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Journal of Quaternary Science

DOI:
10.1002/jqs.3234

Published: 01/10/2020

Peer reviewed version

Journal of Quaternary Science

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Journal:	*Journal of Quaternary Science*
Manuscript ID	JQS-19-0112.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	12-May-2020

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Keywords:	Wicklow Trough, Irish Sea, tunnel valley, glacial processes, Irish Sea Ice Stream

Formational history of the Wicklow Trough: a marine transgressed tunnel valley revealing ice flow velocity and retreat rates for the largest ice stream draining the late-Devensian British-Irish Ice Sheet

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ABSTRACT

The Wicklow Trough is one of several Irish Sea bathymetric deeps, yet unusually isolated from the main depression, the Western Trough. Its formation has been described as proglacial or subglacial, linked to the Irish Sea Ice Stream (ISIS) during the Last Glacial Maximum. The evolution of Wicklow Trough and neighbouring deeps, therefore, help understand ISIS dynamics, when it was the main ice stream draining the former British-Irish Ice Sheet. The morphology and sub-seabed stratigraphy of the 18 km long and 2 km wide Wicklow Trough is described here from new multibeam echosounder data, 60 km of sparker seismic profiles and five sediment cores. At a maximum water depth of 82 m, the deep consists of four overdeepened sections. The heterogeneous glacial sediments in the Trough overlay bedrock, with indications of flank mass-wasting and subglacial bedforms on its floor. The evidence strongly suggests Wicklow Trough is a tunnel valley formed by time transgressive erosional processes, with pressurised meltwater as the dominant agent during gradual or slow ice sheet retreat. Its location may be fault controlled, and the northern end of the Wicklow Trough could mark a transition from rapid to slow grounded ice margin retreat, which could be tested with modelling.

Keywords: Wicklow Trough; Irish Sea; tunnel valley; glacial processes; Irish Sea Ice Stream

INTRODUCTION

The seafloor of the western Irish Sea reveals a number of deeps which include the Lambay Deep, Codling Deep and Wicklow Trough (Jackson *et al.*, 1995) (Fig. 1) These bathymetric deeps have steep sides (with slopes up to 12°), are linear, and have been described as tunnel valleys (Eyles and McCabe, 1989). They are similar to those in other high-latitude continental shelf settings, most notably within the North Sea (Ehlers and Linke, 1989; Piotrowski, 1994; Huuse and Lykke-Andersen, 2000).

They are inferred as formed by glacial processes at the Last Glacial Maximum (LGM) (Eyles and McCabe, 1989; Wingfield, 1989), when the Irish Sea Ice Steam (ISIS) advanced through the basins of the Irish Sea and Celtic Sea and then retreated rapidly, draining the British-Irish Ice Sheet (BIIS) (Lockhart *et al.*, 2018; Small *et al.*, 2018; Scourse *et al.*, 2019). The Wicklow Trough lies approximately 10 km offshore of the town of Wicklow, running almost parallel to the eastern Irish coast (Fig. 1). It is located on a flat and shallow (generally <60 m water depth) platform to the west of, and isolated from, a major glacially eroded deep nearly 100 km long and up to 150 m deep, the Western Trough, which connects the North Channel to St Georges Channel (Jackson *et al.*, 1995; Mellet *et al.*, 2015) (Fig. 1).

During ISIS advance at the LGM, glacigenic material was typically deposited directly on top of bedrock and primarily as diamicton generally referred to as The Irish Sea Till (Ó Cofaigh and Evans, 2001). Having reached its southern extent at the edge of the Celtic Sea Shelf, disintegration of the BIIS began shortly after (Chiverrell *et al.*, 2013, 2018; Praeg *et al.*, 2015; Lockhart *et al.*, 2018; Small *et al.*, 2018; Scourse *et al.*, 2019). Following an initial rapid phase of retreat between Scilly and the Wexford – Pembroke line, by approximately 22.5 – 21.2 ka BP the ISIS front had reached the study area at the Wicklow Trough (Chiverrell *et al.*, 2013). At this stage ISIS retreat slowed down with a series of still-stands and oscillations recorded along the coastlines of Ireland and Wales (Chiverrell *et al.*, 2013, 2018; Smedley *et al.*, 2017; Small *et al.*, 2018). Marine-terminating ice eventually evacuated the north Irish Sea basin shortly after 19.8 ka BP (Chiverrell *et al.*, 2018). The southernmost position of a water-terminating retreating ISIS margin is documented 80 km to the northwest of the Wicklow Trough (Van Landeghem, Wheeler and Mitchell, 2009). The opening of the North Channel between 16 – 15 ka BP allowed the tide to propagate throughout the Irish Sea, with the present-day coastline emerging around 6 ka BP (Ward *et al.*, 2016). The area around the Wicklow Trough is also characterised by contemporary dynamic sediment wave fields and quasi-stable sediment banks (Whittington, 1977; Warren and Keary, 1988; Jackson *et al.*, 1995; Wheeler, Walshe and Sutton, 2001; Van Landeghem *et al.*, 2009).

The Wicklow Trough is conspicuous in its location isolated from the main glacial incision, the Western Trough, and remains poorly understood in relation to ISIS dynamics. The Wicklow Trough has been given a late-to post-glacial sub-aerial fluviatile origin during a period of low sea level based on morphology and minor tributaries from onshore rivers (Whittington, 1977). In a contrasting hypothesis, the Wicklow Trough and the other Irish Sea bathymetric deeps are considered tunnel valleys. These would have sub-glacially formed by meltwaters driven by a high hydrostatic head, and filled with glaciomarine sediments as a result of glacio-isostatic downwarping (Eyles and McCabe, 1989). If the bathymetric deeps offshore the eastern Irish coast are tunnel valleys, their development could be related to ice margin retreat rate and/or the erosive power of the subglacial meltwater (Livingstone and Clark, 2016).

The aim of this study is to investigate the formation and development of the Wicklow Trough and contextualise this with the variable pattern of ISIS advance and retreat. We interpret the geomorphology and shallow acoustic stratigraphy of the Wicklow Trough through the spatial integration of new geophysical and sedimentological data, with the following objectives:

1. to determine whether the Wicklow Trough was cut by pro-glacial rivers or by subglacial meltwater;
2. to reconstruct and understand the formation and evolution of the Wicklow Trough in relation to the neighbouring deeps and the underlying geology;
3. to tentatively relate the formation and evolution of the Wicklow Trough and the other deeps with ice stream dynamics.

This study contributes to the growing knowledge of Irish Sea Ice Stream dynamics and British-Irish Ice Sheet drainage, whilst adding to the understanding of the formation of the many incisions in the seabed of the Irish Sea.

METHODOLOGY

Data Acquisition

Multibeam echosounder (MBES), sparker seismic data and vibrocores were acquired as part of the 2009 Irish Sea Marine Assessment (ISMA) survey CV0926 (Wheeler et al., 2009) on the *RV Celtic Voyager* (Fig. 2). The vessel was equipped with an EM3002D multibeam echosounder acquiring bathymetry and backscatter data in the 300 kHz range using dynamically focused beams. The horizontal accuracy (x, y) was usually less than 50 cm with a vertical accuracy (z) of <15 cm obtained for the processed bathymetry data. Data processing was performed on board with the CARIS HIPS and SIPS software package to remove erroneous pings and correcting for tidal and water displacement offsets.

Sub-bottom data was gathered using a Geo-Source 400 sparker system. Approximately 60 km of sparker lines were collected in an area that measures approximately 30 km^2 (Fig. 2). The system consisted of a 6 kJ pulsed power supply operating at a frequency of between 0.5 and 2 kHz predominantly. The unfiltered return signal was picked up in a Geo-Sense single channel hydrophone array. A maximum penetration of 50 m below the seabed was achieved before signal attenuation with a vertical resolution of up to 30 cm.

Five vibrocores of up to 3 m length were collected with a Geo-Resources 6000 vibrocoring system to help groundtruth seismic data (Fig. 2). Retrieved vibrocores were split onshore and logged visually.

Geophysical Data Processing

MBES data processing

The output from the CARIS HIPS and SIPS software consisted of ungridded, tidally corrected XYZ data that was subsequently gridded using QPS Fledermaus v.7 to a 2 x 2 m cell resolution. Gridded raster data was then exported to ArcGIS v10.6 for use in groundtruthing and morphological analysis.

Sparker data processing

Seismic sparker data was incorporated into Kingdom software (IHS Markit) in SEG-Y format and merged with navigation data. A bandpass filter was applied (0.9-1.2 - 5-6 kHz) and an automatic gain control of 50 and 100 ms. Seismic interpretation was also performed in Kingdom. Horizons were picked manually, and seismic depths were converted from two-way travel time to metres using a velocity of 1600 ms^{-1}.

