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# The timing and magnitude of the British–Irish Ice Sheet between Marine Isotope Stages 5d and 2: implications for glacio-isostatic adjustment, high relative sea levels and 'giant erratic' emplacement

J. D. SCOURSE*
Department of Earth and Environmental Sciences, University of Exeter, Penryn Campus, Penryn, Cornwall, TR10 9FE, UK

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ABSTRACT: The extent, chronology and dynamics of the pre-Marine Isotope Stage (MIS) 2 last British–Irish Ice Sheet (BIIS) are not well known. Although the BRITICE-CHRONO Project has detailed the maximum extent and retreat phases of the last BIIS for the period after 30 ka and into the Last Glacial Maximum (LGM), the Project identified several pre-existing datasets and generated new data that implied glaciation pre-dating the LGM but which post-dated the Last Interglacial (Eemian; MIS5e); these data are reviewed here. There are no dated till units but are other indicators clearly indicative of glaciation: deep-sea ice-rafted detritus flux into the adjacent NE Atlantic, cosmogenic rock-exposure age dating from glaciated surfaces in Wales and the island of Lundy (Bristol Channel), and optically stimulated luminescence (OSL) ages of proximal glacifluvial sequences on the Isle of Lewis (Outer Hebrides) and in the Cheshire Basin. Taken together these indicate BIIS inception during MIS5d, growth into MIS4 and evidence for dynamic retreat–advance phases during MIS3. OSL evidence for high relative sea level indicated by raised beaches in southern Ireland during MIS4 and 3 at a time of lowered glacio-eustatic sea level indicates substantial glacial isostatic loading, explained by the early growth of the BIIS during the last cold stage. High relative sea level during MIS4 and 3 coincident with adjacent calving ice sheet margins provides an explanation for the rafted giant erratics found around the shores of southern Britain and Ireland.


KEYWORDS: British–Irish Ice Sheet; giant erratic; glacial isostatic adjustment; Marine Isotope Stages 3 and 4; relative sea level

## Introduction

> *'Dr Synge … now suggests that much of the Irish succession, including the Courtmacsherry beach, is "much younger than previously thought". Indeed, he seriously argues for a Middle Devensian age for the beach formerly ascribed to the Hoxnian!'*
>
> (Kidson et al., 1977)

There has long been speculation and discussion about the nature of the last British–Irish Ice Sheet (BIIS) prior to the Last Glacial Maximum (LGM). The recently completed BRITICE-CHRONO Project (Clark et al., 2022) has integrated terrestrial and marine geomorphological, stratigraphic and geochronological data constraining the maximum advance and retreat dynamics of the last BIIS between 31 and 15 ka, effectively reconstructing the Marine Isotope Stage (MIS) 2 inception of the BIIS prior to, and through, the LGM (Peltier et al., 2015) until final deglaciation following Greenland Stadial 1 (Rasmussen et al., 2014). In addition to generating new geochronological datasets, the Project undertook a rigorous quality control review of all legacy data with a bearing on BIIS dynamics (Small et al., 2017). In doing so, the Project highlighted datasets and observations that cannot be readily assimilated into the MIS2 time window, or that are anomalous against the weight of the independent evidence. Whilst some of these are isolated outliers and appear to relate to technical errors in, for example, geochronology, as indicated by the Bayesian statistical analyses of the datasets (Small et al., 2017), others, together, provide clues as the presence and behaviour of the ice sheet prior to MIS2 but following the Last Interglacial (MIS5e).

The suggestion that the BIIS was in existence prior to MIS2 during the last cold stage is not new (cf. Mitchell et al., 1973; Bowen et al., 1986; Bowen 1999; McCabe 1987; Gibbard et al., 2022). Based on cosmogenic rock-exposure age dating and aminostratigraphy of 'shelly' glacial deposits, and motivated by perceived mismatches with the advances of the Laurentide and Fennoscandian ice sheets, Bowen et al. (2002) argued that the LGM was merely the most recent manifestation of a BIIS that had an earlier inception, possibly through 'much of Devensian time' (p.89, *op. cit.*), that an earlier BIIS had greater ice extent than at the peak of the LGM and that the evidence for glacial deposits of this earlier advance had been misinterpreted as Late Devensian in age. This interpretation received criticism on the basis of the aminostratigraphic approach used to provide some of the evidence on which it was based (McCarroll, 2002), cosmogenic rock-exposure ages indicating extensive ice cover during MIS2 (Ballantyne, 2010) and the large body of published data indicating very limited ice extent around Scotland around 30 ka (Hall et al., 2003) prior to major advance during the LGM. Much of the latter discussion focused not on the existence of the BIIS earlier in the Devensian, but rather on the extent of BIIS immediately prior to the LGM advance and on the magnitude of that advance relative to an earlier advance during the last cold stage.

*Correspondence: J. D. Scourse, as above.
Email: j.scourse@exeter.ac.uk

Since 2002 a series of papers have been published that present data that pertain to possible growth and significant advance of the BIIS prior to MIS2. None of these papers present evidence for dated till units, unlike the unequivocal evidence for the MIS2/LGM ice sheet (Clark et al., 2022); neither can any of these papers, in isolation, can be taken as providing anything other than circumstantial support for a pre-Late Devensian BIIS. However, taken together, they provide a convincing a priori case for erecting an hypothesis that the BIIS first developed into a significant ice sheet much earlier in the last cold stage than at 31 ka. The purpose of this paper is to review this evidence and to promote this hypothesis for future testing.

