Journal of Archaeological Science 33 (2006) 756–766

Journal of Archaeological SCIENCE

http://www.elsevier.com/locate/jas

A side-scan sonar and high-resolution Chirp sub-bottom profile study of the natural and anthropogenic sedimentary record of Lower Lough Erne, northwestern Ireland

B. Lafferty*, R. Quinn, C. Breen

Centre for Maritime Archaeology, Environmental Sciences Research Institute, School of Environmental Sciences, University of Ulster, Coleraine, Co. Derry, Northern Ireland BT52 1SA, UK

Received 6 June 2005; received in revised form 7 October 2005; accepted 20 October 2005

Abstract

A geophysical survey (side-scan sonar and high-resolution sub-bottom profiling) combined with established chrono- and bio-stratigraphic markers are used to reconstruct the evolutionary history of Lower Lough Erne, northwestern Ireland since the end of the last glacial. Discrete acoustic units define four prominent sedimentation cycles, one Late-glacial and three Holocene, within the seismic stratigraphy. Basin development is predominantly controlled by climate until the Mid Holocene when the effects of cultural activity are related to pronounced signatures in the seismic record. An enhanced reflector marking the termination of the Early Holocene sedimentation cycle is associated with the elm decline and forest clearance during the Neolithic (between approximately 5800 cal. BP and 5300 cal. BP). The associated increase in sediment input, by infilling minor topographic lows and basins, has a smoothing effect on the morphologic expression of the original basin. Onlapping and truncated reflectors in the penultimate acoustic unit define further modification of lake bed relief by removal of sediment from the system during engineered lowering of the lake levels that began in the 1880s. Acoustic anomalies identified on the side-scan sonar data are linked with cultural activity and are identified as having the potential to facilitate the recent establishment and migration of invasive zebra mussels through the Erne system.

Keywords: Seismic-stratigraphy; Side-scan sonar; Basin development; Cultural impact; Lower Lough Erne

1. Introduction

Human activities are widely acknowledged as having the ability to alter the nature and composition of the Earth's surface such that the resulting landscape must be considered a synthesis of natural and cultural elements [1,21,33]. In altering the nature and composition of landscapes humans also have the potential to inadvertently transform ecosystem function and structure [7,13,24,34]. This paper investigates the impact of human activity on the development and ecological functioning of the underwater landscape of Lower Lough Erne, Co. Fermanagh in the northwest of Ireland. The lake has an area of approximately 109 km^2, and is the third largest lake in Britain and Ireland [43] (Fig. 1). It is part of the Erne system, which comprises a complex of lakes and rivers draining a catchment of 4212 km^2. There is a long history of human occupation in the county with the Sites and Monuments Record (SMR) [14] listing 1818 sites of cultural significance. These sites tend to be concentrated in the lowlands throughout the Erne system emphasising the attraction of these waterways from at least the Mid Holocene onwards. Devenish Island, the southernmost island on the Lough, is renowned for its antiquity. Founded in the sixth century it is described as one of the greater ecclesiastical sites in Ireland [48]. To date 17 logboats (the earliest having a Radiocarbon Age of 4636 ± 20 BP) have been discovered around the lakeshores [20]. However, until now there has been no systematic investigation of the lake bed and sub-sediments for sites of cultural significance.

* Corresponding author.
E-mail address: b.lafferty1@ulster.ac.uk (B. Lafferty).

0305-4403/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2005.10.007

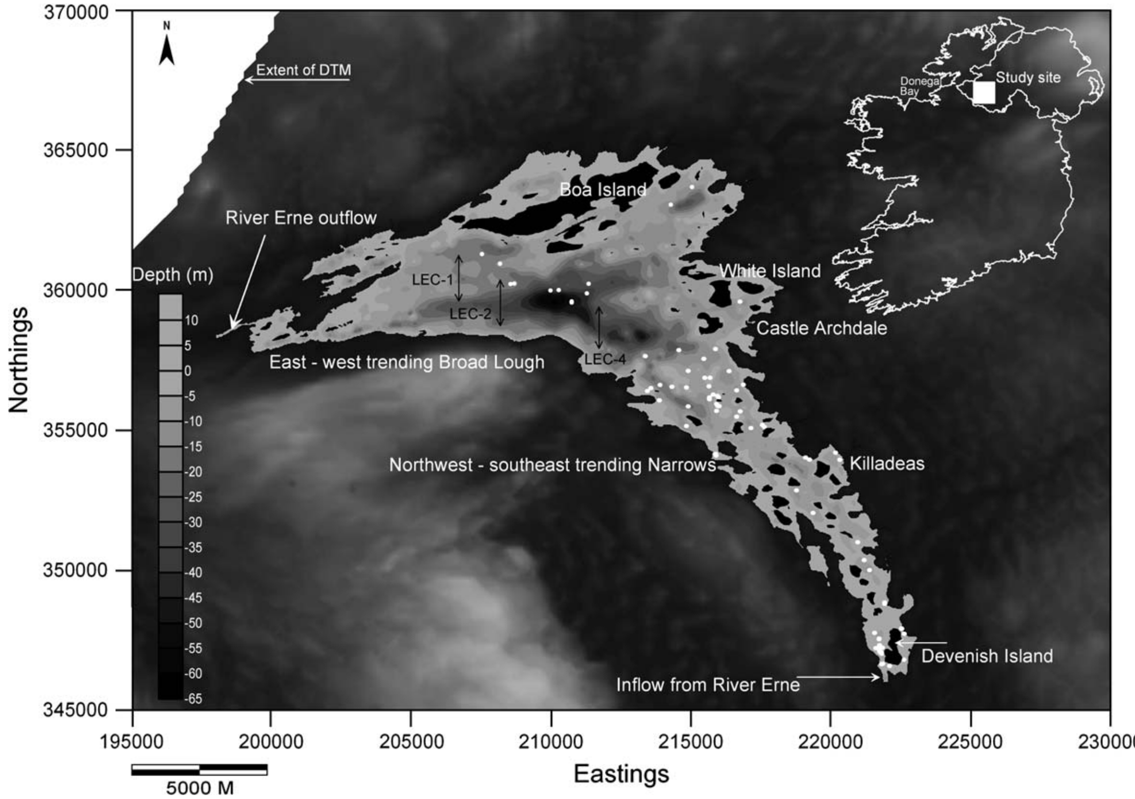


Fig. 1. Location and bathymetric map (digitized from 1:25,000 map) [40] of Lower Lough Erne northwest of Ireland, showing the Broad Lough and the Narrows. Lines (e.g. LEC-1) indicate the location of the seismic data presented in Fig. 2. White dots indicate location of acoustic anomalies identified on the side-scan sonar data. For the sake of clarity the high density survey grids are not presented. Black areas are islands. Place names are referred to in the text.

