Ice sheet extension to the Celtic Sea shelf edge at the Last Glacial Maximum

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Abstract

Previous reconstructions of the British-Irish Ice Sheet (BIIS) envisage ice streaming from the Irish Sea to the Celtic Sea at the Last Glacial Maximum, to a limit on the mid-shelf of the Irish-UK sectors. We present evidence from sediment cores and geophysical profiles that the BIIS extended 150 km farther seaward to reach the continental shelf edge. Three cores recently acquired from the flank of outer Cockburn Bank, a shelf-crossing sediment ridge, terminated in an eroded glacigenic layer containing two facies: overconsolidated stratified diamicts; and finely-bedded muddy sand containing micro- and macrofossil species of cold water affinities. We interpret these facies to result from subglacial deformation and glacimarine deposition from turbid meltwater plumes. A date of 24,265 ± 195 cal BP on a chipped but unabraded mollusc valve in the glacimarine sediments indicates withdrawal of a tidewater ice sheet margin from the shelf edge by this time, consistent with evidence from deep-sea cores for ice-rafted debris peaks of Celtic Sea provenance between 25.5-23.4 ka BP. Together with terrestrial evidence, this supports rapid (ca. 2 ka) purging of the BIIS by an ice stream that advanced from the Irish Sea to the shelf edge and collapsed back during Heinrich event 2.

Keywords: British-Irish Ice Sheet; Last Glacial Maximum; Celtic Sea; Cockburn Bank; glacigenic sediments; Heinrich Event 2

1. Introduction

The maximum extents attained by former ice sheets provide a basic constraint on reconstructions of their thickness and dynamics. Although the southernmost extent of the last British-Irish Ice Sheet (BIIS) has long been disputed (e.g. Mitchell et al. 1973; Scourse 1991; Scourse and Furze 2001, Bowen et al. 2002), it is now agreed that onshore glacigenic deposits in Ireland and southern Britain provide evidence of an advance of the Irish Sea Ice Stream into the Celtic Sea during the Last Glacial Maximum (LGM), around 25-23 ka BP[1] (Scourse 1991; Ó Cofaigh & Evans 2001, 2007; Greenwood and Clark 2009; Chiverrell & Thomas 2010; Clark et al. 2010; McCarroll et al. 2010; Ó Cofaigh et al. 2012; Chiverrell et al. 2013). The extent of this advance across the continental shelf has been constrained by a dozen British Geological Survey (BGS) vibrocores acquired in the late 1970s that penetrated surficial sand and gravel to reach sediments of glacial character (Fig. 1; Pantin and Evans 1984). These undated sediments were interpreted to include subglacial till and glacimarine mud, and their distributions used to propose a grounding line on the mid-shelf, correlated to an LGM limit across the Isles of Scilly (Fig. 1; Scourse et al. 1990, 1991; Scourse and Furze 2001; Scourse et al. 2009b). Till-like sediments at the base of two cores near the shelf edge were suggested to represent residual ice-rafted deposits (Fig. 1; Scourse et al. 1990, 1991). The proposed grounding line has been noted to represent a minimum extent of glacial ice, given that glacimarine sediment at the base of several cores could be underlain by (un-cored) subglacial till (Sejrup et al. 2005). Ice-marginal landforms have not been recognized in the Celtic Sea,

[1] all ages in calendar years before present (BP)

which is dominated by a system of shelf-crossing ridges interpreted as palaeo-tidal sand banks (Stride 1963; Bouysse et al. 1976; Stride et al. 1982), overlain at one site (49/-09/44, Fig. 1) by both subglacial till and glacimarine mud (Pantin and Evans 1984; Evans 1990; Scourse et al. 1990, 1991, 2009b).

Here we present new field evidence of glacigenic sediments on the Celtic Sea shelf, the first in over three decades, including the first direct determination of their age. The results are based on sediment cores (obtained with a 6 m vibrocorer) and subbottom profiles (2-5 kHz pinger) acquired in 2014 by the R/V *Celtic Explorer* near the edge of the Irish continental shelf (Fig. 1). Our aim is to rapidly communicate findings that have broad significance for on-going investigations of the seaward extent and dynamics of the last ice sheet advance across the Celtic Sea. The implications of the results for the origin of the Celtic Sea ridges will be considered in a separate publication.

