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Regional-scale abrupt Mid-Holocene ice sheet thinning in the western Ross Sea, Antarctica

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ABSTRACT

Outlet glaciers drain the majority of ice flow in the Antarctic ice sheet. Theory and numerical models indicate that local bed topography can play a key role in modulating outlet glacier response to climate warming, potentially resulting in delayed, asynchronous, or enhanced retreat. However, the period of modern observations is too short to assess whether local or regional controls dominate ice sheet response on time scales that are critical for understanding ice sheet mass loss over this century and beyond. The recent geological past allows for insight into such centennial-scale ice sheet behavior. We present a cosmogenic surface-exposure chronology from Mawson Glacier, adjacent to a region of the Ross Sea that underwent dynamic marine-based ice sheet retreat following the Last Glacial Maximum. Our data record at least 220 m of abrupt ice thinning between 7.5 and 4.5 ka, followed by more gradual thinning until the last millennium. The timing, rates, and magnitudes of thinning at Mawson Glacier are remarkably similar to that documented 100 km to the south at Mackay Glacier. Together, both outlet glaciers demonstrate that abrupt deglaciation occurred across a broad region in the Mid-Holocene. This happened despite the complex bed topography of the western Ross Sea and implies an overarching external driver of retreat. When compared to regional sea-level and ocean-temperature changes, our data indicate that ocean warming most likely drove grounding-line retreat and ice drawdown, which then accelerated as a result of marine ice sheet instability.

INTRODUCTION

Some sectors of the Antarctic ice sheet are currently experiencing abrupt thinning and mass loss (McMillan et al., 2014; Shepherd et al., 2018). Bed topography will play a key role in modulating the future response of the ice sheet via its ability to control the spatial pattern and rate of outlet glacier retreat and corresponding ice sheet thinning (Schoof, 2007; Favier et al., 2014; Seroussi et al., 2017). However, the length of modern observations is too short to confidently evaluate how bed topography influences ice sheet response to climate warming on centennial time scales. By investigating regions of marine-based ice sheets that have undergone deglaciation in the past, we can better understand the drivers and mechanisms of abrupt, stepwise ice sheet behavior, which is crucial for contextualizing modern ice loss and for improving predictions of future contributions to sea-level rise (DeConto and Pollard, 2016; Small et al., 2019).

During the last deglaciation in the Ross Sea, the grounding line of the ice sheet retreated more than 1000 km from near the continental shelf edge to its modern position (Anderson et al., 2014; Halberstadt et al., 2016; McKay et al., 2016; Lowry et al., 2019). Perhaps the most dynamic ice sheet changes are recorded in the western Ross Sea (Fig. 1), associated with complex bed topography—a combination of seamounts, shallow banks, and overdeepened basins. Geomorphological evidence documents the multifaceted retreat of marine-terminating portions of East Antarctic outlet glaciers in this region (Lee et al., 2017; Greenwood et al., 2018). However, the timing of this ice loss is poorly constrained except at Mackay Glacier, which experienced abrupt up-glacier thinning in the Mid-Holocene (Jones et al., 2015). Differences in bed topography and associated glacier geometry can lead to neighboring outlet glaciers that respond to external forcing independently of one another (Felikson et al., 2017). For this reason, an isolated record of abrupt ice loss may not reflect the wider-scale pattern of ice sheet retreat. Empirical records from multiple glaciers with differing ice geometries are crucial to determine whether ice sheet outlets retreated at different times, governed by bed topography, or in concert, driven by regional external changes.

We present new results of ice sheet thinning in the southwestern Ross Sea. We applied cosmogenic ^{10}Be surface-exposure dating to vertical transects of glacially transported erratic cobbles at Mawson Glacier. Our results demonstrate that abrupt ice loss of several hundred meters occurred at a similar rate and duration across multiple outlet glaciers in the Mid-Holocene, despite complex bed topography. This implies a common, most likely ocean-temperature, forcing of ice sheet retreat at this time.

FIELD SITES AND METHODS

Mawson Glacier is the second-largest glacier draining the East Antarctic Ice Sheet into the Ross Sea along the Scott Coast of Victoria Land, Antarctica (Fig. 1). At the Last Glacial Maximum, this outlet glacier thickened, coalesced with ice from Mackay Glacier 100 km to the south, and flowed out through the Joides and Drygalski Troughs (Anderson et al., 2014; Lee et al., 2017; Greenwood et al., 2018).

