# Response to interactive comments on:
# "Past Ice-Sheet Behaviour: Retreat Scenarios and Changing Controls in the Ross Sea, Antarctica" by A. R. Halberstadt et al.

*We would like to thank all reviewers for their constructive and insightful suggestions which have helped us to improve this manuscript. Reviewer's comments are shown in black font, and the author response is shown in red italics. Author's comments reference manuscript changes by line number, corresponding to the attached Track Changes document* ('Paleodrainage_edits')

## Response to editor comments (Chris Stokes):

I think the authors could have been a bit more explicit in the Introduction as to how this builds on and complements a lot of previous work in this area, i.e. in summarising what is known, but highlighting the outstanding issues/key research questions. I acknowledge that there is some attempt to do this, but this area has attracted a lot of attention and so the rationale could be clearer.

*The paragraph that was already in '1 Introduction' (P2, lines 8-17) has been moved to '2 Study Area' and significantly reinforced by a detailed overview of previous work done in this area (P3, line 13 - P4, line 11).*

## Response to reviewer #1 (N. R. Golledge):

The submitted manuscript presents new and legacy marine geophysical data from the Ross Sea, Antarctica, and uses this to reconstruct the pattern of flow both at the LGM and during its retreat. The paper is very well-written and well illustrated, with clear conclusions that are robust with respect to the data presented. I have no problem in recommending that the paper be accepted with only a few minor edits.

My only gripe really is that there has been quite a lot of Ross Sea work published recently, and not all of it is acknowledged here. This is unfortunate, because the papers I'm thinking of lend considerable support to the interpretations presented by the present authors and so would nicely bolster their arguments. In particular it would be good to acknowledge McKay et al., 2016 (Geology), who came to very similar conclusions based on different data.

*A paragraph has been added to '2 Study Area' (P3, line 13 - P4, line 11), providing an overview of previous work done in this area. The work done by McKay et al (2016) is included in that discussion.*

Clearly I have a bias in this regard, but I think it would be good if the efforts of the modelling community were also acknowledged. It is often stated in introductions to 'empirical' studies that the new data will help 'constrain numerical models', indeed, the current authors do this in the very first sentence of the Abstract. But what is the point of modellers using these geological data, if the models they produce are then disregarded? Maybe sometimes the modelling can help with the geological interpretations, rather than the other way around.

There are of course many modelling papers out there, but I know for a fact that Golledge et al., 2012, 2013, and 2014 all mention that retreat most likely started first in the deeper parts of the outer Ross Sea, and that the pattern of retreat was a product of incoming fluxes from both EAIS and WAIS, and was highly dependent on the location of bedrock highs. To illustrate my point, I'm uploading a figure showing the modelled grounding-line positions from the simulations published in McKay et al 2016, overlain on Figure 7 of the submitted paper. Personally I see a considerable amount of agreement there, which is gratifying because it means the models are getting something right!

*It's very exciting to see the convergence between recently modelled grounding lines (Golledge, McKay, DeConto & Pollard, etc.) and our new reconstructions from purely geological and geophysical data. A paragraph explicitly discussing the contribution of the modelling community and the agreement between recent models and our reconstruction has been added under section '5.4 Comparison with existing deglacial models' (P18, line 32 – P19, line 10).*

Anyway, I'm not insisting that the authors have to cite all these papers, but it would be nice to 'close the loop' in a sense and recognise that sometimes synergies between modellers and empiricists can allow a convergence of views that together really show how flawed the 'swinging gate' model is.

Other than this, I can't really find fault with the paper, so I commend the authors for doing a great job pulling the data together and hope to see this published soon.

## <u>Response to reviewer #2 (J. P. Klages):</u>

Halberstadt et al. combined new multibeam swath-bathymetric data with already existing bathymetric and seismic datasets to present an extensive and comprehensive view of ice sheet extent and retreat in the Ross Sea Embayment (RSE), Antarctica. On the basis of this new compilation the authors were able to reconstruct flow pathways and retreat dynamics during and subsequent to the Last Glacial Maximum across the entire RSE, which led to some new conclusions about the ice sheet history in that region. The paper is well written, easy to grasp, but sometimes slightly lengthy and repetitive. The figures support the text sufficiently, however some figures could be easily combined with others in order to provide more clarity, and to save space. Generally and after consideration of the edits suggested below, I would like to see this manuscript published as it provides a new and valuable combination of datasets that allow a detailed insight into the Ross Sea Embayment glacial history.

As the editor already pointed out, I would like to see a more detailed implementation of this work with previous work from the area, especially in the introduction. In particular, more recent papers such as Bart and Owolana (2012), QSR and McKay et al. (2016), GEOLOGY need to be considered in this regard. Extensive work has been performed in the RSE and the authors should point out more clearly what is known so far, how their new results fit into these previous results, and how their newly presented results complement and maybe change them.

*An extensive discussion of previous studies in the RSE has been added to '2 Study Area' (P3, line 13 - P4, line 11) and includes these references.*

I further encourage the authors to incorporate the results of previous modelling efforts in more detail (e.g. recent studies by Golledge et al.) in order to define synergies. This would reveal the progress already achieved, but would also highlight the need for necessary future work. Building onto that it should be emphasized how empirical future work in the area could focus in order to reduce existing data-model mismatches.

*A paragraph has been added addressing model-data convergence and mismatches under section '5.4. Comparison with existing deglacial models' (P18, line 32 – P19, line 10).*

The authors should further point out that sediments and reliable radiocarbon dates for min. GL retreat are urgently needed in order to verify their hypotheses. Since their interpretations are exclusively based on geophysical data, they should phrase much more carefully in many parts of the manuscript. The lack of age control should be the strongest motivation for future work in the area.

*A caveat reminding the reader that absolute radiocarbon ages are necessary for constructing an absolute retreat history is now mentioned in '2 Study Area' (P4, lines 11-12), '5.4 Comparison with existing deglacial models' (P19, lines 9-10), and reiterated in '6 Conclusions' (P21, lines 21-24).*

*Geomorphic studies and radiocarbon dates complement each other; ages are required to integrate these reconstructed grounding-line patterns with larger-scale modeling efforts and previous work on Ross Sea deglacial chronology, but geomorphic context is also critical for interpreting radiocarbon dates and sediment facies. We feel that interpretations of relative timing can be reliably extracted from this comprehensive geomorphic dataset, giving it stand-alone value, yet reliable radiocarbon ages will increase the meaningfulness of this data in a larger context. This interrelationship is alluded to on P16, lines 13-15 and lines 18-19.*

Lastly, the introduction should emphasize the significance of the RSE for Antarctic ice sheet stability in more detail, maybe also in regard to other large embayments such as the Weddell and Amundsen Sea Embayment. Therefore, the significant contributions by The RAISED Consortium (2014) should be incorporated.

*Antarctic-wide context for this study has been included in '1 Introduction' (P2, lines 2-4).*

And – but this is just my personal opinion – I would suggest to slightly change the title of the manuscript to "Past Ice-Sheet Behaviour in the Ross Sea Embayment, Antarctica: Retreat Scenarios and Changing Controls".

*It is our hope that this paper will appeal to a wide and diverse audience, beyond just the scientists mostly focused on the Ross Sea. We hope that the existing title will attract modelers and workers studying glacial stability, in addition to Ross Sea-specific scientists. Thus, the Ross Sea location descriptor is relegated to the subtitle.*

If the aforementioned issues and the minor edits and suggestions in the supplementary file will be met sufficiently, I fully support the publication of this manuscript in C2 "The Cryosphere".

Technical corrections, suggestions for improving the readability, and some concerns from my side are listed in a supplementary file by page and line number.

*Indicates that the change has been corrected: **

P1, line 8: Replace "on" with "for" (*for* numerical ice-sheet models) *

P1, line 12: Delete "in contact with the bed"

*Replaced sentence with: "Recessional geomorphic features in the WRS indicate virtually continuous back-stepping of the ice-sheet grounding line." (Instead of 'indicate virtually continuous retreat of the ice sheet in contact with the bed). (P1, lines 12-13)*

P1, line 22: Change to "The Ross Sea Embayment (RSE) drains ~25% of the AIS into the Ross Sea and thus is the largest drainage basin in Antarctica, fed by multiple ice streams…". *

P2, line 11: Change to "Multibeam swath bathymetry provides a record of bed conditions beneath the former ice sheet, …". *

P2, line 12: Change to "These landforms record flow behaviour and past thermal regimes of formerly grounded ice."

*Corrected, although this paper does not address the implications of landform formation under different thermal regimes and therefore that term was omitted.*

P2, lines 15-16: Change to "This unique and integrated dataset … much higher resolution, thereby revealing the palaeo-ice sheet bed with a much higher resolution compared to their modern counterparts."

*Sentence now states (P2, lines 22-24): "This unique, integrated dataset provides an opportunity to view the paleo ice-sheet bed at a much higher resolution than is possible beneath the modern ice shelf and ice sheet." The original sentence was upheld in order to use the phrase 'much higher resolution' only once in the sentence.*

P2, lines 17-19: Change to "…this dataset to define glacial geomorphic features that characterize past flow and retreat dynamics, thus reconstruct ice-sheet paleodrainage across the Ross Sea Embayment during and subsequent to the LGM."

*Corrected, with the word 'define' changed to 'identify' since this study maps and interprets pre-defined geomorphic features.*

P2, line 21-22: "Change to "…, which preferentially eroded along pre-existing tectonic lineaments (you may give a reference here)."

*Corrected; the Cooper et al., 1991 reference applies to this statement as well.*

P3, line 5: Write "Austral summer". *

P3, line 16: Replace "cannibalized" with "eroded" or "obliterated". *

P3, line 24: Replace "post-LGM" with "postglacial", since some features may be covered by sediments that started to deposit prior to the LGM. *

P3, lines 24-25: Replace "(post-)LGM" with "glacial" since some of the subglacial features in the RSE do not necessarily record LGM ice cover.

*For clarity, these features are now described as having 'formed during the last glacial cycle' (P5, line 12).*

Results section:

I suggest renaming section to "Results and interpretation".

*Descriptions of glacial geomorphic features have been moved up into the Methodology section, as suggested by the interactive comment from Marco G. Jorge (below).*

Descriptions of features and references to similar, already described features elsewhere are largely missing – at least for the new dataset. Which landforms did you detect, how would you describe them, do they resemble already published features, and how do you interpret them on that basis (Description – Reference – Interpretation – Significance).

- *MSGLs:*
    - *Description (P5, line 17, line 25)*

    - *Ref (Clark, 1993; Tulaczyk et al., 2001; Shaw et al., 2008; Ó Cofaigh et al., 2008; Fowler, 2010; King et al., 2009; Anderson, 1999; Livingstone et al., 2012; Stokes and Clark, 1999; Shipp et al., 1999; Ó Cofaigh et al., 2002; Dowdeswell et al. 2004; Spagnolo et al., 2014, Heroy and Anderson, 2005)*
    - *Interpretation (P5, lines 18-20, lines 23-27)*
    - *Significance (P5, lines 21-22)*
- *Drumlinoid:*
    - *Description (P6, line 1, lines 12-14)*
    - *Ref (Benn and Evans, 2010)*
    - *Interpretation & Significance (P6, lines 3-5)*
        - *Interpretation & Significance is discussed further in the context of the Ross-Sea-specific drumlinoid features (P11, line 18-23)*
- *Subglacial channels:*
    - *Description (P6, line 19-20)*
    - *Ref (Lowe and Anderson, 2003; Anderson and Fretwell, 2008; Smith et al., 2009; Nitsche et al., 2013; Witus et al., 2014; Alonso et al., 1992; Wellner et al., 2006; Greenwood et al., 2012)*
    - *Interpretation & Significance (P6, line 23)*
        - *Interpretation & Significance is discussed further in the context of the Ross-Sea-specific channels (P10, lines 25-28)*
- *GZWs:*
    - *Description (P7, line 5-6, lines 13-17)*
    - *Ref (Alley et al., 1986, 1989; Anderson, 1999; Anandakrishnan et al., 2007; Alley et al., 2007; Dowdeswell et al., 2008, Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015; Shipp et al., 1999; Jakobsson et al., 2012; Simkins et al., in press; Anderson, 1999; Heroy and Anderson, 2005; Mosola and Anderson, 2006)*
    - *Interpretation (P7, lines 6-8,)*
    - *Significance (P7, line 6, lines 11-14)*
- *Marginal moraines:*
    - *Description (P7, lines 25-27)*
    - *Ref (Dowdeswell and Fugelli, 2012; Winkelmann et al., 2010; Klages et al., 2013; Batchelor and Dowdeswell, 2015; Hoppe, 1959; Lindén and Möller, 2005; Todd et al., 2007; Dowdeswell et al., 2008; Shipp et al., 1999; Jakobsson et al., 2011; Simkins et al., in press)*
    - *Interpretation (P7, line 28 – P8, line 2)*
    - *Significance (P7, lines 30-32)*
- *Linear iceberg furrows:*
    - *Description (P8, lines 26-27)*
    - *Ref (Fricker and Padman, 2006; Brunt et al., 2010; MacAyeal et al., 2003; Jakobsson et al., 2011, Larter et al., 2012)*
    - *Interpretation (P8, line 27 – P9, line 9)*
    - *Significance (P9, lines 9-11)*
- *Gullies:*
    - *Description (P9, line 14)*
    - *Ref (Anderson, 1999; Evans et al., 2005; Gales et al., 2012; Shipp et al., 1999)*
    - *Interpretation (P9, lines 15-17, lines 18-19)*
    - *Significance (P9, line 14, line 17-18)*

- *Arcuate iceberg furrows:*
    - *Description (P9, lines 20-21)*
    - *Ref (Anderson, 1999)*
    - *Interpretation (P9, lines 22-24)*
    - *Significance (P9, lines 22-23)*

P3, lines 28-29: Change to "Subglacial landforms form beneath permanently grounded ice that exerts the offset buoyant forces by the ocean."

*Do you mean 'offsets the buoyant forces exerted by the ocean'? The first part of the change was made and the second half of the change was interpreted as described above (P5, lines 15-16).*

P4, line 27: Replace "equivocal" with "controversial" and give reference(s) for this statement.

*This sentence was altered to: '[channels have been observed…] although their origin and link to subglacial meltwater is not evident.' (P6, lines 23-24)*

P5, lines 4-5: Rephrase to "Ice-marginal features form within the grounding zone, the transition from permanently grounded ice to ice that decoupled from its bed to become a floating ice shelf."

*This has been corrected, with the exception of 'grounding zone' which has been replaced with 'grounding line'. We feel that the majority of the GZWs and certainly all of the marginal moraines were formed at a distinct and identifiable ice margin, and we are attempting to step away from the grounding 'zone' terminology unless there is evidence for a diffuse 'zone' rather than a 'line' (P7, lines 1-2).*

P5, line 5: Either mark listed features as examples (e.g. GZWs, marginal moraines, …) or list all of them.

*The ice-marginal features discussed in this paper (GZWs, marginal moraines, and linear iceberg furrows) are all listed in this sentence (P7, line 3).*

P5, lines 11-12: Not exclusively – large GZWs may also indicate higher sediment flux.

*This sentence now reads: "Large GZWs can imply longer episodes of stability…" rather than "Large GZWs mark longer episodes of stability..." (P7, line 13)*

P5, lines 13-14: Also reference Dowdeswell and Fugelli (2012), GSA Bulletin in this context. *

P5, line 14: Replace "stratification is" with "reflectors are". *

P5, lines 20-21: They were also described with clearly asymmetric shapes (cf. Winkelmann et al., 2010, QSR; Klages et al., 2013, QSR).

*References added, and sentence altered to reflect the existence of both symmetric and asymmetric marginal moraines (P7, lines 25-28).*

P6, line 2: Reference Larter et al. (2012), QSR and Klages et al. (2015), Geomorphology in this context. They described and interpreted those features.

*Klages et al. (2015) was added as a reference. Larter et al. (2012) proposes a conceptual model for the ploughing of linear features, but did not observe corrugation ridges in their study area, the Filchner Trough. Thus, they are cited in P9, line 1 accordingly.*

P6, line 5: Rephrase to "Their association with vertical tidal movement…". *

P6, line 17: Rephrase and avoid "propelled". *

P6, line 21: Be more specific here and write: "Shelf-edge gullies on high-latitude continental margins…" since gullies are found on most continental margins. *

P7, line 8: Write "… any potentially pre-existing subglacial landforms."

*Corrected, with the exception of the word 'subglacial' since iceberg furrows could also overprint ice-marginal features*

P8, line 6: Replace "monopolize" with "dominate". *

P8, lines 9-10: Not only – they mainly imply bulldozing of proglacial debris. *

*Many processes have been invoked to form shelf-edge gullies, and it seems that the processes that cause these features is still uncertain and likely highly variable. This sentence (now P9, lines 15-17) has been altered to reflect the multitude of processes that could cause gully formation.*

> *From Gales et al., 2012: "Antarctic gully formation has been attributed to erosion by:*
>
> *(1) mass flows, such as sediment slides, slumps, debris flows, and turbidity currents, with triggering mechanisms including resuspension by shelf and contour currents, gas hydrate dissociation, tidal pumping beneath large icebergs and near ice shelf grounding lines, iceberg scouring, tectonic disturbances, and rapid accumulations of glaciogenic debris at the shelf edge during glacial maxima [Larter and Cunningham, 1993; Vanneste and Larter, 1995; Shipp et al., 1999; Michels et al., 2002; Dowdeswell et al., 2006, 2008];*
>
> *(2) subglacial meltwater discharge from ice sheet grounding lines during glacial maxima or deglacia- tions, whether by constant release [Wellner et al., 2001; Dowdeswell et al., 2006, 2008, Noormets et al., 2009] or more episodic and large-scale release [Wellner et al., 2006] possibly by meltwater evacuation from subglacial lakes [Goodwin, 1988; Bell, 2008]; and*
>
> *(3) dense water overflow [Kuvaas and Kristoffersen, 1991; Dowdeswell et al., 2006, 2008; Noormets et al., 2009]."*

P8, lines 15-16: The GZWs are large but not visible in the bathymetric data? Do you mean wide but relatively thin so that they are hardly visible in the bathymetry? *Yes.* Specify here. The same applies for lines 25-27. *

P8, lines 29-30: Rather write something like: "Phases of different flow directions in the ERS can clearly be identified by the presence of multiple generations of overprinting linear features." *

P9, line 2: Replace "ensure" with "proof".

*The word 'confirm' was used to replace 'ensure'.*

P9, line 3: Rephrase to "… each flowset only slightly deviate by less than 10°, thus are assumed to represent…".

*Sentence now reads: "The orientation of linear features within a single flowset deviate by generally less than 10°, and thus each flowset is assumed to represent a single flow configuration whose component lineations were formed contemporaneously (cf. Clark, 1999)." (P12, lines 18-20)*

P9, line 4: Replace "isochronously" with "simultaneously" or "contemporaneously". *

P9, line 5: Delete "after" and replace with "cf.". *

P9, line 5-7: Modify sentence to "Assuming that all flowsets were shaped during and subsequent to the LGM, a relative chronology of their formation can be assessed based on their landward succession and cross-cutting relationships with other flowsets". *

P9, lines 7-8: Modify sentence to "In order to characterize large-scale regional flow patterns, discrete flowsets within the 10° deviation are assumed to reflect a similar ice-flow configuration."

*All of the linear features in each flowset generally fall within the ~10° deviation. This sentence is meant to convey that multiple flowsets were grouped together for ease of* *analysis. <u>Groups</u> of flowsets could (and do) span a range greater than the 10° deviation. Thus, this sentence (P12, lines 23-25) was altered for clarity to read: "In order to characterize large-scale regional flow patterns, flowsets with discrete yet similar orientations were assumed to reflect a similar ice-flow configuration and grouped together for analysis."*

P9, lines 9-10: Modify sentence to "Our new compilation of RSE bathymetric data reveals that major flow patterns in the ERS generally deviate from the trough-parallel drainage that was described previously (…)."

*Corrected with modifications. The word 'generally' was replaced with 'often', since the dominant flow pattern in the ERS remains trough-parallel. Sentence now reads: 'Our new compilation of multibeam data reveals that major flow patterns in the ERS often deviate…' (P12, line 26)*

P9, lines 10-12: Modify to "Flow in Glomar Challenger Basin may have been only partially parallel to the trough axis. We propose that a distinct cluster of linear features indicates flow also across an inter-ice stream ridge towards Whales Deep."

*Flow in GCB was at one time trough-parallel, and at another time across-trough. However, describing flow as 'partially parallel to the trough axis' implies that these two configurations coexisted. They perhaps did, to some extent, but that's not what the sentence was meant to convey. This sentence was rewritten for clarity (P12, lines 28-30): "Some flowsets in Glomar Challenger Basin exhibit evidence of trough-parallel flow (flowsets a-c, Fig. 4), but other flowsets indicate flow across an inter-ice-stream ridge towards Whales Deep (flowsets d-h, Fig. 4)."*

You sometimes write "Whales Deep" or "Whales Deep trough" – be consistent. *

P9, line 12: Replace "curved" with curvilinear". *

P9, lines 13-15: Modify sentence to "For those, rose diagrams were used to exclude the possibility the curvature indicates two discrete flow events with very similar orientations." *

P9, line 16: Replace "mirror" with "resemble". *

P9, line 17: Replace "display generally" with "record". *

P9, line 18: Write "…to the trough axis, pointing towards…". *

P9, line 20: Replace "as" with "to indicate". *

P9, lines 24-25: Rephrase to "We interpret the LGM grounding line in outer Drygalski Trough to have been situated just north of Coulman Island, marked by the outermost GZW (cf. Shipp et al., 1999)." *

P9, line 26: Replace "field" with "cluster" and give reference to figure here. *

P9, lines 26-27: Specify here. Recorded MSGLs rather give local evidence and provenance gives regional information.

*The allusion to till provenance was unnecessary and was removed.*

P9, line 29: Rephrase to "In JOIDES Trough, maximum ice extent is suggested to be recorded by the large-scale GZW (J1) on the mid-outer shelf (Fig. 3)". *

P9, lines 29-30: Rephrase to "We base this hypothesis primarily on the presence of an up to 8m-thick glaciomarine drape in the outer trough (Fig. 3a).

Do you have evidence for this statement (cores)? If not, phrase more carefully here. *

P9, line 30 – P10, line 3: Rephrase to "The observation of LGM-age carbonates on surrounding banks (…) and the presence of LGM-age tephra layers in glaciomarine sediments on the outer shelf (…) further support this assumption." *

P10, line 3: Are you really sure? Maybe these linear features are MSGLs as well but just represent an older ice advance prior to MIS2.

*These features are linear but do not have the extreme parallel conformity displayed by the ERS linear iceberg furrows. Thus, they are now described as 'straight furrows.' This explanation has been added to the text (P13, lines 25-26).*

P10, lines 4--5: Rephrase to "The LGM limit in Pennell Trough coincides with the large--scale GZW (…), located ~120 lm landward of the shelf break (Howat and Domack, 2003). *

P10, lines 7--9: Rephrase to "Large--scale GZWs at the shelf break, linear features that extend across the outer shelf, and extensive shelf--edge gullies (you could cite Gales et al., 2013, Geomorphology here) indicate that grounded ice likely reached the shelf break (…)." *

P10, lines 9--10: Rephrase to "Thin glaciomarine sediments occur on the outer shelf and may hint at a relatively short period of ice--free conditions." Give reference for this statement and consider the possibility that post--LGM strata may be thin but was strongly reworked by scouring or winnowing, especially on outer shelves. This weakens your argument. Same with thick glaciomarine drapes – in some locations (e.g. Palmer Deep) they are extremely thick and people assumed that this drapes started to deposit well before the LGM but then they realized it was just of Holocene age. If you don't have radiocarbon ages, phrase more carefully.

