A multi-proxy palaeolimnological study to reconstruct the evolution of a coastal brackish lake (Lough Furnace, Ireland) during the late Holocene.

Cassina Filippo[a,]*, Catherine Dalton[a], Mary Dillane**[b],** Elvira de Eyto[b], Russell Poole[b], Karin Sparber[a]

[a] Department of Geography, Mary Immaculate College, University of Limerick, Co. Limerick, Ireland

[b] Marine Institute, Newport, Co. Mayo, Ireland

*Corresponding author. Mary Immaculate College - University of Limerick, South Circular Road, Limerick, Co. Limerick, Ireland. E-mail: filippo.cassina@gmail.com.

Abstract - This study examines the evolution of Lough Furnace, a coastal brackish lake in the west of Ireland, using high-resolution sensors in the water column and palaeolimnological examination of the sediment archive. Palaeoenvironmental reconstructions suggest that meromixis formed as a result of sea level rise prior to ca. 4,000 cal. yr BP. Increased seawater inflow has progressively led to permanent water stratification, which caused the onset of anoxia, making the monimolimnion a harsh environment for biological life. Diatom floristic interpretations suggest a progressive upcore increase in salinity, which is paralleled by a reduction in cladocera remains. Diagenetic processes have not altered the sediment organic matter signature. Organic matter mainly derives from freshwater DOC and appears to be linked to the presence of peat bogs in the catchment as confirmed by the C/N ratio. Upcore variations in the C/N ratio with a ca. 800-year periodicity have been interpreted as the result of alternating dry and wet climatic phases during the late Holocene, which appear synchronous with the NAO and long-term solar cycles. The current hydrology is largely controlled by freshwater inflow, which determines permanent meromictic conditions. Overturns are rare, requiring a specific combination of factors such as exceptionally dry and warm summers followed by cool autumns. According to the climate projections for the next century in Ireland, permanent meromictic conditions will probably continue.

Keywords: lagoon; hydrology; stable isotope; C/N, diatoms; late Holocene.

1. Introduction

Coastal lagoons formed at the land-sea interface are rare habitats representing only 5.3% of European coasts (Barnes, 1980). Coastal lagoons are common around the shores of the Baltic, Mediterranean and the Black Sea (Doody, 2005), whilst on the northwest European Atlantic they are naturally rare (Barnes, 1989; Joint Nature Conservation Committee, 1996).

The land-sea interface is an exceptionally dynamic zone that shows strong non-linear physical and biological forces from both terrestrial and marine environments (Talley *et al*., 2003). Lagoons are paralic systems (Guelorget & Perthuisot, 1992), characterised by marine, brackish and freshwater deposits. These environments are generally unstable and susceptible to variations in hydrological components making them the most changeable and vulnerable environments on Earth (Viaroli *et al*., 2007). The main natural hydrological components include droughts, flooding, storms and sea-level rise (Kennish & Paerl, 2010), all of which are likely to be impacted by increased global warming (IPCC, 2007; Dunne *et al*., 2008). The presence of both fresh and marine water combined with lagoon geomorphology may lead to the development of ectogenic meromictic conditions, where an external source of saline water into a fresh water lake restricts water column circulation to a surface layer (Walker & Likens, 1975; Hakala, 2004). Salinity is the primary stratification driver and temperature and thermal circulation processes are impeded. Therefore, overturns are limited to the top layer (*i.e.* mixolimnion), whilst the bottom of the lake (*i.e.* monimolimnion) can develop anoxia that represents a threat to aquatic life.

Climate fluctuations have occurred over different time-scales, spanning decades to millennia. Lagoons are generally short-lived coastal features formed during the Holocene (Kjerfve, 1986) and represent unique habitats vulnerable to climate change. In particular they are endangered by progressive sea level rise, which has been recorded over the Holocene and is expected to continue into the future (IPCC, 2007; Bates et al., 2008; Dunne *et al.*, 2008). Palaeoclimatic records suggest the existence of multiple periods of rapid climate change during the Holocene in North Atlantic Ocean land masses (Mayewski *et al.* 2004; Wanner *et al.*, 2008). A transition to generally warm but relatively unstable conditions characterised the late Holocene (Moros *et al.*, 2004 (Turney *et al.*, 2006; Swindles *et al.*, 2010) that have been associated with solar variability (Mauquoy *et al.*, 2008), changes in the strength of the thermohaline circulation (Bianchi & McCave, 1999) and the North Atlantic Oscillation (NAO) (Nesje & Dahl, 2003; Trouet *et al.*, 2009). Changes in relative sea level (RSL) are part of a complex pattern involving seawater volume and mass change, tectonics and dynamic changes due to external forcing exerted on the sea surface (Chao *et al.*, 2002; Mörner, 2006) while Glacio-Isostatic Adjustment (GIA) also played an important role (Horton 2006; Miettinen *et al.*, 2007). A strong north-south trend in glacio-isostatic loading is evident in the British Isles, where uplift is evident in central and western Scotland and Northern Ireland and is coincident with submergence in southwest England and southern Ireland (e.g. Shennan & Horton, 2002; Roberts *et al.*, 2006; Smith *et al.*, 2006; Gehrels, 2010). The extent to which globally averaged sea levels have risen over the Holocene is unclear (Edwards, 2006). A number of global (Klemann & Wolf, 2007; NOAA, 2012) and local (e.g. Tushingham & Peltier, 1992; Shennan & Horton, 2002; Brooks & Edwards, 2006; Vink *et al.*, 2007; Engelhart & Horton, 2011;) RSL databases of the Holocene have been collated. Brooks & Edwards (2006) estimate a rise from ca. -6 m ca. 7,000 cal. yr BP to ca. -2 m approximately 5,000 cal. yr BP for Ireland and British Isles. However, despite a range of quantitative relative sea level data (e.g. Sinnott, 1999; Devoy *et al.*, 2006), precise and reliable information about changes since the early Holocene for parts of the Irish coastline remains incomplete (Brooks *et al.*, 2008).

A number of ecological studies have been conducted and published on Irish lagoons (e.g. Parker, 1977; Parker & West, 1979; Pybus & Pybus, 1980; Healy *et al*., 1982; Norton & Healy, 1984; Healy, 1997; Healy, 1999a, b; Oliver, 2005; Roden & Oliver, 2010). However, these inventorial surveys provided only a snapshot examination of physico-chemical and biological data. Long-term data sets are needed to aid in the understanding of coastal ecosystems (Talley *et al*., 2003). For almost all lakes, palaeolimnology is the only means of obtaining data on past trends (Battarbee, 1999). Coastal lagoons provide a suitable sedimentary environment for palaeoecological study because they are relatively sheltered from wave and tide exposure (Bennion & Battarbee, 2007) and are influenced by changes affecting both freshwater and marine environments (Ryves *et al*., 2004). Therefore, sediments contain the ontogeny (*i.e.* development through time) of basins themselves. Sediments also record information on atmospheric deposition and its terrestrial watershed (O'Sullivan, 2004) as well as changes derived from the marine environment (e.g. marine transgression). Palaeolimnology of coastal lakes also assists in determining the presence of marine or non-marine deposition, which in turn can be potentially linked back to climate patterns (Battarbee *et al*., 2002; Lotter, 2005). Many palaeoecological studies have successfully reconstructed the evolution of coastal lagoons by combining a number of proxies (e.g. Müller & Mathesius, 1999; Weckström, 2006; Cearreta *et al*., 2007; Blázquez & User, 2010). However, only a very small number of studies have been conducted on coastal lagoons in Ireland (Buzer, 1981; Holmes *et al*., 2007).

In a European context lagoons are recognised as vulnerable systems (Airoldi & Beck, 2007). The Habitats Directive (92/43/EEC) aims to maintain biodiversity through the conservation of natural habitats and by defining Special Areas of Conservation (SACs). Additionally, lagoons are included in the Water Framework Directive (WFD) (2000/60/EC) as priority habitats for conservation (Annex I). The Directive aims to achieve good ecological status in all relevant waters between 2015 and 2027 and requires baselines of reference conditions prior to anthropogenic impact to be identified. Moreover, the identification of natural background conditions and longer-term natural variability is often essential for conducting informed lake management programs

(Smol, 2008). In the absence of long-term data, and considering the dynamic nature of coastal lagoons, palaeolimnological reconstructions offer perhaps the only source of information regarding baseline reference conditions.

The aim of this paper is to reconstruct the evolution of Lough Furnace, a brackish coastal lagoon on the western coast of Ireland, during the late Holocene using a multiproxy palaeolimnological approach. Particular attention was focussed on the reconstruction of meromixis formation as a result of the relative sea level rise. The palaeolimnological investigation of this hydrologically complex system was furthermore augmented using high-resolution time series data on salinity, temperature and dissolved oxygen measured through the water column over a two-year period, to better understand modern and future system dynamics. The influence of climate variability on the palaeohydrology of Furnace and the future hydrological scenarios given the predicted global warming make this study highly relevant.

2. The study area

Lough Furnace is located in the Burrishoole catchment (N 53°55’22’, W 9°34’20”) at the north-eastern corner of the Clew Bay (northwest Ireland) (Figure 1a). The geology of the catchment is dominated by metamorphic rocks of late Precambrian age (Long *et al.*, 1992), represented by schists, gneiss and quartzites (Whelan *et al.*, 1998). Catchment land cover consists of peat bog and forestry (Bossard *et al.*, 2000). The upper part of the catchment is considered to be one of the best examples of an active blanket bog (NPWS, 2001), which represents 71% of the catchment today (Bossard *et al.*, 2000) while forest plantations occupy 23% of the catchment (Forest Inventory and Planning System, unpublished data). Pollen records from the Late Glacial suggest early development of woodland, its subsequent decline and then the development of peat and bog ca. 5,000 cal. yr BP (Browne, 1986). Anthropogenic influences of fire and grazing probably accelerated deforestation (Coxon *et al.*, 1991). From the 13th to the 18th centuries the Burrishoole Channel was an important port, which facilitated trade with northern Mayo through the Nephin Beg mountains (Synge, 1963). Since the mid-1950s the Burrishoole catchment has been an important site of fisheries research, with fish census and catchment monitoring being conducted by the Marine Institute.

Furnace is part of the Clew Bay Complex SAC (site code 1482) and is described as a good example of a deep, stratified, saline coastal lake in a very natural state (NPWS, 2001). The lake has a surface area of 141 ha, a maximum depth of 21 m, a diameter of 1850 m, and it is approximately 800 m wide on average. Furnace is located to the south of the catchment (Figure 1b) and receives highly coloured drainage waters (52-112 mg l^{-1} PtCo; Marine Institute, unpublished data) that strongly limit the photic zone depth (ca. 1.7 m). The Burrishoole Channel connects Furnace to the sea in Clew Bay and semidiurnal tides flow northward into the lake.

Furnace is a permanently meromictic lake and only a single water column overturn is known to have occurred on the 12th September 1995 (Salmon Research Agency, 1995). This caused a major fish kill that wiped out trout and char that were caged in the lake at the time. Measurements of oxygen revealed an epilimnion depleted in oxygen (<2 mg l^{-1} DO) whilst the temperature profile showed isothermal conditions (ca. 17°C). The summer of 1995 was exceptionally hot with average air temperatures of ca. 17°C and low rainfall (175 mm) (Marine Institute, unpublished data). The water temperature within the hypolimnion from June to August 1995 was 4-5°C warmer than any previously recorded measurements (Salmon Research Agency, 1995). Due to the negligible input of freshwater in the summer of 1995, the halocline progressively disappeared and stratification was maintained by the thermocline only (Salmon Research Agency, 1995). As the weather cooled in the early autumn, isothermal conditions were mainly responsible for the mixing event, which moved anoxic water upward from the monimolimnion. An examination of summer rainfall records (*i.e.* the sum of precipitation in June, July and August) from 1960 (Marine Institute, unpublished data) suggests that rainfall in 1976, 1983 and 2006 were lower than 1995, but no overturns were documented. Therefore, it is likely that the combination of the disappearance of both halocline and thermocline together with the contribution of a northerly wind caused the 1995 event (Russell Poole, pers. comm.). Similar lagoon dynamics were documented by Lamont *et al.*, (2004), who found that the upwelling of anoxic water depends on the coincidence of strong winds and low levels of precipitation, which results in a weak salinity stratification. The fish kill associated with the 1995 overturn was probably due to the upwelling of hydrogen sulphide rather than anoxic waters. The permanent or extended stratification of Furnace causes the accumulation of H_2S and its lethal effects on fish are known (e.g. Lamont *et al.*, 2004; Luther *et al.*, 2004).

