

Anonymous Referee #1

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Review: "The internal structure of the Brunt Ice Shelf from ice-penetrating radar analysis and implications for ice shelf fracture" by King et al.

The authors present samples of GPR data from studies on the Brunt ice shelf in the vicinity of Halley Station, giving insights into the complicated composition of the ice shelf, and interpreting its role for fracture propagation. The paper is very well written and neatly structured, and it is a valuable contribution to research into ice shelf stability. It presents a combination of data from lots of different sources, but unfortunately only shows very little data of the long radar profiles. I have some comments and suggestions for the authors which I think should be considered before publication:

The authors present three short sections of GPR data, of which two are part of long profiles along flow direction of the ice shelf. It is a bit disappointing that only so little of the data is shown. Especially as the positions of the shown profiles is quite far downstream. Showing a profile from further upstream could give an indication about the temporal evolution of the ice shelf interior structures. This is not discussed at all here, but would strengthen the paper. Additionally it would be interesting to discuss the accumulation of snow respectively to the time since the ice came over the grounding line. Does this give any hints about how much sea-water infiltrated ice there is? What about the hydrostatic equilibrium? As there is a very good surface elevation model this could be easily discussed and shown?

The white lines in Fig. 2 do not represent the radar profiles, they indicate the location of the surface elevation profiles, which are derived from the WorldView DEM. The caption has been changed to make this clear. The elevation profiles show that the topography becomes difficult to traverse in the region within 20 km of the grounding line, hence we did not record radar profiles in this area. The reviewer raises interesting and pertinent questions about the evolution of structures and accumulation along-flow which a future targeted study could address. The radar profiles described here were acquired as part of an operational survey to relocate Halley Station, which limited the area of investigation.

How is the flow velocity varying along the flow line of the radar profiles? Looking at flow velocity maps of the Brunt it seems to me that that velocity is not necessarily steadily increasing along flow. Is it possible that the bending of the layers in the firn, and also the bending of the brine infiltration layer is due to shortening along flow? Is the wavelength of the surface undulations changing along flow?

The reviewer is correct, the present flow speed does show variation from grounding line to ice front, there has also been historic variations in the flow speed of the entire ice shelf (Gudmundssen et al 2017). Therefore horizontal shortening may have taken place. New text added Page 5, lines 28&29, Page 7 Lines 5&6.

Looking at Figure 2, there seems to be a rather sharp transition between the first part of the profile, from which no radar data is shown, where there are rather deep valleys between the "Railway sleepers", and the second part, where the height difference seems to level out. Is this due to the local variations of accumulation? Or might this be also due to a change in the flow regime? This would be interesting to discuss.

In the absence of ground truth information from the inner part of the ice shelf, we do not feel we have sufficient information to discuss this. The flow speed increase in about 1971 is likely a

significant factor but some dated accumulation profiles either side of the change would be needed to prove this.

Is it possible from the radar data to determine the timing of the last brine infiltration by comparing the radar layers on top of the meteoric ice blocks and within the troughs? In figure 5 it looks like as if the bending brine infiltration layer to the right of the block is more or less the same isochrones as the first smooth layer on top of the block.

We do not think that dating brine infiltration can be done by relating the brine reflection to isochrones in the firn. There are many places where the brine reflection cross-cuts the firn isochrones (most clear in Fig. 7). The cartoon in Fig 8 seeks to demonstrate that brine infiltration from below can occur as the firn is pushed below sea level by the weight of accumulation above, so that there is no time correspondence between firn deposition and brine infiltration.

Are the secondary infiltration events limited to the ice between the "Railway Tracks"? This would be interesting to discuss.

If the reviewer means by secondary infiltration the kind labelled in Fig. 7 as 'Recent brine infiltration', then this has only been observed immediately adjacent to the presently-active rift called Chasm 1.

The overall structure of the manuscript is very clear, but I do not understand why the authors present the sentinel data in the last part of the discussion instead of in the observation section.

We feel that the Sentinel-1 data can only be understood after the basics of the internal structure have been established. It is an aid to interpretation rather than a primary observation. Its particular application is in establishing how fractures interact with the internal structure and we feel that is more of a discussion of what the structure results mean.

As there are a lot of figures, I am not sure whether figure 8 is really necessary. The point could be made by referring to figure 2.

We disagree because Fig 8 summarises the production of the two types of structure in a readily accessible and memorable form.

The labels of the lower panels in figure 2 are hardly readable, maybe this should be changed.

Agreed, figure changed.

Interactive comment on “The internal structure of the Brunt Ice Shelf from ice-penetrating radar analysis and implications for ice shelf fracture” by Edward C. King et al.

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King et al. document the highly variable nature of the Brunt Ice Shelf and either document or hypothesize source origins and mechanisms for the various components. This worked is framed in the context of the role of ice shelf heterogeneity in controlling rift propagation. The observations are particularly unique and will make a valuable contribution to the literature on the topic. Below, I highlight a number of issues that I feel would strengthen the manuscript.

Pg 1, Ln 15 – This is a unique observation (compared to rift behavior on other ice shelves) and likely reflects the significant differences in ice thickness between the meteoric blocks and ice melange, correct? On other ice shelves (e.g., Larsen, Amery), rift propagation is rapid through meteoric ice and slow through suture zones give their different material properties/fracture toughnesses, as you subsequently describe in the introduction. It might be worth making this point of differing behavior more explicit in the main text.

