Holocene thinning and grounding-line retreat of the Darwin-Hatherton glacier system, Antarctica

Abstract

Outlet glaciers of the East Antarctic Ice Sheet thickened throughout the Transantarctic Mountains during Marine Isotope Stage II and fed a grounded ice sheet in the Ross Embayment. Exposure and radiocarbon ages of glacial deposits in four ice-free areas alongside Hatherton and Darwin glaciers record several hundred meters of late Pleistocene to early Holocene thickening relative to present, followed by thinning through the Holocene, as the grounding line of the Ross Sea Ice Sheet retreated to the south. Darwin and Hatherton glaciers retreated from their high-stands later than glaciers farther south, contrary to the long-held “swinging gate” model of grounding line retreat. Converging flowlines from Byrd and Mulock Glaciers in front of Darwin Glacier may have opposed rapid grounding line retreat to the mouth of Darwin Glacier, while the grounding line continued to retreat in the central Ross Embayment.

**Introduction**

*The Swinging Gate*

A thick ice sheet filled the Ross Embayment of Antarctica during Marine Isotope Stage 2 (MIS-2), grounded near Coulman Island (73° S) (Anderson et al., 2013). After 13 ka, the grounding line retreated >1,200 km to its current position along the Siple Coast. Conway et al. (1999) proposed that grounding line recession followed the pattern of a swinging gate, with its hinge in the eastern Ross Sea. They based this hypothesis on three chronologies:

(i) Mollusk colonies, shells, and seals re-inhabited beaches in Northern Victoria Land. Radiocarbon ages of these remains require the presence of open water by 8 cal. kyr BP.

(ii) Radiocarbon ages of freeze-dried algae found in former ice-marginal ponds alongside Hatherton Glacier, a tributary of Darwin Glacier, suggest that the glacier system reached its present configuration before 6.8 kyr BP (Bockheim et al., 1989).

(iii) An ice flow model of Roosevelt Island best fits the observed Raymond bump (Raymond, 1983) in radar layers if divide flow initiated ~3.2 kyr BP.

This chronology has been repeatedly modified with multiple new lines of evidence. Martín et al. (2006) used a thermomechanically coupled transient model to refine the estimate of the initiation of divide flow at Roosevelt Island. They found that a high power (n=4) rheology is required to match the shape of the Raymond bump, and that divide flow likely initiated 3000 +1,200/-700 yr BP. Todd et al. (2010) mapped and dated deposits alongside Reedy Glacier, and showed that thinning initiated ~13 kyr BP and had largely ceased by 1 kyr BP. Exposure ages from deposits alongside Shackleton and Beardmore Glaciers show that these glaciers had reached modern elevations by 7.4 kyr BP, and the chronology at Scott Glacier shows that the Ross Ice Shelf grounding line reached its present position between Reedy and Scott Glaciers around 3 kyr BP (Spector et al., unpublished). This suggests that a 1100 km-long section of the TAMs front deglaciated almost contemporaneously.

Anderson et al. (2004) used a numerical model of the Darwin-Hatherton glacier system to show that fluctuations of Hatherton Glacier may have lagged changes at the mouth of Darwin Glacier by as much as 1100 years. This uncertainty causes considerable overlap with the date of deglaciation in Northern Victoria Land (7.8 kyr BP); therefore, it may not be valid to directly apply Bockheim et al.’s (1989) Hatherton Glacier chronology to interpret changes in grounding line position. However, Anderson et al. did not have knowledge of the bed topography or basal conditions at Hatherton or Darwin Glaciers; their analysis is therefore open to reinterpretation using new data from aerial and ground geophysics surveys (cf Riger-Kusk, 2011).

In this paper, we revisit the chronology of the Darwin and Hatherton glaciers since the penultimate glaciation with surface exposure ages of glacial erratics and radiocarbon ages of freeze-dried algae. Advances in radiocarbon dating since the 1980s and the advent of surface exposure dating allow us to examine the history of this glacier system in much higher spatial resolution and temporal precision than Bockheim et al. (1989) were able to do. The data presented here do not contain enough temporal overlap between the Darwin Glacier and Hatherton Glacier chronologies to discuss the response time of Hatherton Glacier to changes at the mouth of Darwin Glacer. In another paper, we will use a 1.5-dimensional finite-volume flowband model to determine what can be deduced about LGM and deglaciation conditions at the mouth of Darwin Glacier from the more complete chronologies we have constructed from alongside Hatherton Glacier.