2. Results

The study area includes outer Cockburn Bank, a shelf-crossing ridge over 10 km wide that rises up to 50 m above the inter-ridge area to the SE (Figs 1, 2a). Pinger profiles show the ridge to be composed of weakly stratified sediments that thin across the inter-ridge area (Fig. 2b,c). Previous studies of the Irish-UK shelf assign upper Pleistocene sediments to a single unit, the Melville Formation, stratigraphically overlain by surficial sands and gravels 0-3 m thick that are only locally seismically resolved (e.g. Fig. 2c; Pantin and Evans 1984; Evans 1990).

2.1 Cored sediment facies

Three cores (≤1 m) from the lower flank of Cockburn Bank, located 1.1 km apart in water depths of 164-168 m (Fig. 2), penetrated brownish sand with gravel and shells up to 0.8 m thick, to terminate in up to 0.4 m of stiff to sticky greyish sediment (Fig. 3). The latter includes two facies, referred to as stratified diamict and bedded muddy sand, truncated by the surficial sandy layer (Fig. 3).

Stratified diamict: cores CE14003-VC60 and VC63 terminated in 0.21 m and 0.35 m respectively of stiff grey poorly-sorted and heterogeneous sediment, including contorted laminae of mud and fine sand with scattered granules, and lenses or beds of muddy sand with gravel and small shells, commonly aligned (Fig. 3). Shear strengths in the range of 3.6-5.8 kg/cm^2 indicate overconsolidation (Fig. 3; e.g. Anderson et al. 1991). In VC60, a prominent shear plane truncates a lower interval with subhorizontal laminae, beneath an upper interval including coarser lenses. In VC63, a lower laminated interval is truncated beneath an inclined series of sheared layers, or clasts, of stiff laminated diamict alternating with muddy sand with small aligned shells.

Bedded muddy sand: core VC64 terminated in 0.4 m of sticky grey finely-bedded to laminated sediment, consisting primarily of silty fine sand but with both finer and coarser layers, and some evidence of bioturbation (Fig. 3). The facies is denser than that in cores VC60 and VC63, but normally consolidated with shear strengths <3 kg/cm^2 (Fig. 3). The sediment contains a diverse microfossil assemblage, with reworked (broken/damaged) and *in situ* species; the latter include benthic foraminifera indicative of cold (boreal) waters (e.g. *Cassidulina reniforme*, *Islandiella norcrossi* and *Elphidium clavatum*), as well as differentsized growth series of ostracod instars suggesting a quiescent depositional environment. The basal 2 cm of the core yielded a chipped but unabraded valve of *Macoma cf. moesta* (Fig. 3d), a bivalve of Arctic distribution, that returned an AMS ^{14}C age of 24,265 ± 195 BP (24,460-24,070 cal BP, BETA #377772).

2.2 Seismic-scale sediment geometries

The three cores are comparable in length to the seabed return of the pinger (1-2 ms) and do not coincide with any reflection within the ridge (Fig. 2b,c). Thus the sediments at the base of the cores could correspond either to a thin layer at the top of the Melville Formation, or to its entire thickness (Fig. 2). Previous seismic profiles across the Celtic Sea ridges, including Cockburn Bank, show large-scale cross-beds indicating a mainly sandy composition (Stride 1963; Bouysse et al. 1976; Stride et al. 1982; Pantin and Evans 1984; Evans 1990; Marsset et al. 1999). We infer the lower flank of Cockburn Bank, over a distance of at least 1.1. km, to be capped by a thin (<1.5 m) layer of stratified diamict and bedded muddy sand, unconformably overlain by surficial sand and gravel (Fig. 3).

Across the inter-ridge area, the Melville Formation thins (<10 m) and is locally discontinuous (Fig. 2b,c). A diamict comparable to those in VC60 and VC63 was previously recovered 10 km to the SE in core 48/-10/53 (Fig. 2); the 2.2 m long core terminated in 6 cm of stiff grey sandy mud (>50% silt) with fine gravel (Scourse et al. 1990 and BGS field log). The core location is imprecise (≤1 km, Decca), but the depth of the diamict corresponds with the top of the Melville Formation (Fig. 2c). We infer that the eroded layer of stratified diamict and muddy sand at the top of the Melville Fm on the flank of Cockburn Bank extends at least 10 km across the inter-ridge area, as a layer of uncertain (0-10 m) thickness (Fig. 2c). A similar but sandier (>50%) stiff diamict was recovered at the shelf edge 75 km to the SE, adjacent to Little Sole Bank, in the lower 8 cm of 1.53 m long core 48/-09/137 (Fig. 2a; Scourse et al. 1990 and BGS field log), suggesting that such sediments may be discontinuously present beneath surficial sand and gravel along tens of kilometres of the outer Irish-UK shelf.

