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Internal dynamics condition centennial-scale oscillations in marine-based ice-stream retreat

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ABSTRACT

Rates of ice-stream retreat over decades can be determined from repeated satellite surveys and over millennia by paleoenvironmental reconstructions. Centennial time scales are an important temporal gap in geological observations of value in process understanding and evaluation of numerical models. We address this temporal gap by developing a 3 ka and 123 km retreat time series for the Irish Sea ice stream (ISIS), a major outlet draining the last British-Irish ice sheet. The Llŷn Peninsula (northwest Wales, UK) contains numerous ice-marginal indicators from which we reconstructed a robust chronological framework of margin oscillations. The landscape documents the retreat of a former marine-terminating ice stream through a topographic constriction, across a reverse bed slope, and across variations in calving margin width. New dating constraints for this sequence were integrated in a Bayesian sequence model to develop a high-resolution ice-retreat chronology. Our results show that retreat of the ISIS during the period 24–20 ka displayed centennial-scale oscillatory behavior of the margin despite relatively stable climatic, oceanic, and relative sea-level forcing mechanisms. Faster retreat rates coincided with greater axial trough depths as the ice passed over a reverse bed slope and the calving margin widened (from 65 to 139 km). The geological observations presented here over a 123-km-long ice-retreat sequence are consistent with theory that marine-based ice can be inherently unstable when passing over a reverse bed slope, but also that wider calving margins lead to much faster ice retreat.

INTRODUCTION

Ice streams are corridors of fast ice flow in ice sheets, flanked by ice flowing up to an order of magnitude slower (e.g., Stokes and Clark, 1999), and they can contribute up to 90% of ice-sheet discharge (e.g., Bamber et al., 2009). Considerable attention has been focused on the stability of marine-based ice streams in Antarctica and Greenland because of their potential contribution to rapid ice-sheet collapse (e.g., Joughin and Alley, 2011; Joughin et al., 2014; Rignot et al., 2014). This is especially important in Antarctica, where large parts of the grounding line rest below sea level on reverse bed slopes that deepen up ice. In such circumstances, retreat increases the ice thickness at the grounding line, leading to increased ice flux and unstable grounding line positions across the reverse bed slope, and promoting rapid retreat—known as the marine ice-sheet instability hypothesis (Schoof, 2003; Thomas et al., 2011; Weertman, 1974; Jones et al., 2015). However, numerical modeling suggests that not all grounding lines on reverse bed slopes are inherently unstable (e.g., West Antarctica; Gudmundsson et al., 2012), and they may stabilize at constrictions of the calving margin (e.g., Marguerite Bay ice stream; Jamieson et al., 2012). There is currently a lack of observations for the retreat of marine-based ice streams to inform or act as tests of process models, with available evidence either short in duration (decades; e.g., Carr et al., 2015) or over longer (e.g., multimillennial) time scales.

This temporal gap in geological observations over centennial to millennial time scales is addressed here and used to explore how external forcing (climate, sea-surface temperature, and sea level) and topographic controls (bed slope, trough depth, and calving margin width) condition retreat rate. We studied the Irish Sea ice stream (ISIS; Eyles and McCabe, 1989; Van Landeghem et al., 2009), a major ice stream that drained the last British-Irish ice sheet (BIIS), which operated over hundreds of kilometers, discharging >17% of the total ice mass. Extensive morphostratigraphical evidence is preserved on land around the Irish Sea Basin and records the lateral margins of this marine-terminating ice mass. We focused on the lateral margin adjacent to a topographic high with a shallow reverse bed slope of 60 m relief and 50 km in length and constriction of the ISIS between northwest Wales and eastern Ireland (Fig. 1).