*The Darwin-Hatherton Glacier System*

Darwin Glacier and its tributary Hatherton Glacier are EAIS outlet glaciers that flow through the TAM to the modern Ross Ice Shelf. Outlet glaciers throughout the TAM thickened first at their mouths during MIS-2 in response to thickened, grounded ice in the Ross Sea, and later at their heads due to increased accumulation after the LGM (Todd et al., 2010). Lateral moraines of MIS-2 age have been used to interpret ice thicknesses of both the grounded Ross Ice Sheet and EAIS outlet glaciers (Bockheim et al., 1989; Denton et al., 1989; Todd et al., 2010; Spector et al., unpublished).

Bockheim et al. (1989) mapped lateral moraines and drift sheets in ice-free valleys alongside Hatherton Glacier, and dated these deposits based on weathering, soil characteristics, and a small number of radiocarbon ages of freeze-dried algae. These algae grew in glacier-dammed ponds, and they died as the glacier thinned and drained the ponds after the local LGM. These ages thus provide a good proxy for the glacier margin position through time, subject to the uncertainties of the pond size. Bockheim et al. (1989) tentatively attributed the Britannia II drift sheet to the LGM, and interpreted the Britannia I drift several hundred meters inboard as a Holocene readvance or stillstand. They named the unweathered drift sheet immediately adjacent to the glacier margin the Hatherton drift. Two much older drifts they termed the Danum (MIS-6) and Isca (much older, but undated).

The Britannia II drift lies 100 m above the current glacier margin at the head of Hatherton Glacier, and 450 m above the current margin in the middle of the glacier profile. Bockheim et al. (1989) extrapolated this to infer up to 1100 m of thickening at the confluence of Darwin Glacier with the Ross Ice Sheet during MIS-2, although they found no deposits there. Anderson et al.’s (2004) numerical model yielded a more modest 800 m of thickening. Forthcoming cosmogenic *in situ* 14C measurements from bedrock at the mouth of Darwin Glacier will constrain the LGM ice thickness at the mouth of Darwin Glacier.

Storey et al. (2010) revisited the Lake Wellman area, where Bockheim et al. (1989) found 450 m of LGM thickening, and used surface exposure dating to determine the age of the Britannia and Hatherton drift limits. Their ages for the Britannia drift range from 22 to 182 kyr BP, but they interpreted a cluster of five ages with a mean of 35 kyr BP to represent the age of the drift sheet. They correlated the Hatherton drift, only 70-100 m above glacier level, to minor LGM thickening or a Holocene deglaciation event. These interpretations would indicate either that Hatherton Glacier did not respond to thickening of ice in the Ross Sea during MIS-2, or that ice in the Ross Sea did not ground and thicken during MIS-2. These results are in conflict with the vast majority of glacial geological data (e.g., Baroni and Hall, 2004; Conway et al., 1999; Denton et al., 1989; Stone et al., 2003; Todd et al., 2010; Bromley et al., 2010), marine geologic data (e.g., Shipp et al., 1999; Domack et al., 1999), geophysical data (e.g., Price et al., 2007; Conway et al., 1999), and model results (e.g., Anderson et al., 2004; Waddington et al., 2005; Martín et al., 2006; Pollard and Deconto, 2009; Whitehouse et al., 2011).

Joy et al. (2014) revisited the upper Hatherton Glacier in order to date the deposits in Dubris and Bibra valleys using surface exposure dating. They showed the Britannia II drift is in fact of MIS-6 age, and the Britannia I drift is Holocene in age. Using Storey et al.’s (2010) conclusion that lower Hatherton Glacier did not thicken at the LGM, they suggested that the ice thickness of the upper Hatherton Glacier is predominantly controlled by accumulation-driven fluctuations of the EAIS, and that the EAIS ice was thinner during the LGM. However, the LGM in Antarctica is known to be later than the global LGM by thousands of years (Stone et al., 2003; Hall et al., 2015), and the Holocene age of the Britannia I drift is in agreement with ages from glaciers throughout the TAM (Todd et al., 2010; Spector et al., unpublished).