We collected glacial deposits from two sites along the northern margin of the modern-day Mawson Glacier and its floating extension, the Nordenskjöld Ice Tongue (Fig. S1 in the

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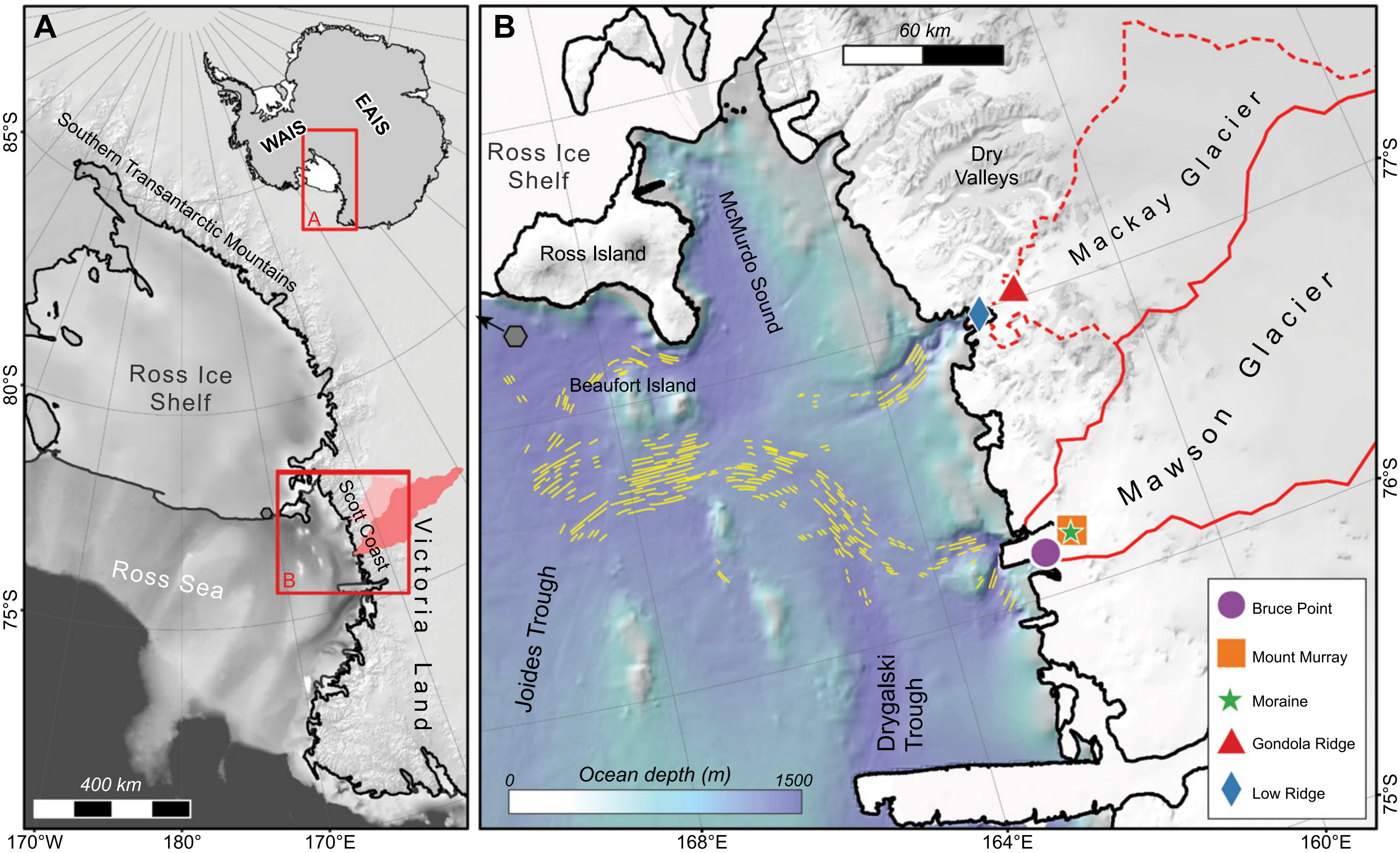

Figure 1. Study region. (A) Ross Sea sector of Antarctica, which drains both West Antarctic (WAIS) and East Antarctic (EAIS) ice sheets. (B) Map of the Scott Coast region in the western Ross Sea. Records of past ice thickness change come from Mawson Glacier (Bruce Point and Mount Murray) and Mackay Glacier (Low Ridge and Gondola Ridge). Megascale glacial lineations mapped on the seafloor are shown as yellow lines, and gray hexagon denotes the location of sediment core CH-2 (McKay et al., 2016).