GEOMORPHIC SETTING AND SAMPLING

During the Last Glacial Maximum (LGM), the ISIS reached the Isles of Scilly in the Celtic Sea (~50°N; Fig. 1A) at ca. 26–25 ka (Smedley et al., 2017) and then retreated rapidly (at >300 m yr^{-1}) into the northern Irish Sea Basin by 21.9–20.7 ka (Chiverrell et al., 2013). The Llŷn Peninsula, northwest Wales, formed a bedrock-cored obstruction to the ISIS eastern margin; the peninsula is 45 km long with a maximum elevation of 521 m (Fig. 1). Channel bathymetry shows a topographical high and narrowing of the ice stream trough (Fig. 1A). Glacial isostatic adjustment modeling for this region at 21 ka (Bradley et al., 2011) indicated local relative sea levels (RSL) at –40 to –50 m (Figs. 1A and 1B). The continuous record of ice-rafted debris (IRD) flux throughout the LGM from the OMEX2K marine core on the adjacent Goban Spur continental margin (Haapaniemi et al., 2010) suggests an uninterrupted calving flux from the marine-terminating ISIS. The Llŷn Peninsula was a lateral, terrestrial protrusion adjacent to a gentle axial reverse bed slope (Fig. 1C) across which the marine-terminating ice margin retreated northward.

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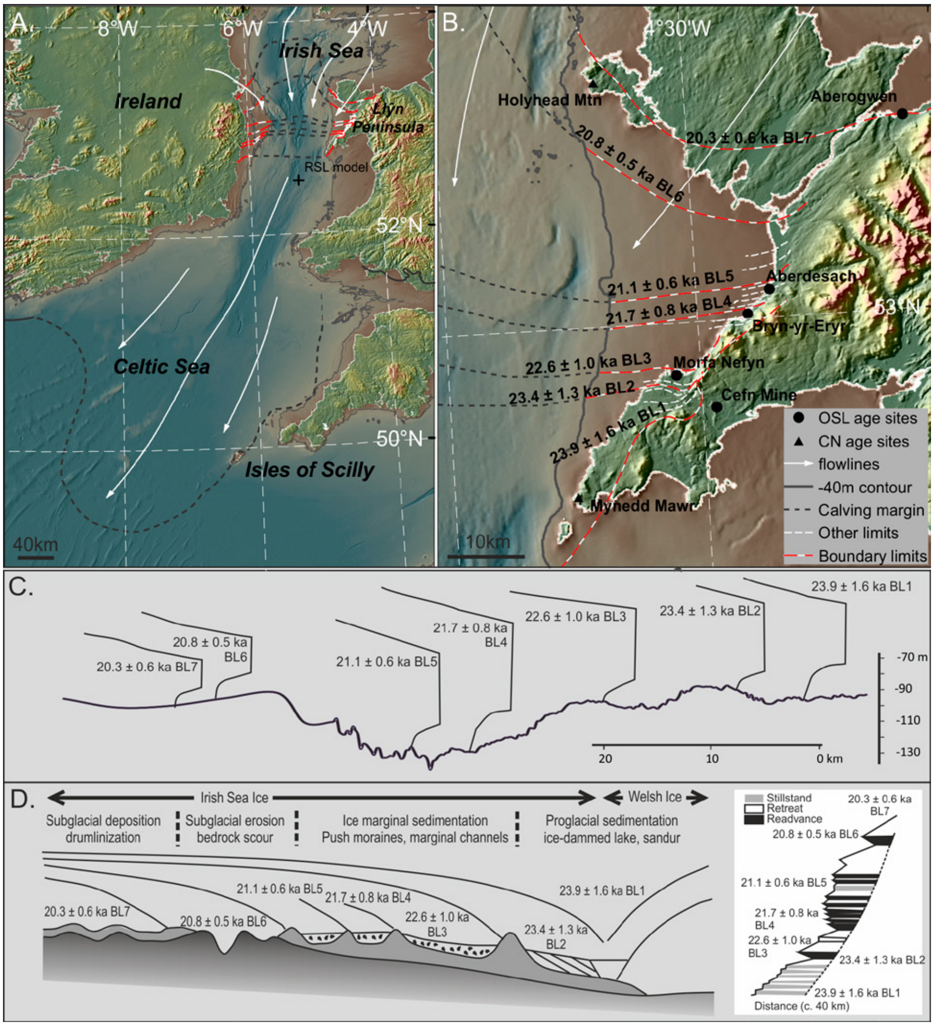

