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Geomorphological and seismostratigraphic evidence for multidirectional polyphase glaciation of the northern Celtic Sea

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ABSTRACT: High-resolution seismic and bathymetric data offshore southeast Ireland and LIDaR data in County Waterford are presented that partially overlap previous studies. The observed Quaternary stratigraphic succession offshore southeast Ireland (between Dungarvan and Kilmore Quay) records a sequence of depositional and erosional events that supports regional glacial models derived from nearby coastal sediment stratigraphies and landforms. A regionally widespread, acoustically massive facies interpreted as the 'Irish Sea Till' infills an uneven, channelized bedrock surface overlying irregular mounds and deposits in bedrock lows that are probably earlier Pleistocene diamicts. The till is truncated and overlain by a thin, stratified facies, suggesting the development of a regional palaeolake following ice recession of the Irish Sea Ice Stream. A north–south oriented seabed ridge to the north is interpreted as an esker, representing southward flowing subglacial drainage associated with a restricted ice sheet advance of the Irish Ice Sheet onto the Celtic Sea shelf. Onshore topographic data reveal streamlined bedforms that corroborate a southerly advance of ice onto the shelf across County Waterford. The combined evidence supports previous palaeoglaciological models. Significantly, for the first time, this study defines a southern limit for a Late Midlandian Irish Ice Sheet advance onto the Celtic Sea shelf. Copyright © 2020 John Wiley & Sons, Ltd.

KEYWORDS: British Irish Ice Sheet; ice limits; northern Celtic Sea; Quaternary stratigraphy; seismics

Introduction

Regional glacial models

Current models depict the Last Glacial Maximum (LGM, 26.5–19 ka BP) limits of the British Irish Ice Sheet (BIIS) extending beyond the present-day shores of Ireland (Clark *et al.*, 2009a; Greenwood and Clark, 2009a, 2009b). Models of Celtic Sea shelf glaciation have similarly been revised to reflect evidence of grounded ice as far south as the continental shelf edge during the LGM (Praeg *et al.*, 2015; Lockhart *et al.*, 2018; Scourse *et al.*, 2019). For most of the 20th century, however, the south coast of Ireland was considered to lie beyond LGM limits, the so-called Southern Irish End Moraine (SIEM; Charlesworth, 1928).

These models have been replaced, and the SIEM has been interpreted as a major recessional stage, based on recent studies of the evidence for ice flow patterns and phasing (Greenwood and Clark, 2009a, 2009b) and dated stratigraphies of onshore- and offshore-directed LGM ice flows across the southern Irish coastline (Ó Cofaigh and Evans, 2001a, 2007; Ó Cofaigh *et al.*, 2012). Glacigenic sediment sequences in the south coast areas of counties (Co.) Wexford and west Waterford (east of Cork Harbour) are associated with westward flow along and into the coastal fringe by ice margins associated with the Irish Sea Ice Stream (ISIS). Following that phase of glaciation, the tills and deglacial sediments deposited by the ISIS were overridden by offshore-directed ice flows, with the implication that this phase of glaciation resulted from the advance of the Irish Ice Sheet (IIS) across ground recently occupied by the ISIS during the advance of inland ice onto the continental shelf (Ó Cofaigh *et al.*, 2012). Further west, in west county Cork and Kerry, the IIS is modelled to comprise the radial flowlines of the 'The Kerry–Cork Ice Cap' (Wright, 1927; Farrington, 1965), which also extended some distance offshore and eastwards across east Cork and west Waterford before being directed southwards by southward-flowing inland ice (Ó Cofaigh and Evans, 2007).

Glacial sediments and landforms of south-east Ireland

Quaternary sediments exposed along the south coast of Ireland famously overlie a raised marine platform, 'The Courtmacsherry Platform' (Wright and Muff, 1904). The lowermost unit typically comprises subhorizontally bedded, openwork, densely packed gravel (McCabe and Ó Cofaigh, 1996), interpreted as a raised beach deposited during Marine Isotope Stage (MIS) 3–4 (Ó Cofaigh *et al.*, 2012). East of Cork Harbour, head deposits above these raised beach gravels are in turn capped by up to 10 m of a widespread massive, fine-grained, shelly diamict (traditionally called the 'Irish Sea Till') containing far travelled erratics of northern provenance (e.g. Ailsa Craig microgranite) and northward-deformed sediment inclusions of underlying head deposits (Ó Cofaigh and Evans, 2001b). Radiocarbon dating of reworked shells from the Irish Sea Till constrain the maximum age of this ice advance to 24 ka BP (MIS2), i.e. the LGM (Ó Cofaigh and Evans, 2007). The Irish Sea Till is overlain by

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stratified sediments (gravel, sand and mud), interpreted as glaciofluvial or glaciolacustrine deglacial deposits that were subsequently glacially tectonized (Ó Cofaigh and Evans, 2001b; Evans and Ó Cofaigh, 2003; Ó Cofaigh *et al.*, 2012).

At Ardmore Bay and Whiting Bay in west Waterford (Fig. 1), deposition of the intrasequence stratified sediments is suggested to have been in glaciolacustrine environments now above sea level; these lakes therefore either resulted from ice damming during ice recession south and eastwards, or by moraines along the ice margin that were eroded by a post-glacial marine transgression (Ó Cofaigh *et al.*, 2012). The determination of palaeocurrents indicates onshore- (northwards) directed sediment progradation of the stratified sediments with southward-directed tectonization (Ó Cofaigh and Evans, 2001b). The optically stimulated luminescence (OSL) dates on deglacial outwash from above the Irish Sea Till determined by Ó Cofaigh *et al.* (2012) suggest their formation between 24.4 and 21.6 ka BP. Given a ~24 ka age for the south coast 'Irish Sea Till' (Ó Cofaigh and Evans, 2007), ISIS withdrawal from the south coast by this time indicates that the duration of ISIS advance into and retreat from the Celtic Sea Shelf was rapid, possibly 300–600 m a^{-1}, and associated with a destabilized marine-based ice sheet margin (Small *et al.*, 2018) and rapid iceberg calving (Bigg *et al.*, 2010).

A series of papers on south coast sediment exposures (Ó Cofaigh and Evans, 2001a, b, 2007; Ó Cofaigh *et al.*, 2012) propose a reconstruction of glacial events in the region based on detailed sedimentology and age constraints on sequences provided by radiocarbon dating of reworked shells in 'Irish Sea Till' and the luminescence dating of overlying stratified sands. In summary, the model details LGM events in south-east and southern Ireland as (i) the onshore advance of a grounded ISIS across a narrow coastal fringe region of southern Ireland before 24 ka BP, depositing a fossiliferous glaciotectonite (an 'Irish Sea Till' equivalent); (ii) withdrawal of the ISIS from the coastal fringe and the deposition of stratified sand and silty sand sequences; and (iii) offshore directed flow of the IIS, forming subglacial sediments partially from the deformation of these stratified sediments, such as at Ardmore and Whiting Bays, west Waterford and Kilmore Quay, Co. Wexford.

It is not clear if the aforementioned offshore IIS flow in east Cork/west Waterford is correlative with the ice flow which forms the uppermost glacigenic diamict in Waterford coastal sections east of Dungarvan, such as the Blackhall Till at Bannow/Cullenstown (Fig. 2) (Culleton, 1978; Warren, 1992; Gallagher and Thorp, 1997; Gallagher *et al.*, 2004). In these tills, distinctly 'inland' lithologies including Leinster granite have indicated a generally N–S-oriented ice flow in east Co. Waterford. This ice flow is presumed to have extended offshore in these models, based also on striae evidence, but the identification of coastal stratigraphies as last glacial in age is questioned (McCabe, 1998). More recent landform mapping from digital elevation models indicates the occurrence of streamlined landforms crossing the Suir River valley north of Waterford City, interpreted as an LGM-aged north to south subglacial 'flowset' across east Co. Waterford (Greenwood and Clark, 2008, 2009a; GSI, 2016). However, the precise pattern and extent of LGM ice flow(s) in the region have not been made clear from previous work.