*Good point. Rephrased (P14, lines 4-5).*

P10, lines 11--12: You could easily combine Figs. 3 and 5. Try to implement Fig. 3 with Fig. 5 and rephrase sentence to "Figure 3 shows … directions based on the appearance of linear features and GZWs."

*Figs. 3 and 5 were combined and the sentence was changed accordingly.*

P10, lines 15--16: Rephrase to "Bathymetric records from the WRS only revealed sparse and isolated patches of linear features that hamper meaningful interpretations of former subglacial flow behaviour and direction."

*This rephrased sentence implies that patchy data coverage caused WRS linear features to appear sparse and isolated. However, bathymetric data coverage over the WRS is actually quite extensive; the linear features are described here as sparse and isolated because they were only observed in small patches either isolated in a few areas and mostly on the backs of GZWs, despite comprehensive coverage. The original sentence was slightly altered for clarity: "…the WRS contains sparse and isolated patches of linear features, providing only glimpses of subglacial flow behaviour and direction despite extensive multibeam data coverage. Therefore, most paleo-drainage interpretations in the WRS are based on ice-marginal features." (P14, lines 11-13)*

P10, line 22: Replace "ice--marginal features" with "moraines of GZWs". *

P10, line 23: Use "seafloor" rather than "seascape" and delete "grounded". *

P10, line 28: Give reference for this statement.

*The observation of the subglacial meltwater channels, and the interpretation that these channels were active during deglaciation, are not published; they stem from data collected during the recent NBP1502A cruise and are the subject of ongoing research within this group. Thus, this sentence (P14, lines 26-27) has now been changed to "We observe [meltwater channels…]".*

P11, lines 1--2: Same here and cite for example Smith et al., 2009, Quaternary Research in this context.

*See above.*

P11, line 3: Replace "scattered" with "a few".

*'Scattered' was replaced with 'isolated clusters of'*

P11, line 5: Replace “to the east and the west” with “east- and westwards”. *

P11, line 6: Say “during general deglaciation”.

*This sentence was altered for clarification, to emphasize the implications of observing ice-marginal features in the deepest part of Central Basin – that ice remained grounded in Central Basin during deglaciation of that area, instead of lifting off the bed. Thus, the sentence now reads: “…ice-marginal features in the Central Basin indicate that ice remained in frequent contact with the bed during deglaciation of this area.” (P15, lines 4-5)*

P11, line 6: Rather say “retreat behaviour” instead of “retreat pattern” and “dominated” rather than “dictated”.

*Corrected, although ‘dictated’ was replaced instead with ‘controlled’ not ‘dominated’*

P11, line 8: Not the GZWs and moraines back-stepped onto banks but the GL. *

P11, lines 9-10: I don’t understand that. One main process of marginal moraine formation is the rain-out of debris-rich material proximal to the GL. So there is no need for flowing ice really in order to deposit a moraine. It can be a slight pushing effect but that could also origin from very slow concentric flow away from the bank. If you don’t have lineations then you cannot say that there was a flow across this bank. Also consider reading Klages et al. (2013), QSR in that context.

*Good point – that is true for a moraine. However, we still observe highly asymmetric features that we interpret as GZWs on banks, calling for some sediment mobilization. The sentence was altered to reflect this (P15, lines 9-11).*

P11, line 12: Rather write “These findings are supported by modelling approaches that…”. *

P11, line 15: Rather write “Reconstructed steps in GL retreat…” *

P11, line 16: Replace “time-steps” with “phases” or “episodes” and delete “representing an interpretation of relative timing”. It’s redundant. *

P11, line 20: Delete “back-stepping” and write “indicating a slowly retreating GL”. Delete “in their path”.

*I don’t think that the geomorphic observations in this area directly support the interpretation of slow GL retreat. In this area (southern Drygalski), retreat was likely relatively quick, based on the small sizes and repeating nature of back-stepping moraines and GZWs.*

P11, lines 21-22: Clarify what you mean here. Why does drainage of an ice sheet nourishes an ice sheet?

*This sentence now reads: “Drainage from the EAIS flowed into the Ross Sea Embayment until the last stage of deglaciation” – although it was moved to later in the text (P17, lines 25-28).*

P11, line 24: Rather write “unaffected by topography”. *

P11, lines 26-28: Write “Linear features on the ERS seafloor are overprinted by large-scale GZWs, indicating episodes of GL retreat that was interrupted by phases of temporary stabilization”.

*This alteration was incorporated, and a secondary component was added to highlight the preservation of linear features and lack of small-scale recessional features. The sentence now reads: “Linear features on the ERS seafloor are overprinted only by large-scale GZWs (Fig. 3). These large-scale GZWs likely record periods of grounding-line stabilization, punctuated by episodes of ice sheet decoupling and grounding line retreat that back-stepped tens to hundreds of kilometres in distance and preserved linear features.” (P15, lines 27-30)*

P11, line 29: Delete “behaviour”. *

P12, line 4: Replace “entails” with “requires”. *

P12, lines 6-8: Write "Trough-parallel flow was then established and ice began to retreat landward from the outer continental shelf in all ERS basins, interrupted by phases of stationary deposition of GZWs…." *

P12, lines 8-10: Write "Different generations of MSGLs are preserved as the GL retreats, but we would not … of streaming would have occurred, leaving one-directional MSGLs." Delete sentence in lines 9-10.

*Corrected, although 'leaving one-directional MSGLs' was instead replaced with 'remoulding the bedform field.' Not sure what a one-directional MSGL is.*

P12, line 14: Include "the presence of" between "on" and "large". *

P12, line 15: Replace "curve across" with "flow onto neighbouring". *

P12, lines 18-24: Write "Grounded ice retreated into Whales Deep to a mid-shelf location where it halted long enough…, before it retreated towards the inner shelf to halt again indicated by GZW e3". *

How can an ice sheet not be in contact with the bed during retreat? That is contradicting. It would be an ice shelf then. And also an ice plain just prior to floatation may still create MSGLs. But an absence of subglacial landforms such as MSGLs does definitely not imply the absence of grounded ice. Rephrase completely and give alternatives with sufficient references.

*This sentence was removed.*

P12, lines 25-27: Flow and thus subglacial sediment deposition on inter-ice stream ridges has recently been described as being very low (Klages et al., 2013, QSR). Cold-based ice may characterize them that is strongly coupled to its bed. At least include this different interpretation in your discussion.

*This was added as a new sentence (P16, lines 21-22): 'During trough-parallel flow, ice grounded on inter-ice-stream ridges was likely sluggish and cold-based, and strongly coupled to the bed (Klages et al., 2013)' (i.e. before flow was routed over the inter-ice-stream ridge)*

P13, line 1: Delete "each", replace "sequence" with "succession" and write "…of events that could be tested if a greater coverage of …Basin would be available. It could illuminate cross-cutting … flowsets that are crucial … ." *

P13, lines 3-6: Write "Additional multibeam bathymetric surveys of inter-ice stream ridges would also provide a better understanding of the general flow pattern (cf. Klages et al., 2013, QSR). Furthermore, reliable radiocarbon ages constraining min. GL retreat on the Whales Deep inner shelf would provide the only possibility in order to give evidence for early retreat and the formation of a 'long-lived' grounding-line embayment."

*Corrected, with slight changes (P17, lines 13-14): "marine radiocarbon dates constraining grounding-line retreat on the Whales Deep inner shelf might provide evidence for early retreat…"*

P13, line 10: Replace "highly" with "often" and give a few of those references. *

P13, line 16: Replace "north-to-south" with "southward". *

P13, lines 22-23: Write "This study but also previous studies suggest an initial significant GL retreat within the northern Drygalski Trough are consistent … recession of the GL …"

*Sentence now reads: "This study and previous marine studies (Licht et al., 1996; Cunningham et al., 1999; Anderson et al., 2014) suggest early grounding-line retreat within the northern Drygalski Trough, consistent with the swinging gate model." (P18, lines 15-17)*

P13, line 24: Write "…GL retreat on the remaining Ross Sea shelf (Fig. 7)…." *

P13, line 25: Replace "calls for the persistence" with "suggests a persisting". It's actually not really clear what you try to say here. Try to rephrase. *

*Sentence now reads: "In particular, our marine-based reconstruction suggests persistent EAIS drainage into the WRS throughout deglaciation…"(P18, lines 19-20).*

P13, line 32: Are the ages from those publications rather ambiguous? If yes, rather delete sentence. If you keep it, you have to say why it is 'complicated' and give references for that statement.

*Sentence removed.*

P14, line 1: Include "geophysical" after "marine".

*Sentence altered (P18, lines 28-29), omitting 'geophysical marine [data]': "Neither the swinging gate nor the saloon door model incorporate observations from the continental shelf…"*

P14, line 16: Replace "seascape" with "seafloor". *

P14, line 20: You could cite Larter et al. (2009) and Graham et al. (2009) here. *

P14, lines 28-29: Which features transition into MSGLs?

*Drumlinoids transition into MSGLs. Clarified.*

P14, line 31: Delete "ages and". *

P15, line 1: Replace "lithification" with "consolidation". *

P15, line 6: Rephrase and give reference.

*Rephrased. Mosola and Anderson 2006 initially suggested this concept and are already cited here (P20, lines 12-15).*

P15, line 8: Delete "Complex". *

P15, lines 12-15: This passage is unclear. Rephrase.

*Sentence now reads: "Grounded ice in Little America Basin flowed over its eastern bank and converged with an outlet glacier draining Marie Byrd Land (flowset n, Fig. 4). This flow pattern implies that at one point, Little America Basin was not able to drain all of the ice flowing into it and therefore some of that ice was forced eastward out of the trough." (P20, lines 20-23)*

P15, lines 20-23: You need to mention also the external forcings for GL retreat here such as atmospheric, ocean, and ice characteristics. I have the feeling that this should also go into the introduction.

*The entire paragraph (P20, line 31 – P21, line 7) was modified to read: "Physiography exerts a first-order control on regional ice stream flow and retreat dynamics, and seafloor geology plays an important subsidiary role in controlling ice behaviour. These controls influence regional retreat patterns; more localised ice behaviour is still under investigation. Numerous other processes affect glacial dynamics, such as ice-shelf buttressing, sediment shear strength and ice-bed coupling, and subglacial meltwater (e.g. Boulton et al., 2001; Dupont and Alley, 2005; Stearns et al., 2008). External forcings such as tidal effects, circumpolar deep water incursion and under-melting of ice shelves, and atmospheric effects are also influential (e.g. Rignot, 1998; Zwally et al., 2002; Arneborg et al., 2012; Walker et al., 2013). Ross Sea retreat was asynchronous between troughs, suggesting differential responses to these processes. Ongoing work on characterizing Ross Sea glacial geomorphology highlights the effect of these forcings on local grounding-line stability."*

P15, line 26: Delete "recessional" and write "…geomorphic features that indicate episodic, …". However, rapid and episodic are contradictory. Either specify and write that rapid retreat was interrupted by episodes of stillstand or just write "episodic retreat" (cf. Dowdeswell et al., 2008, GEOLOGY).

*'Episodic' was removed.*

P15, line 28: Replace "over" with "across". *

P15, line 29: Replace "indicators" with "features". *

P15, line 30: Replace "was" with "has likely been".

*... 'was' replaced with 'is believed to have been'*

P16, line 1: Add "shelf" behind "Ross Sea". *

P16, line 1: Use inverted commata for the two model names. *

P16, line 2: Replace "in the Ross Sea" with "here".

*... 'in the Ross Sea' was removed*

P16, line 5: Write "Ross Sea shelf". *

P16, line 7: Replace "can be" with "are likely".

*Replaced 'can be' with 'are'*

P16, line 8: Replace "wasn't" with "was not". *

Add to the conclusions that there is a STRONG need for sediments and radiocarbon ages in order to verify or reject a lot of your hypotheses.

*This sentence was added to '6 Conclusions' (P21, lines 21-24): 'Additional analyses of Ross Sea continental shelf sedimentology and additional reliable radiocarbon ages marking grounding-line retreat are necessary to test and refine the deglacial patterns proposed here. A radiocarbon chronology will help integrate our grounding-line reconstruction with previous work done on Ross Sea deglacial history.'*

Tables and figures

Table 1: Since this table is very long, it could also go into the supplementary material. If you decide leaving it, please also add a column "Reference/data access", if available.

*The table will go into Supplementary Material.*

Figure 1: Indicate location of Fig. 2a. * Delete the left arrow pointing away from "WAIS". * Use the northward orientation of this figure for all the following figures. * Include scalebar. * In the figure caption add "et al." to the Fretwell reference. *

Figure 2: Use orientation from Fig. 1 for clarity. * Use white font color also for "i" in Fig. 2a. * Also give scalebar. * In Fig. 2b give vertical and horizontal scalebars in metres. * Give colorscales and north arrows for all the panels. * Alternatively use orientation of Fig. 1 also here and say in caption that they are all S-N oriented.

Give a reference for your statement that the basin is composed of soft deformation till.

*The figure caption now reads: "MSGLs (3-5 m in amplitude) on the inner shelf of Glomar Challenger Basin occur above a glacial erosional surface, imaged by the high-frequency seismic" since there are no cores correlated to this CHIRP image to support that interpretation.*

Figure 3: Give lateral scalebars and increase font size. Give scalebar for main panel. *

Figure 4: Indicate location of this figure in Figure 3 and give scalebar. *

*Location is indicated in Fig. 1 instead.*

Figure 5: Dismiss this figure and combine with Figure 3. Also change references in text accordingly. *

Figure 6: Give scalebar and again, be consistent with figure orientations. * Take Figure 1 as basis for all other figures. * Is there radiocarbon evidence for the scenario of ice persisting on banks?

*Ice persisting on banks is interpreted from geomorphological observations. To my knowledge, the only current radiocarbon evidence for ice persisting on banks is the Taviani et al., 1993 carbonates on the JOIDES and Mawson outer shelf bank-tops.*

Figure 8: Give scalebars. Are the colorscales in ‘b’ and ‘c’ the same as in ‘a’?

*Yes. This was added to the figure caption.*

Indicate location of profile more obvious. *

Figure 9: Use smaller and white arrows. The different colors for the locations of lineations and GLs are enough. *

Figure 10: Very nice figure.

Figure 11: Give scalebar. *

## **Response to interactive comment (Marco G. Jorge):**

This is a very interesting study. The comments below might help improving the manuscript.

P4, L12-16: The definition of drumlin is incorrect. It is incorrect to define drumlins as downstream-tapering forms – morphometric data indicates that the majority of drumlins is symmetric and that drumlins wider/steeper on their lee side are as common as drumlins with wider/steep stoss than lee (see Spagnolo et al., 2009, 2011, 2012). Drumlins are defined in the paper as being over 10m high; morphometric data shows that drumlins less than 10m high are very common.

*This work uses the identification of drumlinoid features to constrain ice flow direction. In order to achieve that goal, we must ensure that the observed features form subglacially, and that they indicate ice flow direction. Thus, the discussion of drumlinoids in this paper has been reduced to only what is necessary for this context-specific interpretation: first, a paragraph describing this large and variable class of features in Methodology (‘3.1 Subglacial Features’), and second, a paragraph describing the features observed in the eastern Ross Sea and why they can be interpreted to indicate paleo ice-flow in the Discussion section (‘4.2 Eastern Ross Sea’).*

*Under Methodology: “Smaller scale streamlined landforms, with lengths hundreds of metres to a few kilometres, comprise a number of landform classes such as drumlins, crag and tails, and megaflutes. We group these landforms here as a single class of drumlinoids. While their internal composition can be difficult to determine in the marine environment, and their formation mechanisms remain uncertain, this family of landforms is widely and most simply taken to record the former ice flow direction (Benn and Evans, 2010). In Antarctica, drumlinoids are most often observed at the transition between crystalline bedrock and sedimentary deposits (Wellner et al., 2001, 2006; Graham et al., 2009).” (P6, lines 1-14).*

*Under Discussion: “The only drumlinoids observed in the Ross Sea occur on the inner shelf of Glomar Challenger Basin (Fig. 2c), covering ~300 km$^2$, and are associated with a near-surface occurrence of crystalline bedrock (Anderson, 1999; Shipp et al., 1999). Because these features are moulded predominantly from bedrock, they likely formed over multiple glacial cycles. They do, however, exhibit highly uniform orientations (Fig. 2c) that are consistent with MSGL orientations seaward of the drumlinoids, indicating that the most recent phase of ice flow was likely responsible for the final drumlinoid shape.” (P11, lines 18-23).*

C1 P4, L12-16: Defining drumlins as “moulded sedimentary landforms” is reductionist and not self-explanatory. Drumlin genesis is not fully understood and there is a range of putative mechanisms, some erosional, some depositional, etc. For example, see Eyles et al., 2016 (Sed.

Geology).

*See above.*

P4, L12-16: Following the previous comments, the rationale for grouping drumlins with crag-and-tails (asymmetric, downstream-tapering forms) is invalid. Only some drumlins are crag-and-tails or crag-and-tail-like. A genetic definition for crag-and-tails would be useful.

*See above.*

P4, L14-16: Sentence seems to imply that crag-and-tails are not "moulded sedimentary landforms" (that with internal structure data it would be possible to differentiate between drumlins and crag-and-tails). Reword considering previous comments.

*See above.*

Section 3 (Methodology): Main focus should be on the paleoglaciological reconstruction framework. Geomorphological features, their classification and glaciological significance would be presented under Methodology (instead of results), such as in a table. The same applies to other concepts that appear for the first time in the Results (e.g., flowset).

*Geomorphic features have been moved from Results into the Methodology section. The subheading Flowsets, however, remain in Results because we consider that analysis to our interpretation of data, rather than a description of data.*

Section 4 (Results): Consider re-organizing; for example, sub-sections 4.4 and 4.5 focus on geographical areas, whereas 4.1 to 4.3 present landforms. Using more levels (e.g., grouping landforms under a specific header) could help. Some of the information presented under Results would better come under Introduction and Methodology. See previous comment.

*Changes suggested in the previous comment have been enacted, so the Results section contains only two subheadings: '4.1 Western Ross Sea', and '4.2 Eastern Ross Sea'. 'Flowsets' has been moved to under Eastern Ross Sea with a subheading 4.2.1.*

**Additional Notes:**

- *Figure numbers have been changed due to the merging of Fig. 5 and Fig. 3*
- *Additional changes to manuscript are shown in the attached document, recording edits using Track Changes ('Paleodrainage_edits.pdf').*

# Past Ice-Sheet Behaviour:
# Retreat Scenarios and Changing Controls in the Ross Sea, Antarctica

A. R. Halberstadt[1], L. M. Simkins[1], S. L. Greenwood[2], J. B. Anderson[1]

[1]Department of Earth Science, Rice University, Houston, Texas 77005, USA
[2]Department of Geological Sciences, Stockholm University, 10691 Stockholm, Sweden

*Correspondence to*: A. R. Halberstadt (ar.halberstadt@rice.edu)

**Abstract.** Studying the history of ice-sheet behaviour in the Ross Sea, Antarctica's largest drainage basin, ~~the Ross S~~can improve our understanding of patterns~~, timing,~~ and controls on marine-based ice-sheet dynamics~~,~~ and provide constraints ~~on~~ for numerical ice-sheet models. Newly collected high-resolution multibeam ~~swath~~ bathymetry data, combined with two decades of legacy multibeam and seismic data, are used to map glacial landforms and reconstruct paleo ice-sheet drainage.

During the Last Glacial Maximum, grounded ice reached the continental shelf edge in the eastern but not western Ross Sea. Recessional geomorphic features in the western Ross Sea indicate virtually continuous back-stepping of the ice-sheet grounding line~~retreat of the ice sheet in contact with the bed~~. In the eastern Ross Sea, well-preserved linear features and a lack of small-scale recessional landforms signify rapid lift-off of grounded ice from the bed. Physiography exerted a first-order control on regional ice behaviour, while seafloor geology played an important subsidiary role.

Previously published ~~grounding-line retreat~~deglacial scenarios for Ross Sea are based on low-spatial-resolution marine data or terrestrial observations; however, this study uses high-resolution ~~Ross Sea~~basin-wide geomorphology to constrain ~~marine deglaciation~~grounding-line retreat on the continental shelf.~~-~~ Our analysis of retreat patterns suggests that: (1) retreat from the western Ross Sea was complex due to strong physiographic controls on ice-sheet drainage~~ a large embayment formed in the eastern Ross Sea~~; (2) retreat was ~~complex and~~ asynchronous across Ross Sea and between troughs; ~~and~~ (3) the eastern Ross Sea largely deglaciated prior to the western Ross Sea following the formation of a large grounding-line embayment over Whales Deep; and (4) our glacial geomorphic reconstruction converges with recent numerical models that call for significant and complex East Antarctic Ice Sheet and West Antarctic Ice Sheet contributions to the ice flow in the Ross Sea.

## 1 Introduction

~~With a catchment area encompassing ~25% of the entire Antarctic Ice Sheet, the~~ The Ross Embayment drains ~25% of the Antarctic Ice Sheet into the Ross Sea and is thus ~~is~~ the largest ice drainage basin in Antarctica, fed by ~~and receives drainage from~~ multiple ice streams sourced from the East Antarctic (EAIS) and West Antarctic (WAIS) ice sheets (Fig. 1). The nature of ice-sheet paleodrainage and retreat in the Ross Sea has significant implications for understanding the dynamics of the WAIS and EAIS, and their respective sensitivities to ~~climate change~~factors that govern ice behaviour. These insights may also aid understanding of ice dynamics in the other large embayments around Antarctica, such as the Weddell Sea and Amundsen Sea Embayments, where large uncertainty in paleo-ice extent and grounding-line retreat remains (Bentley et al., 2014). Recent ~~paleo-~~ice-sheet ~~flow~~ models indicate complex ice behaviour in the Ross Sea, particularly during deglaciations (e.g. Pollard and DeConto, 2009; Golledge et al., 2014; DeConto and Pollard, 2016). Geologic reconstructions of ice dynamics from the Ross Sea continental shelf can provide critical tests for these models.