The deglaciation chronology of the Darwin-Hatherton glacier system has been used as one of three key constraints in the swinging gate model of Ross Sea grounding-line retreat (Conway et al., 1999). However, this chronology was based on a handful of bulk radiocarbon ages. Radiocarbon dating techniques in the 1980s required a gram of carbon, while modern techniques require only ~1 mg (CITATION NEEDED), and thus these results likely have an averaging effect on the age. Furthermore, these samples were collected alongside Hatherton Glacier, which is >50 km from the modern grounding line, and is influenced both by a lagged response to grounding line position and by changes in surface mass balance. It is therefore necessary to gain a more holistic view of the deglaciation history of these glaciers in order to accurately assess the timing both of the establishment of the modern grounding line position and of steady flow at Hatherton Glacier.

Description of Deposits

We refer the reader to the comprehensive paper by Bockheim et al. (1989) for a more complete description of the deposits. Here we only summarize the general characteristics of each deposit, noting observations pertinent to our chronology that may be missing from the description of Bockheim et al.

**Methods**

*Exposure dating of glacial erratics and bedrock*

*Radiocarbon dating of sub-fossil algae*

*Numerical model*

**Results: Exposure dating**

Hatherton Glacier

*Britannia II*

Our chronology supports the conclusion of Joy et al. (2014) that the Britannia II deposit is a product of the penultimate glaciation. While Joy et al. give a mean 10Be age of 126 ± 3.2 kyr BP (n = 5), we find an 26Al age of 141 ± 3 kyr (n = 9; reduced Χ2 = 1.35). Recalculation of Joy et al.’s ages using an updated estimate of the 10Be production rate yields an age of 138 ± 4 kyr, in close agreement with our 26Al age. Our initial attempt to date the Britannia II limit using 10Be resulted in a widely spread dataset (FIGURE), which yielded an age of ~133 kyr BP (n = 9; reduced Χ2 = 57.9). This underestimation of 10Be ages is consistent throughout most of the samples that we dated using both 10Be and 26Al. We attribute it to a persistent analytical bias at the CAMS accelerator between the years 20xx and 20xx. This will be discussed later in the paper.

*Britannia I*

The Britannia I drift limits alongside Hatherton Glacier reveal a stable maximum extent between 7.5 and 8.5 kyr BP (Figure X). Variations in the age of the limit of deposition are to be expected, as many variables can control the local scale dynamics of the glacier margin, including local wind patterns, air temperatures, and bed topography (need citation here; this is really just a thought). Therefore, the 7.5 kyr BP age of the limit on Updog Mountain should not be interpreted as differing significantly from the 8 kyr or 8.2 kyr ages from Danum Platform and Dubris Valley, which are virtually in the same position relative to the glacier profile. The probability peak at Magnis Valley is slightly older than the upper valleys, at ~8.6 kyr BP; however, as these ages are reported with 1-sigma errors, this is likely not statistically significant.

*Lake Wellman*

While we were not able to obtain reliable exposure ages from the Britannia deposits in the Lake Wellman area, radiocarbon ages of algae from former Lakes Wellman show a strong dependence of age on elevation, with a stable maximum position from 13 kyr BP until ~8 kyr BP, followed by steady thinning to modern elevations by the late Holocene. Bockheim et al. (1989) and Storey et al. (2010) were not able to differentiate between the Britannia I and II drifts at Lake Wellman, but King et al. (2017) mapped the Britannia II limit slightly outboard of the Britannia I limit. There were no algae present in the Britannia II drift, and we did not sample it for surface exposure dating.

Darwin Glacier

We visited the Brown Hills and Diamond Hill, adjacent to Darwin Glacier and the Ross Ice Shelf in December, 2014. Previous attempts to date the deposits at the mouth of Darwin Glacier proved inconclusive (Bockheim et al., 1989; Joy, 2013).