Supplemental Material[1]). Samples were collected for ^{10}Be analysis in vertical transects at Bruce Point and Mount Murray and from a moraine on the flank of Mount Murray. The two sites were selected based on their location near the terminus of the glacier where the greatest thickness changes likely occurred, their proximity to modern fast-flowing ice, and their relief above the current ice surface in order to maximize the signal of ice surface lowering and minimize the chance of cosmogenic nuclide inheritance from nonerosive ice (see the Supplemental Material). To minimize the effects from clast recycling, snow or cold-based ice cover, supraglacial transport of sediment, and reorientation by periglacial or colluvial processes, our sample selection focused on lightly weathered, striated, bulleted, and faceted erratic cobbles that were resting precariously on intact, glacially molded and windswept bedrock. Moraine sampling focused on large, prominent boulders that did not show evidence of post-depositional movement or reorientation.

We processed quartz-bearing samples from 46 cobbles and three boulder tops for ^{10}Be analysis to constrain the timing, magnitude, and rate of past ice thickness and margin change for Mawson Glacier. The physical and chemical procedures that we used to obtain ^{10}Be concentrations are outlined in the Supplemental Material. We calculated, analyzed, and plotted surface-exposure ages using iceTEA software (Jones et al., 2019). The age calculation used the framework of the CRONUScalc program (Marrero et al., 2016), the recent ^{10}Be production rate calibration data set of Borchers et al. (2016), and the nuclide-specific scaling model *LSDn* (Lifton et al., 2014). We then identified and removed outliers and estimated past thinning rates from the vertical transects using Monte Carlo least-squares regression analysis (see the Supplemental Material).

RESULTS

The exposure ages at Mawson Glacier decrease with elevation and are concentrated to between ca. 8 and ca. 4.5 ka at both elevation transects (Fig. 2; Fig. S3). During this time period, 22 samples record 220 m of ice surface lowering at Bruce Point, and eight samples record 125 m of lowering at Mount Murray, ~10 km farther up-glacier. Linear regression analysis indicates that this thinning event started at least by 7.3–6.4 ka (2σ) and continued for ~705 yr at a best-fit rate of 35 cm yr^{-1} (21–437 cm yr^{-1}, 2σ) at Bruce Point, and by 6.1–5.4 ka for ~515 yr at a best-fit rate of 26 cm yr^{-1} (10–416 cm yr^{-1}, 2σ) at Mount Murray (Figs. S5 and S6). Thinning of the glacier likely initiated before these times, and we cannot rule out that ice surface lowering continued below the present-day glacier surface. We consider the timing and style of abrupt thinning to be broadly consistent across sites; while thinning at Mount Murray appears to possibly lag that at Bruce Point, it is not possible to determine whether this is due to geological or glaciological processes (see the Supplemental Material).

A history of final thinning and ice margin retreat is recorded at Mawson Glacier between the episode of rapid thinning and the present day (Fig. 2). Three ages from ca. 3.3 ka to ca. 2.2 ka likely record 16 m of ice surface lowering at Mount Murray. Exposure ages from a moraine located adjacent to Mount Murray indicate that Mawson Glacier was slightly more extensive than today at ca. 1.3–0.5 ka (Fig. S4), while

[1]Supplemental Material. Supplemental table of sample information and detailed description of methods. Please visit https://doi.org/10.1130/GEOL.S.13046525 to access the supplemental material, and contact editing@geosociety.org with any questions.