The contrast with other ice shelves has been added to the Abstract as well as sections 1, 5, 6 and 7

Pg 1, Ln 22: upstream dynamics of the ice sheet. This could be modified to include the “upstream and far reaching impacts of such changes”, and include a citation of Reese et al., 2018.

Done

Pg 1, Ln 23-24: Previous work by Hulbe et al. (2010) on the Ross Ice Shelf, Walker et al. (2015) on the Amery Ice Shelf, and McGrath et al. (2014) and Borstad et al. (2017) on the Larsen C ice shelf have also suggested and documented this association in detail. A more comprehensive review of the relevant literature is appropriate here since this forms the overriding context for the manuscript.

Done

Pg 1, Ln 27: What is meant by “the suture zones can deform more rapidly without fracturing”? In previous work, authors have noted that rifts are frequently arrested by suture zones, suggesting that these flowbands have a higher fracture toughness than the neighboring meteoric ice. Can you clarify the connection between the more rapid deformation and the observations of rift arrest?

Phrase removed and replaced with reference to fracture toughness as part of improved literature review.

Pg 1, 26, 28:29: Is there a suitable citation for the viscosity of marine ice? In my opinion, it is overly simplistic to attribute the observations of rift arrest solely to the likely unique (but largely unmeasured) material properties of marine ice. As your findings suggest, ice mélanges and suture zones are highly heterogenous with numerous sources and numerous processes at play, and at present, I don't think we really know which of these unique characteristics (temperature, water content, altered crystal fabric, existing flaws/fractures) are responsible for arresting rift propagation. As such, it seems appropriate to acknowledge this complexity, which your findings corroborate.

Done, see improved literature review.

Pg 2, Ln 11: What is the scale of the “large blocks”?

Figures added to provide the scale. Pg 2 Ln 22.

Pg 2, Ln 11: What is meant by the inner part of the ice shelf? Can this be labeled/marked on Figure 2?

Figures added to text to define 'inner part'. Pg2, Ln 23.

Pg 2, Ln 22: Replace "the early system" with "previous efforts."

Done.

Pg 3, Ln 5: Given the significant topographic relief and ice velocities, how were the various DEM images from the two year interval aligned? What number of DEMs were included?

Text added, Section 2.1

Pg 3, Ln 24 (and Figure 3): What is the source for the ice velocities?

Added reference to MEASURES velocity product (Rignot et al)

Pg 3, Ln 25: The GPR observations are occurring over a highly heterogenous ice shelf, with likely significant spatial and vertical variations in ice density. In this context, can you describe your radar velocity derivation? Is this assumed constant across the ice shelf? If so, what uncertainties does this introduce to the analysis?

Text added to section 3. We use a uniform wave speed for both migration and depth conversion because we do not have CMP data to generate a wave speed profile. We are not attempting any quantitative analysis in this paper

Pg 4, Ln 5:25: What are the uncertainties on these depth estimates given radar velocity uncertainties?

Text added in Section 3

Pg 7, Ln 5: What is the actual statistical correlation between backscatter amplitude and the radar derived topography? Although the authors are only noting "its existence," it would be worth discussing C-band depth penetration in more detail.

Correlation is $r = 0.607$, $p = 0$. We do not agree that a discussion of C-band penetration will enhance this paper but we do think that the radar dataset from the Brunt could be used for a quantitative analysis of the Sentinel-1 backscatter data.

Figure 6: Add scale bar.

Added axes labels to show grid dimensions.

Please include Figure 13.

Done

A. Booth (Referee) a.d.booth@leeds.ac.uk

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I enjoyed reading this paper, and getting an insight into the internal structure of a topical ice shelf. I suspect that most of these comments should be very straightforward for the reviewers to address; my main concern is that the discussion seems a little brief, and there might be some room to consider quantifying some of the properties considered in the Conclusions.

Abstract - seems a little qualitative. Can we add a few numbers in? The ice thickness, for example? Quantify specifically what is meant by thicker and thinner bands of ice?

Values added.

Line 25 – possibly a little bit of a pedantic request, which potentially can't even be better-specified anyway. . . But might be worth adding the actual date of Halloween just to formalise the onset of rifting?

Done (yes, a little bit)

P2 Line 25 – does the heterogeneity of Brunt Ice Shelf actually make it an ideal place to study rift propagation? Presumably, you'd also want to characterise and compare it through homogeneous ice too - perhaps Brunt is actually too heterogeneous to be useful? I don't think this invalidates the study by any stretch, I just think that a more measured description could be better.

'ideal' replaced by 'unique' to recognise that the Brunt may be an end-member ice shelf.

P3 Line 26 – give the manufacturer "Sensors&Software" too, and the model name is stylised PulseEKKO PRO. Also, when were the radar data acquired?

Done, Section 3.

P3 Line 26 – clarify what is continuous about the acquisition mode - e.g., "towed behind a snow mobile, with traces recording continuously." Also, at what speed was the snow mobile towed, since this ultimately dictates the spatial sampling interval.

Done, Section 3.

P3 Lines 1 and 2 – filter parameters required.

Done, Section 3.

Section 4.1. I appreciate that Line 04, Line 05, and Line 62 are so-called because this is the naming convention given by the PulseEKKO, but for the purposes of this manuscript should this be simplified just to (e.g.) Profiles 1, 2 and 3?

Disagree. A link should be maintained between data that is published and any archive of those data. Renumbering profiles in papers unnecessarily breaks that link with no real benefit to the reader.

What radar velocity was used to depth convert and migrate? Did you take any account of a firm gradient, or was it an average velocity?