Figure 1. A: Location and geomorphological context of Llŷn Peninsula in Irish–Celtic Sea region. Coastline (gray line) and likely calving fronts (dashed black lines) are based on modeled relative sea level (RSL; –40 m) for Llŷn Peninsula derived from integrated glacial isostatic adjustment (GIA) input of Bradley et al. (2011). B: Dated sites (OSL—optically stimulated luminescence; CN—cosmogenic nuclide), reconstructed ice limits, and ages derived from Bayesian modeling. These are plotted over Nextmap™ and European Marine Observation and Data Network (EMODnet, http://www.emodnet.eu) topographical data. C: Schematic axial Irish Sea ice stream (ISIS) marine retreat sequence displayed over bed topography estimated as 10th percentile (deepest) of water depths between –40 m seafloor contours in EMODnet bathymetric data set with 215 × 215 m resolution, averaged across the seafloor. D: Schematic lateral retreat sequence and paleoenvironments across Llŷn Peninsula; inset shows retreat–stillstand–re-advance sequence discerned from morphostratigraphy (after Thomas and Chiverrell, 2007) and new ages in this study.

Well-preserved glacial geomorphology and >30 km of coastal exposure on the Llŷn Peninsula are the basis for a time-distance ice-retreat and re-advance reconstruction for the ISIS. The frequency (>30) and small scale (<500 m) of inferred ice-marginal oscillations along the coast of the Llŷn Peninsula suggest centennial-scale responses to local glaciological conditions rather than climate forcing (Thomas and Chiverrell, 2007). Here, we provide new age constraints using optically stimulated luminescence (OSL) dating for seven ice-marginal positions on the Llŷn Peninsula to complement existing cosmogenic nuclide (CN) ages (McCarroll et al., 2010). For site descriptions and field methods, see the GSA Data Repository[1].

LABORATORY AND ANALYTICAL METHODS

OSL dating determines the time elapsed since mineral grains were exposed to sunlight prior to burial. Ages were determined for eight samples (Table 1) using measurements of equivalent doses (D_e) on single grains of quartz (212–250 μm) to identify those grains that were well bleached prior to sediment burial. Dose rates were determined using inductively coupled plasma–mass spectrometry (ICP-MS) and ICP atomic emission spectroscopy (ICP-AES), in addition to in situ gamma spectrometry. D_e values were divided by the dose rates to calculate ages. All existing CN ages were recalculated using a local production rate (LLPR; Fabel et al., 2012).

Age measurements were interrogated using a Bayesian sequence model (Bronk Ramsey, 2009), based on a prior model (i.e., hypothetical "relative order" of events) developed independently of the age information. The prior model here is the relative distance reconstruction of ice-margin oscillations from south to north across the Llŷn Peninsula (Thomas and Chiverrell, 2007). Bayesian modeling was undertaken in OxCal 4.2 (Bronk Ramsey and Lee, 2013) using a uniform phase sequence model punctuated by boundaries, which generated modeled ages for seven major ice-marginal limits (boundary limit [BL] 1–7; see Fig. 1). It was run as an outlier model to assess outliers in time using a Student's *t* distribution ($p < 0.05$), which defines the distribution of the outliers and an outlier scaling of 10^0–10^4 yr (Bronk Ramsey, 2009). For full details of the analytical methods, see the GSA Data Repository.

RESULTS AND DISCUSSION

Bayesian modeling confirms a conformable ice-retreat sequence with an overall agreement index of 87.4%, which exceeds the recommended 60% threshold (Bronk Ramsey, 2009). Three measurements were identified as outliers: the OSL age for sample T4CEIF02 (18.0 ± 3.0 ka), and the CN ages for samples HM-1 and MM1, which probably represent nuclide inheritance (insufficient removal of rock by glacial erosion). The modeled output of boundary ages forms a consistent temporal sequence of retreat by the eastern ISIS lateral margin (Table 1) and is similar to CN ages from ice-molded schist bedrock on the western margin (Ballantyne et al., 2006) recalculated using the LLPR to 21.9 ± 1.1 ka, 21.0 ± 1.1 ka, and 21.2 ± 1.1 ka.