3. Discussion - glacigenic sediments at the Celtic Sea shelf edge

Our results show that stiff stratified diamicts are found on as well as adjacent to seabed ridges along the Irish-UK shelf edge (Fig. 2) and occur in association with bedded glacimarine sediment dated to the LGM (Fig. 3). We interpret these sediments as an eroded sheet of glacigenic deposits that includes both subglacially deformed and ice-proximal glacimarine sediment .

The stratified diamicts in cores VC60s and VC63 are overconsolidated and contain shears and contorted layers (Fig. 3), consistent with loading and deformation beneath a grounded ice sheet (Evans et al. 2006). Alternatively, such sediments might result from iceberg rafting and turbation, in which poorly-sorted debris is deposited and reworked, with pre-existing material, by icebergs ploughing the seabed (Dowdeswell et al. 1994). However, such a process does not account for the finely-bedded glacimarine sediments in VC64 (Fig. 3), which record suspension settling of silt and fine sand in a quiescent environment, with pulsed input of coarser material. Deposition of this sediment is difficult to explain by iceberg rafting on an open Atlantic shelf; moreover, iceberg turbation of the muddy sand would not in itself result in the stratified diamict.

We argue that the simplest means to explain the presence of both glacigenic facies observed at the shelf edge is the advance and retreat of a tidewater ice sheet margin. Ice advance across a mid-latitude Atlantic shelf implies glacimarine deposition by suspension settling from turbid and buoyant meltwater plumes, at rates that decrease seaward, in addition to contributions from ice rafting (Syvitski and Praeg 1989; Syvitski 1991). In our interpretation, the overconsolidated stratified diamicts on outer Cockburn Bank are subglacially deformed sediments that were originally deposited beyond the ice margin and then overridden during its advance (cf. Ó Cofaigh et al. 2011); these are overlain by undeformed muddy sands deposited proximal to the retreating ice margin from meltwater plumes, at rates that diluted any input of gravel from iceberg rafting. Grounding line retreat resulted in the time-transgressive deposition across the shelf of a sheet of glacigenic deposits, subsequently eroded and reworked by strong marine currents to contribute to the distribution of surficial sand and shelly gravel.

Our interpretation is compatible with evidence from glacigenic sediments previously cored across the Irish-UK shelf (Fig. 1), similarly inferred to form a discontinuous layer at the top of the Melville Formation on and between the seabed ridges (Pantin and Evans 1984; Evans 1990). Together with boulders found at seabed across the shelf, Pantin and Evans (1984) interpreted these sediments as ice-rafted material, but noted that they could also be interpreted as an eroded sheet of glacial deposits. The cored sediments were interpreted by Scourse et al. (1990, 1991) to include overconsolidated and homogenous lodgment till deposited beneath an ice margin grounded on the mid-shelf, overlain in one core from a ridge flank (49/-09/44, Fig. 1) by glacimarine mud, consistent with landward retreat of a tidewater ice sheet margin; to seaward, ice rafting was argued to account for the deposition either of glacimarine mud or, near the shelf edge, of till-like sediment (Fig. 1). The latter comprises the stiff diamict of cores 48/-10/53 and 48/-09/137 described above, its texture and poor microfossil content noted to reflect ice-proximal or lodgment till affinities (Fig. 1; Scourse et al. 1990, 1991). Based on our cores, we suggest this to be subglacially deformed sediment, part of a sheet of overconsolidated diamicts likely to be present across the shelf, including beneath cored glacimarine muds as suggested by Sejrup et al. (2005).

