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Clark, C.D., Chiverrell, R.C., Fabel, D. et al. (3 more authors) (2021) Timing, pace and controls on ice sheet retreat: an introduction to the BRITICE-CHRONO transect reconstructions of the British–Irish Ice Sheet. Journal of Quaternary Science, 36 (5). pp. 673-680. ISSN 0267-8179

https://doi.org/10.1002/jqs.3326

JOURNAL OF QUATERNARY SCIENCE (2021) **36**(5) 673–680 ISSN 0267-8179. DOI: 10.1002/jqs.3326

JQS Journal of Quaternary Science QRA Quaternary Research Association

Timing, pace and controls on ice sheet retreat: an introduction to the BRITICE-CHRONO transect reconstructions of the British–Irish Ice Sheet

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Received 1 March 2021; Revised 24 March 2021; Accepted 9 April 2021

ABSTRACT: Motivated to help improve the robustness of predictions of sea level rise, the BRITICE-CHRONO project advanced knowledge of the former British–Irish Ice Sheet, from 31 to 15 ka, so that it can be used as a data-rich environment to improve ice sheet modelling. The project comprised over 40 palaeoglaciologists, covering expertise in terrestrial and marine geology and geomorphology, geochronometric dating and the modelling of ice sheets and oceans. A systematic and directed campaign, organised across eight transects from the continental shelf edge to a short distance (10s of kilometres) onshore, was used to collect 914 samples which yielded 639 new ages, tripling the number of dated sites constraining the timing and rates of change of the collapsing ice sheet. This special issue synthesises these findings of ice advancing to the maximum extent and its subsequent retreat for each of the eight transects to produce definitive palaeogeographic reconstructions of ice margin positions across the marine to terrestrial transition. These results are used to understand the controls that drove or modulated ice sheet retreat. A further paper reports on how ice sheet modelling experiments and empirical data can be used in combination, and another probes the glaciological meaning of ice-rafted debris.

KEYWORDS: British Irish Ice Sheet; BRITICE CHRONO; radiocarbon dating; luminesence dating; cosmogenic dating

On a warming Earth, ice sheets reduce in mass and raise the global sea level. Glaciologists have been galvanised into action by societal requirements to forecast this sea level rise over the coming decades and centuries. Numerical ice sheet models are needed to make such forecasts but the scale of the task, along with incomplete physical understanding of ice sheet processes, makes this difficult. To help improve the robustness of forecasts, and motivated by the quote below, the BRITICE-CHRONO project sought to develop knowledge of the former British–Irish Ice Sheet so that it can be used as a data-rich environment to improve ice sheet modelling approaches.

'We highlight that developing a demonstrable skill in ice sheet projection is hampered by a lack of data and observations for verification and testing. This is particularly acute for the marine ice sheet instability. Improved geological histories of ice sheet changes and the forcing that caused them could greatly assist in building such a skill.' (IPCC, 2010 p. 25).

An additional reason for seeking knowledge of the maximum extent, volume and demise of the last British–Irish Ice Sheet, including that over the North Sea, is to improve predictions of regional sea level changes across Europe and Scandinavia. This is because knowledge of glacio-isostatic adjustments from ice mass unloading of the lithosphere crucially affects forecasts of regional sea level. Future changes in sea level cannot be adequately predicted without accounting for the still ongoing changes from the last glaciation. The BRITICE-CHRONO project had the aims described above and continued the century-long endeavour of Quaternary scientists to better understand palaeo ice sheets and their climate interactions.

The BRITICE-CHRONO project

The project comprised a consortium of over 40 palaeoglaciologists, covering expertise in terrestrial and marine geology and geomorphology, geochronometric dating, and the modelling of ice sheets and oceans. It ran from 2012 to 2018 with £3.7 million in funds plus use of the Natural Environment Research Council's research ship, the *RRS James Cook* for two dedicated research cruises, and dating facilities (the National Environmental Isotope Facility and Radiocarbon Facility in Glasgow). The chief aim was to conduct a systematic and directed campaign to collect and date material to constrain the timing and rates of change of the marine-influenced sectors of the collapsing British–Irish Ice Sheet.

A series of 23 BRITICE-CHRONO publications report on new dates and their stratigraphic and glaciological contexts, and then build regional reconstructions of the glacial history of the various regions (Peters *et al.*, 2016; Sejrup *et al.*, 2016; Arosio *et al.*, 2018; Small *et al.*, 2017a, 2018; Evans *et al.*, 2017, 2018a,b; Smedley *et al.*, 2017a; Bateman *et al.*, 2018; Callard *et al.*, 2018,

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2020; Roberts *et al.* 2018a,b, 2020; Chiverrell *et al.* 2018; Lockhart *et al.* 2018; Wilson *et al.*, 2018; Bradwell *et al.*, 2019; Ó Cofaigh *et al.*, 2019; Scourse *et al.*, 2019; Tarlati *et al.*, 2020). These publications mostly focused on either marine or terrestrial areas. The purpose of this special issue of *The Journal of Quaternary Science* is to report on, add to, and synthesise these findings in a seamless manner. This is done with new Bayesian modelling of geochronosequences to produce coherent and definitive syntheses of palaeogeographic reconstructions of the back-stepping ice margins across the marine to terrestrial transition. These results on the timing and pacing of ice withdrawal are then used to understand the main controls that drove or modulated ice sheet retreat (Benetti *et al.*, 2021; Bradwell *et al.*, 2021a,b; Chiverrell *et al.*, 2021; Evans *et al.*, 2021; Ó Cofaigh *et al.*, 2021; Scourse *et al.*, 2021). A further paper reports on how ice sheet modelling experiments and empirical data can be used in combination (Ely *et al.*, 2021), and another probes the glaciological meaning of ice-rafted debris (Wilton *et al.*, 2021).

Historical perspective on the extent of the last British–Irish Ice Sheet

In the late 1800s, shortly after it had been recognised that parts of Britain and Ireland hosted landforms and features of glacial origin such as moraines, glacially transported boulders and striated bedrock, maps reconstructing the ice sheet started to be drawn (e.g. Geikie, 1894). These were based on a small amount of actual evidence along with some large conjecture to fill the gaps (Fig. 1A). The ice sheet was drawn as extending beyond the coastline to the edge of the continental shelf. Viewed today this stands as an inspiring hypothesis. Many decades later, when fieldworkers had more thoroughly picked over the landscape searching out glacial landforms and deposits, the picture of the ice sheet changed dramatically. It was now reconstructed as a much smaller version, which did not connect with ice from Scandinavia and barely extended offshore (Fig. 1B). It was of course appropriate to pay greater attention to what the accumulating field evidence said and to reduce conjecture, but we now recognise two problems. The first being that just because evidence of glaciation in some areas could not be found, or was subdued, did not mean that the ice sheet did not cover those areas; see, for example, the reconstructed ice-free areas in northeastern Scotland and southern Ireland in Fig. 1B. Secondly, because most fieldwork had been land-based it biased the reconstructions, drawing ice as only short distances offshore. An explosion of new techniques and data collected by ship-borne geophysics led to an overturning of the small-ice model when it was discovered that grounded ice extended in many places across the continental shelf (Fig. 1B), albeit with much uncertainty about when. These new findings of a much larger and marine-influenced ice sheet motivated BRITICE-CHRONO to tackle the marine sectors, and to track retreat across the marine to terrestrial transition.

