A sediment model and retreat history for the Ross Ice (Sheet) Shelf in the Western Ross Sea since the Last Glacial Maximum

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Summary Three sediment gravity cores collected from beneath the McMurdo Ice Shelf and six piston cores from the Erebus Basin (in McMurdo Sound) and the Lewis Basin (north of Ross Island) were analysed in order to construct a retreat history for the West Antarctic Ice Sheet in the Ross embayment since the Last Glacial Maximum. The cores display a characteristic succession of sedimentary facies that record a transition from deposition beneath a marine terminating ice sheet to open-marine conditions. The base of the succession comprises a slightly consolidated, clast-rich muddy diamict dominated by basement clasts from the Transantarctic Mountains, and interpreted as melt-out from the basal debris layer debris proximal to a retreating grounding zone. The diamicts are overlain by sparsely-fossiliferous (reworked diatom frustules) and non-bioturbated mud and fine sands that lack lonestones and are derived from a mostly local source (McMurdo Volcanic Group). This facies is interpreted to have been deposited in a sub-ice shelf setting. Overlying the sub-ice shelf muds are diatom bearing muds and diatomaceous oozes that are indicative of open water conditions, and contain evidence of iceberg rafting. The succession in the open-water Lewis Basin north of Ross Island differs slightly, with the diamict being much sandier and sedimentation rates 1-2 orders of magnitude higher. We also identify a strong relationship between sand provenance and the position of the Ross/McMurdo Ice Shelf calving lines. During periods of glacial advance, regionally grounded ice transports large volumes of sediment derived from the Transantarctic Mountains to the south into Windless Bight, and Erebus and Lewis basins, while during retreat of the grounding line, the sub-ice shelf environment is largely characterized by local sourced terrigenous muddy sedimentation. During open water conditions, hemipelagic sedimentation appears to dominate, with a minor IRD component consisting of sediment with a notable Transantarctic Mountain provenance. Our chronology was developed from twenty three AMS ^{14}C ages, obtained from bulk organic carbon in acid insoluble organic (AIO) material.

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Introduction

Previous seismic and sediment core studies indicate that between 26.5 and 19.5 ka (LGM), the Ross Ice Shelf was grounded (forming the Ross Ice Sheet) near the edge of the continental shelf (~Coulman Island), approximately 700m below modern sea-level (Anderson et al., 1992; Domack et al, 1999; Bart et al, 2000), and the retreat of both grounding and calving lines since the LGM have been reconstructed using cores collected from the open Ross Sea and ice seismic reflection profiles (e.g. Licht et al., 1996; Conway et al., 1999; Domack and Harris, 1998; Domack et al., 1999; Shipp et al., 1999). Radiocarbon dating of organic matter in sediment cores has provided a chronology for post-LGM retreat of the Ross Ice Sheet that showed the grounding line retreated from the outer Drygalski Trough to the vicinity of Ross Island between ~11,000 and 7,000 ^{14}C yr BP (Domack et al., 1999; Conway et al., 1999).

Methods

Three sediment gravity cores from beneath the McMurdo Ice Shelf were collected during 2003 and 2006. In addition, we six piston cores from the Erebus Basin (in McMurdo Sound) and the Lewis Basin (north of Ross Island), collected by the *USCGC Glacier* as part of Operation Deep Freeze (DF) in 1979-80 were also studied (for core sites, see Figure 1). Three Hot Water Drill (HWD) access holes were made in the McMurdo Ice Shelf, through which a gravity corer was deployed.

To develop a chronology, we have adopted the technique of Andrews et al. (1999), correcting our AIO dates by subtracting the surface ^{14}C date from stratigraphically-lower ^{14}C dates. This method appears to give consistent results with a precision of around ±500 yrs (Andrews et al., 1999) for diatomaceous-rich sediments, which are abundant in the Ross Sea. However, it is less reliable for the transitional ice shelf/grounded glacial sediments, where the reworking of old carbon and a lack of primary production leads to errors that are likely to be several thousand years too old (e.g. Domack et al., 1999; Licht et al., 1998). Ice-rafted debris (IRD) was quantified by summing grains exceeding 2 mm in size, in 1 cm thick horizontal bands, on x-radiographs of the split core. Dry sieving and Sedigraph analysis determined grain size frequency distribution at 0.5 phi intervals for the sand and mud fractions, while modal petrographic analysis (300+ grain point count) for the 63-500 μm fraction was undertaken on grain mount thin sections. Provenance was subdivided in minerals and lithics derived from the Transantarctic Mountains or from the more locally sourced McMurdo Volcanic Group. The most distinctive indicator of the Transantarctic Mountains provenance is quartz, which