## The timing and magnitude of the BIIS prior to MIS2

### *Evidence of glaciation*

#### *Ice-rafted debris in the deep ocean*

The presence of ice-rafted detritus (IRD) in deep-sea cores clearly indicates, to first order, that an ice sheet draining into the marine environment has a significant calving margin and is therefore of sufficient magnitude to extend to the coast from accumulation areas inland (Scourse et al., 2009). Therefore, the presence of IRD indicates the presence of ice bodies, or an ice sheet, of considerable magnitude. It is, however, critical that, when using IRD evidence from deep-ocean sediment cores to reconstruct ice sheet dynamics on adjacent landmasses, appropriate tools are used to fingerprint the IRD to specific ice streams. In the North Atlantic, for instance, icebergs calved from ice streams draining all ice sheets surrounding the ocean transported IRD to be deposited within the basin (Scourse et al., 2009; Wilton et al., 2021) during the last glacial cycle, including significant quantities of Laurentide Ice Sheet-sourced material deposited on the European margin (Grousset et al., 2000, 2001; Peck et al., 2007a; Scourse et al., 2009; Haapaniemi et al., 2010; Wilton et al., 2021). Dating pulses of IRD flux to the seabed without source fingerprinting thus risks conflating evidence from different ice streams, and proximity is no guide as to source. Although deep-sea IRD evidence was cited by Bowen et al. (2002) to support their interpretation of pre-LGM BIIS growth, this evidence preceded the main phase of research on the attribution of IRD to ice stream source in the North Atlantic.

Peck et al. (2007a), Scourse et al. (2009) and Hibbert et al. (2010) reviewed the multiple fingerprinting techniques (petrological/geochemical, geochronological, biostratigraphic) available to fingerprint IRD to source, and based on these, proposed the differentiation of BIIS-sourced IRD from IRD of far-field origin, notably Laurentide-sourced IRD, in deep-sea cores capturing IRD flux along the NE Atlantic European margin. Based on this analysis, Scourse et al. (2009) concluded that the bulk of the IRD records from cores along the continental margin west of Britain and Ireland are overwhelmingly dominated by the near-field BIIS rather than far-field sources. Only two of the core records reviewed by Scourse et al. (2009) extend beyond MIS2 into a significant part of MIS3, giant piston cores MD01-2461 from the Porcupine Seabight west of Ireland (Peck et al., 2006, 2007a, 2007b; Fig. 1) and MD95-2006 from the Barra Fan (Kroon et al., 2000; Knutz et al., 2001, 2002; Wilson et al., 2002; Austin et al., 2004; Fig. 1). Neither MD01-2461 nor MD95-2006 extend to the base of MIS3 (60 ka), but MD04-2822 (Hibbert et al., 2010) from the Rockall Trough (Fig. 1) – not reviewed in Scourse et al. (2009) – contains a continuous IRD record spanning the last 175 ka, and hence the whole of the last cold stage.

MD01-2461 contains a continuous record of MIS3 IRD flux from 58 ka. A very small flux, including differentiated BIIS IRD (Peck et al., 2007b), is registered between 57.5 and 52.5 ka, with a peak at 53 ka (Fig. 2). Values then drop almost below detection until 50 ka when a continuous flux is registered through to the MIS2 peak; there is a clear peak in IRD just after 40 ka and just preceding Heinrich (H) layer 4. H5 marks the start of a continuous IRD flux on this margin. The MIS3 flux is small compared to the MIS2 flux; the peak at 40 ka reaches ~100 000 IRD grains (>150 μm) $cm^{-2}$ $ka^{-1}$, whereas the peak at H2 reaches ~400 000 IRD grains (>150 μm) $cm^{-2}$ $ka^{-1}$. Using a combination of novel methods of non-invasive core analysis with conventional destructive sampling on nearby vibrocore CE18011_VC2 from the western side of the Porcupine Bank proximal to MD01-2461 (Fig. 1), O'Reilly et al. (2022) report continuous but fluctuating IRD flux between 37.5 ka (base of the core) to just prior to the base of an unconformity at 27 ka.

Only IRD concentration (not flux) data are available for MD95-2006. Sedimentation style changes in this core at ~30 ka from hemipelagic to turbiditic (Knutz et al., 2002; Wilson et al., 2002), but the lower hemipelagic section captures marked millennial-scale pulses of IRD concentration from 56.5 ka through to MIS2 (Wilson et al., 2002; Scourse et al., 2009). The longer adjacent MD04-2822 record from the Rockall Trough (Hibbert et al., 2010), which includes the differentiation of BIIS-sourced from far-field IRD, indicates initial IRD flux following the Last Interglacial around 90 ka. The flux remains low and fluctuating until 72 ka, coincident with a significant increase in the frequency abundance of the polar foram *Neogloboquadrina pachyderma* (sinistral). Hibbert (2011) speculates that the BIIS had reached a sufficient size at this time to deliver IRD to the core site across the shelf. IRD flux reaches a peak of 20 000 grains >150 μm $cm^{-2}$ $ka^{-1}$ at ~65 ka, falling into MIS3, another peak at ~42 ka and then declining until the start of the rise to the MIS2 peak at 30 ka; peak flux during MIS2 was 120 000 grains >150 μm $cm^{-2}$ $ka^{-1}$. This dataset represents the first clear offshore evidence for the presence of a significant BIIS during MIS4.

A lower resolution but more extended record of Middle and Late Pleistocene IRD from Deep Sea Drilling Site (DSDP) 548 on the Goban Spur (Fig. 1) has been interpreted to indicate an initial but unstable growth phase of BIIS during MIS5d, significant IRD flux at ~60 ka, coincident with H6 (MIS4), and lower but consistent IRD flux through MIS3 (Fabian et al., 2023).