Glacial features offshore south-east Ireland

Previous studies of the region immediately offshore Waterford Harbour have included analysis of restricted multibeam bathymetric data and sub-bottom acoustic surveys (Fig. 1) (Gallagher and Thorp, 1997; Gallagher, 2002; Gallagher *et al.*, 2004). These studies established the presence of submerged glacigenic topography and sedimentary facies perched on the nearshore bedrock platform and a post-MIS 5e age for the deeply incised extension of the Barrow River channel, extending south beyond Waterford

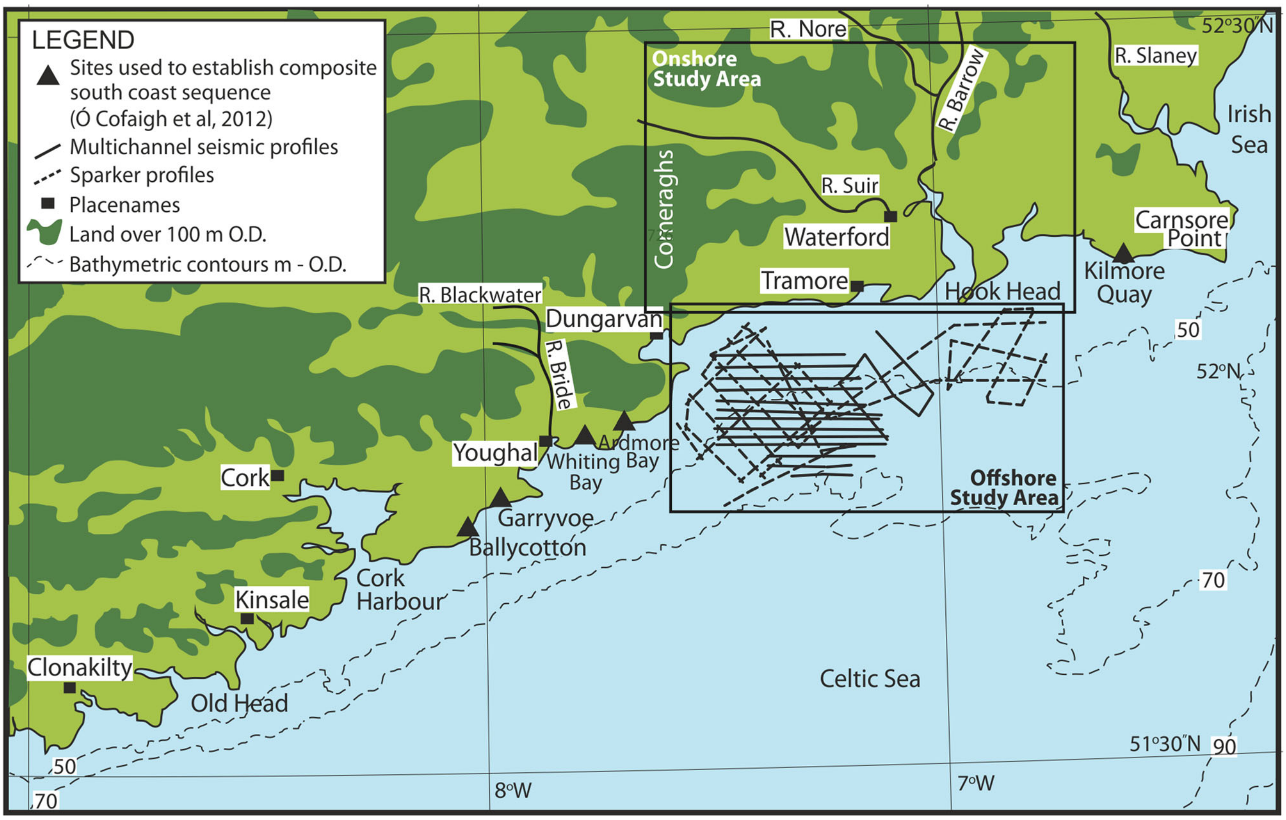


Figure 1. Map of onshore study site location in south-east Ireland and location of the offshore seismic dataset used in the study with key locations mentioned in the text. [Color figure can be viewed at wileyonlinelibrary.com]

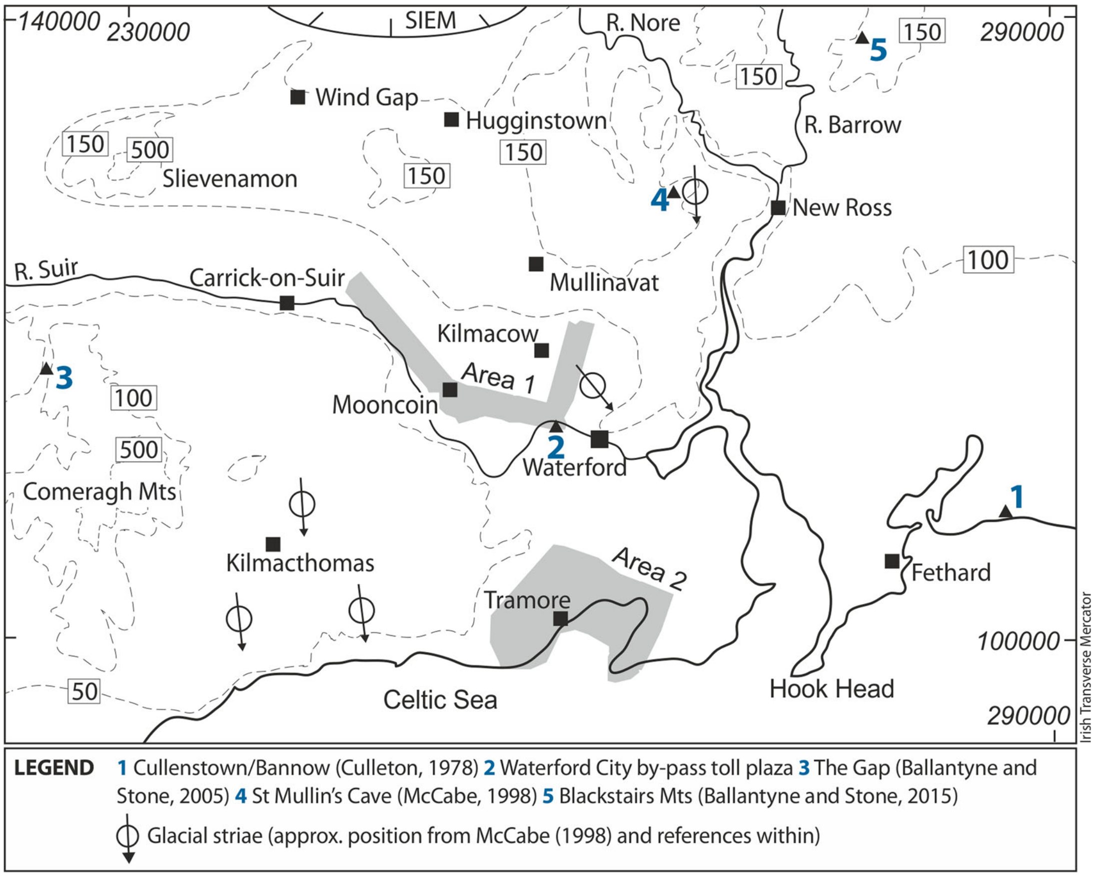


Figure 2. Location of the LIDaR data in Areas 1 and 2 and previously published indicators of glacial flow patterns in south-east Ireland with placements mentioned in the text. [Color figure can be viewed at wileyonlinelibrary.com]

Harbour. Cutting of the bedrock channel on the nearshore shelf was linked to greatly enhanced (glaciofluvial meltwater) discharges along Tertiary aged drainage routes (the Suir–Barrow river system) with down-cutting on the shelf coeval with a eustatic lowstand of up to −56 m O.D. (Malin Ordnance Datum). Gallagher *et al.* (2004) mapped a series of generally NNW–SSE-trending arcuate bathymetric ridges that cross the nearshore limestone bedrock platform to the south-west of Hook Head (Fig. 1). These were interpreted as glacial moraines associated with the withdrawal of ISIS ice margins eastward along the coastline.

This study

Our study area lies directly offshore of a key coastal transect containing multiple sites used to establish robust geochronologies of LGM ice flows in this region. South-east Ireland is an important location in establishing the glacial history of the last BIIS, as it straddles the proposed confluence of several ice sheet sector flow paths and has a well-exposed and documented series of coastal sediment sequences (Fig. 1). In this paper, we present new high-resolution seismic and bathymetric data for an area offshore southeast Ireland, and new digital elevation data for Co. Waterford including two LIDaR patches. From these data we produce a seismostratigraphy that is integrated into a regional LGM ice sheet event chronology.

Regional setting

The offshore study area is located in the north central Celtic Sea, on the shallow (<70 m water depth) shelf between Dungarvan and Kilmore Quay, south-east Ireland (Fig. 1). The area is situated ~80 km west of the junction of the Celtic Sea and Irish Sea at Carnsore Point. The present seabed topography in the area is generally smooth and flat, dominated by sheets of mobile sandy drifts (Fig. 3).

Inshore and north of the study site, to the east of the N–S-oriented upland spine of the Comeragh Mountains, Co. Waterford (726 m), several major rivers, including the rivers Suir and Barrow, drain generally southwards across undulating lowlands (Fig. 2). These rivers join at the head of the prominent Waterford Harbour estuary on the south coast. West of the Comeragh Mountains, into Counties Cork and Kerry, generally higher elevation E–W-oriented undulating hill and valley terrain is formed by large-scale Variscan-aged (Late Carboniferous onwards) folding. This has imparted a general E–W pattern to superficial drainage (e.g. the River Suir), except for the River Blackwater, which turns abruptly southwards west of Dungarvan and crosscuts the regional topography to merge with the River Bride and flow onto the coast at Youghal (Fig. 1).

Materials and methods

Bathymetric data

High-resolution multibeam echo sounder (MBES) surveying of the study area has been undertaken during the INFOMAR seabed mapping programme of the Geological Survey Ireland and Marine Institute in 2006 to the present. Publicly available multibeam bathymetric data have been processed and integrated into regional datasets by INFOMAR. The data are gridded at 10-m resolution for display and analysis in Fledermaus or ArcMap (Fig. 3).