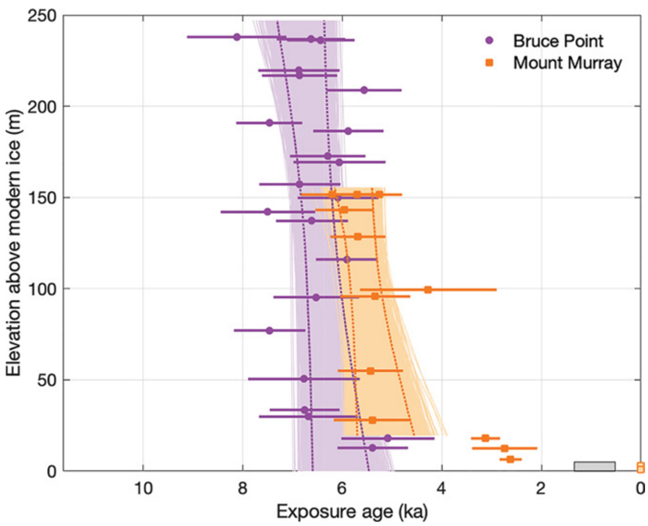

Figure 2. Holocene exposure ages from Mawson Glacier (Antarctica) plotted as a function of elevation. Samples identified as potential outliers are not included here, but the full data set is plotted in Figure S3 (see footnote 1). Two "modern" samples at Mount Murray are included as pale squares (0 ka). Ages are shown as the mean with 1σ uncertainty. Modeled random linear regressions of the abrupt thinning episode are shown for each transect (dotted lines denote 95% confidence bounds). The age uncertainty range (1.3–0.5 ka) for the Mount Murray moraine is plotted as a horizontal gray bar.

two samples with very low nuclide concentrations from the base of the Mount Murray transect imply that the final few meters of glacier thinning occurred relatively recently (Fig. 2; Fig. S3).

DISCUSSION

Placed in a wider deglacial context, the record of thinning at Mawson Glacier allows us test whether ice sheet outlets in the western Ross Sea retreated in concert or independently and, in turn, whether regional or local factors were most important.

The timing, style, and magnitude of thinning at Mawson Glacier is nearly identical to that documented 100 km to the south at Mackay Glacier (Jones et al., 2015) (Fig. 3). In particular, an abrupt thinning event is recorded by both outlet glaciers at ca. 7.5–5 ka. The start of this event is based primarily on Mackay Glacier, where only ~30 m of thinning happened between the Last Glacial Maximum (ca. 22 ka) and the Mid-Holocene. Irrespective of the exact timing of abrupt thinning, large-scale ice loss occurred at Mawson and Mackay Glaciers in the Mid-Holocene. Both glaciers also record a period of apparent gradual thinning and then a final phase of ice margin retreat and ice surface lowering in the Mid- to Late Holocene (Fig. 3), which further highlights the consistent regional signal of Holocene deglaciation along the Scott Coast in the western Ross Sea.

The deglacial history of adjacent marine areas is documented from a combination of data sets. A marine sediment core records a minimum age of grounding-line retreat of 8.6 ± 0.2 cal. kyr B.P. (calibrated ^{14}C kyr B.P.) 60 km east of Ross Island (core CH-2; McKay et al., 2016), and relative sea-level curves recording the isostatic response to the unloading of grounded ice indicate that final major retreat in McMurdo Sound occurred at 7.5 cal. kyr B.P. (Hall et al., 2004). Megascale glacial lineations mapped on the seafloor show that ice from Mawson and Mackay Glaciers merged north of Beaufort Island at an unknown time in the past (Fig. 1), while grounding-zone wedges deposited on top of these lineations document subsequent east-west retreat of the grounding line from Joides Trough toward the Scott Coast (Greenwood et al., 2018; Lee et al., 2017). Unfortunately, current chronologies from marine sediment cores in the area are inconsistent with inferences from geomorphology due to significant radiocarbon-age biases (Prothro et al., 2020), limiting the potential to link marine-based ice sheet retreat to our records onshore. However, our new constraints at Mawson Glacier and those at Mackay Glacier provide a near-continuous record of broadly simultaneous outlet glacier thinning along the Scott Coast. Glacier modeling demonstrates that ice drawdown directly corresponds to changes at the grounding line (Payne et al., 2004; Jones et al., 2015), implying that these onshore data document the rapid retreat of grounded ice in the western Ross Sea in the Mid-Holocene.