Evidence from cores MD13-3438, MD95-2002, MD03-2692 and MD04-2845 from the Bay of Biscay (Toucanne et al., 2023; Fig. 1) indicates the presence of a BIIS during MIS 4. Although limited in extent, with no evidence for coalescence of the BIIS with the Fennoscandian Ice Sheet (FIS) in the North Sea as in MIS2 (Clark et al., 2022; Batchelor et al., 2019), they interpret geochemical fingerprinting data as indicating an active Irish Sea Ice Stream (ISIS) that retreated as early as ca. 68–65 ka.

#### *Lundy and Wales: cosmogenic rock-exposure age dating*

A coherent set of cosmogenic rock-exposure ages from ice-moulded bedrock and glacially transported boulders from the island of Lundy in the outer Bristol Channel (Fig. 1; Rolfe et al., 2012) proved anomalous in relation to the evidence deriving from the BRITICE-CHRONO Project from the Celtic Sea and Isles of Scilly (Smedley et al., 2017; Scourse et al., 2019, 2021; Fig. 1) in terms of both age and ice extent. Clearly glaciated (cf. Mitchell, 1968), the age of the glaciation impacting Lundy remained uncertain until nine paired samples yielded $^{26}Al/^{10}Be$ exposure ages between 31.4–48.8 ka ($^{10}Be$) and 31.7–60.0 ka ($^{26}Al$) that indicated early to mid-Devensian MIS3–4 glaciation; these ages have been recalculated to give

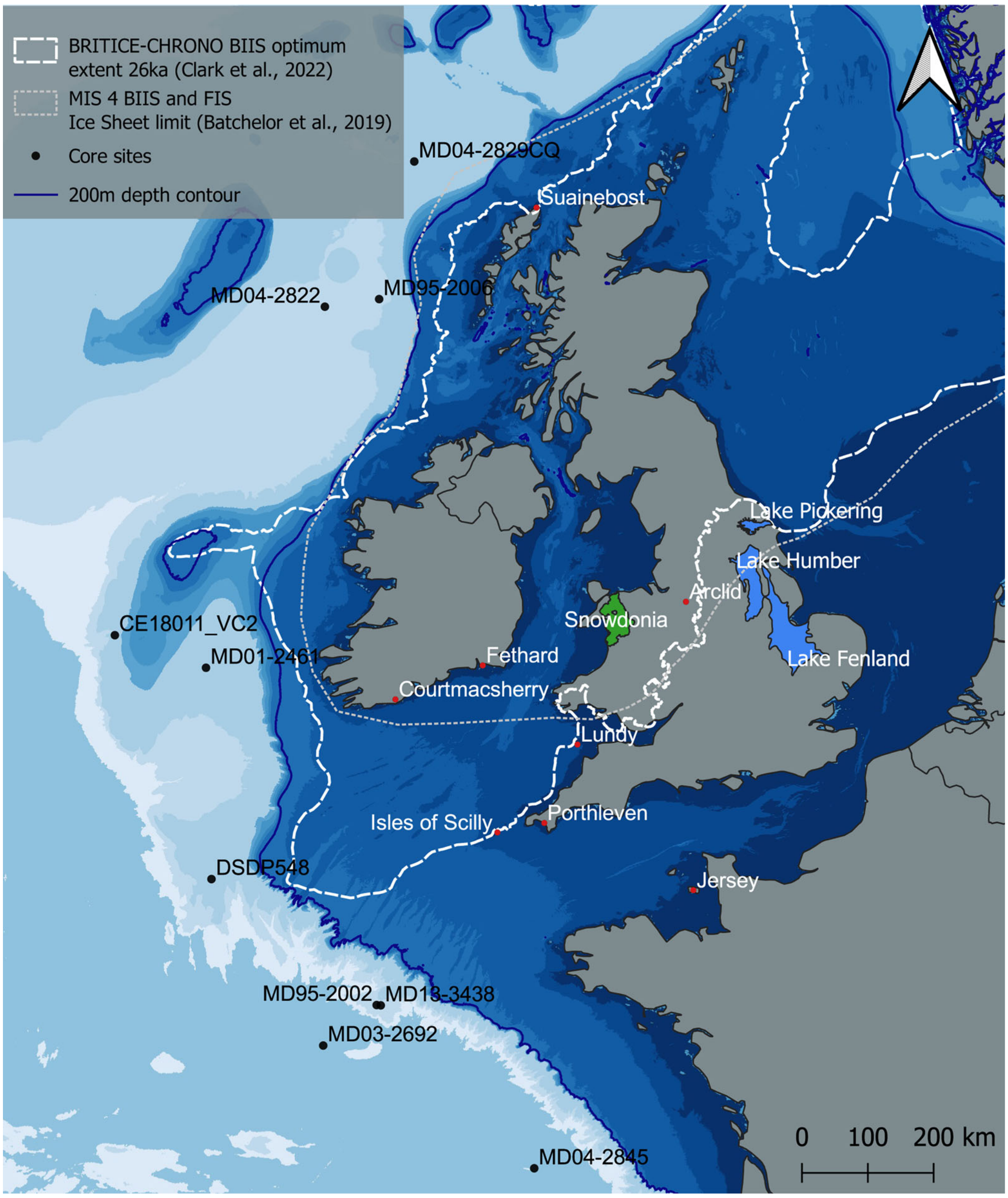


**Figure 1.** Location map. Cores MD01-2461 (Porcupine Seabight), MD95-2006 (Barra Fan), MD04-2822 (Rockall Trough), MD04-2829 (Rosemary Bank), CE18011_VC2 IRD (Porcupine Bank) and DSDP 548 (Goban Spur); Isles of Scilly, BRITICE-CHRONO MIS2 maximum ice limit, Lundy, Snowdon/Glyderau, Suianebost (Lewis), Glacial Lake Pickering, Glacial Lake Fenland, Courtmacsherry, Howe's Strand, Broad Strand, Fethard, Arclid and Porthleven. [Color figure can be viewed at wileyonlinelibrary.com]