The finely-bedded glacimarine sediment in VC64 is comparable to the Melville Laminated Clay in cores farther landward on the shelf (Fig. 1), which grain size analyses show to consist of sandy silt to silty sand, almost entirely lacking in gravel, and containing an ostracod fauna indicating extremely low energy conditions of almost no currents (Scourse et al. 1990, 1991; Scourse and Furze 2001). Scourse et al. (1990, 1991) acknowledged that the presence of such deposits across an open Atlantic shelf was difficult to explain by iceberg rafting, especially given glacially lowered sea levels for which modeling suggests significantly increased tide and wave energies in the Celtic Sea (Belderson et al. 1986; see Scourse et al. 2009b). We note that along tidewater ice sheet margins the action of tidal and wave-induced currents may be limited by water column stratification, due to summer input of turbid and buoyant meltwater plumes and winter sea ice cover, which together favour low energy seabed conditions (Syvitski and Praeg 1989; Syvitski 1991).

3.2 Implications for BIIS advance and retreat

On the above interpretation, the radiocarbon date on a single mollusc valve from glacimarine sediment in VC64 provides a maximum age on sedimentation along a tidewater ice margin, which was retreating from the shelf edge after 24.3 ka BP. This compares with evidence from deep-sea cores on the Celtic margin for increases in ice-rafted debris (IRD) of Irish-Celtic Sea provenance, with a smaller peak at c. 25.5-24.5 ka BP and a main peak at 23.6-23.4 ka BP encompassing Heinrich Event 2 (HE2; Scourse et al. 2001, 2009a; Auffret et al. 2002). These peaks are consistent with evidence from southern Ireland and the Isles of Scilly for an advance and retreat of the Irish Sea Ice Stream (ISIS) around 25-23 ka (Ó Cofaigh and Evans 2007; Ó Cofaigh et al. 2012; McCarroll et al. 2010; see Chiverrell and Thomas 2010; Chiverrell et al. 2013). Greenland ice cores record a northward migration of the polar front during this period, suggesting the IRD peaks correspond to ISIS advance under cold conditions before 24.5 ka BP, followed by retreat under warmer conditions (Scourse et al. 2009a). This is supported by numerical modeling of the BIIS of increases in iceberg flux during rapid phases of ice stream advance and retreat, as part of binge-purge cycles that were phase-locked to regional climate variations with <1 ka delay (Hubbard et al. 2009).

Our results thus support previous interpretations linking IRD flux in deep-sea cores to a short-lived advance and retreat of the Irish Sea Ice Stream (Scourse and Furze 2001; Scourse et al. 2009a,b). However, they further indicate that the BIIS extended across the Celtic Sea to the Irish-UK continental shelf edge, up to 150 km seaward of previously proposed limits (Fig. 1). We infer a rapid (2 ka) purging of the ice sheet, involving a cycle of ISIS advance and collapse during HE2. Our results add to regional evidence of a highly dynamic BIIS drained by marine-based ice streams (Clark et al. 2010). Further field data and modeling studies are required to test our findings, which have implications for the thickness of the BIIS, for the dynamics of the ISIS in interaction with changing sea levels, as well as for the age and origin of the seabed ridges.

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Figure Captions

1 – The Celtic Sea relative to ice sheet limits. Top left: Quaternary ice sheet extents after Svendsen et al. (2004). Main figure: minimum extent of the last British-Irish Ice Sheet (BIIS) from Sejrup et al. (2005), including a proposed grounding line on the Celtic Sea mid-shelf suggested to record an advance of the Irish Sea Ice Stream (ISIS) to the northern Isles of Scilly (based on similar heavy mineral assemblages in the Scilly and Melville Tills; Scourse et al. 1990, 1991). The grounding line was drawn from the distribution of glacigenic facies (Scourse et al. 1990, 1991) at the base of ten vibrocores acquired in the late 1970s by the then Institute of Geological Sciences, now British Geological Survey (BGS). System of seabed ridges up to 60 m high mapped from Olex data(Gebco08). GS = Great Sole Bank, Co = Cockburn Bank, LS = Little Sole Bank.

2 – Study area at the shelf edge of the Irish-UK Celtic Sea: a) Location of data acquired on and adjacent to Cockburn Bank during the CE14003 campaign of the Celtic Explorer, relative to existing data held by BGS and OGS (seabed ridges drawn from Olex data, edges approximate; Co = Cockburn Bank, LS = Little Sole Bank); b) 2-5 kHz pinger profile across the lower flank of Cockburn Bank, showing locations of acquired cores; c) composite interpreted profile across Cockburn Bank and the inter-ridge area to the SE, showing correlation to

stratigraphic units of Pantin and Evans (1984) as well as the projected locations of the acquired cores and of BGS vibrocore 49/-10/53.