~~Results from marine geological research, including integrated seismic stratigraphy, geomorphology, and sediment core analyses, indicate that both the EAIS and WAIS advanced across the continental shelf during the Last Glacial Maximum (LGM; Licht et al., 1999; Shipp et al. 1999; Mosola and Anderson 2006; Anderson et al., 2014). The relative contributions of the EAIS and WAIS to ice flow and subsequent paleodrainage retreat behaviour in the Ross Sea remain controversial. Results from several land-based studies have led to the conclusion that the WAIS dominated ice flow during the LGM (e.g. Denton and Marchant, 2000; Hall et al., 2000, 2015). However, offshore till provenance analyses indicate that the EAIS and WAIS had roughly equal contributions to ice draining into the Ross Sea (Anderson et al., 1984; Licht et al., 2005; Farmer et al., 2006). Significant drainage of EAIS into the western Ross Sea is also supported by interpretations from seafloor glacial geomorphology (Shipp et al., 1999; Mosola and Anderson, 2006; Greenwood et al., 2012; Anderson et al., 2014) and exposure age dating in the Transantarctic Mountains (e.g. Jones et al., 2015).~~

Multibeam ~~swath~~ bathymetry ~~produces~~ provides a direct ~~picture~~ record of ~~the~~ bed conditions ~~under~~ beneath the former ice sheet, revealing landforms associated with past ice flow. These landforms ~~are powerful indicators of~~document the flow behaviour~~, and can be used to reconstruct paleo-flow dynamics~~ of formerly grounded ice. Here we compile legacy multibeam ~~swath~~ bathymetry data from 41 cruises over the last 20 years (Supplementary Table 1), combined with recently acquired high-resolution multibeam data, ~~in order~~ to characterize glacial geomorphic features across the Ross Sea. This unique, integrated dataset provides an opportunity to view the ~~seafloor~~ paleo ice-sheet bed at a much higher resolution than is possible beneath the modern ice shelf and ice sheet. We can improve our understanding of factors that control regional ice-sheet dynamics and test existing ice-sheet retreat models by using this dataset to ~~map the distribution of~~ identify glacial geomorphic features that characterize past flow and retreat dynamics. ~~and t~~These geomorphic features are used to~~us~~ reconstruct ice-sheet paleodrainage across the Ross Sea during and ~~following~~ subsequent to the LGM.

## 2 Study Area

The Ross Sea contains seven bathymetric troughs (Fig. 1), which are remnants of the extensional tectonic history of the region (Lawver et al., 1991). Ice streams preferentially occupied these troughs and eroded along pre-existing tectonic lineaments, scouring~~ed~~ the seafloor over multiple glacial cycles (Cooper et al., 1991; Anderson, 1999). The eastern Ross Sea (ERS) and the western Ross Sea (WRS) have distinctly different characteristics in terms of seafloor geology and physiography. ~~The ERS is dominated by a single, large rift basin, bounded by Ross Bank and Marie Byrd Land, with near-surface stratigraphy dominated by unconsolidated Plio-Pleistocene sediments that thicken in a seaward direction (Alonso et al., 1992; De Santis et al., 1997).~~ The WRS is geologically complex with older and more consolidated strata locally occurring at or near the seafloor (Cooper et al., 1991; Anderson and Bartek, 1992). The WRS contains high-relief banks and deep troughs, and thus serves as an analogue to the modern Siple Coast grounding line where banks currently serve as ice rises and provide a buttressing effect to the grounding line (e.g. Matsuoka et al., 2015). The ERS is dominated by a single, large rift basin, bounded by Ross Bank and Marie Byrd Land, with near-surface stratigraphy ~~dominated~~comprised of~~ by~~ unconsolidated Plio-Pleistocene sediments that thicken in a seaward direction (Alonso et al., 1992; De Santis et al., 1997). The ERS has more subdued physiography consisting of broad troughs separated by low-relief ridges~~ and provides an analogue to the interior portions of the modern grounding line~~ (Fig. 1).

Results from marine geological research, including integrated seismic stratigraphy, geomorphology, and sediment core analyses, indicate that both the EAIS and WAIS advanced across the continental shelf during the Last Glacial Maximum (LGM; Licht et al., 1999; Shipp et al., 1999; Mosola and Anderson, 2006; Anderson et al., 2014). The relative contributions of the EAIS and WAIS to LGM ice flow and subsequent paleodrainage and retreat behaviour in the Ross Sea remain controversial. Results from several land-based studies have led to the conclusion that the WAIS dominated ice flow during the LGM (e.g. Denton and Marchant, 2000; Hall and Denton, 2000; Hall et al., 2015). However, offshore till provenance analyses indicate that the EAIS and WAIS had roughly equal contributions to ice draining into the Ross Sea (Anderson et al., 1984; Licht et al., 2005; Farmer et al., 2006). Significant drainage of the EAIS into the western Ross Sea is also supported by interpretations from seafloor glacial geomorphology (Shipp et al., 1999; Mosola and Anderson, 2006; Greenwood et al., 2012; Anderson et al., 2014), exposure age dating in the Transantarctic Mountains (e.g. Jones et al., 2015), and numerical ice-sheet models (e.g. Golledge et al., 2013, 2014; McKay et al., 2016; DeConto and Pollard, 2016).

Based on the WRS continental shelf record, the Drygalski Trough grounding line is thought to have stepped back from its LGM position south of Coulman Island by ~13.0 cal ka and reached Drygalski Ice Tongue by ~11.0 cal ka (Licht et al., 1996; Cunningham et al., 1999; McKay et al., 2008; Anderson et al., 2014). In Terra Nova Bay, however, just north of Drygalski Ice Tongue, radiocarbon dates from raised beaches place the establishment of ice-free conditions at ~8.2 ka. The grounding line retreated into McMurdo Sound at ~7.7-7.8 ka, based on a radiocarbon-dated marine shell (*Adamussium colbecki*; Licht et al., 1996), ice-dammed lakes (Hall and Denton, 2000), and relative sea-level records (Hall et al., 2004; 2013). Ages from sediment cores collected by McKay et al. (2008) place grounding-line retreat in McMurdo Sound at ~10.0 ka. More recent results from McKay et al. (2016) indicate that the grounding line may have reached the vicinity of Ross Island prior to ~8.6 cal ka, although a relative sea-level record from raised beaches on the southern Scott Coast suggest final unloading of grounded ice at ~6.6 ka (Hall et al., 2004). In general, land-based ages of deglaciation lag behind the marine record (Anderson et al., 2014), suggesting that either marine grounding-line retreat may have preceded continental ice thinning, and/or that grounding-line retreat proceeded westward from the WRS towards the coast.

Dynamic ERS ice-stream behaviour has been hypothesized, including pre-LGM retreat and subsequent re-advance (Bart and Owolana, 2012). ERS marine radiocarbon ages suggest very early retreat from the continental shelf break during or before the LGM (Licht and Andrews, 2002; Mosola and Anderson, 2006; Bart and Cone, 2012; Anderson et al., 2014), although methods for obtaining these dates remain highly problematic due to possible reworking of old carbon (Licht and Andrews, 2002) and uncertainties of appropriate marine reservoir corrections (Hall et al., 2010). Conversely, terrestrial studies of ice-sheet thinning and measurements of post-glacial rebound in Marie Byrd Land indicate that ERS deglaciation occurred throughout the Holocene (Stone et al., 2003; Bevis et al., 2009). A comprehensive review of Ross Sea deglaciation is provided by Anderson et al. (2014), reviewing the extensive work that has been done in this region. Outstanding challenges in the Ross Sea include integrating and improving marine and terrestrial chronologies, as well as constraining the contributions of the EAIS and WAIS to ice flow in the Ross Sea, their respective behaviour, and their sensitivity to various forcings. Here we use the Ross Sea-wide glacial geomorphological record to reconstruct the regional pattern of deglaciation and provide a spatial framework for interpreting point-sources of information such as cores and ages.

## 3 Methodology

This study synthesizes multibeam datasets from across the Ross Sea, combining legacy ~~multibeam~~ data (Supplementary Table 1) with newly collected, high-resolution ~~multibeam~~ data collected in key areas for characterizing the nature of ice-sheet retreat (Fig. 2a). The combined ~~multibeam~~ ship tracklines across Ross Sea cover over 250,000 km, providing unparalleled coverage of multiple paleo-ice streams. ~~of the Ross Sea.~~ New, high-resolution ~~swath~~ multibeam bathymetry data were acquired during an RV/IB *Nathaniel B. Palmer* NBP1502A cruise to the Ross Sea in the 2014-2015 A~~a~~ustral summer. These data were collected with a Kongsberg EM-122 system in dual swath mode with a 1°x1° array, 12 kHz frequency, and gridded at 20 m. Vertical resolution varies from about 0.2-~~% –~~0.07% of water depth (Jakobsson et al., 2011); therefore, at water depths of 500 m, geomorphic features with sub-meter amplitudes can be resolved. Horizontal resolution is similarly depth-dependent and, in water depths of 500 m, is about 9 m. Ping editing was completed onboard using CARIS and imported into ArcGIS. In addition to multibeam data, newly acquired high-frequency seismic data (3.5 kHz sub-bottom data collected with a Knudsen CHIRP 3260 using a 0.25 ms pulse width) were interpreted along with legacy CHIRP data.

The seafloor geologic setting has been recorded in legacy seismic reflection data across the Ross Sea. We refer to seismic records as either ‘high-frequency’ denoting 3.5 kHz CHIRP data or ‘low-frequency’ referring to traditional seismic data (20-600 Hz). Low-frequency seismic lines from cruise PD-90, originally published in Anderson and Bartek (1992), were combined with ANTOSTRAT Project seismic lines compiled by Brancolini et al. (1995). These previous investigators recognized seaward thickening units ~~Previously interpreted seismic units identify facies~~ bounded by glacial unconformities, where each surface represents a glacial advance that ~~cannibalized~~ eroded the previous substrate and deposited till and glacimarine sediments above the newly ~~eroded~~ formed surface.

## ~~4 Results~~

Glacial geomorphic features imprinting the Antarctic continental shelf are divided into three main categories, largely following the classification scheme of Benn and Evans (2010). These are: (1) subglacial features, such as mega-scale glacial lineations (MSGLs)~~, grooves~~, drumlinoid features~~, megaflutes~~, and subglacial channels; (2) ice-marginal features, such as grounding zone wedges (GZWs), marginal moraines, and linear iceberg furrows; and (3) proglacial features, ~~including~~ such as gullies and arcuate iceberg furrows (Fig. 2). These features occur above the most recent shelf-wide glacial unconformity (with the exception of drumlinoids) and are covered by post-~~LGM~~ glacial sediments. They are, therefore, interpreted as features ~~as~~ formed during the last glacial cycle~~LGM and post-LGM features~~ (e.g. Shipp et al., 2002; Mosola and Anderson, 2006).~~ We describe these landform classes here and present their Ross Sea-wide distribution in Fig. 3.~~

### 3~~4~~.1 Subglacial Features

Subglacial features ~~are~~ form beneath permanently ~~ed under~~ grounded ice~~, where the ice~~that is thick enough to offset buoyant forces exerted by the ocean~~ and remains permanently in contact with the bed~~. MSGLs (Fig. 2b), ~~are~~ the most common subglacial features on the Antarctic continental shelf, are streamlined features with high parallel conformity (Clark, 1993). While the actual formation process for MSGLs is still debated (e.g. Tulaczyk et al., 2001; Shaw et al., 2008; Ó Cofaigh et al., 2008; Fowler, 2010), they are interpreted as having formed under streaming ice due to their association with modern ice streams (King et al., 2009) and their occurrence within paleo-glacial troughs (Anderson, 1999; Livingstone et al., 2012). The streamlined nature of MSGLs makes them excellent indicators of ice-flow direction (Clark, 1993; Stokes and Clark, 1999; Shipp et al., 1999; Ó Cofaigh et al., 2002; Dowdeswell et al. 2004; Spagnolo et al., 2014).

Previous studies have shown that MSGLs are associated with a massive seismic facies interpreted as the deformation~~ing~~ till layer deposited above the latest glacial unconformity (Shipp et al., 1999; Ó Cofaigh et al., 2002, 2005; Heroy and Anderson, 2005). Most MSGLs in the Ross Sea have amplitudes of 1-9 m, and lengths of about 1-10 km.~~, and are characterized by extreme parallel conformity.~~ As these features are ~~strongly~~ associated with ~~actively~~ deforming till, MSGL amplitudes should not be greater than the thickness of the deforming till layer.~~ Grooves, in contrast, are erosional features characterized by generally larger and more variable amplitudes (e.g. Heroy and Anderson, 2005).~~

Smaller scale streamlined features, with lengths of hundreds of metres to a few kilometres, comprise a number of landform classes such as drumlins, crag and tails, and megaflutes. We group these landforms here as a single class of drumlinoids. While their internal composition can be difficult to determine in the marine environment, and their formation mechanisms remain uncertain, this family of landforms is widely and most simply taken to record the former ice flow direction (Benn and Evans, 2010). ~~Drumlins and crag-and-tail forms are elongate, large-scale features (heights of tens of meters and lengths of hundreds of meters to a few kilometres) that taper in the direction of ice flow (e.g. Menzies, 1979; Benn and Evans, 2010). Crag-and-tail landforms are sculpted bedrock features, whereas drumlins are moulded sedimentary landforms (Benn and Evans, 2010). We group both features as drumlinoids given their similar morphology and implications for ice flow, as well as a lack of information on the internal structure of the observed Ross Sea features.~~

~~Megaflutes are elongate, small-scale features (heights of meters and lengths generally less than 200 meters) that taper in the direction of ice flow. They typically are associated with drumlinoid features and, because of their small size, are imaged only in high-resolution multibeam and side-scan sonar records.~~ In Antarctica, drumlinoids ~~and megaflutes~~ are most often observed at the transition between crystalline bedrock and sedimentary deposits (Wellner et al., 2001, 2006; Graham et al., 2009). ~~In the Ross Sea, drumlinoids and megaflutes are restricted to a single, prominent field in Glomar Challenger Basin and along the western flank of Drygalski Trough where crystalline bedrock occurs at or near the sea floor. Because these features are moulded from predominantly crystalline and sedimentary bedrock, they likely formed over multiple glacial cycles. They do, however, exhibit highly uniform orientations (Fig. 2c) that are consistent with MSGL orientations seaward of the drumlinoids, indicating that the most recent phase of ice flow was likely responsible for the final drumlinoid shape.~~

Subglacial meltwater channels have been reported from a number of locations on the Antarctic continental shelf, though almost exclusively incising crystalline bedrock on the inner shelf (e.g. Lowe and Anderson, 2003; Anderson and Fretwell, 2008; Smith et al., 2009; Nitsche et al., 2013; Witus et al., 2014). Channels ~~on the Ross Sea continental shelf~~ in sedimentary substrates are rare, but have been previously observed on the Ross Sea continental shelf by Alonso et al. (1992), Wellner et al. (2006), and Greenwood et al. (2012), though their origin and link to subglacial meltwater ~~has earlier been equivocal~~is not evident.~~. Our newly acquired high-resolution multibeam data in the Ross Sea reveal subglacial channels that are clearly associated with ice-marginal features such as grounding zone wedges and recessional moraines (Simkins et al., in review; Fig. 2d). The channels are incised into till deposited above the LGM unconformity, and are sometimes overprinted by ice-marginal landforms; therefore, these are subglacial meltwater channels that were active during the most recent glacial recession. The implication of these channels with regard to ice-sheet dynamics and paleodrainage is still under investigation and not discussed in this paper.~~

### 43.2 Ice-Marginal Features

Ice-marginal features form at the grounding line, ~~the ice margin, where ice~~marking the transition~~s~~ from ~~being~~ permanently grounded ice ~~to the bed~~ to ice that has ~~and d~~decouple~~ds~~d from its bed to become a floating ice shelf or a calving ice cliff~~the seafloor~~. They include GZWs, marginal moraines, and linear iceberg furrows.

GZWs are depositional features (Fig. 2f, 2g), characterized by relatively steep foreset slopes that result in asymmetrical morphologies, broadly indicating ice-flow direction during GZW deposition. GZWs are ~~depositional features (Fig. 2f, 2g)~~ formed during periods of stability of the grounding line. They grow as sediment is delivered to the grounding line through subglacial bed deformation and basal debris melt-out (e.g. Alley et al., 1986, 1989; Anderson, 1999; Anandakrishnan et al., 2007; Alley et al., 2007; Dowdeswell et al., 2008, Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015). ~~GZWs are characterized by steep foreset slopes that result in asymmetrical morphologies, broadly indicating ice-flow direction during GZW deposition.~~ ~~Sedimentation at grounding lines, forming~~The growth of GZWs~~,~~ can stabilize an ice sheet against small-scale relative sea-level rise and ice-sheet thinning by reducing the minimum ice thicknesses necessary to counter buoyancy effects (Alley et al., 2007). Large GZWs can imply~~mark~~ longer episodes of stability of the ice margin (Alley et al., 2007, Dowdeswell and Fugelli, 2012). ~~The internal structure of large GZWs is occasionally detectable in low-frequency seismic data and includes distinct foreset beds indicative of wedge growth (e.g. Anderson, 1999; Heroy and Anderson, 2005), but more often internal stratification is not resolved in seismic data (e.g. Mosola and Anderson, 2006; Batchelor and Dowdeswell, 2015).~~ Here, GZWs are grouped into three categories: small-scale, intermediate-scale, and large-scale. Small-scale GZWs have heights less than 10 m, cannot be traced across an entire trough width, and generally are only observable in high-resolution multibeam and side-scan sonar data (e.g. Shipp et al., 1999; Jakobsson et al., 2012; Simkins et al., in ~~review~~press). Intermediate-scale GZWs range from 10-50 m heights and often display very sinuous fronts. Large-scale GZWs (Fig. 2g) have heights exceeding 50 m and extend across the entire trough width. The internal structure of large GZWs is occasionally detectable in low-frequency seismic data and includes distinct foreset beds indicative of GZW progradation (e.g. Anderson, 1999; Heroy and Anderson, 2005; Dowdeswell and Fugelli, 2012), but more often internal reflectors are not resolved in seismic data (e.g. Mosola and Anderson, 2006; Batchelor and Dowdeswell, 2015).

Ice-m~~M~~arginal moraines ~~(Fig. 2e) are largely symmetric in cross section (Dowdeswell and Fugelli, 2012). They are generally believed to be formed by push-processes (Batchelor and Dowdeswell, 2015)~~(Fig. 2e) are often symmetric in cross section (Dowdeswell and Fugelli, 2012), but can also display a slightly asymmetric shape (Winkelmann et al., 2010; Klages et al., 2013). They are generally believed to be formed by push-processes (e.g. Batchelor and Dowdeswell, 2015).~~.~~ ~~In the Ross Sea, moraines are mostly observed as fields of small repeating ridges with heights of 1-4 m.~~ Low-amplitude (<5 m) f~~F~~eatures with similar characteristics are sometimes interpreted as De Geer moraines, whose development is influenced by seasonal or cyclic processes (Hoppe, 1959; Lindén and Möller, 2005; Todd et al., 2007), or transverse ridges (Dowdeswell et al., 2008) which does not imply seasonal formation. Due to their limited amplitudes, these features are ~~only~~ best resolved~~able~~

with high-resolution bathymetric mapping techniques, ~~including~~ such as the EM122 multibeam system and side-scan sonar (e.g. Shipp et al., 1999; Jakobsson et al., 2011; Simkins et al., in ~~review~~press).

~~Iceberg furrows form when deep-keeled icebergs contact the bed, causing scours on the seafloor (Lien et al., 1989). Arcuate iceberg furrows are classified as proglacial features (discussed in section 4.3), but we consider linear furrows to be ice-marginal features (Fig. 2h). The margins of marine-based ice sheets with low-slope profiles are particularly susceptible to tidal fluctuations, causing large areas of the ice sheet to intermittently contact the seafloor (Fricker and Padman, 2006; Brunt et al., 2010). We interpret linear furrows to form within this diffuse grounding zone, where ice is hovering at the buoyancy limit and cyclically contacting the seafloor. Small repeating corrugation ridges typically occur within fields of furrows or within individual furrows (Figs. 2h, 2k; Anderson, 1999; Jakobsson et al., 2011). Although the exact mechanism for their formation remains somewhat controversial, corrugation ridges are thought to form as icebergs move vertically with tides, causing iceberg keels to intermittently contact the bed (Jakobsson et al., 2011; Graham et al., 2013). Their tidal association is based on the occurrence of identical features in proglacial arcuate iceberg furrows (Anderson, 1999) and comparison of corrugation amplitude and spacing with tidal modelling (Jakobsson et al., 2011).~~

~~Here, we associate linear furrows with ice-shelf breakup events when icebergs near the grounding line are held upright within an iceberg armada (MacAyeal et al., 2003; Jakobsson et al., 2011). A deep keel capable of ploughing a linear furrow once ice has fractured could also have existed as an irregularity at the ice base prior to calving. Thus, linear furrows could also form by ploughing of ice-base irregularities in a diffusive grounding zone, as ice is intermittently in contact with the bed while still connected to fully grounded ice upstream. Both mechanisms for linear furrow formation signify that ice was still moving as a coherent body in contact with the seafloor. Linear furrows often display a geomorphic expression similar to MSGLs; however, they are erosional features whereas MSGLs are interpreted as either depositional or deformational features. Furrows should have more variable flow directions than MSGLs and exhibit more variable orientations in a seaward direction. However, linear furrows tend to exhibit high parallel conformity and are consistent with MSGL orientations. We argue that linear forward motion is propelled by the upstream ice flow; therefore, their significance for ice-flow direction is the same as MSGLs. For this reason, linear furrows and MSGLs are grouped into the inclusive term of 'linear features.'~~

Linear iceberg furrows exhibit high parallel conformity, often display a geomorphic expression similar to MSGLs, and are consistent with MSGL orientations. These linear furrows, however, are erosional features whereas MSGLs are interpreted as either depositional or deformational features. The margins of marine-based ice sheets with low-slope profiles are particularly susceptible to tidal fluctuations, causing large areas of the ice sheet to intermittently contact the seafloor (Fricker and Padman, 2006; Brunt et al., 2010). We interpret linear furrows to form within this diffuse grounding zone, where ice is hovering at the buoyancy limit and cyclically contacting the seafloor. Alternatively (or additionally), linear furrows may be associated with ice-shelf breakup events when icebergs near the grounding line are held upright within an iceberg armada

(MacAyeal et al., 2003; Jakobsson et al., 2011, Larter et al., 2012). Small repeating corrugation ridges have been observed within fields of iceberg furrows or within individual iceberg furrows (Figs. 2h, 2k; Anderson, 1999; Jakobsson et al., 2011, Klages et al., 2015). Although the exact mechanism for their formation remains somewhat controversial, corrugation ridges are thought to form as icebergs move vertically with tides, causing iceberg keels to intermittently contact the bed (Jakobsson et al., 2011; Graham et al., 2013). Their association with vertical tidal movement is based on the occurrence of identical features in proglacial arcuate iceberg furrows (Anderson, 1999) and comparison of corrugation amplitude and spacing with tidal modelling results (Jakobsson et al., 2011). Similarly, a deep keel capable of ploughing a linear furrow once ice has fractured could also have existed as an irregularity at the ice base prior to calving, forming linear furrows in a diffusive grounding zone. Both mechanisms for linear furrow formation signify that ice was still moving as a coherent body in contact with the seafloor. We argue that the linear forward motion that ploughs these furrows is caused by upstream ice flow; therefore, their significance for ice-flow direction is the same as MSGLs. For this reason, linear furrows and MSGLs are grouped into the inclusive term of 'linear features.'