The timing of abrupt ice loss in the western Ross Sea appears to lag changes elsewhere in this sector of the ice sheet. Based on available chronological data, geomorphology, and ice sheet modeling, the period of Mid-Holocene ice loss in the western Ross Sea possibly occurred after large-scale ice drawdown recorded at outlet glaciers 900 km to the south in the southern Transantarctic Mountains (Spector et al., 2017), and likely occurred several thousand years after deglaciation of the eastern and central Ross Sea (Halberstadt et al., 2016; McKay et al., 2016; Bart et al., 2018; Lowry et al., 2019). Grounding-line retreat and corresponding ice drawdown in the western Ross Sea then became more gradual during the Mid- to Late Holocene, similar to that recorded in parts of the southern Transantarctic Mountains (Spector et al., 2017), reaching a near-modern ice geometry within the last millennium.

Synchronous abrupt thinning at Mawson and Mackay Glaciers implies a common mechanism and regional-scale driver of Mid-Holocene ice loss. The overdeepened bed topography of the western Ross Sea likely determined the style of this ice loss (Jones et al., 2015), where initial grounding-line retreat across a retrograde slope into deeper water leads to further accelerated retreat and enhanced ice drawdown, known as marine ice sheet instability (Weertman, 1974; Schoof, 2007). However, complex bed topography should result in outlets retreating independently of each other, and, therefore, the consistent timing of abrupt thinning implies an overarching external driver of retreat. Sea-level rise has been linked to late-glacial ice surface lowering in northern Victoria Land (Goehring et al., 2019), but it is unlikely to have been the driver of deglaciation in the western Ross Sea during the Holocene. Local sea level plateaued in the Early Holocene as the glacial isostatic signal began to dominate the remaining rise in global mean sea level (Fig. 3). Sea level then fell toward the present-day level due to isostatic uplift, reflecting the major ice loss in this region in the Mid-Holocene (Hall et al., 2004; Whitehouse et al., 2012; Argus et al., 2014). Ice sheet simulations constrained by onshore and offshore chronological data indicate that ocean warming likely drove Holocene deglaciation in the Ross Sea sector (Lowry et al., 2019). An increase in ocean temperature through the Holocene could have initiated the abrupt thinning event recorded at Mawson and Mackay Glaciers (Fig. 3), but all climate scenarios used by Lowry et al. (2019) predicted earlier ice sheet retreat and thinning in the western Ross Sea than that indicated by the geological constraints (Fig. S7). The model-data discrepancy may imply a cooler ocean in this region, whereby the ice sheet responded to subdued but cumulative warming, or a delayed enhanced warming relative to the central Ross Sea, but unfortunately no ocean temperature proxy records currently exist from the Ross Sea to test this. Additionally, pinning points associated with the complex bed topography of the western Ross Sea could have delayed the timing of grounding-line retreat and, thus, the timing of abrupt regional ice loss. Coarse-grid ice sheet models are unable to accurately simulate retreat over complex bed topography (Cuzzone et al., 2019) and ice sheet loss in this region differs between several models, and all models fail to replicate the timing of recorded Mid-Holocene ice loss (Fig. S7; see the Supplemental Material).

Our new ice thinning chronologies from Mawson Glacier together with previously published data from Mackay Glacier demonstrate that abrupt regional-scale deglaciation occurred in the western Ross Sea in the Mid-Holocene.