3 –Results from cores CE4003-VC64, VC63 and VC60: a-c) photographs, X-radiographs, interpreted lithofacies and physical properties (density from GeoTek MSCL densiometer, shear strength from hand-held Torvane); d) photo of chipped but unabraded valve of *Macoma moesta* washed from lower 2 cm of VC64, which yielded an AMS ^{14}C age of 24460-24070 Cal BP (BETA-377772).

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Figure 1
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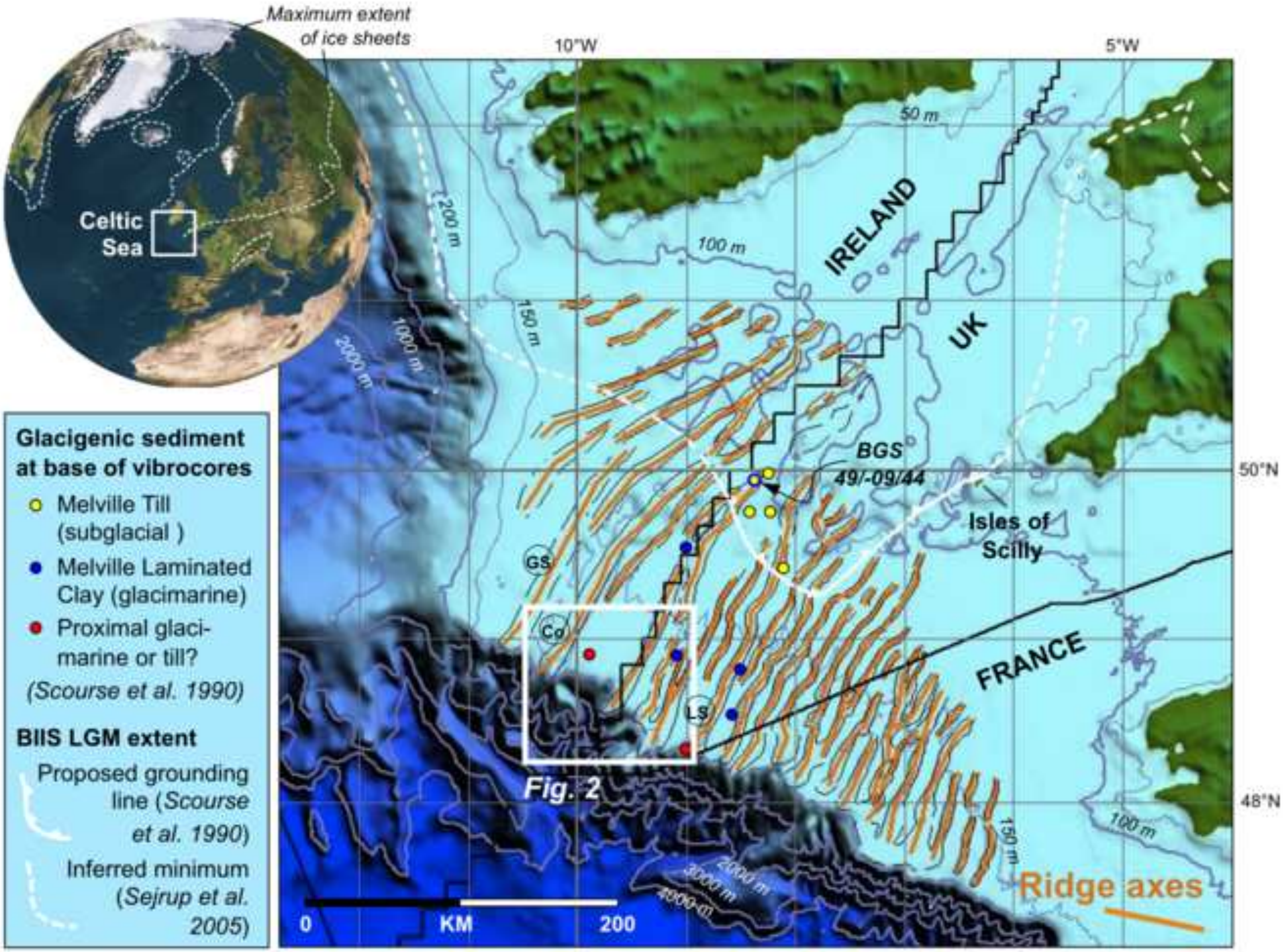