We used a single wave speed value (0.168 m/ns) for both migration and depth conversion in the absence of any data. Text added to Section 3.

P4 L15: Might be worth simply explaining the term 'multiple'?

Done

P4 L30-31: Seems like a slightly irrelevant point? Almost the style of comment one would write to address a reviewer's question!

Left in. This explanation is in the same class as explaining the term 'multiple' which was the reviewer's last recommendation – it helps none-geophysicists to understand concepts and terminology that are common currency within the discipline.

P5 L10: I agree that the horizontal reflection is likely a brine infiltration front but there are two other compelling observations that support this interpretation. First, the reflection appears in places to cross-cut the firm stratigraphy (where you don't think the impermeable barrier is present), implying that the reflection represents a hydrological rather than stratigraphic discontinuity. Secondly, the radar signal is vastly attenuated immediately below it, suggesting a transition in an electrically conductive regime. Might be worth dropping this evidence in, in support?

Done

P7 L30: A point of discussion rather than a recommendation here, but is the behaviour of the Halloween Crack rather contradictory to the observed propagation of the Larsen C rift? Rift propagation seemed to be slowed down when propagating through suture zones of marine ice, and accelerated through regions with more homogeneous meteoric ice. For Brunt, you're suggesting that the crack preferentially seeks to propagate through the mélange. . . Potentially worth a comment on this – it might add another comparative dimension to what (at the moment) reads like a bit of thin Discussion?

Text on this contrasting behaviour now included in the Abstract and Sections 1, 5, 6 and 7

P8 – Conclusions. There feels like some speculation introduced here, and some of this might be better placed in the discussion. Can you comment on the absolute or relative temperature, strength and density of the ice in question?

More speculative material moved to discussion. Conclusions re-written.

Figures: All of generally high quality, but the captions seem over-long. They contain useful information, although some is already contained in the main text. Cut out the repetition, and shorten their overall length?

Caption shortening done.

Figure 2: Axis labels in elevation profiles will likely be too small to be readable.

Fixed

Figure 4: You include a Vertical Exaggeration annotation in Figure 5, so why not Figure 4 as well?

Done

Figure 10 (and P7 Line 5): It's difficult to judge the correlation between the data in these figures; there are obviously a lot of lumps and bumps, but when presented like this it's difficult to appreciate their alignment and how well a big elevation bump corresponds to a high backscatter

response. Can you derive a correlation coefficient or (possibly even better, as a third panel in this figure) cross-plot the elevation and the backscatter?

Text added to give correlation values.

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17 pages (111 KB)

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The internal structure of the Brunt Ice Shelf from ice-penetrating radar analysis and implications for ice shelf fracture

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Abstract. The rate and direction of rift propagation through ice shelves depends on both the stress field and the heterogeneity, or otherwise, of the physical properties of the ice. The Brunt Ice Shelf in Antarctica has recently developed new rifts which are being actively monitored as they lengthen and interact with the internal structure of the ice shelf. Here we present the results of a ground-penetrating radar survey of the Brunt Ice Shelf aimed at understanding variations in the internal structure. We find that there are flow bands composed mostly of thick (c. 10 250m) meteoric ice interspersed with thinner (c. 150m) sections of ice shelf that have a large proportion of sea ice and sea-water-saturated firm. Therefore the ice shelf is, in essence, a series of ice tongues cemented together with ice mélange. The changes in structure are related both to the thickness and flow speed of ice at the grounding line and to subsequent processes of firn accumulation and brine infiltration as the ice shelf flows towards the calving 15 front. It is shown that rifts propagating through the Brunt Ice Shelf preferentially skirt the edges of blocks of meteoric ice and slow their rate of propagation when forced by the stress field to break through them, in contrast to the situation on other ice shelves where rift propagation speeds up in meteoric ice.

1 Introduction

20 Ice shelves provide an important buttressing mechanism that restrains the ice flow from ice sheet interiors towards the ocean. The disintegration of the Larsen A and B ice shelves on the east coast of the Antarctic Peninsula resulted in substantial acceleration of the glaciers that formerly flowed into the area lost (De Rydt et al 2015, Hulbe et al 2008, Rignot et al 2004, Rott et al 2011, Scambos et al 2004, Shuman et al 2011). These events have led to considerable current interest in the mechanisms of ice shelf fracture and breakup and the associated 25 consequences for the far-reaching upstream impacts of such changes (Reese et al 2018). Work on several ice shelves has demonstrated an association between internal structure and the rate and direction of rift propagation. On the Ronne Ice Shelf Hulbe et al. (2010) noted that crack tips coincided with suture zones between ice

originating from adjacent outlet glaciers through most of the advective path, with rifts propagating through the suture zones only near the ice front. On Amery Ice Shelf, Walker et al. (2015), showed rifts changing their propagation direction several times on entering the suture zone between two ice streams. A number of studies have focussed on the Larsen C Ice Shelf since the break-up of its northern neighbour (Glasser et al 2009, Jansen et al 2013, Kulesa et al 2014, McGrath et al 2012). Here, the details of the formation of suture zones with a high proportion of marine ice in areas immediately downstream of coastal promontories has been documented (Holland et al 2009, Jansen et al 2013). The suture zones are composed of accreted marine ice, sea ice, fallen meteoric blocks and accumulated snow from both drift snow captured in the surface depression and direct snowfall (Jansen et al 2013, Leonard et al 2008, McGrath et al 2013). Numerous rifts in the meteoric ice bands terminate against the suture zones indicating that the heterogeneous ice within the zones has higher fracture toughness, providing resistance to rift propagation through the ice shelf (Borstad et al 2017). When the large rift in Larsen C Ice Shelf broke through the suture zone, the speed of propagation increased markedly as the rift traversed meteoric ice. Suture zones are thinner, warmer, and more heterogeneous than the meteoric ice and may have differences in water content and crystal fabric, all of which likely vary spatially throughout the zone. Which combination of these factors is most important in determining fracture toughness is still unknown. These examples from various ice shelves show that it is important to understand the internal composition and structure of ice shelves as this may impact on the rate and path of fracture. However, direct observations on the control exerted by internal structure on crack propagation are limited. Here we present for the first time direct evidence that the path of propagation is directly influenced by deep lying structures within an Antarctic ice shelf.

