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Sea-level change and inner shelf stratigraphy off Northern Ireland

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Abstract

New seismic stratigraphic, vibracore and AMS ^{14}C dates from two sites off the Northern Ireland coast yield information on the deglacial to present sea-level history and shelf evolution of the region. A lowstand of sea level at about 30 m below present sea level recorded by fossils in a lowstand shoreline deposit occurred around 13.4 cal ka B.P. following a period of rapid isostatic uplift associated with a RSL fall of 6–7 cm/yr.

Following the lowstand, contrasting styles of sedimentation characterized the two study sites. In the sheltered environment of Belfast Lough, the lowstand shoreline was overtopped and buried by transgressive facies of intertidal and shallow sub-tidal mud and sandy mud. On the high-energy Portrush coast, the inner shelf sedimentary sequence is characterized by a basal conglomerate overlain by well-sorted sands with occasional interbedded gravel.

Keywords: sea-level change; late Quaternary; Northern Ireland; seismic reflection; vibracores; isostasy

1. Introduction

Observations on changes in the sea level (Fairbanks, 1989; Chappell and Polach, 1991; Barnhardt et al., 1997) have led to sophisticated numerical models which estimate changes in sea level due to isostasy and eustasy on a global scale (Lambeck and Purcell, 2001; Peltier, 2002; Clark and Mix, 2002). These models serve as a proxy for observational data in most locations because of the scarcity of direct observations. This is especially true with respect to the position of local relative sea levels at lower-than-present locations. A shortcoming of the global models, however, lies in their low spatial resolution. With the relatively small model grid cells employed, extensive areas of formerly glaciated terrain are represented by a single sea-level curve. This problem becomes especially acute along continental margins where models are often unable to cope with local (short wavelength) variations in lithospheric thickness as well. Reliance on uncertain ice thickness estimates and the timing of deglaciation can further weaken model accuracy. This proves frustrating to those gathering the field data that are used in models; while field observations were the fundamental data which spawned models, the models often do not feed back adequately to assist in solving regional geological and stratigraphic problems (McCabe, 1997).

In Ireland, many archeological and natural history questions revolve around whether changing sea levels permitted a land bridge to Great Britain (Mitchell and

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Ryan, 2001; Devoy, 1995). Similarly, research on glacial stratigraphy (Clark et al., 2004) and coastal evolution (Shaw and Carter, 1994) relies on an understanding of late Quaternary, relative sea-level changes. Models presently provide a crude framework for understanding the sea-level history of this area (Lambeck and Purcell, 2001; Lambeck and Chappell, 2001; Shennan et al., 2002a,b), but the timing and extent of glaciation/deglaciation, the continental margin location and the extensive perimeter of the island setting present a challenge to accurate models (McCabe, 1997; McCabe et al., 2005).

In 1998 we gathered some of the first seismic reflection data from offshore of Northern Ireland, and speculated on a sea-level lowstand position there at 30 m water depth (Cooper et al., 2002). Here we present the interpretation of additional seismic reflection data and underwater vibracores from east of this previous work, and data from new underwater vibracores. These vibracores provide ground truth to our remotely sensed observations of Northern Ireland's inner shelf, and also represent the first published descriptions of the late Quaternary stratigraphy of that region's inner shelf. In addition, a series of new radiocarbon dates of vibracore subsamples provides a chronological context for sea-level change.

2. Location and geological setting

The study sites are located in Northern Ireland, United Kingdom, between the 20 m and 40 m isobaths in outer Belfast Lough, and between 15 m and 30 m isobaths offshore of Portrush, County Antrim, some 90 km northwest of Belfast (Fig. 1). The bedrock in this region is dominated by extensive flows of Tertiary basalt that form 80 m high cliffs between the two study sites (Wilson, 1972). The basalt overlies Cretaceous chalk that also crops out on the western side of Belfast Lough and along the north coast. A dolerite sill forms a chain of small islands (The Skerries) that partly shelter the Portrush study area. A large beach (Curran Strand) exists in the lee of The Skerries, and smaller, pocket beaches occur in several other locations (Fig. 1b). Belfast Lough forms a 20 km-long, 10 km-wide indentation in the Northern Ireland coast that is the geomorphic expression of a bedrock fault subsequently modified by ice erosion (Manning et al., 1970). Bedrock along the Belfast Lough shoreline includes material ranging from Paleozoic to Tertiary age (Geological Survey of Northern Ireland, 1997).

Glacial ice covered this area in the late Quaternary. The late glacial history is complex, with early ice advancing from Scotland, and later ice confined to local ice caps in mountains (McCabe, 1987; McCabe et al., 2005). Glacial sediments crop out locally along the coast, and a large moraine is believed to underlie Causeway Bank (Fig. 1).

Glacial-marine muddy sediment accumulated during deglaciation (McCabe et al., 1994). It is widespread offshore (Cooper et al., 2002), and crops out along the coast and inland to about 20 m elevation (McCabe et al., 1994; McCabe et al., 2005). It has not been dated where it is best exposed at Portballintrae (Fig. 1), but is a time-transgressive deposit which, through its contained foraminiferal fauna, has provided high resolution temporal constraints on the deglacial history of the region (McCabe and Clark, 2003; McCabe et al., 2005). At Portballintrae (Fig. 1) sand and gravel rest unconformably on glacial-marine mud (McCabe et al., 1994). This offlap deposit is up to 3 m thick and dips offshore along the coast (photographs in Cooper et al., 2002, their Fig. 3).

The seafloor near Portrush is generally sandy (Lawlor, 2000). The sand is well sorted and relatively fine, with a mean size between 1–3 phi. Bedrock crops out locally near the cliffed coast and near the Skerries. Adjacent to rock outcrops and in constrictions formed by it, gravel dominates the seafloor. Mud occurs throughout much of Belfast Lough, although rock crops out in several places (Parker, 1982).

The seafloor dips gently seaward from the sandy beaches until about the 30 m isobath. Off high cliffs it drops off more rapidly and the seafloor is highly irregular (Cooper et al., 1998; Lawlor, 2000). The Causeway Bank, off Giants Causeway, forms a linear bathymetric shoal parallel to the coast with 5–10 m of bathymetric relief (Fig. 1b). The muddy bottom of Belfast Lough very gently deepens from the inner to the outer Lough (Fig. 1c).

The coast is wave dominated, with a significant wave height of around 2 m on the north coast, falling to 1.3 m at Belfast (Jackson et al., 2005). Wind is generally from the southwest.

3. Previous work

Recent analysis of late glacial microfossils (McCabe et al., 2005) has demonstrated major millennial-scale events during the deglacial period in which isostatic and eustatic effects have combined to produce a complex, late Quaternary regional sea-level history. This field data is at odds with numerical models of sea-level variability (Lambeck and Purcell, 2001; McCabe et al., 2005) and points to more complex cryo–lithosphere interactions than currently assumed.

