Cosmogenic $^{14}\text{C}$ in bedrock reveals complex glacial maximum and retreat of Darwin Glacier, Antarctica

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The goal of this project is to use cosmic ray-produced $^{14}\text{C}$ produced in quartz to determine past ice sheet thickness adjacent to Darwin Glacier in the Ross Embayment of Antarctica (Figure 1). Chronologies from Darwin Glacier, and its tributary Hatherton Glacier, have been used to constrain the timing of the last deglaciation in this region$^{1-3}$. However, those chronologies constrain fluctuations far from the modern grounding-line and are likely to be strongly influenced by changing patterns of surface mass balance and glacier-specific basal conditions. We sought to better constrain the timing of deglaciation by dating glacier erratics at the confluence of Darwin Glacier with the modern Ross Ice Shelf, but the scarcity of erratics from the last glacial cycle at this location prevented us from constraining the maximum ice thickness and glacier retreat prior to ~6 kyr BP. Instead, we must turn to $^{14}\text{C}$ in bedrock to extend our erratics-based chronology further back in time and higher in elevation.

$^{14}\text{C}$ is easily measured using standard accelerator mass spectrometer techniques, but chemical isolation of C from quartz proves more difficult, and there is significant potential for contamination from young carbon in the environment$^4$. Even trace amounts of environmental carbon can overprint the $\text{in situ}$ cosmogenic signal, leading to $^{14}\text{C}$ concentrations several orders of magnitude higher than the maximum concentration produced by cosmic rays. While great advances have been made in C extraction from quartz over the past few decades, contamination is still a great concern. We encountered this problem on our first attempt to measure $^{14}\text{C}$ in the bedrock from Darwin Glacier. In our case, the likely source of the contaminant was the set of reagents used during surfactant separations to isolate the quartz from feldspars. Skipping this step and etching the quartz with hydrofluoric and nitric acid removed the problem of contamination by environmental $^{14}\text{C}$.

In this application, the exposure age determined from the $^{14}\text{C}$ concentration in the quartz is taken to be a maximum age. This is because we cannot be certain that the duration of the last ice cover was long enough for the $\text{in situ}$ $^{14}\text{C}$ to decay to background concentrations. Therefore, there could be a significant amount of inherited nuclides from the last period of exposure. Because rock at lower elevations is covered more frequently by the ice sheet than rock at higher elevations, the effect of inherited nuclides is likely to increase with elevation. At some point in the elevation profile, we expected a sudden increase in $^{14}\text{C}$ concentration to the saturation concentration. The lowest elevation sample saturated with respect to $^{14}\text{C}$ would provide an upper bound on the ice sheet surface at the Last Glacial Maximum, while the highest unsaturated sample would provide the lower bound.

Given the hypothesized increase in concentration with elevation, our results are quite surprising. Instead of increasing monotonically with elevation, leading to an easily interpreted demarcation of the former ice sheet surface, the $^{14}\text{C}$ concentrations in our elevation transect show a strong dependence on aspect (Figure 2). Samples from the south side of Diamond Hill, adjacent
to Darwin Glacier, show that ice was ≤ 500 m thicker than present at the LGM. The onset of thinning occurred prior to 6 kyr BP, but the precise timing is not well constrained by the data Figure 3. Paired with our erratics transect, this indicates slow and steady thinning through the latter half of the Holocene. Any rapid drawdowns of the ice surface would have occurred prior to 6 kyr BP and are not recorded by our data.

On the north side of Diamond Hill, adjacent to the small Diamond Glacier, the apparent exposure ages are all well below saturation. This shows that the summit of Diamond Hill (1287 m asl) was covered by ice during the last glaciation, while the downglacier flank of the mountain was ice-free (Figure 3). The summit was exposed ≤ 11 kyr BP, and the ice here thinned by 500 m in < 6 kyr. This rate of deglaciation is much higher than that recorded on the Darwin Glacier side of Diamond Hill. This is likely because the ice flowing to the north of Diamond Hill was fed in large part by flow over Bastion Hill. This flow was cut off by the high topography as the glacier thinned, resulting in a drastic decrease in ice flux north of Diamond Hill. The high surface gradient at the LGM constrained by our data suggests that the ice-shelf proximal (southeast) side of Diamond Hill was a zone of strong ablation from turbulent katabatic winds descending off the summit. Therefore, Diamond Hill was not only an obstacle to ice flow during the last glaciation, but it also exerted a strong control on the near-surface winds and thus the surface mass balance of Darwin Glacier.

Exposure ages of erratics throughout the Transantarctic Mountains show that most of the western Ross Embayment between Ross Island and Scott Glacier (Figure 1) deglaciated rapidly ~8 kyr BP. Our results from Darwin Glacier reveal that the deglaciation history of the Darwin-Hatherton glacier system does not fit in with the larger pattern of deglaciation in the Ross Sea. This is likely because of strong convergence of the Darwin Glacier flowband with the much larger Mulock and Byrd glaciers. This convergence caused dynamic thickening that opposed the rapid thinning associated with grounding-line retreat. Thus, it is possible that ice sourced from Byrd, Darwin, and Mulock remained thick and grounded south of Minna Bluff until the middle to late Holocene, despite the especially deep seafloor in this location. If this is the case, convergent flow resulting from outlet glacier geometry could act to enhance ice sheet stability even in the presence of strong sea level forcing and reverse bed slope, as is predicted by some idealized ice sheet model experiments.

References


**Figures**

**Figure 1:** a. The Ross Embayment of Antarctica, showing locations mentioned in the text and flowlines from the Transantarctic outlet glaciers. The Last Glacial Maximum grounding line is shown in black, near the edge of the continental shelf. Grounding-line retreat initiated ~13 kyr BP. b. Bathymetry in front of the Darwin-Hatherton Glacier system. Discovery Deep is the deepest part of the seafloor in the Ross Embayment. c. The Darwin-Hatherton Glacier system and the adjacent Byrd Glacier. The modern grounding-line is shown in black. Our field locations are labeled; only Diamond Hill is discussed in detail here because all other sites contained plentiful glacial erratics, and there was no need for bedrock dating at those locations.
Figure 2: Sample locations and bedrock in situ $^{14}$C exposure ages at Diamond Hill. The thick black line shows the modern grounding-line; thinner black lines are 100 m contours. Ages and internal uncertainties are labeled for bedrock samples only. Units are years BP. The north and south sides of Diamond Hill have very different exposure histories, suggesting that topography played an important role in the dynamics of the LGM and deglaciation.
Figure 3: All exposure age and algae radiocarbon data from Diamond Hill. All data are taken to be maximum ages. Anomalously old algae radiocarbon ages are likely the result of a hard-water effect. Grey curves indicate inferred ice surface history. The Diamond Glacier margin chronology shows that Diamond Hill was capped in ice at the LGM, and only became uncovered < 11 kyr BP. The relatively rapid thinning of Diamond Glacier suggests that it was cut off from its source, which likely flowed over Bastion Hill. This chronology is inconsistent with a separate mountain glacier covering Diamond Hill because deglaciation began at the summit and proceeded downwards, which is the opposite of what would be expected for a mountain glacier. The Darwin Glacier margin chronology shows that ice was ~500 m thicker at the LGM. Deglaciation was slow and steady from 6 kyr BP to < 3 kyr BP. There is no record of rapid drawdown of Darwin Glacier, but this could have occurred prior to 6 kyr BP.