RESULTS AND INTERPRETATION

Morphology

The Wicklow Trough is a rectilinear submarine deep that is orientated N-S and characterised by an irregular, complex seafloor consisting of areas of sediment waves and four overdeepened sections (Fig. 2). The Trough is approximately 18 km long and is generally 2 km wide throughout. It is 82 m below sea-level at its deepest point and incised roughly 60 m relative to the surrounding seabed. It has an abrupt initiation at its northern terminus with the seabed morphology consisting of sediment waves that form the northern tip of the adjacent India Bank (Fig. 1) which continues into the Trough here separating it from the Codling Deep (Fig. 1). Heading south, the India Bank then forms the eastern edge of the Wicklow Trough.

Within the Trough, the valley flanks vary in gradient and asymmetry. In the north, the western flank has a much smaller gradient (generally less than 1.5°). The eastern flank in the northern part of the Wicklow Trough (being also the western edge of the India Bank) has a mean gradient of 12°. The central part of the Trough shows a greater degree of flank symmetry with slopes of 5 - 10°. In the south, the western flank exhibits a steeper gradient (on average 8°) and the eastern flank is shallower (less than 3° typically). The uppermost part of the western flank is bound by a shallow sand plateau incised by channels. Towards its southern terminus, the Wicklow Trough gradually shallows out to 40 mbsl. To the south of the Trough is the Arklow Bank (Fig. 1).

To the southwest, a sediment wave field is bordered by an irregularly curved ridge that is roughly 5.5 km in length (Fig. 2A). The ridge has a NW – SE orientation at its northern end before curving to the west at its southern section. As the ridge traverses the Trough at its southern section, it separates a small northern deep from the rest of the main deeps (Fig. 2A). This enclosed northern deep is 55 mbsl and displays an undulating seabed pattern (Fig. 2A).

To the south of the ridge structure lies the second overdeepened section (Fig. 2B). It is bound to the south by a ridge that runs NW – SE with an extended arm that runs N – S. The maximum water depth within this section is roughly 70 m and the seabed exhibit an irregular undulatory pattern with, generally symmetrical, trochoidal sediment waves adjacent to the western valley wall of the Trough (Fig. 2B).

To the south, the third overdeepened section has a maximum water depth of 82 m (Fig. 2C). At the base of the valley flank in this area, there is a circular depression (Fig. 2C). Measuring roughly 185 m in diameter, it has a relief of approximately 10 m relative to the surrounding seabed. The seabed morphology in this third enclosed deep is strongly irregular with ridges running traverse and sub-parallel to the main axis of the Trough. This third overdeepened section is separated from the southernmost, and fourth, overdeepened section by a SW – NE ridge that is approximately 10 m in height.

The fourth overdeepened section is up to 79 mbsl and shallows towards its southern terminus exhibiting a highly irregular seabed (Fig. 2D). From the SW – NE ridge that separates the third and fourth overdeepened sections, at the base of the western valley flank of the Trough, is a sediment wave field that runs in a N – S orientation for 5 km to the southern terminus of the Trough (Fig. 3). The rest of the seabed towards the southern terminus of the Trough is rugged and undulatory (Fig. 2).

Down-core Sediment Profiles

Vibrocore VC1 was taken from the top of the ridge structure south of seismic line SL1 (Fig. 2) and is 2.7 m long and comprises two distinctive facies and (Fig. 3). The upper 1.5 m is dominated by a brown heterolithic gravel with a sandy matrix (Fig. 3, see image a). At approximately 1.5 m depth in the core, there is a sharp boundary between the sandy gravel and the underlying grey-brown silty sand which has occasional phosphate nodules (Fig. 3, see image b – note the contact is disturbed by coring).

VC2 was collected within this sediment wave field (Fig. 2) and is 2.85 cm in length and (Fig. 3). The upper 2 m approximately comprises relatively clean, brown sands with occasional layers (50 cm thick) that are sand dominated but contain cobbles up to 7 cm in diameter (Fig. 3, see image c). From 2 m to the base of the core, there are finer, light brown sands with alternating bands of dark-brown silty sand with wavy contacts (Fig. 3, see image d).

VC3 was retrieved from the top of the western flank of the Trough (Fig. 2) and is 2.9 m long and (Fig. 3). The upper 0.5 m comprises dark grey to brown silty sands and gravelly sands that contain pebbles ranging from 1 – 4 cm in diameter (Fig. 3, see image e). From approximately 0.5 to 2.25 m depth, the core comprises light brown medium to coarse sands with occasional gravel that have no obvious structures. At approximately 2.25 m in the core, there is a change in lithology to a gravelly sand with some cobbles (Fig. 3, see image f).

VC4 was collected near the top of the western flank (Fig. 2) and is 0.76 m long and (Fig. 3). It is dominated by a dark grey to green clayey-sand with infrequent pebbles (1 cm) and a 11 cm cobble at 0.37 m depth in the core (Fig. 3, see image g).

VC5 was collect from the fourth overdeepened section, south of SL5 (Fig. 2). It is 1 m long and consists of dark-brown, coarse, shelly sands and gravels for the upper 0.28 m with some pebbles that range in size from 2 – 5 cm (Fig. 3, see image h). From 0.28 to 0.55 m it is comprised of brown silty sands. At 0.56 m there is a sharp contact with the underlying lithology, which is a brown-grey clayey silt. The base of this unit is marked by another sharp contact with 5 cm of light brown silty sands (Fig. 3, see image i).

Subsurface Seismic Stratigraphy

In total, seven separate seismic units were identified from the sparker seismic profiles from the Wicklow Trough consisting of an acoustic basement and an overlying sequence of six units abbreviated as SU1-SU7 (Fig. 4). These units were defined based on seismic sequence and facies analysis and linked to geomorphic features identified on MBES data where possible. In addition, these acoustic units were groundtruthed using sediment facies from the vibrocore descriptions where possible and correlated with previous stratigraphic frameworks for the area (Jackson *et al.*, 1995).

The acoustic basement (SU1) is interpreted as bedrock and represents the oldest unit in the stratigraphy. It was not consistently observed on all profiles (e.g. SL1, SL2, SL4: Fig. 5-6) although where present, it is characterised as acoustically transparent with some moderate to strong parallel reflectors that are gently dipping (SL3, SL5, SL6, SL7: Fig. 6-8). The top of the unit is marked by the reflector R1, which is generally horizontal and found at about 80 mbsl. On SL6 this reflector is seen to dip beneath the Trough from 16 to 37 mbsf (Fig. 7).

The primary infill of the Trough is a seismic unit with a strong variance in acoustic signature (SU2). Generally, SU2 has an amorphous signature with chaotic, laterally discontinuous and hummocky reflectors that have a low to medium amplitude. Some internal structure can be discerned and hyperbolic point diffraction in places are likely due to the presence of boulders. Its base is not always discernible, but where it is present it is marked by a strong basal reflector (R1) (SL3, SL5-7: Fig. 6-8). It is generally marked at the top by the seabed reflector (R6). The seismic signature of SU2 is concurrent with that for the Chaotic Facies of Jackson *et al.* (1995), which is described as ranging from a few metres to 25 m thick, and comprising predominately of gravels with muds, sands and cobbles, as well as occasional boulders.

At the western end of the SL2 profile, the ridge separates the southernmost extent of the first overdeepened section from the main part of the Trough (Fig. 5). The ridge and west flank are composed of seismic facies which contains low to moderate amplitude, laterally continuous, parallel to sub-parallel reflectors (SU3) (Fig. 5).This tabular, stratified seismic signature for SU3 consistent with the description of the Prograded Facies of Jackson *et al.* (1995). The base of this unit is marked by a moderate, undulating reflector at between approximately 0 – 32 mbsf (Fig. 5). On SL4, near the base of the western flank, is a prominent incision demarking a break in slope, which is coincident with a circular depression identified from MBES data (Fig. 2C and Fig. 6). The signature consists of low to moderate amplitude, laterally continuous, parallel to sub-parallel reflectors (SU3).

The western flank of the Trough is composed of a seismic unit that contains moderate to strong chaotic reflectors that are discontinuous (SU4) (SL1-6: Fig. 5-7). The top of this unit is marked by the R6 reflector. This unit is correlated with the Upper Till member of Jackson *et al.* (1995), described as being tabular and unstratified in seismic profiles and comprising clays with a range of other sediment from sand to boulders. It is found to outcrop at the seabed across the Irish Sea (Jackson *et al.*, 1995). On the eastern flank of the Trough there is a seismic unit with gently dipping, closely spaced, parallel, medium to high amplitude reflectors (SU5) (SL4: Fig. 6).

