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Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation

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The grounding line of the ice sheet in the Ross Sea, Antarctica, retreated between the Last Glacial Maximum and the present. However, the timing of the retreat and the interplay of factors controlling ice stability in this region[1] remain uncertain. Here we use 180 radiocarbon dates to reconstruct the chronology of moraine construction on the headlands adjacent to western McMurdo Sound. On the basis of these dates we then assess the timing of ice expansion and retreat in the Ross drainage system that is fed from both the East and West Antarctic ice sheets. We find that grounded ice in the western Ross Sea achieved its greatest thickness and extent during the last termination, between 12,800 and 18,700 years ago. Maximum ice thickness at our site coincides with a period of high accumulation as recorded by the West Antarctic Ice Sheet Divide ice core[2]. Recession of the ice sheet from the headland moraines began about 12,800 years ago, despite continued high accumulation and the expansion of land-based glaciers at this time. We therefore suggest that the grounding-line retreat reflects an increased marine influence as sea levels rose and the ocean warmed. We suggest that future instability in the ice sheet grounding line may occur whenever the ocean forcing is stronger than forcing from accumulation.

The Antarctic Ice Sheet (AIS) gains mass from accumulation. However, because of the cold environment, there is little ablation by surface melting. Instead, mass loss occurs in nearly equal parts from shedding of icebergs and from melting by sea water at grounding lines and beneath ice shelves[3]. The stability of the marine margins is affected by subglacial thresholds that anchor grounding lines and by ice shelves that buttress ice streams. Thinning by basal melting can increase seaward discharge and dislodge ice from thresholds, leading to inland drawdown and perhaps even collapse of entire drainage systems. Such thinning, from incursion of relatively warm Circumpolar Deep Water onto the continental shelf, is the cause of ongoing grounding-line recession in the Amundsen Sea sector and has prompted reports that West Antarctic Ice Sheet (WAIS) collapse may be underway[4,5].

The ongoing situation in the Amundsen Sea sector raises the question of whether unstable behaviour is characteristic of the entire AIS. As a result of its importance to global sea level and climate, there has been a long-standing effort to decipher AIS response to the pronounced warming that terminated the last global glaciation. One view postulates repeated episodes of ice collapse, from peaks of iceberg-rafted debris in the Scotia Sea[6]. Each peak is taken to reflect rapid ice discharge. The largest peak is coeval with an exceptional sea-level rise—dubbed Meltwater Pulse 1-A (MWP1-A)—of about 15 m within 300 years, beginning at 14,700 years ago[7]. On the basis of geophysical fingerprinting, the amount of sea-level rise during MWP1-A attributed to Antarctica ranges from 7–8 m (ref. 7) to as much as 15 m (ref. 8). The implication is that AIS collapse can contribute significantly to sea-level rise during warming climate. An additional implication is that rapid ice discharge into the Southern Ocean could have global consequences, as MWP1-A is postulated to have triggered the Antarctic Cold Reversal in the south and Bølling–Allerød warmth in the north[9].

The thesis of a dynamic ice sheet during the last termination depends on the assumptions that iceberg-rafted debris pulses register discharge episodes from the AIS and that fingerprinting uniquely identifies Antarctica as a major source of MWP1-A. Testing these assumptions requires corroborative evidence from the continent itself, yet detailed terrestrial chronologies of Antarctic ice fluctuations remain sparse. As a result of a breakthrough in finding organic remains buried within a notable moraine belt in the Transantarctic Mountains (TAM), we here present a chronology of maximum ice thickness during the last glaciation in the Ross drainage system, one of the largest in Antarctica.

The Ross drainage system is an integral part of both the East and West Antarctic ice sheets (Fig. 1), encompassing about one-fourth of their combined surface area. Flow lines extend back to the main divide of both ice sheets. Outlet glaciers from East Antarctica pass through the TAM into the Ross Ice Shelf or the Ross Sea, and WAIS ice streams flow into the Ross Ice Shelf. Owing to the interaction of alpine topography with regional wind patterns and local albedo, the entire TAM shows a complex mosaic of blue-ice zones and ice-free areas from sublimation. This effect reaches its culmination in the McMurdo sector, where a combination of wind-driven sublimation and ice-pirating has resulted in a largely ice-free oasis. It is from this ice-free area, as well as others along the TAM, that much of the geologic evidence of former ice-surface elevations in the Ross drainage system has been derived (Supplementary Figs 1 and 2).