*Brown Hills*

The Brown Hills lie adjacent to Diamond Glacier—a distributary lobe of Darwin Glacier—and to the Ross Ice Shelf. During glacial periods, Diamond Glacier would very likely have crossed the Brown Hills and connected with the Ross Ice Sheet. However, because the ice-free topography here is several hundred meters above sea level, the ice would have been thin, fast flowing (Kavanaugh et al. 2009), and very soon cut off from the thick ice sheet during retreat. Therefore, we would expect ages from recessional deposits in the Brown Hills to predate the chronologies of Hatherton or Darwin Glaciers.

We dated five erratics from the Brown Hills, including the Diamond Glacier side of Diamond Hill. The highest of these samples was a fresh-looking granite cobble taken from a weathered deposit high on Diamond Hill (877 m asl). While it was unweathered compared with the pre-LGM deposit it was perched on, it yielded a 10Be age of 205 ± 5 kyr, and thus it is either (i) recently exhumed from the older deposit, or (ii) a deposit of the last glaciation, with a high level of inherited 10Be. A single date from this deposit is not a good age constraint; however, based on the weathering characteristics of the pre-LGM deposit on which the rock sits, we conclude that thick ice covered much of Diamond Hill at least once in the Pleistocene. We did not find deposits of the last glaciation high on Diamond Hill.

The exposure ages of the erratics from the Brown Hills also provide only circumstantial constraints on the last glacial advance. One rock was heavily pitted and stained and yielded a 10Be age of 196 ± 5 kyr. Of the remaining three, only one gave a Holocene exposure age (7.1 ± 0.2 kyr; 390 m asl). The other two dated to 33.7 ± 0.9 kyr (385 m asl) and 17.8 ± 0.4 kyr (450 m asl). This dataset shows no dependence on elevation or distance from the current glacier margin, likely because of inherited 10Be or local scale fluctuations not controlled by regional ice dynamics or climate. However, this does show that ice had largely retreated from the Brown Hills, and therefore had disconnected from the Ross Ice Shelf/Sheet by ~7 kyr BP. The implications of this result for the larger glacier system are unclear; however, future analyses of *in-situ* cosmogenic 14C in bedrock from the Brown Hills may provide further insight.

*Diamond Hill erratics*

The only relatively fresh, unweathered erratics on Diamond Hill were perched on glacially sculpted bedrock domes overlooking Darwin Glacier, ~10 km upglacier from the modern grounding line. We dated 8 of these erratics, spanning 135 m of elevation above the current glacier margin, and we collected bedrock samples at each site where we collected erratics. There was no clear limit of deposition. These 8 erratics give 10Be ages spanning the latter half of the Holocene, from 5.2 ± 0.2 kyr BP 135 m above the current glacier margin, to 0.3 ± 0.03 kyr BP at the current glacier margin. The rate of thinning appears to have been relatively constant between 5.2 and 3.1 kyr BP, after which it slowed down.

Anderson et al. (2004) showed that the LGM ice surface was higher than 135 m above the current glacier margin, and we note that the lack of deposits does not necessarily imply ice-free conditions at the LGM. The ice above this could have been cold-based and debris-free, and thus did not deposit as it retreated from the side of Diamond Hill. The steep terrain and shear size of Diamond Hill prevented us from covering every piece of ground; however, we did climb to the top of Diamond Hill on the northern (ice-shelf proximal) side, and descended on the western (Brown Hills proximal) side, and we found no indication of LGM deposits.

*Diamond Hill bedrock*

We analyzed 10Be, 26Al, and 14C in an elevation transect of granitic bedrock from Diamond Hill in order to constrain the ice thickness at the LGM. While these measurements will not allow us to determine the timing of the LGM, using 14C enables us to constrain the elevation of the LGM ice surface. Within the range of erosion rates typically found in Antarctic bedrock (<1 micron/yr), 14C concentrations reach secular equilibrium in <30 kyr (Figure XXX). Because of the short half-life of 14C, a few thousand years of ice cover during the LGM will create a detectable signal of burial, while rock that was not covered with ice in the last 30 kyr will remain at its equilibrium concentration. Therefore the LGM ice surface elevation will be bracketed above by the lowest sample that is saturated with respect to 14C and below by the highest unsaturated sample.

