Response to reviewers

Reviewer comments: *italics*

Response: plain font

Reviewer 1

i) A few aspects of the methods need clarification.

Stage 4 of the bathymetry reconstruction suggests the model is constrained by observational data; how do these data differ from what was used as input in Stage 1? What is left to tighten the inversion?

The data used in stage 1 is a grid of bathymetry interpolated between the known bathymetric data points. In contrast, only the point data is used as a bathymetric input in stage 4. After steps 1-3 the gravity derived bathymetry should be a good match to the general shape and amplitude of the bathymetry. However, shifts/errors due to un-modelled geology may be present which incorrectly move the inversion away from the true values. Step 4 ensures the bathymetric model accurately matches the constraining observations where they are available, hence giving the best possible integrated model. Note if the gravity model was perfect there would be no residual shift at stage 4.

Revised text:

> Estimation of the sub-ice shelf bathymetry from the gravity data used a four-step procedure (for details see Supplementary material, Section 1). First, to initiate the inversion we used interpolated grids of ice surface, sub-surface topography and bathymetry from direct observations (Fig. 3 and 4a). The gravity effect of these surfaces was calculated and subtracted from the compiled free-air gravity anomaly (Fig. 4b) to give an estimated Bouguer anomaly. The second stage was to isolate the gravity signatures in the Bouguer anomaly due to bathymetry not described by direct observation. A low pass (150 km) filter isolated signatures due to crustal thickness variations. A ~50 mGal anomaly north of the location of Halley VIa Research station (Fig. 4b) is interpreted from magnetic and gravity data to be a large mafic intrusion 80 km long, 30 km wide and ~6km thick (Jordan and Becker 2018). The gravity anomaly from this structure significantly distorts any bathymetric inversion. A 3D gravity model of this body was therefore constructed. Both the long wavelength crustal anomaly and the gravity model of the mafic intrusion were subtracted from the Bouguer anomaly. This provides a residual gravity anomaly due only to un-modelled variations in sub-ice shelf bathymetry, and un-modelled upper crustal geology. The third stage of the inversion process converts the residual gravity anomaly to variations in bathymetry using the Bouguer slab formula. Adding the calculated bathymetric variations back to the initial bathymetric grid gives a preliminary gravity-derived estimate of bathymetry. The fourth and final stage of the inversion process forces the inverted bathymetry to match observational point data where it is available, providing the best possible bathymetric model (Fig. 3). The final bathymetric model (Fig. 4c) retains uncertainties due to un-modelled geological structures; however, it reveals the broad structure of the sub-ice shelf bathymetry and subglacial topography.

Can you clarify how the ice shelf base/draft was determined? Line 106 and line 210 both suggest radar data were used; line 166 (Methods) suggests only that shelf thickness (draft) was determined using an assumed density profile and the freeboard height.

Are density assumptions valid, since the shelf is partly composed of (fused by) marine ice?

We have revised the text as follows:

> Although airborne radar measurements of ice shelf draft were available, it was difficult to accurately determine ice shelf draft with these methods. Instead, the ice shelf draft along selected flow lines was calculated based on assumptions of a floating ice column and the density profile of the ice, to translate the freeboard into ice thickness. A common mid-point survey (CMP) of the top 30 m constrained the mean density in the firn pack to 750 kg/m3, and nominal ice densities of 920 kg/m3 were assumed below 50 m. These densities were applied uniformly across the ice shelf without local corrections for incorporated icebergs.

Explain how Fig 5 shows that contact with the MIR is limited to <1.3-3 km2 (line 215).

This estimate is based on the area of deformation. We have revised the text as follows:

> The DEM analysis of the MIR shows that the area of deformation caused by contact between the base of the ice shelf and the McDonald Bank is limited to an area of less than 1.3 to 3 km2 (Fig. 5). Strain rates upstream of the MIR (Figure 8 in De Rydt et al., 2018) show the compressive regime in the ice shelf resulting from grounding in 2015.