20 1.1 Study Area

The Brunt Ice Shelf is located on the eastern coast of the Weddell Sea (Fig. 1), and forms the southernmost portion of a complex ice shelf that incorporates the Stancomb-Wills Glacier Tongue and the Riiser-Larsen Ice Shelf to the east. The Brunt Ice Shelf flows northwest from the coast of Coats Land with a speed of $>500 \text{ m a}^{-1}$ at the calving front, although there is strong temporal variability in the flow regime (Gudmundsson et al 2017). The flow is restrained by grounding at the McDonald Ice Rumples (Fig. 1) in the northeast corner of the ice shelf (Thomas, 1973a, b, 1979).

The grounding zone between the Brunt Ice Shelf and the grounded ice in Coats Land is steep and heavily crevassed, so that the entire ice sheet breaks up into large blocks between 2500 and 6000m long and 250 to 900m wide. Therefore, the majority of the ice shelf within 15 to 20km of the grounding line actually comprises icebergs surrounded by sea ice and has large topographic relief (Fig. 2). Accumulation of falling and drifted snow infills

the topography such that the surface of the downstream part of the Brunt Ice Shelf undulates gently giving little indication of the underlying structure. The presence of marine ice deposited at the base of the ice shelf is highly likely (Khazendar & Jenkins 2003, Khazendar et al 2009).

In this study, we use ice-penetrating radar surveys to describe aspects of the internal structure of the Brunt Ice Shelf and interpret potential mechanisms for its development. Previous studies of the ice shelf using radio echo-sounding (Bailey and Evans, 1968; Walford, 1968) showed that echo strength from the base of the ice was highly variable and that there were regions of very high attenuation where no basal echoes were recorded. The high attenuation was attributed to the percolation of sea water or the presence of saline ice formed from sea water. We have applied up-to-date radar sounding equipment and techniques to provide better spatial coverage and resolution than the previous efforts.

An extensive network of GPS monitoring stations has been established on the Brunt Ice Shelf as part of the infrastructure for Halley 6 Research Station (Anderson et al 2014). Recently, two significant new rifts developed in the ice shelf (De Rydt et al 2017), one an extension of 'Chasm 1' (Fig.1) which has remained unchanged since the 1970s, one a new rift named 'Halloween Crack' (from the date of formation on 31 October 2016). Thus the region around Halley Station is a unique place to study the impact of ice shelf structural heterogeneity on fracture propagation because dynamic changes are underway within a well-monitored environment and the station provides a logistic hub to undertake extensive ground-penetrating radar survey. The rate and direction of propagation of Halloween Crack changed when the crack tip entered a region of thicker ice shelf thought to comprise closely-spaced blocks of meteoric ice (De Rydt et al 2017). In this paper, we use radar results to determine the degree of heterogeneity in ice shelf internal structures and discuss how this came to be.

In Section 2 the regional surface and basal topographic data is reviewed. In Section 3 the radar data acquisition and processing is described. Section 4 describes and interprets the radar profiles. In Section 5, we will discuss the radar profiling results in terms of the internal structure of the ice shelf and the implications for fracture propagation are presented in Section 6.

2 Observations

2.1 Surface topography

The surface topography (Fig. 2) is based on a number of 3 m resolution WorldView DEM tiles acquired between 2012 and 2014. To stitch tiles together, one tile, which included the buildings of Halley 6 station was designated the anchor tile, adjacent tiles were shifted manually in x, y and z coordinates (without rotation) to match

identifiable points between pairs, particularly in near-static areas around the McDonald Ice Rumbles and on the grounded ice sheet. There are several distinctive topographic regions as follows.

- An inner region within 20 km of the grounding line. Here there are large areas where the snow surface is between 1 and 10 m above sea level (blue colours in Fig.2).
- Curvilinear bands where the average elevation is 35 m above sea level (orange colours in Fig. 2). These bands can be traced from the grounding line to the calving front. They have a distinctive appearance created by undulations which is reminiscent of close-spaced railway sleepers. For the purposes of description, we term them ‘railway tracks’. The spacing of the ‘sleepers’ is around 1.5 km (profile A-A’, Fig. 2).
- Intervening bands where the average elevation of the ice shelf is low, in particular in the first 20 km from the grounding line large areas are within 2m of sea level with scattered highs rising to 35-40 m. With distance from the grounding line, the broad troughs become filled in while the peaks decline in elevation from 35-40 m to 25-30 m (Profile B-B’) in Fig. 2. High points in these bands are more widely spaced and irregular than in the ‘railway tracks’.
- Steep-sided, flat bottomed rifts with walls around 30 m high. These are locally known as chasms (Chasm 1 and Chasm 2, Fig. 2). The chasms extend 30 km into the ice shelf from the south.