A sampling framework for dating to constrain ice retreat

An extensive framework exists about ice extent, flow geometry and the pattern of retreat as revealed in glacial landforms, discovered and mapped by many, and compiled in a map and

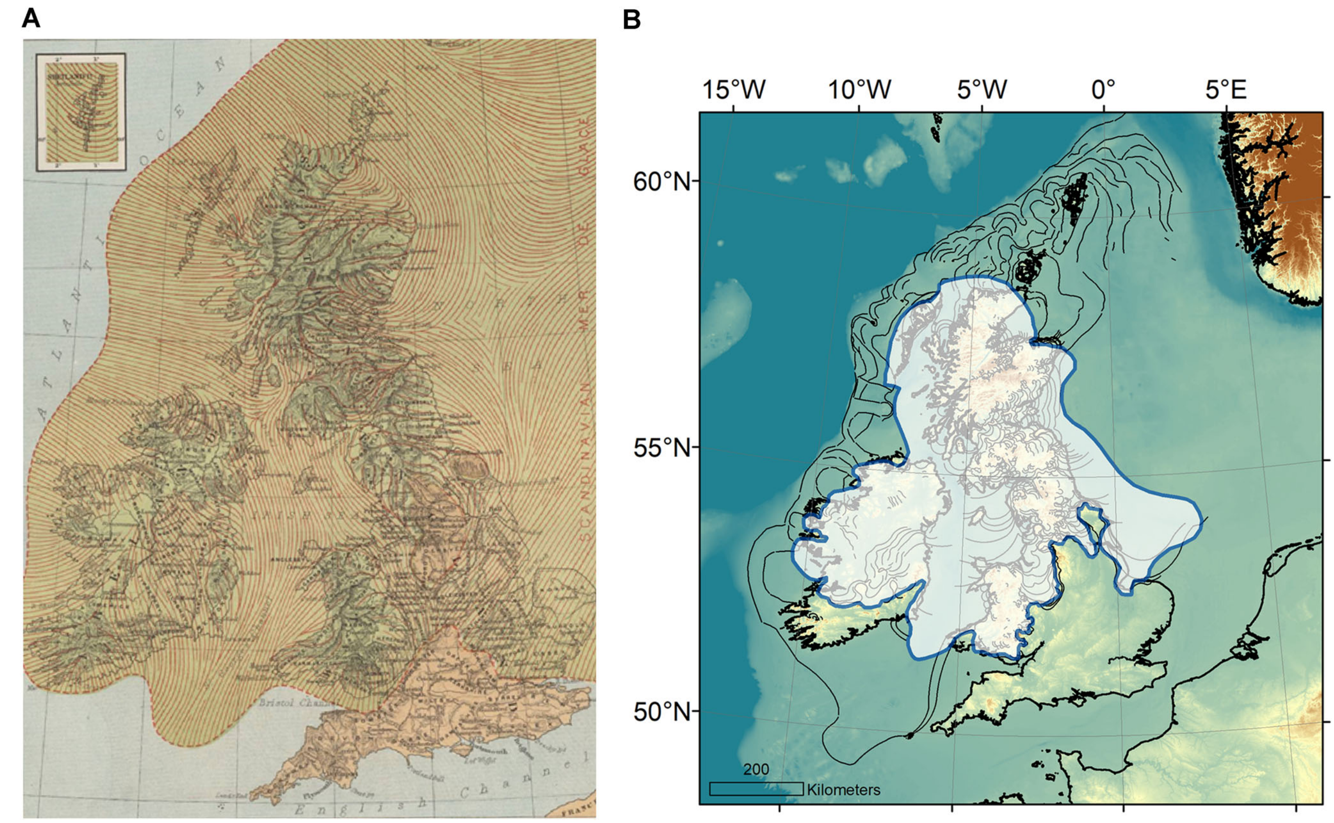

Figure 1. Three depictions of the extent of the British–Irish Ice Sheet. (A) Geikie (1894) used a small amount of evidence along with some large conjecture to reconstruct the ice sheet reaching the edge of the continental shelf and being confluent with Scandinavian ice over the North Sea. (B) By the 1980s, accumulation of substantial amounts of evidence from glaciogenic sediments and landforms, and less use of conjecture, led to a much smaller ice sheet being reconstructed, summarised here (blue line) by Bowen *et al.*, (1986). In the 21st century, data collected by ship-borne geophysics allowed widespread observations of seafloor moraines and grounding lines and that overturned the small-ice model (black lines show ice extent and retreat, modified from Clark *et al.*, 2012). Reconstructions returned to the large-ice model and confluence with the Scandinavian Ice Sheet. This retreat pattern, however, had much uncertainty about timing, which glacial stage was represented and rates of retreat; these uncertainties provided the motivation for BRITICE-CHRONO and this special issue. [Color figure can be viewed at wileyonlinelibrary.com]

geographic information system by the BRITICE project (Clark *et al.*, 2004, 2018; Evans *et al.*, 2004). Landforms such as moraines, meltwater channels, eskers and drumlins were used to define the ice sheet extent and the pattern of retreat shown in Fig. 1B. Coupled with the legacy of published geochonometric dates and their stratigraphic contexts the pattern was used to produce a palaeogeographic reconstuction of the shrinking ice sheet at seven timesteps between 27 and 15 ka BP (Clark *et al.*, 2012). In this work, however, it was noted that the dating constraints were too few in number and that the ad hoc collection of dating sites had tended to oversample some locations because of the availability of stratigraphic sections, for example at the coasts, whereas huge areas remained blank. Timing of ice margin fluctuations in the offshore sector was mostly unknown and with uncertainty even extending to questions of which glaciation, the last (Devensian, MIS 2; Weichselian) or earlier glaciations such as the Anglian (MIS 12) or Wolstonian (MIS 6)? With a well-defined pattern of retreat a smaller number of dates are required because the pattern naturally interpolates between point data. The BRITICE-CHRONO project therefore used the pattern as a sampling template for an ambitious dating programme to acquire new constraints (many hundreds of dates) on the timing and pace of ice retreat. Eight transects were devised to act as a framework to sample material for dating the retreat from the shelf edge until onshore (Fig. 2A).