A fundamental constraint on lake basin investigations has been imposed by the inaccessibility of the environment. However, developments in acoustic technologies and an understanding of how sound behaves in sediments provide a rapid and non-invasive means of extracting information from these potentially valuable landscape records. The remote sensing techniques employed to investigate the geophysical properties of the Lower Lough Erne Basin include high-resolution Chirp sub-bottom profiler and a side-scan sonar system. The Chirp sub-bottom profiler is used to record continuous vertical sedimentary sequences of the lake basin, according to their acoustic reflectivity, to depths of approximately 30 m. Assessment of high-resolution sub-bottom data has greatly improved understanding of the evolutionary history of many lakes [8,16,25,31,38,51] and has also proved valuable in underwater archaeological investigations [44,45,46]. Side-scan sonar systems provide a graphic representation of how materials on the lake floor interact with acoustic energy. The instrument is an important remote sensing technique for mapping surfical features and is also playing an increasingly significant role in underwater archaeological investigations [11,12,47].

The primary aim of this study is to explore the development of the Lower Lough Erne Basin from the end of the last glacial cycle. Specific attention is given to identifying signatures associated with human activities and exploring the potential effects of associated perturbations on the evolution and overall functioning of the lake system. Lake basins, because of their effectiveness as sediment traps, are important natural archives and are therefore regarded ideal sites for investigating landscape and ecosystem change promoted by anthropogenic forcing [2,6,13,36,42].

2. Methodology

The sedimentary infill of the Lough Erne Basin was investigated using an EdgeTech SB-216S Chirp sub-bottom profiler. During the survey the instrument was towed 1 m below the lake surface, at a speed of approximately 7 knots (3.5 m s^{-1}). A 2–10 kHz source sweep was transmitted at six pulses per second. This frequency range ensures that sediment layers as close as 0.1 m can be resolved. Approximately 72 km of high-resolution sub-bottom profile data were acquired. Data were logged both digitally and in hardcopy format. Boat draft and depth of towfish restricted the survey of the Narrows to the navigable channel (Fig. 1). The displayed vertical scale on the Chirp sub-bottom profiles are recorded in metres and are based on a sound velocity of 1500 m s^{-1}.

The quality of the data was such that post-processing was not necessary. Individual acoustic units (AU) were identified according to general concepts in seismic stratigraphy [5,37]. Units were delimited based on reflection relationships between adjacent seismic sequences together with seismic reflection parameters including amplitude, continuity and frequency.

The acoustic units identified thus describe bodies of relatively uniform acoustic signatures compared with the underlying or succeeding units.

The character of the lake bed was mapped using a dual-frequency EdgeTech Model 272-TD towfish and an EdgeTech Model 260-TH processor. Approximately 235 km of side-scan data were acquired. The fish was towed 1 m below the lake surface at a speed of approximately 4 knots (2 m s^{-1}). Both 100- and 500-kHz operational frequencies were used and swath widths were set at 400 m and 200 m, respectively. The higher frequency provides greater resolution of lake bed features and is therefore the preferred frequency for archaeological surveys. A high-resolution survey of the entire Lough, although desirable from a cultural perspective, was not possible because of time and resource restrictions. It was decided that the Narrows would potentially be the most rewarding in terms of archaeology and therefore, the area over which to conduct the high-resolution survey. This decision was based on the fact that the largely sheltered and shallow nature of the Narrows is likely to have attracted more cultural activity in the past than the more exposed waters of the Broad Lough (Fig. 1). Trackline spacing of 300 m for the 100-kHz survey and 100 m for the 500-kHz ensured overlapping coverage of approximately 150%. A Litton Marine, LMX-400 series Global Positioning System (GPS) receiver provided positional data (±1 m accuracy), with differential corrections from the marine beacon system.

The acoustic units identified on the side-scan sonar data were characterised according to the strength of the acoustic signature. High-energy backscatter or a strong return signal is associated with a hard substrate (e.g. rock or diamict) and low energy backscatter or a very weak return is associated with fine-grained deposits (e.g. silt and fine sand). Detailed reviews of side-scan record interpretation are found in standard texts [17,27]. Ground truthing of the acoustic units that define the lake bed sediment zones was conducted using a suspended, low-light underwater video camera.

Sub-bottom data are correlated (in terms of unit thickness, position on the profile and signature attributes) with regional events reported in the literature [4,18,26,41,53]. It is understood that, because of local and altitudinal variations in landscape composition and development, the proxies identified in various natural archives in the region are not likely to be directly comparable with phases of development in Lough Erne. However, in the absence of more local palaeo-information, the sites referred to are considered to provide a reasonable framework against which to interrogate the seismic stratigraphy of the Lough Erne Basin.

3. Results

All of the sub-bottom profiles display some degree of pulse interference and approximately 33 km, including a large proportion of the Narrows, are subject to complete obliteration. These interference signatures are associated with the presence of gas in the sediments, the origin of which tends to be attributed the decay of organic matter [9]. Acoustic turbidity, the most common gas signature identified on the Lough Erne data, appears as a dark smear on the record and is caused by the scattering of the acoustic energy (Fig. 2). Where acoustic blanking occurs reflections are faint or absent due to gas absorption of acoustic energy in overlying sediments [9].

In the resolvable portions of the profiles the penetration limit of the acoustic pulse is defined by the acoustic basement, which describes the basin floor (Fig. 2). Four seismic units, referred to as acoustic units (AU), labeled AU1–4 are identified (Table 1, Fig. 2). AU1 is most prevalent along the southern flank of the main trough and tends to parallel the acoustic basement. The external geometry most closely resembles sheet drape with unit boundaries concordant both at the base and top of the unit. AU2 is limited in its distribution and tends to be associated with topographic lows and slopes. AU3.1 is characterised by a sheet drape geometry which when overlying an irregular surface, tends to be wavy. AU3.2, the thickest of the units identified, is characterised by parallel to divergent reflection configurations. The internal reflectors of both AU3.1 and 3.2 are truncated in places. AU3.3 is characterised by a parallel and at times slightly divergent reflection configuration and directly overlies AU3.1 in places (Fig. 2a). It displays a sheet drape geometry with the lower boundary onlapping sub-adjacent units resulting in a general smoothing and masking of basin relief. AU4 is characterised by faint or absent internal reflectors. This unit tends to be associated with acoustic turbidity and its upper reflector marks the lake bed. It also occurs as discrete mounds in places (Fig. 2, Table 1).

The acoustic units delimiting the sedimentary zones of the lake bed are presented in Table 2. The side-scan sonar data reveal that the lake bed is characterised predominantly by low energy backscatter returns. This signature correlates spatially with AU3.3 and, to a lesser extent, AU4 on the seismic data (Table 2). AU5 is a complex signature defined by areas of largely high-energy backscatter returns interrupted by small discrete acoustic shadows. This unit is generally confined to depths less than 20 m and predominates in the northern section of the Narrows and at the eastern end of the Broad Lough. Two small but distinct patches of AU5 are also identified at the southern end of the Narrows between the lakeshore and the eastern side of Devenish Island (Fig. 3). Composite unit AU3/5 is identified on the northern side of islands and at the western end of the trough. On the north and eastern end of the main trough high-energy backscatter returns are correlated with where the acoustic basement crops out on the lake bed.