3. Methods

3.1 Monitoring water quality

The water column in Furnace was monitored by the Marine Institute by means of an Automatic Water Quality Monitoring Station (AWQMS) (Lakeland Instrumentation) (Figure 1c). A Datasonde DSX5 (Hydrolab OTT) with temperature, dissolved oxygen and conductivity sensors collected water column measurements from 0 m to 13 m depth. Data were recorded at two minute intervals by a Campbell Scientific CR1000 datalogger, with an average of 0.17 m between measurement intervals (depending on weather conditions). A backup and continuous temperature record was also collected using tidbits (Onset). Data were collated for the period January 2009 to December 2010. Hydrological data analysis involved the comparison of in-lake parameters with climatic data. Rainfall, air temperature and wind speed data recorded at the Furnace meteorological station were provided by the Marine Institute together with Furnace and Feeagh water level (OTT water level recorders) and tidal data recorded by tidal gauges at Belmullet (Co. Mayo). Plots of salinity, temperature dissolved oxygen (DO) were constructed using DPlot 2.3.0.7 (Hyde Soft Computing). The Wedderburn number (Stevens & Lawrence, 1997), an index for determining lake stability, was calculated using lake bathymetry, water salinity, water temperature and wind speed data by means of Lake Analyzer Web (Read *et al.*, 2011).

3.2 Sediment core sampling

A 146 cm sediment core was collected from the central part of Furnace (11 m depth; Figure 1c) in the winter 2008 using a rodless piston corer (Chambers & Cameron, 2001). The sediment was extruded vertically and subsampled at 1 cm resolution.

3.2.1 Chronology

The sediment core was dated using both radiometric (^{210}Pb, ^{137}Cs and ^{241}Am) and AMS radiocarbon techniques. Radiometric analysis was performed at the Bloomsbury Environmental Isotope Facility (BEIF) at University College London (UCL). Samples were analysed using an ORTEC HPGe GWL detector. Dates were determined using the Constant Rate Supply (CRS) model (Krishnaswami *et al.*, 1971; Appleby & Oldfield, 1978), whilst sediment accumulation rates (SARs) were calculated using unsupported ^{210}Pb and sediment density data and were expressed both as g cm^{-2} y^{-1} and cm yr^{-1}.

Accelerated mass spectrometry (AMS) radiocarbon analysis was performed at the CHRONO Centre, Queen's University Belfast (QUB). Four bulk sediment samples were selected in the absence of macrofossils. Calibration of radiocarbon dates was conducted using INTCAL09 (Reimer *et al.*, 2009) by means of Calib 6.0 software (Stuiver *et al.*, 2005). Two sigma (2σ) age ranges (95.4% probability) were utilised (Björck & Wolhlfarth, 2001). Dates obtained from the two different dating techniques were matched using a linear regression and estimated dates through the sediment core were calculated.

3.2.2 Lithostratigraphy, stable isotopes and geochemistry

After a preliminary visual inspection in order to identify variations in the lithological composition, organic matter and carbonate content were determined as loss on ignition (*i.e.* LOI_{550} and LOI_{950}) according to Heiri *et al.* (2001).

Carbon and nitrogen stable isotopes sample preparation was based on the combination of methods proposed by Talbot (2001) and Wolfe (2001). Analysis was carried out at the Geochemistry Laboratory, Trinity College Dublin (TCD) with a Thermo Delta Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS) using International Atomic Energy Authority reference standards (IAEA-NO3 for nitrogen, USGS-24 and IAEA-CH-6 for carbon). Elemental weight percentage composition of carbon and nitrogen was used to calculate the C/N ratio. Stable isotopes results are expressed using the delta notation for carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). A linear correlation was conducted between $\delta^{15}N$ and the C/N ratio as well as $\delta^{15}N$ and nitrogen (%) using SigmaPlot 11.0 (Systat Software 2008) to test for the presence of sediment diagenesis (Thornton & Mc Manus, 1994). To support diatom inferred palaeosalinity (see below), salinity reconstruction was additionally derived from the $\delta^{13}C$ record according to the equation [*i.e.* salinity $‰ = (\delta^{13}C+30.5)/0.54$)] proposed by Emeis *et al.* (2003). The authors examined the relationship between $\delta^{13}C$ and salinity and proposed that organic matter stable carbon isotopes could be used to detect and quantify salinity changes in surface water when fossil diatom assemblages are not well preserved.

Geochemical analysis (*i.e.* Fe, Mn, Cu, Mg) was carried out at Dundalk Institute of Technology using Flame Atomic Absorption Spectroscopy (FL-AAS) following US EPA method 3051a for sample preparation. Results are expressed as mg g^{-1} dry weight (DW).

3.2.3 Fossil diatoms

Fossil diatoms were prepared and concentrations determined according to Battarbee *et al.* (2001). Slides were prepared using Naphrax® as a mounting medium. Diatom identification and enumeration was carried out using a Leica DME microscope at 1000x magnification. Taxonomic identification was achieved mainly according to Snoeijs' series (Snoeijs, 1993; Snoeijs & Vilbaste, 1994; Snoeijs & Potapova, 1995; Snoeijs & Kasperovičienė, 1996; Snoeijs & Balashova, 1998) and Krammer & Lange-Bertalot (1986-1991) floras. A total of 66 taxa had abundances >1% and occurred in more than two samples (see supplementary data). The diatom morphological dissolution index (F index) (Flower & Lokhoshway, 1993; Ryves *et al.*, 2006) was calculated to quantify frustule dissolution. Diatom taxa were divided into groups according to their salinity tolerance and their habitat. Zonation of the diatom data was performed with constrained cluster analysis, CONISS method using the Psimpoll 4.27 software (Bennett, 2008). The number of significant zones was then identified by applying the broken-stick model (Bennett, 1996). A diatom conductivity transfer function was applied using the European Diatom Database (EDDI, 2001). Diatom-inferred conductivity (log $\mu S\ cm^{-1}$) reconstructions were carried out using the weighted average (WA) and locally weighted-weighted averaging (LWWA) numerical methods. Results were also converted to salinity according to the equation: salinity (‰) = $0.67\times10^{-3}\times$conductivity ($\mu S\ cm^{-1}$) (Pawlowicz, 2008; Pieters & Lawrence, 2009). The modern analogue technique (MAT) (Overpeck *et al.*, 1985) was run to ascertain the ratio of analogues between fossil and modern datasets.

3.2.4 Fossil cladocera and sponge spicules

Fossil cladocera sample preparation followed Frey (1986). Because of the low abundance of cladocera remains, results are expressed as total number of fragments g^{-1} wet weight (WW). Sponge spicules were encountered during cladocera counts and expressed as spicules g^{-1} WW. No detailed taxonomic classification was conducted.

4. Results

4.1 Modern hydrology

Marked variations in water levels in Furnace are evident (Figure 2a). The total water level amplitude was approximately 1.4 m with a minimum of 0.6 m and a maximum of 2.0 m. Variations in water level are the result of both tidal inflow from the south and inflow from the upstream lake to the north along with some short tributary streams flowing directly into Furnace. Water level changes in Furnace with fortnightly periodicity imposed by tides, which are estimated to intrude in a volume equivalent to 6-25% of the total lake volume each fortnight (Parker, 1977). Furnace water level maxima follow a similar pattern to spring high tides with time lags evident. This could be the result of the presence of the Burrishoole channel, which delays tidal inflow into the lake. Similarities with the water level in the upstream lake Feeagh are evident. Water level in Feeagh is determined by rainfall levels and increases in the Feeagh level automatically creates a greater freshwater inflow into Furnace. Rainfall was higher in 2009 than in 2010 (1794 mm and 1222 mm, respectively) (Figure 2b), A flash-flood in the Burrishoole catchment occurred on the 2nd July 2009 when 67 mm of rainfall fell in less than 24 hours. Excessive rainfall led to increased water levels in Feeagh that subsequently led to a rise in water levels in the downstream Furnace. Additionally, increased rainfall between August 11th and the 8th of September (289 mm) determined a water level increase of ca. 0.6 m in Feeagh, which led to an increase (ca. 1.1 m) in Furnace. Similar patterns were evident in 2010.

The salinity profile confirms Furnace is a meromictic lake (Figure 2c). The profile is characterised by the presence of a denser and more saline permanent monimolimnion. The surface water salinity is generally below 5‰ whilst the monimolimnion is ca. 18‰. The mixolimnion generally covers the top 4 m of the water column and it deepens mainly as a result of increased precipitation. Differences in rainfall patterns between 2009 and 2010 appear to determine the variations in the mixolimnion depth. In fact, reduced precipitation in 2010 results in a reduced mixolimnion depth, which is generally above 3 m with the exception of October 2010. Higher surface water salinity is also evident and freshwater conditions (<0.5‰) only appeared in October as a result of increased rainfall in September 2010.

During 2009 temperatures of ca. 12°C are evident in the monimolimnion below 6 m depth (Figure 2f), whilst surface water is influenced by seasonal air temperature. Winter (January to mid March) lowers surface water temperature (3°C at 2 m depth). Isothermal conditions characterise May, with temperatures in the region of 12°C through the water column, and the highest temperatures at the water column top are reached from mid-June to August (ca. 16-20°C). From September to the end of the year surface water temperatures gradually decrease reaching ca. 4°C at the end of December. A similar pattern is evident for 2010 with temperatures gradually increasing in March leading to isothermal conditions in April. Warming of the mixolimnion gradually occurs from mid April to September and highest temperatures (19°C) were recorded in June. Reduced precipitation and highest lake water salinity determined an increase in bottom water temperatures from ca. 8°C in May to ca. 13°C in July.

Dissolved oxygen (DO) concentrations are closely linked to salinity stratification, which determines anoxia of the bottom water (Figure 2e). In 2009 DO concentrations were <1% below ca. 6 m depth showing anoxic conditions. In contrast, surface water oxygen concentrations were generally over 75% DO and over-saturated conditions to 120% DO are evident in spring and summer. Oxygenation of the monimolimnion is evident in 2010. Waters up to 75% DO replace anoxic conditions from March to July, when oxygen levels rapidly decline and anoxic conditions appear again below 5 m depth. At the surface over-saturated conditions are evident from January to September 2010. This is coincident with lower rainfall and a shallower mixolimnion.

The Wedderburn number (W) is a parameter used to estimate the internal response of a lake to wind forcing helping to determine the probability that upwelling occurs. W values greater than 0 indicate that upwelling does not occur, whilst values lower than 0 suggest that upwelling is likely. The W number was calculated for Furnace during 2009 and 2010 (Figure 2f) and results are fragmentary due to the absence of data. High W values are mostly evident in January, February, September and December 2009 and coincide with the mixolimnion deepening. W is closer to 0 in July and August 2009. Lower values around 0 are evident in 2010 with the exception of few peaks between January and March.

4.2 Sediment Core Chronology

The equilibrium between the activity of total and supported ^{210}Pb occurs at approximately 9.5 cm depth. The maximum activity of the unsupported ^{210}Pb is recorded at 2.5 cm. The radionuclide ^{137}Cs exhibits a well-resolved peak at 2.5 cm depth and ^{241}Am shows a distinct peak at 3.5 cm depth. The lack of two distinct ^{137}Cs peaks might be related both to the slow sedimentation rate and to the sediment subsampling resolution adopted (1 cm). The CRS model indicates that the top 8.5 cm cover the past 115 years with 8.5 cm depth representing the year 1883. Artificial radionuclides are in good agreement with the CRS model, which places the 1963 layer just under 3 cm depth.

Results from four radiocarbon dates indicate that the core dates to between 3,689-3,830 cal. yr BP (3,472±20 ^{14}C yr) at 139 cm depth (Figure 3). Samples are in chronological order and good linearity (R^2= 0.993) resulted.

The ^{210}Pb and AMS dating techniques were compared using linear regression. An age-depth model is shown in Figure 3. Good linearity (R^2= 0.985) resulted suggesting that the combined ^{210}Pb and ^{14}C dating methods provide reliable results. The estimated chronology, expressed as cal. yr BP, calculated from linear regression is used for the interpretation of change in the core physical, chemical and biological proxies.