Dating results

Terrestrial fieldwork and offshore geophysical and seabed coring investigations were used to locate targets for dating and to establish the stratigraphic and glaciological contexts of the samples. The project conducted >1500 person-days of field data collection including 18 000 line-kilometres of marine geophysical data, with sampling for dating spread across 914 sites (Fig. 2B) and comprising a total of ~15 tonnes of samples. A quality control exercise was undertaken on all reported 1231 legacy dates (Small *et al.* 2017a) and BRITICE-CHRONO generated 639 new ages: 336 radiocarbon, 156 optically stimulated luminescence (OSL) and 157 terrestrial cosmogenic nuclide (TCN) assessments. The new dates have tripled the number of usable dated sites, resulting in the British–Irish Ice Sheet now being the world's most well constrained retreating ice sheet (Fig. 3).

The special issue papers

This special issue mostly synthesises the results from the above dating campaign, reported in a series of transect papers that document the timing of ice marginal positions at the maximum extent, and as the ice margin withdrew. For each transect, the timing and pacing of ice retreat have been used to interpret the main controls that drove or modulated deglaciation.

An important aspect of the work was to have a common approach across all transects. Calibration of dates and protocols for their reporting and use across all radiocarbon and cosmogenic analyses was done in common. The two luminescence laboratories (Aberystwyth and Sheffield) had different methods and statistical protocols but acted in unison via some inter-laboratory comparisons. For the first time in reconstructing whole ice sheet-scale dynamics, a standardised Bayesian modelling approach was adopted (Ramsey, 2009; Buck and Meson, 2015) to build chronosequences of retreat (e.g. Chiverrell *et al.*, 2013) for all transects. This was applied to the existing legacy dates, filtered to include just those that contain ice extent in our time window (35 to 15 ka), and to our newly generated BRITICE-CHRONO geochronological database. This method provides a basis for quantitatively

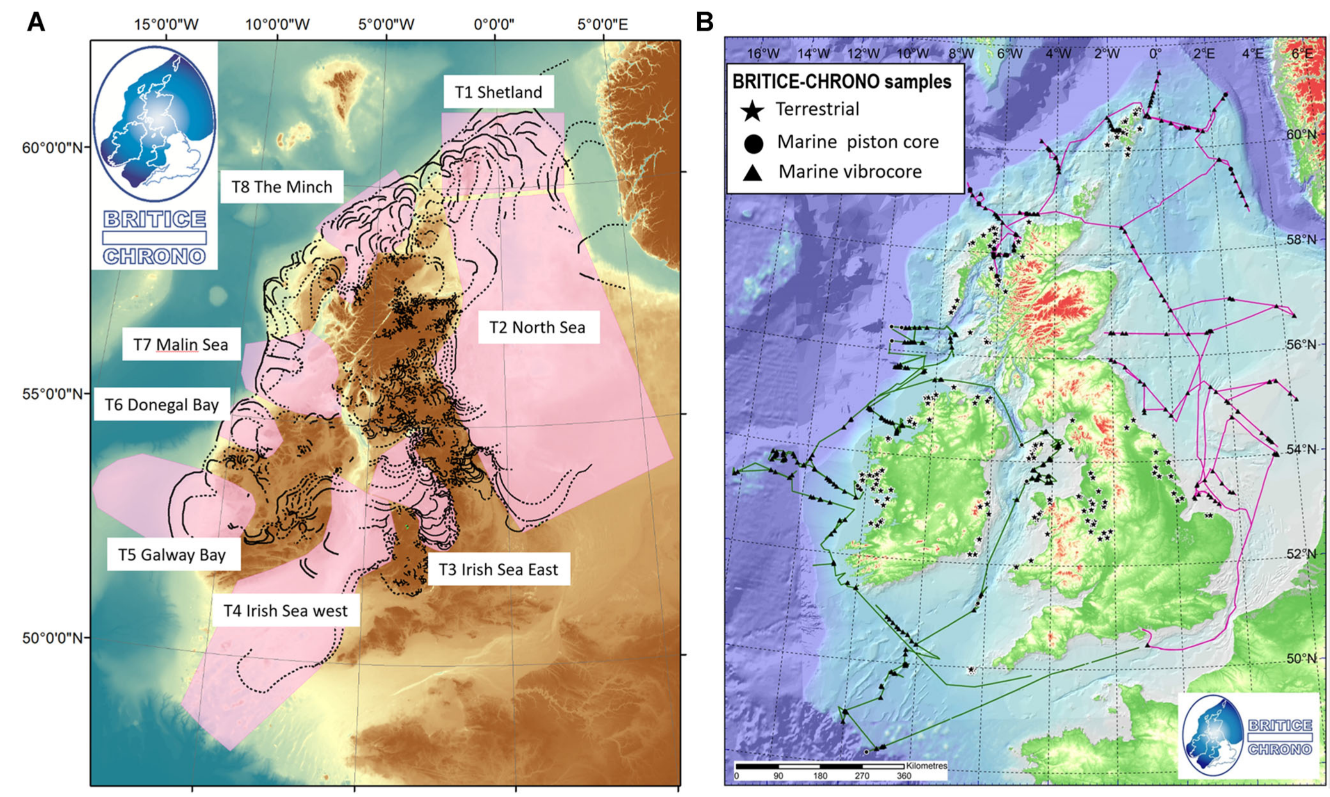

Figure 2. (A) The eight BRITICE-CHRONO transects used as sampling frameworks to collect material for dating. (B) Ship cruise tracks and location of piston and vibro core samples, from the two research cruises; JC106, 17 July to 24 August 2014; and JC123, 3 July to 3 August 2015. Also shown are the terrestrial sites sampled. [Color figure can be viewed at wileyonlinelibrary.com]