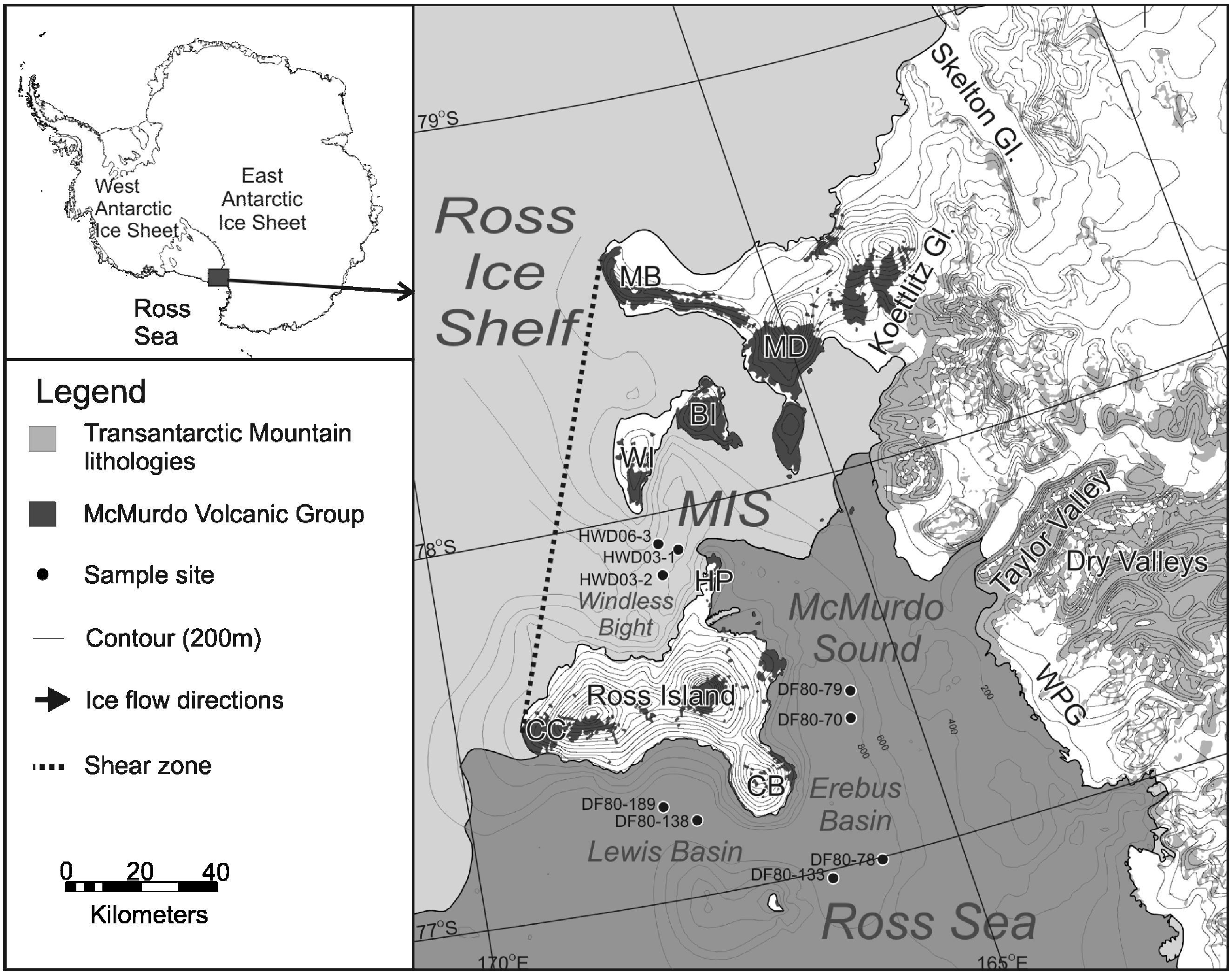

Figure 1 Map of Ross Island region showing the core sites and localities mentioned in text. The two main provenance areas and raised beaches locations (Dochat et al., 2000; Hall and Denton, 1999) discussed in text are also shown. BI = Black Island, CB = Cape Bird, CC = Cape Crozier, HP = Hut Point Peninsular, MB = Minna Bluff, MD = Mount Discovery, WI = White Island, WPG = Wilson Piedmont Glacier.

is absent in the McMurdo Volcanic Group (Kyle, 1990), but can be attributed to granites and metasediments, and quartz arenite and arkosic sandstone of the Beacon Supergroup that crops out throughout the Transantarctic Mountains. Notably, rounded quartz with overgrowths can be directly attributed to Devonian Taylor Group (Beacon Supergroup) sandstones (Korsch, 1974). Pyroxene is another important provenance marker, with pigeonite being of Ferrar Dolerite origin, and augite of McMurdo Volcanic Group origin (Smellie, 1998). Bulk mineralogy was quantified by XRD. Quantitative diatom abundances and concentration were also determined, primarily for use as a sea-ice proxy (e.g. the relative abundance of *F. curta*), and diatom concentration was used as a proxy for biogenic productivity/reworking. To test for the presence of supraglacial debris that might have passed through the McMurdo Shelf at Windless Bight site, a 20-m-long ice core from near HWD03-01 was melted and filtered at 1 m intervals.

Results

Facies model for transition from grounded ice sheet to seasonally open water

We have identified three distinct facies from which we infer the retreat of both the grounding line and calving line of the Ross Ice Shelf: 1) sub-ice shelf diamict; 2) sub-ice shelf sand and mud; and 3) open-water diatom mud and ooze with IRD.

Sub-ice shelf diamict facies

The sub-ice shelf diamict facies is distinguished by its lithology and Transantarctic Mountain provenance. Diatom concentrations are low, and valves are usually broken. The assemblages also have relatively higher abundances of fossil and oceanic forms. We have not recovered any diamict that we believe to be deposited beneath grounded ice. However, given its unconsolidated nature, the diamict is likely to have resulted from meltout from the basal debris zone