Shallow channel features occur within the overdeepened sections, typically incised into SU2, that are infilled by a seismic unit typically with moderate to high amplitude oblique parallel and lenticular reflectors (SU6) (SL3, Fig. 6-7). These are marked by the base by a strong reflector horizon (R4). Similar deposits, correlated in this study with SU6, were noted as partially or completely filling hollows in major incisions by Jackson *et al.* (1995) who described them as the Sea Bed Depression member. In the eastern end of the SL3 profile, within the second overdeepened section, there are is a shallow (approximately 10 m deep), 500 m long concave depression that has been infilled by a seismic unit consisting of moderate to strong reflectors that are oblique to the seabed (SU6) (Fig. 6). Towards the centre of the Trough on SL6, an asymmetric V-shaped channel is identified as being cut into SU2 to a depth of 12 mbsf (Fig. 7). It is subsequently infilled by a seismic unit comprising slightly dipping, parallel and continuous reflectors (SU6). Where the third overdeepend section is discernible on the SL7 profile, a shallow channel feature can be identified to a depth of roughly 14 m below the seabed, which has been infilled by SU6 (Fig. 8b). It is comparable with the structure highlighted in SL6 (Fig. 7). A similar shallow channel structure is observed in the fourth overdeepened section (Fig. 8a). The base of this structure is resolved to a depth of approximately 6 mbsf and has an asymmetric, V-shaped morphology. The base of this structure is observed to incise and underlying reflection. The infill of this structure grades from low amplitude chaotic to dipping reflectors at the base to moderate amplitude oblique parallel and gently dipping reflectors (SU6) (Fig. 8a).

The uppermost unit forms the sediment waves that are found prominently in the northeast and sporadically throughout the Trough (SU7) (SL1-3 & 7: Fig. 5-6 & 8). S7 exhibits moderate to high dipping reflectors that also display cross-bedding. The base of this unit is generally marked by a strong, laterally continuous basal unconformity (R5), which occurs at a depth of up to 8 m below seafloor (mbsf). Jackson *et al.* (1995) describes the Upper Sediment Layer (SL1) as tabular-stratified accumulations of mobile sediment resting on an erosive surface. In this study, SU7 is correlated with the Surface Sands Formation (Upper Member) of Jackson et al. (1995).

DISCUSSION

The Wicklow Trough: proglacial river or subglacial tunnel valley?

Based on correlation with regional stratigraphic frameworks (Whittington, 1977; Jackson *et al.*, 1995), we suggest that Wicklow Trough has been incised into glacial till deposited by the ISIS (SU4; Fig. 5 & 6) and into the underlying bedrock (SU1; Fig. 7). The Wicklow Trough contains a number of subglacial landforms on its floor, and that is the evidence for a subglacial formation mechanism as opposed to a pro-glacial sub-aerial one. The ridge structure in the northern part of the Trough comprises relatively clean gravels in the upper 1.5 m, overlying silty sand in the lower part with an erosive contact between the two (Fig. 3; VC1). On profile SL2 (Fig. 5), this ridge comprises sediments that appear to be bedded sediments. The morphology of this structure from MBES data and its seismic character would suggest it could be an esker (Greenwood *et al.*, 2016). The formation of eskers within tunnel valleys is not uncommon and support the concept of confined subglacial meltwater flow within the tunnel valley (Ó Cofaigh, 1996; Hooke and Jennings, 2006; Jørgensen and Sandersen, 2006; Kehew, Piotrowski and Jørgensen, 2012; Bjarnadóttir, Winsborrow and Andreassen, 2017).

The longitudinal profile of Wicklow Trough highlights an irregular base that contains a series of troughs and sills at varying depth levels (Fig. 8). This sort of profile strongly suggests that the Trough was carved by water that was driven under pressurised flow (i.e. glaciostatic pressure from ice sheet overburden) rather than by a gravity gradient (e.g. like in a fluvial system). The segmented overdeepened areas, separated by ridges, may also suggest multiple phases of erosion and so a non-simultaneous formation of the Trough (Janszen *et al.*, 2012). The Wicklow Trough exhibits a slightly sinuous course along its N-S orientation (Fig. 2) which suggests that it hasn't been generated by direct glacial erosion (i.e. abrasion) (van der Vegt, Janszen and Moscariello, 2012). Generally direct glacial erosion is conceded to be a minor, or secondary, component of tunnel valley formation, if present at all (Ó Cofaigh, 1996; Huuse and Lykke-Andersen, 2000; van der Vegt, Janszen and Moscariello, 2012). Instead, tunnel valleys are typically interpreted as being formed by subglacial meltwater, released either in steady-state or catastrophic conditions (Praeg, 2003; Hooke and Jennings, 2006; Kristensen et al., 2007; Lonergan et al., 2006; Van der Vegt; Kehew).

Geological controls on the location of the Wicklow Trough

To the east of the Wicklow Trough is a major, glacially eroded channel; the Western Trough (Fig. 1). The Wicklow Trough is conspicuous in its isolation on the shallow platform that shoulders the Western Trough, with abrupt terminations at its northern and southern ends. This type of tunnel valley morphology often coincides with changes in underlying substratum (van der Vegt, Janszen and Moscariello, 2012). Tunnel valleys occur in a variety of substrate types but, predominately, they are found in areas that are composed of relatively soft substrate that is poorly consolidated, or eroded into certain kinds of bedrock (Janszen, Spaak and Moscariello, 2012; van der Vegt, Janszen and Moscariello, 2012; Dove *et al.*, 2017). The Wicklow Trough is located on a bounding fault between Carboniferous sandstone to the east with Cambrian metamorphic rocks and sandstones to the west (Fig. 9a). These rocks have been blanketed by till deposited as part of the ISIS (Eyles and McCabe, 1989; Jackson *et al.*, 1995; Ó Cofaigh and Evans, 2001). The presence of an underlying structural lineament (i.e. the fault) may not be the dominant control on Wicklow Trough's location and morphology, but it certainly could have caused weakness in the underlying substratum, facilitating significant erosion (Phillips, Everest and Diaz-Doce, 2010). The co-location of the Wicklow Trough with this bounding fault suggests it could have had a strong control on its location. A similar explanation was proposed for Beauforts Dyke, a tunnel valley in the North Channel (Callaway *et al.*, 2011). The presence of softer substratum (i.e. Carboniferous sandstones) on the east of the faulted contact which underlies Wicklow Trough may also go some way to explaining the falling thalweg of the eastern flank (Fig. 9a), which would have been preferentially eroded compared to the more resistant metamorphic rocks to the west.

Tunnel valley formation related to ice margin retreat dynamics

In morphology, the Wicklow Trough is similar to the Type 4 channels of Passchier *et al.* (2010); < 1 km wide and < 50m deep. This type of channel is interpreted to have originated from catastrophic drainage of subglacial meltwater (Passchier *et al.*, 2010). This process requires large volumes of meltwater to build up behind an ice margin and be released when a certain pressure threshold is exceeded (Kehew, Piotrowski and Jørgensen, 2012; van der Vegt, Janszen and Moscariello, 2012). The result is that tunnel valleys are often infilled by thick, homogeneous sequences of outwash material (Piotrowski, 1994). However, there remain concerns around the large volumes of meltwater required to be available for such catastrophic releases, and its applications in a marine environment where a frozen ice-margin would be unlikely (Ó Cofaigh, 1996; van der Vegt, Janszen and Moscariello, 2012).

The steady-state formation process of tunnel valleys requires continuous, subglacial meltwater flow that gradually erodes into the substratum, which is typically soft (Kehew, Piotrowski and Jørgensen, 2012; van der Vegt, Janszen and Moscariello, 2012). As part of a steady-state model, meltwater generation and discharge are generally in equilibrium, although it is accepted that minor outbursts can recur episodically (Kehew, Piotrowski and Jørgensen, 2012; van der Vegt, Janszen and Moscariello, 2012).

The multiple phases of erosion in the observed four overdeepened areas would suggest a time transgressive model for the formation of the Wicklow Trough, with headward erosion during grounded ice margin retreat accompanied by pressurised subglacial meltwater discharge. Within this time transgressive model, the process of subglacial meltwater (i.e. glaciofluvial) erosion at the base of the ice stream is coeval with deposition (i.e. backfill) beneath the outer margin of the ice stream as headward advance continues. Similar models have been proposed for tunnel valleys in the German (Janszen, Spaak and Moscariello, 2012) and Dutch (Praeg, 2003) sectors of the North Sea. The subglacial meltwater is pushed towards the margin by the pressure created by the overlying ice. This meltwater can travel along the basal ice contact or through the substrata depending on its permeability. Given its overpressurised nature, this meltwater proves a strong erosive agent and so channelization occurs where sediments are erodible.

Correlation of seismic and vibrocore data from the Wicklow Trough with previous, regional investigations (Jackson *et al.*, 1995) suggests that its infill is dominated by heterogeneous sediments, deposited during the retreat of the last ISIS in an ice-proximal to glaciomarine setting. As grounded ice margin retreat occurs, there is progressive headward erosion and a new tunnel valley segment is incised further upstream (Janszen *et al.*, 2012). At this point debris flows may occur at the previous site of proximally discharged sediment accumulation. Whilst subglacial meltwater is proposed here as the primary mechanism for tunnel valley formation, it is possible that episodic outburst discharge may have occurred as the ice margin retreated which accentuated the Trough (Fig. 2) (Huuse and Lykke-Andersen, 2000; van der Vegt, Janszen and Moscariello, 2012; Livingstone and Clark, 2016).