2.2 Sub-glacial topography

The BEDMAP 2 database (Fretwell et al, 2013) was used to map the subglacial topography beneath the grounded ice in Coats Land (Fig. 2). Within the mapped area there are two 10 km wide troughs with an intervening ridge that are oriented approximately orthogonal to the grounding line. Ice flow speed derived from InSAR data (Rignot et al. 2017) shows that within the troughs flow speed peaks at 105 ma^{-1} and 100 ma^{-1} , whereas ice flowing off the ridges has a flow speed of between 15 and 35 ma^{-1} (Fig. 3).

3 Radar acquisition and processing

The data were collected between December 2015 and February 2016 using a commercial ground-penetrating radar system (Sensors and Software PulseEKKO PRO) operating at a centre frequency of 50 MHz. The system was mounted on a sledge, which was towed behind a snow mobile travelling at 15 km/hr, with traces recorded continuously. Positioning information was recorded using a dual-frequency GPS receiver and the satellite range information was processed through the Canadian Geodetic Service Precise Point Positioning service in kinematic

mode. This methodology provided radar profiles with positions accurate to around 0.5m. The radar data were processed using ReflexW software by applying a bandpass filter (with corner frequencies 10/20/60/120 MHz), a spherical spreading correction, a horizontal filter to remove the direct arrival, and time migration. A fixed wave speed of 0.168 m/ns was used for both migration and depth conversion because the construction of a detailed wave speed model for the ice shelf using multiple common mid-point determinations was beyond the scope of the survey. We therefore elected to use the fresh water ice wave speed of 0.168 m/ns throughout. We estimate that our figures for the thickness of the ice shelf where most of that thickness is made up of meteoric ice have an uncertainty of about 20%. Where there is significant thickness of firn, the use of a uniform wave speed underestimates the overall ice shelf thickness by approximately 5%.

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4 Radar data

4.1 Data description

In this section, we will first describe the reflection character of some example radar profiles taken from a large data set. We will then interpret the different reflection facies observed in terms of their glaciological origins.

15 Portions of two flow-line radar profiles 1800 m long are presented in Figure 4. The locations are shown in Fig. 2. Line 04 was acquired in one of the ‘railway track’ bands of slightly higher topography. Line 62 was acquired in the adjacent lower topography region to the west of Line 04.

Line 04 (Fig. 4a,b) has a near-surface radar facies of undulating, layered, continuous reflections between 13 and 60 m thick. This facies is colour-coded yellow in the figures. The layered facies lies above a second facies with irregular, scattered reflections of highly variable amplitude (colour-code blue). The deepest sections of the interface between the two facies are characterized by very high amplitude, laterally continuous reflections (orange). The remainder of the profile is largely reflection-free until a band of curvilinear reflections at between 240 and 270 m below surface. The events marked as multiples are reflections that arise from internal reverberation between strong reflectors.

25 Line 62 (Fig. 4c,d) also has an upper radar facies of undulating, layered, continuous reflections, this time between 13 and 40 m thick. There are three regions with irregular, scattered reflections of variable amplitude forming prominent highs in the section. Between these highs there is a near-horizontal reflection with very high amplitude at approximately 40 m below surface (the surface is at 22 m above sea level). This reflection has a prominent

multiple. Below the three highs, there are weak, scattered reflections then, at around 150 m depth, a set of high-amplitude, curvilinear reflections.

Figure 5 shows another example and more detailed view of the radar reflection facies described above. Line 05 (for location see Fig. 2) is located in one of the lower topography bands in the ice shelf but adjacent to some isolated ridges. The upper radar facies of undulating, layered, continuous reflections is between 21 and 50 m thick. The second facies of irregular, scattered reflections of variable amplitude forms a single high between 450 and 680 m along the profile. Elsewhere, the base of the layered facies is a very high amplitude reflection which is conformable to the layers above in some places and is flat-lying between 170 and 330 m along the profile.

4.2 Interpretation

- 10 The undulating, layered, continuous reflection facies is interpreted as firm deposited in-situ on the ice shelf. The reflections are isochrones, therefore the spacing between them gives an indication of the local relative accumulation rate e.g. (Vaughan et al 2004, Vaughan et al 1999). The radar system does not have sufficient vertical resolution to image individual annual layers, the reflections observed are the result of the convolution of returns from many, more finely-spaced, reflectors.
- 15 The radar facies with irregular, scattered reflections of variable amplitude is interpreted as the returns from blocks of meteoric ice embedded in the ice shelf (this facies is coloured blue in Figs 4 and 5). Figure 6 shows a visual satellite image of the region around the grounding line (the location is shown as a black rectangle on Fig. 2). It is evident that the ice flowing over the grounding line is completely riven by crevassing and that the ice shelf at this point comprises more or less closely packed icebergs held together by sea ice (Fig. 6b). The
- 20 curvilinear reflections at depth on Lines 04 and 62 (Fig. 4) are interpreted as arising from the ice/water interface at the base of the embedded icebergs. The undulations of the firm reflections in the upper radar facies (yellow colouring) indicate differential accumulation between and over the embedded ice bergs (Figs. 4 and 5). It is also possible that undulations in the firm may, in part, be due to horizontal shortening induced by historic changes in flow speed of the ice shelf (Gudmundssen et al., 2017).
- 25 The very high amplitude reflection (orange colour in figures) that is near-horizontal on Figure 4c and in parts cross-cutting and parts conformable with the firm layering in Figure 5 is interpreted as a brine infiltration front. The reflection cross-cuts the isochronal reflections, suggesting a later, non-stratigraphic origin. There is strong attenuation beneath the reflector which, together with the very high amplitude, suggests a large contrast in electrical conductivity. Liquid brine was found in a hole drilled in 'thin ice shelf' to the west of the MacDonald
- 30 Ice Rumples (Thomas 1973). The brine was found at a depth 1.5m below sea level. Its temperature was -10°C,