exposure between ~33 and 52 ka (Gibbard et al., 2022), indicating ice cover significantly earlier than the glaciation of the Isles of Scilly at 25.5 ka (Smedley et al., 2017). Based on these data, Rolfe et al. (2012) suggest the build up of the BIIS during MIS4 with an oscillating ice margin between 60 and 40 ka, exposure of the island between 40 and 35 ka, followed by renewed growth into MIS2. Noting the apparently anomalous nature of these Lundy data, the interpretation that the exposed rock surfaces result from glaciation has been challenged by Carr et al. (2017) who prefer an interpretation based on rock surface lowering and exposure as a result of granite weathering. Clearly the evidence for the glaciation of Lundy is contested. Carr et al. (2017) admit that Lundy may have been glaciated at some stage and the island is located between the Gower Peninsula to the north and Fremington to the south (Scourse & Furze, 2001), both localities with well-developed glacigenic sequences. This context, and the emerging data for pre-MIS2 BIIS glaciation, put the Lundy data in a new and less anomalous light. If accepted, comparison of the Rolfe et al. (2012) interpretation with the BRITICE-CHRONO reconstruction (Clark et al., 2022) for MIS2 would place Lundy outside the maximum extent of the Late Devensian ice sheet as a non-overprinted glacial erosional landsystem generated during an earlier more extensive ice advance following the Last Interglacial.

Hughes et al. (2022) have published complementary evidence based on $^{10}$Be and $^{26}$Al cosmogenic rock exposure age data from the summits of Yr Wydda (Snowdon) and Y Glyderau, the highest mountains in Wales (Figs. 1 and 2). Here, 12 $^{10}$Be and five $^{26}$Al ages of 61–78 ka indicate that the summits of these mountains were not covered by the Welsh Ice Cap during MIS2 but that they were covered by ice during MIS4. They argue that this indicates thicker ice over Wales than in MIS2 and is consistent with an extensive BIIS that reached as far as across the continental shelf in the west during MIS4 as during MIS2.

### *Scotland and the Cheshire Basin: optically stimulated luminescence ages*

As part of the BRITICE-CHRONO Project, Bradwell et al. (2021) generated optically stimulated luminescence (OSL) ages