Every acoustic anomaly (small, discrete signatures that appear out of context with ambient environment) identified on the side-scan sonar data is also recorded (Table 3). The majority are located in the Narrows and are distributed in clusters, at the northern end where the Narrows meets the Broad Lough, in the centre, and at the southern end around Devenish Island (Fig. 1). The anomalies identified in the Broad Lough are dispersed throughout the north and eastern portion of the trough.

4. Interpretation

AU1 conforms to the irregularities in the underlying acoustic basement and based on its stratigraphic position, is

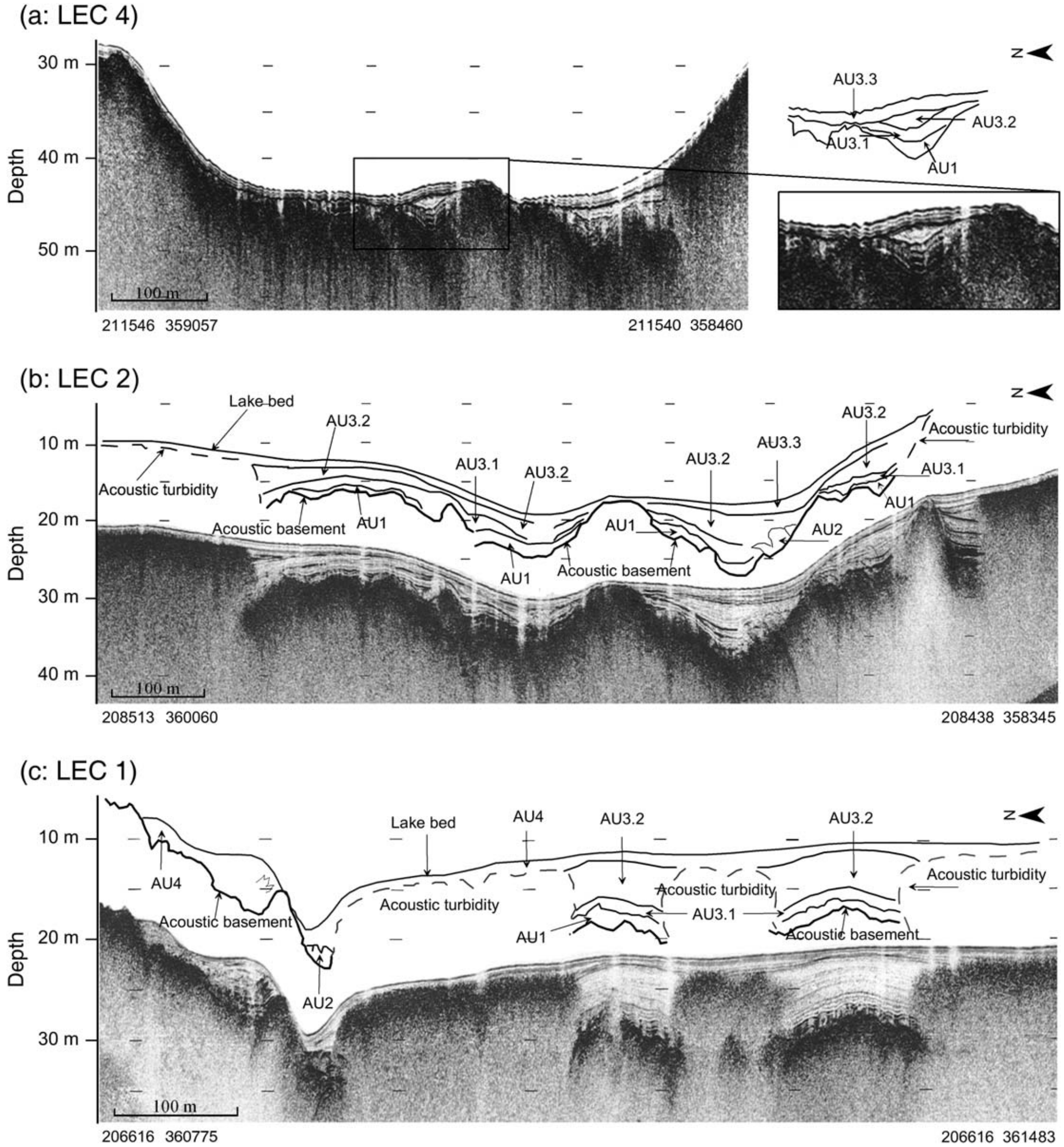
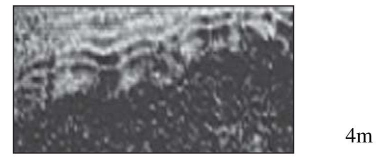
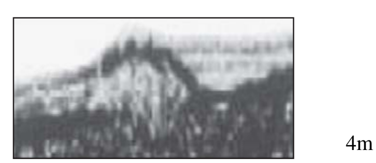


Fig. 2. Portions of three high-resolution cross basin sub-bottom profiles showing the stratigraphic development of the basin floor from the end of the last glacial cycle to the present-day lake bed. Sediment thickness varies throughout the profiles. Line drawing illustrates the acoustic units (AU) identified. Each unit is distinguished on the basis of contact relations and internal layering characteristics as revealed by its acoustic reflectivity (Table 1). Vertical exaggeration is approximately 20. Locations are indicated in Fig. 1.

interpreted as Late-glacial in origin (approximately 13,000–10,000 BP) [35]. The alternating high and low amplitude reflectors are associated with the climatic instability that characterised the period, where ameliorating conditions were interrupted by a cold spike at approximately 10,600 BP [35]. The Late-glacial in Ireland is expressed in deposits comprising laminated or unlaminated clays at the base, overlain by a layer of clay-mud, with organics and topped by clay containing frost-fractured stone fragments [53]. Clay-rich, fine-grained sediments tend to produce enhanced reflectors [29] similar to the high amplitude reflectors of AU1. A similar seismic signature to that defined by AU2 is associated in the literature with slumping processes [50]. There is a paucity of such slump associated signatures in Lough Erne (only three confined areas of AU2 are identified) which suggests that downslope movement of sediments within the basin was achieved through either a continuous creep or a number of small slope failures. The absence of slump features indicates either one or both of these mechanisms [10]. The reflector separating AU1 and 3.1 is interpreted as defining the end of the Late-glacial and the onset of Holocene sedimentation. The fact that the successive stratal surfaces of AU1 and 3.1 generally parallel each other indicates that there is little appreciable change in the surface relief of the basin between each phase of deposition. This, in turn, suggests that no significant event occurred within the basin during these deposition phases to alter sedimentation dynamics. Evidence from inter-drumlin lakes in the region shows that during the Early Holocene sedimentation rates

Table 1
Characteristics of the acoustic units (AU) that define the stratigraphic architecture of the Lower Lough Erne sediments