Within the Wicklow Trough there are shallow channels seen to incise into the main Trough infill (SU2) (Fig. 7 and Fig. 8). These channels are seen to be infilled by units that are acoustically stratified (i.e. SU6). Episodic englacial discharge during ice margin retreat, or even during limited readvance, can be invoked to explain the origin of these channels. The infilling sediments can be interpreted as being deposited as backfill under quiet glaciomarine to marine settings (Praeg, 2003; Passchier *et al.*, 2010). This inference is consistent with the description for the Seabed Depression Member of Jackson *et al.* (1995), which is correlated with SU6. VC5 was recovered from one of these channels in the fourth overdeepened section. The base of the core comprised fine-grained clay rich sediments indicating deposition in quiet, possibly quiet glaciomarine-like settings, and overlain by coarser, shell-rich sediments deposited as ice retreated (Fig. 3).

Regional development within the context of ice stream dynamics

Whilst the location of the Wicklow Trough can be partly explained by substratum and structural lineaments, its development has implications for our understanding of past ISIS dynamics (Fig. 9). Tunnel valleys have been shown to form beneath the outermost kilometres of an ice stream, likely during temporary standstills and minor re-advances, and that former ice-marginal positions can therefore be constrained on the basis of their presence (Sandersen *et al.*, 2009). The northern extent of Wicklow Trough coincides with the retreat line of the ISIS at approximately 22.5 – 21.2 ka BP (Chiverrell *et al.*, 2013) (Fig. 10d). Prior to this stage, the retreat rate of the grounded ice margin was believed to have been rapid, at rates of 152 m a^{-1} (Small *et al.*, 2018). Between 21.6 – 19.5 ka, ice marginal retreat northward from Wicklow was less rapid at ~21 m a^{-1} (Small *et al.*, 2018). The Wicklow Trough, and surrounding geomorphology, offers evidence to test ideas suggested by ice margin chronological modelling efforts in this part of the Irish Sea (Fig. 10), and whether the northern end of this tunnel valley marks a transition from rapid to slow grounded ice margin retreat, with indications of ice margin oscillation.

Initial erosion of Wicklow Trough could have occurred during the advance phase of the ISIS, following deposition of the glacial till (SU4) overlying bedrock (SU1) (Fig. 9b). However, it is likely that the main downcutting of the Trough was through the erosive power of large amounts of pressurised meltwater generated by a rapidly retreating grounded ice margin. This downcutting would have been augmented by the weakening of the substratum by local structural lineaments (Fig. 10a). As the ISIS retreated, it slowed down in the constriction of St. Georges Channel (Smedley *et al.*, 2017; Small *et al.*, 2018). During this slower retreat phase, the Wicklow Trough would have had time to widen and deepen as more meltwater was discharged through it. The slow retreat phase of ice streams is known to allow for the formation of moraines (Livingstone and Clark, 2016) and the Arklow Bank, south of Wicklow Trough, is believed to have a morainic core (Warren and Keary, 1988; Wheeler, Walshe and Sutton, 2001) (Fig. 9c). A slower, moderate ice retreat rate would also allow for episodic outbursts of meltwater of higher magnitude than the steady-state conditions, which further deepen and eventually infill the Wicklow Trough (Fig 9d).

The N-S orientation of the Wicklow Trough is in line with the northward retreat direction of the ISIS, with time-transgressive headward erosion proposed as the primary formation mechanism. As the ISIS retreated further northward, we can invoke similar processes elsewhere. For example, north of Wicklow Trough, orientated roughly NW-SE, is the Codling Deep (Fig. 9). Generally, if the headward development of a tunnel valley is faster than the ice margin retreat, it will be able to extend continuously. If, however, growth of the tunnel valley is slower than the ice retreat it is likely to be discontinuous (Livingstone and Clark, 2016). Thus, tunnel valley development may have ‘skipped’ northwards as either ice margin retreat increased, or meltwater availability or erosive power decreased. There is supporting sedimentological evidence for ice margin stillstands along the east Irish coast at this stage (McCabe and Ó Cofaigh, 1995). Furthermore, the orientation of Codling Deep, in addition to meltwater channels on the shoreside of Wicklow Trough, would suggest onshore retreat of the ISIS at this point (Small *et al.*, 2018). Although the Wicklow Trough and Codling Deep have a bathymetric expression on the seafloor, there is a possibility that there are other tunnel valleys in this vicinity which have been infilled. Along the southeast Irish coast there is evidence for an oscillatory ice marginal retreat (Rijsdijk, Warren and van der Meer, 2010). The presence of eskers and shallow-infilled channels within the Wicklow Trough would suggest there was limited readvance with further meltwater discharge being actively channelled through the Trough (Bjarnadóttir, Winsborrow and Andreassen, 2017) (Fig. 9d). As the marine transgression continued, sea-level fluctuation would have brought about slope instabilities and mass-wasting deposits. These sediments were re-worked during the Holocene to form the sediment waves and sediment banks we observe today (Fig. 9e).

Post Irish Sea Ice Stream retreat: strong currents, slope failures and the preservation of the bathymetric deep

During the marine transgression as the ISIS retreated, tidal elevation amplitudes are understood to have varied significantly across the Irish Sea in response to changing water depths (Uehara *et al.*, 2006; Bradley *et al.*, 2011; Ward *et al.*, 2015). In the south Irish Sea after 14 ka BP modelled tidal elevation amplitudes were higher (in the region of 3 m) than present until a shift in a degenerate amphidromic point after 12 ka BP (Ward *et al.*, 2016). This change in local tidal amplitude in the vicinity of Wicklow Trough is suggested as a mechanism by which valley flank sediment could have been destabilised, and failure induced, leading to mass-wasting deposits (i.e. SU5). The strong currents caused by tidal channelling within the Wicklow Trough, can help explain why the trough is only partly filled and maintains a bathymetric expression today (Callaway *et al.*, 2011).

CONCLUSIONS

This study is the first attempt to characterise the Wicklow Trough specifically using comprehensive seabed acoustic, seismic and ground-truthing data to elucidate its formation and evolution. From the synthesis of this data and analysis, the following conclusions can be drawn:

1. The Wicklow Trough is a tunnel valley that is part of a series of tunnel valleys generated by the Irish Sea Ice Stream;
2. The Wicklow Trough is likely to have formed by multiple subglacial processes, with pressurised meltwater acting as the dominant agent in a time transgressive model during grounded ice margin retreat after ice streaming into the Celtic Sea at the Last Glacial Maximum;
3. The location and orientation of the Wicklow Trough is unusually isolated from the main tunnel valleys in the Irish Sea and this may have been controlled by an underlying fault;
4. The series of deeps offshore the eastern Irish coast suggest either an increase in ice margin retreat rate, or a decrease in meltwater availability and/or its erosive power. The northern end of the Wicklow Trough may mark a transition from rapid to slow retreat of the grounded Irish Sea Ice Stream around 21.5 ka BP, and this could be tested in detailed modelling;

5. The suggested infill of the Wicklow Trough is predominately glacial outwash sediments which form a heterogeneous mix, possibly containing boulders, with indication of slope instabilities and mass wasting deposits on the flanks.

Acknowledgements
The sparker and MBES data were collected by UCC with the assistance of the INFOMAR programme as Irish Public Sector Data (INFOMAR: Geological Survey Ireland (GSI) and the Marine Institute) and licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence. We thank the Geological Survey Ireland / Marine Institute for the use of their vibrocorer and sparker seismic system. We are grateful to the captain and the crew of CV0926 onboard *RV Celtic Voyager* for their work, support, cooperation and patience during the surveys and sampling. Shiptime was funded by state grant administered by the Marine Institute. The authors would like to thank Oisín McManus (Marine Institute) for his assistance with MBES data. We are grateful to IHS Markit for providing the academic licence for the KINGDOM software package to iCRAG. This paper has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092 and is co-funded under the European Regional Development Fund and by iCRAG industry partners. The authors would like to thank Dayton Dove and 1 anonymous reviewer for their constructive criticism and suggestions which greatly improved this manuscript.

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FIGURE CAPTIONS

Figure 1 A: location of the study area (black box) in the Irish Sea. General bathymetry is taken from EMODnet (EMODnet Bathymetry Consortium, 2018). B: localised bathymetry courtesy of INFOMAR with the main geomorphological features. The Wicklow Trough is highlighted by a black box presented in Figure 2.

Figure 2 Bathymetry of Wicklow Trough with vibrocore locations and sparker seismic profile lines. Also highlighted are representative MBES features (labelled boxes).

Figure 3 Logs of cores used in this study with core photography highlights.