Fig 5 appears to show anomalies in surface elevation between different datasets (lidar flight lines vs stereo-image DEM), particularly closer to the grounding line – can you comment on or compare the (un)reliability of these datasets? If the ice surface heights are data-dependent, what does this mean for draft calculations?

The LiDAR is very reliable. The largest error is an offsets due to tidal effects, which we have not corrected for. This will be a few meters at most. The DEM was a combination of Worldview2 and Cryosat2. We have now replaced the Cryosat 2 coverage (where the biggest discrepancy with the LiDAR data was found), with the latest REMA topography. As can be seen from the image, the match is much better especially near the grounding line, to the extent where you can't actually see the LiDAR lines very well.

Which velocity measurements or model were used to convert distance to time in Fig 6? Could simply be stated in the figure caption.

This is now stated in the Figure caption as suggested.

ii) Former grounded ice reconstruction

It would be useful to see the seismic profile across the McDonald Bank (line 61, line 225 – is it possible/permitted to reproduce this figure?) and also where, specifically, it crosses the bank (e.g. to inform your comment on line 228-229). What direction do these bedded glacial sediments dip in? What grounded ice geometry would be consistent with the seismic structure – your interpreted grounded ice flow trajectory (Fig 4) would suggest the bank was lateral to ice flow reaching the *continental shelf edge, but is now perpendicular to flow from the shelf (switch from lateral to ice frontal position).*

I wonder whether there are sufficient seismic data (coverage or resolution?) to detect this switch, or to evaluate your reconstruction? Are there any structures related to the re-grounding of the Brunt Ice Shelf on this bank? Can different generations of sedimentation be detected?

The seismic data were acquired by the Norwegian Antarctic Research Expedition in 1976/77 and 1978/79. The original data are no longer available, but instead are presented as crude line drawings based on sparker data. To better incorporate this data we revise the text as follows:

> At these times, glacial depositional processes operating between the ice streams occupying Filchner Trough and the Brunt Basin likely formed the layered glacial sediments of the McDonald bank interpreted from seismic surveys (Elverhøi and Maisey, 1983). Although seismic lines at different orientations are required to fully characterise the internal architecture and processes forming this deposit, the line drawings based on sparker data presented by Elverhøi and Maisey (1983, Profile 5, page 486) suggest the layered glacial sediments dip westwards into the Weddell Sea. At least two of these layers (Units 1 and 2) were interpreted as being of 'glacial origin', but whether they are 'glaciomarine sediments, till and/or glacially compacted glaciomarine sediments, cannot be determined'. These layers have subsequently been truncated along the steep eastern slopes of the McDonald Bank, presumably by erosive ice advances along the south-to-north oriented trough under the BIS. The relatively flat top of the McDonald Bank may the product of glacial planation processes by ice shelves during, and either side of peak glacial conditions.

Line 185-90: I suggest removing the references to grounding line positions from the series of brackets here, and making your interpretations separately. i.e. report in these few sentences where the topographic highs are, and then finish the paragraph stating that you interpret these high points as likely pinning points, perhaps both for grounded ice retreating from its maximum extent (grounding line positions) and stabilisation points for subsequently floating ice. On first reading it seemed as if you were calling on independent evidence of grounding line positions that you now match up with your new bathymetry, but I don't think that's the case.

We have followed this suggestion and rewritten this section as follows:

> A number of topographic highs occur in the Brunt Basin. Two of these are high enough to make contact with the base of the SWGT at the Lyddan Ice Rise, and the base of the BIS at the McDonald Bank. Other topographic highs are present in the NNW oriented part of the Brunt Basin under the SWGT including a series of at least three transverse ridges on the flanks of the trough (marked as inferred grounding lines 1-3 in Fig. 4c). Our gravity-derived topography predicts these ridges are in contact with the base of the SWGT, which is not indicated by ice velocity or satellite imagery. Instead, we suggest that these ridges fall just short of the base of the ice. Two similar transverse ridges at the present day grounding line in the East-West oriented part of the trough beneath the SWGT (marked as inferred grounding line 4 in Fig. 4c). We interpret these topographic highs as likely pinning points, perhaps both for grounded ice retreating from its maximum extent (grounding line positions) and stabilisation points for subsequently floating ice.