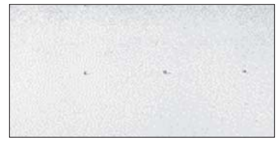
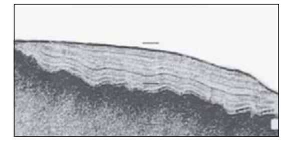
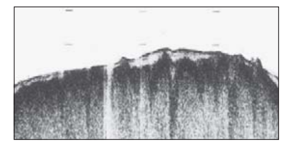
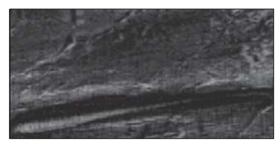
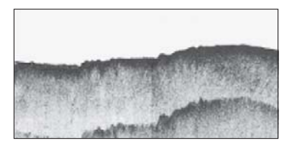
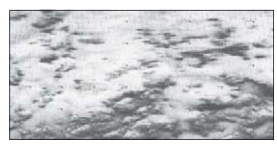
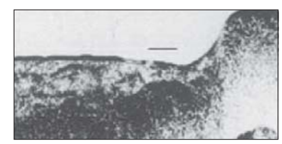
Acoustic Unit	Reflection characteristics	Type example
AU1	Characterised by discontinuous high amplitude and high frequency reflectors. The reflectors are wavy and tend to parallel the acoustic basement. Unit boundaries are concordant both at the base and top of the unit. Maximum thickness recorded – 1.9m	
AU2	Characterised by mounded geometry and chaotic internal reflectors. The upper boundary is generally onlapped by flank reflections and the basal surface appears to be concordant. Maximum thickness recorded – 3.9m	
AU3.1	Characterised by a parallel reflection configuration. Reflector amplitudes range from moderate to high, are largely continuous and frequency tends to be uniform. Maximum thickness recorded – 2.6m	
AU3.2	Characterised by parallel to divergent reflection configurations. The upper boundary is onlapped by flanked reflectors. Reflector amplitude and frequency are variable. Maximum thickness recorded – 7.6m	
AU3.3	Characterised by a parallel and at times slightly divergent reflection configuration. The lower boundary onlaps sub-adjacent units. The reflectors are high amplitude at the boundaries, moderate to low internally. Maximum thickness recorded – 1.9m	
AU4	Characterised by its generally mounded geometry. The upper boundary displays moderate to high amplitude reflections and is internally discontinuous and faint or reflector free. Maximum thickness recorded – 1.9m	

The type examples are extracted from 72 km of Chirp high-resolution sub-bottom profiles acquired in February 2002.

were low and only started to increase after 6600 cal. years BP [26]. AU3.1 is interpreted to represent a similar period of sedimentation in the Lower Lough Erne Basin.

AU3.1 developed as the climate improved from the end of the last glacial. Between 6000 and 7000 BP, temperatures rose to a point where they were 1 or 2 °C warmer than today [35]. In tandem with these ameliorating conditions, woodlands evolved to their climax phase (hazel–oak–elm–alder) at around 7000 BP, persisting for almost 2000 years before they were dramatically altered by the elm disease that swept western Europe. The termination of AU3.1 sedimentation is considered to be the result of the combined effects of both this natural event and human induced changes in the catchment. The elm decline is a pronounced feature in most Irish pollen records and has become an important bio-stratigraphical marker for the earlier Neolithic period [39]. Pollen evidence and ^{14}C dates suggest Neolithic farming activity was concentrated in the centuries immediately after the elm decline. Tree clearance for agriculture

Table 2
Type examples of acoustic units, defining the lateral distribution of sediments, identified on the lake bed of Lower Lough Erne

Acoustic Unit	Type example (Side-scan sonar)	Type example- (Chirp sub-bottom profiler)
AU 3 **Side-scan:** low backscatter,smooth texture, **Chirp:** couplets of thin moderate and thick weak signals *Fine sediments*		
AU 5 **Side-scan:** predominantly high backscatter small discrete shadow areas **Chirp:** irregular strong signal *gravels*		
Acoustic basement **Side-scan:** predominantly high backscatter, **Chirp**: smooth undulating strong signals *Boulder pavement*		
AU 3/5 **Side-scan:** low to medium backscatter, **Chirp**: chaotic internal reflections *Gravel/fines*		

Classification is based on correlating side-scan sonar data and Chirp sub-bottom profiles. Interpretations, assisted by underwater video imagery, are in italics.

would have contributed to the general decline in woodland during this period. The seismic signature indicating the transition from AU3.1 to 3.2 sedimentation phase is interpreted to represent this period of landscape change within the catchment. The number and range of megalithic tombs, structures largely associated with Neolithic burial practices, in the Lough Erne region attest to a substantial human presence during this period [14]. Court tombs (the earliest type of megalithic tomb)

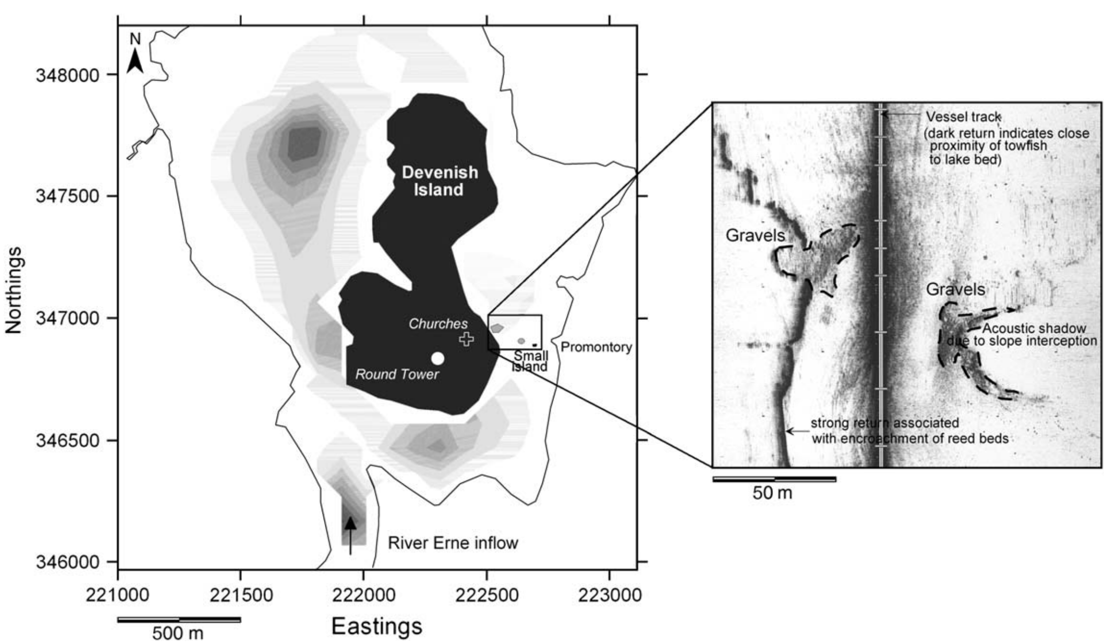
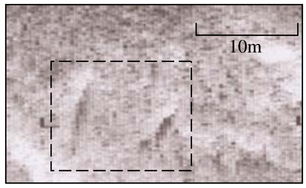
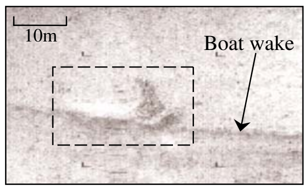
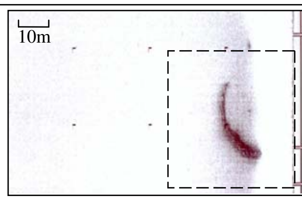
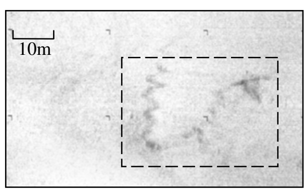
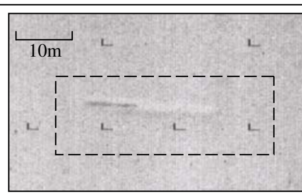
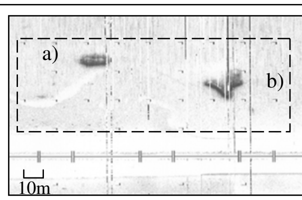