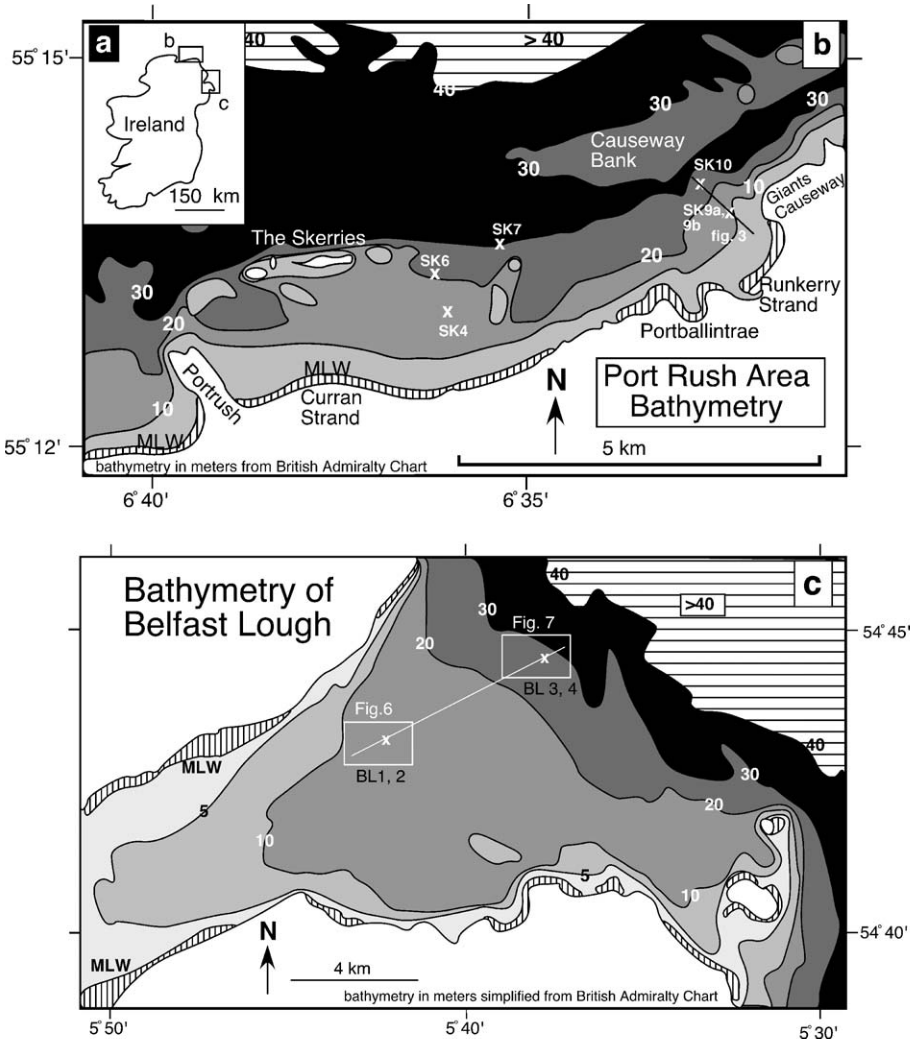

Fig. 1. Map of the study areas. a) Map showing the study areas in Northern Ireland. Boxes are enlarged in b and c. b) Bathymetric map of Northern Irish coast from Portrush to Giants Causeway; c) bathymetric map of Belfast Lough. The numbered lines are seismic tracks shown in later figures. On b and c the numbered lines are seismic tracks shown in later figures, cores are labeled and located with an x. Bathymetric contours are labeled; the vertically rules area is intertidal.

Carter (1982) summarized early work on Holocene sea levels in the area. He recognized a higher-than-present sea-level position in post-glacial times at +5 m approximately 5 ka BP, and speculated on a Holocene lowstand around 15 m below present sea level at approximately 10 ka BP. He noted, however, that there was no field data to support either the depth or time of the lowstand. (Fig. 2).

The transgressive stratigraphy in upper Belfast Lough was recorded in many foundation investigations (Manning et al., 1970) and comprises a freshwater peat up to 1 m thick at depths down to 15 m below present sea level. This is overlain by a sequence of clays subdivided on the basis of their molluscan fauna into lower, intermediate and upper units. The lower unit contains an intertidal fauna and remains of the intertidal seagrass, *Zostera marina*. It varies in thickness from 15 cm to 4.3 m. The intermediate unit is characterized by abundant *Pholas* sp. and indicates increasing water depth. The upper unit contains abundant molluscs of diverse types, and is interpreted as deepwater estuarine conditions with a water depth of 9 to 10 m (Manning et al., 1970). The basal peat was dated at 10.3 ka cal BP (9130 ± 120 BP, radiocarbon years) at −12 m while wood from −9 m dated at 9.8 ka cal BP (8715 ± 200 BP, radiocarbon years) (Fig. 2) (Manning et al., 1970). The peat dates, while not sea-level indicators, constrain sea level below these depths at specific times.

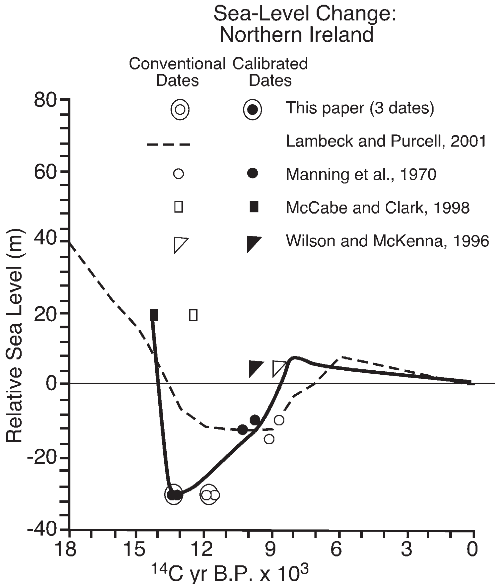

Fig. 2. Sea-level reconstruction for Northern Ireland. Conventional and calibrated (Calib, ver. 5.0) radiocarbon dates are shown for earlier freshwater peat dates in Belfast Lough (Manning et al., 1970) and the River Bann (Wilson and McKenna, 1996) discussed in text, for highstand date on Rough Island (McCabe and Clark, 2003), and from this work. Dashed curve represents modeled sea-level record in conventional radiocarbon years for area east of Belfast Lough by Lambeck and Purcell (2001).

Cooper et al. (1998, 2002) gathered the first extensive seismic reflection and side scan sonar records from off Northern Ireland. They recognized Quaternary stratigraphic units in the offshore directly seaward of Portballintrae, where McCabe et al. (1994) had described them on land. The section they interpreted included bedrock as basement, with patches of scattered till resting on it. Glacial-marine mud was common and cropped out commonly in water depths greater than 30 m. Surficial sand rested unconformably on the glacial-marine mud. Out to 32 m water depth, the sand ranged up to 10 m in thickness and extended as a sheet-like deposit. Seaward of 30 m isobath, sand was worked into sandwaves with several m of relief. Glacial-marine mud appeared to crop out in swales between the sand waves.

Cooper et al. (2002) suggested that the lowstand of sea level in the Portrush study area was near 32 m below present sea level based on: 1) erosional notches cut in till and bedrock (their Fig. 7), and 2) the termination of offlap sand units observed on land (their Fig. 7). They speculated that the reflectors within the surficial sand unit might be peat deposits similar to peat that was recorded <10 km to the west in the River Bann estuary by Wilson and McKenna (1996), as well as in Belfast Lough (Manning et al., 1970). More recently, McDowell et al. (2005) interpreted seismic reflectors 10 km west of Portrush as possible peat layers.

A broadly similar deglaciation and sea-level history was developed for Scotland (Shennan et al., 2002a,b, 2005; Lloyd et al., 1999). The land-based record from locations near Northern Ireland appear well constrained, but suggest no excursion of sea level much below present in the late Pleistocene/early Holocene (Shennan and Horton, 2002). Many of the lowstand curves from here have no data from the time of the sea-level lowstand, however (Shennan and Horton, 2002).

4. Methods

In June 1997 we gathered seismic reflection observations with a 2–16 kHz swept frequency Edgetech X-Star chirp towfish. We gathered 150 km of tracklines from the Portrush study area and 70 km of tracklines from the Belfast Lough site. Navigation was logged from a DGPS receiver and was accurate to ±10 m. Rossfelder-type vibracores were collected from the *R/V Lough Foyle* in June 2004 on the basis of the seismic reflection profiles. The corer was a Rossfelder P-3 model with a steel barrel and 7.5 cm diameter plastic liner. It was outfitted to collect up to 6 m long cores.

