., Stokes, C. R., and Canals, M.: A groove-ploughing theory for the production of mega-scale glacial lineations, and implications for ice-stream mechanics, J. Glaciol., 49, 240–256, 2003.

Conway, H., Catania, G., Raymond, C. F., and Gades, A. M.: Switch of flow direction in an Antarctic ice stream, Nature, 419, 465–467, 2002.

Cuffy, K. M. and Paterson, W. S. B. (Eds.): The Physics of Glaciers, Elsevier Inc., Oxford, UK, 2010.

Curry, P. and Pudsey, C. J.: New Quaternary sedimentary records from near the Larcen C and former Larsen B ice shelves; evidence for Holocene stability, Antarct. Sci., 19, 355–364, 2007.

Eliminado: ¶

Davies, B. J., Hambrey, M. J., Smellie, J. L., Carrivick, J. L., and Glasser, N. F.: Antarctic Peninsula Ice Sheet evolution during the Cenozoic Era, Quaternary Sci. Rev., 31, 30–66, 2012.

Domack, E. W., Canals, M., Camerlenghi, A., Gilbert, R., Amblas, D., Wilmott, V., Calafat, A. M., Urgeles, R., DeBatist, M., Casamor, J. L., and Rebesco, M.: Complete swath map coverage of the Gerlache Boyd Strait paleo ice stream: an example of collaborative seafloor mapping in the Antarctic Peninsula, XXVIII SCAR Open Science Conference, Bremen, Germany, 26-28 July 2004, Abstract S11/P08, 2004.

Domack, E., Duran, D., Leventer, A., Ishman, S., Doane, S., McCallum, S., Amblas, D., Ring, J., Gilbert, R., and Prentice, M.: Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch, Nature, 436, 681–685, 2005.

Domack, E., Amblas, D., Gilbert, R., Brachfeld, S., Camerlenghi, A., Robesco, M., Canals, M., and Urgeles, R.: Subglacial morphology and glacial evolution of the Palmer deep outlet system, Antarctic Peninsula, Geomorphology, 75, 125–142, 2006.

Dowdeswell, J. A., Ottesen, D., Evans, J., Ó Cofaigh, C., and Anderson, J. B.: Submarine glacial landforms and rates of ice-stream collapse, Geology, 26, 819–822, 2008.

Eittreim, S. L., Cooper, A. K., and Wannesson, J.: Seismic stratigraphic evidence of ice-sheet advances on the Wilkes Land margin of Antarctica, Sediment. Geol., 96, 131–156, 1995.

Evans, J., Dowdeswell, J. A., and Ó Cofaigh, C.: Late Quaternary submarine bedforms and ice-sheet flow in Gerlache Strait and on the adjacent continental shelf, Antarctic Peninsula, J. Quaternary Sci., 19, 397–407, 2004.

Evans, J., Pudsey, C. J., Ó Cofaigh, C., Morris, P., and Domack, E. W.: Late Quaternary glacial history, flow dynamics and sedimentation along the eastern margin of the Antarctic Peninsula Ice Sheet, Quaternary Sci. Rev., 24, 741–774, 2005.

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., 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, doi:10.5194/tc-7-375-2013, 2013.

Gades, A., Raymond, C. F., Conway, H., and Jacobel, R.: Bed properties of Siple Dome and adjacent ice streams, West Antarctica, inferred from radio-echo sounding measurements, J. Glaciol., 46, 88–94, 2000.

Gilbert, R., Domack, E. W., and Camerlenghi, A.: Deglacial history of the Greenpeace Trough: ice Sheet to Ice Shelf transition in the Northwestern Weddell Sea, Antarct. Res. Ser., 79, 195–204, 2003.

Glasser, N. F., Davies, B. J., Carrivick, J. L., Rodés, A., Hambrey, M. J., Smellie, J. L., and Domack, E.: Ice-stream initiation, duration and thinning on James Rosse Island, northern Antarctic Peninsula, Quaternary Sci. Rev., 86, 78–88, 2014.

Golledge, N. R., Levy, R. H., McKay, R. M., Fogwill, C. J., White, D. A., Graham, A. G. C., Smith, J. A., Hillenbrand, C.-D., Licht, K. J., Denton, G. H., Ackert jr, R. P., Maas, S. M., Hall, B. L.: Glaciology and geological signature of the Last Glacial Maximum Antarctic ice sheet, Quaternary Sci. Rev., 78, 225-247, 2013.

Graham, A. G. C. and Smith, J. A.: Palaeoglaciology of the Alexander Island ice cap, western Antarctic Peninsula, reconstructed from marine geophysical and core data, Quaternary Sci. Rev., 35, 63–81, 2012.

Gudmundsson, G.H.: Transmission of basal variability to a glacier surface, J. Geophys. Res.: Solid Earth,108, 2253, 2003.