The boundary ages (Figs. 1 and 2) show that the ISIS took ~3 k.y. to retreat a net distance of 123 km (~33 m yr^{-1}) across the seafloor adjacent to the Llŷn Peninsula, which was much slower than the 390 km retreat from its terrestrial maximum on the Isles of Scilly at ca. 26–25 ka (Smedley et al., 2017) to south of the Llŷn Peninsula by 23.9 ± 1.6 ka (~244 m yr^{-1}). Retreat across the Llŷn Peninsula was interrupted by >30 stillstands or re-advances of the lateral ice margin (Thomas and Chiverrell, 2007), which averages to a substantial marginal pause represented by morphostratigraphic evidence every ~100 yr. Based on the median boundary ages, retreat rates of the ISIS increased northward across the Llŷn Peninsula, with the fastest retreat rates of 84–118 m yr^{-1} between BL5 (21.1 ± 0.6 ka) and BL7 (20.3 ± 0.6 ka), in comparison to retreat across the southern Llŷn Peninsula at

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[1] GSA Data Repository item 2017258, site descriptions and field and analytical methods, is available online at http://www.geosociety.org/datarepository/2017/, or on request from editing@geosociety.org.

TABLE 1. MODELED AGES FOR EACH BOUNDARY LIMIT (IN BOLD), AND UNMODELLED OSL AND CN AGES (±1σ)

Prior	Age (ka)
BL1	**23.9 ± 1.6**
T4CEIF01	21.9 ± 4.4
T4CEIF02*	18.0 ± 3.0
BL2	**23.4 ± 1.3**
MM1*	26.0 ± 1.4
MM2	24.3 ± 1.4
BL3	**22.6 ± 1.0**
T4MNEF03	21.8 ± 3.7
BL4	**21.7 ± 0.8**
T4BRYN02	19.7 ± 1.7
T4BRYN03	19.2 ± 1.6
BL5	**21.1 ± 0.6**
T4ADES01	18.9 ± 3.1
BL6	**20.8 ± 0.5**
HM-1*	23.4 ± 1.3
HM-2.1	20.4 ± 1.1
HM-2.2	21.5 ± 1.3
HM-3	21.2 ± 1.2
HM-4	20.2 ± 1.0
BL7	**20.3 ± 0.6**
T4ABER01	18.1 ± 1.6
T4ABER03	20.2 ± 1.9

Note: BL—boundary limit; OSL—optically stimulated luminescence; CN—cosmogenic nuclide.

*Identified as outlier in Bayesian sequence model.