After return of the corer to the deck, cores were cut into 1.5 m lengths if long enough. They were capped and stored upright on the deck and returned to the sedimentology laboratory at the University of Ulster within a week. In the lab, cores were opened, photographed and described. Samples were removed for grain size analyses and all shells in one half of the core were removed for possible radiocarbon dating.

Shells from the cores were identified at the Ulster Museum (Dr Julia Nunn personal communication). Samples selected for radiocarbon dating were stored in aluminum foil until shipment. Radiocarbon dates are reported as calibrated ages with a reservoir correction of 400 years (Stuiver and Reimer, 1993, Calib. version 5.0.2).

5. Results

5.1. Seaward of the Causeway Coast

Seismic reflection observations landward of the Skerries were all similar. We interpret glacial-marine sediment (Gm) to represent acoustic basement in most areas (Figs. 3 and 4). Its surface is marked by a strong, continuous reflector to about the 30 m isobath. Seaward of this depth, till and bedrock crop out near The Skerries

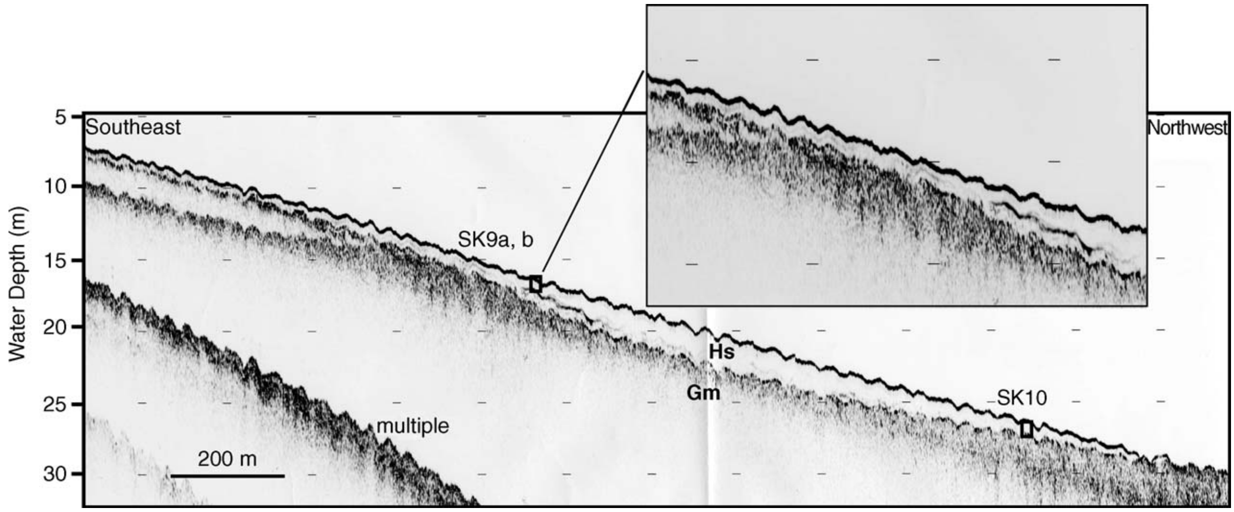

Fig. 3. Interpreted seismic reflection profile showing core targets off Runkerry. Locations of profiles and cores are shown on Fig. 1b. Gm is glacial marine, Hs is Holocene sand.

and Causeway Bank, but glacial-marine material is observed further offshore beneath large sandy bedforms (Cooper et al., 2002). Unconformably overlying the glacial-marine mud is an acoustically transparent unit with prominent internal reflectors. From side scan sonar observations and surficial grab samples, we know this acoustic unit is principally sand (Hs) (Cooper et al., 1998; Lawlor, 2000). This surficial sand unit is less than 5 m thick, and dips seaward. It abruptly thins and terminates at the 30 m isobath in most locations (Cooper

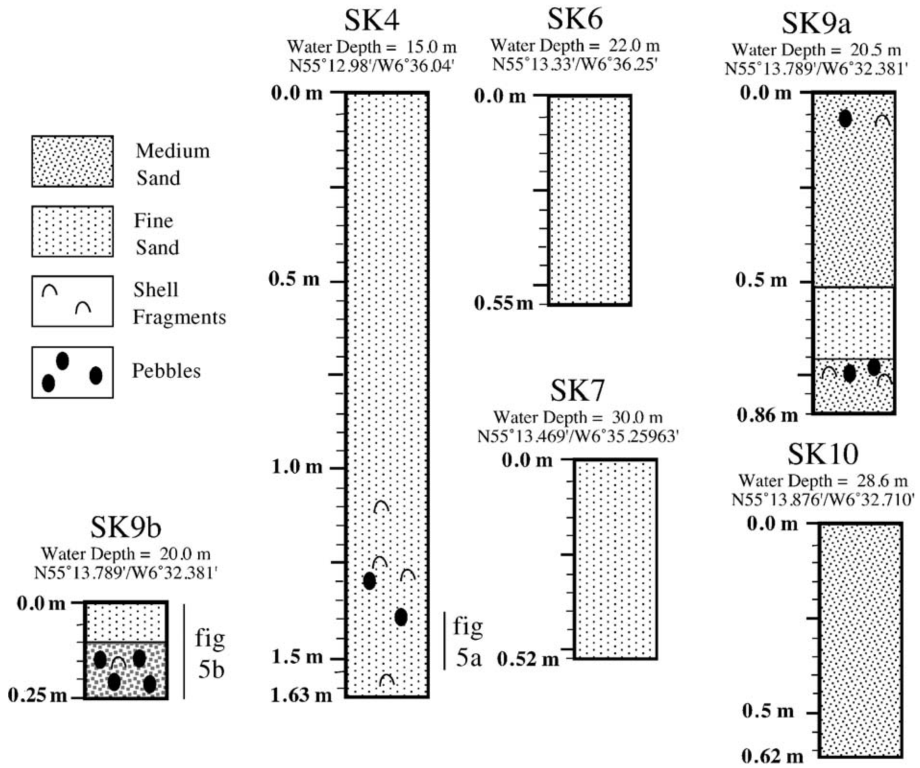

Fig. 4. Core logs for Skerries area. Lines show location of core photos shown in Fig. 5; core locations shown in Fig. 1b.

et al., 2002) (Fig. 3). The strong reflectors within the surficial sand unit generally dip seaward and terminate on the glacial-marine contact at water depths between 15 and 20 m. In some places these reflectors are closely spaced and subparallel to the seafloor, as off the River Bann to the west (McDowell et al., 2005); in other areas they take on a channel-like appearance (Cooper et al., 2002). They approach the surface in most locations and appear to crop out on or very near the seafloor off Runkerry Strand (Fig. 3).

Three vibracores were gathered landward of the Skerries, and three additional cores from off Runkerry Strand (Figs. 1, 3, 4). Two of the latter cores, SK9a, SK9b, were from less than 100 m apart. Most cores were less than 1 m in length and all were dominated by fine, well-sorted sand. Rare shell fragments were preserved in the cores, but no sedimentary structures were recorded, save one burrow trace. The two longest cores, SK9a and SK4, encountered some gravel and shell fragments at depth (Figs. 4 and 5). Comparison of the seismic line with the core lengths indicates that the cores should have reached or penetrated the strong acoustic reflectors in the sand unit. Off Runkerry Strand, one core, SK9b, penetrated 10 cm of fine sand and met refusal in coarse basalt, chalk and flint gravel (Fig. 5b). At this location the acoustic reflector within the sand was believed to be nearly at the seabed.