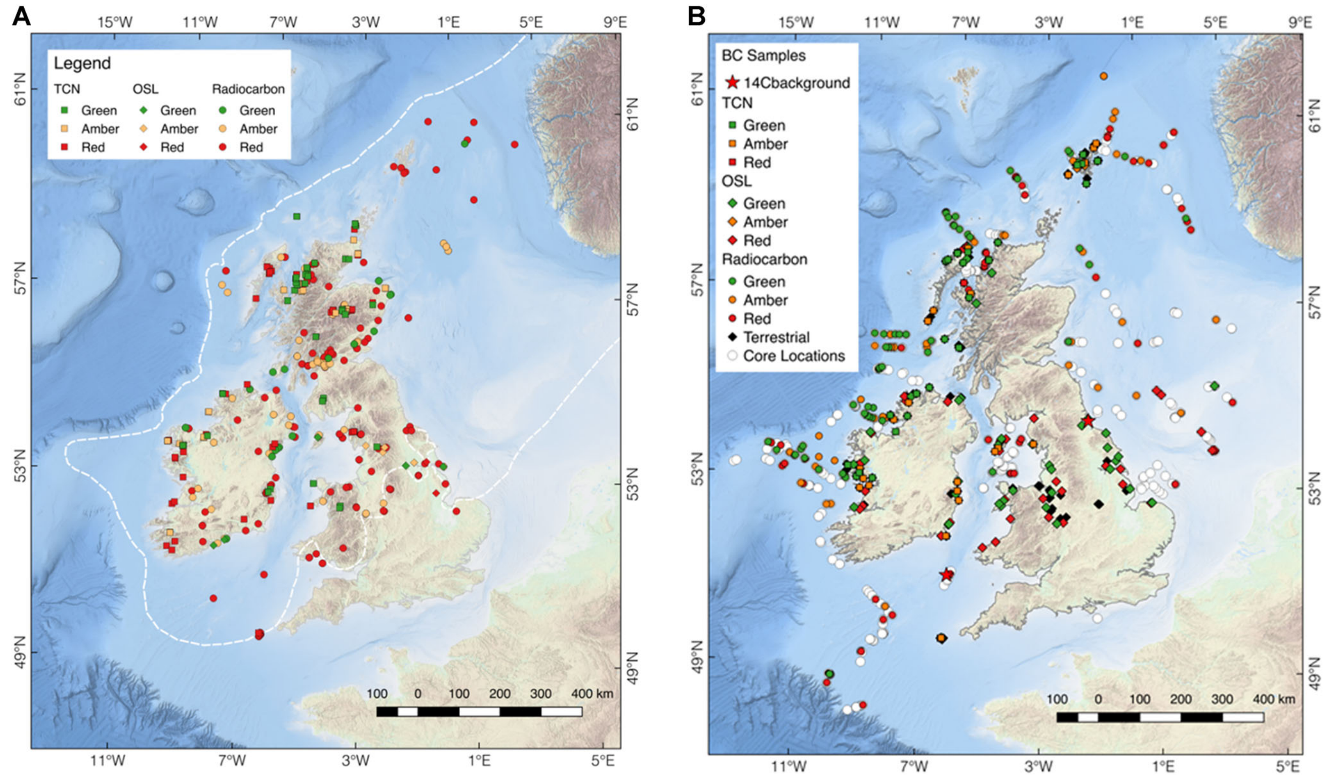

Figure 3. Dated sites that constrain ice sheet advance or retreat across the techniques of radiocarbon, optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclide (TCN). (A) Legacy dated sites (i.e. from the literature) categorised as green, amber or red, based on a quality control assessment from Small *et al.* (2017b). (B) The BRITICE-CHRONO (BC) sample locations. Those in colour yielded dates and were also assessed by the same quality control system. Background radiocarbon activity (^{14}C) was assessed from samples of infinite age from the Isles of Scilly. [Color figure can be viewed at wileyonlinelibrary.com]

identifying dates that may be suspect (outliers), and thereby reasonably ruled out. Importantly for our now large database, it also offered a method of integration across our three dating techniques and for incorporating marine reservoir uncertainties in radiocarbon dating. Its third advantage is that for dates that are closely spaced and with overlapping error bars, it permitted a narrowing of the probability age range, thereby increasing precision. To ensure consistency of calibration and a common method of reporting in all publications, all dates were held centrally in a BRITICE-CHRONO master spreadsheet and formally released to transect teams from this. This full database will be put in the public domain in a future paper.

On Shetland and for the surrounding area (Transect 1, Fig. 2A), Bradwell *et al.* (2021a) resolve a long-term uncertainty as to whether Shetland hosted its own ice cap that deflected wider ice sheet flow, or whether the islands were at times inundated with North Sea ice flowing across it. The stratigraphic and glaciological contexts of the dates are described and the new dates reported in full; 32 TCN exposure ages from glacially transported boulders, four OSL dates from terrestrial settings, and 34 radiocarbon dates from marine sediments closely associated with ice sheet deglaciation. A sector-wide reconstruction is provided. A large ice mass varying in size between local ice cap and wider ice sheet (distinct from that in mainland Scotland) is reconstructed over the Shetland–Orkney Platform. The authors report on the timing of ice margin fluctuations and reconstruct the coalescence and separation of Shetland and Scandinavian ice, and a rapid ice collapse event. Ice marginal adjustments and readvances, and the rapid collapse are explained in terms of changes in ice mass geometry, effects of coalescence, and marine-influenced processes.

The North Sea basin is difficult to reconstruct given its size and the influence of competing ice from Britain and Scandinavia. Transect 2 grew in size during the life of the project to cover almost the entire North Sea basin (Fig. 2A), and so it is no longer a simple transect. Bayesian modelling of the retreat sequence was therefore run along two transects: one running from Scotland to the east, and another to the southeast, capturing both the east-to-west and south-to-north axes of ice retreat. Six papers report the new dates, their stratigraphic and glaciological contexts, and reconstructions of glacial history for the various regions from the Yorkshire coast down to Norfolk (Evans *et al.*, 2017, 2018a,b; Bateman *et al.*, 2018) and for the offshore regions including Dogger Bank (Roberts *et al.*, 2018a,b). An interesting methodological advance was the extraction of core samples for OSL dating on the marine cruise for sites that were terrestrially exposed at the time of deposition. In the transect overview paper, Evans *et al.* (2021) report some new dates and use the two Bayesian transects to analyse a total of 68 BRITICE-CHRONO dates (53 OSL and 15 radiocarbon) and 37 legacy dates to build a reconstruction of ice margin extent and retreat. Key questions answered by the reconstruction include: how far did British ice extend? how, when and where did British and Scandinavian ice uncouple? to what extent did marine inundation of the northern North Sea trigger retreat? and what were the main controls on ice flow dynamics and the pattern of retreat?