SARs calculated from the CRS model and AMS radiocarbon dates are in agreement. Low SARs (<0.019 g cm^{-2} yr^{-1}) were derived from the ^{210}Pb chronology and from the AMS radiocarbon dates (<0.048 cm yr^{-1}) and suggest that 1 cm of sediment is deposited in approximately 28 years (on average).

4.3 Lithology and stable isotopes

Results of lithology (LOI_{550}, LOI_{950}), stable isotopes ($\delta^{13}C$, $\delta^{15}N$), carbon, nitrogen and the C/N ratio are shown in Figure 4.

Cores of sediment extracted from Furnace were brownish black in colour (Hue 5YR 2/2; Oyama & Takehara, 1967) and exhibited homogeneous soft peaty-silt composition with no visible changes. Strong hydrogen sulphide smells were evident during sampling, indicating the presence of anoxia in the monimolimnion. LOI_{550} ranges between 17 and 30% and an increasing trend is evident from ca. 3,300 cal. yr BP upcore.

$\delta^{13}C$ is steady from the core bottom to ca. 3,200 cal. yr BP around ca. -27.5‰ and a slight $\delta^{13}C$ increase to -26.7‰ is evident ca. 500 cal. yr BP. The top of the core shows a small $\delta^{13}C$ reduction. $\delta^{13}C$-inferred salinity ranges between 0.2 and 2.0‰ indicating a small increase through time. However, because the equation was developed on a very different system (*i.e.* the Baltic Sea; Emeis *et al.*, 2003), results are treated cautiously.

A reduction in $\delta^{15}N$ values is evident from the core bottom to ca. 2,500 cal. yr BP (to 2.5‰) with two peaks at ca. 3,900 cal. yr BP (3.6‰) and ca. 3,300 cal. yr BP (2.9‰). An increase is evident to the core top where the highest value (4.0‰) is recorded.

Elemental carbon ranges from 10 to 20%, nitrogen ranges from 0.9-1.3%, while C/N ratios range between 9 and 17 through the core. A C/N increase from the core bottom (13 C/N) to ca. 17 at ca. 1,900 cal. yr BP is evident. The C/N trend is not uniform and it is characterised by five distinct lows with ca. 800 yr intervals.

4.4 Metals

Metal profiles are shown in Figure 5. Iron concentrations vary from a maximum of 25.3 to a minimum of 7.2 mg Fe g^{-1}. A decline in concentrations at the core bottom (ca. 4,000 cal. yr BP) is evident with a reduction from 25.3 mg Fe g^{-1} to 10.6 mg Fe g^{-1} at ca. 3,100 cal. yr BP. From thereon

Fe concentrations are relatively stable to the top of the core. Manganese concentrations are generally much lower than those of iron, ranging from 6.5 to 0.2 mg Mn g^{-1}. A similar reduction in concentrations upcore are evident also for Mn. The Fe/Mn ratio exhibits an overall increasing trend in the core ca. 4,100 cal. yr BP with ratios increasing from ca. 4 to ca. 40. From ca. 1,000 cal. yr BP the Fe/Mn ratio increases to the core top reaching maximum values (ca. 70 Fe/Mn). Copper concentrations range from 0.3-0.6 mg Cu g^{-1}. The maximum Cu/Mn value (3.4) is recorded at the core top (ca. 300 cal. yr BP). Magnesium ranges between 1.2 and 2.6 mg Mg g^{-1} in the core and a slight increasing trend from ca. 3,600 cal. yr BP to the core top is evident.

4.5 Fossil diatoms

A summary diagram of diatom species occurrence (>2%; n=23) is presented in Figure 6. The broken stick model suggested two statistically significant zones: Zone 1 - ca. 4,300-2,900 cal. yr BP and Zone 2 - ca. 2,900-500 cal. yr BP. Fossil assemblages in zone 1 are mainly dominated by *Achnanthidium minutissimum* (15%), *Cyclotella shumannii* (12%), *Cyclotella radiosa* (10%) and *Brachysira vitrea* (7%). A decreasing trend characterises some species such as *Denticula tenuis* (6 to 3%), *Aulacoseira alpigena* (8 to 3%), *Cyclotella comensis* (8 to 2%), *Diatoma tenuis* (7 to 1%) and *Tabellaria floculosa* (6 to 2%), whilst *Fragilaria exigua* (3 to 8%) increases. The assemblages in zone 1 are also represented by the presence of *Cyclotella cyclopuncta*, *Eunotia incisa*, *Cocconeis placentula*, *Fragilaria capucina*, *F. capucina* var. *gracilis*, *Staurosirella pinnata* and *Pseudostaurosira brevistriata* which have abundances lower than 2%. The dominant species in zone 2 is *Achnanthidium minutissimum* (max 19%) together with *Cyclotella comensis* (max 14%), *Aulacoseira alpigena* (15%) and *Fragilaria exigua* (13%). Differences with respect to zone 1 are evident for *Cyclotella shumannii*, *C. radiosa* and *Brachysira vitrea*, which are lower in abundance in zone 2, whilst *Denticula tenuis* disappears. An increase in *Tabellaria floculosa* (up to 7%) is evident at the top of zone 2. Species such as *Cyclotella cyclopuncta*, *Eunotia incisa*, *Cocconeis* *placentula*, *Fragilaria capucina*, *F. capucina* var. *gracilis*, *Staurosirella pinnata* and *Pseudostaurosira brevistriata* maintain abundances similar to zone 1. The appearance of species with more brackish affinities, such as *Cyclotella choctawhatcheeana*, *Cocconeis scutellum*, *Diatoma moniliformis*, *Ctenophora pulchella*, *Nitzschia valdestriata* and *Rhoicosphenia abbreviata* (all <5% abundance) characterise zone 2.

Silica dissolution was generally evident in all taxa classified including strongly silicified species (e.g. *Navicula radiosa*, *Pinnularia neomajor*). Weakly silicified species such as *Asterionella formosa* are only present at the core top. Dissolution was present from ca. 4,300 cal. yr BP to ca. 600 cal. yr BP, where the F index varies between 0.4 and 0.8 (Figure 6). At the core top the preservation index is closer to unity (1.0) indicating a well-preserved assemblage.

Diatom ecology is summarized as benthic or planktic and revealed a system dominated by benthic species (Figure 6). Planktic forms ranged between 15 and 50%. No change of species life form dominance is evident throughout the core. According to salinity tolerances, taxa were grouped into (I) freshwater species, (II) freshwater species with brackish water affinity, (III) brackish and (IV) marine species (Figure 6). Freshwater species were abundant through the entire core (ca. 40%). A greater abundance of freshwater taxa with brackish water affinity was evident (ca. 40-50%). Species with more brackish water affinity were generally less abundant (<20%), however, increases were evident for both fresh-brackish and brackish species from ca. 2,500 cal. yr BP upward. Marine species were present in very low abundances (<3%). To reconstruct past conductivity the combined EDDI conductivity training set was applied, although fossil taxa found in Furnace only represented between 26 and 56% of the species included in training set. WA diatom inferred conductivity (DI-conductivity) ranges between 2.9-3.4 log μS cm^{-1} (*i.e.* 794-2511 μS cm^{-1}) and there is a slight increase in DI-conductivity through the core (Figure 6). Similar values (3.0-3.7 log μS cm^{-1}; 1000-5011 μS cm^{-1}) resulted from the LWWA. The Modern Analogue Technique (MAT) provided MinDC values between 105 and 149, suggesting no close analogues in the training set (EDDI, 2001).

4.6 Cladocera and sponges

Simple quantitative measures of cladocera fragments and sponge spicule concentrations were used in this study (Figure 6). A clear overall decreasing upcore trend in cladocera remains is evident with drop from 2.1 x 10^3 fragments g^{-1} at ca. 4,300 cal. yr BP to 0.3 x 10^3 fragments g^{-1} WW at ca. 3,900 cal. yr BP. From here to the core top fragment concentrations remain below 1 x 10^3 fragments g^{-1} WW except for a peak between 2,400 and 2,300 cal. yr BP. Higher concentrations of sponge spicules are evident. Values reduce from 9.166 x 10^3 spicules g^{-1} WW at ca. 4,300 cal. yr BP to 0.4 x 10^3 spicules g^{-1} WW at approximately 1,800 cal. yr BP. From here to the core top concentrations are below 0.4 x 10^3 spicules g^{-1} WW with spicules absent in many samples.

5. Discussion

5.1 Modern hydrology: stability and mixing events

Lagoons are subject to natural hydrological dynamism due to their location and their relatively shallow depth (Gouze *et al.*, 2008). Climatic patterns together with basin morphology and freshwater or saline inflows determine large fluctuations and rapid changes in the physical and chemical characteristics. The characteristics can reduce dissolved oxygen (Levin *et al.*, 2009; Pena *et al.*, 2010), which is progressively depleted by organic matter degradation (Kountoura & Zacharias, 2011).

The hydrology of Furnace reflects the effect of both tidal and freshwater inflow. It is evident that freshwater inflow determines the overall lake water levels while High Spring Water (HSW) leads to periodically higher water levels. The period between July and September 2009 was characterised by 562 mm of rainfall and led to a progressive water level increase in the upstream Lough Feeagh and a subsequent rise in water levels in Furnace that persisted until mid-October

2009. The increased water level minimised the tidal effect with the exception of HSW. Higher water levels associated with catchment drainage appear to preclude salt-water inflow at High Neap Water (HNW). In contrast, following dry spells when water levels are lower in Furnace the tidal effect is more pronounced even at HNW (Brett, 2010).

When meromixis occurs, denser brackish water forms the monimolimnion, which is overlain by a mixolimnion of less saline water deriving from the watershed and precipitation (Hakala, 2004). In Furnace, the freshwater inflow is a primary driver in forming a strong halocline that varies its depth through seasons as a result of the balance of catchment runoff and seawater inflow. Furnace is a saline lake with a natural but modified tidal inlet (Healy *et al.*, 1997). A weir holds back the lake water and helps maintain permanent and stable meromictic conditions (Healy *et al.*, 1997; NPWS, 2001). The deep water is well protected from recirculation and is stagnant (Parker, 1977). The detailed hydrological data confirmed that Furnace is permanently stratified due to the presence of a strong halocline, which prevents the water column mixing. This condition has lead to extended anoxia in the monimolimnion, which was additionally confirmed by a typical hydrogen sulphide smell. The Wedderburn number (W) (Shintani *et al.*, 2010) calculated for Furnace confirmed that water column overturn by wind forcing is improbable. On the other hand, a partial overturn appeared in spring and summer 2010. Reduced precipitation determined isohaline conditions through the water column as recorded in March, at the beginning of April and July. In parallel, DO concentration increased in the monimolimnion. It is interesting to note how the thermocline reduced in this period leading to isothermal conditions through the water column, which has the potential to mix the water column. Additionally, the oxygen profile suggests that the temporary oxygenation of the monimolimnion might be interpreted as the result of reduced rainfall that allowed more tidal oxygenated water to flow into Furnace. To date, Furnace water column recording is still ongoing to obtain a long-term monitoring period to detect the existence of seasonality of partial overturns and better interpret the influence of the climate on hydrology.

Predictions of future climate change permit hypotheses of potential lake responses. An increase in the frequency and intensity of extreme precipitation and a significant increase of 0.01 mm/year in mean precipitation were found to have occurred at Furnace between 1960-2009 (Fealy *et al.*, 2010). A tendency towards wetter winters and drier summers has been observed over the last few decades (Murphy & Washington, 2001; Parsons & Lear, 2001), and projected climatic changes suggest a further increase in precipitation during the winter months and reductions during summers in Ireland (Dunne *et al.*, 2008; Fealy *et al.*, 2010). Drier summers have the potential to weaken the halocline in Furnace, and, as a result, stratification may only be maintained by the thermocline. One might think that future predicted climatic conditions could result in more frequent overturns in Furnace, however, temperature projections derived from three global circulation models and two emissions scenarios (A2 and B2) suggest that the greatest warming will be experienced in the autumn and spring seasons by 2080 (IPCC, 2000; Fealy *et al.*, 2010). An increased tendency for overturns is therefore unlikely in Furnace, since hot summers followed by cool autumns are needed to reach isothermal conditions through the water column and determine the water column mixing. Permanent meromictic conditions will potentially characterise Furnace in the future, with rare water column overturns caused by a combination of temperature, precipitation and wind.