Heroy, D. C. and Anderson, J. B.: Ice-sheet extent of the Antarctic Peninsula region during the Last Glacial Maximum (LGM) – insights from glacial geomorphology, Geol. Soc. Am. Bull., 117, 1497–1512, 2005.

Johnson, J. S., Bentley, M. J., Roberts, S. J., Binnie, S. A., and Freeman, S. P. H. T.: Holocene deglacial history of the northeast Antarctic Peninsula – a review and new chronological constraints, Quaternary Sci. Rev., 30, 3791–3802, 2011.

Joughin, I., Fahnestock, M., MacAyeal, D. R., Bamber, J. L., and Gogineni, P.: Observation and analysis of ice flow in the largest Greenland ice stream, J. Geophys. Res., 106, 34021–34034, 2001.

Joughin, I., Smith, B. E., Howat, I. M., Scambos, T., and Moon, T.: Greenland flow variability from ice-sheet-wide velocity mapping, J. Glaciol., 56, 415–430, 2010.

Kilfeather, A. A., ÓCofaigh, C., Lloyd, J. M., Dowdswell, J. A., Xu, S. and Moreton, S. G.: Ice-stream retreat and ice-shelf history in Marguerite Trough, Antarctic Peninsula: Sedimentological and foraminiferal signatures, Geol. Soc. Am. Bull., 123, 997-1015, 2011.

Eliminado: Heroy, D. C., Sjunneskog, C., and Anderson, J. B.: Holocene climate change in the Bransfield Basin, Antarctic Peninsula: evidence from sediment and diatom analysis, Antarct. Sci., 20, 69–87, 2008.¶

Knight, P. G., Sugden, D. E., and Minty, C. D.: Ice flow around large obstacles as indicated by basal ice exposed at the margin of the Greenland ice sheet, J. Glaciol., 40, 359–367, 1994.

Larter, R. D. and Barker, P. F.: Seismic stratigraphy of the Antarctic Peninsula Pacific margin: a record of Pliocene–Pleistocene ice volume and paleoclimate, Geology, 17, 731–734, 1989.

Larter, R. D. and Vanneste, L. E.: Relict subglacial deltas on the Antarctic Peninsula outer shelf, Geology, 23, 33–36, 1995.

Lawver, L. A., Sloan, B. J., Barker, D. H. N., Ghidella, M. E., von Herzen, R. P., Keller, R. A., Klinkhammer, G. P., and Chin, C. S.: Distributed, active extension in Bransfield Basin, Antarctic Peninsula: evidence from multibeam bathymetry, GSA Today, 6, 1–6, 1996.

Leventer, A., Domack, E., Dunbar, R., Pike, J., Stickley, C., Maddison, E., Brachfield, S., Manely, P., and McClennan, C.: Marine sediment record from East Antarctica margin reveals dynamics of ice-sheet recession, GSA Today, 16, 4–10, 2006.

Livingstone, S. J., Ó Cofaigh, C., Stokes, C. R., Hillenbrand, C. D., Vieli, A., and Jamieson, S. S. R.: Antarctic palaeo-ice streams, Earth-Sci. Rev., 111, 90–128, 2012.

Marshall, S. J. and Cuffey, K. M.: Peregrinations of the Greenland Ice Sheet divide in the last glacial cycle: implications for central Greenland ice cores, Earth Planet. Sc. Lett., 179, 73–93, 2000.

Luckman, A., Padman, L., Jansen, D.: Persistent iceberg groundings in the western Weddell Sea, Antarctica, Remote Sens. Environ., 114, 385-391, 2010.

Nereson, N. A., Hindmarsh, R. C. A., and Raymond, C. F.: Sensitivity of the divide position at Siple Dotne, West Antarctica, to boundary forcing, Ann. Glaciol., 27, 207–214, 1998.

Eliminado: ¶
Knight, P. G., Sugden, D. E., and Minty, C. D.: Ice flow around large obstacles as indicated by basal ice exposed at the margin of the Greenland ice sheet, J. Glaciol., 40, 359–367, 1994.¶

Nývlt, D., Košler, J., Mlčoch, B., Mixa, P., Lisá, L., Bubík, M., Hendriks, B.W.H.: The Mendel Formation: Evidence for Late Miocene climatic cyclicity at the northern tip of the Antarctic Peninsula, Palaeogeogr. Palaeoclimatol. Palaeoecol., 299, 363-384, 2011.

Ó Cofaigh, C., Davies, B. J., Livingstone, S. J., Smith, J. A., Johnson, J. S., Hocking, E. P., Hodgson, D. A., Anderson, J. B., Bentley, M. J., Canals, M., Domack, E., Dowdeswell, J. A., Evans, J., Glasser, N. F., Hillenbrand, C. D., Larter, R. D., Roberts, S. J., and Simms, A. R.: Reconstruction of ice-sheet changes in the Antarctic Peninsula since the Last Glacial Maximum, Quaternary Sci. Rev., 100, 87–110, 2014.