Ice emanating from the Lake District and northern Irish Sea flowed southwards and then onshore, terminating 100 km further south at a margin as far as the English Midlands. This flow path forms the basis of Transect 3, being unusual in starting as ice shown to be grounded below sea level at that time, which then flowed up a reverse bed slope and onshore. Chiverrell *et al.* (2018) focus on the northern, mostly marine part of the transect. Eight new TCN exposure ages and 11 new OSL ages, along with recalibration of some legacy dates, permitted a reconstruction of deglaciation reconciling ice thinning on the Isle of Man and the Lake District, with withdrawal of the adjacent marine-calving ice margins. For the first time, an age constraint is placed on the Scottish Readvance in the region. Although primarily driven by climate warming, retreat rates were found to vary widely because of variations in the width of the calving margins and with bed topographic influences including stabilisation points on the Isle of Man. The southern and terrestrial part of the transect is reported by Chiverrell *et al.* (2021) who date the advance of ice to its maximum southern extent and decipher the retreat sequence which laid down a complex series of moraines and associated outwash deposits, fans and lake sediments. Retreat northwards across the reverse bed slope resulted in a time-transgressive back-stepping of ice-dammed lakes as the margin withdrew. Thirty-six new OSL dates (three of them using bleaching depth profiles in cobbles) combined with legacy OSL and radiocarbon dates were used in a Bayesian chronosequence of retreat that determined the timing of ice margins during deglaciation. The pace and timing of retreat, driven primarily by climate, was found to be mediated by ice piracy from the adjacent Irish Sea Ice Stream (Transect 4 in Fig. 2), local topographic factors and by the influence of the ice-dammed lakes. As Irish Sea ice withdrew, Welsh ice, in places, briefly expanded to fill the vacated space.

On Transect 4 (Irish Sea West), two publications used new dates to track variations in the speed of grounding line retreat as the Irish Sea Ice Stream withdrew through a narrowing and shallowing of its trough. On the west (Irish) bank of the ice stream, Small *et al.* (2018) used TCN exposure and OSL ages to build a retreat reconstruction providing estimates of the rate of retreat. They demonstrated that changes in trough cross-sectional geometry exerted a strong control on the pace of retreat, and suggested that pinning of the margin in this constriction led to dynamic thinning which preconditioned subsequent rapid retreat. On the east (Welsh) bank of the ice stream (Llŷn Peninsula), Smedley *et al.* (2017a) applied luminescence dates to a detailed geomorphological record of ice margins along the peninsula which yielded an exceptionally high-resolution chronology over 3000 years and 123 km of retreat. This revealed centennial-scale ice marginal oscillations at a time of stable climate, implying unforced grounding line variations arising from glaciological instabilities. Faster retreat rates coincided with greater trough depths and wider calving margins. Much further south, at the southernmost terrestrial extent, new dates acquired on the Isles of Scilly (Smedley *et al.*, 2017b) lay to rest a longstanding controversy as to whether last glacial ice reached this far south. It did. A further controversy is addressed (Lockhart *et al.*, 2018) regarding the megaridges that exist down the central trunk of the ice stream bed: are they glaciogenic bedforms or do they arise from tidal currents? They appear to be both; tidally induced sediments mantling a partially eroded glacial topography. In Scourse *et al.* (2019) the maximum extent of the Irish Sea Ice Stream is shown to be 150 km further south than hitherto reconstructed and right up to the continental shelf break in the Celtic Sea. The timing of advance to this position and retreat from it are constrained by new radiocarbon dates, and reasons for the ensuing rapid retreat are suggested.

In this special issue, Scourse *et al.* (2021) use 93 dates to build a combined T3 and T4 retreat sequence. They do this by building a single Bayesian chronosequence extending from southern Scotland to the Celtic Sea, combining data from T3 and T4, and using published Bayesian sequences that document ice retreat from the largely terrestrial retreat sequence from the English Midlands to the North Wales coast (Chiverrell *et al.*, this volume) and from the Irish Sea back into northeast Ireland (Chiverrell *et al.*, 2018). The reconstructed margin retreat extends for some 800 km from the shelf break in the Celtic Sea to southern Scotland and encompasses a time interval of 10 000 years. The pace of retreat varies widely, as noted earlier in relation to bed topography. A short-lived purging of mass propagating down the ice stream is suggested to enable the margin to advance as far as the shelf break. This non-steady ice stream behaviour (surging) explains both the over-extension of ice in the Celtic Sea and the early onset of retreat of ice in the adjacent Transect 3 catchment. Increased outflow along the ice stream is thought to have stolen ice from the accumulation area feeding ice to the English Midlands in an act of catchment piracy.

On Transect 5, Galway Bay, two publications (Peters *et al.*, 2016; Callard *et al.*, 2020) use new dates and seafloor mapping and stratigraphy to reconstruct the timing of maximum extent on this part of the continental shelf, west of Ireland, and track its retreat back across the shelf. Big surprises were evidence of grounded ice on the seafloor of the Porcupine Bank, indicating that ice extended further west than typically thought in earlier reconstructions, and the finding of a prolonged pause in retreat at a large grounding zone complex on the mid-shelf. Retreat from the inner shelf, and across the marine to terrestrial transition, is covered by Roberts *et al.* (2020), who plot ice margin withdrawal and link it to the terrestrial evidence of ice margins and flow patterns. The whole sequence of retreat from Porcupine Bank until tens of kilometres onshore is reconstructed using Bayesian modelling in the transect overview paper (Ó Cofaigh *et al.*, 2021) with the timing and pace of retreat plotted and analysed in terms of drivers. The analysis uses 86 new dates (53 radiocarbon, 29 TCN and 4 OSL). Onset of retreat is thought to be due to glacio-isostatically induced high relative sea levels promoting increased calving. Once half way across, the continental shelf retreat slowed, perhaps as a consequence of shallower water depths and exacerbated by sedimentary build-up of the grounding zone wedge here, further stabilising the margin. Further retreat was slow, becoming pinned on islands, until the margin finally back-stepped onshore.

On the shelf northwest of Ireland, the large Malin Sea Ice Stream drained ice to the shelf break and was confluent to the south with a large lobe of ice extending from Donegal Bay (Fig. 1B). Together, these flow paths fed sediment to the huge Donegal–Barra Fan. These areas are the subject of Transects 6 and 7, written up as an overview synthesis by Benetti *et al.*, (2021) and using 73 new dates (38 TCN, 18 radiocarbon and 17 OSL) in a Bayesian chronosquence of retreat. Timing of the maximum extents and retreat rates for both flowpaths are reported, with notable differences in retreat rates between the two. The reconstruction encompasses the geometry and timing of separation of Scottish and Irish ice, and then further retreat inland to an autonomous Donegal Ice Dome. The early onset of retreat from the shelf edge is explained by increasing water depths by ice-loading which promoted increased ice-calving. This reconstruction is underpinned by a series of publications on the offshore (Small *et al.*, 2017a; Arosio*et al.*, 2018; Callard *et al.*, 2018; Ó Cofaigh *et al.*, 2019; Tarlati *et al.*, 2020) and onshore regions (Wilson *et al.*, 2018).