Fig. 3. Map of the south-eastern portion of Lower Lough Erne showing Devenish Island, one of the greater ecclesiastical sites in Ireland (see Fig. 1 for location in Lough). Other than the small gravel deposits indicated the lake bed in this part of the Lough is composed largely of fine-grained sediments. The gravels, small island and promontory indicated may represent the first real evidence of a causeway or fording point linking the island with the lakeshore. Archaeologists have long speculated on the possibility of a bridging feature in the area.

Table 3
Examples of the acoustic anomalies identified on the 100 and 500 kHz side-scan sonar data acquired in Lower Lough Erne, Co. Fermanagh

Anomaly number and description	Anomaly Image
Anomaly 1 Substrate: AU3/5 Two linear features of high backscatter and shadow areas. *2 Log boats*	
Anomaly 2 Substrate: AU3 Triangular area of variable tones and discrete, elongate shadow area *Unknown*	
Anomaly 3 Substrate: AU 3 Comma shaped feature of predominantly high energy backscatter *Mooring chain colonised with zebra mussels*	
Anomaly 4 Substrate: AU3 Triangular area of medium to high backscatter with medium backscatter U-shaped tail. *Seaplane wing section and trail associated with movement*	
Anomaly 5 Substrate: AU3 Linear feature of medium backscatter with prolonged shadow area. *Sunderland seaplane*	
Anomaly 6 Substrate: AU3 a) linear feature of predominantly high backscatter, a prolonged shadow trail. b) complex configuration of predominantly high backscatter. *Unknown but located close to reported seaplane scuttle site.*	

An anomaly is defined as any feature that appears out of context with the surrounding area. See Fig. 1 for distribution of anomalies on the lake bed. Tentative pre-ground truthing interpretations are in italics and are based on correlating dimensions and acoustic geometry with known features together with local knowledge of lake bed features.

predominate, suggesting people occupied the area from the beginning of the Neolithic. In addition, a number of stone axes, characteristic of the period and essential for forest clearance, have been found in the River Erne south of the Narrows [56]. These axes provide credible circumstantial evidence for forest clearance around the Lough. Woodland clearance, associated with Neolithic activity and the decline in elm, would have had a significant effect on the hydrology of the catchment. The removal of protective tree cover would have increased runoff, accelerated soil erosion and resulted in enhanced sediment inputs to the lake system. The inferred increase in nutrients derived from an increased input of soil organic matter is likely to have enhanced the productivity of the lake. In Lake Neuchâtel in Switzerland, the identification of a higher trophic state about 6000–5000 years BP is associated with erosion and nutrient input induced by Neolithic agricultural activities [52]. In other European lake studies similar increases in productivity have been found to induce shifts in fish dominance for example from coregonids to other species [32].

After the Neolithic, the next significant phase of change in the Irish landscape took place in the middle of the 19th century [19]. AU3.2, the thickest of the recorded units in the sub-bottom profiles, is interpreted to represent this prolonged period of event free development of the Lough Erne basin. There is a discernable change in surface relief with AU3.2 filling minor basins and generally smoothing the topographic detail of the basin floor. Further smoothing is revealed by the fact that the internal reflectors of AU3.3 do not parallel the reflectors in the underlying units. The truncated reflectors at the upper boundary of the penultimate unit suggest that the AU3.2 sedimentation phase was interrupted abruptly by the removal of sediment from the system. In the 1880s a scheme, intended to alleviate flooding problems in the area lowered the lake level by approximately 2.5 m [15]. Water level was further lowered in the 1940s, by approximately a further 0.5 m, subsequent to the installation of turbines at the outlet (Fig. 1) for electricity supply [22]. It is unclear whether sediment removal occurred during both of these lake lowering events. However, it is suggested that because of the extent of the drawdown during the flood alleviation scheme the AU3.2/3.3 reflector is associated with the 1880s event. Such lowering of lake levels can induce gross changes in littoral habitats [3]. Littoral vegetation provides refuge and breeding grounds for fish species such as rudd, pike and bream. Altering or degrading the habitat can therefore have a significant impact on fish populations. In addition complex assemblages of invertebrate animal species including chironomid insects and microcrustaceans such as the '*Alona*' complex would also be affected with loss of littoral habitat.

The upper boundary of both AU3.3 and, in places, AU4 marks the contemporary lake bed. As discussed earlier, gas charging has the potential to obliterate internal layering of sediments in seismic data. It is therefore considered that the internally faint and at times reflector free character of AU4 defines gas charged portions of AU3.3. This interpretation is further supported by the fact that AU4 tends to be coupled with acoustic turbidity on the seismic profiles (Fig. 2). The domes of AU4 identified on the lake bed are caused by gas inflation of the sediments (Table 1). Discrete domes on sea or lake beds represent the initial stage of pockmark formation [29]. It is likely therefore that the domes of AU4, identified in Lough Erne will eventually form pockmarks through gas expulsion. The penetration and signal intensity of AU3.3/4 on the seismic data and the generally low backscatter returns on the side-scan sonar data indicate that the lake bed is largely composed of fine-grained sediments (Table 2). Gravels (AU5) and boulder deposits (the exposed acoustic basement) are also identified. The small patches of gravel that occur in isolation at the southern end of the Narrows at Devenish Island are of particular interest (Fig. 3). It is acknowledged, and logboat finds appear to corroborate this, that throughout the ages, people are likely to have used boats as the most typical means of accessing the island. However, although to date there is no obvious physical evidence, archaeologists have also considered the possibility of a fording point or causeway (familiar features in the Irish landscape) linking the Island to the lakeshore. The juxtaposition of the gravel deposits identified on the side-scan sonar data east of Devenish with a small island and a promontory on the lakeshore together with shallow water depths provide the first tangible evidence for the possible existence of one or other of these bridging features (Fig. 3). It is possible that the smaller of the two gravel deposits is an underwater extension of the small island. The gravel deposits will be examined in greater detail in diver and camera investigations during subsequent field seasons.