5.2 Reconstruction of meromixis during the late Holocene

Due to their location, coastal lakes are in contact with the sea, receiving saline water inflows and meromixis can be considered as part of lake evolution (Hakala, 2004). The development of ectogenic meromixis in Furnace is mainly a result of the tidal influence, which has progressively increased in the past and it is probably related to sea-level rise.

5.2.1 The onset of meromixis

Measurement of redox-sensitive metals (Fe, Mn and Cu) in lake sediment can enable reconstruction of redox potential at the water bottom and the onset of meromixis in coastal areas (e.g. Sparrenbom *et al.*, 2006; Nichol *et al.*, 2007). Variation in redox conditions determines metal migration from the sediment to the water column and this process can also lead to the exhaustion of the pools in the sediment (e.g. Kristiansen *et al.*, 2002; Kristensen *et al.*, 2003). A shift from oxygenated to oxygen-depleted bottom waters is suggested by reductions in sediment manganese and iron at ca. 3,400 cal. yr BP in Furnace. Mn is known to be very soluble compared to most inorganic ions (Davison, 1993). Under anoxic conditions it reduces from Mn^{4+} to Mn^{2+} and leaves the sediment accumulating in oxygen-depleted bottom waters. Reduced manganese tends to disappear first (Kristensen *et al.*, 2003), which is also the case in Furnace, where it reaches background concentration at ca. 3,400 cal. yr BP, whilst Fe concentrations decrease more steadily upcore. The Fe/Mn ratio is a useful tool to reconstruct variations in redox conditions (Boyle, 2001). In particular, reducing conditions are suggested by an inverse correlation between Fe and the Fe/Mn ratio ($r= -0.44$, $p= 0.02$). This is the case of metal profiles in Furnace, which are reinforced by the upcore increase of copper. Copper is generally negatively correlated with Fe and Mn (Basaham, 1998) and its accumulation in sediments has been described as an indicator of anoxia (Sohlenius *et al.*, 2001; Kawakami *et al.*, 2008). Under anoxic conditions Cu^{2+} shows a strong affinity for complexing with sulphur and it precipitates as copper sulphide (Cu_xS_y), which is stable (Balistrieri *et al.*, 1994; Jung *et al.*, 1996). Sulphate reduction in organic-rich coastal marine sediments usually leads to the precipitation of pyrite (FeS_2) (Skei *et al.*, 2003), and copper sulphides may co-precipitate even in the presence of iron sulphides (Oakley *et al.*, 1980). However, the relative stability of Fe and the increase of Cu from ca. 2,100 cal. yr BP suggest that iron sulphide precipitation did not occur in Furnace. Indeed, Basaham (1998) demonstrated that FeS_2 precipitation did not take place in the anoxic Al-Arbaeen lagoon (Red Sea) sediments, where Cu was preferentially associated with organic matter. Therefore, it can be assumed that because of the ability of Cu to form stable organic complexes (Shank *et al.*, 2004) and the presence of high concentrations of complexing organic ligands in Furnace humic waters, copper is preferentially associated with organic matter in Furnace sediments (e.g. Hullebusch *et al.*, 2003; Sparrenbom *et al.*, 2006). In summary, the upcore increase in the Cu/Mn ratio, which is an indicator of reducing conditions and anoxia formation (e.g. Jung *et al.*, 2006), supports the parallel increase in the Fe/Mn ratio in Furnace as suggested by Pearson correlation ($r = 0.94$, $p < 0.01$).

Carbonate precipitation is a common process in coastal systems (López & Lluch, 2000) and the main forms are calcium and magnesium carbonates. In particular, magnesium calcite [$CaMg(CO_3)_2$] deposits are characteristic of brackish and saline sediments (Stumm & Morgan, 1981). A slight increase of the LOI_{950} measurements (13 to 19%) is evident, and it might suggest an accumulation of carbonates from ca. 3,500 cal. yr BP. Additional support is given by the parallel increase in Mg that might be associated with the carbonate phase. Seawater inflow potentially isolates bottom water, thus impeding water column mixing, and in turn determines increased calcite precipitation and the onset of anoxia. It is accepted that organic matter preservation is enhanced by permanent bottom water anoxic conditions (Meyers & Teranes, 2001). Therefore, the increase of LOI_{550} approximately 3,500 cal. yr BP, which parallels LOI_{950}, might be a result of anoxia formation leading to enhanced organic matter accumulation in the sediment.

5.2.2 Biological response

Diatoms in Furnace inhabit the water column surface and littoral zones and their productivity is probably constrained by peat-coloured waters coming from the catchment. The floristic composition reflects the strong freshwater influence. The ecological subdivision of taxa into salinity groups indicates that the fossil record is mainly represented by benthic and planktic freshwater species together with fresh-brackish taxa able to tolerate slightly brackish conditions. The diatom assemblages show a slight progression to fresh-brackish and brackish water affiliated taxa from approximately 1,800 cal. yr BP onwards. Similar shifts with increasing salinity in coastal areas have been documented in a number of studies (e.g. Westman & Hedenström, 2002; Emeis *et al.*, 2003;

Bao *et al.*, 2007). In particular, the Furnace diatom profile resembles diatom associations described by Bao *et al.* (2007), who found species assemblages mostly dominated by the freshwater epiphyte *Achnanthidium minutissimum* during the evolution of the Traba coastal wetland (Spain). The increase in *Diatoma tenuis* from ca. 900 cal. yr BP might also indicate increased influx of marine water to the lake as suggested by Mills *et al.* (2009).

Quantitative reconstructions of diatom-inferred (DI) conductivity were constrained by poor frustule preservation and poor training set representation and thus the inferences are not wholly reliable (Ryves *et al.*, 2006; Ryves *et al.*, 2009). Silica dissolution has altered fossil diatoms causing partial loss of the record and it might be a factor responsible for the large number of unclassified taxa. Valve dissolution depends on a number of factors such as pH, salinity, temperature, depth, water permanence, meromixis and sediment accumulation rates (SARs) (e.g. Lewin, 1961; Marshall & Warakomski, 1980; Hurd *et al.*, 1981; Barker *et al.*, 1994; Reed, 1998; Bidle *et al.*, 2002; Ryves *et al.*, 2006; Roubeix *et al.*, 2008). Diatom frustules are preserved in the sediment only if SARs are high enough to prevent opal dissolution in opal-unsaturated bottom waters (Bohrmann, 1986; Emeis *et al.*, 2003). Furnace had very low SARs (ca. 0.04 cm yr^{-1} on average). A further limitation in determining DI-conductivity was the lack close analogues between fossil taxa in Furnace and taxa in the used calibration datasets. Fossil taxa constituted between 26-56% of the training set assemblages. However, WA DI-conductivity increases from ca. 750 to 2,511 µS cm^{-1} (ca. 0.5-1.7‰ salinity) and the oligohaline conditions are in harmony with the floristic changes and upcore increases in brackish species. A salinity transfer function developed by Martin (2001) for Scottish lagoons was also applied, however, there was a poor match (7%) between modern and fossil assemblages. Reed (2007) proposed that transfer functions may only be accurate for sites included in the training set while Saros (2009) commented strong seasonal salinity in lagoons may result in poor ecological inferences when annual mean chemical conditions are employed in transfer functions. Emeis *et al.* (2003) proposed that organic matter stable carbon isotopes could be used to detect and quantify salinity changes in surface water when fossil diatom assemblages are not well preserved. Salinity reconstruction based on $\delta^{13}C$ in Furnace suggests an increase from ca. 0.2‰ to 2‰. The $\delta^{13}C$ inferred salinity is of a similar range to the diatom-inferred increase, however the inferences diverge at the core top.

An increase in mixolimnion salinity is also suggested by the parallel reduction of cladocera remains. The study of Hofman & Win (2000) showed that prior to the Littorina transgression, the Baltic Sea had a rich cladoceran and chironomid fauna typical of freshwater habitats, which reduced and disappeared after that event. The cladocera remains in Furnace sediments could represent the remains of individuals transported by freshwater inflows from the upstream lake and/or could be autochthonous species able to withstand a certain degree of salinity (e.g. Sarma *et al.*, 2000; Green *et al.*, 2005). However, no cladocera were found in modern water samples and the decline in cladocera remains in Furnace is coincident with a progressive increase in salinity reconstructions. Sponges, which are sensitive to extended anoxic conditions (Boundy-Sanders *et al.*, 1999; Bond & Wignall, 2005), provide additional support to the hypothesis of meromixis formation. A decrease in sponge remains parallels dissolved oxygen reduction in the monimolimnion inferred from redox-sensitive metals. The decline in spicules from ca. 2,000 cal. yr BP might be driven by prolonged anoxia and hydrogen sulphide formation (Engstrom & Wright, 1984; Thauer *et al.*, 2007). This potentially made the monimolimnion a harsh environment precipitating benthic community collapse and supporting only bacterial activity (Grall & Chauvaud, 2002; Hakala, 2004; Conley *et al.*, 2007). However, further inferences would require systematic taxonomic and ecological sponge spicule classification.

5.2.3 Sources of organic matter

Allochtonous organic matter includes a variety of ligno-cellulosic debris and soil-derived organic material (Meyers, 1997) including particulate organic carbon (POC) and dissolved organic carbon

(DOC). In particular, fluxes of DOC from peatlands assume particular relevance since high DOC is leached to surface runoff and groundwater (Barry & Foy, 2008). In Furnace, the majority of land-derived material passes through the upstream lake Feeagh and the terrigenous material becomes diluted with autochthonous material (Parker, 1977). The comparison of sediment $\delta^{13}C$ values with C/N ratios showed ranges typical of organic inputs to coastal environments (Lamb *et al.*, 2006) indicating a strong land-derived influence. $\delta^{13}C$ and $\delta^{15}N$ values from Furnace are typical of sediments from peat-dominated catchments (e.g. Skrzypek *et al.*, 2008; Diefendorf *et al.* 2008) and a number of studies have revealed similar signals in lagoons and estuaries (e.g. Müller & Mathesius, 1999; Müller & Voß, 1999). The nature of the sediment organic matter is further confirmed by similar results from the upstream catchment lake (Dalton *et al.*, 2010).

Organic matter degradation is minimal under anoxic conditions (Meyers, 1997) and sediment $\delta^{13}C$ is considered to be more conservative in comparison to $\delta^{15}N$ and the C/N ratio (Thornton & Mc Manus, 1994). However, microbial reworking during early diagenesis has the potential to modify the original $\delta^{13}C$ and $\delta^{15}N$ value (Lehmann *et al.*, 2002; Lamb *et al.*, 2006). Yamaguchi *et al.* (2010) found similar $\delta^{13}C$ increases in a saline meromictic lake and attributed this to preferential microbial decomposition of low-$\delta^{13}C$ labile components such as amino acids. Furthermore, a shift to positive $\delta^{13}C$ values has been linked to progressive salinity increases (Emeis *et al.*, 2003). Additionally, in coastal waters the pH-dependent equilibrium between CO_2 ($\delta^{13}C$ -8‰) and HCO_3^- ($\delta^{13}C$ 0‰) tends more to bicarbonate composition and in-lake derived organic matter would then reflect lower $\delta^{13}C$ values (Emeis *et al.*, 2003).

As a result of permanent water stratification anoxic conditions may form and denitrification leads to a release of ammonium with a consequent $\delta^{15}N$ rise (> +10‰) (Ogawa *et al.*, 2001). In similar conditions, ammonification resulting from the bacterial reduction of organically-bound nitrogen can also lead to a reduction in $\delta^{15}N$ values (Teranes & Bernasconi, 2000). This could be the case at the bottom of the Furnace core, where fractionation in the order of ca. 1‰ determines a

$\delta^{15}N$ upcore reduction from 3,800 to ca. 2,300 cal. yr BP. The nitrogen stable isotope trend parallels the reduction in redox-sensitive metals and it might suggest ammonification at the sediment-water interface. Interpretation of the increase of $\delta^{15}N$ from ca. 1,000 cal. yr BP, when it is assumed that the lagoon hydrodynamics were similar to modern conditions (*i.e.* permanent meromixis), proved inconclusive. Diagenetic processes might be responsible (Yamaguchi *et al.,* 2010), however correlations between $\delta^{15}N$ with the C/N ratio (r= 0.0459, p= 0.810) and between $\delta^{15}N$ and nitrogen (r= -0.163, p= 0.390) proposed by Thornton & Mc Manus (1994) suggested no significant relationships and thus no organic matter alteration by diagenesis.