Pudsey, C. J., Barker, P. F., and Larter, R. D.: Ice Sheet retreat from the Antarctic Peninsula shelf, Cont. Shelf. Res., 14, 1647–1675, 1994.

Pudsey, C. J., Evans, J., Domack, E. W., Morris, P., and Del Valle, R. A.: Bathymetry and acoustic facies beneath the former Larsen-A and Prince Gustav ice shelves, north-west Weddell Sea, Antarct. Sci., 13, 312–322, 2001.

Rebesco, M., Liu, Y., Camerlenghi, A., Winsborrow, M., Laberg, J. S., Caburlotto, A., Diviacco, P., Accettella, D., Sauli, C., Wardell, N., and Tomini, I.: Deglaciation of the western margin of the Barents Sea Ice Sheet – a swath bathymetric and sub-bottom seismic study from the Kveithola Trough, Mar. Geol., 279, 141–147, 2011.

Rebesco, M., Domack, E., Zgur, F., Lavoie, C., Leventer, A., Brachfeld, S., Willmott, V., Halverson, G., Truffer, M., Scambos, T., Smith, J., Pettit, E.: Boundary condition of grounding lines prior to collapse, Larsen-B Ice Shelf, Antarctica, Nature, 345, 1354-1358, 2014.

Reinardy, B. T. J., Larter, L. D., Hillenbrand, C. D., Murray, T., Hiemstra, J. F., and Booth, A. D.: Streaming flow of an Antarctic Peninsula palaeo-ice stream, both by basal sliding and deformation of substrate, J. Glaciol., 57, 596–608, 2011.

Roe, G. H. and Lindzen, R. S.: The mutual interaction between continental-scale ice sheets and atmospheric stationary waves, J. Climate, 14, 1450–1465, 2001.

Scambos, T. A., Hulbe, C. L., and Fahnestock, M.: Climate-induced ice shelf disintegration in the Antarctic Peninsula, in: Antarctic Peninsula Climate Variability, edited by: Domack, E. W., Leventer, A., Burnett, A., Bindschadler, R., Convey, P., and Kirby, M., Antarct. Res. Ser. 79, American Geophysical Union, Washington, D.C., 79–92, 2003.

Simms, A. R., Milliken, K. T., Anderson, J. B., and Wellner, J. S.: The marine record of deglaciation of the South Shetland Islands, Antarctica since the Last Glacial Maximum, Quaternary Sci. Rev., 30, 1583–1601, 2011.

Sloan, B. J., Lawver, L. A., and Anderson, J. B.: Seismic stratigraphy of the Larsen Basin Eastern Antarctic Peninsula, in: Geology and Seismic Stratigraphy of the Antarctic Margin, edited by: Cooper, A. K., Barker, P. F., and Brancolini, G., Antarctic Res. Ser. 68, American Geophysical Union, Washington, D.C., 59–74, 1995.

Smith, R. T. and Anderson, J. B.: Ice-sheet evolution in James Ross Basin,Weddell Sea margin of the Antarctic Peninsula: the seismic stratigraphic record, Geol. Soc. Am. Bull., 122, 830–842, 2009.

Smith, T. and Anderson, J. B.: Seismic stratigraphy of the Joinville Platform: implications for regional climate evolution, in: Tectonic, Climatic and Cryospheric Evolution of the Antarctic Peninsula, edited by: Anderson, J. B. and Wellner, J. S., American Geophysical Union Special Publication 063, American Geophysical Union, Washington, D.C., 51–62, 2011.

Stokes, C. R. and Clark, C. D.: The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice-stream location and vigour, Boreas, 32, 264–279, 2003.

Eliminado: K

Vanneste, L. E. and Larter, R. D.: Deep-tow boomer survey on the Antarctic Peninsula Pacific Margin: an investigation of the morphology and acoustic characteristics of Late Quaternary sedimentary deposits on the outer continental shelf and upper slope, in: Geology and Seismic Stratigraphy of the Antarctic Margin, Part 1, edited by: Cooper, A. K., Barker, P. F., and Brancolini, G., American Ggophysical Union, Washington, D.C., 97–121, 1995.

Wellner, J. S., Lowe, A. L., Shipp, S. S., and Anderson, J. B.: Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: implications for ice behavior, J. Glaciol., 47, 397–411, 2001.

Wellner, J. S., Heroy, D. C., and Anderson, J. B.: The death mask of the antarctic ice sheet: comparison of glacial geomorphic features across the continental shelf, Geomorphology, 75, 157–171, 2006.

Willmott, V., Canals, M., and Casamor, J. L.: Retreat history of the Gerlache–Boyd ice stream, Northern Antarctic Peninsula: an ultra-high resolution acoustic study of the deglacial and post-glacial sediment drape, in: Antarctic Peninsula Climate Variability, edited by: Domack, E. W., Leventer, A., Burnett, A., Bindschadler, R., Peter, C., and Kirby, M., Antarct. Res. Ser., 79, 183–194, 2003.