Finally, in our clockwise tour of the ice sheet, the last transect, T8 – The Minch, covers a prominent ice stream that drained the northwestern sector of the Scottish Ice Sheet. In Bradwell *et al.*, (2019), seafloor evidence of grounding zone wedges along with new timing constraints demonstrated that retreat of the ice stream's grounding line was episodic and dynamically conditioned by the trough shape and bed strength imparted by the underlying geology. A step change in retreat rate, out of line with any external climate or sea level forcing, was interpreted to have arisen due to the loss of the ice stream's buttressing ice shelf. In the transect overview publication, Bradwell *et al.* (2021b) synthesise the 104 new age assessments along with their stratigraphic and geomorphological contexts to build a reconstruction of the timing of advance and retreat for the Minch Ice Stream, underpinned by Bayesian chronosquence modelling. The main finding is that the ice stream was prone to dynamic instability, hastening its demise and profoundly altering the wider ice sheet. They also set the ice stream in the wider context of ice marginal fluctuations on the adjacent Hebridean Islands and in mainland Scotland, and with a time frame extending as far back as around 40 ka BP. For example, a pre-Late Devensian (pre MIS 2) ice sheet advance to the island of Lewis is reconstructed based on new evidence, pointing out that the Minch Ice Stream likely operated in MIS 3.

From transect reconstructions to an ice-sheet-wide palaeoglaciology

The transect reconstructions presented in this special issue represent state of the art benchmark statements on what is currently known, with all chronological assessments quality controlled, on a common calibration scheme and using Bayesian modelling to deal with outliers. Referring back to the largely undated pattern of retreat in Fig. 1B, each of these transect reconstructions have dated the maximum last glacial ice extents on the continental shelf and plotted the timing and pace of withdrawal until the ice sheet back-stepped onto land. Ice retreat was not always monotonic and steady; rather, the speed of retreat was sometimes rapid (collapsing) and sometimes slow, and with prominent stillstands and oscillations or readvances. Each transect reconstruction has analysed within-transect variations in the pace of retreat and sought to establish the hierarchy of controls for these variations, be they climate, sea level, topographic or geological factors or glaciological instabilities. A later BRITICE-CHRONO paper, in preparation, will take a whole ice sheet approach and examine variations between transects to establish the extent to which different ice sheet sectors responded synchronously. Also in this paper will be a reconstruction of the whole ice sheet with palaeoglaciological maps (extent, velocity, thickness and flow geometry) at thousand year timesteps between 31 and 15 ka BP, and including changes in palaeotopography and sea level. The transect reconstructions in this special issue are the underpinning evidence for this ice-sheet-wide reconstruction, a large benefit being their common and directed system of analysis across the whole domain.

A data-rich environment to improve ice sheet and glacio-isostatic adjustment modelling

A motivation of BRITICE-CHRONO was to build information on ice sheet behaviour and retreat such that the British–Irish Ice Sheet becomes a useful data-rich environment to improve ice sheet modelling. Work on this is underway and with four different ice sheet models engaging with the new data. The Gowan plastic ICESHEET model (Gowan *et al.*, 2016) was fitted to the BRITICE-CHRONO and Scandinavian DATED (Hughes *et al.*, 2016) ice limits to provide mass loading estimates for use in northen hemispheric GIA modelling to better constrain relative sea level variations. These data have informed four of our transect papers (Ó Cofaigh *et al.*, 2021; Evans *et al.*, 2021; Scourse *et al.*, 2021; Benetti *et al.*, 2021), have been used in a GIA modelling investigation on fingerprinting of Meltwater Pulse 1A (Lin *et al.*, 2021), and used in a project forecasting 21st century sea levels around Britain and northwestern Europe, the UKCP18 Marine Report (Palmer *et al.*, 2018). The Parallel Ice Sheet Model (PISM, Winkelmann *et al.*, 2011) has been heavily used, in one case nudged towards fitting the BRITICE-CHRONO ice limits and in another case with ensemble runs independent of them and then tested against them. Publications are forthcoming from these experiments. Ice discharge fluxes derived from the PISM ice sheet modelling have been used to seed and drive modelling of iceberg trajectories (using the model of Levine and Bigg, 2008) in the North Atlantic. This was to address questions of how ice sheet mass balance relates to variations in ice-rafted debris (Wilton *et al.*, 2021). The higher-order adapative mesh model, BISICLES (Conford *et al.*, 2013), which permits fine-scale resolution grids near ice streams, for example, has been applied to address three important questions, all making direct comparisons with BRITICE-CHRONO data. Firstly it was used on Transect 8 (The Minch) to simulate and explore the role of marine ice sheet instability and ice shelf buttressing in regulating retreat (Gandy *et al.*, 2018 and Bradwell *et al.*, 2019). Secondly, at a whole-ice-sheet scale, Gandy *et al.* (2019) ran experiments to explore the extent to which the BISICLES model could correctly simulate the location and evolution of ice streams compared against the evidence. Finally, it has been run (Gandy *et al.*, 2021) to assesss the physical plausibility of an empirically reconstructed ice collapse event over the North Sea (Sejrup *et al.*, 2016; Evans *et al.*, 2021). This involved choosing between 70 ensemble experiments using quantitative model–data comparison tools finding the best match regarding ice flow directions, margin positions and satisfying the new deglacial age dates. Techniques were developed to impove the manner in which ice sheet model simulations can be quantitatively compared (scored) with the empirical evidence (Ely *et al.*, 2019, 2021). This included the new tool ATAT, an automated timing accordance tool for comparing ice sheet model output with geochronological data (Ely *et al.*, 2019) and which has been used in a number of the modelling studies noted above. An ice sheet model frequently used for the Antarctic Ice Sheet (Pollard and DeConto, 2009) was applied to the BRITICE-CHRONO ice limits to explore the climate drivers of retreat (Gasson *et al.*, 2019). To encourage further modelling on this now well constrained British–Irish Sheet Ice Sheet (31 to 15 ka BP), empirical data will be put in the public domain on ice margin positions and their timing, including empirically constrained modelled data on palaeotopographies, ice thickness (and volume), and ice flow geometry and velocity.

The BRITICE-CHRONO team

The project was led by CD Clark and the Steering Group of RC Chiverrell, D Fabel, RCA Hindmarsh, C Ó Cofaigh and JD Scourse. At the heart of the project and responsible for planning and conducting fieldwork, data collection and interpretation were the transect teams led by T Bradwell (T1 and T8), DJA Evans (T2), RC Chiverrell (T3), JD Scourse (T4), C Ó Cofaigh (T5) and S Benetti (T6 & 7). Major themes of activity were led by D Fabel (in charge of geochronology), C Ó Cofaigh (marine geology), RC Chiverrell (terrestrial geology), JD Scourse (ice-rafted debris) and RCA Hindmarsh (ice sheet modelling). Jenny Doole was the project administrator and the project employed seven postdoctoral researchers: M Burke, L Callard, JC Ely, A Medialdea, M Saher, D Small and R Smedley. A much longer list of project members and collaborators can be gleaned from the authorship list of the papers in this special issue.