The consensus from geologic data is that during the last glaciation the grounding line, now located along the inland margin of the Ross Ice Shelf, migrated seaward, causing grounded ice to spread across the present-day Ross Sea[10,11]. Reconstruction of this grounded ice from glaciological modelling is useful for

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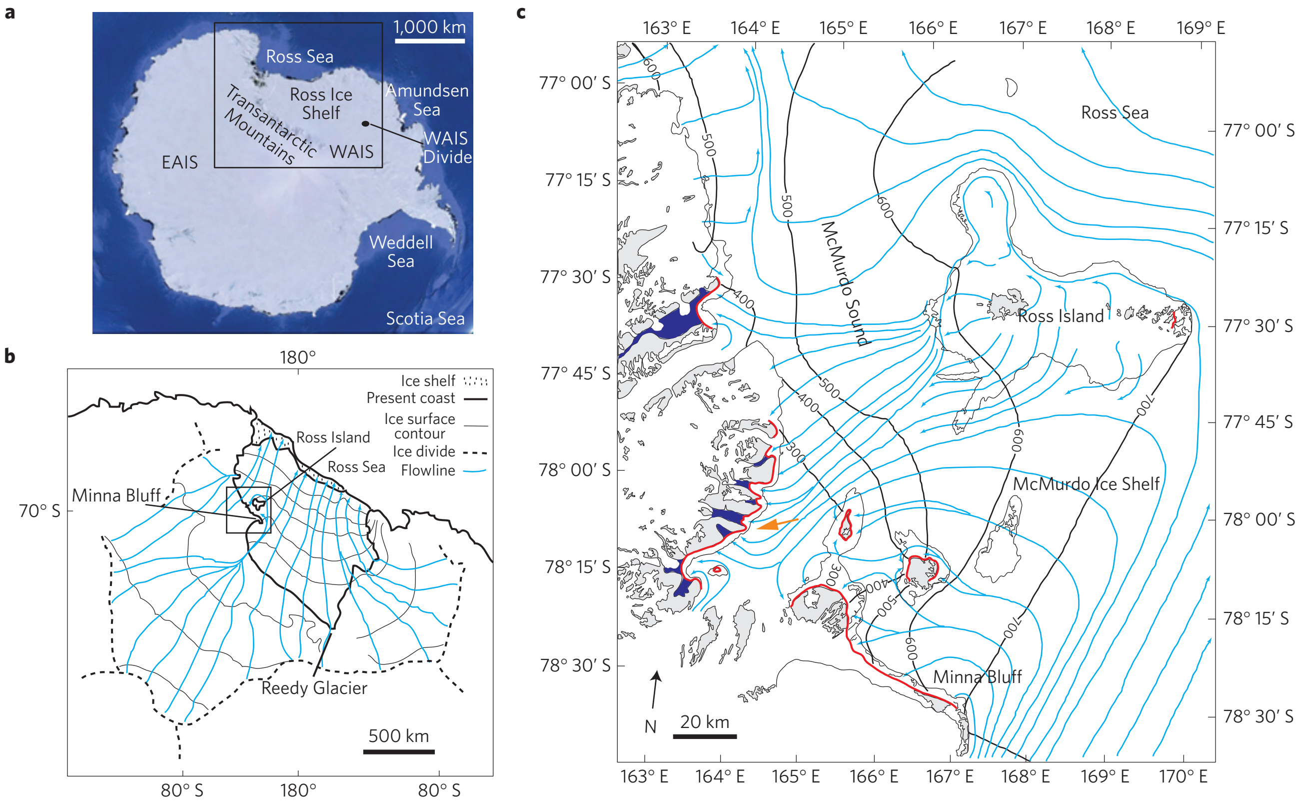

Figure 1 | Geologic setting of the McMurdo Sound field area. a, Map of the Antarctic Ice Sheet. The square shows the location of the Ross drainage system, depicted in more detail in **b**. **b**, Reconstruction of the Ross drainage system at the Last Glacial Maximum. Light blue lines here and in **c** denote ice-flow lines. **c**, Ice-flow reconstruction for McMurdo Sound at the Last Glacial Maximum derived from geologic data, modified after[28]. The red lines indicate the headland moraine belt. Dark blue depicts ice-dammed lakes. The orange arrow refers to the location of the photograph in Fig. 2.

deriving former ice volume and for assessing driving mechanisms for grounding-line fluctuations, such as variations in sea level[12], accumulation[13] and basal melt[14,15]. However, such modelling has had limited success in reconstructing documented former ice limits in the TAM, possibly because of complex topography and sublimation. Here, we focus on robust, well-dated geologic evidence of surface elevation changes to establish the timing of deglaciation and its relation to driving mechanisms.

