Quaternary Science Reviews 140 (2016) 101–124

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Sedimentology and chronology of the advance and retreat of the last British-Irish Ice Sheet on the continental shelf west of Ireland

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A R T I C L E I N F O

Article history:
Received 12 December 2015
Received in revised form
9 March 2016
Accepted 11 March 2016
Available online 4 April 2016

Keywords:
British-Irish Ice Sheet
Retreat rate
Grounding zone wedge
Readvance
Radiocarbon
Sedimentology
Geomorphology
Ice shelf
Killard Point Stadial
Nahanagan (Younger Dryas) Stadial

A B S T R A C T

The last British-Irish Ice Sheet (BIIS) had extensive marine-terminating margins and was drained by multiple large ice streams and is thus a useful analogue for marine-based areas of modern ice sheets. However, despite recent advances from investigating the offshore record of the BIIS, the dynamic history of its marine margins, which would have been sensitive to external forcing(s), remain inadequately understood. This study is the first reconstruction of the retreat dynamics and chronology of the western, marine-terminating, margin of the last (Late Midlandian) BIIS. Analyses of shelf geomorphology and core sedimentology and chronology enable a reconstruction of the Late Midlandian history of the BIIS west of Ireland, from initial advance to final retreat onshore. Five AMS radiocarbon dates from marine cores constrain the timing of retreat and associated readvances during deglaciation. The BIIS advanced without streaming or surging, depositing a bed of highly consolidated subglacial traction till, and reached to within ~20 km of the shelf break by ~24,000 Cal BP. Ice margin retreat was likely preceded by thinning, grounding zone retreat and ice shelf formation on the outer shelf by ~22,000 Cal BP. This ice shelf persisted for ≤2500 years, while retreating at a minimum rate of ~24 m/yr and buttressing a >150-km long, 20-km wide, bathymetrically-controlled grounding zone. A large (~150 km long), arcuate, flat-topped grounding-zone wedge, termed here the Galway Lobe Grounding-Zone Wedge (GLGZW), was deposited below this ice shelf and records a significant stillstand in BIIS retreat. Geomorphic relationships indicate that the BIIS experienced continued thinning during its retreat across the shelf, which led to increased topographic influence on its flow dynamics following ice shelf break up and grounding zone retreat past the GLGZW. At this stage of retreat the western BIIS was comprised of several discrete, asynchronous lobes that underwent several readvances. Sedimentary evidence of dilatant till deposition suggests that the readvances may have been rapid and possibly associated with ice streaming or surging. The largest lobe extended offshore from Galway Bay and deposited the Galway Lobe Readvance Moraine by <18,500 Cal BP. Further to the north, an ice lobe readvanced at least 50 km offshore from Killary Harbour, possibly by ≤15,100 Cal BP. The existing chronology currently does not allow us to determine conclusively whether these readvances were a glaciodynamic (internally-driven) response of the ice sheet during deglaciation or were climatically-driven. Following the <18,500 Cal BP readvance, the Galway Lobe experienced accelerated eastward retreat at an estimated rate of ~113 m/yr.

1. Introduction

Marine-terminating sectors of large ice sheets are considered to be potentially inherently unstable and sensitive to climatic and ocean forcing(s) (Cook et al., 2005; Rignot et al., 2010; Glasser et al., 2011). Palaeo-glaciological data in the form of glacial geology and

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http://dx.doi.org/10.1016/j.quascirev.2016.03.012
0277-3791/

geomorphology is increasingly used to constrain numerical ice sheet models of present and future ice sheet change (e.g. Bentley et al., 2010; Robinson et al., 2011; Lecavalier et al., 2014). A logical step towards improved model accuracy will come from advancing our knowledge of previous ice sheet behaviour along marine-terminating margins. By developing a thorough understanding of ice sheet behaviour during the Pleistocene, from maximum extent to final retreat, palaeoglaciological assessments enable improved understanding of the controls on modern ice sheet dynamics and provide a means of testing the veracity of predictive models. The last British-Irish Ice Sheet (BIIS) is a potential analogue for marine-based ice sheet retreat because it consisted largely of marine-based (~300,000 km^3) ice with termini fed by ice streams and flanked by ice shelves (Clark et al., 2012a).

Ongoing efforts to reconstruct the size, dynamic behaviour and chronology of the last BIIS have recently focused on its marine-terminating margins on the continental shelves around Ireland and Britain (e.g. Bradwell et al., 2008; Ó Cofaigh et al., 2010; Peters et al., 2015). This extends from over a century of largely terrestrially-based research on the last BIIS (Clark et al., 2012a). In the south of Ireland, these efforts have extended the maximum southern position of the ice sheet (Fig. 1) hundreds of kilometres beyond previous reconstructions (Scourse et al., 1990; Ó Cofaigh and Evans, 2007; Praeg et al., 2015). Marine research north of Scotland provides sedimentary evidence for a coalescence of the BIIS with the Fennoscandian Ice Sheet (Sejrup et al., 1994) and recent analyses of bathymetric data provide evidence for grounded ice extending across the West Shetland Shelf (Bradwell et al., 2008). West of Ireland, geomorphic analyses of new bathymetric data provide compelling evidence for the extension of grounded ice to the shelf break west of the Malin Sea and Donegal Bay during the LGM and subsequent lobate readvances during deglaciation (Benetti et al., 2010; Dunlop et al., 2010; Ó Cofaigh et al., 2010; Fig. 1). Geomorphic, sedimentary and micropaleontological analyses show that the last BIIS reached the Porcupine Bank, west of Ireland (Fig. 1), and that its behaviour there was dynamic, fluctuating in extent and forming an ice shelf over the Slyne Trough (Peters et al., 2015). These offshore studies have led to a general shift in the prevailing consensus on BIIS maximum extent from a marine margin that did not extend far past the modern western Irish coastline (Bowen et al., 1986) to one that predominantly reached the edge of the continental shelf (Clark et al., 2012a; Fig. 1).