The project has been a large and complex campaign and great thanks are here extended to the enthusiastic and hardworking researchers at the core of the project and extending to the many collaborators and friends of the team. Our activities benefitted widely from generous collaborations. Many people put in long hours in the field, on ships, in laboratories, in logistical planning and on analysis, far outstripping the rather notional 'investigator hours' that we are forced to document in research proposals! It has been truly amazing to witness such dedication and good humour throughout. New friendships have been built or strengthened, and aside from the scientific discoveries and advances, we are confident that a sure legacy is the building of a strong team of interconnected researchers primed to tackle further endeavours. This is quite something, especially in an often fragmented and competitive (and sometime fractious) community of Quaternary researchers. Thank you all, and especially to NERC for funding the project.

Our final thanks from BRITICE-CHRONO are extended to Professor Arjen Stroeven for taking on the role as Guest Editor of this the special issue. He is a highly accomplished palaeoglaciologist from different ice sheets and so was the perfect choice to act in judgement. Thank you for seeing it through with such skill. We are also grateful to the Chief Editors of *The Journal of Quaternary Science*, Professors Geoff Duller and then Neil Roberts for their work in making this special issue happen.

Acknowledgements. This work was supported by the UK Natural Environment Research Council consortium grant, BRITICE-CHRONO, NE/J009768/1; NERC Cosmogenic Isotope Analysis Facility (Allocations 9139.1013, 9155.1014) and NERC Radiocarbon Facility (Allocations 1722.0613, 1878.1014, 1976.1015); the SUERC AMS Laboratory, East Kilbride; and the BGS Marine Operations team (vibrocorer) and NOC/NMEP team (piston corer). We also thank the Master and crew of the *RRS James Cook* during cruises JC106 and JC123. This work has also benefitted from funding from the European Research Council under the European Union's Horizon 2020 research and innovation programme (PalGlac; Grant agreement No. 787263).

References

Arosio R, Crocket KC, Nowell GM *et al.* 2018. Weathering fluxes and sediment provenance on the SW Scottish shelf during the last deglaciation. *Marine Geology* **402**: 81–98

Bateman MD, Evans DJA, Roberts DH *et al.* 2018. The timing and consequences of the blockage of the Humber Gap by the last British-Irish Ice Sheet. *Boreas* **47**: 41–61.

Benetti *et al.* 2021. Reconstruction of the timing and pace of ice margin retreat across the Atlantic margin of the British-Irish ice sheet; Donegal Bay and Malin Sea. *Journal of Quaternary Science*.

Bradwell T, Small D, Fabel D *et al.* 2019. Ice-stream demise dynamically conditioned by trough shape and bed strength. *Science Advances* **5**: eaau1380.

Bradwell T, Small D, Fabel D *et al.* 2021a. Pattern, style and timing of British–Irish Ice Sheet retreat: Shetland and northern North Sea sector. *Journal of Quaternary Science*.

Bradwell T, Small, D & Fabel, D, *et al.* 2021b. Pattern, style and timing of British-Irish Ice Sheet advance and retreat over the last 45,000 years: evidence from NW Scotland and the adjacent continental shelf. *Journal of Quaternary Science*.

Bowen DQ, Rose J, McCabe AM *et al.* 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews* **5**: 299–340.

Buck CE, Meson B. 2015. On being a good Bayesian. *World Archaeology* **47**: 567–584.

Callard SL, Ó Cofaigh C, Benetti S *et al.* 2018. Extent and retreat history of the Barra Fan Ice Stream offshore western Scotland and northern Ireland during the last glaciation. *Quaternary Science Reviews* **201**: 280–302.

Callard SL, Ó Cofaigh C, Benetti S *et al.* 2020. Oscillating retreat of the last British-Irish Ice Sheet on the continental shelf offshore Galway Bay, western Ireland. *Marine Geology* **420**: 106087.

Chiverrell RC, Thrasher IM, Thomas GSP *et al.* 2013. Bayesian modelling the retreat of the Irish Sea Ice Stream. *Journal of Quaternary Science* **28**: 200–209.

Chiverrell RC, Smedley RK, Small D *et al.* 2018. Ice margin oscillations during deglaciation of the northern Irish Sea Basin. *Journal of Quaternary Science* **33**: 739–762.

Chiverrell RC, Thomas GSP, Burke M *et al.* 2021. The evolution of the terrestrial-terminating Irish Sea glacier during the last glaciation. *Journal of Quaternary Science*.

Clark CD, Hughes ALC, Greenwood SL *et al.* 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* **44** 112–146.

Clark CD, Ely JC, Greenwood SL *et al.* 2018. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet. *Boreas* **47**: 11–27.

Cornford SL, Martin DF, Graves DT *et al.* 2013. Adaptive mesh, finite volume modeling of marine ice sheets. *Journal of Computational Physics* **232**: 529–549.

Ely JC, Clark CD, Small D *et al.* 2019. ATAT 1.1, an Automated Timing Accordance Tool for comparing ice-sheet model output with geochronological data. *Geoscientific Model Development Discussions* **12**: 933–953.

Ely, Clark CD, Hindmarsh RCA *et al.* 2021. Recent progress on combining geomorphological and geochronological data with ice sheet modelling, demonstrated using the last British–Irish Ice Sheet. *Journal of Quaternary Science*.

Evans DJA, Bateman MD, Roberts DH *et al.* 2017. Glacial Lake Pickering: stratigraphy and chronology of a proglacial lake dammed by the North Sea Lobe of the British-Irish Ice Sheet. *Journal of Quaternary Science* **32**: 295–310.

Evans DJA, Roberts DH, Bateman MD *et al.* 2018a. A chronology for North Sea Lobe advance and recession on the Lincolnshire and Norfolk coasts during MIS 2 and 6. *Proceedings of the Geologists' Association* **130**: 523–540.

Evans DJA, Roberts DH, Bateman MD *et al.* 2018b. Sedimentation during Marine Isotope Stage 3 at the eastern margins of the Glacial Lake Humber basin, England. *Journal of Quaternary Science* **33**: 871–891.

Evans DJA, Roberts, DH, Bateman, MD *et al.* 2021. Retreat dynamics of the eastern sector of the British-Irish Ice Sheet during the last glaciation. *Journal of Quaternary Science*.

Gandy N, Gregoire LJ, Ely JC *et al.* 2018. Marine ice sheet instability and ice shelf buttressing of the Minch Ice Stream, northwest Scotland. *The Cryosphere* **12**: 3635–3651.