Eliminado: ¶

Eliminado: ¶

Table 1. Reef and shoal areas in the northwestern Weddell Sea[*].

Eliminado:

Latitude	Longitude	Notes
65.237°S 65.183°S	59.251°W *to* 58.213°W	"Robertson reef", 49 km long, bearing 005° numerous high points, shallow depth (est. ~ 100 m depth)
66.912°S 66.813°S	60.133°W *to* 59.468°W	"Bawden reef", extending 34 km from s. end of ice rise, arcuate, bearing 020° numerous high points, shallow depth (est. ~100 m depth)
66.174°S 66.177°S 66.025°S	58.968°W w 58.721°W e 58.806°W n	"Jason shoals", 12 x 18 km region, 3-4 high points; shallow depth at west end (est. 100-150 m depth)
65.784°S	58.237°W	"Hektoria 1 shoal", single point (est. > 150 m depth)
65.849°S	57.276°W	"Hektoria 2 shoal", single point (est. > 150 m depth)
65.692°S	56.956°W	"Hektoria 3 shoal", single point (est. > 150 m depth)
66.292°S	56.975°W	"Hektoria 4 shoal", single point (est. > 150 m depth)

[*] Based on sea ice and small iceberg strand sites, and winter sea ice fracture loci, seen in MODIS image data archived at http://nsidc.org/data/iceshelves_images/index_modis.html

Table 2. Continental shelf domes estimated area, and minimum and maximum estimated ice volumes using the simple Bodvarsson-Vialov model (Bueler et al., 2005).

Eliminado:

Continental Ice Dome	Area (km^2)	Ice volume (km^3)	
		Minimum	Maximum
Hugo Dome	13675	10000	11200
Marr Dome	4950	2500	3300
Brabant Dome	12850	8200	10200
Livingston Dome	8075	5000	5500
Snow Hill Dome	14835	10800	14000
Robertson Dome	7560	5000	6200
Hektoria Dome	12920	9300	12000
TOTAL	74865	50800	62400

Table 3. Flow path systems estimated area (continental shelf), and minimum and maximum estimated ice volumes.

Eliminado:

Flow Path System	Area (km^2)	Approximate length (km)	Ice volume (km^3)	
			Minimum	Maximum
Biscoe Trough	4625	125	2842	4254
Palmer Deep and hugo Island Trough	15000	230	9570	17255
Barbant	850	60	564	719
Gerlache-Croker-Boyd Straits	10675	300	9234	16402
South Bransfield Strait streams	5600	110	4211	5834
Erebus-Terror	7125	190	3905	6935
Robertson Trough	18300	330	13066	26149
Larsen-B embayment	10700	217	6736	11937
TOTAL	72875	1562	50128	89485

Eliminado:

Flow Path System
Biscoe Trough
Palmer Deep and hug
Barbant
Gerlache-Croker-Boy
South Bransfield Strai
Erebus-Terror
Robertson Trough
Larsen-B embayment
TOTAL