The majority of the acoustic anomalies identified on the side-scan sonar data are located in the Narrows with concentrations around Devenish Island and in the northern section where the Narrows meets the Broad Lough (Fig. 1). In archaeological investigations, features identified on the surface in environments subject to continuous sedimentation, as is the case in the Narrows, would generally have been regarded as comparatively recent features. The implication being that features of greater antiquity would over time become buried under post-deposition sediments. However, the identification of an erosion event associated with the lowering of the lake presents the possibility that previously buried materials may now be lake bed features and therefore, in terms of their archaeological potential, warrant extra consideration. The anomalies identified around Devenish will be ground truthed together with the gravel deposits during subsequent field seasons. The acoustic signatures around Devenish have the potential to provide insights into cultural activities dating from the earliest movement of people on the lake until the present day. In contrast, it is likely that a large proportion of the anomalies identified in the Narrows north of Devenish are associated with the recent history of the lake. During World War II flying boat bases were established on the western shores of the Narrows at Castle Archdale and Killadeas (Fig. 1). The Lough provided moorings for 108 flying boats (mainly Catalinas) and was the most westerly UK base of its kind [55]. According to local knowledge, after the war unwanted equipment, including Catalinas, mooring chains and landing lights, was scuttled in the lake. Due to their proximity to Castle Archdale and Killadeas, the anomaly clusters identified in the northern and central Narrows may define the location of at least some of the items scuttled during this period. The large linear feature identified in the deepest area of the Broad Lough is also considered to be associated with the Second World II (Table 3 – Anomaly 5). In November 1943, a Sunderland seaplane crashed and sank in the same area. Anomaly 5 is interpreted as this wreck site. It is unlikely that the Sunderland is a visible feature on the lake bed due to the plane sinking into the fine sediments and post-crash sedimentation. The discrete acoustic signature is, instead, a function of the ability of the acoustic pulse to penetrate the fluidized sediments at the sediment water interface.

The identification of acoustic anomalies and their potential association with cultural activities is of obvious interest to archaeologists and can represent the initial step in generating an underwater equivalent to the Sites and Monuments Record [14]. Conversely, the presence of anomalies on side-scan sonar data may not appear directly relevant to other limnological investigations where acoustic techniques are generally employed for sediment classification and habitat mapping. In these basin-wide investigations small, isolated entities similar to the acoustic anomalies identified in Lower Lough Erne, are usually overlooked and therefore not recorded. It is considered here that their presence is significant and if associated with cultural activities provides further insights into potential anthropogenic impacts on the ecological functioning of lake systems. The high-energy returns produced by a large proportion of the anomalies identified in the Narrows define hard substrates in a predominantly fine sediment environment. Table 3 shows an anomaly (Anomaly 3) interpreted by its location, as the remains of one of the war time mooring chains known to have been abandoned in the area. However, the shape of the acoustic signature and the degree of roughness defined by the speckled appearance of the signature is not consistent with that of a mooring chain. Dredge surveys carried out on the Lough in 1998 identified colonies of zebra mussels (*Dreissena polymorpha*) in the area [49]. Zebra mussels, considered economical and ecological pests, are thought to have arrived in Ireland on the hulls of imported pleasure craft in 1994 [34,54]. Given the degree of roughness defined by Anomaly 3 it is considered that the signature is associated with the mooring chain which is now colonised by zebra mussels. Because zebra mussels require hard substrates to become established [30] it is possible that in providing a firm substrate for pioneer communities the anomalies recorded in Lough Erne may have assisted their spread through the lake system. Pest invasion of this nature can radically alter the structure of a lake ecosystem. Lakes and rivers colonised by zebra mussels often experience 50–75% declines in the biomass of phytoplankton and small zooplankton and a corresponding rise in water clarity [34,54]. Declines of more than 50% in populations of native bivalves are also recorded together with an increase in macrophyte bed thickness and associated benthic animals. Further work is needed, however, to establish if there is a relationship between zebra mussel invasion in Lough Erne and anthropogenic deposits.

5. Conclusions

The work described in this paper emphasizes the sensitivity of acoustic remote sensing techniques in providing new insights into the stratigraphic development of the Lower Lough Erne Basin (Fig. 4). Four sedimentation phases (one Late-glacial and three Holocene) are identified and when related to established stratigraphic markers are found to typify landscape development patterns identified elsewhere in Ireland and in Britain [23,26,28,41,53]. Relating these observed

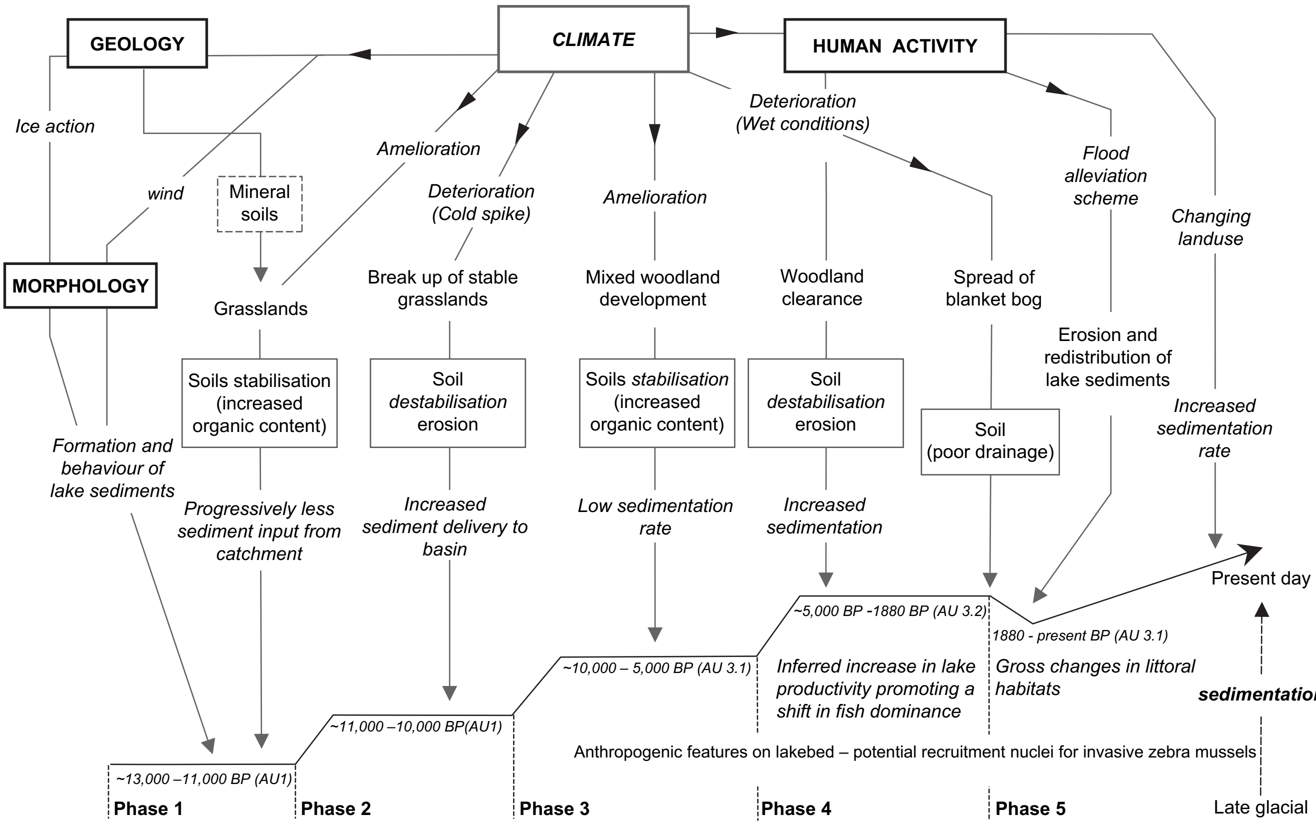


Fig. 4. Evolutionary model of the Lower Lough Erne Basin, northwestern Ireland, from the end of the last glacial to the present. Basin development is controlled by climate until the Mid Holocene when the effects of cultural activity are shown to have a marked effect on the functioning of the system. The phases represent periods of instability.

seismic units and contact configuration to established chrono- and bio-stratigraphical markers is admittedly tentative but this approach does provide a depositional framework which otherwise would not exist.