suggesting a salinity of 125 ‰. Immediately below the brine was bubbly impermeable ice. Brine infiltration has been observed on radar profiles of the McMurdo Ice Shelf (Grima et al 2016, Kovacs & Gow 1975, Morse & Waddington 1994) as well as the Wordie Ice Shelf, the Larsen Ice Shelf and Wilkins Sound (Smith & Evans 1972).

5 The brine reflection observed in Figs. 4 and 5 is considerably deeper than sea level at those locations. Figure 7 shows an example of a radar profile that approaches one of the large rifts in the ice shelf. On this profile there are very high amplitude near-horizontal reflections at two levels. The upper level is close to sea level while the other is 13m lower. We interpret this profile to indicate that there has been recent brine infiltration horizontally from the rift where sea water can be observed in cracks in the sea ice flooring the chasm. We suggest that the other
10 reflection arises from an older brine infiltration event, which may have a different mechanism which will be discussed in the next section.

5 Discussion

We have established that the ‘railway track’ bands of higher elevation originated at the grounding line in locations where there are troughs in the bed topography. Conversely the bands of lower topography originated at
15 ridges in the bed topography beneath Coats Land. Figure 8 summarizes the situation in cross-section. Ice flowed from the troughs in bedrock at a higher rate than off the ridges, providing a steady stream of large, thick blocks of meteoric ice that formed a closely-packed flow band within the ice shelf. Ice that flowed off the ridges in the bed topography was thinner and supplied to the ice shelf at a slower rate. As a result, the meteoric ice blocks were both thinner and more spaced out, resulting in isolated icebergs surrounded by large areas of sea ice (Fig. 2,
20 topographic profile B-B’; Fig. 3c; Fig. 6b).

The majority of Antarctic ice shelves are formed by the coalescence of glaciers or ice streams that flow across the grounding line in structurally coherent bodies, perhaps with some surface or bottom crevassing, but otherwise intact. The Brunt Ice Shelf is one of a class of ice shelves (other examples are Thwaites Glacier Tongue, the western sector of Cook Ice Shelf and the ice shelf lying off the Leopold and Astrid Coast) comprising ice which
25 retains no structural integrity when flowing across the grounding line, and as a result, the blocks of meteoric ice are cemented together by sea ice and drift snow to form the ice shelf.

The process which cements together the ice shelf involves the gaps between meteoric ice blocks being filled first by sea ice and then by drift snow which consolidates into firn (Fig. 9 a&b). The isostatic loading by snow
▲ accumulation pushes the sea ice downwards until it lies below sea level. At this point, the process of firn

consolidation has not advanced to pore close-off and the firn is still porous and permeable, allowing sea water to soak the firn. Freezing cycles then concentrate the salt to leave a brine horizon (Fig. 9c). In Figure 5 the topography on the high-amplitude reflector provides evidence that the brine infiltration may have occurred by sinking of the firn rather than by horizontal spreading of salty water. Warm periods in the summer can produce melt horizons within the firn, creating an impermeable layer. Our hypothesis is that the soaking of the firn from below as it sank to ocean level may have been blocked by the impermeable layer in the region between 50 and 150 m along Line 05 (Fig. 5). This would explain why the brine infiltration reflector is a syncline conformable with the firn layering in this section of profile. The same process may have occurred between 670 and 800 m along the profile, although it is also possible that enhanced accumulation in this region created or deepened the syncline there after the brine horizon had become frozen into place. Another possible explanation of the syncline in the brine reflector between 670 and 800m is horizontal shortening induced by variations in the flow speed of the ice shelf.

It is not clear what controls the termination of the process of brine infiltration and locks the high-amplitude reflector in place within the ice shelf so that it descends below sea level as further accumulation takes place. It is likely that a balance between pore space reduction by compaction of the firn and freezing of sea water in the gaps between ice crystals eventually reduces the permeability of the firn to nothing at a depth shallower than the dry firn pore close-off would be. Another factor may be the formation of marine ice below these sections of developing ice shelf in similar fashion to the formation of marine ice in rifts described by Khazendar and Jenkins (2003). While marine ice is porous and permeable when first formed, it thickens and consolidates over time and could eventually close off access for sea water to the lower sections of firn.

The lower elevation bands between the 'railway tracks' in the Brunt Ice Shelf have many of the characteristics of ice mélange, that is they combine sea ice, marine ice, firn and scattered meteoric ice blocks. Ice mélange has been identified as a prominent feature of the Brunt Ice Shelf/Stancomb Wills Ice Tongue system (Khazendar et al 2009) where large areas were identified on either side of the Stancomb-Wills Ice Tongue cementing together large tabular icebergs. Thought of in this way, the Brunt Ice Shelf is a series of ice tongues cemented together by ice mélange to create a single mass with highly heterogeneous properties.