Surprisingly, our lowest sample that is saturated with respect to 14C is at 472 masl, less than 200 m above the modern ice margin. This allows for two possibilities. First, perhaps the LGM surface was indeed <200 m above the current ice surface. Second, LGM ice could have been >200 m thicker than at present, but this thickening was extremely short-lived. Because it takes only 30 kyr for a rock to reach a concentration analytically indistinguishable from saturation, we will assume that this bedrock surface was saturated prior to the LGM.In the next section, we examine the latter possibility, using a forward model of nuclide production and decay.

If we neglect the upstream lag time to grounding line changes, the algae radiocarbon chronology from Lake Wellman provides a decent estimate of the duration of ice cover during the LGM. The ice margin at Lake Wellman was within 50 vertical m of its maximum position 13 kyr BP and began to retreat after 8.4 kyr BP. The very high equilibrium concentration of 3.55 x 105 atoms/g requires a total (spallogenic + muogenic) production rate of 43 atoms/g/yr, much higher than the 29 atoms/g/yr predicted by the time-independent Lal/Stone scaling scheme (Stone, 2000; Marrero et al., 2016), or any other commonly used scaling schemes. If the bedrock surface at Diamond Hill was saturated before the LGM and experienced the same history of ice cover as Lake Wellman, its concentration upon re-exposure at 8.4 kyr BP would be 2.04 x 105 atoms/g, and its present-day concentration after 8.4 kyr of exposure would be 3.01 x 105 atoms/g. This is well below the measured concentration of 3.55 ± 0.05 x 105 atoms/g.

A bedrock sample (14-HAT-033-DH) taken from 2 m above the current ice margin has a 14C concentration of 1.48 ± 0.03 x 105 atoms/g, well below saturation. This concentration is not immediately interpretable on its own as an exposure age, due to the likely presence of inherited 14C atoms from before the LGM. However, a glacial erratic (14-HAT-032-DH) collected immediately adjacent to this bedrock sample yielded a 10Be exposure age of 304 ± 36 yr. Therefore, because this rock has only just emerged from beneath the ice, we can use its 14C concentration to estimate a burial duration. We assume the bedrock was exposed and saturated with respect to 14C before the LGM. Scaling the production rate for the saturated sample down by 20% (to 34.4 atoms/g) because of the lower elevation, the saturation concentration is 2.84 x 105 atoms/g. We adopt this as the inherited 14C concentration at the time of last burial. Neglecting the very short time of post-LGM exposure from the erratic, the measured concentration corresponds to 5.4 kyr of burial. Alternatively, if we use the production rate of 24.8 atoms/g/yr predicted by the Lal/Stone scaling scheme, the saturation concentration is 2.05 x 105 atoms/g and the corresponding burial time is only 2.66 kyr. This latter estimate can be rejected because the oldest erratic from Diamond Hill is 5.1 kyr old.

This very simple model does not account for 14C produced by muons during burial. If 14-HAT-033-DH had been covered by an average of 100 m (corresponding to a 9170 g/cm2 density-normalized burial depth) of ice, the total production rate would be 0.18 atoms/g/yr, entirely due to muons penetrating the ice cover (I used the predN14depth script in CronusCalc to calculate this; however, this code underestimates the local production rate, so I need to rescale this up accordingly. I’ll figure out how to do that at some point). The corresponding saturation concentration is just 1.5 x 103 atoms/g, which is within the uncertainty of our measurement, even when the uncertainty of the local production rate scaling is taken into account. Thus, production by muons beneath ice cover during times when the surface was buried is not a concern.

What is the glaciological significance of this?