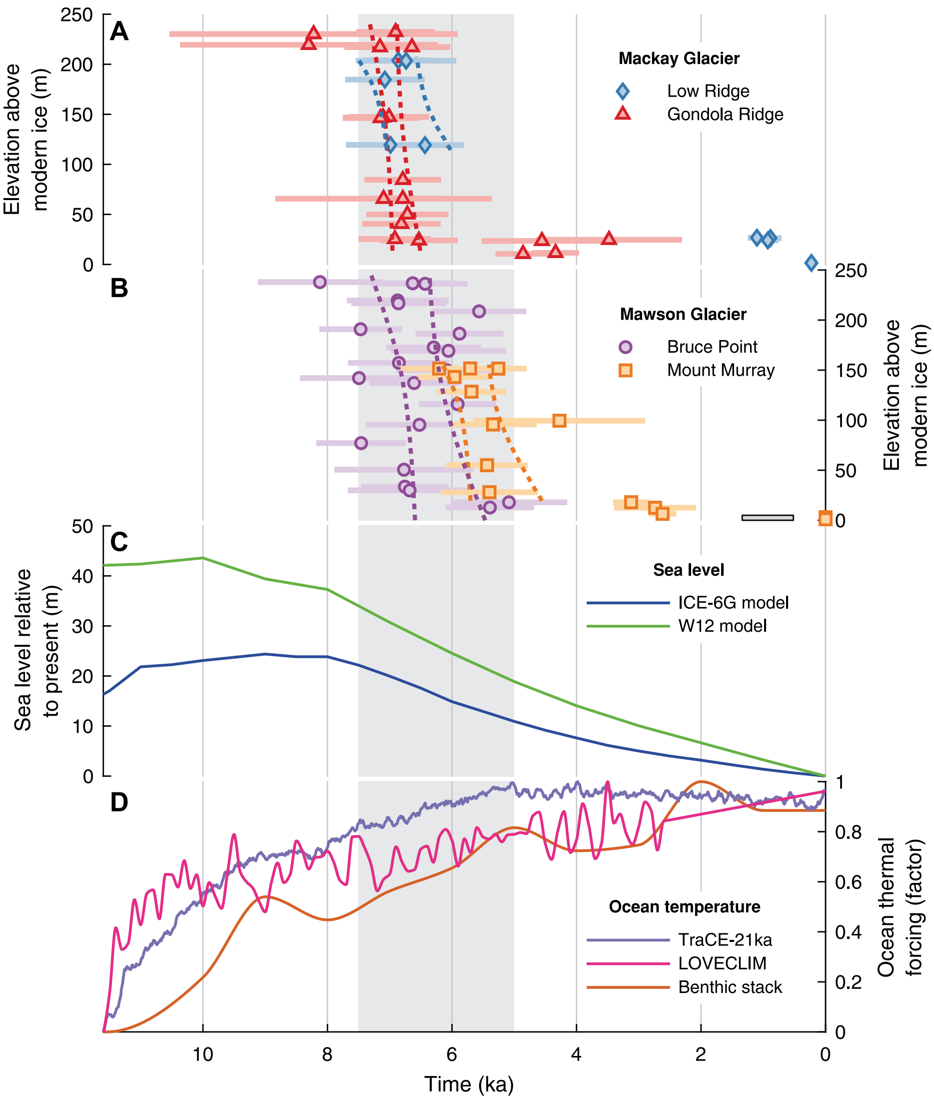

Figure 3. Deglaciation records of the western Ross Sea (Antarctica) and potential forcings. (A) Exposure ages versus relative elevation at Mackay Glacier (Jones et al., 2015), with dotted lines denoting 95% confidence bounds from linear regression analysis. Ages are shown as the mean with 1σ uncertainty. (B) Exposure ages at Mawson Glacier, as shown in Figure 2. (C) Local sea-level change in the western Ross Sea from ICE-6G (Argus et al., 2014) and W12 (Whitehouse et al., 2012) glacial isostatic adjustment models. (D) Model- and proxy-based ocean thermal forcings, similar to those used by Lowry et al. (2019). Temperature anomalies from the TraCE-21ka data set (http://www.cgd.ucar.edu/ccr/TraCE/) and LOVECLIM model (https://www.elic.ucl.ac.be/modx/index.php?id=81) (Ross Sea, 400 m depth) (Liu et al., 2009; Menviel et al., 2011) and the global benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005) have been scaled to 0 to 1 for the Holocene. Gray band in each plot highlights the period of abrupt outlet glacier thinning (7.5–5 ka).

The estimated rate of this thinning is similar between glaciers and to that constrained at some other locations across Antarctica during the Holocene (best-fit rates of 2–167 cm yr^{-1}; Small et al., 2019). In at least the western Ross Sea, retreat across a broad region occurred despite the complex bed topography, likely initiated by ocean warming, which then led to substantial ice drawdown in the Mid-Holocene.

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REFERENCES CITED

Anderson, J.B., et al., 2014, Ross Sea paleo-ice sheet drainage and deglacial history during and since the LGM: Quaternary Science Reviews, v. 100, p. 31–54, https://doi.org/10.1016/j.quascirev.2013.08.020.