This heterogeneity of structure has a number of potential implications. For example, the icebergs of meteoric ice may have a different bulk density compared to the adjacent mixture of firn, sea ice and marine ice in the mélange. If the bulk density was significantly different, it would affect the thickness-from-freeboard calculations that are carried out over ice shelves where there are no ground-truth thickness measurements (Griggs and Bamber 2011). Khazendar et al (2009) estimated the temperature of ice mélange at between -11°C and -7°C and that of meteoric

ice at between -21° and -15°C . This has implications for melt rate calculations and the different types will produce meltwater of different salinity.

The propagation of a large rift through the Larsen C Ice Shelf was shown by Borstad et al (2017) to be faster through meteoric ice than through suture zones, implying greater fracture toughness in the suture zones. It is not known whether the mechanical properties of the ice in suture zones constrained between large homogeneous bodies of meteoric ice such as those in the Larsen C Ice Shelf are similar to the mechanical properties of the ice mélange in the Brunt Ice Shelf. There are strong similarities in the way the material forms but post-formation history may be important in the development of the mechanical properties. For example suture zones can experience high shear strain (Jansen et al 2013) whereas the ice mélange areas of the Brunt Ice Shelf probably do not.

6 Implications for fracture propagation

The heterogeneous structure of the ice shelf influences the rate and direction of the propagation of fractures. Over about half the area of the ice shelf, the location of the meteoric icebergs can be identified from the surface topography (Fig. 2). Where firm accumulation has buried the icebergs completely in the outer part of the ice shelf, the location of the meteoric ice can be mapped using SAR satellite imagery. The top panel in Figure 10 shows a radargram of the upper 90m of ice shelf in the central railway track, following the red line in Figure 11 from its most western point towards the grounding line. The black line in Figure 10 marks the interface between radar facies 1 (firm) and facies 2 and 3 (brine and meteoric ice). The bottom panel shows the backscatter amplitude along the same section from a Sentinel 1A radar image acquired on 29 October 2017. A Gaussian filter with a radius of 40m was applied to suppress small-scale noise. There is a very high correlation ($r = 0.607$, $p=0$) between peaks in the backscatter amplitude and the zones of thin firm overlying the crests of the ice bergs. This correlation is not a coincidence, as the C-band sensor on Sentinel1-A is known to penetrate the surface of the ice (Bingham & Drinkwater 2000), and it is therefore capable of picking up the spatial variability in the structure of the ice near the surface. However, the details of this mechanism remain subject to future study, and here we merely note its existence. Using radar backscatter from Sentinel-1A as a proxy, the spatial distribution of meteoric ice can be mapped across the entire ice shelf, as illustrated in Figure 11.

The complete map of ice shelf heterogeneity provides a unique opportunity to interpret observed changes in the trajectory and propagation speed of two major rifts (Chasm 1 and Halloween Crack) in the ice shelf, and to relate these changes to the internal structure of the ice shelf. To highlight the different ways in which the rifts interact

with the internal structure, we focus on two small regions outlined by the black boxes (A and B) in Figure 11. Region A (Fig. 11) covers the tip of Chasm 1 in November 2017; a detailed view is shown in Figure 12. The overall direction of propagation of Chasm 1 is dictated by the large-scale stress field in the ice shelf, with a trajectory that is perpendicular to the direction of maximum tensile stress (De Rydt et al 2017, Gudmundsson et al 2017). However, Figure 12 shows that at smaller length scales, the exact trajectory is dictated by the location and shape of the meteoric icebergs, and Chasm 1 follows pre-existing lines of weakness along the edges of the icebergs, in particular within the ‘railway track’. Only at one instance, Chasm 1 propagated through an area of meteoric ice (red circle in Figure 12), which coincided with a period of significantly slower propagation rates (De Rydt et al 2017).

Region B (Fig. 11) covers part of the Halloween Crack where the rift propagated through the northern railroad track; a detailed view is shown in Figure 13. The overall direction of propagation is again dictated by the stress distribution in the ice shelf, which forces the Halloween Crack to cross an area with a high concentration of meteoric ice, where the edges of the iceberg are misaligned with the overall direction of propagation (red ellipse in Figure 13). This has resulted in a more complex propagation behaviour, where the rift followed edges of the icebergs for short periods, and broke through the icebergs in places of weakness, such as discontinuities in the ‘railway sleepers’. For the remainder of the trajectory shown in Figure 13, the rift, while generally following a path dictated by the stress field, in detail weaves its way around scattered icebergs within the ice shelf, avoiding fracturing through areas of meteoric ice. Thus, fracture through the Brunt Ice Shelf progresses at contrasting rates to rifts through other documented ice shelves. Elsewhere rift extension rates increase in meteoric ice and decrease in suture zones comprising ice mélange, whereas recent Brunt rifts slow in meteoric ice and speed through ice mélange. This suggests that there is a difference in the physical properties of ice that was formed in similar ways but which had different subsequent histories e.g. amount of shear strain, during advection through the ice shelf.

7 Conclusions

Unusually the Brunt Ice Shelf is composed of alternating bands of ice of two types which have different origins and compositions. The first type is identifiable on visual satellite imagery by a ‘railway track’ appearance and comprises large blocks of meteoric ice originating in the ice sheet in Coats Land which are cemented together by thin strips of sea ice and firn. This type is mostly thick freshwater ice. The second type has a random appearance on satellite images and comprises an ice mélange of scattered, relatively thin blocks of meteoric ice from the

continent separated by large areas of sea ice (probably underlain by marine ice) and firn that has been soaked by sea water and refrozen.