5.3 Sea level rise during the late Holocene

Mid-late Holocene sea level is estimated to be much lower than today. The highest quality sea-level data (*i.e.* primary index points) available from Ireland are mainly located along the southern coast, whilst fewer reliable sea-level index points are found along eastern and western coastlines (Brooks & Edwards, 2006). Confirmation of a sea level rise is suggested by a palaeolimnological study based on fossil diatoms in Lough Hyne (south-western Ireland) that documented a gradual marine transgression from approximately ca. 4,000 cal. yr BP (Buzer, 1981). Furthermore, a sedimentary record from the south coast of Ireland suggest a marine transgression of the inner coastal area from ca. 7,400 cal. yr BP with a sea level of 5.7 m lower than the Ordnance Datum (OD) (Devoy *et al.*, 2004). The sediment sequence suggested a sea level rise of 1.19 m, passing from -1.82 m (OD) at 4,210 cal. yr BP to -0.63 m (OD) at 3,118 cal. yr BP. Shaw (1985) reconstructed a RSL of -0.36 m (OD) 2,103 cal. yr BP that increased to -0.10 m (OD) 746 cal. yr BP. These RSL dates are synchronous with the response in sediment proxies in Furnace. Sediment reconstructions suggest the formation of anoxia at ca. 3,400-3,200 cal. yr BP due to the increasing inflow of marine water. The progressive expansion of the more dense and stagnant monimolimnion and catchment and upstream inputs may account for the later increase in brackish diatoms and disappearance of sponge spicules. At approximately 4,000 cal. yr BP, the mean sea level is estimated to be ca. 1.8 m lower than today (Devoy *et al.*, 2004), and only highest spring tides coupled with strong onshore winds were potentially able to flow into Furnace. The lake hydrology was mostly governed by freshwater discharge from the catchment and salinity was low. Following the progressive increase in the mean sea level, tidal inflows became more frequent and seawater started accumulating in the deepest part of the lake determining the formation of anoxia. The monimolimnion gradually reached modern conditions, where even HNW can flow into Furnace.

5.4 Late Holocene climate variability

The C/N ratio has been employed to reconstruct hydrological changes in coastal environments, for example, change in lake levels (Wolfe *et al.*, 2011), isolation of coastal basins from the sea (Mills *et al.*, 2009) and fluctuations in relative sea level and river discharge (Lamb *et al.*, 2007). Periodic reductions of the C/N ratio may indicate dry periods characterised by reduced precipitation and lower runoff, consequently resulting in lower C/N ratio values mainly deriving from autochthonous phytoplankton. Ombrotrophic peatlands in northern Europe have long been recognized as excellent climate archives (e.g. Barber *et al.*, 2003; Turney *et al.*, 2006; Swindles *et al.*, 2010). In particular, palaeoclimatic studies on peat bogs in Ireland and UK have provided detailed reconstructions of the alteration of wet-dry periods. Turney *et al.* (2006) analysed Irish bogs and lake tree populations and a series of dry phases were recognized (ca. 4,100, ca. 3,200, ca. 2,650, ca. 1,700 and ca. 800 cal. yr BP) indicating a significant reduction in moisture delivery and/or significantly reduced water tables. More recently, widespread water deficits in summer months (2,752-3,102 cal. yr BP, 1,802-2,272 cal. yr BP, 1,482-1,702 cal. yr BP and 1,850-2,000 AD) have been revealed by Swindles *et al.* (2010) from Northern Ireland. Similarly, alternate floods and droughts were identified by Barber *et al.* (2003), who defined a series of phase-shifts to wetter climates from three sites in Ireland and the UK. In particular, the record from the Abbeyknockmoy Bog (Co. Galway) provided a series of major dry periods that corresponded to ca. 4,100, ca. 3,350, ca. 2,900, ca. 2,350, ca. 750 cal. yr BP. The coincidence between Furnace C/N minima (at ca. 4100, 3300, 2400, 1700, 600) and the inferred dry phases from peat bogs is marked. Offsets in dates might be in part due to intrinsic chronological errors and/or differences in regional climates.

It is well known that the NAO influences European climate (Hurrell, 1995; Wanner *et al.*, 2001; Scaife *et al.*, 2008) and a number of studies suggested the existence of interannual to multi-centennial NAO cycles (e.g. Mann *et al.*, 1998; Rimbu *et al.*, 2003, Magny, 2004). Magny (2004) investigated synchronous changes in lake-levels from French pre-Alps and the Swiss plateau. Lake level changes were assumed to be climatically driven and a rather unstable Holocene climate indicated 15 high water level phases attributed to wetter conditions. Wet phases detected in Southern Europe surprisingly correspond to dry phases inferred from Furnace C/N ratio. This suggests that the NAO might represent an important driver in Furnace palaeohydrology, and it is supported by similar findings in the upstream lake Feeagh (Jennings *et al.*, 2000).

Shifts to minimum C/N ratio values occur with ca. 800-year periodicity in Furnace. A number of studies have detected a periodicity in solar activity of ca. 800 years (e.g. Schulz *et al.*, 2004; Turney *et al.*, 2005; Ma, 2007) and these appear to be synchronous with the multi-centennial variations in the NAO recorded in many studies (e.g. Magny, 2004; Hu *et al.*, 2003; Lamy *et al.*, 2006). Karlén & Kuylenstierna (1996) studied a possible correlation between changes in the climate of Scandinavia and changes in solar irradiation. The authors demonstrated that for most of the last 9,000 years a good correspondence between the timing of cold events and the timing of major $\delta^{14}C$ anomalies due to low solar irradiation exists. Similar findings have been proposed by Bernárdez *et al.* (2008), who reconstructed the climatic variability during the late Holocene in the NW Iberian Peninsula and described how a high irradiance controlled precipitation and induced high run-off and increased riverine influx. Therefore, it seems that changes in the solar activity have played a major role in Holocene climate oscillations over the North Atlantic area (Magny, 2004).

6. Conclusions

The multiproxy palaeolimnological reconstruction of Lough Furnace suggests a response to progressive sea level rise and meromixis formation during the late Holocene. Prior to ca. 4,300 cal. yr BP lake salinity was probably close to freshwater conditions. The increased influence of marine water into the basin relative to freshwater input has determined the onset of meromixis, which has become progressively more stable. This determined the formation of anoxia in the monimolimnion from ca. 3,400 cal. yr BP. Anoxia strongly limited the development of benthic communities and it appears that from ca. 2,000 cal. yr BP onwards permanent meromictic conditions persisted. Prior to 3400 cal. yr BP the lake was probably holomictic and mixing events were likely more frequent than today. Since meromixis formation water column stratification has become progressively more permanent and only occasional overturns (coupled with dry summers) have occurred. Modern hydrological monitoring data show that meromixis is mainly dependent on freshwater inflow and temporary isohaline conditions are evident in spring and summer 2010. Climate projections indicate that Furnace overturns might potentially remain rare in the future. Furthermore, this study outlines how the hydrology of the Burrishoole catchment appears to be dependent on the North Atlantic Oscillation and long-term solar cycles, with an alternation of dry and wet local climatic phases recorded during the late Holocene.

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References

Airoldi, L., Beck, M.W., 2007. Loss, Status and Trends for Coastal Marine Habitats of Europe, in: Gibson, R.N., Atkinson, R.J.A., Gordon, J.D.M. (Eds.), Oceanogr. Mar. Biol. Annu. Rev. Taylor & Francis, pp. 345-405.

Appleby, P.G., Oldfield, F., 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5, 1-8.

Bao, R., Alonso, A., Delgado, C., Pages, J.L., 2007. Identification of the main driving mechanisms in the evolution of a small coastal wetland (Traba, Galicia, NW Spain) since its origin 5700 cal yr BP. Palaeogeogr., Palaeoclimatol., Palaeoecol. 247, 296-312.

Barber, K.E., Chambers, F.M., Maddy, D., 2003. Holocene palaeoclimate from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland. Quaternary Science Reviews 22, 521-539.

Barker, P., Fontes, J.-C., Gasse, F., Druart, J.-C., 1994. Experimental Dissolution of Diatom Silica in Concentrated Salt Solutions and Implications for Paleoenvironmental Reconstruction. Limnol. Oceanogr. 39.

Barnes, R.S.K., 1980. Coastal lagoons. The natural history of a neglected habitat. Cambridge University Press, Cambridge.

Barry, C.D., Foy, R.H., 2008. Carbon dynamics and food web reliance on allochthonous carbon in Lough Melvin. Strand 4 Carbon Isotope Analysis Technical Report. Lough Melvin Nutrient Reduction Programme.

Battarbee, R., Jones, V., Flower, R., Cameron, N., Bennion, H., Carvalho, L., Juggins, S., 2001. Diatoms, in: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Kulwer Academic Publishers, Dordrecht, The Netherlands, pp. 155-202.

Battarbee, R.W., 1999. The importance of palaeolimnology to lake restoration. Hydrobiologia 395/396, 149-159.

Battarbee, R.W., Grytnes, J.A., Thompson, R., Appleby, P.G., Catalan, J., Korhola, A., Birks, H.J.B., Heegaard, E., Lami, A., 2002. Comparing paleolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. J. Paleolimnol. 28, 161-179.

Bennett, K.D., 1996. Determination of the number of zones in a biostratigraphical sequence. New Phytol. 132, 155-170.

Bennett, K.D., 2008. Psimpoll v. 4.263. http://chrono.qub.ac.uk/psimpoll/psimpoll.html.

Bennion, H., Battarbee, R., 2007. The European Union Water Framework Directive: opportunities for palaeolimnology. J. Paleolimnol. 38, 285-295.

Bernardez, P., Gonzalez-Alvarez, R., Frances, G., Prego, R., Barcena, M.A., Romero, O.E., 2008. Late Holocene history of the rainfall in the NW Iberian peninsula - Evidence from a marine record. J. Mar. Syst. 72, 366-382.

Bidle, K.D., Manganelli, M., Azam, F., 2002. Regulation of oceanic silicon and carbon preservation by temperature control on bacteria. Science 298, 1980-1984.

Björck, S., Wohlfarth, B., 2001. ^{14}C Chronostratigraphic Techniques in Paleolimnology, in: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Changes Using Lake Sediments. Kluwer, Dordrecht, pp. 205-245.

Blázquez, A.M., User, J., 2010. Palaeoenvironments and Quaternary foraminifera in the Elx coastal lagoon (Alicante, Spain). Quaternary International 221, 68-90.

Bohrmann, G., 1986. Accumulation of biogenie silica and opal dissolution in upper quaternary skagerrak sediments. Geo-Mar. Lett. 6.

Bond, D., Wignall, P.B., 2005. Evidence for Late Devonian (Kellwasser) anoxic events in the Great Basin, western United States, in: Over, D.J., Morrow, J.R., Wignall, P.B. (Eds.), Understanding Late Devonian and Permian-Triassic Biotic and Climatic Events: Towards an Integrated Approach. Elsevier.

Bossard, M., Feranec, J., Otahel, J., 2000. CORINE land cover technical guide - Addendum 2000, Technical report No°40. European Environment Agency, Luxembourg.

Boyle, J.F., 2001. Inorganic geochemical methods in palaeolimnology, in: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Boundy-Sanders, S.Q., Sandberg, C.A., Murchey, B.L., Harris, A.G., 1999. A late Frasnian (Late Devonian) radiolarian, sponge spicule, and conodont fauna from the Slaven Chert, northern Shoshone Range, Roberts Mountains Allochthon, Nevada. Micropaleontology 45, 62-68.

Brooks, A., Edwards, R., 2006. The Development of a Sea-Level Database for Ireland. Irish Journal of Earth Sciences 24, 13-27.

Browne, P., 1986. Vegetational hystory of the Nephin Beg Mountains, County Mayo. Unpublished Ph.D. thesis. Trinity College, Dublin.

Buzer, J.S., 1981. Diatom Analyses of Sediment From Lough Ine, Co. Cork, Southwest Ireland. New Phytol. 89, 511-533.

Cearreta, A., Alday, M., Freitas, M.C., Andrade, C., 2007. Postglacial foraminifera and palaeoenvironments of the Melides lagoon (SW Portugal): towards a regional model of coastal evolution. J. Foraminifer. Res. 37, 125-135.