During the last glaciation, East Antarctic outlets thickened along the TAM front owing to buttressing by ice in the Ross Embayment. This effect decreased inland until it nearly disappeared near the East Antarctic plateau[16,17]. A notable exception occurred in the McMurdo sector where no major outlet reached the coast, leaving a largely ice-free oasis near the middle of the glacial-age Ross drainage system (Fig. 1). As a result, ice grounded in the western embayment, with origins from East Antarctic outlet glaciers, flowed westward across McMurdo Sound to impinge on the TAM from the seaward side, depositing a prominent moraine belt along the coastal headlands[18]. This belt marks the maximum extent of the western sector of grounded ice in the Ross embayment during the last glaciation (Supplementary Figs 3–5).

The terminal moraine belt on the western McMurdo headlands is unique in Antarctica, because its mode of formation allows unprecedented radiocarbon age control (Fig. 2). Radiative heating of sediments on the ice sheet produced small meltwater streams that flowed landward on the sloping ice sheet (Supplementary Figs 6–8). Where they passed off the glacier, the meltwater and its sediment load were trapped between the ice and the headland bedrock. Consequently, meltwater-fed ponds, connected by small streams and supporting copious blue-green algae, occupied this trap. Sediments washed off the ice formed ice-marginal ridges of stratified deposits with interbedded layers of algae. The locus of deposition shifted as the ice margin oscillated slightly up and down the slope. The overall result was a spectacular terminal moraine belt perched on the headlands adjacent to western McMurdo Sound.

We obtained 180 radiocarbon dates of sub-fossil algae from stratified sediments within the headland moraine belt and converted them to calendar years using CALIB 7.0.1 and the INTCAL13 database[19] (Supplementary Table 1). Each date represents a time when, at a specific locality, algae growing in ponds at the ice edge were buried by sediment during moraine construction. The resulting ages fall between ~12,800 and 18,700 yr BP, with no gaps in coverage (Fig. 2). Therefore, we conclude that grounded ice impinged on, and remained at, the moraine belt through this interval, with deglaciation occurring after 12,800 yr BP. This conclusion, along with records from the southern and eastern Ross Embayment that indicate that most deglaciation occurred in the Holocene epoch[17,20,21], make it unlikely that the Ross drainage contributed notably to postulated episodes of ice collapse before 12,800 years ago, including during MWP1-A. As a caveat, we emphasize that our results do not preclude a source elsewhere in Antarctica, although the limited data from two other major regions, the Weddell Sea and East Antarctica[22,23], do not seem to support significant ice collapse during MWP1-A.

Comparison of the moraine chronology with Antarctic climate proxies (Fig. 3) suggests that grounded ice achieved and held its maximum in the western Ross Embayment while accumulation increased, as atmospheric temperatures rose during the last termination[2,24]. Given the close correspondence between the age of the moraine belt and the rise in accumulation, we suggest that the most likely scenario is that this increased accumulation promoted