Despite recent advances in understanding of the marine-terminating sectors of the BIIS, a detailed reconstruction of their retreat behaviour that incorporates chronologically constrained marine sediment analyses has yet to be established. The aim of this study is to reconstruct the dynamic behaviour of the marine-terminating margin of the last BIS on the continental shelf west of Ireland and to provide chronological constraints on its retreat. This is achieved by presenting new sedimentary data from fourteen sediment cores (three were used in a previous study; Peters et al., 2015; Table 1) sampled from the continental shelf west of counties Mayo, Galway, Clare and Kerry, Ireland (Figs. 1 and 2). Using new sedimentological data and detailed geomorphic analyses of bathymetric data, we establish a regional stratigraphy for the western Irish continental shelf that records the marine-based advance, retreat and subsequent readvances of the last BIIS (Late Midlandian; marine isotope stage 2). Five new accelerator mass spectrometer (AMS) radiocarbon dates (Table 2) provide associated chronological control including calculating retreat rates during deglaciation of the shelf.

2. Methods

This study uses single beam bathymetric data compiled by the Norwegian-developed Olex (www.olex.no) sonar data management software to analyse the geomorphology of the continental shelf west of Ireland. The sonar data are a compilation of voluntarily-contributed, geolocated sonar measurements and, in areas of adequate coverage, produces a raster of 5-m resolution cells that typically convey vertical data with a resolution of 1 m (www.olex.no; Bradwell et al., 2008). The bathymetric data is presented as 2D hillshaded surfaces and a series of seafloor profiles to analyse and characterise the geomorphology of glacial landforms (Fig. 2).

Fourteen vibro-cores (see Table 1) were analysed, three of which were used by Peters et al. (2015; Table 1). Cores with the designation CE10008 (Table 1) were collected during the CE10008 research cruise conducted in 2010 with the *RV Celtic Explorer*; cores labelled CE14004 were collected during the "WICPro" (West Ireland Coring Program) research cruise conducted in 2014 with the *RV Celtic Explorer*. X-radiographs of the cores were developed, usually prior to splitting, using a CARESTREAM DRX Evolution system at Ulster University, Jordanstown. The x-radiographs reveal sedimentary structures and clast or dropstone presence in the cores that may be unidentifiable from visual inspection of the core section alone. Structures visible in the x-radiographs are displayed as sketches in the sediment logs and illustrative x-radiograph examples are also provided for most lithofacies. Sediment physical properties (wet bulk density and magnetic susceptibility) were measured prior to splitting using a GEOTEK© multi sensor core logger at the National University of Ireland, Maynooth. These data are displayed in the sediment logs along with mean values calculated for each core that allow intra-core trends to be seen and inter-core comparisons to be made. When large peaks (from individual clasts or section breaks) in the data skew the magnetic susceptibility mean, the data are smoothed by removing outlying values; the excluded measurements are highlighted in the logs. After the cores were split, sediment shear strength was measured using an Impact© shear vane, calibrated by MCC©, at intervals typically guided by lithofacies but generally ≤15 cm. Areas of high clast density or with clast-supported deposits were avoided while collecting shear strength measurements because clast contact with the vane generates spurious results.

The sediment cores were split and stored at 4 °C at Ulster University, Coleraine. Visual and x-radiograph inspections, aided by physical property analyses, identified twelve lithofacies from which 1-cm slabs were subsampled. Subsampling intervals were typically guided by lithofacies descriptions (cf. Kilfeather et al., 2011), usually with at least one subsample per lithofacies and often two, which enabled improved definition of contacts and intra-lithofacies changes. A sampling interval of ≤10 cm was maintained for most of core 10-40 (the longest core examined; Table 1). Subsamples were analysed for water content, grain size and relative abundance of *Elphidium excavatum* forma *clavatum* (Feyling-Hanssen, 1972). Lithic grains >1 mm were removed by dry sieving and reported as a percent by weight of the total sediment sample. The <1 mm fraction was analysed by laser granulometry using a MALVERN Mastersizer© at Trinity College, Dublin, at intervals guided by lithofacies descriptions. In cores 10-40 and 14-59 the number of lithic grains >1 mm were counted and are displayed as number/gram of sediment (cf. Grobe, 1987), which allows a comparison to the lithic grains >1 mm reported as mass percent.

Elphidium Clavatum specimens were identified using the morphological characteristics outlined by Feyling-Hanssen (1972). This species is used for this study because it is well-documented as an opportunistic, arctic-subarctic species that often dominates benthic foraminiferal populations in recently deglaciated marine environments (Hald et al., 1994). *E. clavatum* relative abundance is calculated as a percentage of the total number of well-preserved