Chambers, J.W., Cameron, N.G., 2001. A rod-less piston corer for lake sediments: an improved, rope-operated percussion corer. J. Paleolimnol. 25, 117-122.

Conley, D.J., Carstensen, J., Ærtebjerg, G., Christensen, P.B., Dalsgaard, T., Hansen, J.L.S., Josefson, A.B., 2007. Long-Term changes and Impacts of Hypoxia in Danish Coastal waters. Ecol. Appl. 17, S165-S184.

Coxon, P., Browne, P., Condit, T., Gibbons, M., Hannon, G., Stone, J., 1991. A fieldguide to the Quaternary of North Mayo. IQUA Field Guide 14, 56.

Dalton, C., Jennings, E., Taylor, D., Murnaghan, S., Bosch, K., de Eyto, E., Sparber, K., 2010. Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in contrasting catchments in Ireland. Final report.

Devoy, R.J.N., Nichol, S.L., Sinnott, A.M., 2004. Holocene Sea-level and Sedimentary Changes on the South Coast of Ireland. Journal of Coastal Research. Special Issue (Proceedings of the 8th International Coastal Symposium) 39, 146-150.

Diefendorf, A.F., Patterson, W.P., Holmden, C., Mullins, H.T., 2008. Carbon isotopes of marl and lake sediment organic matter reflect terrestrial landscape during the late Glacial and early Holocene (16,800 to 5,540 cal yr B.P.): a multiproxy study of lacustrine sediments at Lough Inchiquin, western Ireand. J. Paleolimnol. 39.

Doody, P.J., 2005. Europe, Coastal Ecology, in: Shwartz, M.L. (Ed.), Encyclopedia of Coastal Science. Springer, p. 1211.

Dunne, S., Hanafin, J., Lynch, P., McGrath, R., Nishimura, E., Nolan, P., Ratnam, J., Semmler, T., Sweeney, C., Varghese, S., Wang, S., 2008. Ireland in a Warmer World, Scientific Predictions of the Irish Climate in the Twenty-First Century. Community Climate Change Consortium for Ireland (C4I).

EDDI, 2001. European Diatom Database (http://craticula.ncl.ac.uk:8000/Eddi/jsp/index.jsp).

Emeis, K.-C., Struck, U., Blanz, T., Kohly, A., Voß, M., 2003. Salinity changes in the central Baltic Sea (NW Europe) over the last 10000 years. The Holocene 13, 411-421.

Engstrom, D.R., Wright, H.E., 1984. Chemical stratigraphy of lake sediments as a record of environmental change, in: Haworth, E.Y., Lund, J.W.G. (Eds.), Lake Sediments and Environmental History. Leicester University Press, Leicester, pp. 11-68.

Fealy, R., Allot, N., Broderick, C., De Eyto, E., Dillane, M., Erdil, R.M., Jennings, E., Mc Crann, K., Murphy, C., O' Toole, C., Poole, R., Rogan, G., Ryder, L., Taylor, D., Whelan, K., White, J., 2010. RESCALE: Review and Simulate Climate and Catchment Responses at Burrishoole.

Flower, R., Lokhoshway, Y., 1993. An investigation of diatom preservation in Lake Baikal, in: Grachev, M.A. (Ed.), Fifth Workshop on Diatom Algae, Russian Botaincal Society, Irkutsk.

Frey, D.G., 1986. Cladocera analysis, in: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons, New York, pp. 667-692.

Grall, J., Chauvaud, L., 2002. Marine eutrophication and benthos: the need for new approaches and concepts. Global Change Biol. 8, 813-830.

Green, A.J., Fuentes, C., Moreno-Ostos, E., Rodrigues da Silva, S.L., 2005. Factors influencing cladoceran abundance and species richness in brackish lakes in Eastern Spain. Annales De Limnologie-International Journal of Limnology 41, 73-81.

Guelorget, O., Perthuisot, J.P., 1992. Paralic ecosystems. Biological organization and functioning. Vie Milieu 42, 215-251.

Hakala, A., 2004. Meromixis as a part of lake evolution – observations and a revised classification of true meromictic lakes in Finland. Boreal Environ. Res. 9, 37-53.

Healy, B., 1997. Long-term changes in a brackish lagoon, Lady’s Island lake, south-east Ireland. Biology And Environment. Proceedings Of The Royal Irish Academy 97B, 33-51.

Healy, B., 1999a. Survey of Irish coastal lagoons (1996-1998). Background, description and summary of the surveys, Dúchas, Dublin, p. 111.

Healy, B., 1999b. Survey of Irish coastal lagoons (1996-1998). Lagoons surveyed in 1998, Dúchas, Dublin, p. 220.

Healy, B., Bates, R., Mc Grath, D., 1982. Marine Fauna of Co. Wexford - Lady's Island Lake. Ir. Nat. J. 20, 509-560.

Healy, B., Oliver, G.A., Hatch, P., Good, J., 1997. Coastal Lagoons in The Republic of Ireland Volume: No. 19 Lough Furnace. National Parks and Wildlife Service, Department of the Environent, Heritage and Local Governent, Ireland Volume 3.

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estmating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25, 101-110.

Hofmann, W., Winn, K., 2000. The Littorina Transgression in the Western Baltic Sea as Indicated by Subfossil Chironomidae (Diptera) and Cladocera (Crustacea). Int. Rev. Hydrobiol. 85, 267-291.

Holmes, J., Jones, R., Haas, J.N., Mc Dermott, F., Molloy, K., O'Connell, M., 2007. Multi-proxy evidence for Holocene lake-level and salinity changes at An Loch Mór, a coastal lake on the Aran Islands, Western Ireland. Quaternary Science Reviews 26, 2438-2462.

Hu, F.S., Kaufman, D., Yoneji, S., Nelson, D.M., Shemesh, A., Huang, Y., Tian, J., Bond, G., Clegg, B., Brown, T., 2003. Cyclic Variation and Solar Forcing of Holocene Climate in the Alaskan Subarctic. Science 301, 1890-1893

Hurd, D.C., Pankratz, H.S., Asper, V., Fugate, J., Morrow, H., 1981. Changes in the physical and chemical properties of biogenic silica from the central Equatorial Pacific. Part III. Specific pore volume, mean pore size, and skeletal ultrastructure of acid-cleaned samples. Am. J. Sci. 281, 833-895.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation. Science 269, 676-679.

IPCC, 2000. Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, p. 20.

IPCC, 2007. Summary for Policymakers, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jennings, E., Allott, N., McGinnity, P., Poole, R., Quirke, W., Twomey, H., George, G., 2000. The North Atlantic Oscillation: effects on freshwater systems in Ireland. Proceedings of the Royal Irish Academy 100B, 149-157.

Joint Nature Conservation Committee, 1996. Guidelines for Selection of Biological SSSIs: Intertidal Marine Habitats and Saline Lagoons. Joint Nature Conservation Committee, Peterborough.

Karlén, W., Kuylenstierna, J., 1996. On solar forcing of Holocene climate: evidence from Scandinavia. The Holocene 6.

Kennish, M.J., Paerl, H.W., 2010. Coastal lagoons: critical habitats of environmental change, in: Kennish, M.J., Paerl, H.W. (Eds.), Coastal lagoons: critical habitats of environmental change. CRC Press.

Kountoura, K., Zacharias, I., 2011. Temporal and spatial distribution of hypoxic/seasonal anoxic zone in Amvrakikos Gulf, Western Greece. Estuar. Coast. Shelf Sci. 94, 123-128.

Krammer, K., Lange-Bertalot, H., 1986. Bacillariophyceae. Naviculaceae. Gustav Fischer Verlag: New York, Stuttgard. Heidelberg & Berlin: Spektrum Akademisher Verlag.

Krammer, K., Lange-Bertalot, H., 1988. Bacillariophyceae. Bacillariaceae, Epithemiaceae, Surerillaceae. Heidelberg & Berlin: Spektrum Akademisher Verlag.

Krammer, K., Lange-Bertalot, H., 1991a. Bacillariophyceae. Centrales, Fragilariaceae, Eunotiaceae. Heidelberg & Berlin: Spektrum Akademisher Verlag.

Krammer, K., Lange-Bertalot, H., 1991b. Bacillariophyceae. Achnanthaceae. Heidelberg & Berlin: Spektrum Akademisher Verlag.

Krammer, K., Lange-Bertalot, H., 2000. Bacillariophyceae: English and French translation of the keys. Heidelberg & Berlin: Spektrum Akademisher Verlag.

Lamb, A.L., Vane, C.H., G.P., W., Rees, J.G., Moss-Hayes, V.L., 2007. Assessing $\delta^{13}C$ and C/N ratios from organic material in archived cores as Holocene sea level and palaeoenvironmental indicators in the Humber Estuary, UK. Mar. Geol. 244, 109-128.

Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. Earth-Sci. Rev. 75, 29-57.

Lamont, G., Laval, B., Pawlowicz, R., Pieters, R., Lawrence, G.A., 2004. Physical mechanisms leading to upwelling of anoxic bottom water in Nitinat Lake. 17th ASCE Engineering Mechanics Conference. June 13-16, 2004. Unversity of Delaware, Newark, DE.

Lamy, F., Arz, H.W., Bond, G.C., Bahr, A., Pätzold, J., 2006. Multicentennial-scale hydrological changes in the Black Sea and northern Red Sea during the Holocene and the Arctic/North Atlantic Oscillation. Palaeoceanography 21.

Lehmann, M.F., Bernasconi, S.M., Barbieri, A., Mc Kenzie, J.A., 2002. Preservation of organic matter and alteration of its carbon and nitrogen isotope composition during simulated and in situ early sedimentary diagenesis. Geochim. Cosmochim. Acta 66.

Levin, L.A., Ekau, W., Gooday, A.J., Jorissen, F., Middelburg, J.J., Naqvi, S.W.A., Neira, C., Rabalais, N.N., Zhang, J., 2009. Effects of natural and human-induced hypoxia on coastal benthos. Biogeosciences 6, 2063-2098.

Lewin, J.C., 1961. The dissolution of silica from diatom walls. Geochim. Cosmochim. Acta 21, 182-198.

Long, C.B., MacDermot, C.V., Morris, J.H., Sleeman, A.G., Tietzsch-Tyler, D., Aldwell, C.R., Daly, D., Flegg, A.M., McArdle, P.M., Warren, W.P., 1992. Geology of north Mayo. Geological Survey of Ireland.

López, P., Lluch, X., 2000. Sediment geochemistry of a meromictic coastal lagoon, “Es Cibollar” (Majorca, Spain). Limnetica 18, 15-27.

Lotter, A.F., 2005. Multi-proxy Climatic Reconstructions, in: Mackay, A., Battarbee, R.W., Birks, J., Oldfield, F. (Eds.), Global Change in the Holocene. Hodder Arnold, pp. 373-383.

Luther, G.W., Ma, S., Trouwborst, R., Grazer, B., Blickley, M., Scarborough, R., Mensinger, M., 2004. The role of anoxia, H_2S, storm events in fish kills of dead-end canals of Delaware Inland Bays. Estuaries 27, 551-560.

Ma, L.H., 2007. Thousand-Year Cycle Signals in Solar Activity. Solar Physics 245, 411-414.

Magny, M., 2004. Holocene climate variability as reflected by mid- European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113, 65-79.

Mann, M.E., Bradley, R.S., Hughes, M.K., 1998. Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392.

Marshall, W.L., Warakomski, J.M., 1980. Amorphous silica solubilities. II. Effect of aqueous salt solutions at 25°C. Geochim. Cosmochim. Acta 44, 915-924.

Martin, A., 2001. The ecology and palaeoecology of the Charophyte Lamphrotamnium papulosum in UK coastal lagoon. PhD thesis. University College London.

Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. Org. Geochem. 27, 213-250.

Meyers, P.A., Teranes, J., 2001. Sediment Organic Matter, Tracking Environmental Change Using Lake Sediments, pp. 239-269.

Mills, K., Mackay, A.W., Bradley, R.S., Finney, B., 2009. Diatom and stable isotope records of late Holocene lake ontogeny at Indrepollen, Lofoten, NW Norway: a response to glacio-isostasy and Neoglacial cooling. The Holocene 19, 261-271.

Müller, A., Mathesius, U., 1999. The palaeoenvironments of coastal lagoons in the southern Baltic Sea, I. The application of sedimentary C_{org}/N ratios as source indicators of organic matter. Palaeogeogr., Palaeoclimatol., Palaeoecol. 145, 1-16.