### 43.3 Proglacial Features

Shelf-edge gullies on high-latitude continental margins occur where streaming ice reached the continental shelf break (Fig. 2i). ~~T~~Although their origin remains uncertain,~~;~~ they have been attributed to many formative processes, including point sources of sediment-dense meltwater from the grounding line when it was situated at the shelf break (Anderson, 1999; Evans et al., 2005), ~~and also~~or from small-scale slope failure due to accumulation of proglacial sediment (Gales et al., 2012). Both mechanisms imply proximity to the grounding line. Ross Sea shelf-edge gullies have not been extensively surveyed; however, a lack of significant sediment infilling suggests that they were active during the LGM (Shipp et al., 1999).

Arcuate iceberg furrows (Fig. 2j) are common features ~~in the Ross Sea. They are generally clustered~~ near continental~~the~~ shelf margins and on bank tops, overprinting ~~subglacial and ice-marginal features~~any potentially pre-existing landforms. These are clearly proglacial features formed by freely moving icebergs that drifted under the influence of ocean currents and winds. Corrugation ridges have been observed within arcuate iceberg furrows, which is the most compelling evidence that ~~corrugation~~ these ridges result from tidal motion (Anderson, 1999).

## 4 Results

The landform categories set out above were mapped from our composite multibeam dataset and their distributions are presented in Figure 3. We find significant differences in landform assemblage composition and distribution between the WRS and ERS.

### 4.~~4~~1 Western Ross Sea

Drygalski Trough is the deepest region of the Ross Sea with water depths over 1000 m. Within this trough, the most seaward geomorphic expression of the ice-~~-~~sheet grounding line is a large-scale GZW north of Coulman Island (D1, Fig. 3). This is consistent with previous interpretations of the maximum grounding~~-~~ line location (Licht et al., 1999; Shipp et al., 1999). A prominent set of MSGLs extends continuously from the Drygalski Ice Tongue to the approximate latitude of Coulman Island. A few small GZWs occur along the flanks of the trough; otherwise the MSGLs are not overprinted by recessional features. North of Coulman Island, both linear and arcuate iceberg furrows overprint ~~grounding zone wedge~~GZW D1. The outermost shelf is covered by extensive arcuate iceberg furrows, which could have overprinted any older features.

Multibeam data ~~is~~ are scarce in southern Drygalski Trough, a key area for reconstructing the final phase of deglaciation in the WRS. Available data show a field of closely spaced, small-scale GZWs that back-step up the southern margin of Crary Bank, and a set of discrete intermediate-scale GZWs~~,~~ and lineations offshore of Mackay Glacier that record westward grounding line retreat (Greenwood et al., 2012; Anderson et al., 2014).

JOIDES Trough is slightly fore-deepened on the outer shelf, relatively flat on the middle shelf, and slopes steeply into the deep inner shelf Central Basin (Figs. 1, 3). The outer portion of JOIDES Trough is mostly devoid of linear features, with the exception of one group of ~~linear~~ straight furrows. High-frequency CHIRP data show a 4-8 m thick layer of acoustically laminated and draped glacimarine sediments on the outer shelf (Fig. 3a). LGM-age carbonates occur on outer shelf banks on both sides of JOIDES Trough (Taviani et al., 1993; Fig. 3), precluding the presence of grounded ice at those locations. A large-scale, mid-shelf GZW (J1, Fig. 3) is seismically resolved (Shipp et al., 1999), although the GZW crest lacks clear expression in multibeam data. This mid-shelf GZW is separated from the next intermediate-scale GZW near the southern end of Crary Bank (J2, Fig. 3) by an extensive field of iceberg furrows followed by a continuous field of marginal moraines and small-scale GZWs. Southern JOIDES Trough is characterized by a series of meltwater channels associated with GZW erosional notches, ~~emanating from grounding lines,~~ observed at GZW J2 and ice-marginal features south of J2. The channels are incised into till deposited above the LGM unconformity and are occasionally overprinted by marginal moraines, therefore they are interpreted as subglacial channels that were active during the most recent glacial recession.

Pennell Bank and Ross Bank are linked across Pennell Trough by a bathymetric ~~saddle~~ high (referred to here as Pennell Saddle), separating the outer shelf part of Pennell Trough from the deep Central Basin (Fig. 3). A large-scale GZW (P1) occurs at the northern margin of the Pennell Saddle and a thick (up to 14 m) package of layered glacimarine sediments extends northward from beneath the toe of the P1 ~~wedge~~ GZW (Figs. 3b, c). Small-scale sinuous ~~wedges~~ GZWs and relatively straight-crested moraines record the grounding line back-stepping from atop Pennell Saddle southward into Central Basin. These recessional features overprint a large subglacial meltwater channel within the saddle (Fig. 2d).

The Central Basin is a bathymetric low that reaches water depths of over 1000 m, situated south of all three WRS troughs. It contains multiple generations of poorly preserved linear features, suggesting phases of large-scale ice stream flow reorganization through the basin and McMurdo Sound (Greenwood et al., 2012). Numerous pockets of small, marginal moraines are found throughout the Central Basin and do not seem to be oriented parallel to depth contours.

### 4.~~5~~2 Eastern Ross Sea

The ERS contains three major troughs (~~:~~ Glomar Challenger Basin, Whales Deep, and Little America Basin)~~,~~ separated by low-relief ridges that are thought to have separated three paleo-ice streams (Mosola and Anderson, 2006). Linear features ~~monopolize~~ dominate the ERS seafloor and extend to the continental shelf break (Fig. 3). They are associated with GZWs that are large enough to be identified in low-frequency seismic reflection data (Mosola and Anderson, 2006), (Fig. 2g; Fig. 3). Small- and intermediate-scale GZWs and moraines are confined to a few locations and no subglacial channels have been observed in the ERS. Shelf-edge gullies occur at the continental shelf break, implying ~~the presence of basal meltwater outbursts from the grounding line~~the delivery of sediment and meltwater to a shelf-break grounding-line position.

~~Extensive linear features occur throughout Glomar Challenger Basin (Fig. 2b, 3). They exhibit both trough-parallel and trough-sub-parallel orientations.~~ The only ~~large field of~~ drumlinoids observed in the Ross Sea occur on the inner shelf of Glomar Challenger Basin (Fig. 2c), covering ~300 km$^2$, and are associated with a near-surface occurrence of crystalline bedrock (Anderson, 1999; Shipp et al., 1999). Because these features are moulded predominantly from bedrock, they likely formed over multiple glacial cycles. They do, however, exhibit highly uniform orientations (Fig. 2c) that are consistent with MSGL orientations seaward of the drumlinoids, indicating that the most recent phase of ice flow was likely responsible for the final drumlinoid shape. Extensive linear features occur throughout Glomar Challenger Basin (Fig. 2b, 3). They exhibit both trough-parallel and sub-parallel orientations, and are partitioned into discrete clusters based on orientation (see below).~~L~~ Legacy high-frequency CHIRP data in outer Glomar Challenger Basin show thin glacimarine sediments (Fig. 3d) and sediment cores sampled tills that typically occur within 1 to 2 meters of the seafloor. Two closely spaced large-scale GZWs exist at the continental shelf break, observed in low-frequency seismic lines (G1 and G2, Fig. 3).~~However, the morphologies of t~~ These GZWs are wide and long but ~~so~~ relatively thin so ~~subdued~~ that they are not clearly observable in multibeam bathymetry~~ic records~~. Two large-scale composite GZWs on the mid-to-inner shelf (G3, G4) are observed in both low-frequency seismic and multibeam data (Bart and Cone, 2012).

Whales Deep also contains a large-scale GZW at the continental shelf break (W1, Fig. 3), observed only in seismic data, as well as a mid-shelf ~~composite~~ GZW observable in both low-frequency seismic and multibeam records (W2, Fig. 3). ~~About 170 km landward, the front of another large-scale GZW extends only a short distance seaward of the modern Ross Ice Shelf calving line (W3, Fig. 3).~~ A well-developed field of linear features extends from beneath the mid-shelf (W2) GZW to the continental shelf break. Linear features are notably absent south of W2. Little America Basin, like Glomar Challenger Basin, exhibits extensive linear features that extend across the entire trough to the shelf break. ~~It is characterized by three GZWs (L1-3, Fig. 3). These~~ Three large-scale GZWs (L1-3, Fig. 3)~~.~~ are identified from low-frequency seismic data (Mosola and Anderson, 2006), but are too relatively thin to be~~are not~~ observed in the legacy multibeam ~~swath~~ bathymetry, which has limited coverage and quality in this area.

### 4.2.1~~6~~ ERS Flowsets

~~In the ERS, there are clearly multiple generations of linear features.~~ Different flow directions in the ERS can clearly be identified by the presence of multiple generations of overprinting linear features. Discrete flow episodes, corresponding to the formation of distinct sets of linear features, ~~can thus be~~are defined from the population of linear features in the ERS. Linear features were grouped based on their parallel concordance, close proximity, and similar morphometry (~~after~~ cf. Clark, 1999). Rose diagrams were constructed from each group of linear features ~~(Fig. 4)~~ to ~~ensure~~ confirm that features within a flowset have ~~each flowset contains features of~~ similar ~~the same~~ orientations (Fig. 4). ~~Linear features within each flowset are tightly clustered around a small range in orientation, generally within a standard deviation of less than 10°. Each flowset is assumed to represent a single flow configuration, formed isochronously~~ The orientation of linear features within a single flowset deviate by generally less than 10°, and thus each flowset is assumed to represent a single flow configuration whose component lineations were formed contemporaneously (~~after~~ cf. Clark, 1999). Assuming that all flowsets were shaped during and subsequent to the LGM~~ and subsequent deglaciation~~, a relative chronology of ~~flowsets~~ their formation can be~~was~~ assessed based on their landward succession and ~~seaward-most extent of the individual flowsets, as well as any~~ cross-cutting relationships with other flowsets. In order to characterize ~~reduce complexity and best represent~~ large-scale regional flow patterns, ~~-~~flowsets with discrete~~,~~ yet similar ~~clusters of o~~orientations~~,~~ were assumed to reflect a similar ice-flow configuration and grouped together for analysis.~~.~~

Our new compilation of multibeam data reveals that ~~M~~major flow patterns ~~observed~~ in the ERS often deviate from the trough-parallel drainage that has been described previously ~~been assumed~~ (Licht et al., 2005; Mosola and Anderson, 2006; Anderson et al., 2014). Some f~~F~~lowsets in Glomar Challenger Basin ~~partially~~ exhibit evidence of trough-parallel flow (flowsets *a*-*c*, Fig. 4), but other flowsets ~~and also display an extensive group of linear features extending~~indicate flow across an inter-ice-stream ridge towards Whales Deep ~~-~~(flowsets *d*-*h*, Fig. 4). Flowset *g* contains the only curvilinear ~~ed~~ flowlines observed. For this flowset, r~~R~~ose diagrams were used to exclude the possibility that the curvature indicates ~~of linear features within flowset *g* were used to ensure that the curvature was not comprised of~~ two discrete flow events with ~~very~~ similar orientation~~s, but instead populated by linear features that change orientation gradually and consistently~~. In Whales Deep ~~Trough~~, only one flowset is observed, consisting of trough-parallel ~~flow~~ features on the outermost shelf (flowset ~~*i*~~*l*, Fig. 4). Flow indicators in Little America Basin ~~partially mirror~~ resemble the configuration in Glomar Challenger Basin:~~.~~ s~~S~~ome linear features in Little America Basin ~~display generally~~record trough-parallel flow (flowsets *j*, *k*, Fig. 4), while others are oriented oblique to the trough axis, pointing ~~and directed~~ towards Whales Deep (flowsets *l*, *m*, Fig. 4). A third group of linear features indicates flow out of Little America Basin into a neighboring outlet draining Marie Byrd Land to the east (flowset *n*, Fig. 4). Flowsets on the innermost shelf in all three ERS troughs are interpreted ~~as~~ to indicate late-stage deglacial flow configurations.

## 5 Discussion

### 5.1 Last Glacial Maximum ice extent and flow

~~In outer Drygalski Trough, w~~We interpret the LGM grounding line in outer Drygalski Trough to ~~lie~~ have been situated just north of Coulman Island, marked by ~~at~~ the ~~seaward~~outer-most GZW (cf. ~~, in accordance with~~ Shipp et al.,~~ (~~1999;~~ ) (~~D1, Fig. 3). Between Coulman Island and Drygalski Ice Tongue, a prominent ~~field~~ cluster of MSGLs indicates trough-parallel flow (Fig. 3).~~, consistent with results from previous till provenance studies (Anderson et al., 1984). Although data coverage is sparse, no linear flow features are observed south of the ice tongue; however, small ice-marginal features indicate ice was grounded in the deepest parts of Drygalski Trough south of the ice tongue.~~ Therefore, we interpret northward flow at the LGM from at least as far south as the David Glacier outlet (Drygalski Ice Tongue) to a grounding-line north of Coulman Island.

In JOIDES Trough, maximum ice extent is ~~placed~~ suggested to be recorded by~~at~~ the large-scale GZW (J1) on the mid-outer-shelf (Fig. 3). We base this hypothesis ~~,~~primarily ~~due to~~on the presence of up to 8 m of draped glacimarine sediments in the outer trough shown in high-frequency seismic data (Fig. 3a). T~~, and t~~he observation of LGM-age carbonates on surrounding banks (Taviani et al., 1993) and the presence of LGM-age tephra layers in glacimarine sediments on the outer shelf (Licht et al., 1999) further support this interpretation. ~~. This is consistent with Licht et al. (1999), who concluded that ice did not reach the continental shelf break during the LGM based on the presence of LGM-age tephra layers in glacimarine sediments on the outer shelf. Linear~~Straight furrows ~~features~~ that occur seaward of this LGM limit are interpreted as iceberg furrows formed seaward of the LGM grounding line, rather than linear furrows, based on orientations that lack parallel conformity.

The LGM limit in Pennell Trough coincides with ~~is placed at~~ the large-scale GZW (P1, Fig. 3), located ~120 km landward of the shelf break ~~in accordance with(~~ Howat and Domack,~~ (~~2003). High-frequency seismic data show that this ~~wedge~~ GZW prograded across thick glacimarine sediments that fill the outer trough (Fig. 3b, c).

Large-scale GZWs at the shelf break in each ERS trough (Fig. 3), ~~along with~~ linear features that extend across the outer ~~continental~~ shelf ~~within each trough~~, and extensive shelf-edge gullies (Gales et al., 2012) indicate that grounded ice likely reached the shelf break in the ERS (Shipp et al, 1999; Mosola and Anderson 2006). ~~Extensive shelf-edge gullies support the presence of grounded ice at the shelf break.~~ Thin glacimarine sediments ~~occur~~ on the outer shelf ~~and indicate~~ suggest a relatively shorter period of ice-free conditions than in the WRS, and would be consistent with a shelf-break LGM position.

Figure ~~5~~3 shows the interpreted LGM grounding line and paleo-flow directions derived from the seaward-most linear features that ~~occur near this LGM grounding line~~ are assumed to represent LGM flow conditions. Generally, linear features delineate trough-parallel flow, which is consistent with previous LGM flow reconstructions (Shipp et al., 1999; Mosola and Anderson, 2006; Anderson et al., 2014).

### 5.2 Western Ross Sea deglaciation

With the exception of Drygalski Trough, ~~T~~the WRS contains sparse and isolated patches of linear features, providing only glimpses of subglacial flow behaviour and direction despite extensive multibeam bathymetric coverage. Therefore, most paleo-drainage interpretations in the WRS are based on ice-marginal features.

In Drygalski Trough, the ice sheet decoupled from the seafloor and back-stepped rapidly from its LGM position near Coulman Island to a mid-shelf position at Drygalski Ice Tongue, as evidenced by the pristine nature of MSGLs and lack of overprinting ice-marginal landforms. ~~This interpretation is based on a lack of recessional features overprinting MSGL.~~ South of Drygalski Ice Tongue, sparse data ~~are sparse and data~~ with poor quality results from the typical presence of pervasive sea ice~~is poor~~. The most prominent deglacial features are a series of intermediate-size GZWs that back-step westward towards Mackay Glacier from a location north of Ross Island (Greenwood et al., 2012).

In JOIDES and Pennell troughs, fields of closely spaced, small-scale~~,~~ GZWs and ~~ice-marginal features~~marginal moraines (Figs. 2d-f) dominate the seafloor~~scape~~, indicating that ~~grounded~~ ice remained in contact with the seafloor during retreat. This ~~also~~ implies that ~~the~~ overall ~~retreat~~ deglaciation was punctuated by pauses that were long enough to form a small recessional feature, before retreating and forming another recessional feature. Retreat slowed and the grounding line stabilized in the southernmost part of JOIDES Trough at an intermediate-scale GZW (J2, Fig. 3). A subglacial meltwater channel extending from GZW J2 to the south was likely linked to a large meltwater system that was active during deglaciation. We observe m~~M~~eltwater channels ~~are observed~~ in southern JOIDES and Pennell troughs, which are ~~and are~~ associated with retreat of the grounding line from positions of stability (J2, and the Pennell Saddle), leading to final rapid deglaciation of grounded ice in the two troughs. The effect of channelized subglacial meltwater on grounding-line stability is still under investigation.

Ice in the deep Central Basin appears to have retreated quickly, leaving only ~~scattered~~ isolated clusters of recessional moraines. Based on the orientations of these moraines, we interpret a grounding-line embayment that ~~formed~~ opened over the Central Basin, followed by grounding-line retreat toward the ~~and the grounding line then receded to the~~ east and ~~the~~ west (Fig. ~~6~~5). ~~Subglacial and i~~Fields of closely spaced, small-scale ice-marginal features in the Central Basin indicate that ice remained ~~grounded~~ in frequent contact with the bed during deglaciation of this area. Because ice did not lift off from the deep seafloor first, we infer that retreat ~~patterns~~ behaviour ~~were~~ was ~~dictated~~ controlled by a steep ice profile rather than physiography, as the ice did not decouple concentrically according to depth contours.

North of Central Basin, extensive fields of small-scale GZWs and moraines record grounding-line ~~back-step~~retreat onto banks (Figs. ~~7; 8~~6a-b; 7), indicating that ice remained grounded on WRS banks during deglaciation. The presence of ~~wedges~~ GZWs ~~and moraines~~ implies that ice was actively flowing across the banks and mobilizing sediment in order to deposit these marginal features. Thus, ~~these~~ WRS banks ~~acted as~~housed semi-independent ice rises during the late stages of ice sheet retreat from the WRS (Shipp et al., 1999; Anderson et al., 2014; Matsuoka et al., 2015). These findings are supported by ~~M~~modelling results that ~~results~~ indicate the presence of independent, detached ice rises on WRS banks late in deglaciation (Golledge et al., 2014). Additionally, Yokoyama et al. (2016~~in press~~) argue that a grounded ice shelf remained pinned on WRS banks until the late Holocene.

~~Reconstructed grounding-line steps (Fig. 7) illustrate retreat patterns across the Ross Sea. Observed grounding lines are linked together to form discrete time-steps of deglaciation, representing an interpretation of relative timing. These linkages are based on similar morphologies of observed GZWs, extension of grounding line orientations along bathymetric depth contours, and interpretation of local retreat rates from geomorphic features. Southern Drygalski Trough was the last area in the WRS to experience grounding-line retreat, as outlet glaciers (e.g. Mackay Glacier, and David Glacier flowing into the Drygalski Ice Tongue) receded toward the west and north, leaving fields of back-stepping moraines and wedges in their path (Greenwood et al., 2012; Anderson et al., 2014), (Fig. 7). Drainage from the EAIS played an active role in nourishing the ice sheet until the last stage of deglaciation (Fig. 7, steps 7-8). We infer a steep EAIS ice profile over the WRS throughout deglaciation, based on the contribution of EAIS ice through the Transantarctic Mountains (Fig. 6, Fig. 8) and grounding-line recession independent of physiography in the central WRS.~~

### 5.3 Eastern Ross Sea deglaciation

Linear features on the ERS seafloor are ~~not~~ overprinted only by ~~recessional bedforms, other than scattered~~ large-scale GZWs (Fig. 3). These large-scale GZWs likely ~~. This indicates~~record periods of grounding-line stabilization, punctuated by episodes of ice-~~-~~sheet decoupling and grounding-~~-~~line retreat that back-stepped tens to hundreds of kilometres in distance~~,~~ ~~punctuated by~~ and preserved linear features ~~periods of long-term grounding line stability when large GZWs were formed~~.

We propose two alternative ~~behaviour~~ scenarios to explain the observed changes in flow orientation in the ERS. The first scenario ('dynamic flow-switching model') is characterized by alternating regional flow direction throughout the LGM, followed by north-south recession of the grounding line (Fig. 8~~9~~a). In the second scenario ('embayment scenario'), the ice stream occupying Whales Deep experienced extensive retreat, forming a large grounding-line embayment in the ERS (Fig. ~~9~~8b).

The dynamic flow-switching scenario ~~entails~~ requires significant flow reorganization with westward ice flow out of Marie Byrd Land (d1, Fig. 8~~9~~a) followed by eastward flow across the inter-ice-stream ridge between Whales Deep and Glomar Challenger Basin (d2, Fig. ~~9~~8a). Trough-parallel flow was then established (d3, Fig. 8~~9~~a) and~~. In this scenario,~~ ice then began to retreat ~~north-to-south~~landward from the continental shelf in all ERS basins, interrupted by phases of grounding-line stabilization and formation of~~depositing~~ the large GZWs in Whales Deep and Glomar Challenger Basin (d4, Fig. ~~9~~8a~~; G3, W2, then G4, W3, Fig. 3~~). Different generations of MGSLs are preserved as the ~~ice-margin~~grounding-line retreats, but we would not expect them to be preserved if a re-advance or major new episode of streaming had occurred, remoulding the bedform field. ~~s. This scenario relies on preservation of at least three distinct flow orientations throughout three very different stages of flow across the outer shelf.~~ Although there have been examples of preserved flow fabrics during events of flow-switching (Stokes et al., 2009; Winsborrow et al., 2012) or at localized patches of basal friction (Stokes et al., 2007; Kleman and Glasser, 2007), the preservation of such extensive flow fabrics throughout three different ice flow configurations is unlikely.

The embayment scenario proposes the formation of an embayment over Whales Deep, based on the presence of large flowsets in surrounding basins that ~~curve~~ flow across ~~across~~ neighbouring inter-ice-stream ridges into Whales Deep (flowsets g, k, Fig. 4). Trough-parallel flow likely occurred first (e1, Fig. 8~~9~~b), as evidenced by the relatively undisturbed trough-parallel flowset in the outermost part of Whales Deep~~ trough~~. During trough-parallel flow, ice grounded on inter-ice-stream ridges was likely sluggish and strongly coupled to the bed (Klages et al., 2013). An embayment in the Whales Deep grounding line ~~then~~ formed (e2, Fig. 8b), drawing flow from outer Glomar Challenger Basin across the inter-ice-stream ridge into Whales Deep and ~~. Grounded ice stepped south in Whales Deep to a mid-shelf location long enough to~~ depositing a large-scale GZW on the mid-shelf (~~e2, Fig. 9b;~~ W2, Fig. 3). The grounding-line embayment then retreated further towards the Whales Deep inner shelf (e3, Fig. 8b), drawing ~~and then stepped south again to deposit the inner-shelf GZW (e3, Fig. 9b; W3, Fig. 3). An absence of linear features between GZWs W2 and W3 implies that the ice sheet was not in contact with the bed as it retreated. This further implies a relatively thin, low profile ice sheet within Whales Deep. As a result, the Whales Deep embayment drew~~ ice from Glomar Challenger Basin and Little America Basin~~,~~ and prompting flow across the inter-ice-stream ridges into Whales Deep. The ice stream feeding Whales Deep at the LGM may have experienced stagnation or outrun its inner-shelf ice source, destabilizing grounded ice on the outer shelf and causing an embayment to form. Modern

Siple Coast ice streams have been observed to slow and stagnate (Anandakrishnan and Alley, 1997; Joughin and Tulaczyk, 2002), suggesting dynamic behaviour in the past.