Section 4.1: since the only evidence of glacial advance/retreat that could be considered diagnostic in this new dataset are the convergent troughs, the tone of this section is somewhat over-confident and some of the assertions cannot (yet) be supported. These assertions may well be likely but specific *landform or sedimentological evidence is still absent, so I would rephrase the language more towards presenting likely hypotheses than definitive conclusions.*

We have changed the first sentence to state:

> The bathymetry and subglacial topography provide sufficient evidence to propose a range of past ice configurations in the study area.

Elsewhere we have used more careful wording – separating inferences from evidence of past ice configurations. Please see the extensive tracked changes in the revised text.

iii) Discussion – does not evaluate the future development of the Brunt Ice Shelf, as the article introduction states as its aim (line 94), only outlines four possibilities. A paragraph or so of synthesis seems to be lacking here, and I think there is some room for evaluation without going too far out on a limb. Whichever of the four scenarios will develop depends, at least in part, on feedbacks between ice shelf grounding on a distal pinning point, the ice shelf flow regime, the production of ice shelf (berg) keels, the draft and the packing of those keels (inherited from the shelf-sheet grounding line?) Such feedbacks are alluded to through the manuscript, but are not drawn together to inform some of the possibilities that the Discussion scenarios raise.

To address this suggestion we have added the following paragraph:

> Although the outcome of the calving of the ice shelf is not yet known, these four scenarios all show the importance of understanding the geometry the ice shelf and the bed. Which of the four scenarios will develop depends, at least in part, on whether the ice shelf is able to remain in contact with one of the topographic highs on the McDonald Bank. Whilst the depth of the topographic highs is fixed, the contact between the ice shelf and the bed depends on a number of variables. These include the short-term development of the ice shelf flow regime following calving, and its impact on ice shelf draft (e.g. lateral spreading) and structural integrity (e.g. development of further rifts resulting from changes in the strain rate). They also include the long-term influences of processes at the grounding line, such as the thickness and velocity of ice flowing across the Brunt Icefalls which determine the spacing and depth of the iceberg keels.

Line 325-9: the SWG is fed by a much larger (and faster flowing?) supply basin, so presumably sustains a significant ice tongue partly due to high input, even though it's unbuttressed. Does the very different supply catchment for the BIS not make this a poor analogue?

The velocity data added to Fig. 5 suggest rather similar flow rates for the BIS and SWGT

How limited do you think your conclusions or interpretations of future ice shelf development are by the specific three flowlines you have chosen to analyse shelf draft? This is the broad flowline reaching the shallowest part of the McDonald Bank; is it also the deepest draft zone of the shelf? Could keels along other flowlines eventually reground on other topo highs on the McDonald Bank?

Yes – we have now included this in scenario 3.

Figures, annotation & captions

Figure 1. I wonder about the choice of satellite imagery – these show the geography clearly, but don't visualise the structures as well as, for example, Fig 1 in King et al 2018.

This is more recent satellite imagery than King et al 2018. We have used blue shading to highlight the key structures (Chasms 1 and 2 and Halloween Crack).

Figure 3: several missing features either in annotation or caption - I don't see any shading corresponding to swath bathymetry or other sonar data (pale blue shading, in the caption).

- the white lines – calving line and grounding line (should be stated in caption) – from which source and year?

- what are the grey blobs offshore? Iceberg outlines? From what source/year, and are they really needed (could mask out)?

- could you separate the seismic sites for water depth estimates from the historical depth soundings (use different symbols)?

- what's the pink triangle? Halley VIa?

We have re-formatted the figure and caption to address these points. Firstly, we now highlight the areas with swath data coverage more clearly in red. The grey blobs were simply areas with no swath coverage – not icebergs. The seismic and historical depth soundings are now separated. The coastline/grounding line is from the 2013 Antarctic Digital Database, now noted in the caption.