Müller, A., Voß, M., 1999. The palaeoenvironments of coastal lagoons in the southern Baltic Sea, II. $ä^{13}C$ and $\delta^{15}N$ ratios of organic matter sources and sediments. Palaeogeogr., Palaeoclimatol., Palaeoecol. 145, 17-32.

Murphy, S.J., Washington, R., 2001. United Kingdom and Ireland precipitation variability and the North Atlantic sea-level pressure field. International Journal of Climatology 21, 939-959.

Norton, M., Healy, B., 1984. Marine fauna of County Wexford-7. Observations on the ecology and reproductive biology of Sphaeroma hookeri Leach (Isopoda). Irish Naturalists' Journal 21 257-262.

NPWS, 2001. Clew Bay Complex SAC Site Synopsis. National Parks and Wildlife Service, Department of the Environent, Heritage and Local Governent, Ireland.

O'Sullivan, P., 2004. Palaeolimnology, in: O'Sullivan, P.E., Reynolds, C.S. (Eds.), The Lakes Handbook: Limnology and Limnetic Ecology. Blackwell.

Ogawa, N.O., Koitabashi, T., Oda, H., Nakamura, T., Ohkouchi, N., Wada, E., 2001. Fluctuations of nitrogen isotope ratio of gobiid fish (Isaza) specimens and sediments in Lake Biwa, Japan, during the 20th century. Limnol. Oceanogr. 46, 1228-1236.

Oliver, G.A., 2005. Seasonal changes and biological classification of Irish coastal lagoons, Department of Zoology. University College, Belfield, Dublin.

Overpeck, J.T., Webb, T., Prentice, I.C., 1985. Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogues. Quatern. Res. 23, 87-108.

Oyama, M., Takehara, H., 1967. Revised Standard Soil Colour Charts. 13 pp.

Parker, M.M., 1977. Lough Furnace, County Mayo; physical and chemical studies of an Irish saline lake, with reference to the biology of Neomysis integer. Dublin University, Dublin.

Parker, M.M., West, A.B., 1979. The natural history of *Neomysis integer* (Leach) in Lough Furnace, Co. Mayo, a brackish lough in the west of Ireland. Estuarine and Coastal Marine Science 8, 157-167.

Parsons, L.S., Lear, W.H., 2001. Climate variability and marine ecosystem impacts: a North Atlantic perspective. Prog. Oceanogr. 49, 167-188.

Pawlowicz, R., 2008. Calculating the conductivity of natural waters. Limnol. Oceanogr. 6, 489-501.

Pena, M.A., Katsev, S., Oguz, T., Gilbert, D., 2010. Modeling dissolved oxygen dynamics and hypoxia. Biogeosciences 7, 933-957.

Pieters, R., Lawrence, G.A., 2009. Effect of salt exclusion from lake ice on seasonal circulation. Limnol. Oceanogr. 54, 401-412.

Pybus, C., Pybus, M.J., 1980. An ecological study of Lough Murree, a brackish water lake in County Clare. Proceedings of the Royal Irish Academy 80b, 367-384.

Read, J.S., Hamilton, D.P., Jones, I.D., Muraoka, K., Winslow, L.A., Kroiss, R., H. Wu, C., Gaiser, E., 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. Environ. Model. Software 26, 1325-1336.

Reed, J.M., 1998. Diatom preservation in the recent sediment record of Spanish saline lakes: implications for palaeoclimate study. J. Paleolimnol. 19, 129-137.

Reimer, P.J., Baillie, M.G.L., E Bard, E., Bayliss, A., J.W., B., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., HajdaS, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., K.F., K., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. INTCAL09 and MARINE09 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 51, 1111-1150.

Rimbu, N., Lohmann, G., Kim, J.H., Arz, H.W., Schneider, R., 2003. Arctic/North Atlantic Oscillation signature in Holocene sea surface temperature trends as obtained from alkenone data. Geophys. Res. Lett. 30, 1-4.

Roden, C., Oliver, G., 2010. Monitoring and Assessment of Irish Lagoons for the purpose of the EU Water Framework Directive, Unpublished report prepared for the EPA.

Roubeix, V., Becquevort, S., Lancelot, C., 2008. Influence of bacteria and salinity on diatom biogenic silica dissolution in estuarine systems. Biogeochemistry 88, 47-62.

Ryves, D.B., Battarbee, R.W., Fritz, S.C., 2009. The Dilemma of Disappearing Diatoms: Incorporating Diatom Dissolution Data into Paleoenvironmental Modeling and Reconstruction. Quaternary Science Reviews 28, 120-136.

Ryves, D.B., Battarbee, R.W., Juggins, S., Fritz, S.C., Anderson, J.N., 2006. Physical and chemical predictors of diatom dissolution in freshwater and saline lake sediments in North America and West Greenland. Limnol. Oceanogr. 51, 1355-1368.

Ryves, D.B., Clarke, A.L., Appleby, P.G., Amsinck, S.L., Jeppesen, E., Landkildehus, F., Anderson, N.J., 2004. Reconstructing the salinity and environment of the Limfjord and Vejlerne Nature Reserve, Denmark, using a diatom model for brackish lakes and fjords. Canadian Journal of Fisheries and Aquatic Sciences 61, 1988-2006.

Salmon Research Agency, 1995. Annual Report. The Salmon Research Agency of Ireland.

Sarma, S.S.S., Nandini, S., Ramírez García, P., Cortés Muñoz, J.E., 2000. New records of brackish water Rotifera and Cladocera from Mexico. Hidrobiológica 102, 121-124.

Saros, J.E., 2009. Integrating neo- and paleolimnological approaches to refine interpretations of environmental change. J. Paleolimnol. 41, 243-252.

Scaife, A.A., Folland, C.K., Alexander, L.V., Moberg, A., Knight, R.J., 2008. European climate extremes and the North Atlantic Oscillation. J. Clim. 21.

Schulz, M., Paul, A., Timmermann, A., 2004. Glacial-interglacial contrast in climate variability at centennial-to-millennial timescales: observations and conceptual model. Quaternary Science Reviews 23, 2219-2230.

Shaw, J., 1985. Holocene coastal evolution, Co. Donegal, Ireland. Unpublished PhD Thesis, Coleraine, The University of Ulster.

Shintani, T., de la Fuente, A., Niño, Y., Imbergerc, J., 2010. Generalizations of the Wedderburn number: Parameterizing upwelling in stratified lakes. Limnol. Oceanogr. 55, 1377-1389.

Skrzypek, G., Paul, D., Wojtuń, B., 2008. Stable isotope composition of plants and peat from Arctic mire and geothermal area in Iceland. Polish Polar Research 29, 365-376.

Smol, J.P., 2008. Pollution of Lakes and Rivers - A Paleoenvironmental Perspective. Arnold, London.

Snoeijs, P., 1993. Intercalibration and distribution of diatom species in the Baltic Sea. Opulus Press Uppsala.

Snoeijs, P., Balashova, N., 1998. Intercalibration and distribution of diatom species in the Baltic Sea.

Snoeijs, P., Kasperovičienė, J., 1996. Intercalibration and distribution of diatom species in the Baltic Sea.

Snoeijs, P., Potapova, M., 1995. Intercalibration and distribution of diatom species in the Baltic Sea Opulus Press Uppsala.

Snoeijs, P., Vilbaste, S., 1994. Intercalibration and distribution of diatom species in the Baltic Sea.

Sparrenbom, C.J., Bennike, O., Björck, S., Lambeck, K., 2006. Holocene relative sea-level changes in the Qaqortoq area, southern Greenland. Boreas 35, 171-187.

Stevens, C.L., Lawrence, G.A., 1997. Estimation of wind-forced internal seiche amplitudes in lakes and reservoirs, with data from British Columbia, Canada. Aquat. Sci. 59, 115–134.

Stumm, W., Morgan, J.J., 1981. Aquatic Chemistry. Wiley Interscience, New York.

Swindles, G.T., Blundell, A., Roe, H.M., Hall, V.A., 2010. A 4500-year proxy climate record from peatlands in the North of Ireland: the identification of widespread summer 'drought phases'? Quaternary Science Reviews 29, 1577-1589.

Synge, F.M., 1963. The glaciation of the Nephin Beg Range. Irish Geography 4.

Talbot, M.R., 2001. Nitrogen Isotopes in Palaeolimnology, in: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Kluwer Academic Press, Dordrecht, pp. 401-439.

Talley, D.M., North, E.W., Juhl, A.R., Timothy, D.A., Conde, D., de Brouwer, J.F.C., Brown, C.A., Campbell, L.M., Garstecki, T., Hall, C.J., Meysman, F.J.R., Nemerson, D.M., Souza Filho, P.W., Wood, R.J., 2003. Research challenges at the land-sea interface. Estuar. Coast. Shelf Sci. 58, 699-702.

Teranes, J.L., Bernasconi, S.M., 2000. The record of nitrate utilization and productivity limitation provided by δ^{15}N values in lake organic matter - A study of sediment trap and core sediments from Baldeggersee, Switzerland. Limnol. Oceanogr. 45, 801-813.

Thauer, R.K., Stackebrandt, E., Hamilton, W.A., 2007. Energy metabolism and phylogenetic diversity of sulphate-reducing bacteria, in: Barton, L.L., Hamilton, W.A. (Eds.), Sulphate-Reducing Bacteria: Environmental and Engineered Systems. Cambridge University Press, p. 533.

Thornton, S.F., Mc Manus, J., 1994. Application of organic carbon and nitrogen stable isotope and C/N ratios as source indicators of organic matter provenance in estuarine systems: evidence from the Tay Estuary, Scotland. Estuar. Coast. Shelf Sci. 38, 219-233.

Turney, C., Baillie, M., Clemens, S., Brown, D., Palmer, J., Pilcher, J., Reimer, P., Leuschner, H.H., 2005. Testing solar forcing of pervasive Holocene climate cycles. Journal of Quaternary Science 20, 511-518.

Viaroli, P., Lasserre, P., Campostrini, P., 2007. Preface, in: Viaroli, P., Lasserre, P., Campostrini, P. (Eds.), Lagoons and Coastal Wetlands in the Global Change Context: Impacts and Management Issues. Selected papers of the International Conference ‘‘CoastWetChange’’, Venice, 26th - 28th April 2004. Hydrobiologia, Vol. 577.

Walker, K.F., Likens, G.E., 1975. Meromixis and a reconsidered typology of lake circulation patterns. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 19, 442-458.

Wanner, H., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B., Xoplaki, E., 2001. North Atlantic Oscillation - Concepts And Studies. Surveys in Geophysics 22, 321-382.

Weckström, K., 2006. Assessing Recent Eutrophication in Coastal Waters of the Gulf of Finland (Baltic Sea) using Subfossil Diatoms. J. Paleolimnol. 35, 571-592.

Westman, P., Hedenström, A., 2002. Environmental changes during isolation processes from the Litorina Sea as reflected by diatoms and geochemical parameters - a case study. Holocene 12, 531-540.

Whelan, K.F., Poole, W.R., McGinnity, P., Rogan, G., Cotter, D., 1998. The Burrishoole System., in: Moriarthy, C. (Ed.), Studies of Irish Rivers and Lakes. Marine Institute, Dublin, pp. 191-211.

Wolfe, A.P., 2001. Carbon and oxygen isotope analysis of lake sediment cellulose: methods and applications, in: Last, W.M., Smol, J.P. (Eds.), Tracking environmental change using lake sediments.Volume 2: Physical and geochemical methods. Kluwer Academic Publishers, Amsterdam, pp. 373-400.

Wolfe, B.B., Edwards, T.W.D., Hall, R.I., Johnston, J.W., 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. Geophys. Res. Lett. 38.

Yamaguchi, K.E., Oguri, K., Ogawa, N.O., Sakai, S., Hirano, S., Kitazato, H., Ohkouchi, N., 2010. Geochemistry of modern carbonaceous sediments overlain by a water mass showing photic zone anoxia in the saline meromictic Lake Kai-ike, southwest Japan: I. Early diagenesis of organic carbon, nitrogen, and phosphorus. Palaeogeogr., Palaeoclimatol., Palaeoecol. 294, 72-82.