Shipp et al. (1999) identify the inter-ice-stream ridges in the ERS as aggradational features, meaning that they were centres of focused sedimentation. Embayment grounding lines would have stabilized on the edges of the inter-ice-stream ridges on either side of Whales Deep, transporting sediment to these bathymetric features and aggrading the inter-ice-stream ridges. A large embayment over the ERS is also compatible with the interpreted WRS deglaciation pattern, where a steep EAIS profile is inferred. The formation of an embayment in the ERS is consistent with grounding-line recession in the ERS prior to the WRS (Fig. 6c), followed by east-to-west deglaciation of the WRS ~~(Fig. 7)~~.

The two retreat models described here ~~each~~ imply a ~~sequence~~ succession of events that ~~can, in principle,~~can be tested. Greater coverage of high-resolution multibeam data in outer Glomar Challenger Basin, illuminating cross-cutting relationships between flowsets, is crucial for establishing a relative chronology of cross-trough versus trough-parallel flow. Additional multibeam surveys of inter-ice-stream ridges would also provide a better understanding of their role in directing the ~~relative chronology of~~general flow pattern (cf. Klages et al., 2013)~~set formation~~. Furthermore, reliable marine radiocarbon dates constraining ~~on~~ grounding-line retreat on the Whales Deep inner shelf might provide evidence for~~of~~ early retreat and the formation of a long-lived ~~embayment in the~~ grounding~~-~~-line embayment. Based on the available data in this study, the embayment scenario is favoured, due to the landform preservation issues inherent to the dynamic flow-switching model. ~~Thus, the embayment scenario is incorporated into our Ross Sea deglacial reconstruction (Fig. 7).~~

The Ross Sea geomorphological record permits us to reconstruct the pattern of ice flow and retreat independently of a radiocarbon chronology and the associated problems therein. Figure 7 presents reconstructed steps in grounding-line retreat that illustrate deglacial patterns across the Ross Sea. Observed grounding lines are linked together to form discrete episodes of deglaciation. These linkages are based on similar morphologies of observed GZWs, extension of grounding line orientations along bathymetric depth contours, and interpretation of local (albeit qualitative) retreat rates based on geomorphic features. Southern Drygalski Trough was the last area in the WRS to experience grounding-line retreat, as outlet glaciers (e.g. Mackay Glacier, and David Glacier flowing into the Drygalski Ice Tongue) receded toward the west and north, leaving fields of moraines and GZWs (Greenwood et al., 2012; Anderson et al., 2014), (Fig. 7). Drainage from the EAIS flowed into the Ross Sea Embayment until the last stage of deglaciation (Fig. 7, steps 7-8). We infer a steep EAIS ice profile over the WRS throughout deglaciation, based on the contribution of EAIS ice through the Transantarctic Mountains and grounding-line recession unaffected by topography in the central WRS (Fig. 5).

### 5.4 Comparison with existing deglacial models

Currently, there are two very different published retreat scenarios for the Ross Sea (Fig. 9~~10~~). One of these models, the ~~highly~~ often cited ‘swinging gate’ model (e.g. McKay et al., 2008; Hall et al., 2013), calls for a linear grounding line retreat across the Ross Sea, hinged just north of Roosevelt Island and extending to the Transantarctic Mountains (Conway et al., 1999). This model is constrained by the initiation of ice-divide flow over~~ one age~~ ~~from~~ Roosevelt Island, and two locations along the Transantarctic Mountains with ages ~~of~~ from ice-free coastlines~~ along the Transantarctic Mountains,~~ and it indicates deglaciation of the WRS at a faster rate than the ERS. The swinging gate ~~is~~ model implies that controls on ice-sheet dynamics were the same throughout the Ross Sea and that physiography had little influence on ice retreat. This ~~e swinging gate~~ model also implies that ice-sheet retreat from the Ross Sea was controlled mainly by changes in the WAIS catchment, suggesting very high rates of ~~north-to-south~~southward retreat along the coast of the Transantarctic Mountains (Conway et al., 1999; Hall et al., 2013, 2015). Alternatively, ~~T~~the ‘saloon door’ model ~~instead~~ proposes early retreat in the ERS with a grounding-line embayment in the central Ross Sea (Ackert, 2008). The implied drainage pattern of the saloon door model requires significant inputs from both the EAIS and the WAIS. This model is supported by cosmogenic exposure ages indicating a thinner ice-sheet profile in the central Ross Sea than at the margins of the WAIS (Parizek and Alley, 2004; Waddington et al., 2005; Anderson et al., 2014).

This study and previous marine studies (Licht et al., 1996; Cunningham et al., 1999; Anderson et al., 2014) suggest~~calling for~~ ~~an initial large back-step of the~~ early grounding-line retreat within ~~in~~ the northern Drygalski Trough, ~~are~~ consistent with the swinging gate model. However, ~~, which assumes early and rapid recession of grounded ice along the Transantarctic Mountains. The observations of~~ reconstructed grounding-line retreat on the remaining ~~in the rest of the~~ Ross Sea continental shelf ~~(Fig. 7)~~ contrasts ~~s~~ with the swinging gate model (Fig. 7). In particular, our marine-based reconstruction ~~calls~~ suggests ~~for the~~ persistent~~ce of the~~ EAIS drainage into the WRS throughout deglaciation, and indicates ~~s well as~~ significant regional variations in grounding-line behaviour between troughs and across banks. Our reconstruction supports the presence of a grounding-line~~n~~ embayment in the ERS, similar to the saloon door model. Here, grounding-line recession in Glomar Challenger Basin is interpreted to precede retreat in the WRS (Fig. 6c~~8b~~), destabilizing grounded ice in southern Pennell Trough and the Central Basin. Deglaciation of the ERS prior to the WRS supports the observation of the EAIS as a persistent feature in the WRS throughout deglaciation. ~~Additionally, marine radiocarbon dates from previous studies suggest that the ERS deglaciated before the WRS (Licht and Andrews, 2002; Mosola and Anderson, 2006), despite complications dating Antarctic glacial-marine sediments.~~

Neither the swinging gate nor the saloon door model ~~have thus far~~ incorporate~~d marine data,~~ observations from the continental shelf, and, as we show here, are not able to ~~do not~~ fully capture the complexity of grounding-line retreat across the Ross Sea. Our new marine-based model (Fig. 7), reconstructed from comprehensive mapping of seafloor geomorphic features that directly record~~ing~~ grounding-line retreat, can now be used to interpret more detailed Ross Sea paleo-ice sheet behaviour and identify regional differences in deglacial behaviour. Our glacial geomorphic reconstruction independently converges with recent numerical modelling. Model results demonstrate significant EAIS and WAIS contributions to ice flow in the Ross Sea, and suggest that deglaciation was initiated in Ross Sea troughs and influenced by bedrock highs (Golledge et al., 2014; McKay et al., 2016; DeConto and Pollard, 2016). Additionally, DeConto and Pollard (2016) reproduce an early ERS grounding-line embayment confined to Whales Deep and a WRS Central Basin embayment receding to the east and west, while Golledge et al. (2014) simulate repeated occupation of WRS banks by semi-independent ice rises. Regional reconstructions between models and geologic observations are therefore becoming more and more consistent; however, smaller-scale patterns of grounding-line retreat are not yet reproduced at the resolution of modern numerical models. These localized retreat patterns are important for understanding grounding-line dynamics and smaller-scale processes that drive regional ice behaviour. A key target for further refining such efforts must undoubtedly be a robust and reliable radiocarbon chronology.

## 5.5 Physiographic and geological controls on deglaciation

Many cycles of glacial erosion and deposition have led to Antarctic continental shelves characterized by a fore-deepened shelf profile with exposed bedrock on the inner shelf and thicker sediments on the outer shelf (Anderson, 1999). Runaway grounding-line retreat can occur as ice retreats from the outer to inner shelf due to a lack of pinning points to stabilize the grounding line (e.g. Mercer, 1978; Jamieson et al., 2012). In the WRS, banks and volcanic seamounts provided stable pinning points during deglaciation (Anderson et al., 2014; Simkins et al., in ~~review~~press), and bathymetric highs continue to stabilize the modern Siple Coast ice sheet and ice shelf (Matsuoka et al., 2015). Ice-marginal features are observed to back-step up onto WRS banks (Fig. 6~~8~~), demonstrating a strong physiographic control on grounding line behaviour. These banks served as pinning points for retreating ice streams and likely evolved into semi-independent ice rises during deglaciation. WRS banks supported an extensive ice shelf that buttressed WRS grounding lines and contributed to the long-lived presence of the EAIS in the WRS (Anderson et al., 2014; Yokoyama et al., 2016~~in press~~). While slight bottlenecking of ERS inter-ice-stream ridges may have played a role in determining positions of grounding-line stability and the formation of large-scale GZWs (Mosola and Anderson, 2006), the ERS seafloor~~scape~~ is much more topographically subdued than in the WRS. A lack of high-relief banks and troughs permitted more variable flow in the ERS, but did not allow for pinning and stabilization of ice streams as occurred in the WRS.

In addition to physiography, seafloor substrate has also been argued to exert a fundamental control on ice behaviour, as indicated by variations in geomorphic features across different substrates (e.g. Wellner et al., 2001; Larter et al., 2009; Graham et al., 2009). In Antarctica, studies have shown that ice streams flowing across soft, deformable sedimentary beds are characterized by MSGLs (e.g. Wellner et al., 2001, 2006; Ó Cofaigh et al., 2002, 2005; Graham et al., 2009). Ice flowing over unconsolidated beds can mobilize subglacial sediments and develop a thick layer of pervasive deformation till, facilitating faster ice flow than is possible by internal ice deformation (Alley et al., 1989). By contrast, crystalline bedrock or older and more consolidated strata outcropping on the seafloor ~~would be~~ are more resistant to glacial erosion, preventing the development of deforming till underneath a flowing ice stream, and are associated with bedrock erosional features such as drumlinoids that indicate slower ice-flow velocities and stick-slip motion. An excellent example is the field of drumlinoids in inner Glomar Challenger Basin that corresponds to a localized area of outcropping bedrock (Figs. 2c, Fig. 1~~1~~0). At the point where sedimentary deposits lap onto bedrock, these ~~features~~ drumlinoids transition seaward into MSGLs (Anderson, 1999).

The compilation of geological data in Fig. 1~~1~~0 shows the strata beneath the most recent observable glacial erosional surface, representing the substrate that ice flowing across the continental shelf at the LGM would have encountered. The ~~ages and~~ degree of ~~lithification~~ consolidation of these strata ~~are~~ is derived from information obtained from drill cores collected during Deep Sea Drilling Project Leg 28, extrapolated to high-resolution seismic stratigraphic correlations across the Ross Sea (Anderson and Bartek, 1992; Alonso et al., 1992; Anderson, 1999; Bart et al., 2000). The WRS is characterized by more variable geology and by older substrate~~ below the LGM unconformity~~, while mostly unconsolidated Plio-Pleistocene sediments blanket the ERS shelf. Thick and extensive unconsolidated sediments likely contributed to a pervasive layer of deformation till in the ERS (Mosola and Anderson, 2006). This thick layer of deformation till ~~condition~~ facilitated fast flowing ice and transported sediment to large-scale GZWs through a classic till conveyor-belt mechanism. ~~transporting sediment to large-scale GZWs, which then~~Fast-flowing ice likely contributed to a low~~-~~-profile ice sheet that episodically decoupled from the seafloor during retreat from the continental shelf (Mosola and Anderson, 2006). ~~Complex,~~M~~ m~~ore consolidated strata outcropping in the WRS may have limited such pervasive subglacial deformation, potentially causing slower ice stream velocities in WRS troughs. This characteristic seafloor geology, coupled with numerous pinning points, was conducive to a higher profile ice sheet that remained in contact with the seafloor throughout much of its retreat from the continental shelf.

~~Part of flowset *h* (Fig. 4) in Little America Basin is routed eastward away from the Ross Sea (Fig. 11). I~~Grounded ice in Little America Basin flowed over ~~the~~ its eastern ~~-most ridge~~bank and converged with an outlet glacier draining Marie Byrd Land (flowset *n*, Fig. 4). This flow pattern implies that at one point, Little America Basin ~~at its maximum configuration~~ was not able to drain all of the ice flowing into it ~~from its ice stream sources~~and therefore some of that ice was forced eastward out of the trough. ~~The substrate that~~During the LGM, Little America Basin ice streams flowed across ~~during the LGM was composed of~~ late Oligocene and Miocene sedimentary rocks (Fig. 10~~1~~). Thus, it was more resistant to ductile subglacial deformation than the substrates encountered by other ice streams flowing across the ERS. Resulting flow velocities were therefore not high enough to transport all of the ice entering the Little America Basin outlet, some of which was captured and funnelled into the neighbouring outlet.

~~Numerous processes affect glacial dynamics, such as ice-shelf buttressing, tidal amplification, sediment shear strength and ice-bed coupling, and subglacial meltwater. Ongoing work on characterizing Ross Sea glacial geomorphology highlights the effect of these processes on local grounding-line stability.~~ Physiography exerts a first-order control on regional ice stream flow and retreat dynamics, and s~~. S~~eafloor geology plays an important subsidiary role in controlling ice behaviour. These controls influence regional retreat patterns; more localised ice behaviour is still under investigation. Numerous other processes affect glacial dynamics, such as ice-shelf buttressing, sediment shear strength and ice-bed coupling, and subglacial meltwater (e.g. Boulton et al., 2001; Dupont and Alley, 2005; Stearns et al., 2008). External forcings such as tidal effects, circumpolar deep water incursion and under-melting of ice shelves, and atmospheric effects are also influential (e.g. Rignot, 1998; Zwally et al., 2002; Arneborg et al., 2012; Walker et al., 2013). Ross Sea retreat was asynchronous between troughs, suggesting differential responses to these processes. Ongoing work on characterizing Ross Sea glacial geomorphology highlights the effect of these forcings on local grounding-line stability.

## 6 Conclusions

During the LGM, grounded ice reached the continental shelf break in the ERS, but not in the WRS. The WRS seafloor is characterized by ~~recessional~~ geomorphic features that ~~signify~~ indicate~~episodic,~~ periods of rapid recession following the LGM, and ~~indicate~~ record the~~a~~ persistent presence of a steep-profiled EAIS in the WRS throughout deglaciation. Retreat in the ERS was likely initiated by the formation of a large grounding-line embayment ~~over~~ across Whales Deep~~ trough~~. Based on the~~our~~ interpretation of glacial geomorphic ~~indicators~~features, Glomar Challenger Basin in the ERS ~~was~~ is believed to have been completely deglaciated prior to retreat of grounded ice from the deep Central Basin in the WRS. ~~Retreat was asynchronous between Ross Sea troughs.~~

Considering the complex glacial geomorphic assemblages across the entire Ross Sea shelf, the ‘swinging gate’ and ‘saloon door’ models both fail to fully capture the style of deglaciation~~ in the Ross Sea~~. The saloon door model is more consistent with glacial geomorphic observations on the Ross Sea continental shelf, describing a mode of deglaciation that may have occurred in more than one sector as ice ~~the Ross Sea~~ retreated into its component sub-catchments. Based on this study, we conclude that it is eminently clear that deglaciation across the Ross Sea shelf did not involve a linear grounding line across the multiple troughs and banks. Additional analyses of Ross Sea continental shelf sedimentology and additional reliable radiocarbon ages marking grounding-line retreat are necessary to test and refine the deglacial patterns proposed here. A radiocarbon chronology will help integrate our grounding-line reconstruction with previous work done on Ross Sea deglacial history.

Major differences between regional retreat characteristics ~~can be~~are attributed to physiography. Ice was pinned on the high-relief banks in the WRS, whereas the lack of comparable features in the ERS indicates that the WAIS was no~~n’~~t stabilized by pinning points. Similar physiographic controls are likely buttressing the modern Siple Coast grounding line. Seafloor geology played a secondary role in influencing paleodrainage patterns. Younger and relatively unconsolidated Plio-Pleistocene sediments in the ERS, with the exception of Little America Trough, are associated with fast ice flow, whereas the older and more consolidated strata that characterized the WRS seafloor may have hindered pervasive till deformation and contributed to slower ice-stream velocities. These observations can be generalized to other locations with regional seafloor geologic variation, such as the Weddell Sea Embayment. The controls on flow behaviour and ~~deglaciation~~ retreat patterns revealed in our new Ross Sea deglacial reconstruction can now be incorporated into future work on understanding marine ice-sheet behaviour at the modern grounding line and across the Antarctic continental shelf.

## Acknowledgements

This research was funded by the National Science Foundation (NSF-PLR 1246353 to J.B.A) and the Swedish Research Council (D0567301 to S.L.G.). The authors thank the crew of the RV/IB *Nathaniel B. Palmer* and Antarctic Support Contract staff for a successful cruise. We thank Kathleen Gavahan for providing assistance with multibeam datasets, students from Rice University, University of Houston and Louisiana State University for participating in data collection and processing, and Jean Aroom and the Fondren GIS Center, Rice University, for technical support.

## References

Ackert, R.: Swinging gate or Saloon doors: Do we need a new model of Ross Sea deglaciation?, Fifteenth West Antarctic Ice Sheet Meeting, Sterling, Virginia, 8-11 October 2008.

Alley, R.B., Blankenship, D.D., Bentley, C.R., and Rooney, S.T.: Deformation of till beneath ice stream B, West Antarctica, Nature, 322, 57-59, doi:10.1038/322057a0, 1986.

Alley, R.B., Blankenship, D.D., Bentley, C.R., and Rooney, S.T.: Till beneath ice stream B, 4. Till deformation: evidence and implications, J. Geophys. Res., 92, 8921-8929, doi:10.1029/JB092iB09p08921, 1989.

Alley, R. B., Anandakrishnan, S., Dupont, T. K., Parizek, B. R., and Pollard, D.: Effect of sedimentation on ice-sheet grounding-line stability, Science, 315, 1838-1841, doi:10.1126/science.1138396, 2007.

Alonso, B., Anderson, J.B., Diaz, J.T., and Bartek, L.R.: Pliocene-Pleistocene seismic stratigraphy of the Ross Sea: evidence for multiple ice sheet grounding episodes, in: Contributions to Antarctic Research III, Antarctic Research Series, vol. 57, Elliot, D.H. (ed.), American Geophysical Union, Washington D.C, 93-103, doi:10.1029/AR057p0093, 1992.

Anandakrishnan, S. and Alley, R.B.: Stagnation of ice stream C, West Antarctica by water piracy, Geophys. Res. Lett., 24, 265-268, doi:10.1029/96GL04016, 1997.

Anandakrishnan, S., Catania, G.A., Alley, R.B., and Horgan, H.J.: Discovery of till deposition at the grounding line of Whillans Ice Stream, Science, 315, 1835-1838, doi:10.1126/science.1138393, 2007.

Anderson, J.B.: Antarctic Marine Geology, Cambridge University Press, New York, 1999.

Anderson, J.B. and Bartek, L.R.: Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information, in Antarctic Research Series, vol. 56, Kennett, J.P. (ed.), American Geophysical Union, Washington D.C., 231-263, doi:10.1029/AR056p0231, 1992.

Anderson, J.B. and Fretwell, L.O.: Geomorphology of the onset area of a paleo-ice stream, Marguerite Bay, Antarctic Peninsula, Earth Surf. Proc. Land, 33, 503-512, doi:10.1002/esp.1662, 2008.

Anderson, J.B., Brake, C.F., and Myers, N.C.: Sedimentation on the Ross Sea continental shelf, Antarctica, Mar. Geol., 57, 295-333, doi:10.1016/0025-3227(84)90203-2, 1984.

Anderson, J.B., Conway, H., Bart, P.J., Kirshner, A.E., Greenwood, S.L., McKay, R.M., Hall, B.L., Ackert, R.P., Licht, K., Jakobsson, M., and Stone, J.O.: Ross Sea Paleo-Ice Sheet Drainage and Deglacial History During and Since the LGM, Quaternary Sci. Rev., 100, 31-54, doi:10.1016/j.quascirev.2013.08.020, 2014.

Arneborg, L., Wåhlin, A.K., Björk, G., Liljebladh, B. and Orsi, A.H.: Persistent inflow of warm water onto the central Amundsen shelf, Nat. Geosci., 5, 876-880, doi:10.1038/ngeo1644, 2012.

Bart, P.J. and Cone, A.N.: Early stall of West Antarctic Ice Sheet advance on the eastern Ross Sea middle shelf followed by retreat at 27,500 14C yr BP, Palaeogeogr. Palaeocl., 335-336, 52-60, doi:10.1016/j.palaeo.2011.08.007, 2011.

Bart, P.J. and Owolana, B.: On the duration of West Antarctic Ice Sheet grounding events in Ross Sea during the Quaternary, Quaternary Sci. Rev., 47, 101-105, doi:10.1016/j.quascirev.2012.04.023, 2012.

Bart, P.J., Anderson, J.B., Trincardi, F., and Shipp, S.S.: Seismic data from the Northern Basin, Ross Sea record multiple expansions of the East Antarctic Ice Sheet during the late Neogene, Mar. Geol., 166, 31-50, doi:10.1016/S0025-3227(00)00006-2, 2000.

Batchelor, C.L. and Dowdeswell, J.A.: Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins, Mar. Geol., 363, 65-92, doi:10.1016/j.margeo.2015.02.001, 2015.

Benn, D.I. and Evans, D.J.A.: Glaciers and Glaciation, 2, Hodder Education, London, U.K., 2010.

Bentley, M. J., Ocofaigh, C., Anderson, J. B., Conway, H., Davies, B., Graham, A. G. C., Hillenbrand, C.D., Hodgson, D.A., Jamieson, S.S.R., Larter, R.D., Mackintosh, A., Smith, J.A., Verleyen, E., Ackert, R.P., Bart, P.J., Berg, S., Brunstein, D., Canals, M., Colhoun, E.A., Crosta, X., Dickens, W.A., Domack, E., Dowdeswell, J.A., Dunbar, R., Ehrmann, W., Evans, J., Favier, V., Fink, D., Fogwill, C.J., Glasser, N.F., Gohl, K., Golledge, N.R., Goodwin, I., Gore, D.B., Greenwood, S.L., Hall, B.L., Hall, K., Hedding, D.W., Hein, A.S., Hocking, E.P., Jakobsson, M., Johnson, J.S., Jomelli, V., Jones, R.S., Klages, J.P., Kristoffersen, Y., Kuhn, G., Leventer, A., Licht, K., Lilly, K., Lindow, J., Livingstone, S.J., Massè, G., McGlone, M.S., McKay, R.M., Melles, M., Miura, H., Mulvaney, R., Nel, W., Nitsche, F.O., O'Brien, P.E., Post, A.L., Roberts, S.J., Saunders, K.M., Selkirk, P.M., Simms, A.R., Spiegel, C., Stolldorf, T.D., Sugden, D.E., van der Putten, N., van Ommen, T., Verfaillie, D., Vyverman, W., Wagner, B., White, D.A., Witus, A.E. and Zwartz, D.: A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum, Quaternary Sci. Rev., 100, 1-9, doi:10.1016/j.quascirev.2014.06.025, 2014.