Figure 2
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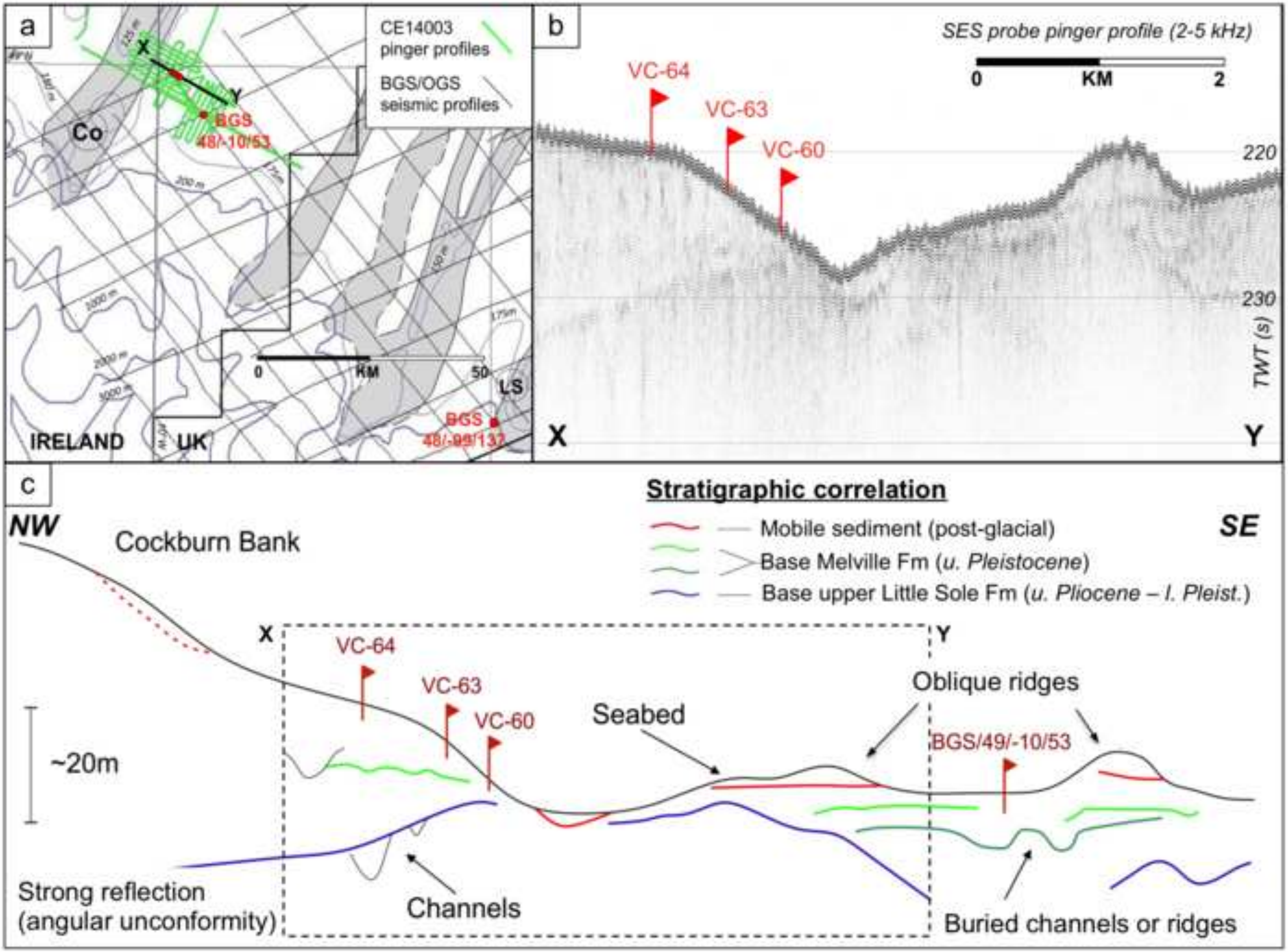