5 While a fracture propagating through the Larsen C Ice Shelf sped up when traversing through meteoric ice and slowed in suture zones, fractures observed in the Brunt Ice Shelf slowed when going through meteoric ice blocks and often routed through the ice mélange in the gaps between the meteoric ice. This contrast in styles of fracture propagation in different ice shelves needs to be better understood so as to improve predictive modelling of ice shelf stability.

Competing interests

The authors declare no competing interests.

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Figure captions

Figure 1: The Brunt Ice Shelf lies off Coats Land on the east side of the Weddell Sea, Antarctica (inset). The surface of the East Antarctic ice sheet slopes steeply down to the grounding line marked by a white line, elevation contours are at 100 m intervals. The ice shelf is partially grounded at the McDonald Ice Rumples. After several decades of sustained ice shelf growth, two rifts have developed in the past two years, marked by red lines. The first was an extension of a dormant rift known locally as Chasm 1, the second appeared on 31st October 2016 and is known as Halloween Crack. Halley Research Station was re-located to the position marked 'Halley 6a' in January 2017.

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Figure 2: Surface elevation of the Brunt Ice Shelf and the bedrock elevation beneath grounded ice in Coats Land. Flow lines downstream from troughs in the bedrock have higher elevation throughout the ice shelf (orange colours). Near to the grounding line these elevated bands comprise closely-spaced ridges resembling railway sleepers, hence we term the bands 'Railway Tracks' for descriptive purposes. White lines show locations of elevation profiles extracted from the digital elevation model and shown below the map. Line locations in black mark sections of radar profiles shown in Figs. 4 and 5. Pink line is location of flow speed profile shown in Fig. 3. Box is the extent of the satellite image shown in Fig. 6.

Figure 3: a) Flow speed profile across a gateway 5km upstream of the grounding line (marked in Fig. 2). b) Surface and bed elevations for the gateway.

Figure 4: Ice shelf cross-sections acquired with a 50 MHz ground-penetrating radar system. Locations are marked in Fig. 2. Radar facies descriptions and interpretations are given in the text a) Line 04 lies along one of the 'Railway Tracks'. Three radar facies are identified (inset). b) Interpretation of Line 04. Radar facies 1 is interpreted as firn accumulated by snow fall and drift on the ice shelf. Radar facies 2 is interpreted as a brine horizon. Radar facies 3 is interpreted as blocks of meteoric ice that originate as ice bergs calved off the inland ice sheet at the grounding line, the blocks are up to 200 m thick. c) and d) Radar cross-section from Line 62 in the thinner ice shelf area between two of the 'Railway Tracks'. The ice bergs are significantly thinner and more widely spaced.

Figure 5: Close-up of a section of radar profile (Line 05, location on Fig. 2) that illustrates different structure on the brine reflection. In some places the reflection is horizontal and cross-cuts reflections in the firn layer. Elsewhere the reflection is conformable with the isochronal reflections in the firn layer.

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Figure 6: Landsat image of the region around the grounding line (location Fig. 2). Intense crevassing occurs 3-4 km upstream of the grounding line. The ice retains no structural integrity on crossing the grounding line, the ice shelf is composed entirely of separated blocks held together by sea ice. Where the ice flows from a subglacial trough the blocks remain closely-packed with narrow channels of sea ice between them, but where the ice flows
10 off a subglacial ridge, the blocks are widely-spaced with extensive areas of sea ice between.

Figure 7: Westernmost section of radar profile from Line 62 (Fig. 2) near Chasm 1. High amplitude reflections interpreted as brine infiltration horizons are observed at 26 m and 39 m below the surface of the ice shelf. The depth of the upper reflection coincides with sea level in the adjacent rift suggesting horizontal migration of sea
15 water through porous and permeable firn recently exposed to the ocean. The lower reflection is interpreted as sea water infiltration that became frozen in place some distance upstream.

Figure 8: Cartoon to illustrate the origin of the two different structures within the Brunt Ice Shelf. A) Ice flowing out of a subglacial trough at around 100ma^{-1} breaks up into closely-packed ice bergs separated by narrow
20 channels in which sea ice forms. B) Where thinner ice flows over the grounding line at a slower rate the supply of ice is insufficient to match the flow speed of the ice shelf (which is driven by the faster ice coming out of the troughs), so the structure comprises thin, widely-spaced icebergs separated by wide expanses of sea ice.

Figure 9: Cartoon to illustrate the process by which sea ice between ice bergs becomes loaded by firn
25 accumulation and driven below sea level by hydrostatic adjustment, allowing sea water to soak into the porous and permeable firn from below.

Figure 10: Top panel: The upper 90 m of a radargram along the railway track near Halley 6 Research Station compared to (bottom panel) the Sentinel-1 backscatter amplitude along the same line.

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Figure 11: Map showing radar backscatter proxy for the presence of meteoric ice. Over most of the ice shelf, black indicates the presence of meteoric ice and white areas correspond to infill by sea ice and firn. Boxes indicate the location of detailed views in Figures 12 and 13. Red line is the location of the profile in Fig. 10.

- 5 Figure 4: Detailed view of the tip of the Chasm 1 Crack (blue curve). The background image distinguishes areas with meteoric ice (dark) from areas with sea-ice overlain by firn. When the crack went through one of the blocks of meteoric ice rather than around it (red circle), the rate of propagation slowed.

Figure 13: Detailed view of part of the Halloween Crack (blue curve). Crack propagation slowed when the crack crossed one of the 'railway tracks' at a high angle to the meteoric ice blocks. Rift extension speed then increased in the ice mélange beyond.