**Results: Ice flow model**

**Discussion**

*Timing of grounding line arrival*

Although our dataset from Diamond Hill is limited to elevations within 135 m of the preset glacier surface, we can conclude that the profiles of Darwin and Hatherton glaciers continued to respond to changes in grounding line position until ~3 kyr BP. The bedrock at the margin of Darwin Glacier is glacially polished and striated, indicating that the glacier was wet-based and erosive at the LGM. Model results indicate that it is likely wet-based even today (Riger-Kusk, 2011), and we thus expect that it was wet-based throughout the Holocene. Therefore, changes at the grounding-line likely propagate upglacier rapidly, and the lag time at the point adjacent to Diamond Hill is short (a few tens of years). Darwin Glacier did not achieve steady flow until ≤ 3 kyr BP, which means that the age of >6.8 kyr BP that Conway et al. (1999) used to constrain the timing of grounding line retreat greatly overestimates the age of the modern grounding-line at the mouth of Darwin Glacier.

The steady thinning of Hatherton Glacier through the Holocene also supports later arrival of the grounding-line relative to glaciers to the north and south (Hall et al., 2015; Jones et al., 2016; Spector et al., unpublished). If there was an episode of very large and rapid thinning at the mouth of Darwin Glacier corresponding to rapid encroachment of the grounding line, this would likely be recorded in the chronologies from Hatherton Glacier. These chronologies give no indication of a dramatic and rapid pulse of grounding-line retreat prior to the oldest erratic at Diamond Hill (5.1 kyr BP). The youngest erratic at Dubris and Bibra Valleys at the head of Hatherton Glacier is ~80 m above and 1.2 km away from the current glacier margin, and dates to 3.3 kyr BP. If these 80 m of thinning were accomplished at the same average rate of thinning (~0.04 m/yr), the glacier would have reached its modern position 1.3 kyr BP, which is consistent with the ages of the youngest erratic from Lake Wellman. Even accounting for a 1.1 kyr response time for Hatherton Glacier (Anderson et al., 2004), this means that the grounding line was still far from its modern configuration ≤ 4.4 kyr BP.

Our data only tell us when the glacier started and finished responding to grounding line retreat, as well as relative rates of retreat; we are not able to discern either the absolute rate of grounding line retreat or the distance to the grounding line at any given time during deglaciation. However, by correlating our chronologies to other datasets within the Ross Sea sector, we can make a first-order estimate of the sensitivity of Hatherton Glacier to grounding line position. Marine sedimentary records show that the grounding line retreated past Ross Island >8.6 kyr BP, ~400 km from the current grounding line of Darwin Glacier (McKay et al., 2016). Hatherton Glacier began to retreat from its last high-stand 8 – 9 kyr BP, suggesting that at this distance the influence of the downstream boundary condition overcame the influence of increased Holocene accumulation. Because marine ice sheet style grounding line retreat is likely much faster than corresponding changes in ice thickness far upglacier, it is difficult to say whether Hatherton Glacier began to respond because the grounding line came within some critical threshold distance, or if the kinematic wave of thinning took until this time to reach the glacier. Alley and Whillans (1984) investigated the effect of sea level rise on the East Antarctic Ice Sheet, and found that it took ~3 kyr for ice at the divide to thin by just a few cm per year, equivalent to the rates of thinning we find at Darwin and Hatherton Glaciers. This modeling experiment used a step change in sea level, which is not realistic; however, it is perhaps analogous to the threshold behavior of marine ice sheet style grounding-line retreat.

In order to determine whether Hatherton and Darwin Glaciers would respond to changes at the LGM grounding line, we modeled the glaciers to the LGM grounding line using a SIA steady-state 1.5D flowband model. While we do not expect the SIA model to faithfully recreate ice dynamics near the grounding line due to the increasing influence of longitudinal stresses that are not accounted for in the SIA, this likely has very little affect on the ice surface profile very far upglacier. We then forced the grounding line to retreat to within 400 km of its modern position, and allowed the profile to evolve.