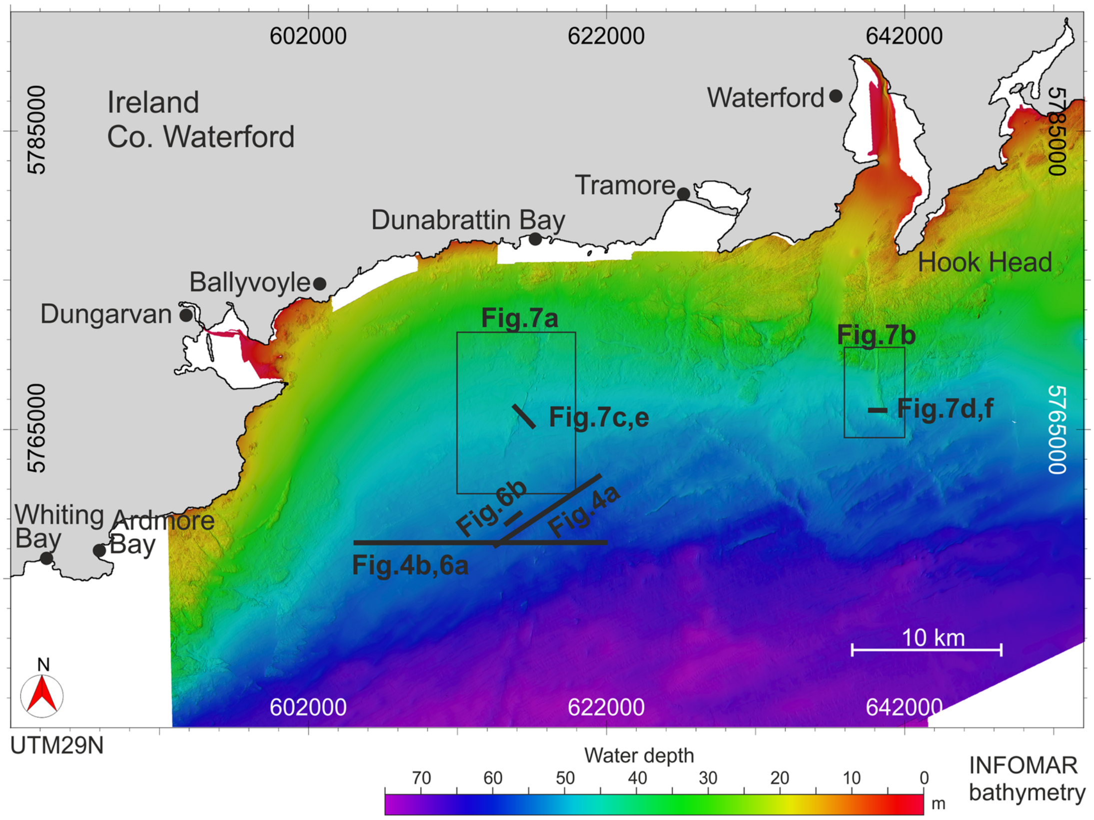


Figure 3. Bathymetric data for the offshore study area and location of multichannel seismic and Sparker profiles shown in the other figures. [Color figure can be viewed at wileyonlinelibrary.com]

Sparker data

A geophysical survey was carried out in September 2012 with the R/V *Celtic Voyager* (Dorschel *et al.*, 2012) and investigated the area between Dungarvan and the Saltee Islands in the Celtic Sea (Fig. 1). The survey was a collaborative research project undertaken by University College Cork and INFOMAR. Acoustic sub-bottom data were acquired using a Geo-Source 400 Sparker system. The system consists of a 1.5-kJ Geo-Pulse power supply and a 200-tips Geo-Spark pulse source. The data were recorded with a mini-streamer towed behind the ship and digitized with a CODA DA200 system. The data show a frequency bandwidth of 0.5–1.2 kHz and images the sub-seabed down to a depth of ~50 m below the seafloor. The Sparker dataset was processed using the CODA software package. Data processing included bandpass filtering and noise attenuation.

Multichannel seismic data

The site was revisited in March–April 2017 with the R/V *Celtic Voyager* (Wheeler *et al.*, 2017). Multichannel seismic data were acquired using the high-resolution seismic system of the University of Bremen, Germany. A 96-channel Teledyne streamer with an active length of ~220 m was used for acquisition and a Sercel micro G.I. gun was employed as the seismic source, using two chambers of 0.1 litre volume each. The frequency content of the data is between 80 and 500 Hz with a main frequency of ~200 Hz, yielding a vertical resolution of ~2–4 m. Data penetration into the sub-seafloor is usually several hundreds of metres in marine sediments, although probably due to the coarse grain size of seabed sediments and the shallow geological basement in the study area, signal penetration is generally lower than 200 m.

For multichannel seismic data processing, the Schlumberger Vista Seismic Data Processing software was used. The seismic data were stacked using CMP bins of 1 m size optimizing the lateral resolution of the data. A normal move-out correction was carried out using interactively picked velocity profiles. The data were filtered using bandpass and FK filters. In addition, special noise attenuation modules were utilized in Vista. Finally, the profiles were migrated using Finite Difference migration before being imported into the interpretation software. For display and interpretation of the seismo -acoustic data, we used the commercial software package Kingdom (IHS Markit). Data interpretation included horizon picking, surface gridding and calculations of bed thickness.

Supplementary acoustic data

High-frequency acoustic sub-bottom profiles produced during the INFOMAR programme and on a number of other cruises were also used in this study. The acoustic data were collected onboard the R/V *Celtic Voyager* with a hull-mounted 3.5-kHz sub-bottom profiler (Pinger, SES 5000 Probe), which provided sub-seafloor penetration of approximately 30 m at best in the study area. These profiles were digitally recorded in CODA format files, containing raw navigation and heave compensation strings, and later converted into SEG-Y files for integration with other datasets in the IHS 'Kingdom' software.

Onshore digital terrain data

Regional digital terrain elevation data from recently released shuttle SAR collections were used to generate hill-shaded digital terrain models (DTMs) for the south-east of Ireland at resolutions of approximately 10 m (ALOS PALSAR TRC data, NASA and University of Alaska, © JAXA/METI 2007). The data supersede existing regional-scale DTMs available for Ireland

and increase the visibility of landform geometries. The data are presented unstretched, and draped by a hill-shaded render from 270°N with an incident light elevation angle at 30°.

LIDaR data acquired during 2011 by the Office of Public Works and by the National Roads Authority for infrastructure planning (Waterford City bypass) were obtained for two areas of south-east Ireland: Area 1 in the Suir Valley and Area 2 around the town of Tramore (Fig. 2). For Area 1, the data were processed to remove survey artefacts, anthropogenic structures and vegetation cover (using the 'last return' of the laser survey signal), and the resulting point cloud data were used to interpolate DTM rasters for each area of a nominal 2-m horizontal and 0.25-m vertical resolution. For Area 2, the data had been previously processed in a similar manner by one of the authors (S. Davies), and was already in a 5-m horizontal resolution raster form.

The LiDaR rasters were relief-shaded using the Relief Visualisation Toolbox (RVT), a program originally developed for archaeological surveys (Kokalj *et al.*, 2011), and draped on a DTM of the same data. Relief-shaded terrain models were generated using the multi-directional shading tool, which composites relief-shade models lit from 16 different azimuths and removes the observation bias of unidirectional illumination. The incident light elevation angle was set at 20°, with a vertical exaggeration of ×3 applied to exaggerate low-amplitude features.

Results

Seismic stratigraphy

Seismo-acoustic data (multichannel seismic data, Sparker and Pinger) obtained from the nearshore area of the Celtic Sea between Dungarvan and Hook Head in southern Ireland (Figs 1, 3 and 4) reveal a number of reflectors and seismostratigraphic units that can be traced between profiles. The seismostratigraphic units were defined using the approach of Mitchum *et al.* (1977) involving seismic sequence and seismic facies analysis. The seismic units were identified based on their seismic reflection pattern, internal reflections and external shape. In total, prominent reflectors, R1–R6, bound six seismic units, the bedrock and SU1–SU5 (Table 1).

The R1 reflector defines the top of bedrock; it is an uneven, high-amplitude boundary that reaches up to the seafloor in places where bedrock outcrops, especially near the coastline (Fig. 4). The internal bedrock structure is generally poorly imaged and characterized by medium- to high-amplitude chaotic, discontinuous reflectors, although steeply dipping internal reflectors interpreted as bedding planes are occasionally seen. The topography of the R1 reflector becomes progressively deeper to the south [90–160 ms two-way travel time (TWT)], with two channels (~2000 m across and ~40 m deep) incised into the bedrock surface (blue and dark blue colours on Fig. 5). The confluence of the channels occurs at