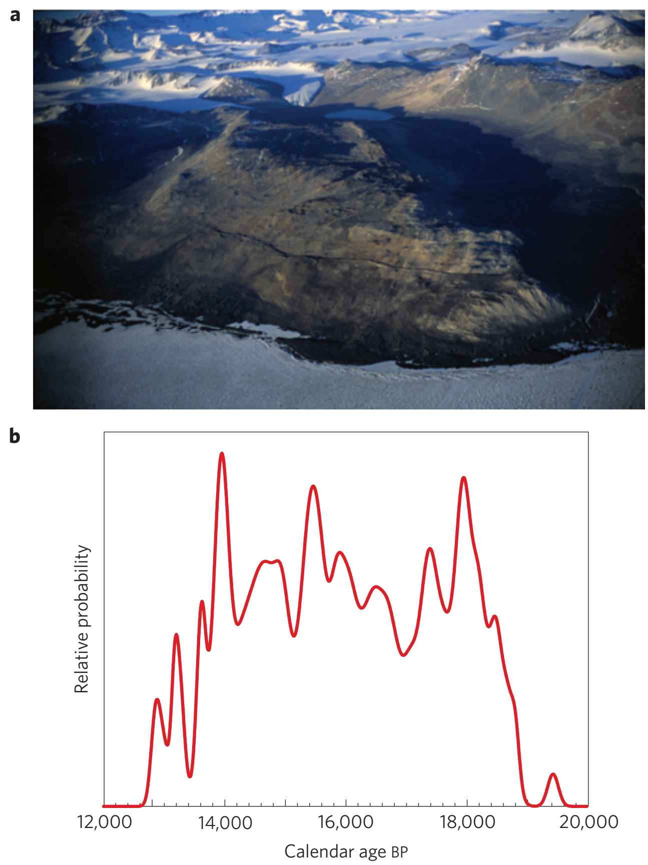

Figure 2 | The headland moraine belt of western McMurdo Sound. a, An aerial photograph of the moraine belt laid down by ice from the Ross Embayment. **b**, The summed probability of all radiocarbon dates of algae from the moraines converted to calendar years. The plot ranges from zero at the base to relatively high probability at the top of the diagram. The age range for the moraine belt, derived from the midpoints of the precipitous decrease in probability at each end of the plot, dates to ~12,800–18,700 yr BP. We consider the sample dating to ~19,500 yr BP to be an outlier in the data set.

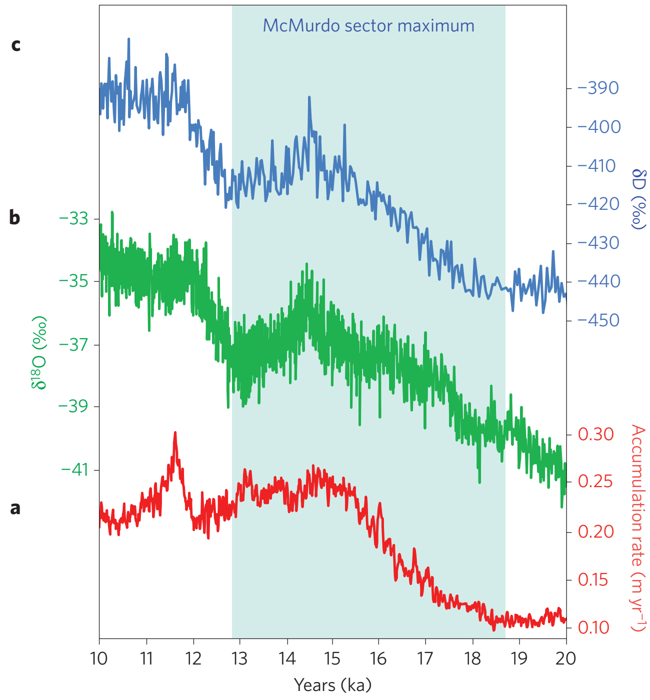

Figure 3 | Comparison of dates of the last ice-sheet maximum in the western Ross Sea with other climate proxies. a, WAIS Divide ice-core accumulation rate relative to 18,500–19,500 years ago (ref. 2). **b**, Oxygen-isotope record, thought to approximate temperature, from the WAIS Divide ice core[2]. **c**, Deuterium-isotope record, also thought to reflect temperature, from the EPICA Dome C ice core of East Antarctica[29,30]. Blue shading reflects the time span of the western Ross Sea ice maximum in the McMurdo sector, from Fig. 2.

thickening, and thus prolonged the maximum, of grounded ice in the western Ross Embayment.

This rise to the headland moraines after 18,700 years ago was superimposed on a slightly lower pre-existing ice sheet, which was still sufficiently thick in the Ross Embayment to dam lakes in ice-free valleys in the TAM as early as ~28,500 years ago (Supplementary Information). We note that accumulation was low before 18,700 years ago[2] (Fig. 3) and therefore was unlikely to have been the cause of this initial ice-sheet expansion. Instead, we infer, as have others, that initial AIS advance was due to lowered sea level and/or reduced ocean melting[12,14].

A key new observation from our chronology is that, despite continued high accumulation, recession from the headland moraines began shortly after 12,800 yr BP, eventually culminating in the southward migration of the grounding line in the Ross Embayment. In contrast, land-terminating glaciers near McMurdo Sound, including both alpine glaciers and Taylor Glacier, an outlet of the East Antarctic Ice Sheet (EAIS), have expanded to positions exceeding those of the last global glacial maximum[25]. This striking difference between the behaviour of land-terminating and marine-based glaciers in the face of continued high accumulation indicates that surface lowering from the headland moraines must have resulted from ocean forcing. In sum, we propose a two-phased response of grounded ice in the western Ross Embayment to warming of the last termination. Early in the termination, we suggest that rising accumulation outpaced any detrimental marine effect, allowing the AIS to thicken and hold its maximum position in the western Ross Embayment. The effect of ocean forcing then exceeded that of accumulation, causing surface lowering shortly after 12,800 yr BP in McMurdo Sound and at later times farther away from the embayment as the marine effect propagated inland. This interplay is likely to be responsible for the late local glacial maxima recorded along upper portions of EAIS outlet glaciers[17,26] and in interior West Antarctica[21,27]. In contrast, land-terminating glaciers, together with those sectors of the AIS unaffected by ocean forcing, have advanced from increased accumulation to reach their maximum of the present day. Our results point to the importance of accumulation in driving ice in the overall Ross drainage but also suggest that ocean forcing ultimately exerted control in the marine sectors.