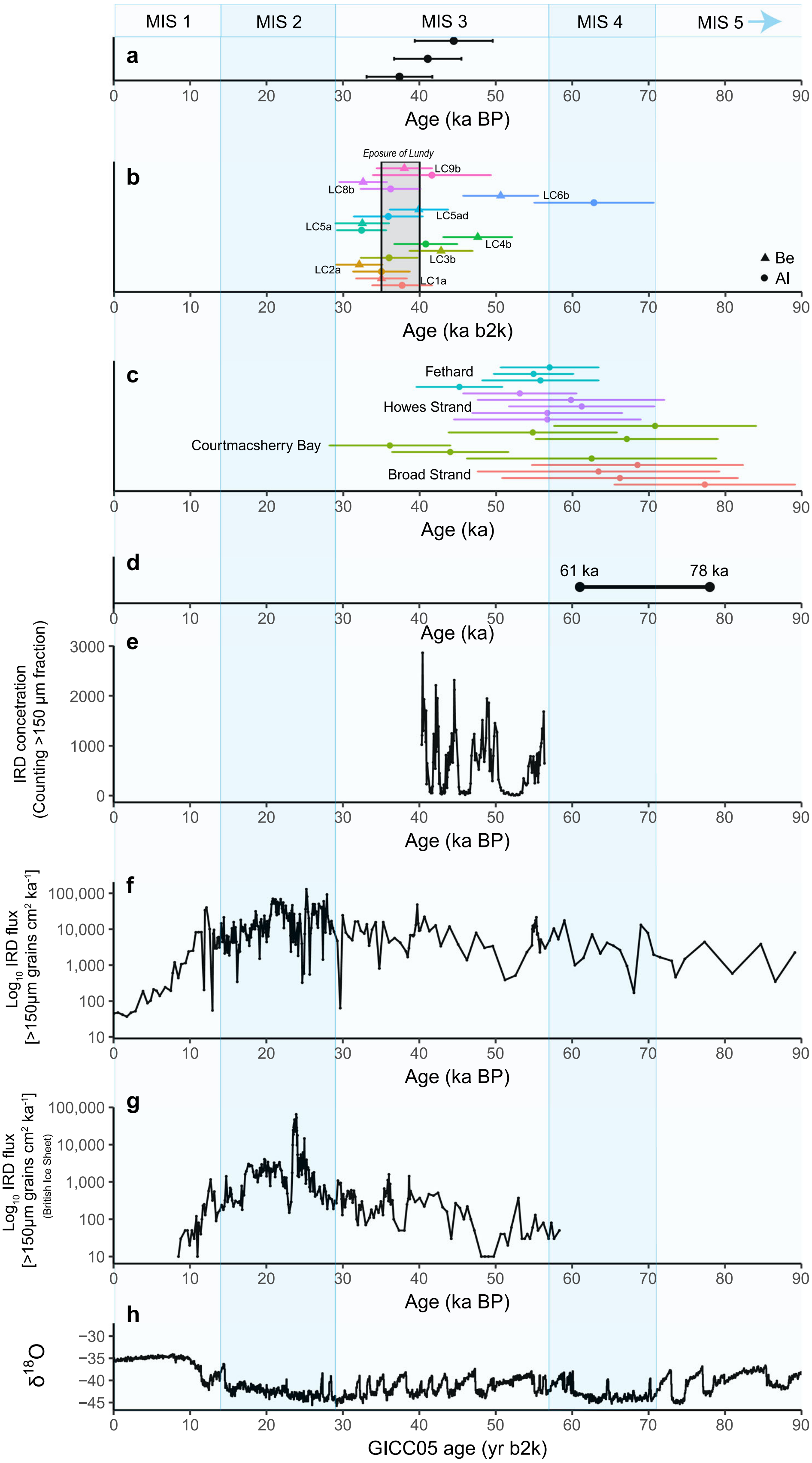


**Figure 2.** Integration of datasets relating to BIIS-related events in MIS3 and 4. (a) Suianebost (Isle of Lewis) proximal glacifluvial OSL ages (Bradwell et al., 2021: fig. 27); (b) Lundy cosmogenic rock-exposure ages (replotted from Rolfe et al., 2012: fig. 7); (c) Courtmacsherry raised beach OSL ages from Howes Strand, Courtmacsherry Bay and Broad Strand (replotted from Ó Cofaigh et al., 2012: fig. 13) and from Fethard (Gallagher et al., 2015); (d) range of cosmogenic rock exposure ages from Snowdonia (Hughes et al., 2022); (e) IRD concentration data from Barra Fan core MD95-2006 (Kroon et al., 2000; Knutz et al., 2001, 2002; Wilson et al., 2002; Austin et al., 2004); (f) IRD flux core MD04-2822 replotted from Hibbert et al. (2010: fig. 8) using the Channell et al. (2016) age model corrected for CALYPSO giant piston core stretching (oversampling, cf. Skinner and McCave, 2003) in the upper portion of the piston core (Hibbert, 2011); (g) IRD flux core MD01-2461 replotted from Peck et al. (2007b); and (h) Greenland ice core δ$^{18}$O (‰) plotted on GICC05 timescale (Rasmussen et al., 2014). In (a)–(c) the symbols represent OSL ages and their published associated errors. [Color figure can be viewed at wileyonlinelibrary.com]

of between 44 and 38 ka on deltaic outwash sands overlain and underlain by till at Suainebost Sands (also known as Traigh Chumail) on the Isles of Lewis in NW Scotland (Figs. 1 and 2). The weighted mean of three OSL measurements is 40.6 ± 2.6 ka and radiocarbon ages on the underlying till (Sutherland, 1986) suggest glaciation after ~40–41 ka during Greenland Stadial 9 (Fig. 2; Bradwell et al., 2021). Deposited in ice-marginal or ice-proximal shallow subaqueous settings, Bradwell et al. (2021) interpret this sequence to indicate a major ice sheet during MIS3 in the NW Highlands of Scotland and with an active Minch Ice Stream prior to ice retreat during the Tolsta Interstadial (Whittington & Hall, 2002) between 38 and 35 ka. These data support OSL ages reported from a glacigenic gravel fan at Howe of Byth, Buchan, NE Scotland (Fig. 1) of between 45 and 38 ka indicating ice-sheet advance as far as the Scottish east coast (Duller et al., 1995; Merritt et al., 2017, 2019).

In the Cheshire Basin, OSL dating of sequences at Arclid (Rex et al., 2023) has demonstrated that the Stockport Sand Formation was deposited in a fluvioglacial context, therefore ice-proximal, between 47 and 41 ka, indicating BIIS development in MIS3. Notably, however, the underlying Chelford Sand Formation, which spans 77–47 ka, has no glacigenic influence and must therefore indicate ice-free conditions.

### *North Sea Basin*

In the North Sea Basin, a number of investigations have reported evidence that might potentially relate to pre-MIS2 ice advances post-dating the Last Interglacial. These include the age of the timing of the early 70-m lake level at Glacial Lake Pickering (Evans et al., 2017; Fig. 1) and the age of glacially impounded Lake Fenland (Straw, 1979; Murton and Murton, 2012; Fig. 1). However, none of these observations is well constrained chronologically. Carr et al. (2006) report evidence for MIS4 glaciation of the North Sea but the authors themselves recognize the ambiguous nature of the evidence, and this is an interpretation challenged by new data from the Bay of Biscay (Toucanne et al., 2023).

## *Relative sea level and glacio-isostatic adjustment*

Because of the association between low interglacial global ice volumes and glacio-eustatic sea level, there has long been an assumption that the raised beaches in southern Britain and Ireland, and in the Channel Islands, found close to, or just above, present mean sea level outside the centres of glacio-isostatic uplift (e.g. Scotland), are interglacial in age (Bates et al., 2003). In response to a proposal that many of these raised beaches constitute Arctic shoreface facies (Eyles and McCabe, 1989), Scourse and Furze (2001) reviewed the evidence then available and concluded, on the basis of geochronological and palaeoecological data, that these sequences are of interglacial, warm stage, affinity, deposited during glacio-eustatic sea level highstands, at some sites with multiple highstands stacked laterally at the same or similar elevations (Fig. 3).