Argus, D.F., Peltier, W.R., Drummond, R., and Moore, A.W., 2014, The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories: Geophysical Journal International, v. 198, p. 537–563, https://doi.org/10.1093/gji/ggu140.

Bart, P.J., DeCesare, M., Rosenheim, B.E., Majewski, W., and McGlannan, A., 2018, A centuries-long delay between a paleo-ice-shelf collapse and grounding-line retreat in the Whales Deep Basin, eastern Ross Sea, Antarctica: Scientific Reports, v. 8, 12392, https://doi.org/10.1038/s41598-018-29911-8.

Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J., and Stone, J., 2016, Geological calibration of spallation production rates in the CRONUS-Earth project: Quaternary Geochronology, v. 31, p. 188–198, https://doi.org/10.1016/j.quageo.2015.01.009.

Cuzzone, J.K., Schlegel, N.-J., Morlighem, M., Larour, E., Briner, J.P., Seroussi, H., and Caron, L., 2019, The impact of model resolution on the simulated Holocene retreat of the southwestern Greenland ice sheet using the Ice Sheet System Model (ISSM): The Cryosphere, v. 13, p. 879–893, https://doi.org/10.5194/tc-13-879-2019.

DeConto, R.M., and Pollard, D., 2016, Contribution of Antarctica to past and future sea-level rise: Nature, v. 531, p. 591–597, https://doi.org/10.1038/nature17145.

Favier, L., Durand, G., Cornford, S., Gudmundsson, G.H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., Payne, A.J., and Le Brocq, A.M., 2014, Retreat of Pine Island Glacier controlled by marine ice-sheet instability: Nature Climate Change, v. 4, p. 117–121, https://doi.org/10.1038/nclimate2094.

Felikson, D., et al., 2017, Inland thinning on the Greenland ice sheet controlled by outlet glacier geometry: Nature Geoscience, v. 10, p. 366–369, https://doi.org/10.1038/ngeo2934.

Goehring, B.M., Balco, G., Todd, C., Moening-Swanson, I., and Nichols, K., 2019, Late-glacial grounding line retreat in the northern Ross Sea, Antarctica: Geology, v. 47, p. 291–294, https://doi.org/10.1130/G45413.1.

Greenwood, S.L., Simkins, L.M., Halberstadt, A.R.W., Prothro, L.O., and Anderson, J.B., 2018, Holocene reconfiguration and readvance of the East Antarctic Ice Sheet: Nature Communications, v. 9, 3176, https://doi.org/10.1038/s41467-018-05625-3.

Halberstadt, A.R.W., Simkins, L.M., Greenwood, S.L., and Anderson, J.B., 2016, Past ice-sheet behaviour: Retreat scenarios and changing controls in the Ross Sea, Antarctica: The Cryosphere, v. 10, p. 1003–1020, https://doi.org/10.5194/tc-10-1003-2016.

Hall, B.L., Baroni, C., and Denton, G.H., 2004, Holocene relative sea-level history of the Southern Victoria Land Coast, Antarctica: Global and Planetary Change, v. 42, p. 241–263, https://doi.org/10.1016/j.gloplacha.2003.09.004.

Jones, R.S., Mackintosh, A.N., Norton, K.P., Golledge, N.R., Fogwill, C.J., Kubík, P.W., Christl, M., and Greenwood, S.L., 2015, Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability: Nature Communications, v. 6, 8910, https://doi.org/10.1038/ncomms9910.

Jones, R.S., Small, D., Cahill, N., Bentley, M.J., and Whitehouse, P.L., 2019, iceTEA: Tools for