Our results show that ocean forcing caused grounding-line recession and interior downdraw in large parts of the Ross drainage system at the end of the last ice age. Whether inland propagation of this effect will continue is uncertain. However, a key buffer is the continued presence of the Ross Ice Shelf. Southward retreat of the ice-shelf front halted about 7,000 years ago at the prominence of Minna Bluff/Ross Island, which extends far seaward of the TAM front near McMurdo Sound[10] (Supplementary Information). Ever since, the shelf front has remained anchored on this prominence, buffering grounding-line retreat farther south. We suggest that the security of the ice-shelf attachment to this topographic anchor is a key to future behaviour of the Ross drainage system. Should the ice shelf break free, there are no similar protuberances farther south to stabilize the shelf front, and the survival of ice that now drains into the ice shelf from both the WAIS and EAIS would be in jeopardy. For the contribution of Antarctic ice to future sea level, we suggest that the fate of the McMurdo pinning point is as important as the role of subglacial thresholds in the Amundsen Sea sector.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

B.L.H. and G.H.D. conceived and implemented the project. B.L.H., S.L.H., M.S.J. and T.N.B.K. collected and analysed the data. G.H.D. and B.L.H. analysed and interpreted glacial records in the Ross Sea region in terms of accumulation changes. B.L.H. and G.H.D. wrote the paper, with contributions from all authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.L.H.

Competing financial interests

The authors declare no competing financial interests.

Methods

Radiocarbon samples of algae were collected from hand-dug and (rarely) natural excavations within moraine sediments, generally within the crests. In most cases, the algae occurred in distinct layers 1–3 cm thick interbedded within silt, sand and/or gravel or, more rarely, as disseminated flakes. Samples were packaged in sterile plastic bags and kept in cool storage before analysis at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) laboratory at Woods Hole Oceanographic Institution. Ages are reported in calendar years with 2-σ error, obtained using the CALIB 7.0.1 program and the INTCAL13 database[19].

Algae have been shown to yield reliable ages for glaciolacustrine deposits in the TAM (refs 31–33). However, as with any aquatic plant, one must assess whether a reservoir correction to the radiocarbon dates is applicable. In this case, we do not apply a correction for the following reasons. First, these algae grew in shallow, ice-marginal ponds and streams. Previous work has shown that algae from such settings commonly yield reliable ages, free of significant reservoir effects[34,35]. Unlike in the Dry Valleys, where deep lakes may preserve stratification, which contributes to large radiocarbon reservoir values[35,36], the ponds and streams in which the headland moraine belt formed were shallow, generally less than a few metres in depth, judging by the maximum extent of lake sediments near the moraines. Moreover, $\delta^{13}C$ values of the dated algae are relatively positive, commonly 0 to −10‰. Such values are typical of shallow-water algae in the Dry Valleys region and support our contention that the samples come from shallow environments that are unlikely to support a significant reservoir effect. In contrast, $\delta^{13}C$ values of deep-water algae in the Dry Valleys more commonly range from −25 to −30‰. In short, we conclude that our dates are not affected by a significant lacustrine reservoir effect due to sequestering of old carbon in a deep lake.

A reservoir effect also can come from the release of trapped CO_2 from ice into melt streams. Such streams would have fed the ponds on the headlands. However, two different studies have shown that CO_2 in surface meltwater streams from glaciers in the McMurdo Sound region equilibrates quickly with the atmosphere[34,35]. Equilibration would have been enhanced in meltwater streams flowing on or adjacent to the ice margin on the headlands, because surface slope would have been similar to that exhibited by turbulent mountain streams. Although we cannot exclude a small amount of old CO_2 entering the ponds owing to direct melt of the glacier margin, as most meltwater enters the ponds from surface flow, this is likely to have had a negligible effect on our ages.

On the basis of the information presented above, we conclude that our dates are reliable indicators of the time of algae growth and hence of moraine formation on the western McMurdo Sound headlands. We note that if a radiocarbon reservoir existed, its effect would have been to make our ages seem older than they should be. This would not alter our conclusions, because it would more firmly place the timing of maximum ice thickness during the last termination, including during and after MWP1-A, and not during the global Last Glacial Maximum.

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