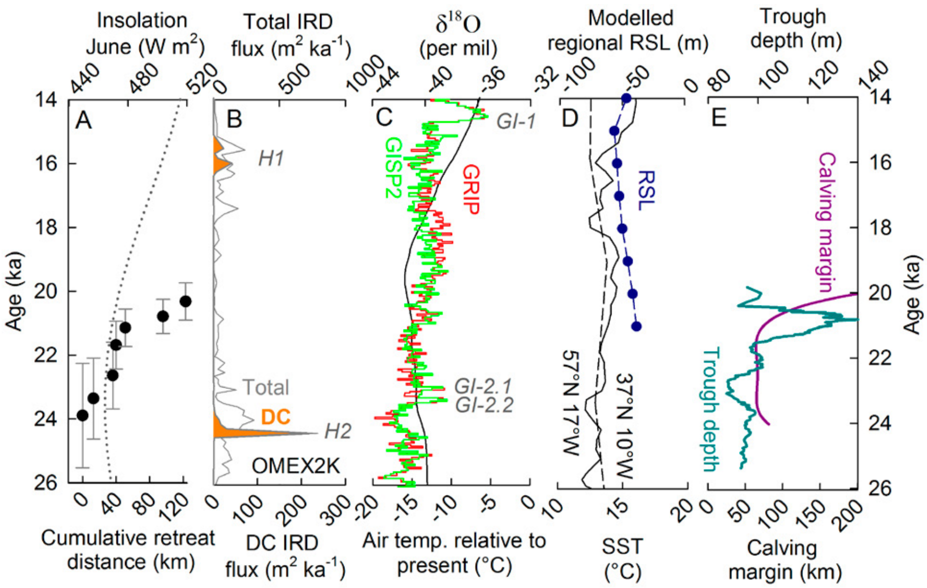

Figure 2. A: Summer insolation for 60°N (Berger and Loutre, 1991) (dotted line) plotted with boundary ages from Bayesian model against axial retreat distance (filled circles). B: Dolomitic carbonate (DC; orange) and total ice-rafted debris (IRD; gray line) flux records from OMEX2K marine core (Haapaniemi et al., 2010). Heinrich events H1 and H2 are highlighted. C: δ^{18}O concentrations (red and green lines) and Greenland interstadials (GI) from the Greenland ice cores (Rasmussen et al., 2014) and modeled surface-air temperatures (black line) relative to present for land masses north of ~45°N (Bintanja et al., 2005). D: Sea-surface temperature (SST) records (black and dashed lines) determined for North Atlantic using alkenones at 37°N, 10°W (Bard, 2002) plotted using updated age model of Bard et al. (2004) and from Ocean Drilling Project (ODP) Site 982 at 57°N, 17°W (Lawrence et al., 2009), and modeled relative sea level (RSL; blue filled circles and dashed line) for Llŷn Peninsula derived from glacial isostatic adjustment (GIA) model of Bradley et al. (2011). E: Likely calving margin widths (purple; transects shown in Fig. 1A) and axial trough depths (turquoise) estimated as 10th percentile (deepest) of water depths for seafloor between –40 m contours in European Marine Observation and Data Network (EMODnet, http://www.emodnet.eu) seafloor bathymetric data set plotted against boundary ages fitted by third-order polynomial.

8–41 m yr^{-1} between 23.9 ± 1.6 ka and 21.1 ± 0.6 ka (BL1 to BL5). Changes in retreat rates typically reflect either external forcing (climate or sea level) or topographic conditions (calving margin width and trough depth), and so the boundary ages for the seven retreat stages are compared with these controls in Figure 2. The trough depths (Fig. 1C) of the ISIS for an axial transect were quantified using the deepest 10% of depths (–87 m to –140 m) present between the –40 m contours in the European Marine Observation and Data Network (EMODnet; http://www.emodnet.eu) bathymetric data set, which has a resolution of 215 × 215 m (Fig. 1A). The calving margin width was defined as the distance along an east-west transect between the –40 m contours in the EMODnet bathymetric data set (Fig. 1A), an approach justified given steady regional RSL at this time (Fig. 2D; Bradley et al., 2011).

Oscillating retreat of the ISIS margin across the Llŷn Peninsula at ca. 24–20 ka occurred when summer insolation at 60°N was consistently low (Fig. 2A), prior to the increase at ca. 20 ka (Berger and Loutre, 1991), which has been cited as triggering retreat of the Laurentide ice sheet (Ullman et al., 2015). Although the age for BL1 (23.9 ± 1.6 ka) lies within uncertainties of the peak in the IRD flux recorded in the OMEX2K marine core in the Celtic Sea (Haapaniemi et al., 2010), the median age suggests that ice retreated to the Llŷn Peninsula after Heinrich event 2 (H2; Fig. 2B). IRD flux then remained low throughout the retreat of the ISIS across the Llŷn Peninsula. The δ^{18}O records from Greenland ice cores and modeled air-surface temperature records for land masses north of ~45°N (Fig. 2C) both suggest limited changes from 23.9 ± 1.6 ka (BL1) to 20.3 ± 0.6 ka (BL7). Sea-surface temperatures (SSTs) determined for the North Atlantic at 37°N, 10°W (Bard, 2002) and 57°N, 17°W (Lawrence et al., 2009) suggest that SSTs were also stable during this period (Fig. 2D). Regional RSL (~–40 m) was stable from 23 to 20 ka (Fig. 2D). The lack of major shifts in climate, SST, or sea level as the ISIS retreated across the Llŷn Peninsula suggests that such external forcing factors were not conditioning the variable retreat rates.