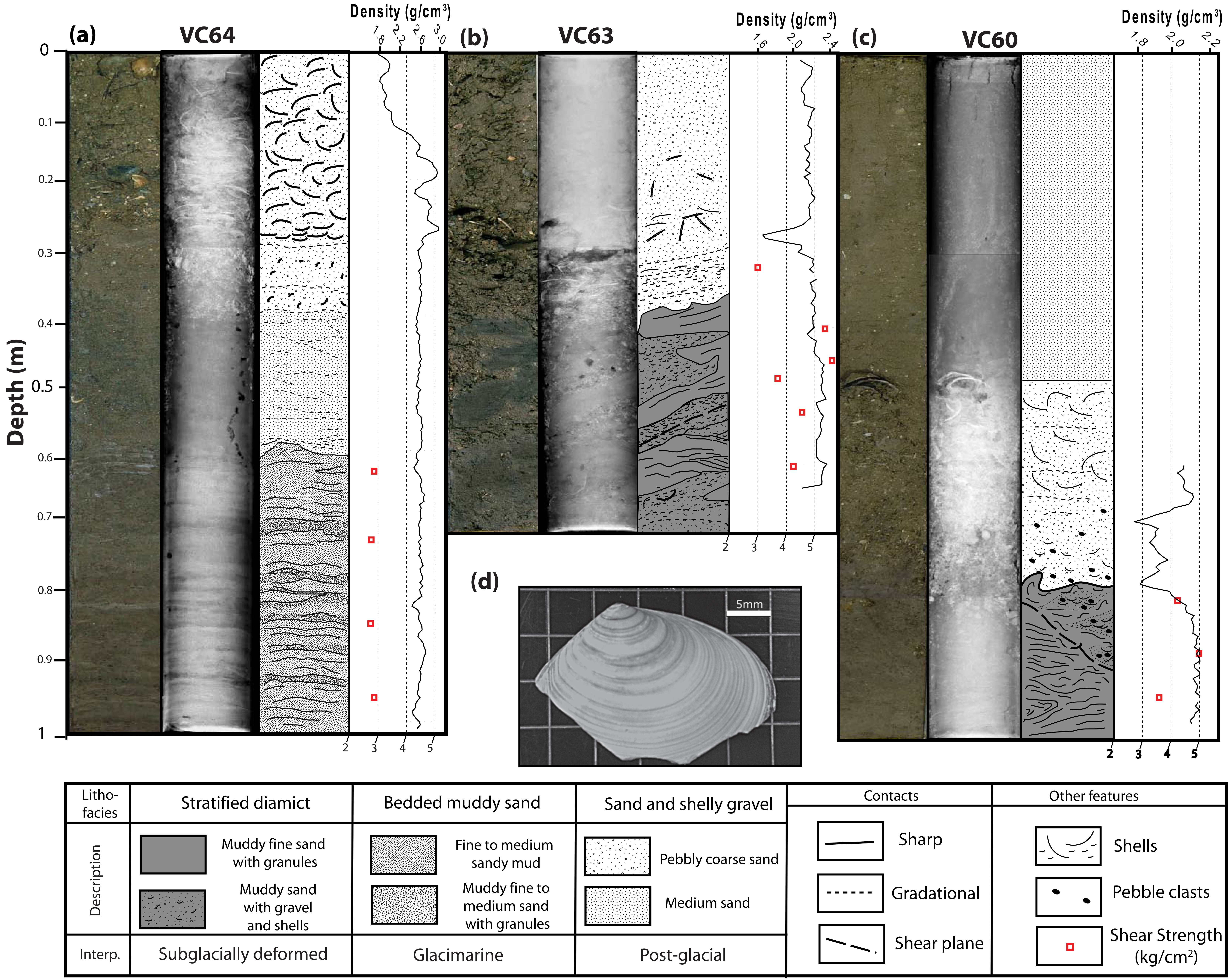

(a)
VC64
Density (g/cm³)
1.8
2.2
2.6
3.0
(b)
VC63
Density (g/cm³)
1.6
2.0
2.4
(c)
VC60
Density (g/cm³)
1.8
2.0
2.2
Depth (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
(d)
5mm
Litho-facies
Stratified diamict
Bedded muddy sand
Sand and shelly gravel
Contacts
Other features
Description
Muddy fine sand with granules
Muddy sand with gravel and shells
Fine to medium sandy mud
Muddy fine to medium sand with granules
Pebbly coarse sand
Medium sand
Sharp
Gradational
Shear plane
Shells
Pebble clasts
Shear Strength (kg/cm²)
Interp.
Subglacially deformed
Glacimarine
Post-glacial