Bevis, M., Kendrick, E., Smalley, R., Dalziel, I., Caccamise, D., Sasgen, I., Helsen, M., Taylor, F.W., Zhou, H., Brown, A., Raleigh, D., Willis, M., Wilson, T. and Konfal, S.: Geodetic measurements of vertical crustal velocity in West Antarctica and the implications for ice mass balance, Geochem. Geophys. Geosyst., 10, Q10005, doi:10.1029/2009GC002642, 2009.

Brancolini, G., (ed): ANDOSTRAT Project, in: Cooper, A.K., Barker, P.F., and Brancolini, G. (eds.), Geology and Seismic Stratigraphy of the Antarctic Margin, Antarctic Research Series, vol. 68, American Geophysical Union, Washington D.C., 1995.

Brunt, K.M., Fricker, H.A., Padman, L., Scambos, T.A., and O'Neel, S.: Mapping the grounding zone of Ross Ice Shelf, Antarctica, using ICESat laser altimetry, Ann. Glaciol., 51, 71–79, doi:10.3189/172756410791392790, 2010.

Clark, C.D.: Mega-scale glacial lineations and cross-cutting ice flow landforms, Earth Surf. Proc. Land., 18, 1-29, doi:10.1002/esp.3290180102, 1993.

Clark, C.D.: Glaciodynamic context of subglacial bedform generation and preservation, Ann. Glaciol., 28, 23-32, doi:10.3189/172756499781821832, 1999.

Conway, H., Hall, B.L., Denton, G.H., Gades, A.M., and Waddington, E.D.: Past and future grounding-line retreat of the West Antarctic Ice Sheet, Science, 286, 280-283, doi:10.1126/science.286.5438.280, 1999.

Cooper, A.K., Barrett, P.J., Hinz, K., Traube, V., Leitchenkov, G., and Stagg, H.M.J.: Cenozoic prograding sequences of the Antarctic continental margin - a record of glacioeustatic and tectonic events, Mar. Geol., 102, 175-213, doi:10.1016/0025-3227(91)90008-R, 1991.

Cunningham, W.L., Leventer, A., Andrews, J.T., Jennings, A.E., and Licht, K.J.: Late Pleistocene–Holocene marine conditions in the Ross Sea, Antarctica: evidence from the diatom record, The Holocene, 9, 129-139, doi:10.1191/095968399675624796, 1999.

~~Davey, F.J., Bennett, D.J., and Houtz, R.E.: Sedimentary basins of the Ross Sea, Antarctica, New Zeal. J. Geol. Geop., 25, 245-255, doi:10.1080/00288306.1982.10421413, 1982.~~

DeConto, R. M. and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, Nature, 531, 591-597, doi:10.1038/nature17145, 2016.

DeSantis, L., Anderson, J.B., Brancolini, G., and Zayatz, I.: Glaciomarine deposits on the continental shelf of Ross Sea, Antarctica, in: Glaciated Continental Margins: An Atlas of Acoustic Images, Davies, T.A., et al. (eds.), Chapman & Hall, London, U.K., 110-113, 1997.

Denton, G.H. and Marchant, D.: The geologic basis for a reconstruction of a grounded ice sheet in McMurdo Sound, Antarctica, at the last glacial maximum, Geogr. Ann. A., 82, 167-212, doi: 10.1111/j.0435-3676.2000.00121.x, 2000.

Dowdeswell, J.A. and Fugelli, E.M.G.: The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets, Geol. Soc. Am. Bull., 124, 1750-1761, doi:10.1130/B30628.1, 2012.

Dowdeswell, J.A., Ó Cofaigh, C., and Pudsey, C.J.: Thickness and extent of the subglacial till layer beneath an Antarctic paleo–ice stream, Geology, 32, 13-16, doi:10.1130/G19864.1, 2004.

Dowdeswell, J.A., Ottesen, D., Evans, J., O'Cofaigh, C.O., and Anderson, J.B.: Submarine glacial landforms and rates of ice-stream collapse, Geology, 36, 819-822, doi:10.1130/G24808A.1, 2008.

Dupont, T.K., and Alley, R.B.: Assessment of the importance of ice-shelf buttressing to ice-sheet flow, Geophys. Res. Lett., 32, L04503, doi:10.1029/2004GL022024, 2005.

Evans, J., Pudsey, C.J., Ó Cofaigh, C., Morris, P.W., and Domack, E.W.: Late Quaternary glacial history, dynamics and sedimentation of the eastern margin of the Antarctic Peninsula Ice Sheet, Quaternary Sci. Rev., 24, 741-774, doi:10.1016/j.quascirev.2004.10.007, 2005.

Farmer, G.L., Licht, K., Swope, R.J., and Andrews, J.T.: Isotopic constraints on the provenance of fine-grained sediment in LGM tills from the Ross Embayment, Antarctica, Earth Planet. Sc. Lett., 249, 90-107, doi:10.1016/j.epsl.2006.06.044, 2006.

Fowler, A.C.: The formation of subglacial streams and mega-scale glacial lineations, P. Roy. Soc. A-Math. Phy., 466, 3181-3201, doi:10.1098/rspa.2010.0009, 2010.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Bar- rand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blanken- ship, 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.

Fricker, H. A. and Padman L.: Ice shelf grounding zone structure from ICESat laser altimetry, Geophys. Res. Lett., 33, L15502, doi:10.1029/2006GL026907, 2006.

Gales, J.A., Larter, R.D., Mitchell, N.C., Hillenbrand, C-D., Østerhus, S., and Shoosmith, D.: Southern Weddell Sea shelf edge geomorphology: implications for gully formation by the overflow of high-salinity water, J. Geophys. Res., 117, F0402, doi:10.1029/2012JF002357, 2012.

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, R.P., Maas, S.M. and Hall, B. L.: Glaciology and geological signature of the Last Glacial Maximum Antarctic ice sheet, Quaternary Sci. Rev., 78, 225-247, doi:10.1016/j.quascirev.2013.08.011, 2013.

Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., and Levy, R.H.: Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning, Nat. Commun., 5, 5107, doi:10.1038/ncomms6107, 2014.

Graham, A.G.C., Later, R.D., Gohl, K., Hillenbrand, C.-D, Smith, J.A., and Kuhn, G.: Bedform signature of a West Antarctic ice stream reveals a multi-temporal record of flow and substrate control, Quaternary Sci. Rev., 28, 2774-279, doi:10.1016/j.quascirev.2009.07.003, 2009.

Graham, A.G.C., Dutrieuz, P., Vaughan, D.G., Nitsche, F.O., Gyllencreutz, R., Greenwood, S.L., Larter, R.D., and Jenkins, A.: Seabed corrugations beneath an Antarctic ice shelf revealed by autonomous underwater vehicle survey: Origin and implications for the history of Pine Island Glacier, J. Geophys. Res., 118, 1356-1366, doi:10.1002/jgrf.20087, 2013.

Greenwood, S.L., Gyllencreutz, R., Jakobsson, M., and Anderson, J.B.: Ice-flow switching and East/West Antarctic Ice Sheet roles in glaciation of the western Ross Sea, Geol. Soc. Am. Bull., 124, 1736-1749, doi:10.1130/B30643.1, 2012.

~~Hall, B.L., Denton, G.H., and Hendy, C.: Evidence from Taylor Valley for a grounded ice sheet in the Ross Sea, Antarctica, Geogr. Ann. A., 82, 275-304, doi:10.1111/j.0435-3676.2000.00126.x, 2000~~

Hall, B.L. and Denton, G.H.: Radiocarbon Chronology of Ross Sea Drift, Eastern Taylor Valley, Antarctica: Evidence for a Grounded Ice Sheet in the Ross Sea at the Last Glacial Maximum, Geogr. Ann. A., 82, 205-336, doi: 10.1111/j.0435-3676.2000.00127.x, 2000.

Hall, B.L., Baroni, C. and Denton, G.H.: Holocene relative sea-level history of the Southern Victoria Land Coast, Antarctica, Global Planet. Change, 42, 241-263, doi:10.1016/j.gloplacha.2003.09.004, 2004.

Hall, B.L., Henderson, G.M., Baroni, C. and Kellogg, T.B.: Constant Holocene Southern-Ocean 14C reservoir ages and ice-shelf flow rates, Earth Planet. Sci. Lett., 296, 115-123, doi:10.1016/j.epsl.2010.04.054, 2010.

Hall, B.L., Denton, G.H., Stone, J.O., and Conway, H.: History of the grounded ice sheet in the Ross Sea sector of Antarctica during the Last Glacial Maximum and the last termination, Geol. Soc. Lond., 381, 167-181, doi:10.1144/SP381.5, 2013.

Hall, B. L., Denton, G. H., Heath, S. L., Jackson, M. S., and Koffman, T. N.: Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation, Nat. Geosci., 8, 625-628, doi:10.1038/ngeo2478, 2015.

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, doi:10.1130/B25694.1, 2005.

Hoppe, G.: Glacial morphology and inland ice recession in northern Sweden, Geogr. Ann., 41, 193-212, 1959.

Howat, I.M. and Domack, E.W.: Reconstructions of western Ross Sea palaeo-ice-stream grounding zones from high-resolution acoustic stratigraphy, Boreas, 32, 56-75, doi:10.1111/j.1502-3885.2003.tb01431.x, 2003.

Jakobsson, M., Anderson, J.B., Nitsche, F., Dowdeswell, J.A., Gyllencreutz, R., Kirchner, N., Mohammad, R., O'Regan, M., Alley, R.B., Anandakrishnan, S., Eriksson, B., Kirshner, A., Fernandez, R., Stolldorf, T., Minzoni, R., and Majewski, W.: Geological record of ice shelf break-up and grounding line retreat, Pine Island Bay, West Antarctica, Geology, 39, 691-694, doi:10.1130/G32153.1, 2011.

Jakobsson, M., Anderson, J.B., Nitsche, F.O., Gyllencreutz, R., Kirshner, A.E., Kirchner, N., O'Regan, M., Mohammad, R., and Eriksson, B.: Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica, Quaternary Sci. Rev., 38, 1-10, doi:10.1016/j.quascirev.2011.12.017, 2012.

Jamieson, S. S. R., Vieli, A., Livingstone, S. J., Cofaigh, C. Ó., Stokes, C., Hillenbrand, C.-D., and Dowdeswell, J. A.: Ice-stream stability on a reverse bed slope, Nat. Geosci., 5, 799-802, doi:10.1038/ngeo1600, 2012.

Jones, R.S., Mackintosh, A.N., Norton, K.P., Golledge, N.R., Fogwill, C.J., Kubik, P.W., Christl, M., and Greenwood, S.L.: Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability, Nat. Commun., 6, 8910, doi:10.1038/ncomms9910, 2015.

Joughin, I. and Tulaczyk, S.: Positive mass balance of the Ross Ice Streams, West Antarctica, Science, 295, 476-480, doi:10.1126/science.1066875, 2002.

King, E. C., Hindmarsh, R. C., and Stokes, C. R.: Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream, Nat. Geosci., 2, 585-588, doi:10.1038/ngeo581, 2009

Klages, J.P., Kuhn, G., Hillenbrand, C.D., Graham, A.G.C., Smith, J.A., Larter, R.D. and Gohl, K.: First geomorphological record and glacial history of an inter-ice stream ridge on the West Antarctic continental shelf, Quaternary Sci. Rev., 61, 47-61, doi:10.1016/j.quascirev.2012.11.007, 2013.

Klages, J.P., Kuhn, G., Graham, A.G.C., Hillenbrand, C.D., Smith, J.A., Nitsche, F.O., Larter, R.D., and Gohl, K.: Palaeo-ice stream pathways and retreat style in the easternmost Amundsen Sea Embayment, West Antarctica, revealed by combined multibeam bathymetric and seismic data, Geomorphology, 245, 207-222, doi:10.1016/j.geomorph.2015.05.020, 2015.

Kleman, J. and Glasser, N.F.: The subglacial thermal organisation (STO) of ice sheets, Quaternary Sci. Rev., 26, 585-597, doi:10.1016/j.quascirev.2006.12.010, 2007.

Larter, R.D., Graham, A.G.C., Gohl, K., Kuhn, G., Hillenbrand, C.D., Smith, J.A., Deen, T.J., Livermore, R.A. and Schenke, H.W.: Subglacial bedforms reveal complex basal regime in a zone of paleo-ice stream convergence, Amundsen Sea embayment, West Antarctica, Geology, 37, 411-414, doi: 10.1130/G25505A.1, 2009.

Larter, R.D., Graham, A.G.C., Hillenbrand, C.D., Smith, J.A. and Gales, J.A.: Late Quaternary grounded ice extent in the Filchner Trough, Weddell Sea, Antarctica: New marine geophysical evidence, Quaternary Sci. Rev., 53, 111-122, doi:10.1016/j.quascirev.2012.08.006, 2012.

Lawver, L.A., Royer, J.Y., Sandwell, D.T. and Scotse, C.R.: Evolution of the Antarctic continental margin, in: Geological Evolution of Antarctica, Thomson, M.R.A. et al. (eds.), Cambridge University Press, Cambridge, UK, 533-540, 1991.

Licht, K. and Andrews, J.T.: A 14C record of late Pleistocene ice advance and retreat in the central Ross Sea, Antarctica, Arct. Antarct. Alp. Res., 34, 324-333, doi:10.2307/1552491, 2002.

Licht, K.J., Jennings, A.E., Andrews, J.T. and Williams, K.M: Chronology of late Wisconsin ice retreat from the western Ross Sea, Antarctica. Geology, 24, 223-226, 1996.

Licht, K., Dunbar, N., Andrews, J.T., and Jennings, A.E.: Distinguishing subglacial till and glacial marine diamictons in the western Ross Sea, Antarctica: implications for a last glacial maximum grounding line, Geol. Soc. Am. Bull., 111, 91-103, doi: 10.1130/0016-7606(1999)111<0091:DSTAGM>2.3.CO;2, 1999.

Licht, K.J., Lederer, J.R., and Swope, R.J.: Provenance of LGM glacial till (sand fraction) across the Ross Embayment, Antarctica, Quaternary Sci. Rev., 24, 1499-1520, doi:10.1016/j.quascirev.2004.10.017, 2005.

~~Lien, R., Solheim, A., Elverhoi, A., and Rokoengen, K.: Iceberg scouring and sea bed morphology on the eastern Weddell Sea shelf, Antarctica, Polar Res., 7, 43-57, doi:10.1111/j.1751-8369.1989.tb00603.x, 1989.~~

Lindén, M. and Möller, P.: Marginal formation of De Geer moraines and their implications to the dynamics of grounding-line recession, J. Quaternary Sci., 20, 113-133, doi:10.1002/jqs.902, 2005.

Livingstone, S.J., O'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, doi:10.1016/j.earscirev.2011.10.003, 2012.

Lowe, A.L. and Anderson, J.B.: Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica,. J. Glaciol., 49, 125-138, doi:10.3189/172756503781830971, 2003

MacAyeal, D.R., Scambos, T.A., Hulbe, C.L., and Fahnestock, M.A.: Catastrophic ice-shelf break-up by an ice-shelf-fragment-capsize mechanism, J. Glaciol., 49, 22-36, doi:10.3189/172756503781830863, 2003.

Matsuoka, K., Hindmarsh, R.C.A., Moholdt, G., Bentley, M.J., Pritchard, H.D., Brown, J., Conway, H., Drews, R., Durand, G., Goldberg, D., Hattermann, T., Kingslake, J., Lenaerts, J.T.M., Martin, C., Mulvaney, R., Nicholls, K.W., Pattyn, F., Ross, N., Scambos, T.A., and Whitehouse, P.L.: Antarctic ice rises and rumples: Their properties and significance for ice-sheet dynamics and evolution, Earth-Sci. Rev., 150, 724-745, doi:10.1016/j.earscirev.2015.09.004, 2015.

McKay, R.M., Dunbar, G.B., Naish, T.R., Barrett, P.J., Carter, L. and Harper, M.: Retreat history of the Ross Ice Sheet (Shelf) since the Last Glacial Maximum from deep-basin sediment cores around Ross Island, Palaeogeogr., Palaeocl., 260, 245-261, doi:10.1016/j.palaeo.2007.08.015, 2008.

McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G. and Kuhn, G.: Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene, Geology, 44, 7-10, doi:10.1130/G37315.1, 2016.

~~Menzies, J.: A review of the literature on the formation and location of drumlins, Earth-Sci. Rev., 14, 315-359, doi:10.1016/0012-8252(79)90093-X, 1979.~~

Mercer, J.H.: West Antarctic Ice Sheet and $CO_2$ greenhouse effect: a threat of disaster, Nature, 271, 321-325, 1978.

Mosola, A.B. and Anderson, J.B.: Expansion and rapid retreat of the West Antarctic Ice Sheet in Eastern Ross Sea: possible consequence of over extended ice streams?, Quaternary Sci. Rev., 25, 2177-2196, doi:10.1016/j.quascirev.2005.12.013, 2006.

Nitsche, F.O., Gohl, K., Larter, R.D., Hillenbrand, C.D., Kuhn, G., Smith, J.A., Jacobs, S., Anderson, J.B. and Jakobsson, M.: Paleo ice flow and subglacial meltwater dynamics in Pine Island Bay, West Antarctica, The Cryosphere, 7, 249-262, doi:10.5194/tc-7-249-2013, 2013.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., and Morris, P.: Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf, Geophys. Res. Lett., 29, 41-1 - 41-4, doi:10.1029/2001GL014488, 2002.

Ó Cofaigh, C., Dowdeswell, J.A., Allen, C.S., Hiemstra, J., Pudsey, C.J., Evans, J., and Evans, D.J.A.: Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream, Quaternary Sci. Rev., 24, 709-740, doi:10.1016/j.quascirev.2004.10.006, 2005.

Ó Cofaigh, C., Dowdeswell, J.A., Evans, J., and Larter, R.D.: Geological constraints on Antarctic palaeo–ice stream retreat rates, Earth Surf. Proc. Land., 33, 513-525, doi:10.1002/esp.1669, 2008.

Parizek, B.R. and Alley, R.B.: Ice thickness and isostatic imbalances in the Ross Embayment, West Antarctica: model results, Global Planet. Change, 42, 265-278, doi:10.1016/j.gloplacha.2003.09.005, 2004.

Pollard, D. and DeConto, R.M.: Modelling West Antarctic ice sheet growth and collapse through the past five million years, Nature, 458, 329-332, doi:10.1038/nature07809, 2009.

Rignot, E.J.: Fast Recession of a West Antarctic Glacier, Science, 281, 549-551, doi: 10.1126/science.281.5376.549, 1998.

Shaw, J., Pugin, A., and Young, R.R.: A meltwater origin for Antarctic shelf bedforms with special attention to megalineations, Geomorphology, 102, 364-375, doi:10.1016/j.geomorph.2008.04.005, 2008.

Shipp, S. and Anderson, J.B.: Grounding zone wedges on the Antarctic continental shelf, Ross Sea, in: Glaciated Continental Margins: An Atlas of Acoustic Images, Davies, T.A., et al. (ed.), Chapman & Hall, London, U.K., 104-105, 1997.

Shipp, S., Anderson, J., and Domack, E.: Late Pleistocene-Holocene retreat of the West Antarctic Ice Sheet system in the Ross Sea: part 1-geophysical results, Geol. Soc. Am. Bull., 111, 1486-1516, doi: 10.1130/0016-7606(1999)111<1486:LPHROT>2.3.CO;2, 1999.

Shipp, S.S., Wellner, J.S., and Anderson, J.B.: Retreat signature of a polar ice stream: sub-glacial geomorphic features and sediments from the Ross Sea, Antarctica, in: Dowdeswell, J.A., O'Cofaigh, C. (eds.), Glacier-influenced Sedimentation on High Latitude Continental Margins, Geol. Soc. Lond., 203, 277-304, 2002.

Simkins, L., Anderson, J., and Greenwood, S.L.: Glacial landform assemblage reveals complex retreat of grounded ice in the Ross Sea, Antarctica, in: Atlas of Submarine Glacial Landforms, Dowdeswell, J., Canals, M., Jakobsson, M., Todd, B., Dowdeswell, E., and Hogan, K. (eds.), in ~~review~~press~~, 2016~~.

Smith, J.A., Hillenbrand, C.D., Larter, R.D., Graham, A.G. and Kuhn, G.: The sediment infill of subglacial meltwater channels on the West Antarctic continental shelf, Quaternary Res., 71,190-200, doi:10.1016/j.yqres.2008.11.005, 2009.

Spagnolo, M., Clark, C. D., Ely, J. C., Stokes, C. R., Anderson, J. B., Andreassen, K., Graham, A., and King, E. C.: Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset, Earth Surf. Proc. Land., 39, 1432-1448, doi:10.1002/esp.3532, 2014.

Stokes, C.R. and Clark, C.D.: Geomorphological criteria for identifying Pleistocene ice streams, Ann. Glaciol., 28, 67-74, doi:10.3189/172756499781821625, 1999.

Stokes, C.R., Clark, C.D., Lian, O.B., and Tulaczyk, S.: Ice stream sticky spots: A review of their identification and influence beneath contemporary and palaeo-ice streams, Earth-Sci. Rev., 81, 217-249, doi:10.1016/j.earscirev.2007.01.002, 2007.

Stokes, C.R., Clark, C.D., and Storrar, R.: Major changes in ice stream dynamics during deglaciation of the north-western margin of the Laurentide Ice Sheet, Quaternary Sci. Rev., 28, 721-738, doi:10.1016/j.quascirev.2008.07.019, 2009.

Stone, J.O., Balco, G.A., Sugden, D.E., Caffee, M.W., Sass, L.C., Cowdery, S.G. and Siddoway, C.: Holocene Deglaciation of Marie Byrd Land, West Antarctica, Science, 299, 99-102, doi:10.1126/science.1077998, 2003.

Taviani, M., Reid, D.E., and Anderson, J.B.: Skeletal and isotopic composition and paleoclimatic significance of Late Pleistocene carbonates, Ross Sea, Antarctica, J. Sediment. Petrol., 63, 84-90, 1993.

Todd, B.J., Valentine, P.C., Longva, O., and Shaw, J.: Glacial landforms on German Bank, Scotian Shelf: evidence for late Wisconsinan ice-sheet dynamics and implications for the formation of De Geer moraines, Boreas, 36, 148-169, doi:10.1111/j.1502-3885.2007.tb01189.x, 2007.

Tulaczyk, S.M., Scherer, R.P., and Clark, C.D.: A ploughing model for the origin of weak tills beneath ice streams: a qualitative treatment, Quatern. Int., 86, 59-70, doi:10.1016/S1040-6182(01)00050-7, 2001.