Retreat across the southern part of the Llŷn Peninsula from 23.9 ± 1.6 ka (BL1) to 21.1 ± 0.6 ka (BL5) occurred at rates between 8 m yr^{-1} and 41 m yr^{-1}. This retreat was characterized by five re-advances, shallower axial trough depths (Fig. 2E), and calving margin widths of 65–77 km. Northward from BL5, separation of the lateral ice-stream margin from the Llŷn Peninsula increased, producing more accommodation space and proglacial outwash between the ice margin and the mountains of Snowdonia. The fastest net axial retreat rates during this lateral uncoupling phase (118 m yr^{-1}) occurred between 21.1 ± 0.6 (BL5) and 20.8 ± 0.5 ka (BL6) and accounted for 42 km out of the total 123 km of axial retreat across the Llŷn Peninsula, interrupted by two small re-advances of the ice margin. Retreat rates then remained high (84 m yr^{-1}) from 20.8 ± 0.5 ka (BL6) to 20.3 ± 0.6 ka (BL7). These faster retreat rates coincided with greater trough depths as the ice front passed across a reverse bed slope (Fig. 2E) and widening of the calving margin to 90 km (BL6) and 139 km (BL7) during stable external conditions; these calving widths were twice as large as during the phase of slower retreat (8–41 m yr^{-1}).

Our results support existing theory that show marine-based ice can be inherently unstable when the grounding line passes over a reverse bed slope (Schoof, 2003; Weertman, 1974). However, in the case of the ISIS, where the reverse bed slope was shallow in comparison to many examples in Antarctica, the wider calving margin likely also contributed to rapid phases of retreat by proportionally reducing the overall effect of lateral drag, which in turn increased ice velocity (Benn et al., 2007; Jamieson et al., 2012). The retreat sequence presented here over centennial time scales provides new geological observations of the sensitivity of marine-based ice-margin retreat to variations in bed topography (depths and widths) during stable external conditions, which could be used to help to evaluate model simulations of physical processes (e.g., Enderlin et al., 2013).

CONCLUSIONS

Geochronometric ages (OSL and CN) integrated in a Bayesian model constrain ice-stream retreat across the Llŷn Peninsula after the LGM and provide critical geological observations for assessing the importance of topographic controls in determining rates of ice-margin retreat on centennial time scales. Northward retreat of the terminus of the ISIS across the topographic constriction of the Llŷn Peninsula was initially slow (8–41 m yr^{-1}) and then increased to 84–139 m yr^{-1}. Ice-margin retreat over 123 km was punctuated by repeated, centennial <1-km-scale oscillations that were apparently not driven by external forcings (climate, SST, sea level), which were stable during this time. Accelerated retreat coincided with greater trough depths and the widening of the calving margin as the lateral margin passed across a reverse bed slope and unpinned from the Llŷn Peninsula. The geological observations presented here support the view that marine-based ice can be inherently unstable when retreating over a reverse bed slope, but they also indicate that widening of the calving margin was likely an important factor in accelerating ice-margin retreat. The centennial-scale retreat of the ISIS improves our understanding of how marine-based ice can respond to variations in bed topography (depths and widths) under relatively stable climatic and oceanic conditions, and this contributes to understanding of the physical processes that could potentially condition future marine ice-sheet instability in Greenland and Antarctica.

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REFERENCES CITED

Ballantyne, C.K., McCarroll, D., and Stone, J.O., 2006, Vertical dimensions and age of the Wicklow Mountains ice dome, eastern Ireland, and implications for the extent of the last Irish ice sheet: Quaternary Science Reviews, v. 25, p. 2048–2058, doi:10.1016/j.quascirev.2006.01.026.