5.2. Belfast Lough

Seismic records from Belfast Lough contrast strongly with those from the Portrush area (Figs. 6 and 7). Acoustic basement, interpreted as bedrock, is represented by a strong, continuous reflector with up to 15 m of sub-bottom relief over less than 0.5 km (Fig. 6). A non-stratified unit occasionally appears over bedrock. Its lower contact with bedrock is difficult to consistently detect, and it is interpreted as till (T). The thickest acoustic unit imaged, more than 10 m thick in places, typically rests on bedrock, though it was occasionally

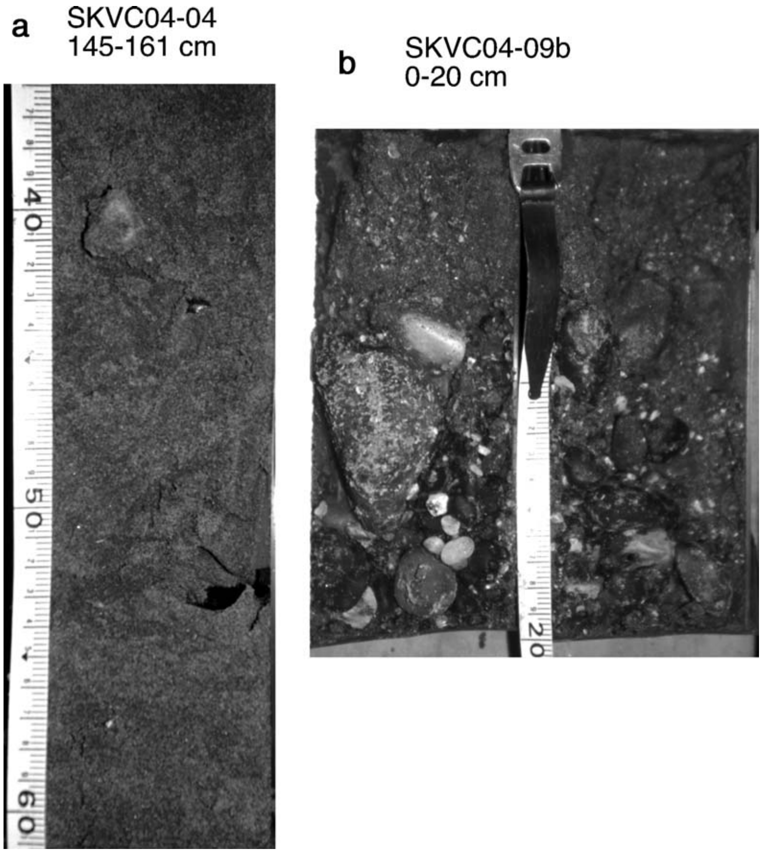

Fig. 5. a) Photograph of Core SK4. Uniform fine sand dominated all cores except for this area near the core bottom where several shell fragments and a 2.5 cm diameter basalt fragment were noted. b) Photograph of Core SK9b. The core was collected where a strong acoustic reflector within the surficial sand deposit appeared to crop out at the seafloor (Fig. 3). The longest dimension of one cobble exceeded the diameter of the core barrel. Locations of photos within cores are shown in Fig. 4.

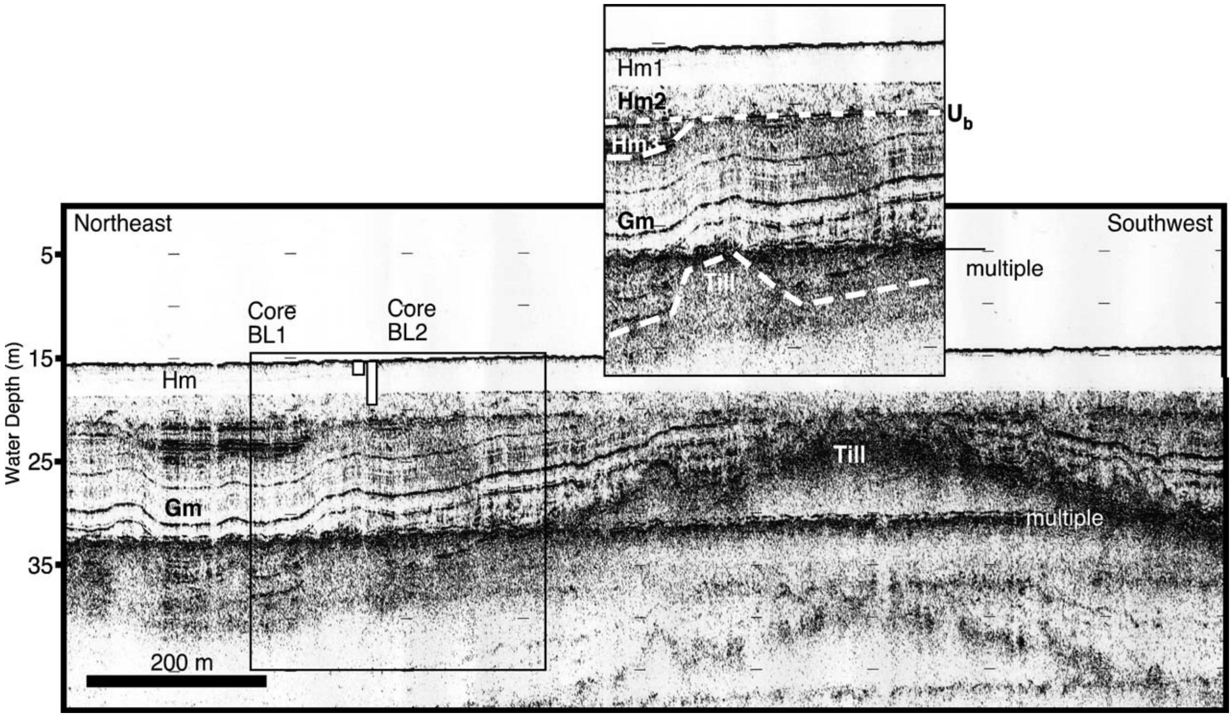

Fig. 6. Interpreted seismic reflection profile showing core locations in the shallow water of Belfast Lough. Inset box is enlargement of line near basin. Locations of profiles and cores are shown on Fig. 1c. Gm is glacial marine, T is till, Hm is Holocene mud.

recorded on till (Figs. 6 and 7). It is acoustically transparent and contains strong, coherent reflectors that are continuous over several kilometers. These reflectors are draped over the underlying units and mimic their relief. We interpret this acoustic unit as glacial-marine sediment (Gm) based on its similarity to other published