Figure 4 A: Description of seismic units found in Wicklow Tough sparker seismic profiles with correlation to the previous stratigraphic framework of Jackson et al. (1995). B: Composite representative stratigraphic cross-section of the Wicklow Trough.

Figure 5 Seismic line 1 (SL1) and SL2 with seismo-stratigraphic interpretation and core locations with depth. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.

Figure 6 Seismic line 3 (SL3) and SL4 with seismo-stratigraphic interpretation and core locations with depth. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.

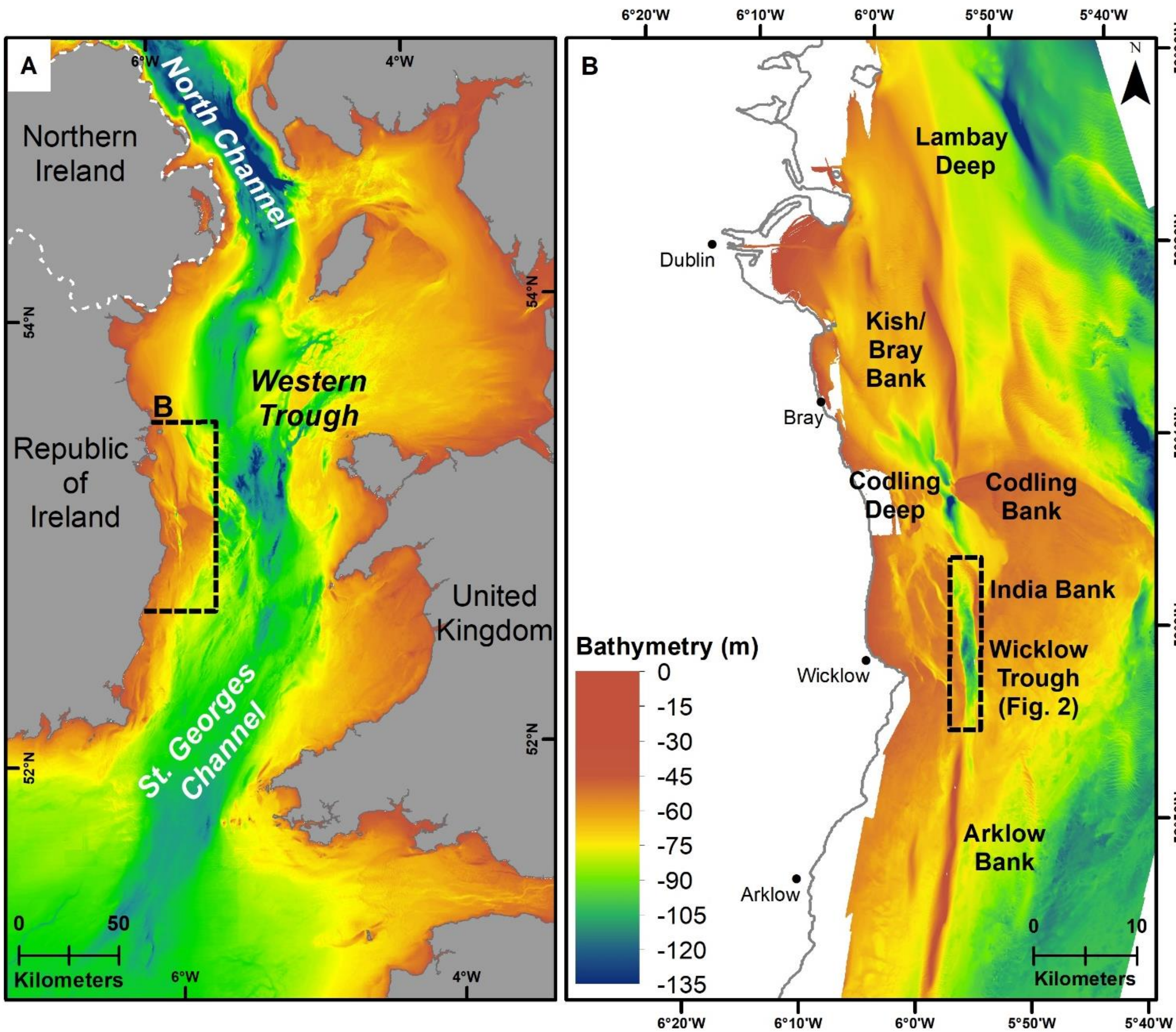
Figure 7 Seismic line 5 (SL5) and SL6 with seismo-stratigraphic interpretation. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.

Figure 8 Seismic line 7 (SL7) with seismo-stratigraphic interpretation with highlighted features. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.

Figure 9 Reconstruction of glacial events during, and following, the ISIS advance in the vicinity of Wicklow Trough.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.



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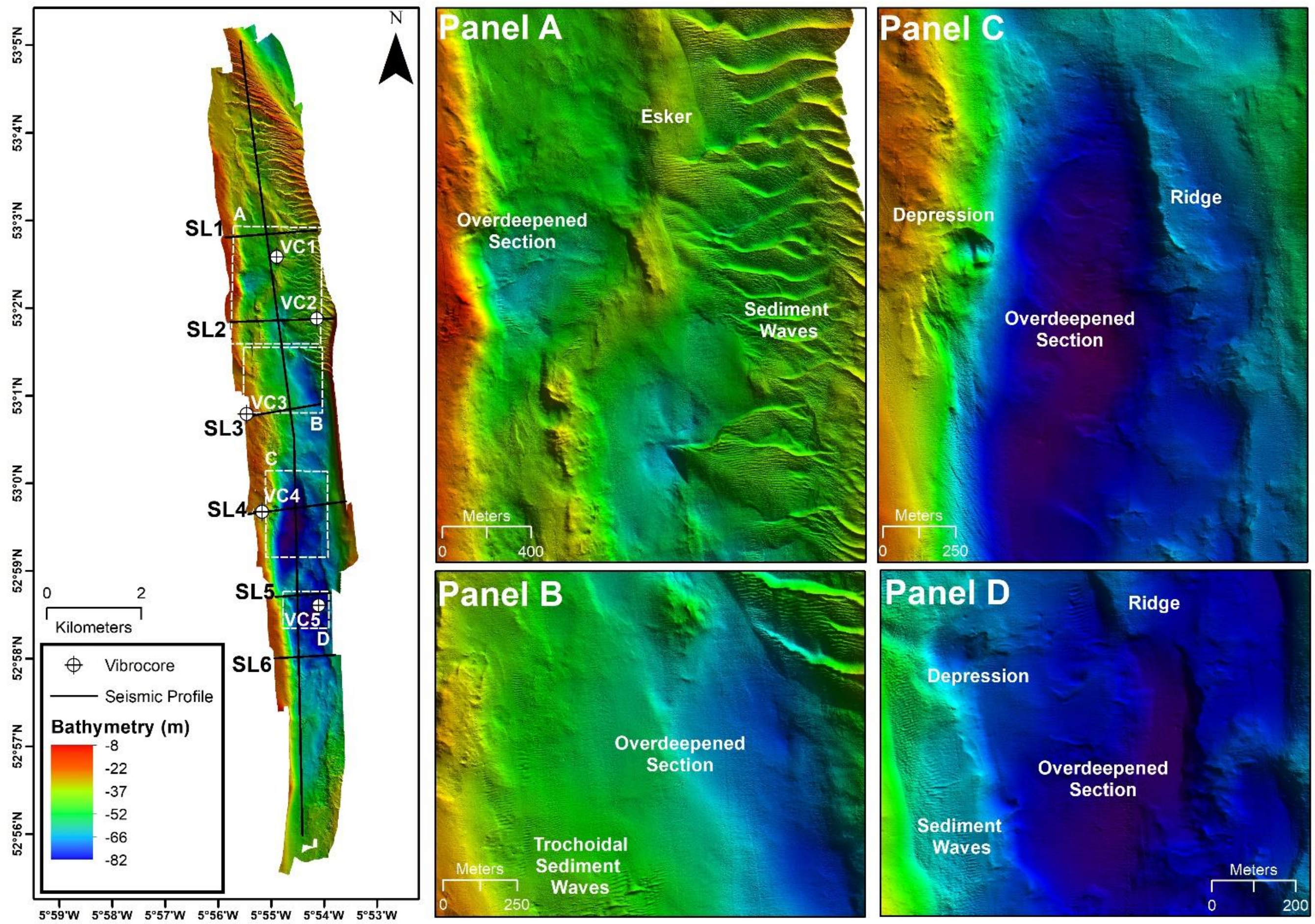