Dating of raised beach sands by OSL at multiple sites in southern Ireland where the Courtmacsherry Raised Beach is exposed provides convincing evidence that this sequence accumulated during a relative sea-level highstand, or series of highstands, during MIS4 and 3 (Ó Cofaigh et al., 2012; Gallagher et al., 2015). The working hypothesis hitherto has been that the Courtmacsherry Raised Beach is interglacial, and most probably Last Interglacial (MIS5e), in age (e.g. Warren, 1985). Ó Cofaigh et al. (2012) present 19 OSL ages from the Courtmacsherry Raised Beach at its type site at Courtmacsherry (ten measurements), at Howe's Strand (five measurements) and at Broadstrand (four measurements; Fig. 1). One result is considered an outlier; the other 18 measurements all yielded ages falling in MIS4 and 3, ranging from 77.3 ± 11.8 to 36.1 ± 7.9 ka (Fig. 2), clearly falsifying the Last Interglacial working hypothesis. A further four samples from the Courtmacsherry Raised Beach at Fethard, County Wexford (Fig. 1), yielded OSL ages between 57 ± 6 and 45 ± 6 ka (Gallagher et al., 2015; Fig. 2) supporting the MIS4–3 ages from the earlier study. A total of 22 OSL ages from the Courtmacsherry Raised Beach therefore indicate deposition during the last glacial stage prior to MIS 2. Both Ó Cofaigh et al. (2012) and Gallagher et al. (2015) conclude that to generate relative sea level (RSL) at an elevation close to modern mean sea level at this time implies significant glacio-isostatic depression and hence ice loading. Ó Cofaigh et al. (2012) highlight the presence of erratics within the raised beach sequences, as previously reported by Wright and Muff (1904), and the lack of any diagnostic palaeoecological content that would enable a palaeoclimatic assessment.

These OSL ages have stimulated renewed interest in dating the supposed interglacial raised beaches in southern Britain and the Channel Islands. Whilst a systematic OSL dating campaign remains to be undertaken, a suite of 25 recently published OSL ages from raised beaches in South Wales, Sussex, the Isle of Wight, Jersey, Normandy and Cornwall, including the Godrevy raised beach, the type-site of the Godrevy Sands and Gravels, previously reported as being MIS5e in age based on aminostratigraphic data (Bowen et al., 1985; James, 1995; Scourse, 1996), have generated data consistent with the Last Interglacial attribution (Barnett et al., 2023). The weighted mean for the Cornish data (seven measurements) is 119 ± 3 ka, the Devon result is 116 ± 9 ka, Jersey 121 ± 14 ka, Wales weighted mean (two measurements)

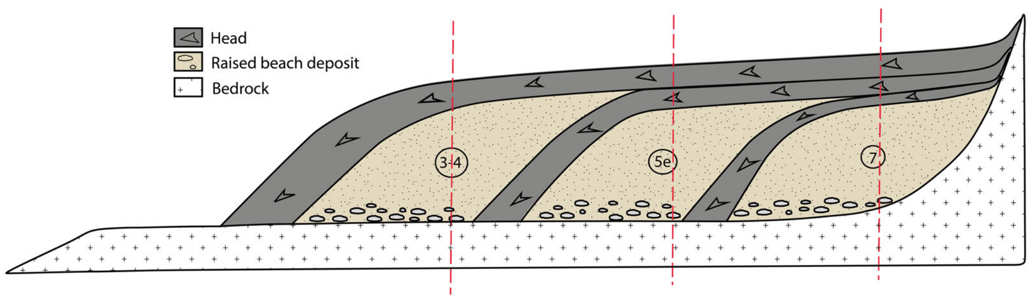


**Figure 3.** Cartoon of raised beach stratigraphy at or just above modern mean sea level exposed in cliff exposures around the coasts of southwest England, southern Ireland and south Wales. Sequences of raised beach sediments of different ages (shown as MIS3–4, 5e and 7) stacked laterally and separated by units of periglacial (solifluction) head. The vertical red dashed lines show hypothetical sections through this sequence at different positions, based on variations in local cliff recession, demonstrating that raised beaches of different ages are exposed at similar elevations underlying head at different locations. [Color figure can be viewed at wileyonlinelibrary.com]

121 ± 8 ka, Isle of Wight 115 ± 10 ka, Sussex (three measurements) ranging from 121 ± 12 to 124 ± 10 ka, and Normandy weighted mean (three measurements) 118 ± 7 ka. These ages support the earlier interpretation that these raised beaches are interglacial, and mostly Last Interglacial, in age and are clearly much older than the OSL ages from the Courtmacsherry Raised Beach. The only younger ages, reported as preliminary (Gilbert, 1996), from a raised beach sequence in Britain, are the OSL ages from Saunton in North Devon that range between 120 and 70 ka; notably these ages are from dune sands that are superposed to the celebrated pink granite 'giant' erratic (see fig. 8b in Scourse and Furze, 2001).

## Discussion

The contrast between the Courtmacsherry (MIS3–4) and mainland Britain and Channel Islands raised beach (MIS5e) OSL ages is striking. Though this chronological contrast might be interpreted as representing a steep glacial isostatic adjustment (GIA) gradient, with Ireland more heavily loaded than mainland Britain, it is more likely that beaches of different ages are laterally stacked against each other at or slightly separated in elevation in relation to modern mean sea level, apart from in localities where neotectonic uplift has generated clear vertical separation of different highstand phases such as eastern Isle of Wight (Preece et al., 1990) and the Sussex Coastal Plain (Bates et al., 2003, 2010; Westaway et al., 2006). Outside the ice limits of Pleistocene glaciation, these beaches of different age will in most cases be separated by spreads of periglacial solifluction deposits ('head'; Fig. 3). Just as the data indicate raised beaches of different interglacial highstand ages at a single site, for example at Portland (Davies and Keen, 1985), at Minchin Hole on the Gower Peninsula (Sutcliffe et al., 1987) and at Fistral Bay in Cornwall (Scourse, 1996), so it is likely that, outside areas of neotectonic uplift, interglacial raised beaches lie stratigraphically laterally juxtaposed with raised beaches of MIS4–3 age. The raised beaches that are exposed and accessible, and which have been sampled for OSL dating, are therefore contingent on accidents of preservation and the extent of recent coastal erosion (Fig. 3).