It remains to be shown that the 135 m of thinning we document at the mouth of Darwin Glacier are due to the approach of the grounding-line, and not a minor adjustment after grounding-line arrival. The chronologies along Hatherton Glacier all record smooth and steady thinning through the Holocene (Figure X), which supports but does not prove smooth and steady retreat of the grounding-line. The effect of a cold, stiff bed would be to delay the propagation upglacier of changes at the grounding-line, which could thus smooth out the signal of rapid thinning at the mouth of Darwin Glacier. To allay this suspicion, we examined the response of Hatherton Glacier to rapid thinning at the mouth of Darwin Glacier, using our 1.5-D flowband model.

*Response of Hatherton Glacier to changes at Darwin Glacier*

Figure X shows our radiocarbon ages from Lake Wellman alongside the exposure ages of glacial erratics from Diamond Hill, plotted against height above the current ice margin. The close agreement between these two chronologies after 5.3 ka indicates that the lag time for Hatherton Glacier to respond to ice thickness changes at the mouth of Darwin Glacier is very short. However, it is also possible that these chronologies correlate by chance, and that thickness changes at the two sites are not one to one.

*Large-scale pattern of grounding-line retreat in the Ross Sea*

The grounding line of the WAIS in the Ross Embayment retreated southward from its maximum position ~12.8 kyr BP (Hall et al., 2015). The rate and pattern of retreat were likely controlled by the bathymetry of the bed; more rapid retreat took place in deep troughs, while ice rises developed on the banks between them (Dowdeswell et al., 2008). Such complex behavior can not be deduced from our data; however, by comparing the timing of grounding line arrival at various points along the TAM front, we can begin to discern what the pattern of grounding-line retreat may have been in the western Ross Sea.

Sub-shelf sedimentation at the Coulman High, near Ross Island, began >8.6 kyr BP (McKay et al., 2016). This is approximately contemporaneous with the establishment of the modern grounding line at Beardmore Glacier, X00 km to the south (Spector et al, unpublished). Darwin and Hatherton Glaciers lie roughly halfway between these two points, yet the timing of grounding-line arrival is much younger. The modern grounding-line at Reedy Glacier/Mercer Ice Stream was established ~2 kyr BP.

This pattern of grounding-line retreat requires that a large region of ice in front of Byrd, Darwin, Mulock, and Skelton glaciers remained grounded long after the grounding-line of the central Ross Embayment had retreated past these points. It remains an open question how far along the TAM front this grounded ice persisted, and if it comprised a single, grounded ice mass or local piedmont lobes.

The delayed deglaciation of the Darwin and Hatherton Glaciers is likely due to the convergence of the flowbands of Byrd and Mulock Glaciers directly in front of Darwin Glacier. Numerical investigations of grounding-line dynamics show that convergent flow can counteract the acceleration of dynamic thinning caused by the Marine Ice Sheet instability (Gudmundsen, 2013). The shear of the Mulock Glacier flowband past Minna Bluff and any transient ice rises on the intertrough ridges would also have served to buttress the upstream ice (Thomas, 1979). Together, these two effects created a sheltered embayment that was able to resist grounding-line retreat longer than glaciers farther to the south.

**Conclusions**

Notes, Questions, things to explore:

1. Did the Britannia II deposit continue all the way back under Britannia I, or does it stop where Britannia I starts up? This is important to be able to determine if Hatherton thinned beyond Britannia I limit between MIS 6 and MIS 2
2. Bockheim pg 247: ”The most conservative course is to interpret these C-14 dates simply as minimum values for ice recession from the sample sites.” I just realized that the receding lobe could leave behind ice-cored stuff that would not require a glacier dam. Therefore, certain of Brenda and Courtney’s anomalously old ages could be from ponds trapped in ice-cored, hummocky terrain that today appears to require an ice dam.
3. It looks like retreat from Magnis Valley initiated ~1 kyr before retreat from Dubris-Bibra Valleys and Danum Platform. Does this mean that it was controlled by the grounding line? Bockheim et al claimed their 6.8 kyr BP date was the time at which the longitudinal profile became steady, but now it is looking more like that is around 3 kyr BP.
4. In order to figure out whether the last 135 m of thinning of Darwin Glacier was due to grounding-line arrival or just some small adjustment after the arrival, I will constrain the flowband model with the Hatherton Glacier chronologies and explore different thinning histories at Diamond Hill.