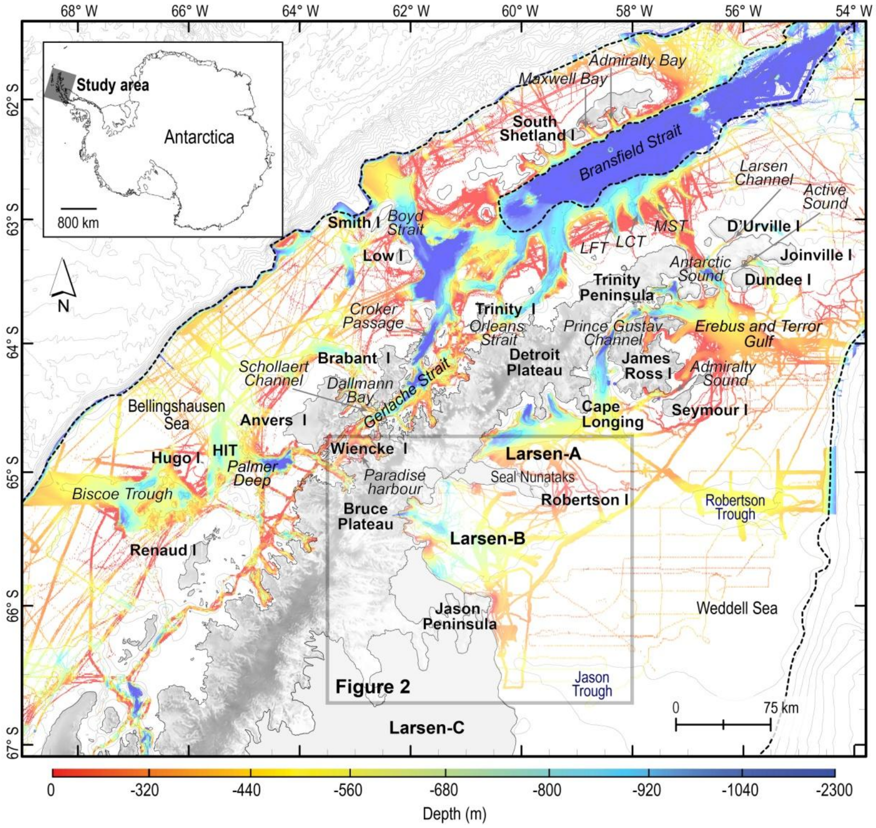


Figure 1. Location map and details of the swath bathymetry database, as compiled up to 2013, around the northern Antarctic Peninsula (AP). Offshore topography is gridded at 30 m. The shelf break is shown as a black dashed line. The grey box indicates the regions detailed in Fig. 2. The background image on land is from RAMP AMM-1 SAR Image 125 m Mosaic of Antarctica; The coastline from the British Antarctic Survey (BAS; http://www.add.scar.org/); The bathymetry contour interval of 250 m is from IBCSO (Arndt et al., 2013). The inset shows the location of the northern AP in Antarctica. Abbreviations: HIT - Hugo Island Trough, LFT - Lafond Trough, LCT - Laclavere Trough, MST - Mott Snowfield Trough

Eliminado:

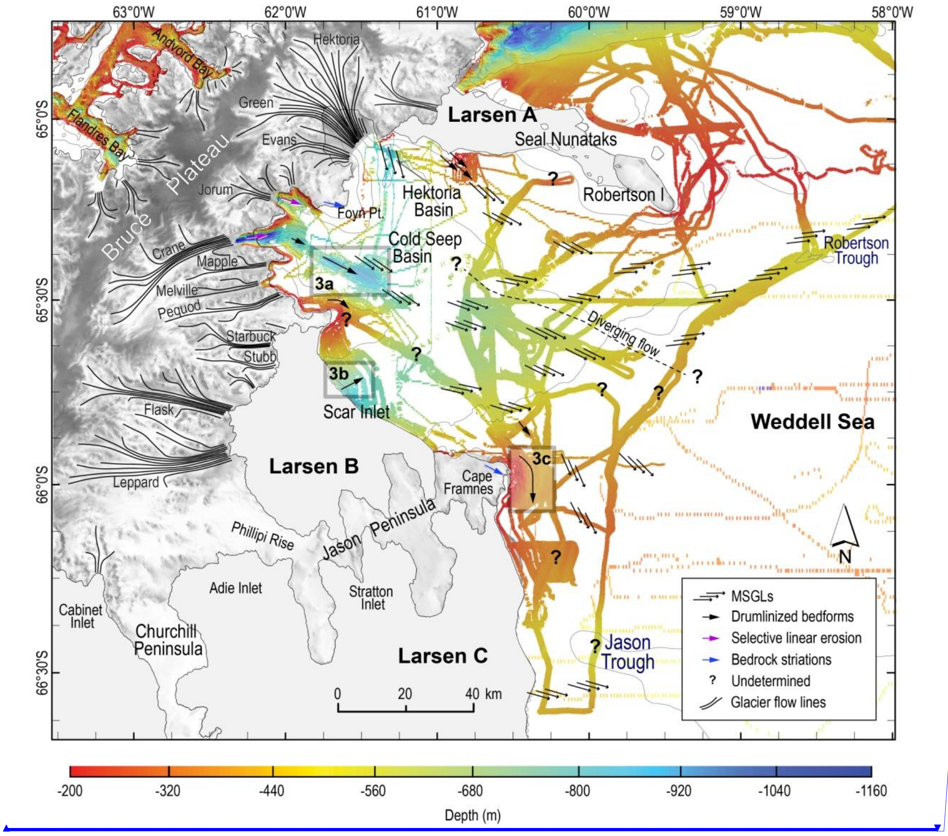
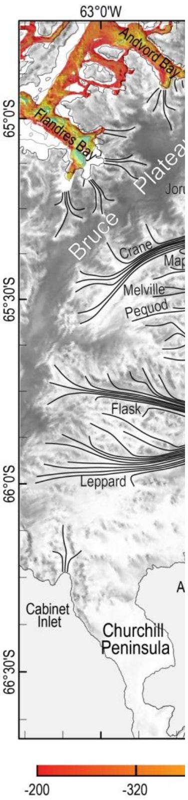


Figure 2. Details of seabed morphology in Larsen-B embayment associated with paleo-flow line trajectories based upon examination of swath bathymetry imagery of the seafloor. Distinct flow trajectories which split the Larsen-B embayment into two outlets by ice flow bifurcation. The bathymetry contour interval of 250 m is from IBCSO (Arndt et al., 2013).The gray boxes show the regions detailed in Fig. 3. For location see Fig. 1.