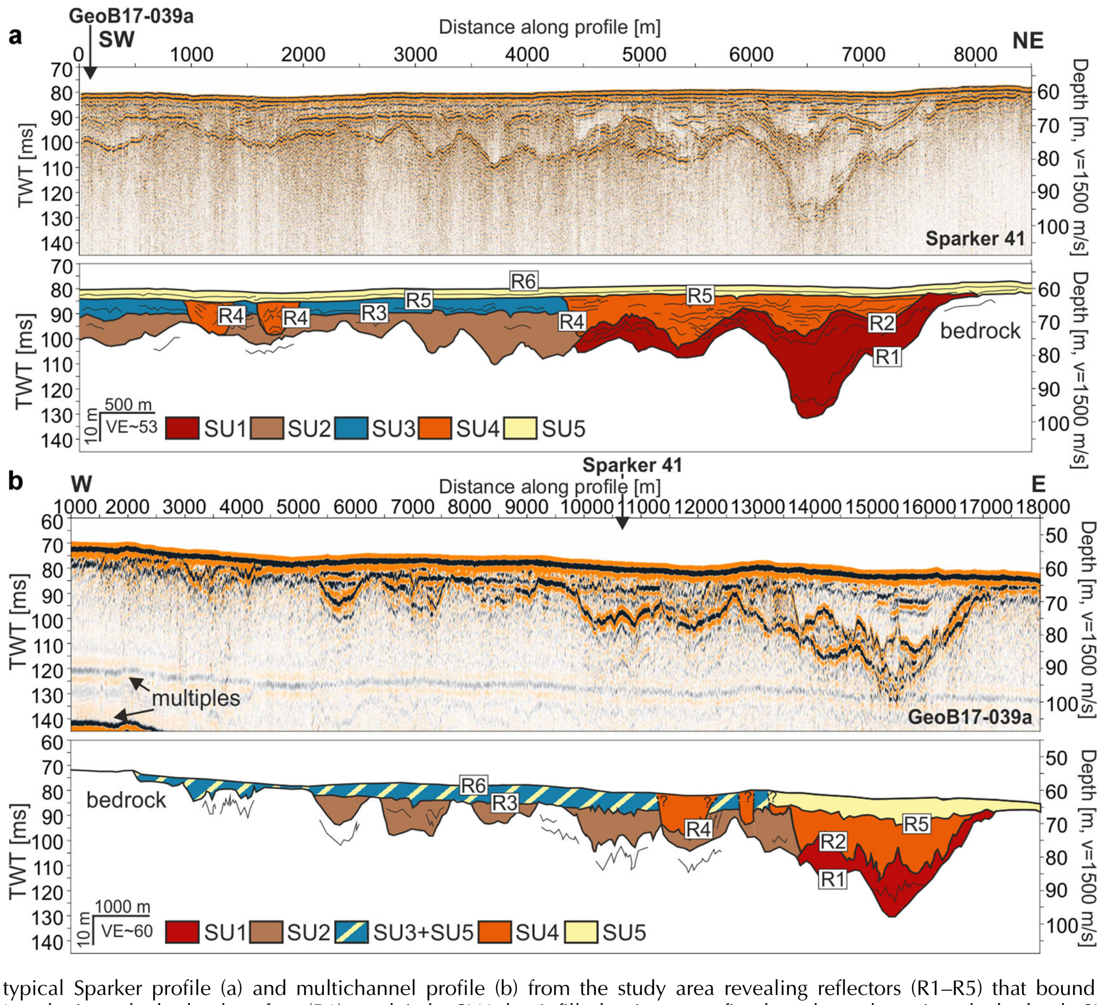
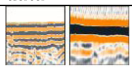
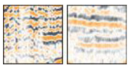
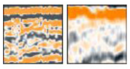
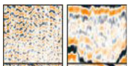
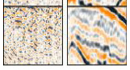
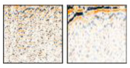


Figure 4. A typical Sparker profile (a) and multichannel profile (b) from the study area revealing reflectors (R1–R5) that bound seismic units (SU1–SU5). Note the irregular bedrock surface (R1) overlain by SU1 that infills, but is not confined to, channels cut into the bedrock. SU1 is thus also of uneven thickness. R3 defines the top of a flat-topped unit (SU2) that infills underlying topography and is itself overlain by unit SU3 (bounded at its top by R4). R5 marks the base of channels infilled by SU4 that incise into SU1, SU2 and SU3. The incisions of R5 often coincide with bedrock. The upper seismic unit (SU5) lies immediately below the seafloor in most of the area excluding areas where bedrock (R1) outcrops at seafloor.TWT, two-way travel time. [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. Seismic facies description of seismic units (SU1 to SU5) and related geological interpretations.

Seismic unit	Bounding reflectors	Seismic reflection pattern in Sparker, MCS data	Continuity	Amplitude	Reflection configuration	External shape	Geological Interpretation
SU5	R6/ seafloor		Continuous	High amplitude reflection interfering with the seafloor	Parallel	Layer	Marine sands and gravels
SU4	R4, R5		Mostly continuous	Low with a few high amplitude reflections	Parallel	Fill	Fluvio-glacial channels
SU3	R5		Discontinuous	Low with a few high amplitude reflections	Parallel, hummocky, transparent	Layer	Lacustrine, outwash plain or palaeo-soil
SU2	R3		Discontinuous	Low to medium	Contorted to chaotic	Fill	Glacial till
SU1	R2		Discontinuous	High	Variably stratified , hummocky in places	Irregular	Eroded remnant sedimentary unit
Bedrock	R1/top of bedrock		Discontinuous	Medium with interbedded high amplitude reflections	Contorted to chaotic	Irregular	Bedrock

the southern limit of the study area. At the western limit of Fig. 5 is a NNW–SSE-oriented alignment of pits in the bedrock (on average 40 m deep).

Seismic unit SU1 is preserved where the bedrock is deepest in the south of the area and is present in both the channels cut into the bedrock and in their vicinity in a series of isolated patches resting on the R1 bedrock surface (Fig. 4). The top of SU1 (R2) reveals an irregular topography with a relief of 10–13 m over a distance of 2–3 km (Fig. 4). Internally, SU1 is characterized by a variety of high-amplitude reflection patterns: in some places hummocky to chaotic, and in others clearly stratified.

Seismic unit SU2 stratigraphically overlies SU1 (where SU1 is present) and mainly rests on bedrock (R1) and infilling topographic lows in R2. The top of SU2 (R3) is relatively smooth, horizontal and of high amplitude, with the unit itself

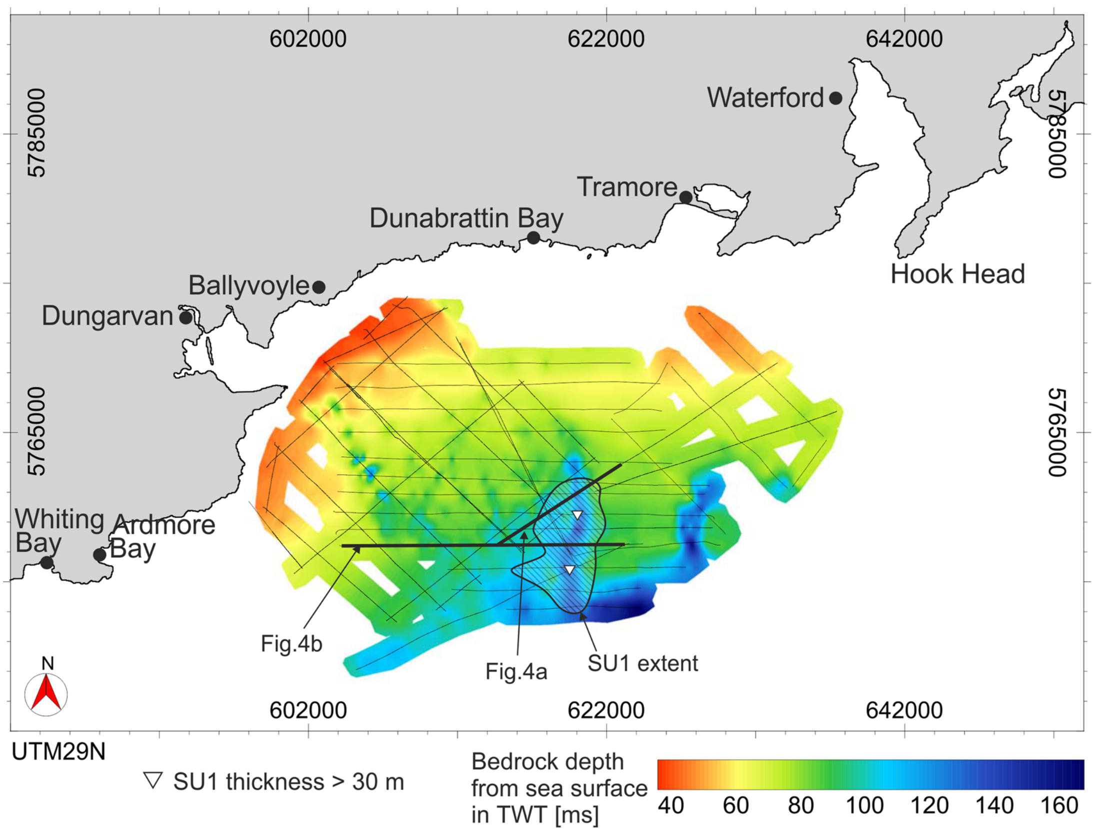


Figure 5. Bedrock surface topography based on the interpolated two-way travel time (TWT) to reflector R1. The spatial extent of SU1 (striped area) is shown as infilling, but not confined to, the channels in the bedrock surface. [Color figure can be viewed at wileyonlinelibrary.com]