Bamber, J.L., Riva, R.E., Vermeersen, B.L., and LeBrocq, A.M., 2009, Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet: Science, v. 324, p. 901–903, doi:10.1126/science.1169335.

Bard, E., 2002, Climate shock: Abrupt changes over millennial time scales: Physics Today, v. 55, p. 32–38, doi:10.1063/1.1537910.

Bard, E., Rostek, F., and Menot-Combes, G., 2004, A better radiocarbon clock: Science, v. 303, p. 178–179, doi:10.1126/science.1091964.

Benn, D.I., Warren, C.R., and Mottram, R.H., 2007, Calving processes and the dynamics of calving glaciers: Earth-Science Reviews, v. 82, p. 143–179, doi:10.1016/j.earscirev.2007.02.002.

Berger, A., and Loutre, M.F., 1991, Insolation values for the climate of the last 10,000,000 years: Quaternary Science Reviews, v. 10, p. 297–317, doi:10.1016/0277-3791(91)90033-Q.

Bintanja, R., van de Wal, R.S.W., and Oerlemans, J., 2005, Modelled atmospheric temperatures and global sea levels over the past million years: Nature, v. 437, p. 125–128, doi:10.1038/nature03975.

Bradley, S.L., Milne, G.A., Shennan, I., and Edwards, R., 2011, An improved glacial isostatic adjustment model for the British Isles: Journal of Quaternary Science, v. 26, p. 541–552, doi:10.1002/jqs.1481.

Bronk Ramsey, C., 2009, Bayesian analysis of radiocarbon dates: Radiocarbon, v. 51, p. 337–360, doi:10.1017/S0033822200033865.

Bronk Ramsey, C., and Lee, S., 2013, Recent and planned developments of the program Oxcal: Radiocarbon, v. 55, p. 720–730, doi:10.1017/S0033822200057878.

Carr, J.R., Vieli, A., Stokes, C.R., Jamieson, S.S.R., Palmer, S.J., Christoffersen, P., Dowdeswell, J.A., Nick, F.M., Blankenship, D.D., and Young, D.A., 2015, Basal topographic controls on rapid retreat of Humboldt Glacier, northern Greenland: Journal of Glaciology, v. 61, p. 137–150, doi:10.3189/2015JoG14J128.

Chiverrell, R.C., et al., 2013, Bayesian modelling the retreat of the Irish Sea ice stream: Journal of Quaternary Science, v. 28, p. 200–209, doi:10.1002/jqs.2616.

Enderlin, E.M., Howat, I.M., and Vieli, A., 2013, High sensitivity of tidewater outlet glacier dynamics to shape: The Cryosphere, v. 7, p. 1007–1015, doi:10.5194/tc-7-1007-2013.

Eyles, N., and McCabe, A.M., 1989, The late Devensian (<22,000 BP) Irish Sea Basin: The sedimentary record of a collapsed ice sheet margin: Quaternary Science Reviews, v. 8, p. 307–351, doi:10.1016/0277-3791(89)90034-6.

Fabel, D., Ballantyne, C.K., and Xu, S., 2012, Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British-Irish ice sheet in NW Scotland: Quaternary Science Reviews, v. 55, p. 91–102, doi:10.1016/j.quascirev.2012.09.002.

Gudmundsson, G.H., Krug, J., Durand, G., Favier, L., and Gagliardini, O., 2012, The stability of grounding lines on retrograde slopes: The Cryosphere, v. 6, p. 1497–1505, doi:10.5194/tc-6-1497-2012.

Haapaniemi, A.I., et al., 2010, Source, timing, frequency and flux of ice-rafted detritus to the northeast Atlantic margin, 30–12 ka: Testing the Heinrich precursor hypothesis: Boreas, v. 39, p. 576–591.