Con formato: Fuente: 12 pto, Negrita



Eliminado:

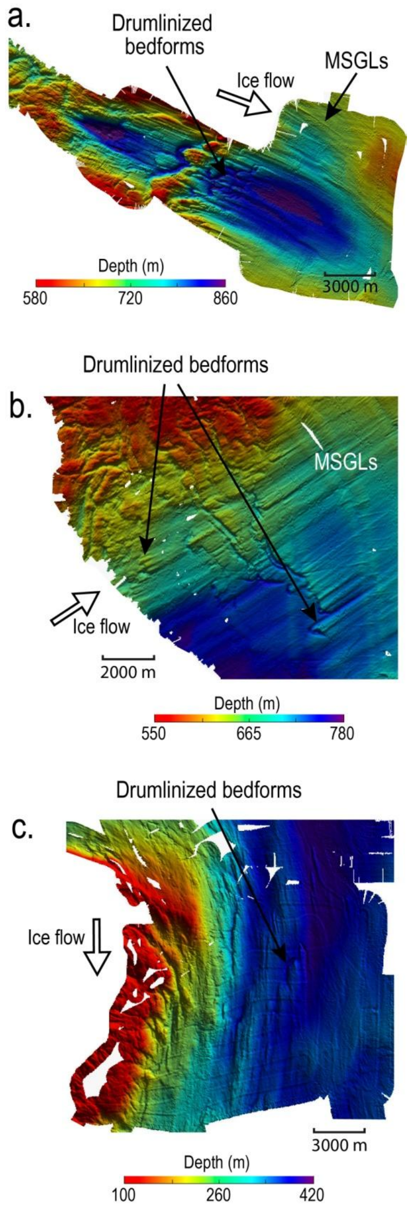


Figure 3. Close-up on the seabed morphology and swath bathymetry perspective views. The location of **(a)-(c)** is presented in Fig. 2. Offshore topography is gridded at 25 m and showed with a vertical exaggeration of X3 **(a)** Bathymetry image showing the Cold Seep Basin region with drumlinized bedforms and Mega Scale Glacial Lineations

(MSGLs) associated to a paleo-ice flow direction, **(b)** Scar Inlet, and **(c)** Cape Framnes, south of the Jason Peninsula. The paleo-ice flow direction is indicated by the white narrow.

Eliminado: SCAR

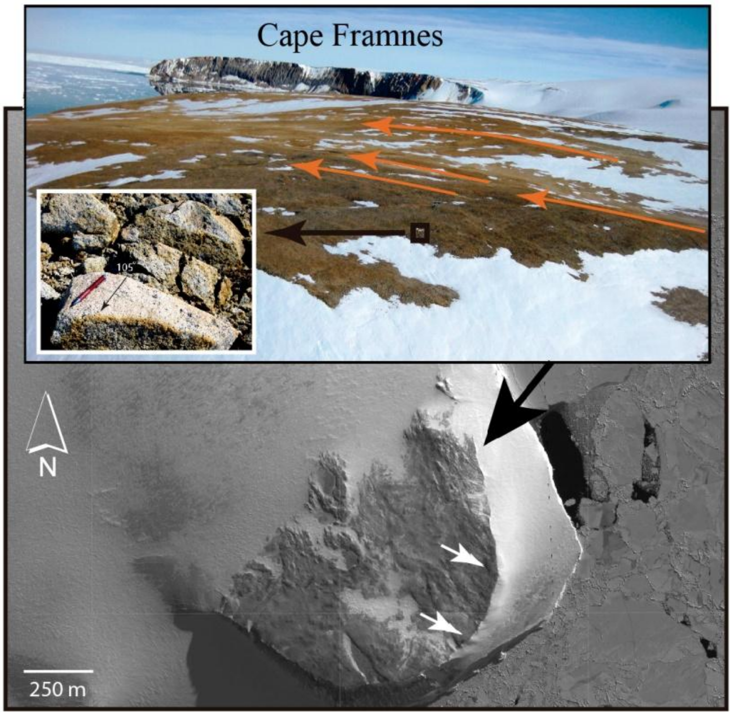


Figure 4. Photography from Cape Framnes showing bedrock striations and flute orientations ESE in agreement with the southward flow orientation observed on the seafloor (this study). The location of the photograph and its aspect is indicated by the black arrow on the Landsat Scenes LIMA. The insets show an isolated bedrock rib, its location on the landscape and the flow direction of striations and bedrock flutes (orange and white arrows) in each case, respectively (Figure modified from a map compiled by Spences Niebuhr, Polar Geospatial Center).