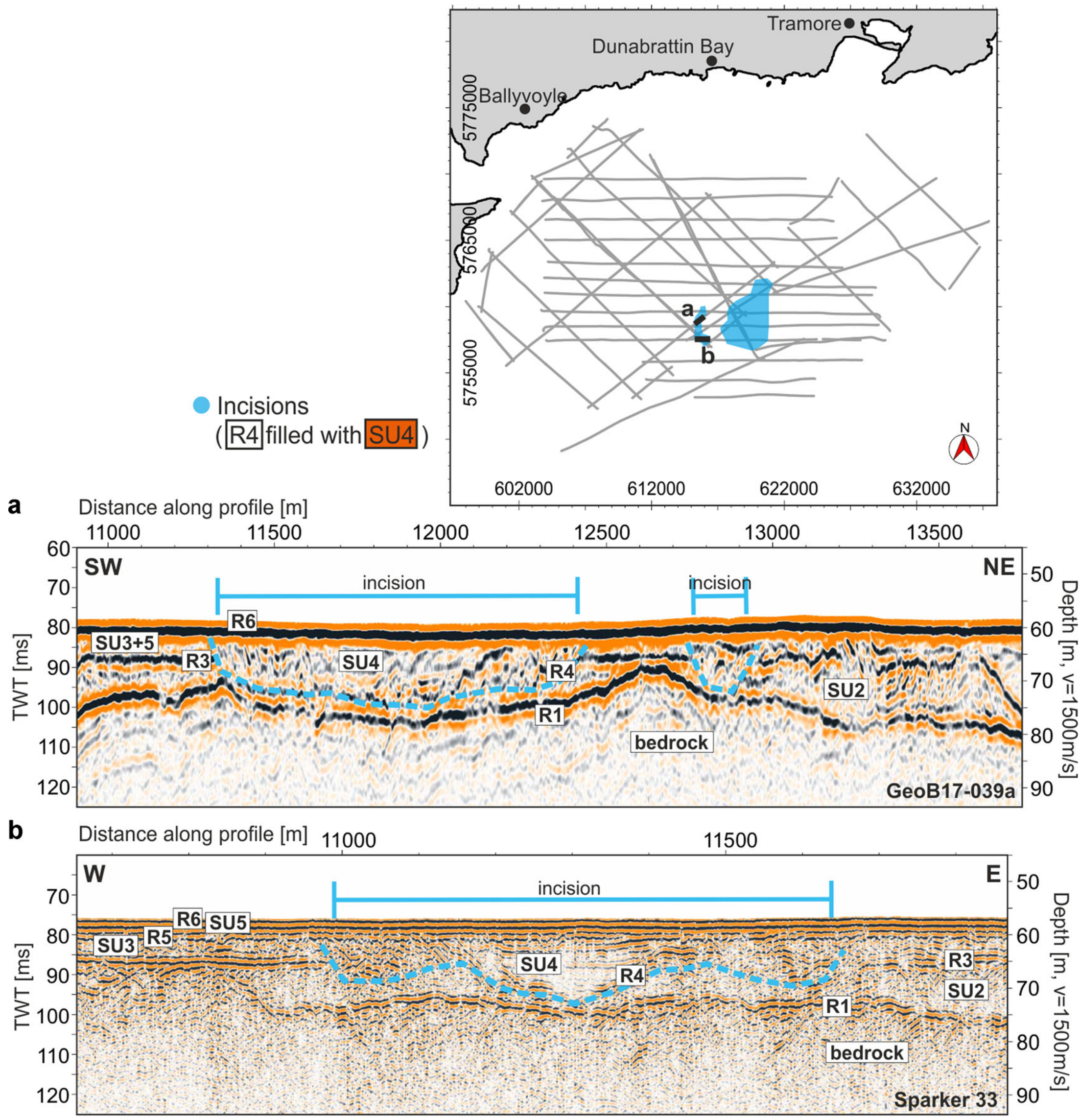


Figure 6. Two examples of channels filled by seismic unit SU4. (a) Multichannel seismic data showing a broad channel incision (R4) to bedrock (R1) truncating R3 that is a high-amplitude reflector forming the top of SU2. (b) Sparker data showing a smaller channel as truncating R3.TWT, two-way travel time. [Color figure can be viewed at wileyonlinelibrary.com]

being of variable thickness (up to 15 m thick). It is characterized by a low-amplitude reflection pattern that is hummocky and chaotic, but also acoustically transparent in places.

Seismic unit SU3 overlies SU2 (Fig. 4) and has a fairly consistent thickness of ~4 m. Sparker data reveal the internal reflection character to be relatively transparent, although stratification is evident in places. SU3 is bounded by both R4 and R5. R5 defines most of the unit, which is relatively flat, smooth and of a lower amplitude than the underlying R3 reflector.

SU1–SU3 are incised by a series of well-defined channels infilled by SU4, the bases of which are defined by R4 (Fig. 6). The channels vary in width from 300 to 1000 m and have a maximum depth of 12 m. They frequently reach the bedrock surface (R1) but do not erode into it. Internally, SU4 is characterized by a series of parallel, low-amplitude reflections, giving it an almost transparent appearance.

SU5 is a relatively thin layer at the seabed covering most of the area except where bedrock outcrops nearer to the coast to the north. In the Sparker and seismic dataset it appears as a high-amplitude reflection at the seafloor that probably results from the constructive interference of the seafloor reflection and the underlying SU5 base reflection. Internal reflections are not resolved.

Offshore seabed morphology

Most of the seabed in the study area, beyond the nearshore bedrock-dominated platform, is a relatively smooth topographic surface with no major bedforms that gently slopes to the south (Fig. 3). The topographic flat is an expression of seismic unit SU5 that pinches out landwards against rising bedrock (Fig. 4b). Bedrock occurs at or near the seabed (under a thin veneer of seabed sand and gravel) widely distributed across the innermost shelf, forming a variably wide area of irregular low-amplitude (<5 m) seabed topography at approx. 40 m water depth. Bedrock outcrop extent is variable along the coastal fringe, widening to a maximum value of 10–15 km due south of Waterford Harbour/Hook Head.

Channels of generally north–south orientation appear to be cut into the extensively fractured and jointed bedrock platform. The widest of these, up to 2 km wide, extends directly from the mouth of Waterford Harbour as a curvilinear trench to the SSW (Fig. 3). It appears to be infilled by SU5. Cutting obliquely southwards from the inner harbour area across the 15-km-wide bedrock platform to the southwest of the headland is a narrower, 0.5-km-wide and 5-km-long channel cut up to 30 m deep into the bedrock (Fig. 3). It is oriented to the SSE and extends beyond the southern tip of Hook Head.

Two prominent seabed ridges trending approximately N–S cross the near-coast seabed (Fig. 3). A ~5-km-long, NNE–SSW-oriented ~2.5-m-high seabed ridge spans the water depth range between 25 and 50 m (Fig. 7a). The ridge is a narrow, elongate, asymmetrical (Fig. 7c) feature, which widens into a small fan-like bead approximately mid-way along its length. The ridge sits directly on top of the bedrock surface (Fig. 7e) and is onlapped in the north-west by small-scale (<1 m) ridges of mobile seabed sands.

The southern limit to the 'Hook Head' bedrock channel (Fig. 3) is marked by the northern end of a 5-km-long, less well-defined seabed ridge which extends to over 500 m wide (Fig. 7b) as an undulating, uneven crested, approximately symmetrical (Fig. 7d) low-relief spread. A Sparker profile across the ridge indicates that it rests directly on the bedrock surface (Fig. 7f).

Onshore glacial geomorphology and geology

Regional DTM data (ALOS PALSAR RTC) for south-east Ireland and several smaller coincident LIDaR datasets (Fig. 8) provide an overview and some detail, respectively, of onshore topography directly north of the offshore study area. In the Suir River valley and in the coastal area around Tramore (Fig. 8b,c) NNW–SSE-oriented sub-parallel low-relief ridges are up to 8 km long by approximately 0.5 km wide (elongation ratios of >1: 16) by 5–10 m high. The ridge