Jamieson, S.S.R., Vieli, A., Livingstone, S.J., Ó Cofaigh, C., Stokes, C., Hillenbrand, C.D., and Dowdeswell, J.A., 2012, Ice-stream stability on a reverse bed slope: Nature Geoscience, v. 5, p. 799–802, doi:10.1038/ngeo1600.

Jones, R.S., Mackintosh, A.N., Norton, K.P., Golledge, N.R., Fogwill, C.J., Kubik, 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, p. 8910, doi:10.1038/ncomms9910.

Joughin, I., and Alley, R.B., 2011, Stability of the West Antarctic Ice Sheet in a warming world: Nature Geoscience, v. 4, p. 506–513, doi:10.1038/ngeo1194.

Joughin, I., Smith, B.E., and Medley, B., 2014, Marine ice sheet collapse potentially under way for the Thwaites Glacier basin, West Antarctica: Science, v. 344, p. 735–738, doi:10.1126/science.1249055.

Lawrence, K.T., Herbert, T.D., Brown, C.M., Raymo, M.E., and Haywood, A.M., 2009, High-amplitude variations in North Atlantic sea surface temperature during the early Pliocene warm period: Paleoceanography, v. 24, PA2218, doi:10.1029/2008PA001669.

McCarroll, D., Stone, J.O., Ballantyne, C.K., Scourse, J.D., Fifield, L.K., Evans, D.J.A., and Hiemstra, J.F., 2010, Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream: Quaternary Science Reviews, v. 29, p. 1844–1852, doi:10.1016/j.quascirev.2010.04.002.

Rasmussen, S.O., et al., 2014, A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy: Quaternary Science Reviews, v. 106, p. 14–28, doi:10.1016/j.quascirev.2014.09.007.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B., 2014, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011: Geophysical Research Letters, v. 41, p. 3502–3509, doi:10.1002/2014GL060140.

Schoof, C., 2003, The effect of basal topography on ice sheet dynamics: Continuum Mechanics and Thermodynamics, v. 15, p. 295–307, doi:10.1007/s00161-003-0119-3.

Smedley, R.K., et al., 2017, New age constraints for the limit of the British-Irish Ice sheet on the Isles of Scilly: Journal of Quaternary Science, v. 32, p. 48–62, doi:10.1002/jqs.2922.

Stokes, C.R., and Clark, C.D., 1999, Geomorphological criteria for identifying Pleistocene ice streams: Annals of Glaciology, v. 28, p. 67–74, doi:10.3189/172756499781821625.

Thomas, G.S.P., and Chiverrell, R.C., 2007, Structural and depositional evidence for repeated ice-marginal oscillation along the eastern margin of the late Devensian Irish Sea ice stream: Quaternary Science Reviews, v. 26, p. 2375–2405, doi:10.1016/j.quascirev.2007.06.025.

Thomas, R., Frederick, E., Li, J., Krabill, W., Manizade, S., Paden, J., Sonntag, J., Swift, R., and Yungel, J., 2011, Accelerating ice loss from the fastest Greenland and Antarctic glaciers: Geophysical Research Letters, v. 38, L10502, doi:10.1029/2011GL047304.

Ullman, D.J., Carlson, A.E., LeGrande, A.N., Anslow, F.S., Moore, A.K., Caffee, M., Syverson, K.M., and Licciardi, J.M., 2015, Southern Laurentide ice-sheet retreat synchronous with rising boreal summer insolation: Geology, v. 43, p. 23–26, doi:10.1130/G36179.1.

Van Landeghem, K.J.J., Wheeler, A.J., and Mitchell, N.C., 2009, Seafloor evidence for palaeo-ice streaming and calving of the grounded Irish Sea ice stream: Implications for the interpretation of its final deglaciation phase: Boreas, v. 38, p. 119–131, doi:10.1111/j.1502-3885.2008.00041.x.

Weertman, J., 1974, Stability of the junction of an ice sheet and an ice shelf: Journal of Glaciology, v. 13, p. 3–11, doi:10.1017/S0022143000023327.

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