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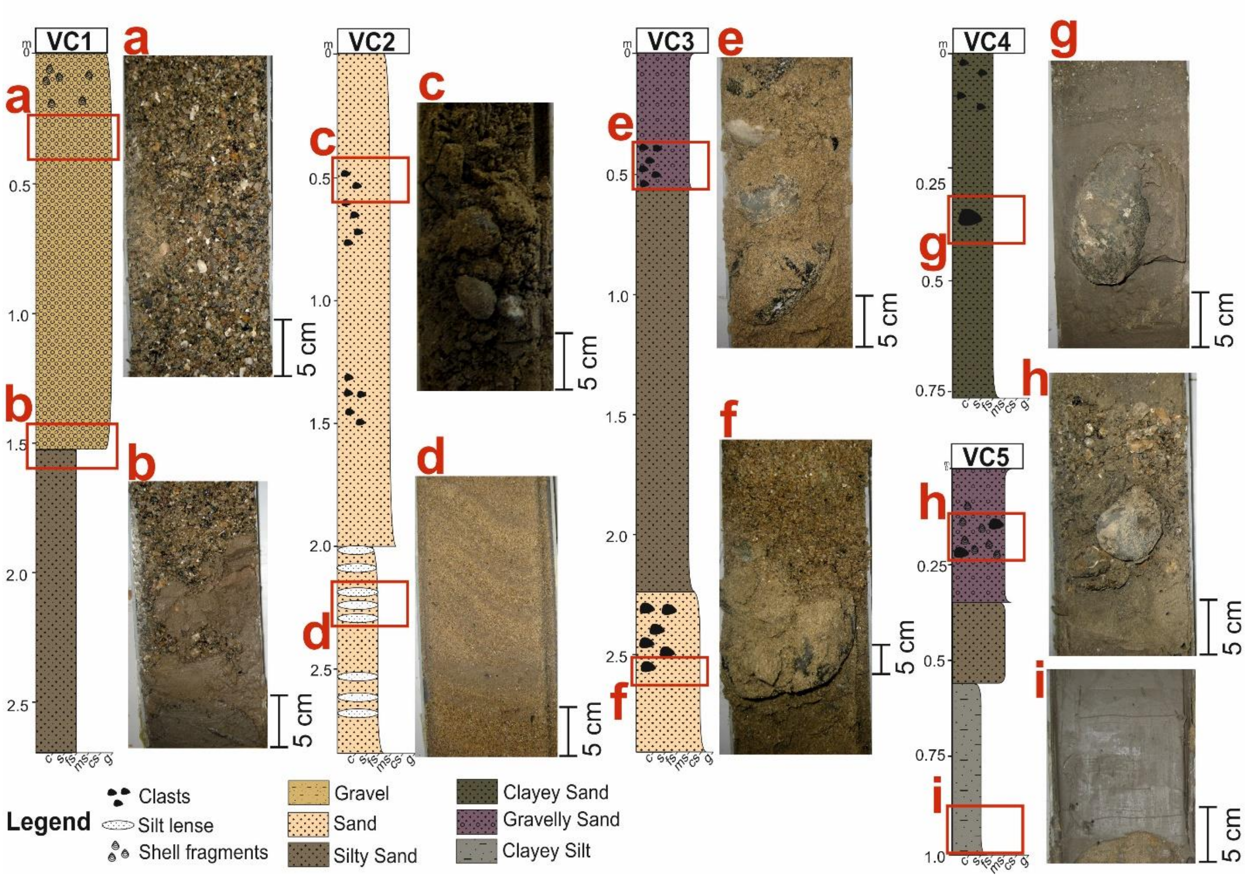
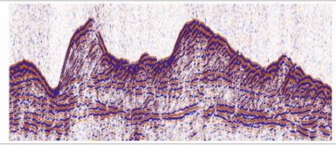
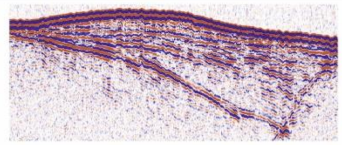
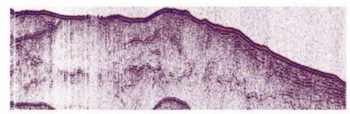
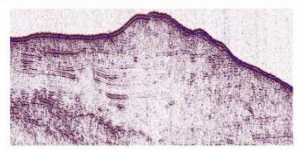
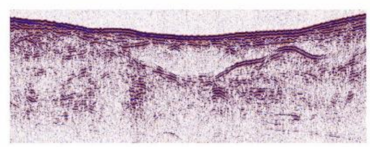
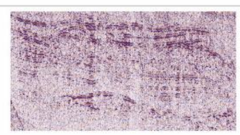
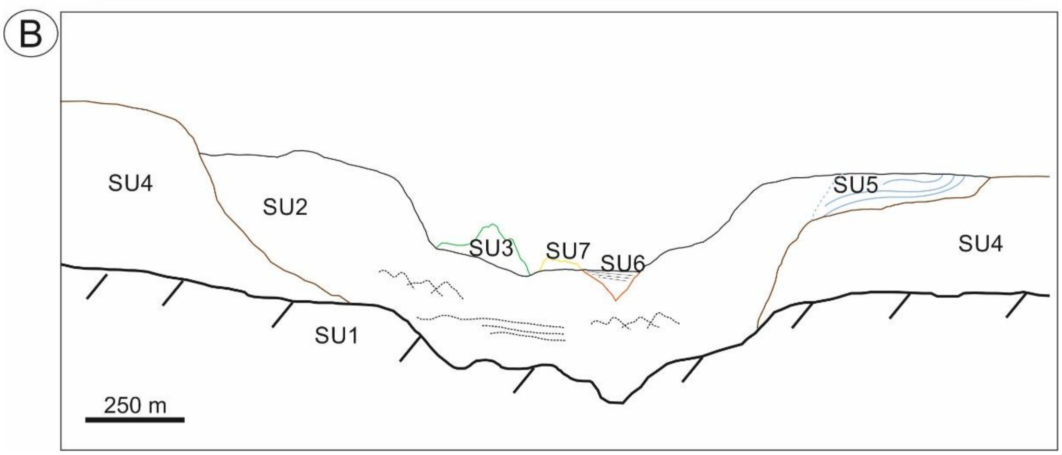


Figure 3 Logs of cores used in this study with core photography highlights.

A

Seismic Unit	Seismic character	Geological Interpretation & Correlation with Jackson et al. (1995)	Visual Example
SU7	Strong dipping reflectors with some cross bedding. Base is marked by strong erosive reflector.	Sediment waves, probably mobile from MBES data, consisting of recent sediments. Correlated with the SL1 member of the Surface Sands Formation	
SU6	Moderate to high amplitude oblique parallel and lenticular reflectors.	Correlated with the Seabed Depression member of the Surface Sands Formation Interpreted to comprise a sandy silt with shell debris, containing a rich temperate Marine microbiota.	
SU5	Gently dipping, parallel, medium to high amplitude reflectors. Reflectors are closely spaced.	No ground-truthing data available. May represent flank slide or slump deposits.	
SU4	The top of the unit contains moderate to strong chaotic reflectors that are discontinuous. The base displays laterally persistence reflectors.	Core profiles suggest varied lithology with silty sands, sometimes with cobbles. Correlated with the Upper Till member	
SU3	Contains internal reflectors that are gently dipping to sub-parallel and are laterally persistent.	Core profiles suggest gravelly sands and silty sands with shell fragments. May be correlated with the Prograded Facies This facies comprises sands with muddy and pebbly components	
SU2	Strong variance in signature. Generally has an amorphous signature with chaotic, laterally impersistent and hummocky reflectors. Sometimes contains prograding, dipping reflectors with moderate to high amplitude.	Similar in seismic character to the Chaotic Facies This facies is interpreted to comprise gavels with silts, sands and cobbles.	
SU1	Acoustically transparent with some strong to moderate parallel reflectors gently dipping.	Potentially bedrock. Lower Palaeozoic metasedimentary rocks.	