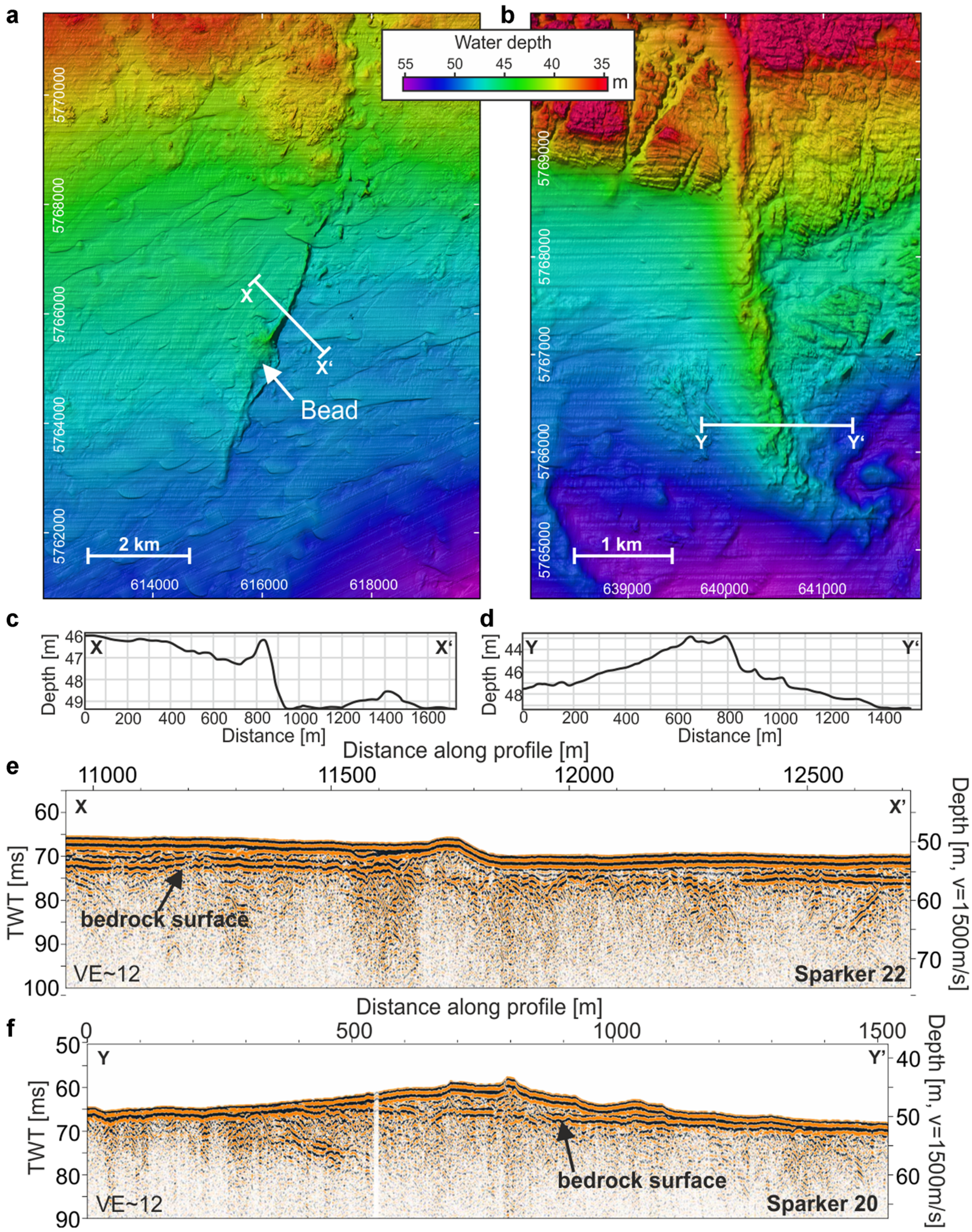


Figure 7. (a,b) Multibeam bathymetry showing two generally N–S-oriented seafloor ridges which extend across bedrock exposed at the seabed and onto the deeper water seabed underlain by a sub-seafloor sedimentary unit offshore south-east Ireland. (c) Two cross-profiles across the ridges with recent seabed sediment accumulations on their western sides consistent with local longshore tidal current regimes. (d,e) Sparker profiles running orthogonally across the ridges showing bedrock below and the R5 reflector partially onlapped by SU5.TWT, two-way travel time. [Color figure can be viewed at wileyonlinelibrary.com]

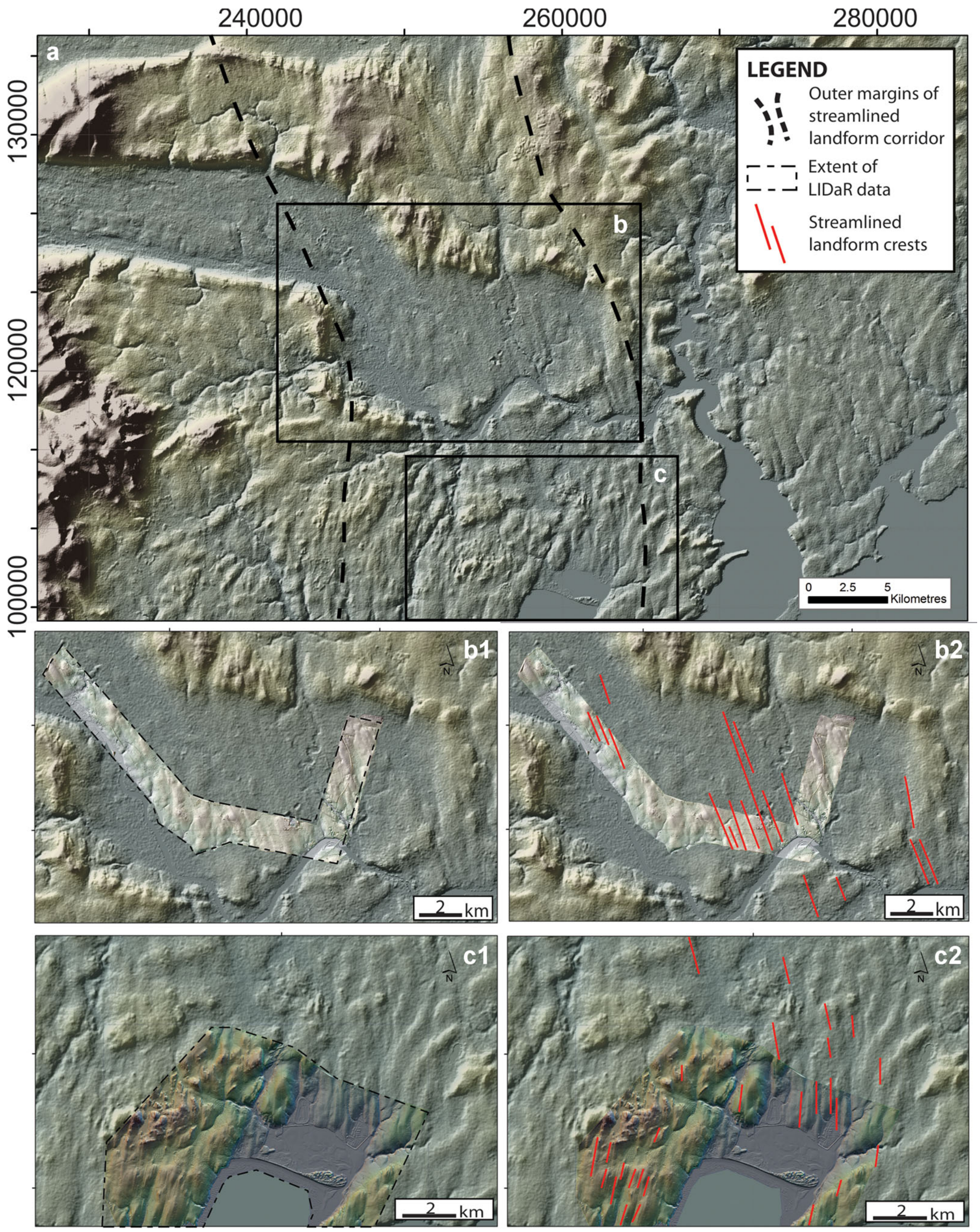


Figure 8. (A) Regional digital elevation model data with an outlined corridor of streamlined landforms extending from north to south in a curvilinear zone across east Co. Waterford. Data credit: ASF DAAC 2015, ALOS-1 PALSAR_Radiometric_Terrain_Corrected_high_res. © NASA 2019 Includes Material © JAXA/METI 2007. Accessed through ASF DAAC 12 June 2019. DOI: 10.5067/Z97HFCNKR6VA. (B1) The regional ALOS-1 DTM overlain by NRA LIDaR data (Vertical exaggeration ×3, hillshading from 16 directions, 20° false-sun altitude) for Area 1 (Waterford). (B2) Mapping of elongate, subparallel, low-amplitude ridge crestlines interpreted as MSGLs crossing the Suir River valley within a well-defined topographic zone. (C1) An RVT hill shade render of NRA LIDaR data for Area 2 (Tramore). (C2) Mapping of subparallel ridge crests within Area 2 demonstrating extension of the streamlined topographic zone to the coastal edge. [Color figure can be viewed at wileyonlinelibrary.com]

crests extend across Areas 1 and 2 covered by the patches of higher resolution LIDaR data, demonstrating they are not artefacts within the coarser resolution dataset (Fig. 8b). The ridges fall within the envelope of ridge geometries interpreted as mega-scale glacial lineations (MSGLs) elsewhere in Ireland (Delaney *et al.*, 2018) and the British Isles (Clark *et al.*, 2009b).

Within Area 1, on the south bank of the River Suir, an aerially concentrated set of boreholes at the site of the current Waterford City By-pass toll plaza (Fig. 2) recovered 'stiff to firm Boulder Clay' across a span of two streamlined landforms. Boulder clays are reported at the surface occurring in thicknesses of generally 15–30 m and up to 42.5 m (Geological Survey Ireland, Geotechnical Section, pers. comm.).

The data presented here support the mapping of a north to south subglacial flow set crossing east Waterford by Greenwood and Clark (2009a) (their fs1). The increase in data resolution used here provides additional detail and a concomitant increase in the quantity of streamlined landforms observed in Area 1 (Fig. 8b), and the occurrence of streamlined landforms in the region is extended towards Tramore into Area 2 (Fig. 8c) and thus onto the coastal fringe.