Waddington, E.D., Conway, H., Steig, E.J., Alley, R.B., Brook, E.J., Taylor, K.C., and White, J.W.C.: Decoding the dipstick: thickness of Siple Dome, West Antarctica, at the last glacial maximum, Geology, 33, 281-284, doi:10.1130/G21165.1, 2005.

Walker, R.T., Parizek, B.R., Alley, R.B., Anandakrishnan, S., Riverman, K.L. and Christianson, K.: Ice-shelf tidal flexure and subglacial pressure variations, Earth Planet. Sci. Lett., 361, 422-428, doi:10.1016/j.epsl.2012.11.008, 2013.

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 behaviour, 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, doi:10.1016/j.geomorph.2005.05.015, 2006.

Winkelmann, D., Jokat, W., Jensen, L. and Schenke, H.W.: Submarine end moraines on the continental shelf off NE Greenland – Implications for Lateglacial dynamics, Quaternary Sci. Rev., 29, 1069-1077, doi:10.1016/j.quascirev.2010.02.002, 2010.

Winsborrow, M. C., Stokes, C. R., and Andreassen, K.: Ice-stream flow switching during deglaciation of the southwestern Barents Sea, Geol. Soc. Am. Bull., 124, 275-290, doi:10.1130/B30416.1, 2012.

Witus, A.E., Branecky, C.M., Anderson, J.B., Szczuciński, W., Schroeder, D.M., Blankenship, D.D. and Jakobsson, M.: Meltwater intensive glacial retreat in polar environments and investigation of associated sediments: example from Pine Island Bay, West Antarctica, Quaternary Sci. Rev., 85, 99-118., doi:10.1016/j.quascirev.2013.11.021, 2014.

Yokoyama, Y., Anderson, J., Yamane, M. Simkins, L.M., Miyairi, Y., Yamazaki, T., Koizumi, M., Suga, H., Kusahara, K., Prothro, L., Hasumi, H., Southon, J.R., and Ohkouchi, N.: Widespread collapse of the Ross Ice Shelf during the late Holocene, P. Natl. Acad. Sci. USA, 113, 2354-2359, doi:10.1073/pnas.1516908113, 2016.

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J and Steffen, K.: Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow, Science, 297, 218-222, doi:10.1126/science.1072708, 2002.

Supplementary Table 1. Multibeam dataset compilation. NBP1502 cruise data were used here with the permission of J.B. Anderson. The remaining Nathaniel B. Palmer (NBP) cruise data were accessed through the Lamont-Doherty Earth Observatory (*marine-geo.org*) and the Oden data are available at *oden.geo.su.se*. Swedish Polar Research = SPR.

| ***Cruise Number*** | ***Vessel*** | ***Multibeam System*** | ***Date*** | ***PI*** |
|---|---|---|---|---|
| NBP9801 | NBP | SeaBeam Instruments 2112 | 1/16/1998 - 2/18/1998 | J.B. Anderson |
| NBP9802 | NBP | SeaBeam Instruments 2112 | 2/22/1998 - 4/2/1998 | S. Honjo |
| NBP9803 | NBP | SeaBeam Instruments 2112 | 5/1/1998 - 6/17/1998 | M. Jeffries/D. Garrison |
| NBP9807 | NBP | SeaBeam Instruments 2112 | 11/1/1998 - 12/12/1998 | R. Dunbar |
| NBP9901 | NBP | SeaBeam Instruments 2112 | 12/26/1998 - 2/4/1999 | M. Jeffries |
| NBP9902 | NBP | SeaBeam Instruments 2112 | 2/12/1999 - 3/22/1999 | J.B. Anderson |
| NBP9909 | NBP | SeaBeam Instruments 2112 | 12/20/1999 - 2/9/2000 | J. Bengtson |
| NBP0001 | NBP | SeaBeam Instruments 2112 | 2/14/2000 - 3/30/2000 | S. Jacobs/T. Kellogg |
| NBP0209 | NBP | Kongsberg EM120 | 12/11/2002 - 12/30/2002 | S. Cande |
| NBP0301 | NBP | Kongsberg EM120 | 1/5/2003 - 1/29/2003 | L. Bartek/B. Luyendyk |
| NBP0301A | NBP | Kongsberg EM120 | 2/1/2003 - 2/18/2003 | P. Bart |
| NBP0301B | NBP | Kongsberg EM120 | 2/20/2003 - 2/22/2003 | W. Smith/V. Asper |
| NBP0302 | NBP | Kongsberg EM120 | 2/24/2003 - 4/4/2003 | A. Gordon |
| NBP0305A | NBP | Kongsberg EM120 | 12/20/2003 - 12/30/2003 | W. Smith |
| NBP0306 | NBP | Kongsberg EM120 | 1/4/2004 - 1/15/2004 | B. Luyendyk/L. Bartek |
| NBP0401 | NBP | Kongsberg EM120 | 1/19/2004 - 2/17/2004 | T. Wilson |
| NBP0402 | NBP | Kongsberg EM120 | 2/21/2004 - 4/6/2004 | M. Visbeck |
| NBP0408 | NBP | Kongsberg EM120 | 10/12/2004 - 12/6/2004 | S. Jacobs |
| NBP0409 | NBP | Kongsberg EM120 | 12/18/2004 - 1/21/2005 | R. Kiene/D. Kieber |
| NBP0501 | NBP | Kongsberg EM120 | 1/28/2005 - 2/13/2005 | A. Gordon |
| NBP0508 | NBP | Kongsberg EM120 | 10/26/2005 - 12/3/2005 | P. Neale |
| NBP0601 | NBP | Kongsberg EM120 | 12/17/2005 - 1/24/2006 | G. DiTullio |
| NBP0601A | NBP | Kongsberg EM120 | 1/30/2006 - 2/2/2006 | W. Smith |
| NBP0602 | NBP | Kongsberg EM120 | 1/30/2006 - 2/21/2006 | J. Stock |

| | | | | |
|---|---|---|---|---|
| NBP0608 | NBP | Kongsberg EM120 | 11/3/2006 - 12/11/2006 | G. DiTullio |
| NBP0701 | NBP | Kongsberg EM120 | 12/22/2006 - 1/28/2007 | S. Cande/P. Castillo |
| NBP0702 | NBP | Kongsberg EM120 | 2/2/2007 - 3/23/2007 | S. Jacobs |
| OSO0708 | *Oden* | Kongsberg EM122 | 11/29/2007 - 1/7/2008 | SPR Secretariat |
| NBP0801 | NBP | Kongsberg EM120 | 1/9/2008 - 1/26/2008 | D. Caron/B. Huber |
| NBP0802 | NBP | Kongsberg EM120 | 1/30/2008 - 2/20/2008 | D. Caron/P. Bart |
| NBP0803 | NBP | Kongsberg EM120 | 2/22/2008 - 3/13/2008 | P. Bart |
| NBP1005A | NBP | Kongsberg EM120 | 1/13/2010 - 1/16/2011 | P. Yager |
| OSO0910 | Oden | Kongsberg EM122 | 2/8/2010 - 3/12/2010 | M. Jakobsson/J.B. Anderson |
| NBP1005 | NBP | Kongsberg EM120 | 11/26/2010 - 1/16/2011 | P. Yager |
| OSO1011 | Oden | Kongsberg EM122 | 12/8/2010 - 1/16/2011 | SPR Secretariat |
| NBP1101 | NBP | Kongsberg EM120 | 1/19/2011 - 2/15/2011 | J. Kohut/A. Kutska |
| NBP1102 | NBP | Kongsberg EM120 | 2/19/2011 - 4/23/2011 | J. Swift |
| NBP1201 | NBP | Kongsberg EM120 | 12/24/2011 - 2/11/2012 | D. McGillicuddy |
| NBP1202 | NBP | Kongsberg EM120 | 2/11/2012 - 2/27/2012 | H. Owen |
| NBP1210 | NBP | Kongsberg EM120 | 1/6/2013 - 2/9/2013 | K. Halanych |
| NBP1302 | NBP | Kongsberg EM120 | 2/12/2013 - 4/5/2013 | D. Hansell/X. Yuan/G. Kooyman |
| NBP1310B | NBP | Kongsberg EM120 | 12/3/2013 - 1/23/2014 | K. Arrigo/R. Aronson |
| NBP1502A | NBP | Kongsberg EM122 | 1/23/2015 - 3/20/2015 | J.B. Anderson |

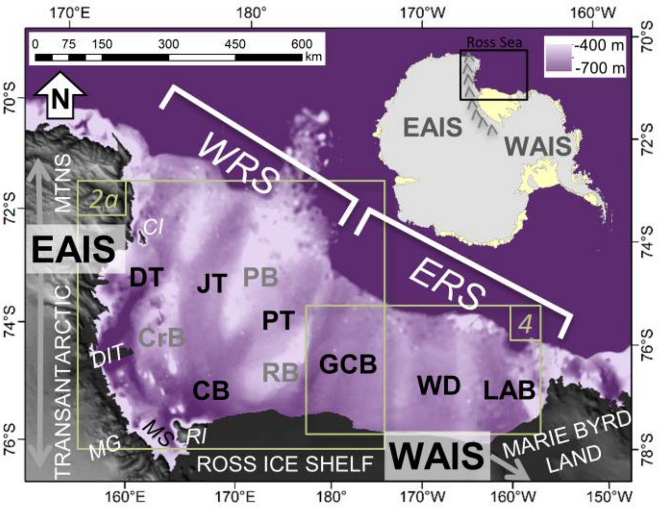

Figure 1. Regional bathymetry of the Ross Sea continental shelf, with bed topography data acquired from BEDMAP2 (Fretwell et al., 2013). Inset shows the West and East Antarctic ice sheets (WAIS and EAIS, respectively), separated by the Transantarctic Mountains, ~~, (cross-hatched area)~~ with the Ross Sea study area outlined. Locations for Fig. 2a and Fig. 4 are shown. WRS (Western Ross Sea), ERS (Eastern Ross Sea), EAIS (East Antarctic Ice Sheet), WAIS (West Antarctic Ice Sheet), DT (Drygalski Trough), JT (JOIDES Trough), PT (Pennell Trough), CB (Central Basin), CrB (Crary Bank), PB (Pennell Bank), RB (Ross Bank), GCB (Glomar Challenger Basin), WD (Whales Deep), LAB (Little America Basin), CI (Coulman Island), DIT (Drygalski Ice Tongue), MG (Mackay Glacier), MS (McMurdo Sound).

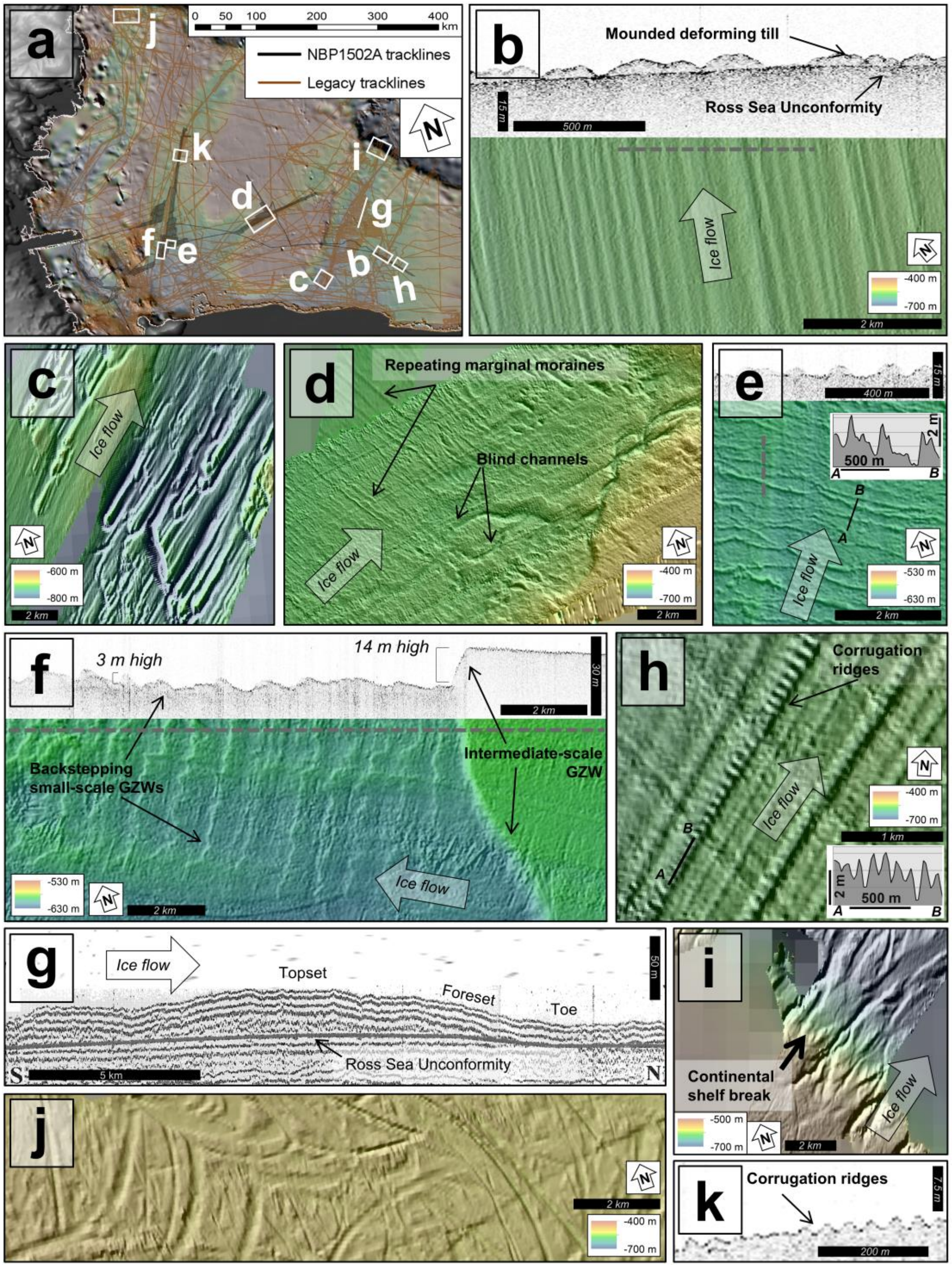

Figure 2. Glacial geomorphic features of the continental shelf. (a) Ross Sea tracklines from cruise NBP1502A (black lines) and legacy (brown) cruises and locations of (b-k). (b) MSGLs (3-5 m ~~in~~ amplitude) on the inner shelf of Glomar ~~-~~Challenger Basin ~~are composed of relatively soft deformation till~~occur above a glacial erosional surface, imaged by ~~the~~ high-frequency seismic data. (c) Drumlinoids on the inner shelf of Glomar Challenger Basin. (d) A subglacial meltwater channel in Pennell Trough ~~with~~ with complex channel morphology~~, and~~ associated with small-scale recessional ice-marginal features. (e) Marginal moraines in JOIDES Trough. (f) Small-scale and intermediate-scale GZWs in JOIDES Trough ~~(~3 m high)~~. (g) Seismic profile showing GZW (4b) in Glomar ~~-~~Challenger Basin modified from Mosola

and Anderson (2006). (h) Linear iceberg furrows with average depth of 14 m; corrugation ridges inside the furrows have heights of 0.5-2 m. (i) Shelf-edge gullies on the eastern Ross Sea continental shelf break. (j) Arcuate cross-cutting iceberg furrows on the outer shelf of Drygalski Trough. (k) Corrugation ridges in outer JOIDES trough, with heights~~. These features have heights~~ ranging from 0.5-2 m. Dashed lines on the multibeam images indicates the location of the CHIRP profiles (vertical scales were ~~.~~calculated from two-way travel time using the sound velocity conversion of 1500 m/s).

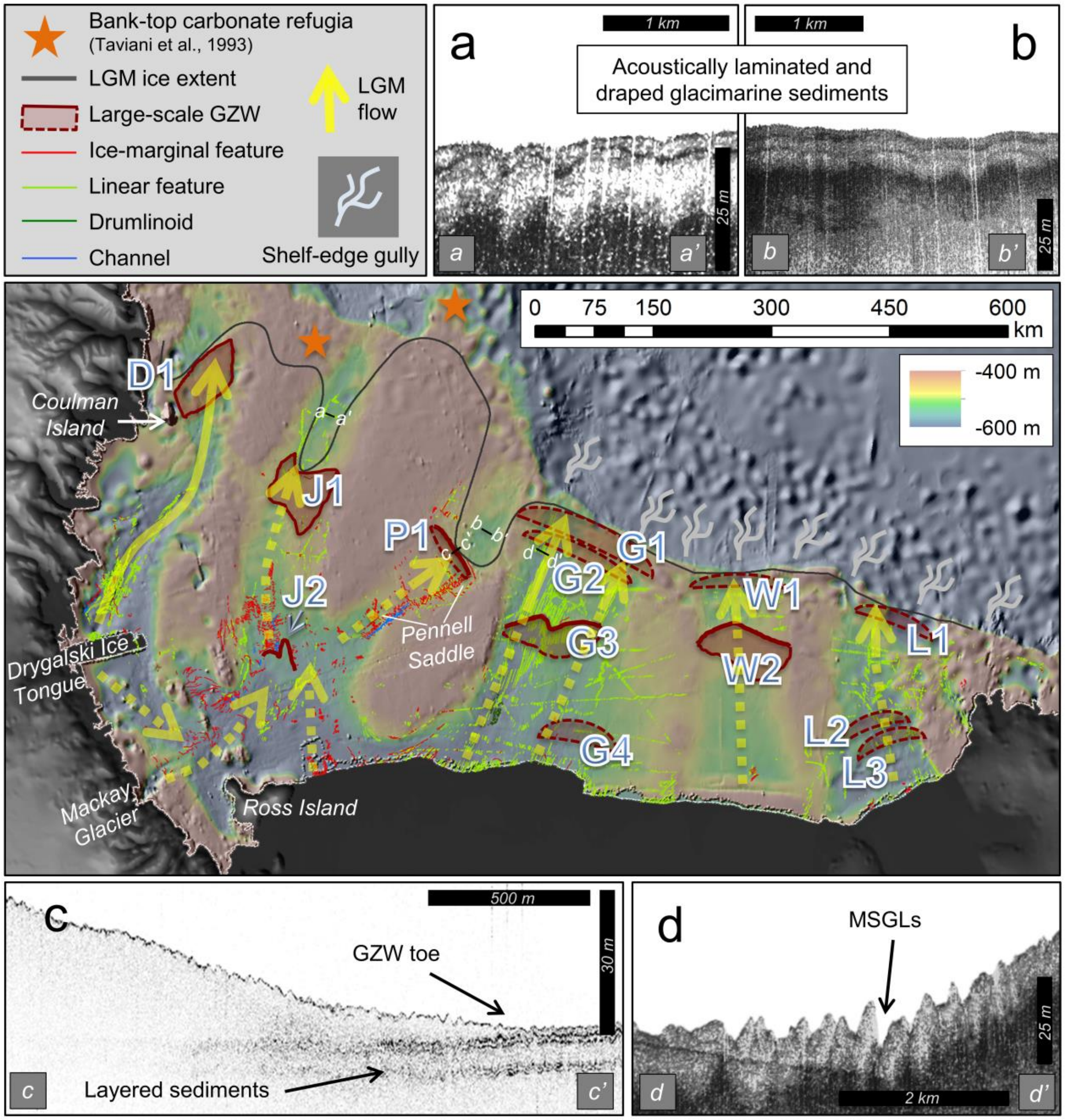

Figure 3. Distribution of geomorphic features and evidence for LGM extent. Large-scale GZWs are outlined with a solid line where the GZW boundary is known, and a dotted line where the boundary is inferred based on depth contours. GZWs that are only identified in seismic lines are symbolized with a dotted lens shape. LGM flowlines based on geomorphic flow indicators are displayed as thick yellow arrows. Dotted ~~lines~~arrows in south-western Ross Sea denote flow patterns based on a geomorphic record of local ice flow out of EAIS outlet glaciers during deglaciation. It remains uncertain whether those flow patterns were also active during the LGM. In the eastern Ross Sea, lineations corresponding to LGM flow ~~(dotted arrows)~~ are also unclear;~~. W~~ we assume that LGM ice streams flowed roughly parallel to trough axes, based on the most seaward flowsets. High-frequency seismic profiles show~~ing~~ thick, draped glacimarine sediments in (a) JOIDES Trough (4-8 m thick) and (b) Pennell Trough (9-14 m thick)~~troughs~~. (c) The LGM GZW foreset in Pennell Trough prograded over thick pre-LGM glacial marine sediments. (d) MSGLs ~~with~~ have no appreciable post-glacial sediments in outer Glomar Challenger Basin.

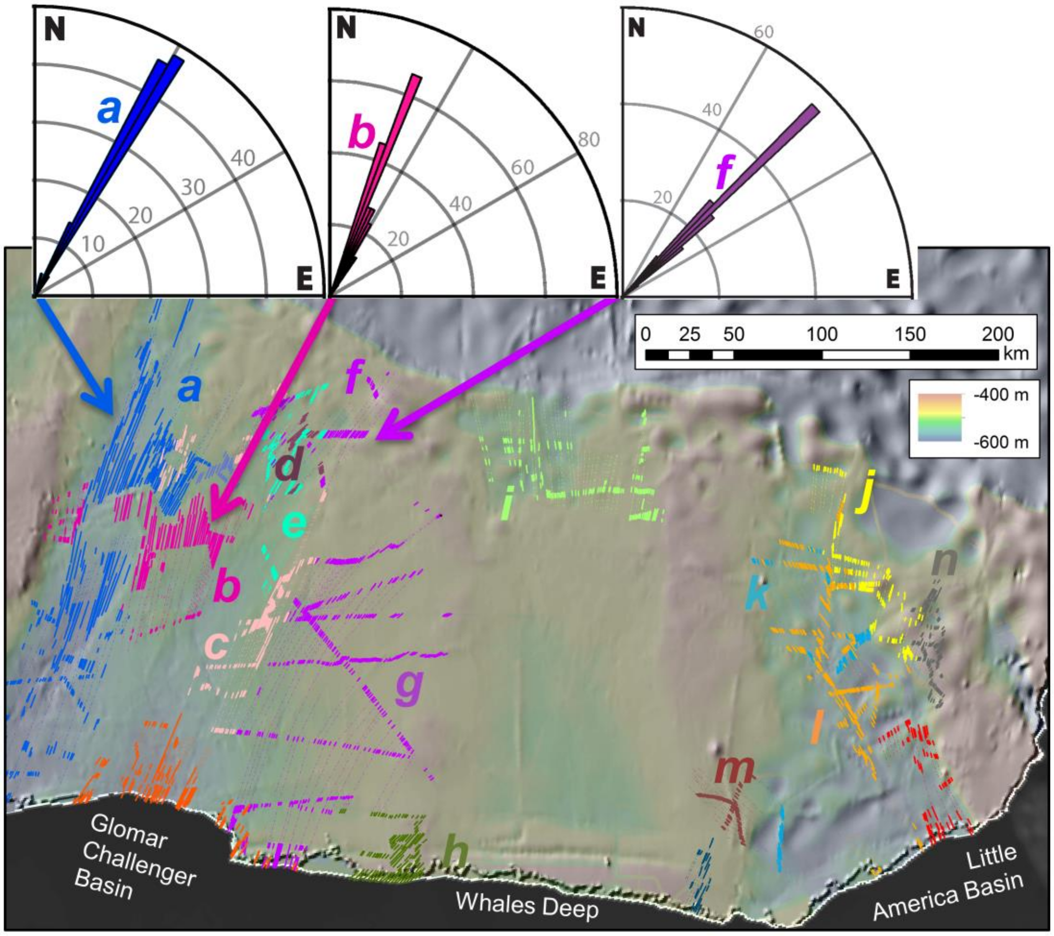

Figure 4. Linear features in the eastern Ross Sea were grouped into flowsets based on features mapped using multibeam data (solid lines) and interpolation between multibeam ~~lines~~ data (dotted lines). Major flowsets are labeled for reference in text. Flowsets were placed in a relative chronology partially based on maximum seaward extent; each orientation represents a different vintage of flow. Three example flowsets and corresponding Rose diagrams are shown ~~in~~ from outer Glomar Challenger Basin.