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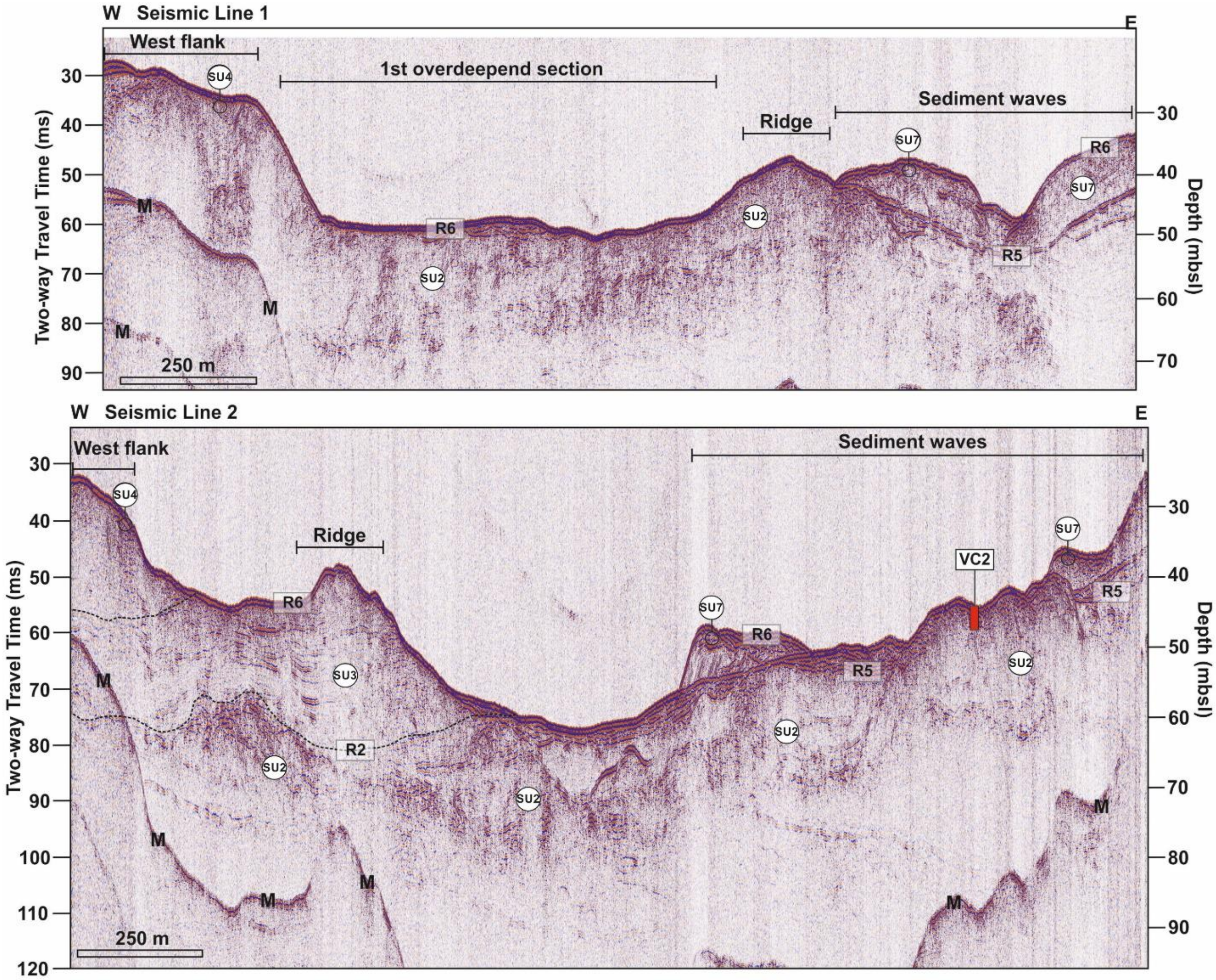

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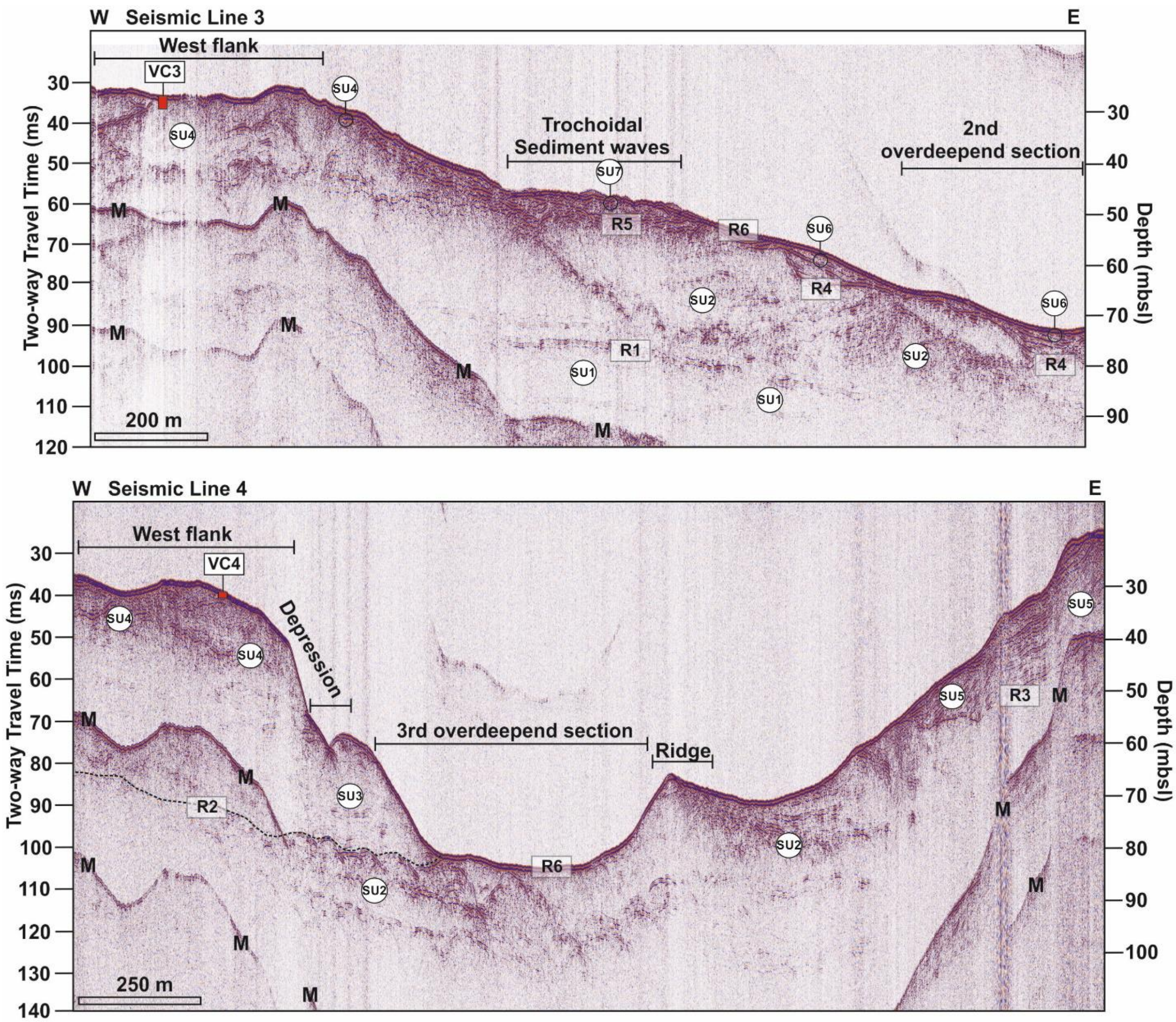


Figure 6 Seismic line 3 (SL3) and SL4 with seismo-stratigraphic interpretation and core locations with depth. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.