plotting and analysing cosmogenic-nuclide surface-exposure data from former ice margins: Quaternary Geochronology, v. 51, p. 72–86, https://doi.org/10.1016/j.quageo.2019.01.001.
Lee, J.I., McKay, R.M., Golledge, N.R., Yoon, H.I., Yoo, K.-C., Kim, H.J., and Hong, J.K., 2017, Widespread persistence of expanded East Antarctic glaciers in the southwest Ross Sea during the last deglaciation: Geology, v. 45, p. 403–406, https://doi.org/10.1130/G38715.1.
Lifton, N., Sato, T., and Dunai, T.J., 2014, Scaling ***in situ*** cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes: Earth and Planetary Science Letters, v. 386, p. 149–160, https://doi.org/10.1016/j.epsl.2013.10.052.
Lisiecki, L.E., and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, v. 20, PA1003, https://doi.org/10.1029/2004PA001071.
Liu, Z., et al., 2009, Transient simulation of last deglaciation with a new mechanism for Bølling-Allerød warming: Science, v. 325, p. 310–314, https://doi.org/10.1126/science.1171041.
Lowry, D.P., Golledge, N.R., Bertler, N.A., Jones, R.S., and McKay, R., 2019, Deglacial grounding-line retreat in the Ross Embayment, Antarctica, controlled by ocean and atmosphere forcing: Science Advances, v. 5, eaav8754, https://doi.org/10.1126/sciadv.aav8754.
Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R., and Balco, G., 2016, Cosmogenic nuclide systematics and the CRONUScalc program: Quaternary Geochronology, v. 31, p. 160–187, https://doi.org/10.1016/j.quageo.2015.09.005.
McKay, R., Golledge, N.R., Maas, S., Naish, T., Levy, R., Dunbar, G., and Kuhn, G., 2016, Antarctic marine ice-sheet retreat in the Ross Sea during the early Holocene: Geology, v. 44, p. 7–10, https://doi.org/10.1130/G37315.1.
McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., and Wingham, D., 2014, Increased ice losses from Antarctica detected by CryoSat-2: Geophysical Research Letters, v. 41, p. 3899–3905, https://doi.org/10.1002/2014GL060111.
Menviel, L., Timmermann, A., Elison Timm, O., and Mouchet, A., 2011, Deconstructing the Last Glacial termination: The role of millennial and orbital-scale forcings: Quaternary Science Reviews, v. 30, p. 1155–1172, https://doi.org/10.1016/j.quascirev.2011.02.005.
Payne, A.J., Vieli, A., Shepherd, A.P., Wingham, D.J., and Rignot, E., 2004, Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans: Geophysical Research Letters, v. 31, L23401, https://doi.org/10.1029/2004GL021284.
Prothro, L.O., Majewski, W., Yokoyama, Y., Simkins, L.M., Anderson, J.B., Yamane, M., Miyairi, Y., and Ohkouchi, N., 2020, Timing and pathways of East Antarctic Ice Sheet retreat: Quaternary Science Reviews, v. 230, 106166, https://doi.org/10.1016/j.quascirev.2020.106166.
Schoof, C., 2007, Ice sheet grounding line dynamics: Steady states, stability, and hysteresis: Journal of Geophysical Research: Earth Surface, v. 112, F03S28, https://doi.org/10.1029/2006JF000664.
Seroussi, H., Nakayama, Y., Larour, E., Menemenlis, D., Morlighem, M., Rignot, E., and Khazendar, A., 2017, Continued retreat of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation: Geophysical Research Letters, v. 44, p. 6191–6199, https://doi.org/10.1002/2017GL072910.
Shepherd, A., et al., 2018, Mass balance of the Antarctic Ice Sheet from 1992 to 2017: Nature, v. 558, p. 219–222, https://doi.org/10.1038/s41586-018-0179-y.
Small, D., Bentley, M.J., Jones, R.S., Pittard, M.L., and Whitehouse, P.L., 2019, Antarctic ice sheet palaeo-thinning rates from vertical transects of cosmogenic exposure ages: Quaternary Science Reviews, v. 206, p. 65–80, https://doi.org/10.1016/j.quascirev.2018.12.024.
Spector, P., Stone, J., Cowdery, S.G., Hall, B., Conway, H., and Bromley, G., 2017, Rapid early-Holocene deglaciation in the Ross Sea, Antarctica: Geophysical Research Letters, v. 44, p. 7817–7825, https://doi.org/10.1002/2017GL074216.
Weertman, J., 1974, Stability of the junction of an ice sheet and an ice shelf: Journal of Glaciology, v. 13, p. 3–11, https://doi.org/10.1017/S0022143000023327.
Whitehouse, P.L., Bentley, M.J., Milne, G.A., King, M.A., and Thomas, I.D., 2012, A new glacial isostatic adjustment model for Antarctica: Calibrated and tested using observations of relative sea-level change and present-day uplift rates: Geophysical Journal International, v. 190, p. 1464–1482, https://doi.org/10.1111/j.1365-246X.2012.05557.x.

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