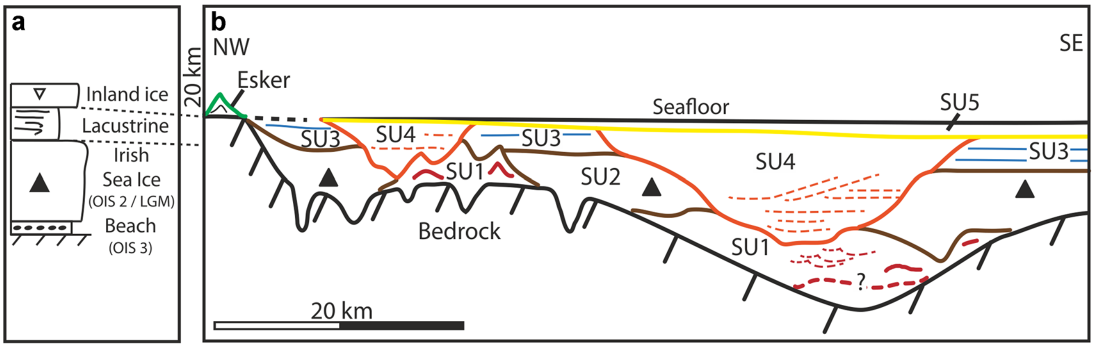


Figure 9. Cartoon cross-section sketch of interpreted seismic stratigraphy and bathymetry of the northern Celtic Sea related to a generalized onshore coastal stratigraphy (after Ó Cofaigh and Evans, 2007). [Color figure can be viewed at wileyonlinelibrary.com]

Discussion

Pre-Quaternary features

Correlations with onshore bedrock mapping suggests that the bedrock platform is probably composed of Ordovician to Carboniferous siliciclastics and limestones with volcanics (MacCarthy *et al.*, 1978; Carlisle, 1979; Tietzsch-Tyler and Sleeman, 1994; Sleeman and McConnell, 1995). The bedrock platform is exposed at the seafloor in the north of the area, and bathymetric data show E–W-striking bedding contacts between rock units cut by N–S and NE–SW fractures (Fig. 3). Excavation along the fractures has formed gullies. The ages of lowland bedrock surfaces across Co. Waterford and the bedrock platform in the offshore area are unknown, but these can be inferred to be at least partially Quaternary in age from the presence of glacial erosional landforms and striae (Fig. 2).

The buried bedrock surface south of the platform has large surface relief. Two clear linear features comprising N–S-oriented channel segments are cut into the bedrock (Fig. 5). The orientation of these erosional forms suggests that these are palaeo-river channels that might have been connected to the N–S-oriented River Barrow–Suir drainage system during sea level lowstand. River Barrow currently enters the Celtic Sea via Waterford Harbour (Fig. 2), while the buried channels occur ~30 km to the south of the river mouth. The series of enclosed bedrock hollows in the west of the area are aligned and oriented towards the topographic valley enclosing Dungarvan (Fig. 2). However, these do not form a coherent channel, and although intriguing, the connection with a possible E–W palaeo-drainage pattern of the River Bride cannot be considered definitive. No clear channel for a palaeo-River Bride is evident in the dataset.

Quaternary stratigraphy

We interpret six seismostratigraphic units in the Quaternary sequence offshore south-east Ireland (bedrock and SU1–5) resting on a bedrock surface (R1) (Fig. 9). For the first time, the units detail the offshore stratigraphic equivalent of Quaternary deposits in recently established lithostratigraphic sequences along the west Waterford coastline (e.g. at Ardmore and Whiting Bays).

SU1 is restricted in extent to channel bases and discontinuous irregularly shaped mounds. It mostly occurs in the deepest areas of R1 topography, but not exclusively. Therefore, it is not interpreted as an early channel fill but rather as a deposit preserved there preferentially, with the channel offering protection from erosion represented by surface R2. Although it is undated, stratigraphically it pre-dates the erosive event, and thus may be from an earlier interglacial or glacial period, e.g. MIS5 or earlier. SU1 is inferred to comprise a mix of stratified deposits and diamicts, which may be or have once been regional in extent.

SU2 is the first laterally extensive unit in the study area. The unit is largely acoustically transparent but contains low-amplitude chaotic reflections in places (Fig. 4). It is truncated by a clear, near-horizontal top reflector (R3). The unit unconformably encloses SU1 and infills undulations and hollows in the bedrock. Based on its seismic characteristics and unit geometry, SU2 is inferred to be diamictic in character (see similar examples in, for example, Dowdeswell *et al.*, 2004; Anjar *et al.*, 2014). Based only on seismic facies analysis, it is difficult to identify the genesis of thick, acoustically unstratified glacigenic sediments (Syvitski, 1991), but from its widespread occurrence, geometry and stratigraphic position at or near bedrock, we consider this unit to correspond to the >10-m-thick regionally extensive diamictic unit observed in onshore outcrops along the south and east coasts of Ireland, i.e. the 'Irish Sea Till'. Along the south coast, the term 'Irish Sea Till' groups shelly, muddy diamicts and glaciotectonites. As it has been age-constrained to the LGM (<24 ka BP), it is thought to have been formed by onshore advance of the ISIS onto the south-eastern coast of Ireland (Ó Cofaigh and Evans, 2001a, 2001b, 2007; Ó Cofaigh *et al.*, 2012).

SU3 is a stratified unit of fairly consistent thickness that drapes R3. It is truncated laterally both by R4 (see below) and by the near-horizontal R5 reflector (Fig. 4). Stratification in SU3 appears to be consistent with deposition as a glaciofluvial/glaciolacustrine sediment; the broadly flat-lying internal reflectors, the lack of strong internal reflectors, and the absence of extensive channelization are all possible indicators of an origin as a low-angle subaqueous spread, possibly bottom-set type deposit (Shaw and Forbes, 1990; Virtasalo *et al.*, 2007). In the nearby Ardmore Bay outcrop on the south coast, glaciofluvial and glaciolacustrine sediments are described that directly overlie the Irish Sea Till (Ó Cofaigh and Evans, 2001b). The sediments vary from massive to laminated sandy mud, through to gravelly sands. This facies range is consistent with the weakly stratified geometry observed in SU3.

The sequence of SU1–3 is deeply incised in places by a prominent undulating reflector, R4, with stratified sediments (SU4) occurring above it. The R4 reflector forms channel-like elongate incisions in the southern part of the study area (Fig. 6). These incisions are oriented approximately N–S, suggesting a period of localized erosion along linear routeways; the western channel is narrower than the broader remnant eastern channel aligned with Tramore Bay onshore to the NNE, but now mostly eroded away (Fig. 6). Within the context of a presumed continuous glacially influenced sequence, these incisions could be either sub-glacial or pro-glacial meltwater channels formed under, or near, an actively deglaciating ice margin. SU4 internal reflectors are cross-stratified, indicating fluvial cut and fill type sedimentation (Figs 4a and 6a,b).

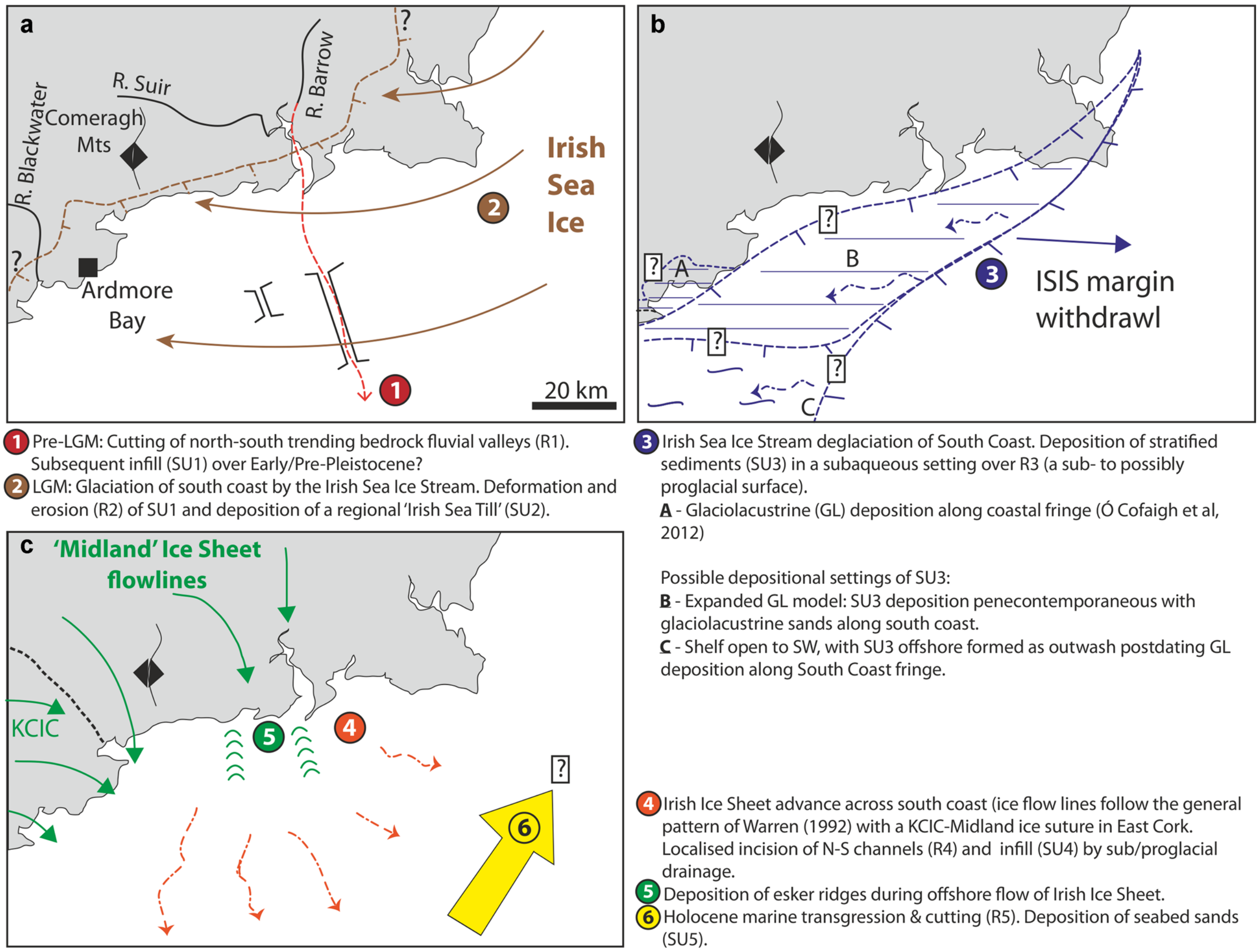


Figure 10. Reconstruction of glacial events during, and following, the LGM in south-east Ireland based on the integration of onshore glacial stratigraphy and the offshore seismic and bathymetric data from this study. [Color figure can be viewed at wileyonlinelibrary.com]