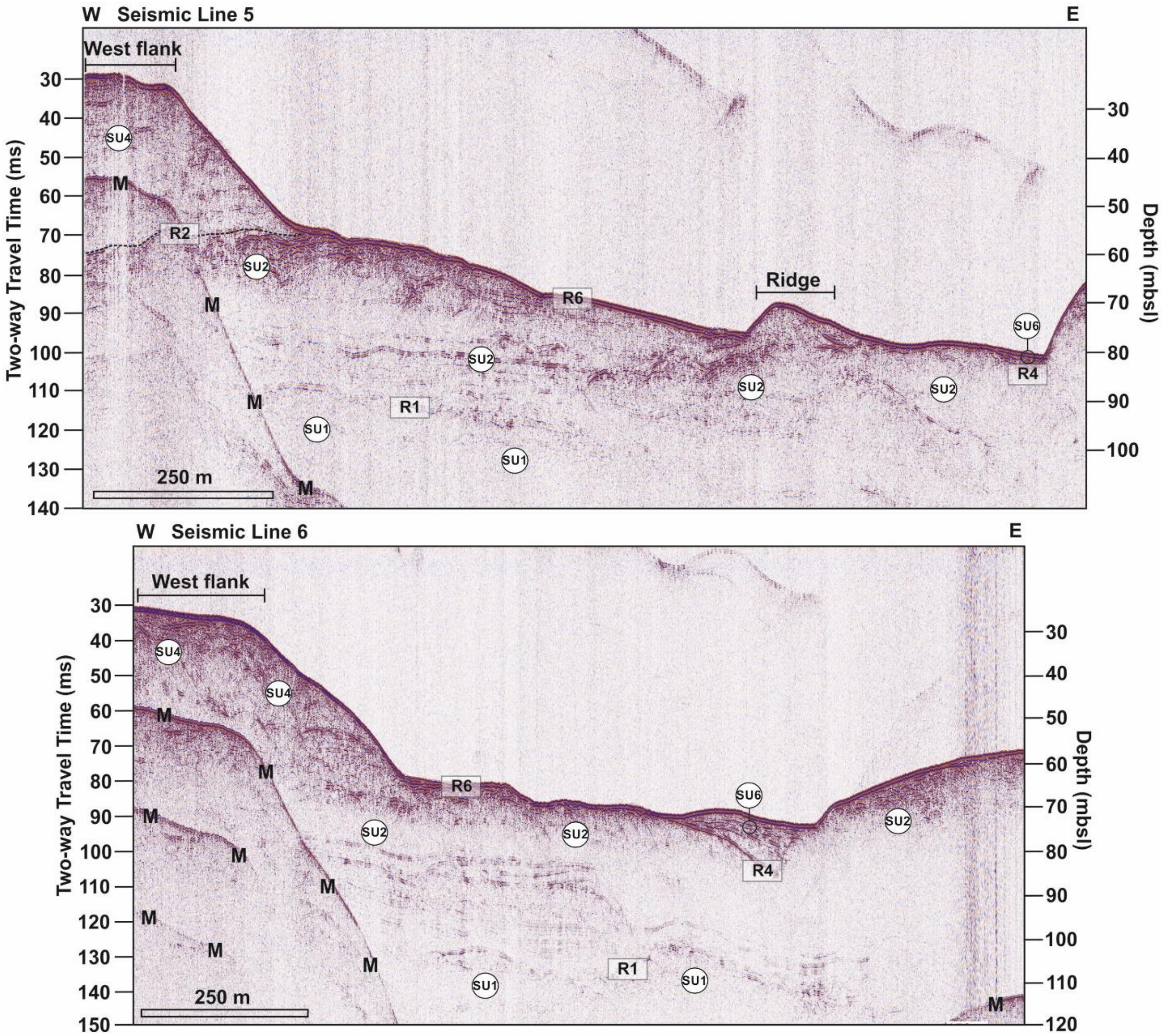


Figure 7 Seismic line 5 (SL5) and SL6 with seismo-stratigraphic interpretation. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.

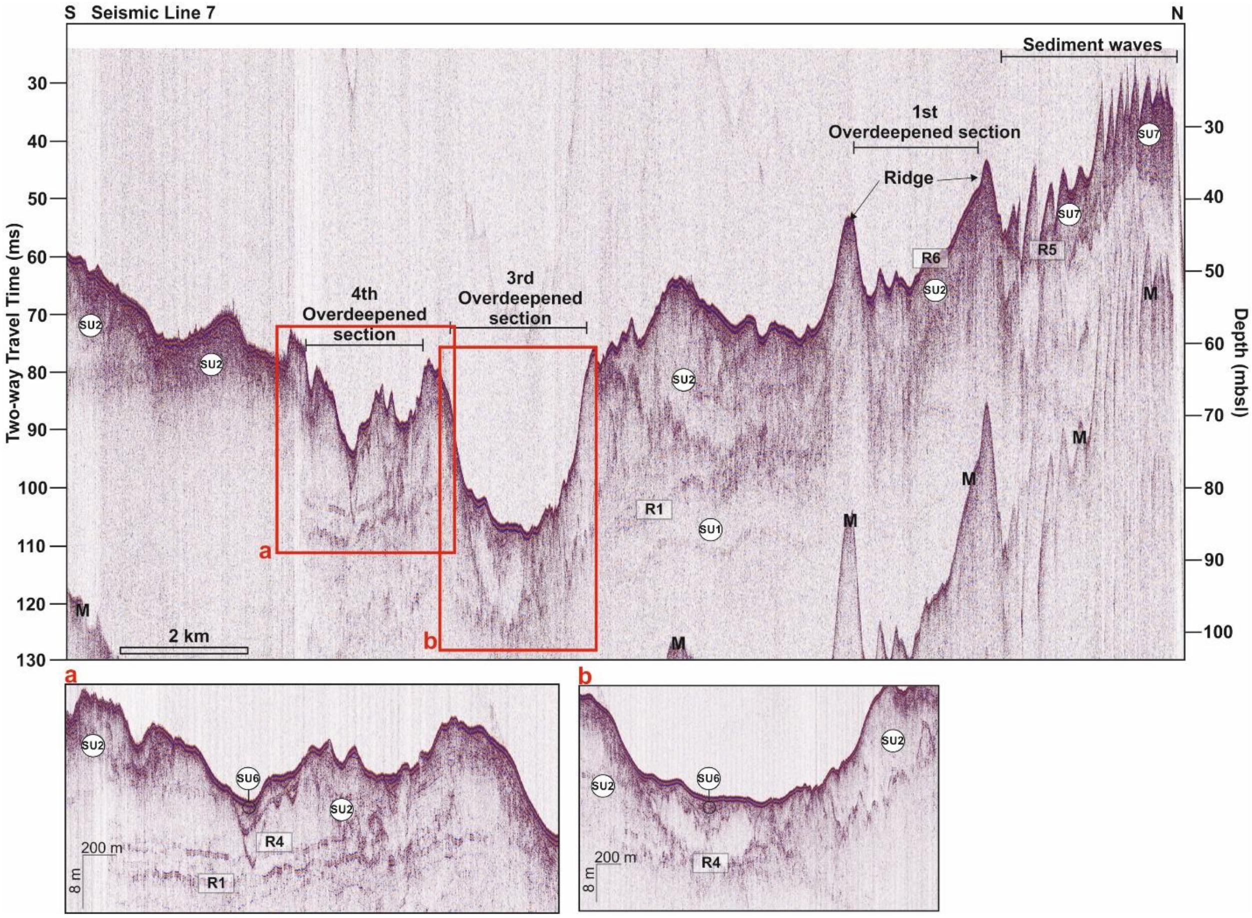
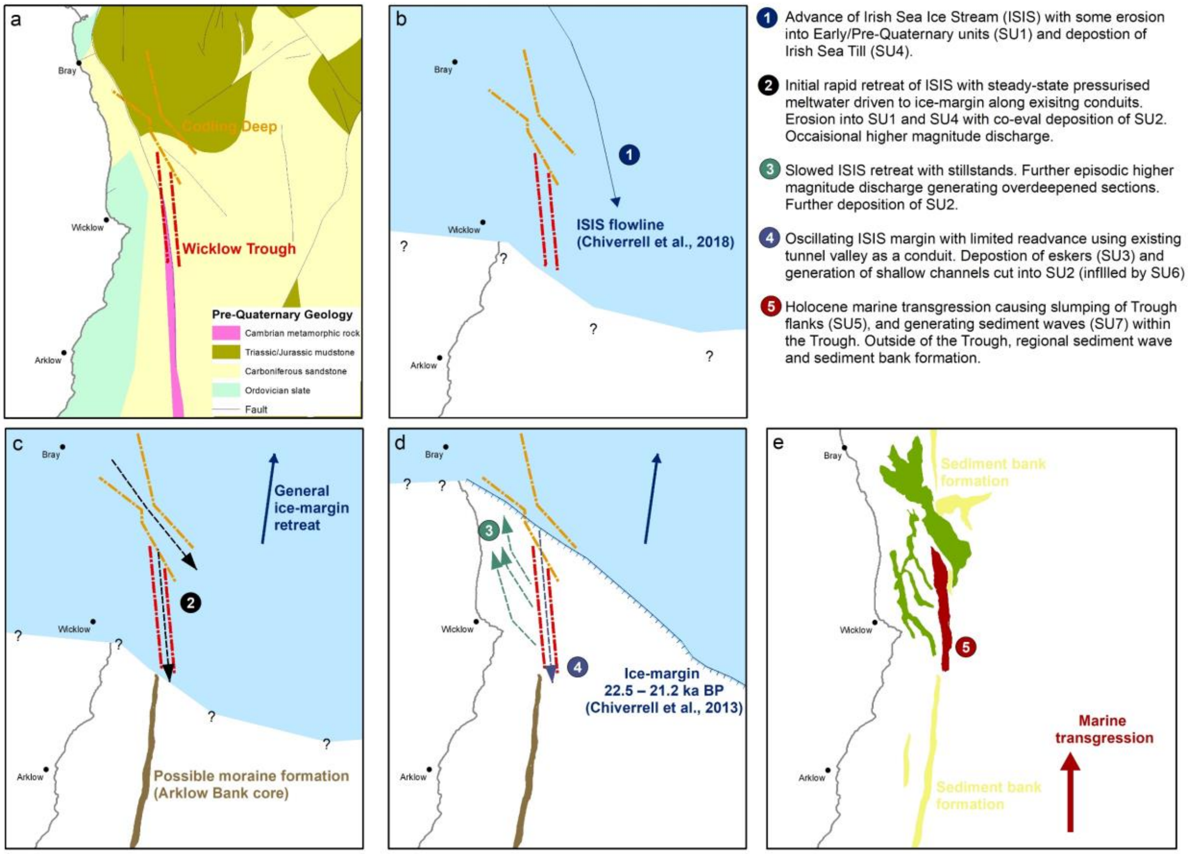


Figure 8 Seismic line 7 (SL7) with seismo-stratigraphic interpretation with highlighted features. Depth is presented in two-way travel time (TWT) and metres below seafloor (mbsf). 'M' indicates seabed multiple.



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