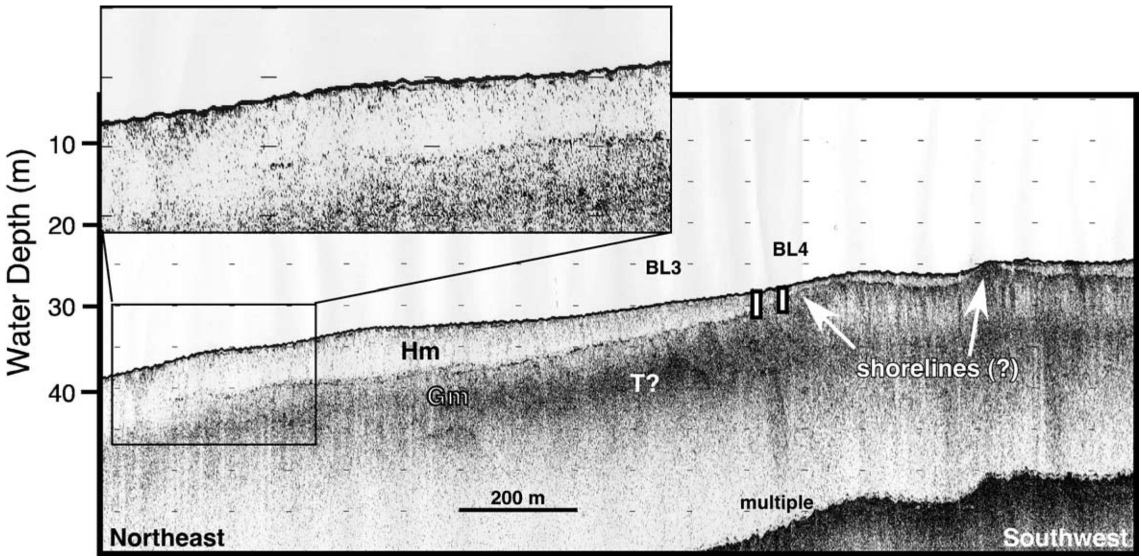

Fig. 7. Interpreted seismic reflection profile showing core locations in the deep water of Belfast Lough. Cores were located on a break-in-slope in glacial-marine sediment that we interpret as the lowstand shoreline. Inset shows detail of the disappearance of the reflector that represents an unconformity on the surface of the glacial-marine sediment. Locations of profiles and cores are shown in Fig. 1c. Gm is glacial marine, T is till, Hm is Holocene mud.

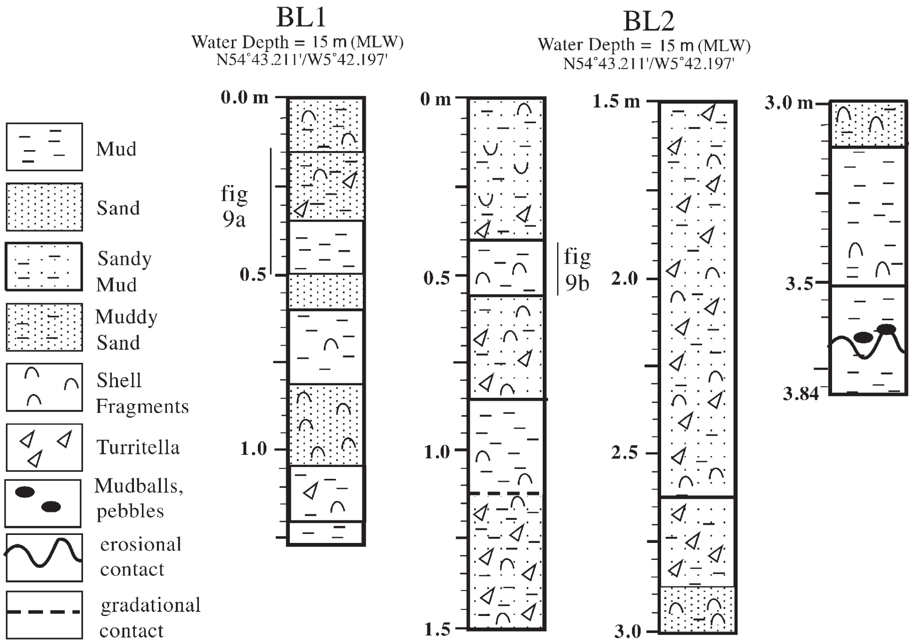

Fig. 8. Core descriptions of BL1, BL2, from inner Belfast Lough. Lines show locations of core photos in Fig. 9. Cores are located in Fig. 7.

descriptions (Barnhardt et al., 1997; McDowell et al., 2005) and occurrence in outcrop on nearby land (McCabe et al., 1994). The surface of the glacial-marine sediment dips very gently seaward, and bears no relationship to underlying reflectors. Internal reflectors within the glacial-marine sediment are truncated by its

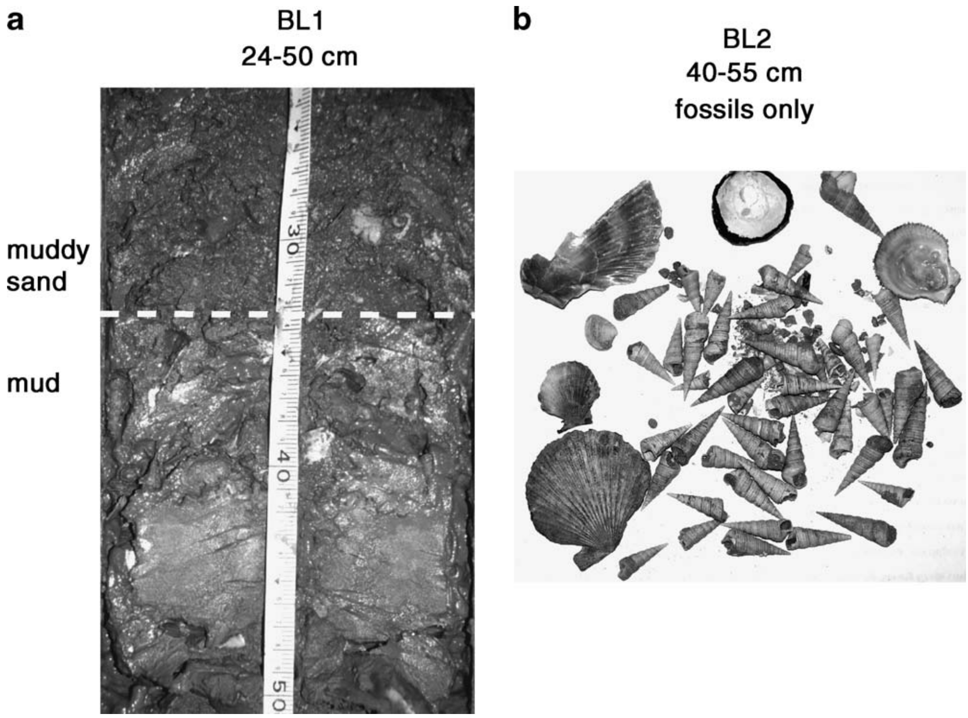

Fig. 9. a) Photograph of typical contact between the sand and mud beds. Location of photo shown in Fig. 8. b) Photograph of abundance and variety of intact shells in typical core interval. Location of photo shown in Fig. 8.

Table 1
List of shells identified in cores

Core BLVC04-01		
	0–15 cm	
		Capulus ungerius
		Turitella communis
	15–35 cm	
		Pectinidae family
		Turitella communis
		Dosinia exoleta
		Anomiidae *family*
		Pecten maximus
Core BLVC04-02		
	0–10 cm	
		Turitella communis
		Corbula sp.
		Hinea incresata?
	10–20 cm	
		Turitella communis
		Corbula sp.
		Nucula sp.
	52–70 cm	
		Aporrhais pes-pelican (truly sublittoral)
		Aequipecten sp.
		Chlamys varia
		Corbula gibba
		Parvicardium sp.
Core part B		
	60–80 cm	
		Turitella communis
		Corbula gibba (muddy sediment only)
Core part C		
	45–85 cm	
		Modiolus modiolus
		Chlamys distorta
		Turitella communis
		Can galena
		Nucula sp.
		Anomiidae family
Core BLVC04-03		
	0–20 cm	
		Garifervensis sp.
		Abra prismatica?
		Abra nitida?
		Dosinia exoleta (muddy gravel)
		Mactridae family
	100–110 cm	
		Arctica islandica
		Nucula
	110–130 cm	
		Aequipecten sp.
		Chlamys varia
		Timoclea ovata
		Ridged scallop (septumradiatum)
		Paleolim tylmostratum
		Hyatella arctica
		Venerupis senegalensis
		Nucula sp.
		Corbula gibba
		Mactridae family
		Anomiidae family

Table 1 (*continued*)