shortly after the retreat of regionally grounded ice. In addition, the ages measured from this unit range between 20.8ka and 25.8 ka ^{14}C BP, which significantly postdate the 26.8 ka ^{14}C BP age for grounded ice in McMurdo Sound (Dochat et al., 2000), and suggest some input of post-LGM carbon, which could not have occurred if the sediment were deposited beneath grounded ice. The fact that we were unable to penetrate this unit may be due to either the presence of an underlying compacted till or the presence of large clasts. Soft-sediment coring and rotary drilling under the McMurdo Ice Shelf, by the ANDRILL Project, near the vicinity of our sub-ice shelf cores, has revealed an over-consolidated till at 1.94m below the seafloor underlying the less consolidated diamict that constitutes this facies in our short cores (Naish et al, in press).

None of our diamicts are stratified, suggesting that marine deposition or reworking of sediments by sub-ice shelf currents was minimal. However, the diamicts in Lewis Basin and northern McMurdo Sound have a lower mud content than the diamict from the Windless Bight site (HWD cores). The winnowing of mud during the melt-out phase may indicate a higher energy environment for Lewis Basin and northern McMurdo Sound, potentially related to marine outwash or sub-ice oceanic circulation.

Sub-ice shelf sand and mud facies

Sub-ice shelf sand and mud are distinguished by low diatom concentrations (with a low percentage of sea-ice forms), a lack of grains >2 mm in diameter, a lack of sand grains derived from the Transantarctic Mountains, and a slow sedimentation rate (0.01-0.05 mm/yr). However, the upper 5 cm of HWD03-1 shows an increase in coarse sand (up to 500 μm) with a Transantarctic Mountain provenance and includes fine gravel with a mixed provenance. The presence of these grains would normally be associated with the calving line of the ice shelf. However, this site is currently beneath the McMurdo Ice Shelf, 5 km from calving line. These grains are too coarse to be transported via sub-ice shelf currents in a settling water column. Modern sub-ice shelf currents (<22 cm/s) are only capable of laterally transporting settling fine sand grains (at most) 1 km beneath the ice shelf (Barrett et al., 2005).