Eliminado: SSW

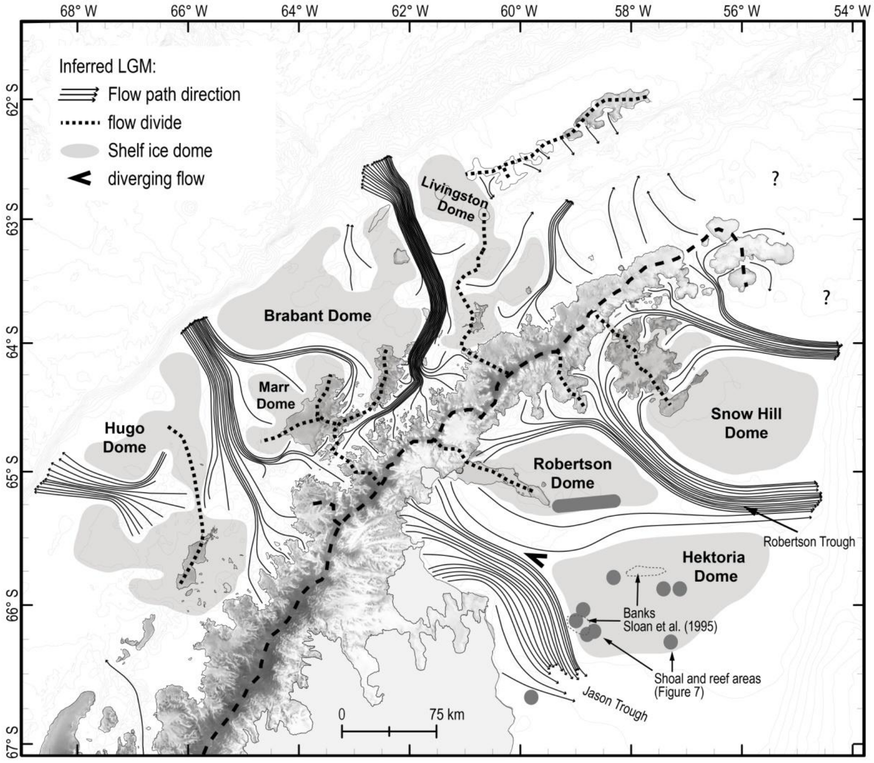


Figure 5. Inferred paleo-ice flow directions and continental shelf ice domes around the northern AP continental shelf at LGM showing ice divides (black short-dashed lines), shelf ice domes (gray areas) and the bifurcating flow in the Larsen-B embayment. The modern divide along the AP (black dash line) is probably not at the same location of the LGM divide, but close. Also identified the topographic banks by Sloan et al. (1995) and the shoal and reef areas of Fig. 7. The bathymetry contour interval of 250 m is from IBCSO (Arndt et al., 2013).

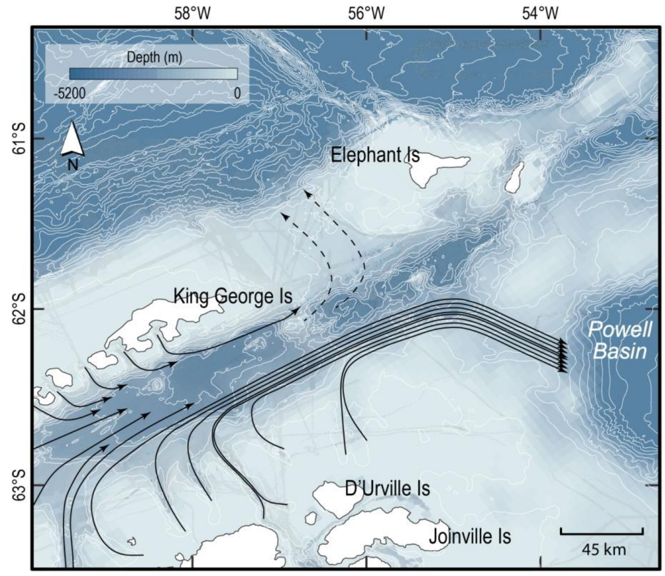


Figure 6. Seabed morphology in Bransfield Strait showing the inferred paleo-flow line trajectories based upon the multibeam imagery (black arrows) and assumptions (black dashed arrows). Background image is from BedMap2 (Fretwell et al., 2013); the island coastline is from the British Antarctic Survey (BAS; http://www.add.scar.org/); the bathymetry contour interval of 250 m is from IBCSO (Arndt et al., 2013).