The MIS4–3 ages on the Courtmacsherry Raised Beach imply significant glacio-isostatic deflection (Ó Cofaigh et al., 2012; Gallagher et al., 2015) and constitute an independent dataset supporting the hypothesis of the early expansion of the BIIS prior to MIS2. The indirect a priori data on which this hypothesis is based are the offshore IRD records demonstrating, to first order, a calving margin delivering icebergs to the North Atlantic from as early as MIS5d (Hibbert et al., 2010) through into MIS3 (Scourse et al., 2009), the geochemical evidence from the Bay of Biscay (Toucanne et al., 2023), the rock-exposure age data from Lundy (Rolfe et al., 2012) and Wales (Hughes et al., 2022), and the OSL ages from ice-proximal deposits in Lewis (Bradwell et al., 2021; Fig. 2).

The magnitude of glacio-isostatic depression indicated by the Courtmacsherry Raised Beach OSL data can only have been generated by a significant proximal ice sheet. Based on far-field sea-level records and $\delta^{18}O$ proxy data, Gowan et al. (2021) generated a global ice sheet reconstruction for the past 80 000 years from which they derive a glacio-eustatic, ice-equivalent, sea level solution (their Fig. 2). This indicates that the most significant eustatic lowstand prior to the LGM was during MIS4, of ~ -80 m. In order to generate RSL close to present mean sea level, this implies a GIA deflection of ~80 m in southern Ireland along the unglaciated coast. Assessment of the magnitude of the ice sheet responsible for this deflection depends critically on location (proximity) and the timing and dynamics of ice sheet evolution, but to first order this deflection indicates adjacent ice sheet maximum thickness of approximately >400 m based on published GIA deflection data (Lambeck, 1996). The OSL evidence from Wales (Hughes et al., 2022) and Lundy (Rolfe et al., 2012) indicates this is probably a minimum estimate.

Though indirect evidence for BIIS inception and glaciation after MIS5d, these data, together, provide clues as to the timing, magnitude (extent and thickness) and dynamics of the pre-MIS2 BIIS. The indicative meaning of IRD—whether flux reflects ice sheet growth, or decay or both—has been raised by Scourse et al. (2009) without clear resolution, though comparison of the compiled IRD records of IRD flux from the NE Atlantic margin with directly dated till sheets and landforms from the continental shelf and adjacent landmasses indicates that flux is, to first order, a reflection of the magnitude of the calving margin. The BIIS IRD flux peaks recorded for MIS4–3 are much smaller than for the LGM (Fig. 2). From this it can be inferred that the pre-MIS2 BIIS, even at its peak, was much smaller in extent than the LGM ice sheet. Reactivation of trough mouth fans on the continental slope, which would have occurred if the ice sheet had extended to the shelf break, has not been reported for this phase (e.g. Bradwell & Stoker, 2015). This interpretation does not support Hughes et al.'s (2022) contention that the MIS4 ice sheet extended as far across the continental shelf as during MIS2. The evidence from the Bay of Biscay suggests no coalescence of the BIIS with the FID in the North Sea (Toucanne et al., 2023).

The evidence for the significant extent and duration of ice-free periods during MIS4–3, from mainland Britain in particular, is clear from accumulations of interstadial and cold climate, non-glacial, sequences. Rex et al. (2023) have reviewed the palaeoecological and palaeoclimatic evidence for the Wretton, Chelford, Brimpton, Cassington and Upton Warren interstadials, and recently described and defined the Arclid Interstadial, all of which characterize MIS4–3 ice-free conditions in central England. Rex et al. (2023) contend that the data from Arclid demonstrate ice-free conditions from 77 to 47 ka. Hall et al. (2003) reviewed the evidence for ice-free conditions in Scotland immediately prior to the MIS2 advance, and the Tolsta Interstadial (Whittington and Hall, 2002) represents ice-free conditions in NW Scotland between 38 and 32 ka (Bradwell et al., 2021). Whilst the glacial and relative sea-level (RSL) data reviewed here support the presence of a major BIIS during MIS4 and into early MIS3, the ice sheet cannot have extended to the English Midlands at this time.

Despite this restricted lateral extent, the magnitude of GIA deflection in Ireland, the evidence for thick ice across Snowdonia and the extension of the MIS4 ice sheet beyond the MIS2 limits locally in the Bristol Channel indicates, at its peak, a significant ice sheet. This can only be reconciled by concluding that the ice sheet must have had a steeper surface gradient compared with the demonstrably low surface gradients of the LGM BIIS, for example across the Celtic shelf (Scourse et al., 2019). The evidence for ice-free conditions in England, the RSL data from Ireland, the geochemical data for an active ISIS, and the OSL data from Wales and Lundy together suggest that during MIS4 and early MIS3, the centre of ice accumulation was further west than in MIS2, in particular over Ireland and the Irish Sea Basin. These interpretations remain as hypotheses for further testing and, if supported, require glaciological and palaeoclimatic explanation. The apparent paradox between a steeper and thicker yet less extensive ice sheet than in MIS2 might be explained by the build up of a largely cold-based ice sheet with limited basal sliding; only if persisting over a longer time would it transition to a dominantly warm-based system with basal sliding, extension and thinning, as apparently was the case in MIS2. This would imply that the MIS4–3 and MIS2 ice sheets were different because of their relative durations; the evidence for millennial-scale pulsing of the MIS3 ice sheet is strong whereas the MIS2 ice sheet existed over a prolonged period (C.Clark, pers. comm., 2023).