The fact that, apart from the Late-glacial and Early Holocene, the prominent reflectors on the seismic record could be associated with human activities emphasizes the importance of considering cultural activities for a fuller understanding of local processes.

- Identifying perturbations provoke consideration of the implications of such events for biological dynamics within the system. It is possible that, as was found in European lake studies, sediment pollution during the Neolithic increased lake productivity and induced a shift in the structure and composition of aquatic communities in Lough Erne. In addition the identification of zebra mussels on anthropogenic material on the lake floor suggests that, not only are humans responsible for the introduction of these pests but by providing hard substrates, they have also facilitated the transformation of a fine sediment environment to mussel beds. These observations are particularly relevant at the present time where there is greater general awareness of environmental change and the need for sustainable management of submerged habitats.
- The identification of a human induced gap or gaps in the Lower Lough Erne sedimentary record and the implication that, during the removal event, sediments are also likely to have been redistributed throughout the system is significant. Lake basins are regarded as important natural archives because of their effectiveness as sediment traps. Due to their 'sink' status the possibility of sediment removal may often be overlooked, nevertheless, knowledge of these events is essential if appropriate use of lake sediments as proxies for climatic and environmental reconstructions is to be achieved. In addition, due to its ability to define the complexity of the depositional environment, the acoustic record represents an effective means of establishing representative locations for coring sites in lakes.

Acknowledgements

We thank Tony Andrew for comments, and R. Navin for assistance in the field. Thanks are also extended to the referees whose comments improved the text. This research was funded by the Environment and Heritage Service, the Department of Environment for Northern Ireland.

References

[1] F.H.A. Aalen, The Irish rural landscape: synthesis of habitat and history, in: F.H.A. Aalen, K. Whelan, M. Stout (Eds.), Atlas of the Irish Rural Landscape, Cork University Press, Cork, 2000, pp. 4–30.