Eliminado: T

Eliminado: s

Eliminado: T

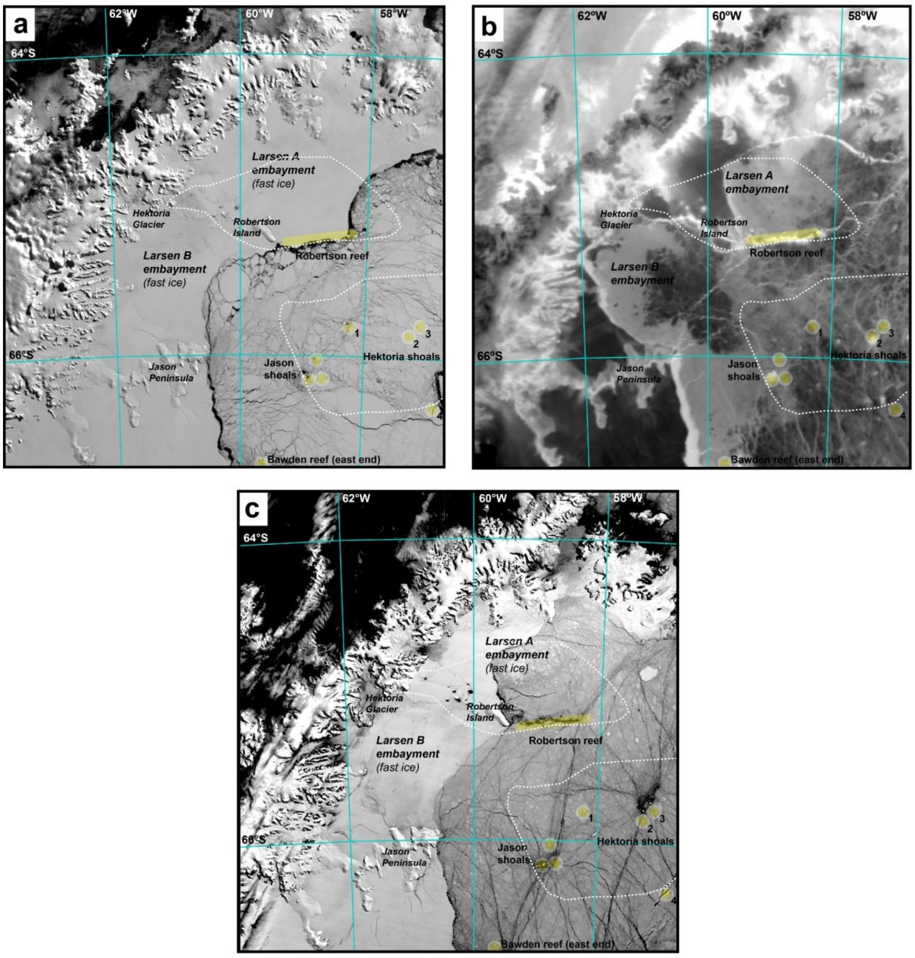


Figure 7. MODerate-resolution Imaging Spectroradiometer (MODIS, 36 band spectrometer) images showing unequivocal evidence of several shoal and reef areas (yellow circle) in the northwestern Weddell Sea, based on sea ice drift and grounding of small icebergs (see also Table 1). The shelf ice domes Hektoria and Robertson are showed in dashed white line. **(a)** 5 October 2007, Band Number (BN) 02 (bandwidth 841-876 nm, spatial resolution of 250 m), **(b)** 20 August 2010, BN 32 (bandwidth 11770-12270 nm, spatial resolution of 1000 m) and **(c)** 26 January 2013, BN 02 (bandwidth 841-876 nm, spatial resolution of 250 m).

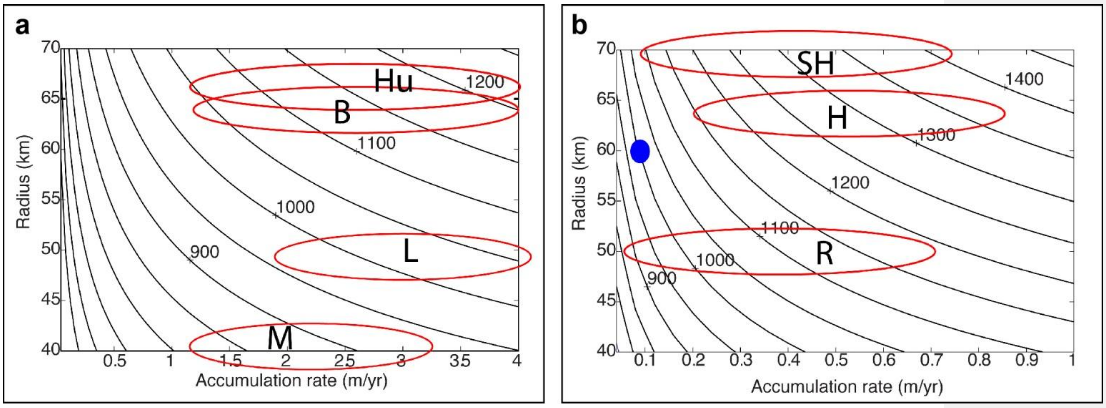


Figure 8. Range of ice thickness expected from **(a)** Marr (M), Livingston (L), Brabant (B), and Hugo (Hu) west AP continental-shelf domes with ice temperature averaging 0ºC, and **(b)** Robertson (R), Hektoria (H), and Snow Hill (SH) east AP continental-shelf domes with ice averaging -20ºC using the Bodvarsson-Vialov model (Bueler et al., 2005). The blue dot is the modern analog Siple Dome in West Antarctica of 1000 m thick that fits well the model. See Fig. 5 for the location of the domes.

Eliminado: where the

Eliminado: is assumed to average

Eliminado: 1