Core BLVC04-03		
	110–130 cm	
		Circumphalus casina (Venus)
		Parvicardium sp.
	170–180 cm	
	(numerous fragments)	
		Balanus sp. (1 intact shell radiocarbon dated)
		Nucula sp. (3 intact shells radiocarbon dated)
		Astarte sp.
		Mactridae family (1 large fragment radiocarbon dated)
Core BLVC04-04		
	45–85 cm	
		Queen sp.
		Dosinia exoleta
		Timoclea ovata
		Corbula gibba
		Mactridae family
		Anomiidae family
		Venerupis senegalensis
		Parvicardium sp.
		Abra sp.
		Antalis sp. (sublittoral)

Identifications were made by Dr. Julia Nunn of the Ulster Museum, Belfast. All shells live in a range of depths from shallow sub-tidal to continental shelf settings.

surface reflector, suggesting that the surface reflector represents the basal unconformity (reflector U_b, Fig. 6). In rare locations, the glacial-marine unit is cut by a channel or basin whose surface is also reflector U_b. Acoustic reflections within this unit (H_3, Fig. 6) are coherent and sub-horizontal and appear enhanced by natural gas (Judd and Hovland, 1992). Above the glacial-marine sediment in most locations are two additional acoustic units. The lower unit, (H_2, Fig. 6), is 2–4 m in thickness and lacks coherent internal reflections. It possesses numerous small areas of enhanced reflectivity, giving the unit a diffuse or "cloudy" impression (Fig. 6). The uppermost acoustic unit, H_1, extends to the seafloor. It is acoustically transparent and corresponds well with muddy sediment previously described from Belfast Lough (Manning et al., 1970). It is present on all profiles, though it rarely exceeds 5 m in thickness.

In deeper water (Fig. 7), signal attenuation appears to obscure deeper reflections. Bedrock is occasionally recognized, but till is apparently thicker and the contact between the two is unclear. Reflections within the glacial-marine mud are also less clear. The unconformity on the surface of the glacial-marine sediment remains relatively strong until about 30 m water depth, when it becomes weaker and discontinuous (Fig. 8). It disappears by 40 m below present sea level.

Two cores that were gathered within 100 m of one another in 15 m depth in Belfast Lough do not appear to have penetrated the unconformity on the surface of glacial-marine mud (Figs. 7 and 9). The cores are similar to one another in stratigraphy with alternating beds of mud and sandy mud (Fig. 9a). Upper and lower contacts between beds are mostly abrupt transitions. Carbonate content in the cores is high, and a wide variety of intact shells were recorded (Fig. 9b; Table 1). The muddy sand deposits were notably enriched with *Turitella communis*, which was abundant in all muddy sands. The lowermost 0.7 m in BL2 was very fine-grained and noticeably denser than other layers in the cores. It was bluish gray with black laminations of reduced sediment with several mudballs up to 5 cm in diameter associated with rare shell fragments at a possible erosional contact near the bottom of the core. No intact shells were observed.

Two additional cores were gathered within 100 m of one another between 29–31 m water depth (Fig. 10). Comparison of the cores and the seismic record suggests that they each penetrated through the Holocene mud to the unit interpreted as glacial-marine mud. Each of these cores collected more than 1 m of fossiliferous, sandy mud, but no finer grained mud layers were observed. Although many fossils were present, *Turitella* was not recorded in the deeper water cores.

Just below 1.5 m sub-bottom depth in each of the deeper water cores, pebbles appeared above a sandy shelly layer (Fig. 10). The transition between the overlying sandy mud and the sand was abrupt, and an angular, 2 cm diameter clast of red clay occurred at the contact in core BL3 at 32.5 m depth (Fig. 11a). The sand deposit is well sorted, with a mean size 2.1 phi and a high proportion of shells and shell fragments. The sand was 11 cm thick in BL3, but the equivalent sand layer in BL4 was only 3 cm thick. Beneath the sandy material in BL3, 20–30 cm of laminated red mud and orange sand occurred (Fig. 11). The laminations range from mm-size partings of sand to centimeter-thick layers. Beneath the laminated material, massive red clay continued to the bottom of the core.

In core BL4, the abrupt contact between the overlying sandy mud and the sand deposit was at about 220 cm in the core, or 31 m water depth (Fig. 11). The sand was well sorted and the same size, as in the adjacent core. Though abundant shell fragments existed in this sandy deposit, none were whole and most were sand-size fragments. In sharp contact with the sand, massive red clay continued beneath the sand. One shell of *Spisula* sp. (Table 1) was observed at 255 cm within the core.

Four radiocarbon dates were obtained from the two deep cores (Table 2). All of the shells that were dated were fresh (Fig. 12), though none were articulated or in life position. Three of the shells from the 11 cm thick sand deposit in BL3 produced similar AMS ^{14}C ages around 13.4 ka cal B.P. (Table 2). The three *Nucula* and one *Balanus* shells were essentially indistinguishable with overlapping calibrated age ranges of 13.3–13.4 cal B.P.; the Mactridae (mussel) fragment was approximately 200 years younger than the other shells (13.13 ka

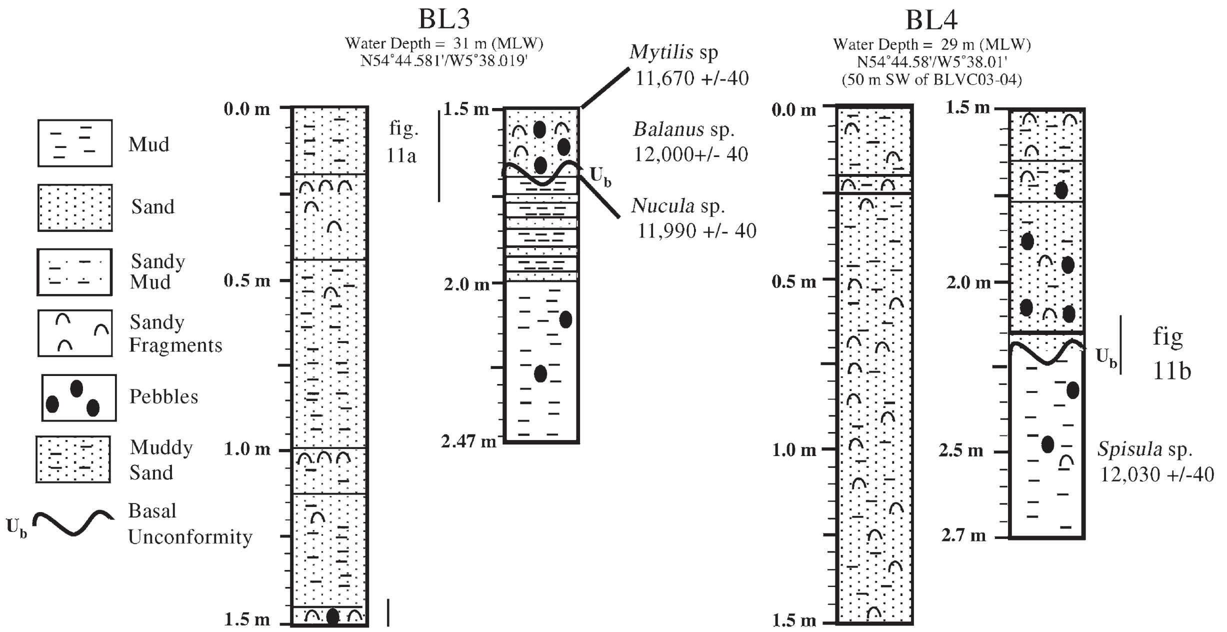

Fig. 10. Core descriptions of BL3, BL4, from outer Belfast Lough. Lines show locations of core photos in Fig. 11. Cores are located in Fig. 7.