[2] N.J. Anderson, Using the past to predict the future: lake sediments and the modelling of limnological disturbance, Ecological Modelling 78 (1995) 149–172.
[3] T.E. Andrew, Biological indications of the current status of rivers and lakes in Northern Ireland, in: J.G. Wilson (Ed.), Eutrophication in Irish Waters, Royal Irish Academy, Dublin, 1998, pp. 48–54.
[4] V. Andrieu, C.C. Huang, M. O'Connell, A. Paus, Late glacial vegetation and environment in Ireland: first results from four western sites, Quaternary Science Reviews 12 (1993) 681–705.
[5] M.E. Badley, Practical Seismic Interpretation, International Human Resources Development Corporation, Boston, 1985.
[6] R.W. Battarbee, Palaeolimnological approaches to climate change, with special regard to the biological record, Quaternary Science Reviews 19 (2000) 107–124.
[7] A.S. Cohen, M.R. Palacios-Fest, J. McGill, P.W. Swarzenski, D. Verschuren, R. Sinyinza, T. Songori, B. Kakagozo, Paleolimnological investigations of anthropogenic environmental change in Lake Tanganika: 1. An introduction to the project, Journal of Paleolimnology 34 (2005) 1–18.
[8] S.P. Cronin, H.F. Lamb, R.J. Whittington, Seismic reflection and sonar survey as an aid to the investigation of lake sediment stratigraphy: a case study from upland Wales, in: J. McManus, R.W. Duck (Eds.), Geomorphology and Sedimentology of Lakes and Reservoirs, John Wiley & Sons Ltd., 1993, pp. 181–203.
[9] A.M. Davis, Shallow gas: an overview, Continental Shelf Research 12 (1992) 1077–1079.
[10] J.R. Desloges, R. Gilbert, Sedimentation in Chilko Lake: a record of the geomorphic environment of the eastern coast mountains of British Columbia, Canada, Geomorphology 25 (1998) 75–91.
[11] R.W. Duck, Applications of side-scan sonar to archaeological sites underwater, in: J. Beavis, K. Barker (Eds.), Science and Site: Evaluation and Conservation, Bournemouth University School of Conservation Sciences, 1995, pp. 109–124.
[12] R.W. Duck, W.M. Dow, Side-scan sonar reveals submerged remains of the first Tay Railway Bridge, Geoarchaeology 9 (1994) 139–153.
[13] K.J. Edwards, G. Whittington, Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland, Catena 42 (2001) 143–173.
[14] EHS (Environment and Heritage Service), Sites and Monuments Record (SMR) for County Fermanagh, Northern Ireland, EHS, 1999.
[15] R. Elder, Development of Soils on the Lacustrine Margins of Lower Lough Erne, Masters thesis, University of Ulster, Coleraine, 1988.
[16] N. Eyles, J.I. Boyce, J.D. Halfman, A. Koseoglu, Seismic stratigraphy of Waterton Lake, a sediment-starved glaciated basin in the Rocky Mountains of Alberta, Canada and Montana, USA, Sedimentary Geology 130 (2000) 283–311.
[17] B.W. Flemming, Side-scan sonar: a practical guide, International Hydrographic Review 53 (1976) 65–91.
[18] J.A. Fossitt, Late Glacial and Holocene vegetation history of Western Donegal, Ireland, Biology and Environment: Proceedings of the Royal Irish Academy, Series B 94 (1994) 1–31.
[19] J.W. Foster, Encountering traditions, in: J.W. Foster, H.C.G. Chesney (Eds.), Nature in Ireland, Lilliput Press, Dublin, 1997, pp. 23–70.
[20] M. Fry, Coití: logboats from Northern Ireland, Northern Ireland Archaeological Monographs: No 4, Environment and Heritage Service, Department of the Environment, Belfast, 2000.
[21] B.G. Gadfelter, Geoarchaeology: the geomorphologist and archaeology, American Antiquity 42 (1977) 519–538.
[22] C.E. Gibson, Lough Erne, in: C. Moriarty (Ed.), Studies of Irish Rivers and Lakes, Marine Institute, Dublin, 1998, pp. 237–256.
[23] A. Goudie, The Human Impact on the Natural Environment, Blackwell Publishers Inc., Oxford, 2000.
[24] K.J. Gregory, Human activity and palaeohydrology, in: K.J. Gregory, L. Starkel, V.R. Baker (Eds.), Global Continental Palaeohydrology, Wiley & Sons, Ltd., 1995, pp. 151–172.
[25] D.L. Gross, R.A. Cahill, Recent geologic development of Lake Michigan (U.S.A.), Hydrobiologia 103 (1983) 193–198.
[26] K. Hirons, K.J. Edwards, Events at and around the first and second *Ulmus* declines: palaeoecological investigations in Co. Tyrone, Northern Ireland, New Phytologist 104 (1986) 131–153.
[27] H.P. Johnson, M. Helferty, The geological interpretation of side-scan sonar, Reviews of Geophysics 28 (1990) 357–380.
[28] R. Jones, K. Benson-Evans, R.M. Chambers, Human influence upon sedimentation in Llangorse Lake, Wales, Earth Surface Processes and Landforms 10 (1985) 227–235.
[29] A.G. Judd, M. Hovland, The evidence of shallow gas in marine sediments, Continental Shelf Research 12 (1992) 1081–1095.
[30] J. Kalff, Limnology: Inland Water Ecosystems, Prentice Hall, New Jersey, 2002.
[31] T. Kulbe, F. Anselmetti, M. Cantonati, M. Strum, Environmental history of Lago di Tovel, Trento, Italy revealed by sediment cores and 3.5k seismic mapping, Journal of Paleolimnology 34 (2005) 325–337.
[32] T. Mehner, M. Diekmann, U. Brämick, R. Lemeke, Composition of fish communities in German lakes as related to lake morphology, trophic state, shore structure and human-use intensity, Freshwater Biology 50 (2005) 70–85.
[33] B. Messerli, M. Grosjean, T. Hofer, L. Núñez, C. Pfisher, From nature-dominated to human dominated environmental changes, Quaternary Science Reviews 19 (2000) 459–479.
[34] D. Minchin, C. Maguire, R. Rosell, The zebra mussel (*Dreissena polymorpha* Pallas) invades Ireland: human mediated vectors and the potential for rapid intranational dispersal, Biology and Environment: Proceedings of the Royal Irish Academy, Series B 103 (2003) 23–30.
[35] F. Mitchell, M. Ryan, Reading the Irish Landscape, fourth ed., Town House, Dublin, 1998.
[36] F. Mitchell, R. Bradshaw, G. Hannon, M. O'Connell, J. Pilcher, W. Watts, Ireland, in: B.E. Berglund, H.J.B. Birks, M. Ralska-Jasiewiezowa, H.E. Wright (Eds.), Palaeoecological Events During the Last 15,000 years: Regional Syntheses of Palaeoecological Studies or Lakes and Mires in Europe, John Wiley and Sons Ltd., 1996, pp. 1–13.
[37] R.M.J. Mitchum, P.R. Vail, J.B. Sangree, Seismic stratigraphy and global changes of sea level, Part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences, Memoirs American Association of Petroleum Geologists 26 (1977) 117–134.
[38] H.T. Mullins, J.D. Halfman, High-resolution seismic reflection evidence for Middle Holocene environmental change, Owasco Lake, New York, Quaternary Research 55 (2001) 322–331.
[39] M. O'Connell, K. Malloy, Farming and woodland dynamics in Ireland during the Neolithic, Biology and Environment: Proceedings of the Royal Irish Academy, Series B 101 (2001) 99–128.
[40] OSNI (Ordnance Survey of Northern Ireland), Fermanagh Lakeland Outdoor Pursuits Map and Navigation Guide, Lower Lough Erne1: 25,000, OSNI, 1984.
[41] J.R. Pilcher, R. Larmour, Late-glacial and post-glacial vegetational history of the Meendoan Nature Reserve, County Tyrone, Proceedings of the Royal Irish Academy, Series B 82 (1982) 277–295.
[42] J. Platt Bradbury, Limnologic history of Lago de Patzcuaro, Michoacan, Mexico for the past 48,000 years: impacts of climate and man, Palaeogeography, Palaeoclimatology, Palaeoecology 163 (2000) 69–95.
[43] Qixing Zhou, C.E. Gibson, R.H. Foy, Long-term changes of nitrogen and phosphorus loadings to a large lake in North-West Ireland, Water Research 34 (2000) 922–926.
[44] R. Quinn, J. Bull, J.K. Dix, Imaging wooden artefacts using chirp sources, Archaeological Prospection 4 (1997) 25–35.
[45] R. Quinn, J. Bull, J.K. Dix, The *Mary Rose* site: geophysical evidence for palaeo-scour marks, The International Journal of Nautical Archaeology 26 (1997) 3–16.
[46] R. Quinn, J. Bull, J.K. Dix, The *Invincible*(1758) site: an integrated geophysical assessment, The International Journal of Nautical Archaeology 27 (1998) 126–138.
[47] R. Quinn, W. Forsyth, K. Barton, S. Rooney, D. O'Hara, Integrated geophysical surveys of The French Frigate *La Surveillante* (1997), Bantry Bay, Co. Cork, Ireland, The Journal of Archaeological Science 29 (2002) 441–451.
[48] C.A. Ralegh Radford, Devenish, Ulster Journal of Archaeology 33 (1970) 55–62.
[49] R.S. Rosell, C.M. Maguire, T.K. McCarthy, First reported settlement of zebra mussels *Dreissena polymorpha* in the Erne System, Co.

Fermanagh, Northern Ireland, Biology and Environment: Proceedings of the Royal Irish Academy, Series B 98 (1999) 191−193.

[50] J.B. Sangree, J.M. Widmier, Seismic stratigraphy and global changes of sea level, Part 9: seismic interpretation of clastic depositional facies, in: C.E. Payton (Ed.), Seismic Stratigraphy: Applications to Hydrocarbon Exploration, American Association of Petroleum Geologists, Tulsa, 1977, pp. 165−184.

[51] C.A. Scholz, D.R. Hutchinson, Stratigraphic and structural evolution of the Selenga Delta accommodation zone, Lake Baikal Rift, Siberia, International Journal of Earth Science 89 (2000) 212−228.

[52] A. Schwalb, P. Hadorn, N. Thew, F. Straub, Evidence for Late Glacial and Holocene environmental change from subfossil assemblages of Lake Neuchâtel, Switzerland, Palaeogeography, Palaeoclimatology, Palaeoecology 140 (1998) 307−323.

[53] A.G. Smith, Late- and Post-glacial vegetational and climatic history of Ireland: a review, in: N. Stephens, R.E. Glasscock (Eds.), Irish Geological Studies in Honour of E. Estyn Evans, Queen's University, Belfast, 1970, pp. 65−88.

[54] D.C. Strayer, N.F. Caraco, J.J. Cole, S. Findlay, M.C. Pace, Transformation of freshwater ecosystems by bivalves: a case study of zebra mussels in Hudson River, BioScience 49 (1999) 19−27.

[55] G. Warner, Flying-boats in Fermanagh, Inland Waterways News 1 (2002).

[56] B. Williams, S. Gormley, Archaeological Objects from County Fermanagh, Blackstaff Press, Belfast, 2002.