The SU1–4 sequence is cut by an uppermost reflector (R6) which onlaps the nearshore bedrock platform. SU1–4 are capped by a thin, regionally distributed gently southward thickening layer (SU5) (Fig. 4). SU5 is thought to represent a seabed sand and gravel lag formed over a marine transgression surface (R6) which has truncated the Quaternary sediment sequence (SU1–4). Groundtruthing by seabed sediment sampling in the area reveals the presence of sands, gravels and shell debris (Dorschel *et al.*, 2012). The subtle, regular undulations in the seafloor (Fig. 7a,b) are interpreted as mobile sand waves in this facies reflecting modern tidal sediment drift patterns.

Quaternary seabed morphologies

Located on the bedrock platform, the two 3–5-km-long N–S-oriented ridges at the seabed are interpreted as eskers (Fig. 7). These subglacial landforms typically have low preservation potential formed in active temperate ice-marginal zones associated with deglaciation (Walder and Fowler, 1994; Chandler *et al.*, 2013). Eskers develop close to the ice margin (Storrar *et al.*, 2014; Livingstone *et al.*, 2015) and their development favours 'hard beds', although channelized subglacial esker systems have been described on a sedimentary substrate as well (Greenwood *et al.*, 2016). Their occurrence on the nearshore shelf indicates the deglaciation of an ice mass that was receding northwards. The western ridge has a fan-shaped spread at its southern end, suggesting efflux of meltwater and deposition into a water body. The eastern ridge is coincident with a gully cut into bedrock to the north, which may have entrained and directed meltwater flow (Greenwood *et al.*, 2016). We consider the eskers to be penecontemporaneous with the deposition of the upper inland till along the West Waterford coastline at Ardmore and Whiting Bay (e.g. Ó Cofaigh *et al.*, 2012) (Fig. 9) as they overlie, at their southern extent, sub-seafloor preserved glacial and glacio-fluvial deposits.

Inferred palaeo-environments and BIIS dynamics

Our interpretation of the offshore seismic data presented here supports a model of sequential ice sheet events involving several phases of glaciation by ice flows from different source areas within the last BIIS. These events along the south-east coastal fringe of Ireland occurred during and post-dated the LGM (Ó Cofaigh *et al.*, 2012) (Fig. 10). The data indicate the development of a subglacial landform assemblage off the coast of Co. Waterford, related to a late-stage north to south offshore extension by the last IIS to at least 15 km offshore. The ice advance is age-constrained to after the withdrawal of the ISIS from the south coast, supporting several studies that have rejected long-standing models for the existence of an SIEM (Charlesworth, 1928) as an inland maximum limit of IIS extension during the last cold period (Hegarty, 2004; Ó Cofaigh and Evans, 2007; Ó Cofaigh *et al.*, 2012). Geomorphic evidence of ice flow patterns presented here supports previous interpretations of north to south ice flow across the region (McCabe, 1998) but implies it dates from the LGM (Fig. 10c).

The subglacial streamlining of the Suir Valley and near the coast at Tramore in east Waterford supports previous mapping of a streamlined bedform 'flow set' (fs1) in the region (Greenwood and Clark, 2009a; GSI, 2016). Based on the distribution of streamlined landforms, the flow paths were spatially restricted and limited to a well-defined corridor (Fig. 8). Streamlining may have been controlled by subglacial ice flow velocities, the presence/absence of subglacial asperities (e.g. bedrock protuberances) and/or the availability of mouldable subglacial sediments. The absence of more laterally extensive subglacial sediments on the nearshore shelf indicates that flow was possibly associated with the southwards extension of an outlet glacier within a wider ice sheet marginal zone. The flow path can be extrapolated northwards across the Slievnamon ridge (possibly along the Hugginstown–Mullinavat col) towards the south-central Midlands. This flow path agrees with a prominent southwards arcuate bulge in the line of the SIEM (Fig. 2) to the immediate north of Hugginstown associated with a generally S- to SE-directed ice dispersal from the south-central Midlands of the IIS (Hegarty, 2004). This model supports re-interpretations of the SIEM as the line of a major recessional stage in the post-LGM retreat of the last IIS towards centres of ice dispersal in the central–west midlands.

Ice advance from inland Irish Ice dispersal centres is limited to after deglaciation of the coastline by the ISIS. The ice extension crossed the lowlands of the River Suir in a constrained corridor southwards towards Waterford Harbour, depositing a subglacial till cover of northern provenance (Culleton, 1978; Warren, 1992; Gallagher and Thorp, 1997; Gallagher *et al.*, 2004) (Fig. 10c). Glaciation of the region during the LGM agrees with recent age constraints of high-elevation surface exposure and erratic boulder emplacement on Slievnamon and at 'The Gap' in the Comeragh Mountains during the last cold period (Ballantyne and Stone, 2015). It also accounts for the restricted distribution of associated glacigenic sediments and erratic carriage within east Co. Waterford, but not across the south-east corner of Ireland (Co. Wexford east of Kilmore Quay).

Based on its stratigraphic position and correlation with coastal exposures, SU2 is correlated with the widespread 'Irish Sea Till' associated with glaciation of the southern Irish coastline east of Cork Harbour by the ISIS. It would thus be possible to correlate SU3 with the stratified sand and silty sands at Ardmore Bay and other locations. However, this has implications for the palaeogeography of ice-marginal configurations relative to the coastal fringe topography (Fig. 10). Such an interpretation suggests that any ice-dammed lake that formed during the recession of the ISIS extended much further south and east from the west Waterford (e.g. Ardmore and Whiting Bays) coastal fringe, implying a substantial transient lake body (Fig. 10b). The inference of a substantial palaeo-lake is consistent with the fine-grained nature of the deposit, implying sedimentation into a low-energy depositional setting such as a standing waterbody quite distal from the sediment input source. Alternatively, the stratified deposits of SU3 may be associated with localized ponding in isolated ice-distal topographic lows exposed on a subaerially exposed shelf surface. This opens up the possibly that SU3 may represent sediment deposited in a variety of settings, including isolated lakes on an outwash plain (Fig. 10b).

Ó Cofaigh *et al.* (2012) suggest that post-Irish Sea Till outwash (mostly glaciolacustrine deposits) in west Waterford were tectonized by the advance of inland-sourced ice sheet margins to beyond the present coastline. This study supports that model, with a separate ice extension from north to south across Co. Waterford at or about the same time giving rise to the streamlined landscape there. Channelization in the seismic stratigraphy (R4) could be proglacial or subglacial in origin, and if the latter, it would suggest that this IIS advance reached more than 15 km beyond the present coastline (Fig. 10c). The occurrence and preservation of the stratified ridges at seabed, interpreted as eskers, indicates that their formation was associated with the youngest ice sheet event in the study area. From the combined onshore evidence along the southern Irish coastline from Cork Harbour to Kilmore Quay, this was a north to south advance to offshore that post-dated recession of the ISIS ice eastwards (Fig. 10c). The seabed ridges therefore do not represent recessional moraines associated with ISIS withdrawal. The occurrence of the eskers also indicates a well-developed subglacial drainage network, consistent with subglacial drainage routing along the path of the proposed outlet glacier crossing east Co. Waterford.

Conclusions

Historically, studies of the Quaternary sequences preserved on the Irish continental shelf have been very limited due to a paucity of high-resolution shallow seismostratigraphic data. A new seismic dataset, used in combination with high-resolution bathymetric data, reveals the Quaternary seismostratigraphy of an area off south-eastern Ireland in the northern Celtic Sea. The chronology and pattern of ice flow resolves issues associated with the nature and pattern of glaciation and deglaciation of this region, and are associated with a complex history of ice sheet sector interplay during and post-dating the LGM. Six seismostratigraphic units (bedrock and SU1–5) record a sequence of erosion and deposition events. The reconstructed event stratigraphy correlates well with recent age-constrained terrestrial evidence of several consecutive phases of ice sheet advances from different source areas across the coastal fringe during the last cold period; this was initially from marine-based (Irish Sea) and subsequently terrestrially centred (south-east Midland) sectors of the last BIIS. The offshore extension from the BIIS across modern Co. Waterford is proposed as the last major ice sheet event to have occurred in the area, post-dating eastward withdrawal of the ISIS.

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Abbreviations. BIIS, British Irish Ice Sheet; IIS, Irish Ice Sheet; ISIS, Irish Sea Ice Stream; LGM, Last Glacial Maximum; MBES, multibeam echo sounder; MSGL, mega-scale glacial lineation; OSL, optically stimulated luminescence; RVT, Relief Visualization Toolbox; SIEM, Southern Irish End Moraine.

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