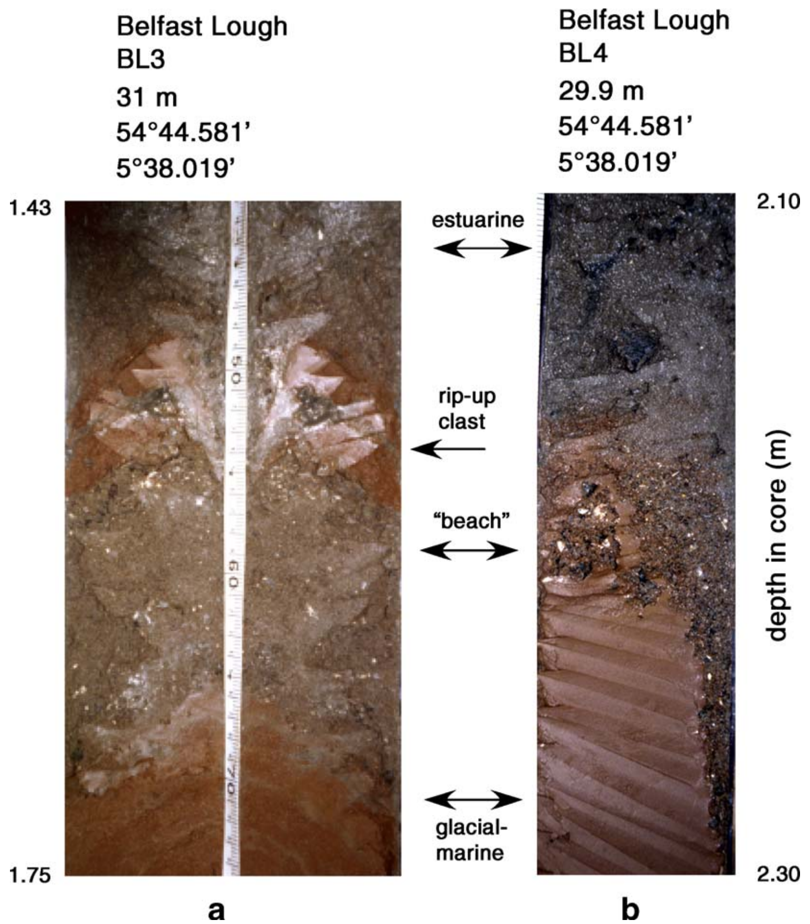

Fig. 11. a) Photo of contact between sandy bed interpreted as a "beach" in core BL3, with overlying sandy mud. The red mud clast is identical to the lower, glacial-marine mud, and is interpreted as a rip-up clast b) laminated sand and mud beneath "beach" deposit in core BL4. Photographs are located in Fig. 10.

cal B.P.) (Table 2). The *Spisula* shell was coincident in age with the *Nucula* and *Balanus*.

6. Discussion

6.1. Causeway Coast

Cores from seaward of the beaches of the Causeway Coast contain fine sand texturally similar to the beaches (Fig. 4). Reflectors within the upper sand unit were earlier postulated to be peat (Cooper et al., 2002; McDowell et al., 2005), based on submarine terrestrial peat deposits cored from a nearby estuary (Wilson and McKenna, 1996). Our new cores correlate gravel with those reflectors where they were reached (Fig. 5). The refusal our corer met in <2 m of sand in most locations is also suggestive of a hard bottom. On one coring attempt, the hardened, stainless steel core cutter came up

Table 2
Radiocarbon dated samples

Sample # [a]	Material calibrated age [b]	$^{13}C/^{12}C$	Conventional ^{14}C age	Comment	Range 1 sigma (2 sigma)
202998	*Nucula* sp.	+1.2	11,990±40 BP	Lowstand beach, shell was fresh, intact	13298–13425 (13246–13542)
202999	*Balanus* sp.	+0.7	12,000±40 BP	Lowstand beach, shell was fresh, intact	13303–13434 (13254–13557)
203000	Mactridae family	+0.7	11,670±40	Lowstand beach, shell was fresh	13059–13195 (12961–13229)
203001	*Spisula* sp.	+0.9	12,030±40	Glacial-marine mud	13314–13468 (13277–13594)

[a] Beta Analytic Lab.
[b] Calib 5.0.2.

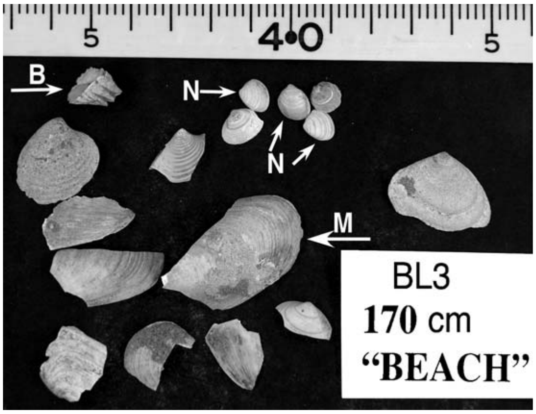

Fig. 12. Photograph of the delicate shells from the beach deposit. Arrows point to those that were radiocarbon dated. Such fine shells would not survive a long transport distance. Shells are from sandy "beach" deposit seen in Fig. 11a. N, *Nucula* sp., B, *Balanus* sp., M, Mactridae family.

with many dents in its cutting edge, again indicating a rocky bottom.

Gravel deposits are not a surprise along the inner shelf, as gravel commonly forms layers on the fine sand beaches of Ireland (Orford et al., 1999, 2003). Gravel occurs from the edge of the frontal dune out onto the shallow nearshore zone when beaches experience erosional periods (Orford et al., 2003). Thus, the reflectors we now interpret as gravel deposits are suggested to mark the presence of a littoral deposits out to approximately the 30 m water depth. This observation, coupled with erosional notches out to the same depth (Cooper et al., 2002), suggests a lowstand position around 30 m water depth along the Causeway Coast. We found no sub-tidal sedimentary record of the mid-Holocene fall of sea level to its present location.

6.2. Belfast Lough

Fossils and sedimentary facies recorded within the Belfast Lough cores correspond well with earlier work (Manning et al., 1970). The cores and seismic observations from Belfast Lough contain a clear record of changing sea level, as observed in other paraglacial locations (Barnhardt et al., 1997; Stea et al., 1998). Glacial-marine mud was deposited initially in relatively deep-water in late glacial times. In Northern Ireland, the last late glacial higher-than-present stand of local relative sea level was at about +20 m at 14.2 ka cal B. P. about 25 km south of the study area (Fig. 2) (McCabe and Clark, 1998, 2003). McCabe and Clark (1998) dated *Elphidium clavatum* in marine mud draped over a drumlin. These animals are not specific to any depth, nor was the deposit that contained them indicative of a shore line, but the mud containing the foraminifer correlates with a shoreline feature nearby at +20 m.