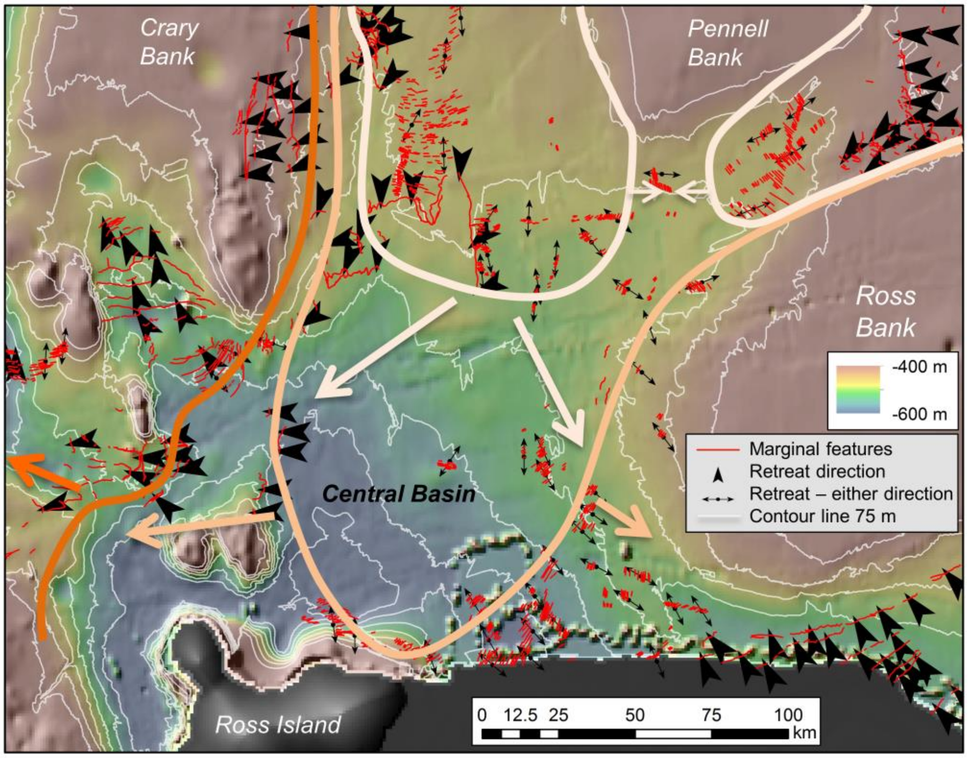

Figure 5. ~~LGM flow based on geomorphic flow indicators. Dotted lines in south-western Ross Sea denote flow patterns based on a geomorphic record of local ice flow out of EAIS outlet glaciers during deglaciation. It remains uncertain whether those flow patterns were also active during the LGM. In the eastern Ross Sea, lineations corresponding to LGM flow (dotted arrows) are also unclear. We assume that LGM ice streams flowed roughly parallel to trough axes, based on the most seaward flowsets.~~

~~Figure 6.~~ Retreat ~~patterns~~ direction in the western Ross Sea ~~are~~ is ~~noted~~ inferred from~~by retreat direction (inferred from~~ GZWs (~~,~~ arrowheads) and symmetric marginal moraines (double-sided arrows). Reconstructed grounding lines (solid lines) are accompanied by large arrows indicating regional retreat. Thin white lines are depth contours at 75 -m increments. Deglaciation in the deep Central Basin did not follow depth contours, implying a steep deglacial EAIS ice profile in order for ice to remain grounded across a range of depths contemporaneously.

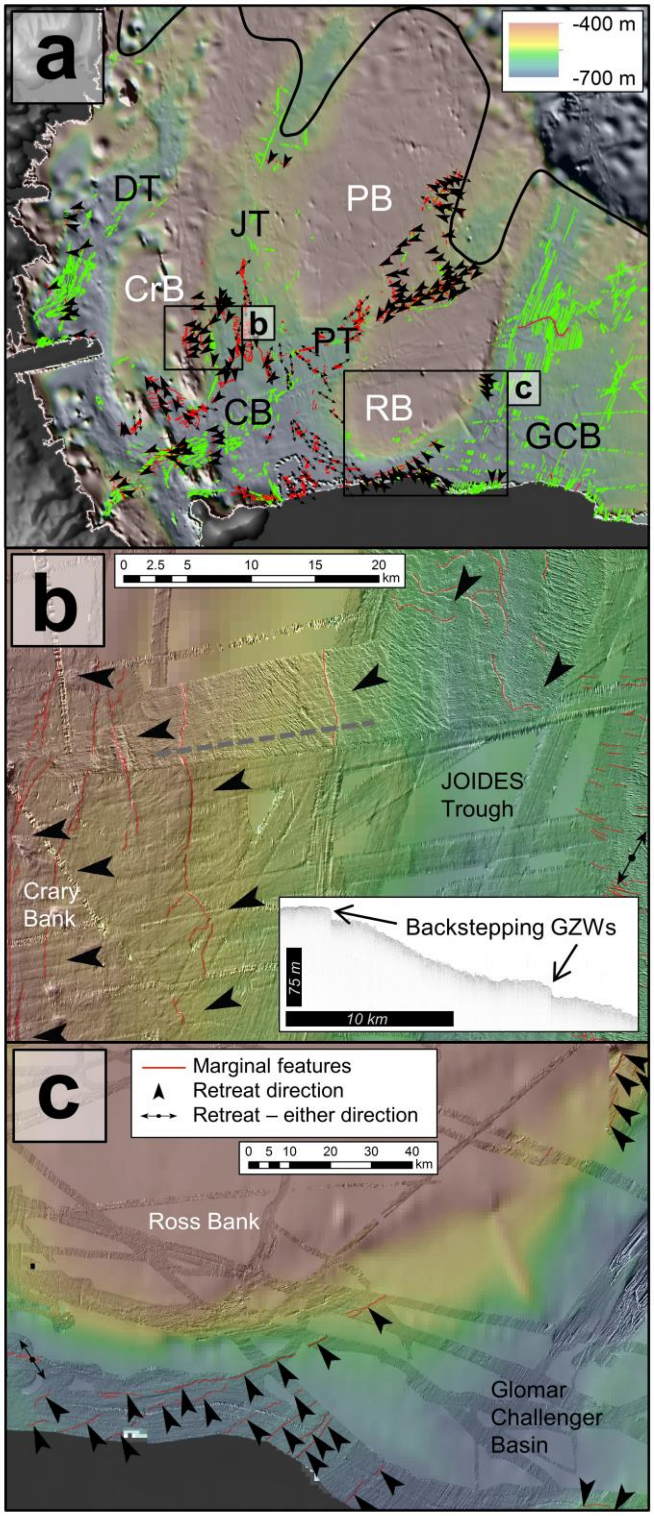

Figure 6. (a-b) Grounding lines are observed to retreat up onto banks, as shown by back-stepping wedges and marginal moraines. Arrowheads denote retreat direction. (c) Back-stepping grounding lines in southwestern Glomar Challenger Basin imply that ice had decoupled there before retreating westward into the WRS. The color scale is consistent between all panels.

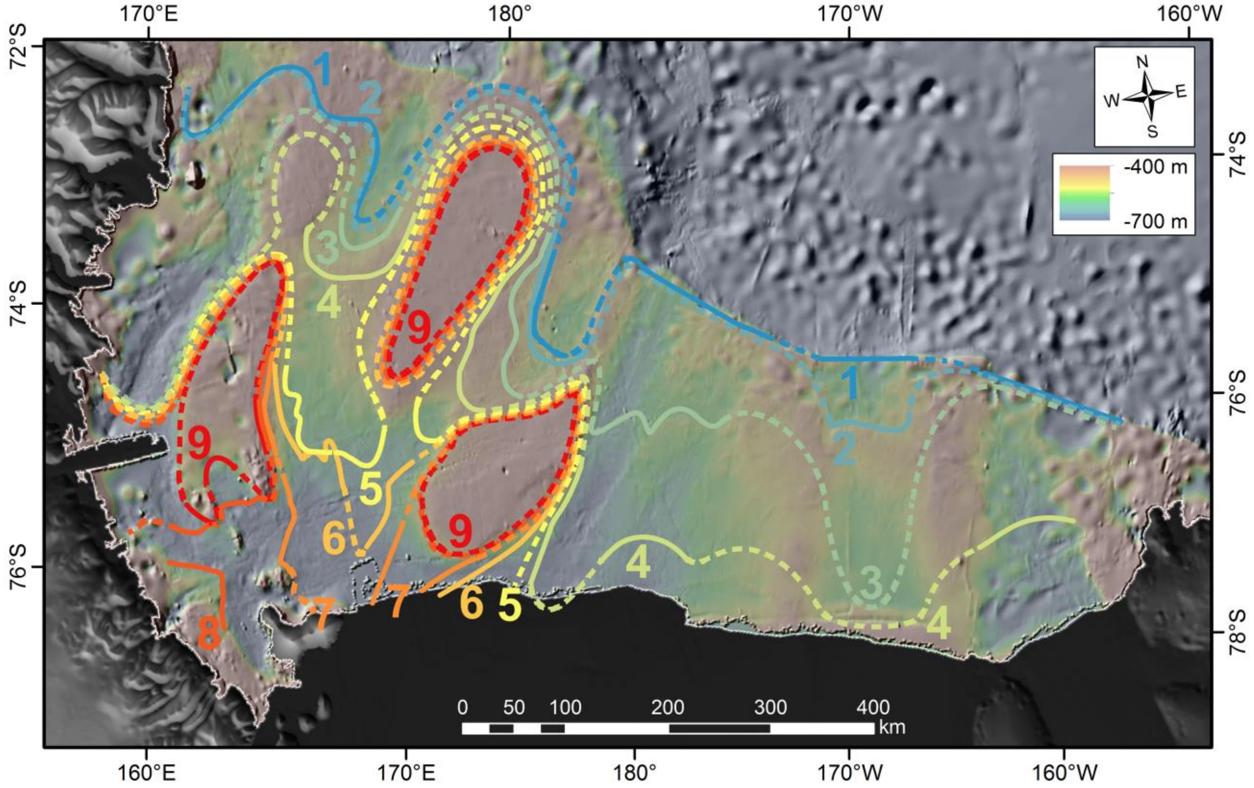

Figure 7. Reconstructed grounding-line retreat across the Ross Sea based on geomorphic indicators of grounding lines (solid lines) and inferred grounding-line locations (dashed). Each line marks a relative step in grounding-line retreat starting with step 1 at the LGM grounding line and ending with step 9 with ice pinned on banks.

~~Figure 8. (a-b) Grounding lines are observed to retreat up onto banks, as shown by back-stepping wedges and marginal moraines. Arrowheads denote retreat direction. (c) Back-stepping grounding lines in southwestern Glomar Challenger Basin imply that ice had decoupled there before retreating westward into the WRS.~~

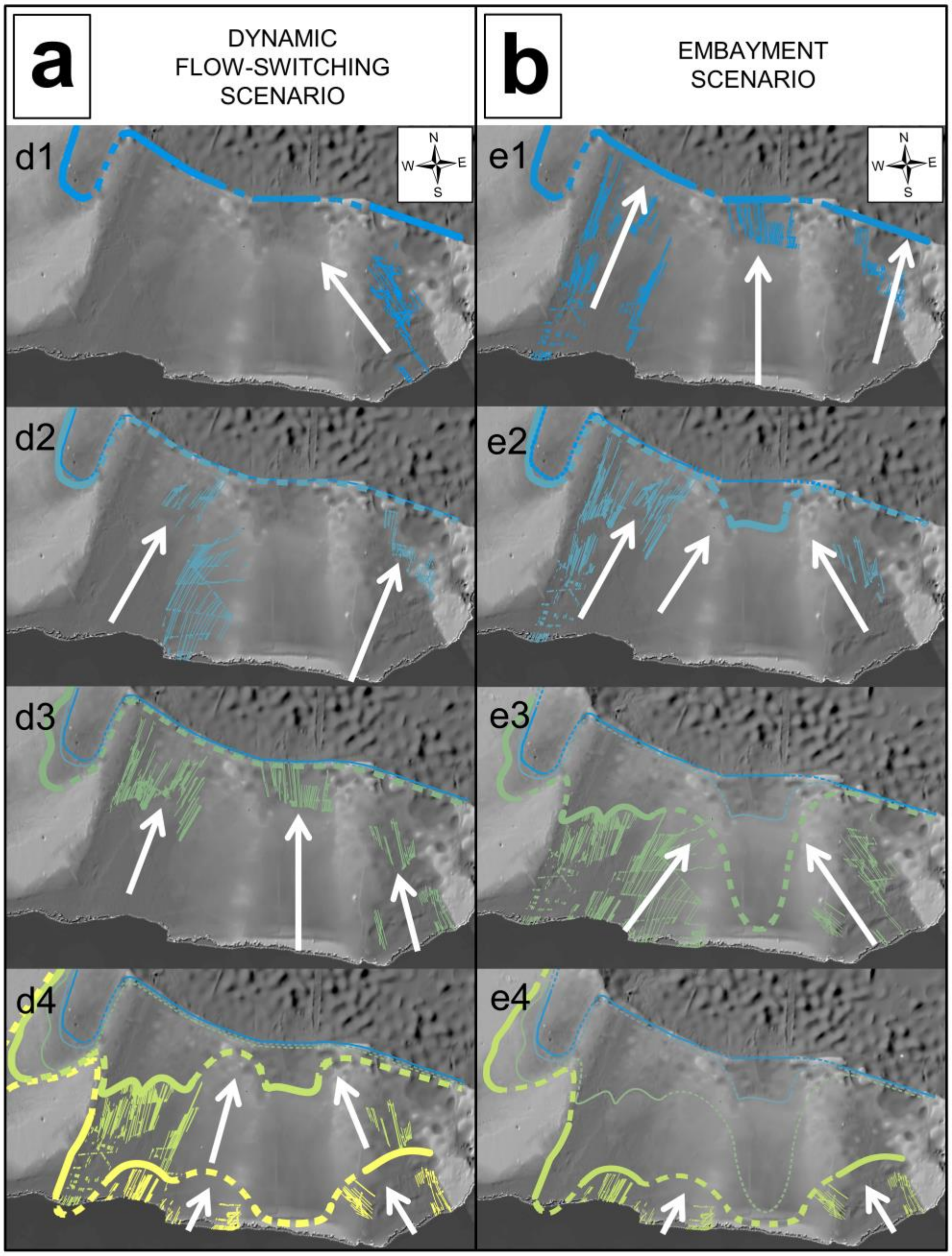

Figure ~~9~~8. Possible retreat scenarios for the eastern Ross Sea interpreted from flowsets. (a) The dynamic flow-switching scenario calls for alternating regional flow directions ~~throughout the LGM~~, followed by north-south recession of the grounding line. This model requires preservation of at least three different flow fabrics as ice remains grounded on the outer continental shelf. (b) In the embayment scenario, a large grounding-line embayment in the eastern Ross Sea forms over Whales Deep. The embayment scenario is independently more consistent with inland paleo-ice thickness reconstructions and seafloor seismic observations.

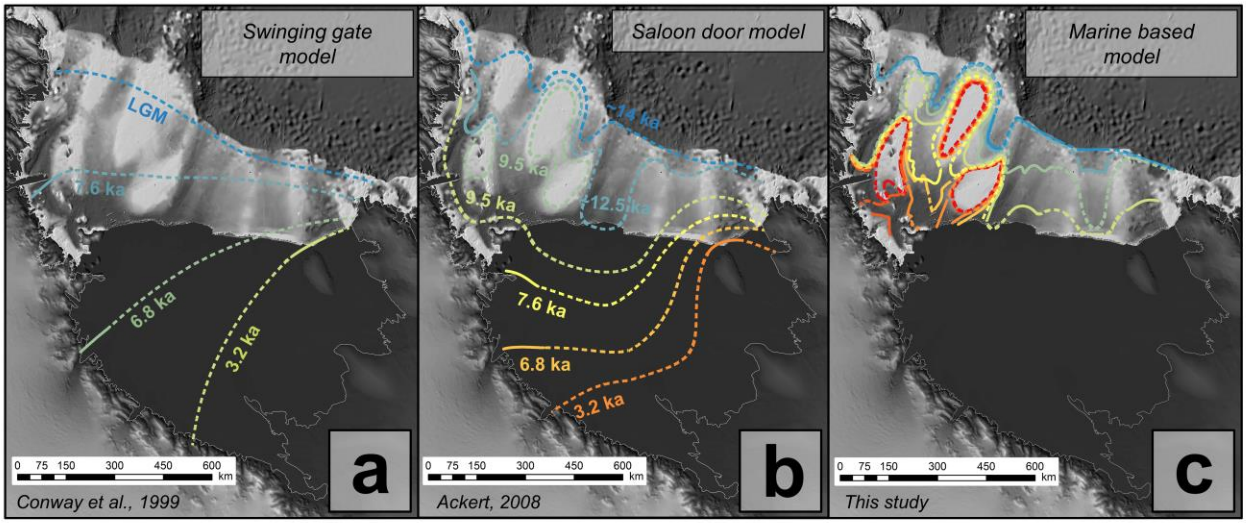

Figure ~~10~~9. Comparison of existing models of Ross Sea deglaciation. (a) The 'swinging gate model' (Conway et al., 1999) assumes a linear grounding line swinging across the Ross Sea, implying that controls on ice-sheet dynamics are the same throughout the Ross Sea and that physiography has little influence on ice retreat. This model indicates deglaciation of the WRS prior to the ERS, and implies that the Ross Sea was filled with WAIS ice during LGM and throughout deglaciation. (b) The 'saloon door' model of deglaciation suggests early retreat in the ERS with a potential grounding-line embayment in the central Ross Sea (Ackert, 2008), requiring significant inputs from both the EAIS and the WAIS. (c) The marine-based reconstruction presented here uses glacial geomorphology to interpret paleo-grounding-line retreat.

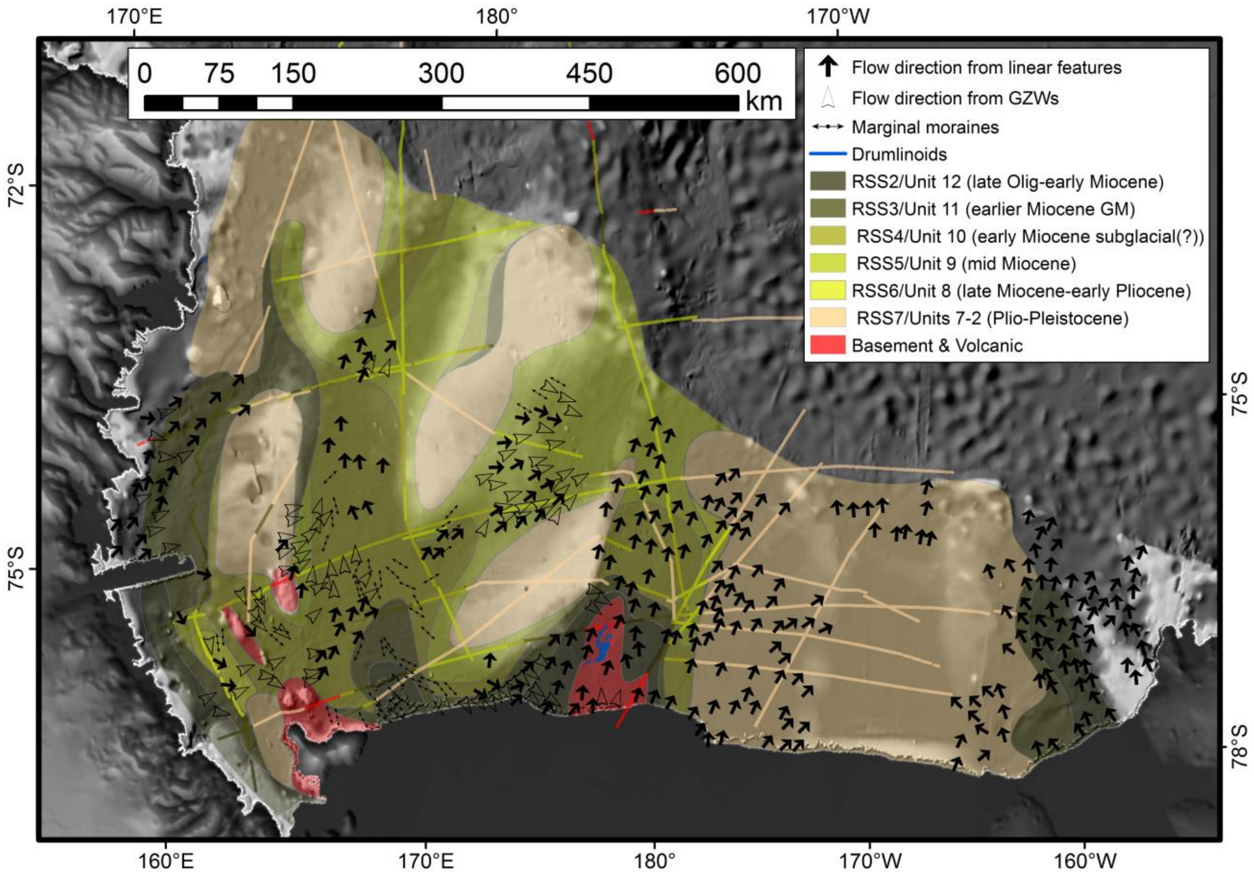

Figure ~~11~~10. Control of seafloor geology on ice dynamics. Geologic boundaries were interpolated from legacy seismic lines (shown here) with pre-interpreted seismic units by Anderson and Bartek (1992) and Brancolini et al. (1995). The WRS is characterized by complex, older and more consolidated strata, where ice streams have eroded down to Oligocene-age strata. Volcanic islands and seamounts outcrop in the southern portion of the WRS. The western side of Glomar Challenger Basin, bordering Ross Bank, contains older and more variable geologic strata outcropping at the seafloor, including a patch of basement outcrop on the inner shelf. In general, thick unconsolidated Plio-Pleistocene strata fill most of the ERS and increase in thickness in an offshore direction (Alonso et al., 1992). Plio-Pleistocene sediments are thin in southern Whales Deep, overlying older Miocene strata. ~~Farther ~~E~~e~~astern~~ in~~ Little America Basin is characterized by~~,~~ lithified late Oligocene through Miocene deposits~~ occur beneath the LGM unconformity~~. Arrows indicating flow direction are based on geomorphic features.