Scourse et al. (2009) demonstrated clear millennial-scale fluctuations in IRD flux at the Rosemary Bank (MD04-2829; Fig. 1), with troughs in IRD during Greenland Interstadials 5–8 (38–32 ka; Rasmussen et al., 2014), a period exactly coincident with the Tolsta Interstadial (38–32 ka). This apparent conflict is resolved if the source of the IRD at Rosemary Bank is the Barra Ice Stream, and not the Minch Ice Stream, as simulated by Wilton et al. (2021: fig. 6). This indicates a restricted but dynamically active BIIS in the western Highlands of Scotland with unglaciated terrain in NW Scotland at this time.

As recognized by Gibbard et al. (2022), the evidence for the BIIS prior to MIS2 during the last cold stage has been overprinted by the later extensive ice advance and much of the evidence removed by erosion. Only in Lundy is there evidence for the MIS4 glaciation extending beyond the MIS2 ice limit. Even here Rolfe et al. (2012) argue for a thin, cold-ice, cover during MIS2 but this was largely unerosive. It is likely, however, that bedforms mapped within the LGM ice limits relating to the earlier MIS4–3 glaciation remain preserved in places as palimpsest remnants. A renewed investigation of potential palimpsest bedforms in the light of the evidence reviewed here would be worthwhile, a proposal put forward by Bowen et al. (2002) albeit on the basis of different a priori evidence and interpretations.

The BRITICE-CHRONO ice sheet reconstruction has stimulated revised GIA simulations incorporating a new LGM BIIS ice sheet model (Bradley et al., 2023). These simulations assume growth of the ice sheet from a state of isostatic equilibrium following the Saalian (MIS6) glaciation prior to the Last Interglacial. The evidence reviewed here would suggest that it is unlikely that ice sheet inception at 31 ka was from a state of isostatic equilibrium and that GIA deflection was ongoing at the time of this inception. The significance of this for future GIA modelling of Britain and Ireland remains to be determined.

In 1977, Kidson stated:

> *'One of the intriguing unsolved problems…of the southern part of [the Irish Sea basin] … is the method of emplacement of the many giant erratics well outside any generally accepted glacial limits. Ice rafting has long been suggested as the agency for the distribution of these giant blocks along the English Channel coast from Cornwall to Sussex (Reid, 1892). The major difficulty in accepting such an explanation has, of course, been that of reconciling the idea of a sea-level close to that of the present, necessary for the emplacement of those erratics found high up on the contemporary shore platform, with glacial maxima' (p. 4).*

The timing of the emplacement of these erratics located from Baggy Point in North Devon to Sussex, exemplified by the 50-tonne garnetiferous microcline gneiss Giant's Erratic at Porthleven in Cornwall (Fig. 1; Mottershead, 1977; Campbell, 1998), has remained elusive (Bates et al., 2000, 2010; Westaway et al., 2006; Bone, 2022; Briant et al., 2022). The evidence reviewed here for high RSL during MIS4–3 coincident with a calving margin for the BIIS provides the combination of conditions envisaged by Reid (1892) and Prestwich (1892) required to transport and emplace these erratics by iceberg rafting. It has been assumed that the timing of ice rafting involved was during the Anglian glaciation (MIS12) or earlier (Kidson et al., 1977; Bone, 2022) but, given the evidence reviewed here, it is likely that at least some were emplaced during MIS4–3. There must have been earlier phases with analogous transitional conditions since erratic boulders occur within the older uplifted marine sequences along the Sussex coast (Bone, 2022). It should not therefore be assumed that MIS4–3 was the only potential window of emplacement (cf. Roberts and Pope, 2018). Nevertheless, the MIS3–4 data reviewed here provide the evidence base to support the process responsible envisaged in Reid's (1892) and Prestwich's (1892) original proposal. Recent attribution of the marginal marine Brown Bank Formation in the southern North Sea to MIS5a–4 lends further evidence to the interpretation of high RSL at this time (Waajen et al., 2024).

## Conclusion

Deep-sea IRD records from the NE Atlantic indicate the initiation of a BIIS with a calving margin as early as MIS5d with varying and sometimes substantial IRD flux throughout MIS4, reduced flux in MIS3 prior to a major increase into the LGM after 30 ka. Cosmogenic rock-exposure age dating of glaciated surfaces in Wales and Lundy indicate major glaciation of western upland Britain during MIS4, with exposure of these surfaces following this event and prior to the LGM. OSL dating of glacifluvial sequences on the Isle of Lewis and in the Cheshire Basin indicate the proximity of the BIIS during phases of MIS3, preceded and followed by ice-free conditions, testifying to dynamic advance and retreat episodes. OSL dating of raised beach sequences in southern Ireland, previously interpreted as interglacial, indicate high RSL during MIS4 and into MIS3. Given global eustatic sea level of about −80 m at this time, this indicates substantial glacial-isostatic loading. This loading can be explained by the evidence for a significant BIIS at this time. The evidence would be consistent with a major ice sheet over Ireland and western upland Britain, with steeper ice gradients than during the LGM and only very occasionally extending across the continental shelf. The inference of a high RSL during the early phases of the last cold stage offers an explanation of the rafted 'giant erratics' on the shore platforms of southern Britain and Ireland. Given the presence of a BIIS throughout much of the last cold stage prior to the LGM, it is probable that isostatic equilibrium had not been attained at the time of the onset of the major growth of the ice sheet at 30 ka; this has implications for GIA modelling of NW Europe.

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## Data availability statement

As a review article, the data that support the findings of this study are openly available in existing publications.

*Abbreviations.* BIIS, British–Irish Ice Sheet; FIS, Fennoscandian Ice Sheet; GIA, glacial isostatic adjustment; H, Heinrich; IRD, ice-rafted detritus; LGM, Last Glacial Maximum; MD, *Marion Dufresne*; MIS, Marine Isotope Stage; NERC, Natural Environment Research Council; OSL, optically stimulated luminescence; RSL, relative sea level.

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