Revised caption for Figure 3:

> Figure 3. Data locations overlain on a MOA satellite image. Yellow lines indicate 2017 aerogeophysical flights collecting radar, gravity and magnetic data. Red shading indicates swath bathymetry data coverage. Blue lines mark radar depth determinations from BEDMAP2 (Fretwell et al., 2013). Orange lines mark location of ICEGRAV 2013 radar and gravity data (Forsberg et al., 2017). Black dots mark seismic determinations of water column thickness under the Brunt ice Shelf (Hodgson et al., 2018). White dots mark soundings from historical ship tracks acquired when the ice front of the Stancomb-Wills Glacier Tongue was less-advanced. White line marks the grounding line/ice shelf edge from the 2013 Antarctic Digital Database. Pink triangle marks approximate location of Halley VIa station from 2012 to 2016.

Figure 4: missing or unclear features in annotation or caption - the depth scale isn't particularly straightforward to match to the shading on the panels, which appears more intense and has hillshade effects. Try a classified colour scale, rather than ramped, perhaps? Or make it clearer at what depth the colour bar saturates and/or at what depth the shelf break is, for reference. Also, consider shifting the bluebrown shift to 0m, rather than the unintuitive brown = submarine as well as terrestrial.

- add a label for 4d to the box in 4c

- note the black dots = seismic soundings

- remove the iceberg(?) polygon outlines, these don't seem to be necessary here

- what are the green outlined features?

- label Fig 6 flowlines on the panel itself (rather than in caption)?

- flow arrows and grounding lines are both hypothesised. Suggest something like ‘Probable orientations of fast grounded ice flow: : :’ and ‘Inferred former grounding line positions based on existence of topographic highs: : :’

4d/5: use either decimal degrees or degrees & minutes (latitude labels) consistently on all figures.

5: label Chasm 1, 2, Halloween Crack to better follow discussion.

6: suggest label/arrow ice flow direction.

We have remade the topographic parts of Figure 4 using a revised colour scale. This scale saturates at +/-1000m and has a central green/blue transition at zero meters elevation. The box and profiles are now ladled with the appropriate figure numbers. We now note the black dots are seismic stations, and the thin black lines locate the edges of the swath bathymetric data coverage (not icebergs). We have included the suggestions for describing the arrows and former grounding lines in the figure captions, and now note that the green lines circles and lines indicate possible past and present pinning points. Figures 3 and 4 now only use whole degrees.

Revised caption for Figure 4:

> Figure 4. Revised topography beneath the Brunt Ice Shelf and Stancomb-Wills Glacier Tongue. (a) Topography derived from direct observations including; swath bathymetry offshore and in areas historically accessible to ships during past calving events, seismic depth sounding of the ice shelf, and radar depth sounding over the grounded ice sheet. (b) Free air gravity anomalies. Data inside black outline from new strapdown gravity data set (Becker et al., 2018). Regional data from ICEGRAV 2013 survey (Forsberg et al., 2017) and previous regional compilations (Jordan et al., 2017). Note gravity ‘high’ outlined in yellow attributed to a large mafic intrusion based on gravity and magnetic signatures (Jordan and Becker, 2018). (c) Integrated bathymetric model including additional constraints from gravity data beneath the ice shelf. Black and white contour is the predicted grounding line. Thin blue contours show areas predicted to be grounded by ice 50, 100 or 200 m deeper than the calculated bed. Black contours show 50, 100, 200m predicted cavity thickness. Probable orientations of past grounded ice flow are indicated by white arrows. Inferred former grounding lines based on mapped topographic highs are marked by numbered black dashed lines (1-3). (d) Detail of Brunt ice shelf. Red lines mark the position of flow-lines plotted in Fig 6. Black dots show seismic stations and thin black lines mark edges of swath bathymetric data coverage. The pink triangle marks the position of Halley VIa Research Station. Green circles and lines indicate possible past and present pinning points. Abbreviations: LIR (Lyddan Ice Rise), SWS (Southern Weddell Sea), MB (McDonald Bank), SWGT (Stancomb-Wills Glacier Tongue), BIS (Brunt Ice Shelf), BB (Brunt Basin), DLGT (Dawson-Lambton Glacier Tongue).