We believe that following this highstand, sea level dropped rapidly to approximately 30 m below present sea level by 13.4 ka cal B.P., based on the continuity of the later-formed transgressive unconformity to that depth in Belfast Lough and the shoreline deposits we interpret from cores BL3, and BL4 (Fig. 13). The unconformity clearly truncates acoustic reflectors in the glacial-marine material and marks the post-lowstand rise in sea level. Similar interpretations were recognized elsewhere (Barnhardt et al., 1997; Kelley et al., 1992; Belknap et al., 2004; Stea et al., 1994). We interpret the sand deposits near the 30 m isobath in the two deeper cores as low-energy beach deposits slightly seaward of an eroding bluff of glacial-marine mud. The well sorted fine sand and abundance of shells of varied species is what is commonly observed in such a modern setting (Doerjes et al., 1986). The angular rip-up clast of red, glacial-marine mud (Fig. 11a), as well as the pristine shells (Fig. 12), are suggestive of rapid deposition of the material, possibly in a storm, with no opportunity for degradation of the fragile shells or rounding of the clast. Thus, although the shells were not animals that lived on a beach, we believe they were deposited on a beach at, or shortly after the time of their death. We believe the

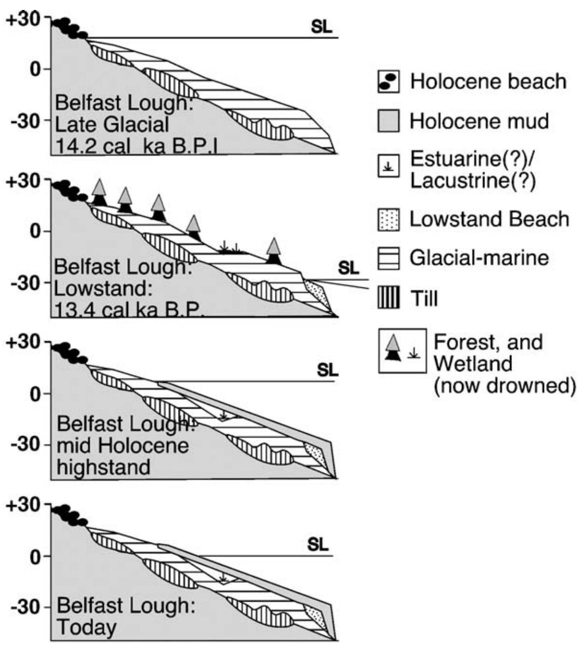

Fig. 13. Shoreline change in Belfast Lough. a) Highstand in late glacial time; b) lowstand in the latest Pleistocene; c) Holocene highstand, d) present sea level.

shells did not travel far (Flessa, 1998), and that their radiocarbon dates mark the time sea level reached −30 m in Belfast Lough.

The dated *Spisula* shell from core BL4, in what is interpreted as glacial-marine sediment (Fig. 10), presents a potential problem because it is only slightly older than the beach deposit. Although we say "glacial-marine" mud, in its uppermost layer, the red mud may simply be a marine deposit formed from reworking of the red glacial-marine muddy sediment abundant in the area. Thus, the *Spisula* sp. shell may have lived in shallow water, contemporaneously and just seaward of the beach. The alternating laminations of red mud and fine sand below the sandy unit in BL3 are suggestive of a nearshore deposit (Reineck and Singh, 1980).

Although we have selected 30 m below present sea level as the lowstand depth, it is possible that sea level fell somewhat lower than this depth. In Belfast Lough the unconformity does not end abruptly at 30 m water depth, but it appears diminished in acoustic contrast at greater depths. It is likely that a ravinement unconformity formed seaward of the beach deposit to a paleo-depth of 10 m or more. Only more cores along a transit into deeper water will provide further insight to that question.

As we interpret the record, the 30 m below present sea-level lowstand requires a relatively rapid fall in sea level from the +20 m high stand of 14.2 ka cal B.P. A minimum of 50 m of uplift in approximately 800 years requires local relative sea-level fall of about 6.3 cm/yr. The timing of the uplift coincides with ice wasting and is likely to have been a period of rapid isostatic readjustment (McCabe et al., 2005). Compared to modern and ancient rates of post-glacial isostatic land adjustment in Scandinavia of 8 cm/yr (Berglund, 2004) under similarly recent deglaciation, the suggested rate for Northern Ireland is not too extreme. Such rapid uplift must have been associated with major crustal instability in the region.

After sea level topped the bluff of glacial-marine sediment, shallow, and then progressively deeper water led to the observed succession of fauna (Fig. 13). The variation of muddy and sandy mud beds in the shallow cores might mark episodic storm events. River and estuarine channels, and possibly lake basins, that existed in Belfast Lough at the time of the lowstand, were drowned by the rising water (Fig. 13). Preservation of the organic-rich estuarine or lake sediment has locally led to methane generation (Fig. 6) as in other glaciated settings (Rogers et al., 2006). The origin of the widespread acoustic unit, Hm2 (Fig. 6), directly above the transgressive unconformity in Belfast Lough is less clear. It is a muddy material, but denser than the surface mud. Rip-up clasts within it may cause the diffuse reflections within the unit. The apparently erosional surface of this unit could represent a response to the lowering of sea level and an increase in wave energy as sea level from the mid-Holocene highstand, but more cores are needed to better define this unit.

6.3. Summary and implications for further work

This study underscores the importance of collecting core samples to verify geological interpretations based on seismic reflection profiles. Earlier workers off The Skerries (Fig. 1) (Cooper et al., 2002) and River Bann, 15 km west of the Skerries (McDowell et al., 2005), interpreted acoustic reflectors within the surficial sand of the inner shelf as buried peat deposits. This was a plausible interpretation because freshwater peat deposits below present sea level had been cored in this coastal zone and used to establish a lower-than-present sea-level position (Wilson and McKenna, 1996). In Maine, USA, we had also cored peat deposits beneath the shoreface and used them in sea-level reconstructions (Kelley et al., 2005). On the exposed coast of Northern Ireland, gravel deposits are also interbedded with beach sand (Orford et al., 2003), so it is not surprising that gravel layers form prominent acoustic reflectors on the shoreface and out to the lowstand position. Although these materials cannot be dated and used for a sea-level curve, their presence establishes confidence in the sea-level reconstruction by demonstrating that shoreline deposits extend to the 30 m isobath. Although we did not gather sufficient seismic data to quantify the geometry of the gravel layers, such a study might permit distinction of onlap and offlap deposits that resulted from the Holocene highstand and subsequent fall to present sea level.

Because of its sheltered setting, Belfast Lough allows accumulation of Holocene mud deposits. These are more readily cored through than the sand and gravel off The Skerries and because of this we reached the transgressive unconformity and associated shoreline deposits with cores. The striking transition of the transgressive unconformity to conformity at depths below the lowstand position (Fig. 7) lends strong credence in our interpretation of the thin, sandy deposit in about 30 m water depth as the lowstand shoreline position. The dated shells are good, but less than ideal sea-level indicators because they appear to have washed onto the beach and are not in life position. The complex radiocarbon calibration curve at the time of the lowstand also lends some uncertainty to the age of the lowstand because there are multiple intersections of the conventional radiocarbon date with the calibration curve. Despite this, Belfast Lough has potential to yield more shells from lowstand positions, as well as shells in life position and wood fragments along the surface of the transgressive unconformity, as has been shown elsewhere (Kelley et al., 1992).

Two implications of the new sea-level lowstand off Northern Ireland are related to the question of a landbridge to Scotland (Devoy, 1995) and the problem with numerical models of sea-level change in this region (McCabe, 1997). A landbridge to Scotland is ruled out for this area of Northern Ireland because water depths >50 m exist between the lowstand shoreline and Scotland. Thus, the oldest archeological site in Ireland, <50 km from the Skerries area (Fig. 1) along the River Bann, was not a site that was reached directly by people on foot.

Recent numerical models of sea-level change along this coast clearly need adjustment to accommodate the data reported in this paper and elsewhere (McCabe, 1997). The rapidity of the late Pleistocene fall in local relative sea level, presumably owing to isostatic uplift of the land, and the depth of the lowstand are not captured by existing models (Lambeck and Purcell, 2001). Similar rapid changes in relative sea level in the Gulf of Maine and Scotian Shelf, Canada (Barnhardt et al., 1997; Stea et al., 1998; Shaw et al., 2002) are observed, but not well accounted for by the coarse nature of existing numerical models (Peltier, 1998). Hopefully, the creation of more refined and spatially diverse sea-level curves such as the one presented herein will promote more realistic numerical models of late Quaternary land and sea-level changes.

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