Therefore, the presence of these sand grains indicates that either the ice shelf front has retreated and then re-advanced over this site, or that reworking of the older diamicts is currently taking place beneath the ice shelf. If the ice shelf had retreated past this site during the Holocene, we would expect to see a significant increase in diatom deposition and a rapid increase in the sedimentation rate (e.g. DF80-189 and DF80-133). This is not the case at either HWD03-1 or HWD03-2 (Fig 3), indicating that there has been no period of seasonally open water above or near the site during the Holocene, despite the evidence from the Taylor Dome ice core showing mid-Holocene climatic optima 1-2ºC above present (Steig et al., 1998). If there has been a period of calving line retreat over the site, it must have been very short lived.

This facies is absent in the McMurdo Sound sites, as grains >2 mm are persistent throughout the core. This suggests that either the ice shelf did not persist at this site for a significant length of time, or this unit has been reworked and eroded. In one core (HWD03-1) a distinctive 7-cm thick dark interval of well-sorted, soft muddy fine to very fine sand (63-97% sand) with mm-scale mud laminations occurs directly above the underlying diamict facies. The sand has a sharp lower contact with load features. Petrographic analysis indicates that the sand is composted of rounded, weathered volcanic glass and lithics. This interval likely represents sediment gravity flows, and indicates that this site experienced some sediment redeposition following grounding line retreat.

Open water diatom mud and ooze facies

This facies is distinguished by its higher accumulation rate (0.19 mm/yr) associated with primary biogenic production. Diatom concentrations are a one to two orders of magnitude higher (between $5x10^8$ and $12x10^9$ v/g) than for the underlying sub-ice shelf facies ($4\text{-}5x10^7$ v/g) and marked by the high abundance of *F.curta,* a diatom that dominates seasonal sea ice and the adjacent water column in the Ross Sea (Leventer, 1998). Associated with this biogenic deposition is the presence of oversized sand and pebbles derived mostly from icebergs calving from glaciers along the Victoria Land coast and Ross Island.

Chronology and discussion

Our radiocarbon chronology implies lift-off of grounded ice occurred in the 900 m-deep marine basins surrounding Ross Island by ~10.1 ka ^{14}C BP. Following lift-off, an ice shelf was maintained to the north of Ross Island until ~8.9 ka ^{14}C BP. We identify a phase of accelerated retreat at that time between the Drygalski Trough and Ross Island, immediately preceding the timing of Meltwater Pulse 1b. At ~8.9 ^{14}C ka BP the calving line became pinned to Ross Island, while the grounding line continued to migrate south, marking the transition from a retreating ice sheet to the development of the present ice shelf mode. Since this time, there is no evidence that the calving line of McMurdo/Ross Ice Shelf has retreated south of its present position, despite an early Holocene climatic optimum up to 2.5ºC warmer than present (Steig et al., 2000; Masson et al., 2000).

Our revised timing of lift-off of grounded ice at Windless Bight just after 10.1 ka ^{14}C BP is slightly earlier than previous estimates from marine sediment cores further north in the Ross Sea (e.g. Domack et al., 1999; Conway et al., 1999; Licht et al., 2002), and earlier than the timing of ice retreat based on ages from proglacial lakes in the Taylor Valley at 8.34 ka ^{14}C yr BP (Hall et al., 2000). These proglacial lakes are inferred to have been formed as the result of the grounded Ross Ice Sheet in McMurdo Sound, which may have lingered longer in the western sector of McMurdo Sound than at our core sites. Our chronology indicates that the retreat of grounded LGM ice from the outer Drygalski Trough to Ross Island occurred rapidly (within 1,000 years) during the early Holocene, yet remains compatible with previous chronologies derived from both the marine and terrestrial records.

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