Gandy N, Gregoire LJ, Ely JC *et al.* 2019. Exploring the ingredients required to successfully model the placement, generation, and evolution of ice streams in the British-Irish Ice Sheet. *Quaternary Science Reviews* **223**: 105915.

Gandy N, Gregoire LJ, Ely JC *et al.* 2021. Collapse of the last Eurasian Ice Sheet in the North Sea modulated by combined processes of ice flow, surface melt, and marine ice sheet instabilities. *Journal of Geophysical Research: Earth Surface* **126**: e2020JF005755.

Gasson E, Clark CD, Ely J *et al.* 2019. Exploring drivers of retreat of the last British-Irish Ice Sheet: a numerical modelling study. *Geophysical Research Abstracts* **21**: EGU2019-16555.

Geikie J. 1894. *The Great Ice Age and Its Relation to the Antiquity of Man*. Edward Stanford: London.

Gowan EJ, Tregoning P, Purcell A *et al.* 2016. ICESHEET 1.0: a program to produce paleo-ice sheet reconstructions with minimal assumptions. *Geoscientific Model Development* **9**: 1673–1682.

Hughes ALC, Gyllencreutz R, Lohne ØS *et al.* 2016. The last Eurasian ice sheets-a chronological database and time-slice reconstruction, DATED-1. *Boreas* **45**: 1–45.

IPCC.2010 *Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Sea Level Rise and Ice Sheet Instabilities*. Stocker TF, Qin D, Plattner G-K *et al.* (eds). IPCC Working Group I Technical Support Unit, University of Bern: Bern.

Levine RC, Bigg GR. 2008. The sensitivity of the glacial ocean to Heinrich events from different sources, as modelled by a coupled atmosphere-iceberg-ocean model. *Paleoceanography* **23**: PA4213.

Lin Y, Hibbert F, Whitehouse P *et al*. (2021). A reconciled solution of Meltwater Pulse 1A sources using sea-level fingerprinting. *Nature Communications* **12**: 2015.

Lockhart EA, Scourse JD, Praeg D *et al*. 2018. A stratigraphic investigation of the Celtic Sea megaridges based on seismic and core data from the Irish-UK sectors. *Quaternay Science Reviews* **198**: 156–170.

Ó Cofaigh C, Weilbach K, Lloyd JM *et al*. 2019. Early deglaciation of the British-Irish Ice Sheet on the Atlantic shelf northwest of Ireland driven by glacioisostatic depression and high relative sea level. *Quaternary Science Reviews* **208**: 76–96.

Ó Cofaigh, Callard SL, Roberts *et al*. 2021. Timing and pace of ice-sheet withdrawal across the marine-terrestrial transition west of Ireland during the last glaciation. *Journal of Quaternary Science*.

Palmer M, Howard T, Tinker J *et al*. 2018. *UKCP18 Marine Report*. Retrieved from https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf

Peters JL, Benetti S, Dunlop P *et al*. 2016. Sedimentology and chronology of the advance and retreat of the last British-Irish Ice Sheet on the continental shelf west of Ireland. *Quaternary Science Reviews* **140**: 101–124.

Pollard D, DeConto RM. 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458**: 329–332.

Ramsey, CB. (2009). Bayesian Analysis of Radiocarbon Dates. *Radiocarbon*, **51**: 337–360.

Roberts DH, Evans DJA, Callard SL *et al*. 2018a. Ice marginal dynamics of the last British-Irish Ice Sheet in the southern North Sea: Ice limits, timing and the influence of the Dogger Bank. *Quaternary Science Reviews* **198**: 181–207.

Roberts DH, Grimoldi E, Callard L *et al*. 2018b. The mixed-bed glacial landform imprint of the North Sea Lobe in the western North Sea. *Earth Surface Processes and Landforms* **44**: 1233–1258.

Roberts DH, O'Cofaigh C, Ballantyne CK *et al*. 2020. The deglaciation of the western sector of the Irish Ice Sheet from the inner continental shelf to its terrestrial margin. *Boreas* **49**: 438–460.

Scourse J, Saher M, Van Landeghem KJJ *et al*. 2019. Advance and retreat of the marine-terminating Irish Sea Ice Stream into the Celtic Sea during the Last Glacial: Timing and maximum extent. *Marine Geology* **412**, 53–68.

Scourse JD, Chiverrell RC, Smedley RK *et al*. 2021. Maximum extent and readvance dynamics of the Irish Sea Ice Stream since the Last Glacial Maximum. *Journal of Quaternary Science*.

Sejrup HP, Clark CD, Hjelstuen BO. 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea. *Geology* **44**: 355–358.

Small D, Benetti S, Dove D *et al*. 2017a. Cosmogenic exposure age constraints on deglaciation and flow behaviour of a marine-based ice stream in western Scotland, 21–16 ka. *Quaternary Science Reviews* **167**: 30–46.

Small D, Clark CD, Chiverrell RC *et al*. 2017b. Devising quality assurance procedures for assessment of legacy geochronological data relating to deglaciation of the last British-Irish Ice Sheet. *Earth-Science Reviews* **164**: 232–250.

Small D, Smedley RK, Chiverrell RC *et al*. 2018. Trough geometry was a greater influence than climate-ocean forcing in regulating retreat of the marine-based Irish-Sea Ice Stream. *GSA Bulletin* **130**: 1981–1999.

Smedley RK, Chiverrell RC, Ballantyne CK *et al*. 2017a. Internal dynamics condition centennial-scale oscillations in marine-based ice-stream retreat. *Geology* **45**: 787–790.

Smedley RK, Scourse JD, Small D *et al*. 2017b. New age constraints for the limit of the British–Irish Ice Sheet on the Isles of Scilly. *Journal of Quaternary Science* **32**: 48–62.

Tarlati S, Benetti S, Callard SL *et al*. 2020. Final deglaciation of the Malin Sea through meltwater release and calving events. *Scottish Journal of Geology* **56**: 117–133.

Wilson P, Ballantyne CK, Benetti S *et al*. 2018. Deglaciation chronology of the Donegal Ice Centre, north-west Ireland. *Journal of Quaternary Science* **36**: 174.

Wilton DJ, Bigg, GR & Scourse, JD *et al*. 2021. Exploring the extent to which fluctuations in ice rafted debris reflect mass changes in the source ice sheet: a model-observation comparison using the last British-Irish Ice Sheet. *Journal of Quaternary Science*.

Winkelmann R, Martin MA, Haseloff M *et al*. 2011. The Potsdam Parallel Ice Sheet Model (PISM-PIK) - Part 1: Model description. *The Cryosphere* **5**: 715–726.