Figures

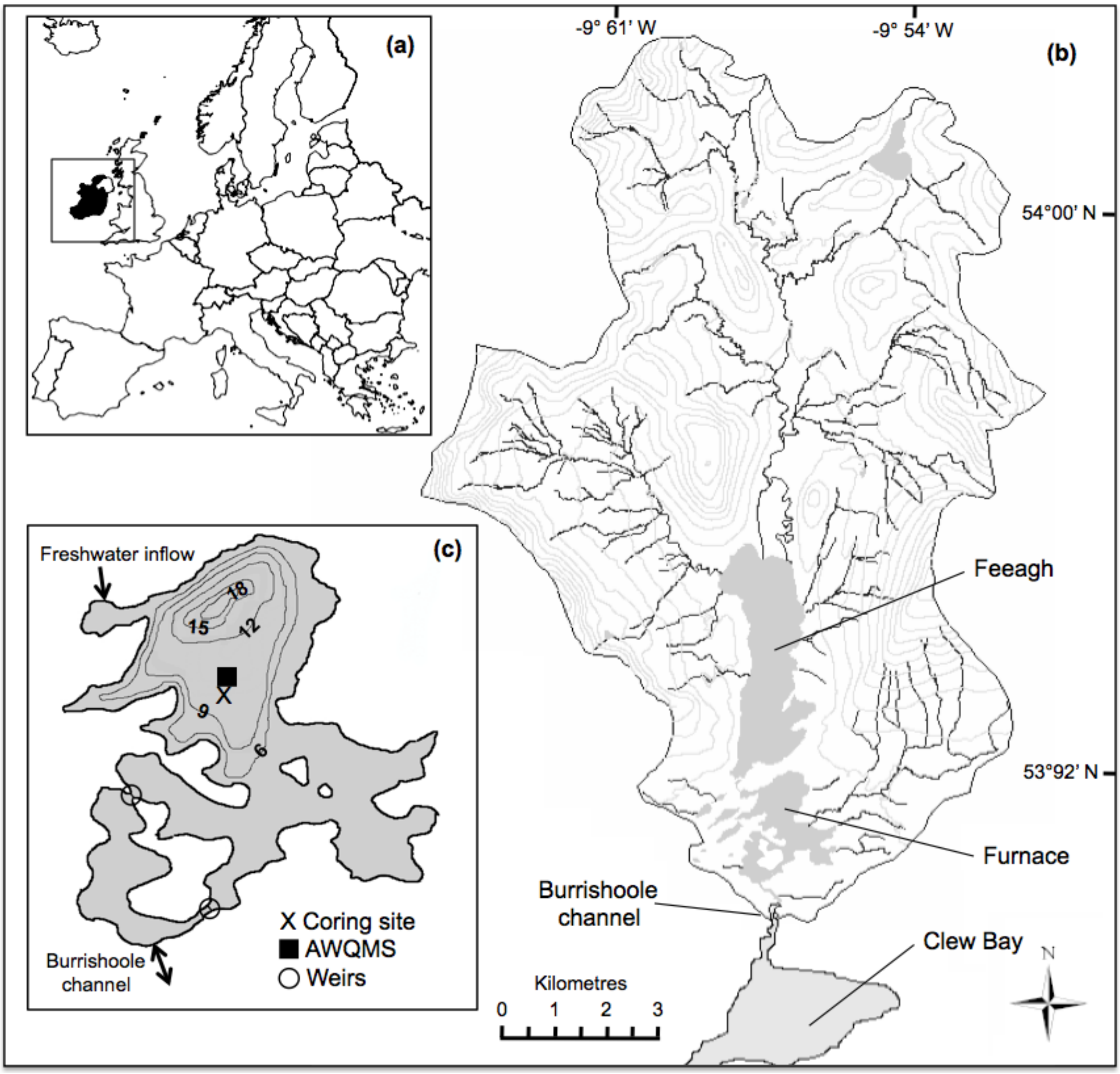
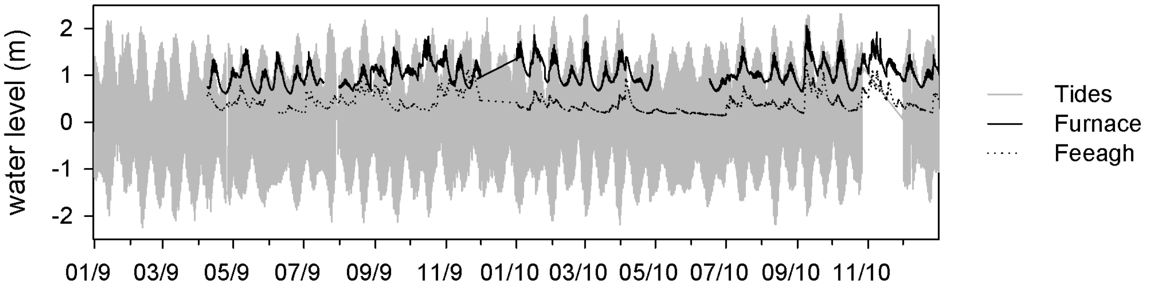
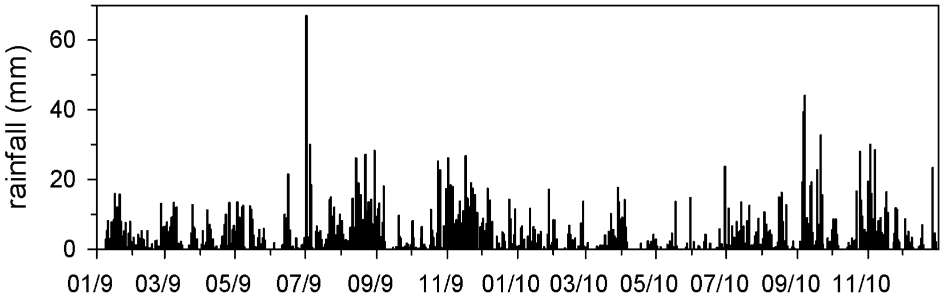


Figure 1 – (a) Location of Ireland, (b) the Burrishoole catchment, (c) bathymetry (m), the coring site, the automatic water quality monitoring system (AWQMS) and weirs position in Lough Furnace.

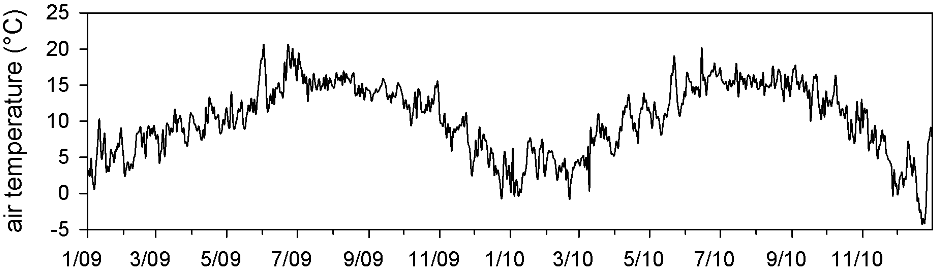
a


water level (m)
2
1
0
-1
-2
01/9
03/9
05/9
07/9
09/9
11/9
01/10
03/10
05/10
07/10
09/10
11/10
Tides
Furnace
Feeagh

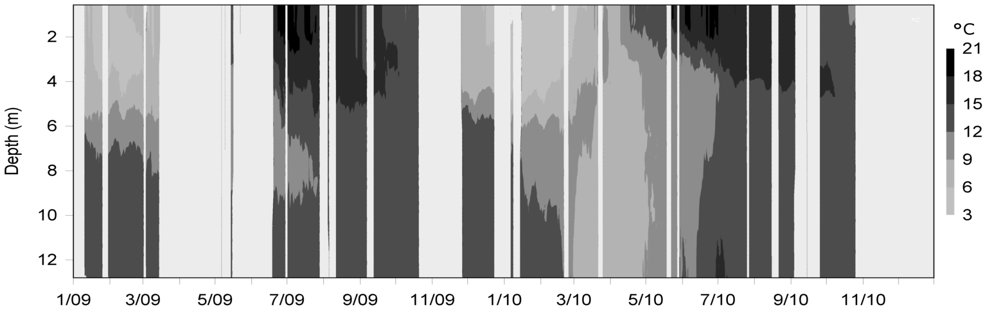
b


rainfall (mm)
60
40
20
0
01/9
03/9
05/9
07/9
09/9
11/9
01/10
03/10
05/10
07/10
09/10
11/10

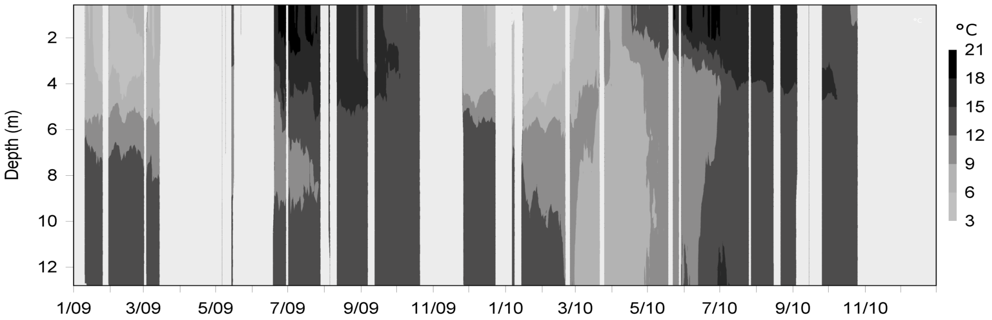
c


air temperature (°C)
25
20
15
10
5
0
-5
1/09
3/09
5/09
7/09
9/09
11/09
1/10
3/10
5/10
7/10
9/10
11/10

d


Depth (m)
2
4
6
8
10
12
1/09
3/09
5/09
7/09
9/09
11/09
1/10
3/10
5/10
7/10
9/10
11/10
°C
21
18
15
12
9
6
3

e


Depth (m)
2
4
6
8
10
12
1/09
3/09
5/09
7/09
9/09
11/09
1/10
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5/10
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11/10
°C
21
18
15
12
9
6
3

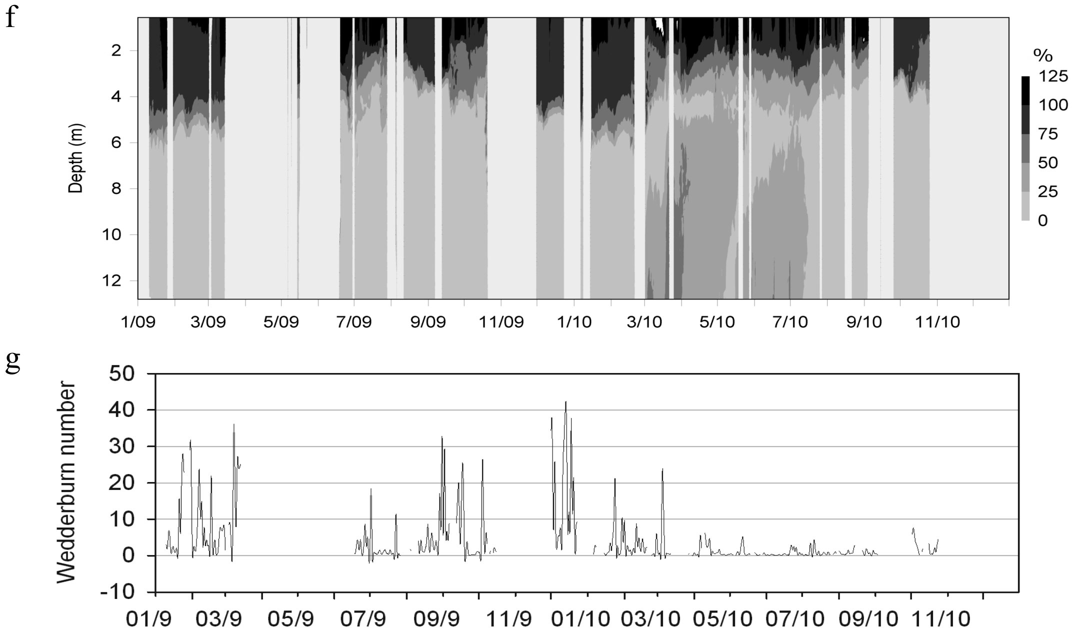

Figure 2 – (a) Furnace (dark line) and Feeagh (dotted line) water level and tides (grey line) (m); (b) rainfall (mm); (c) air temperature (°C); (d) Furnace salinity (‰); (e) temperature (°C), (f) dissolved oxygen (%) and (g) the Wedderburn number.

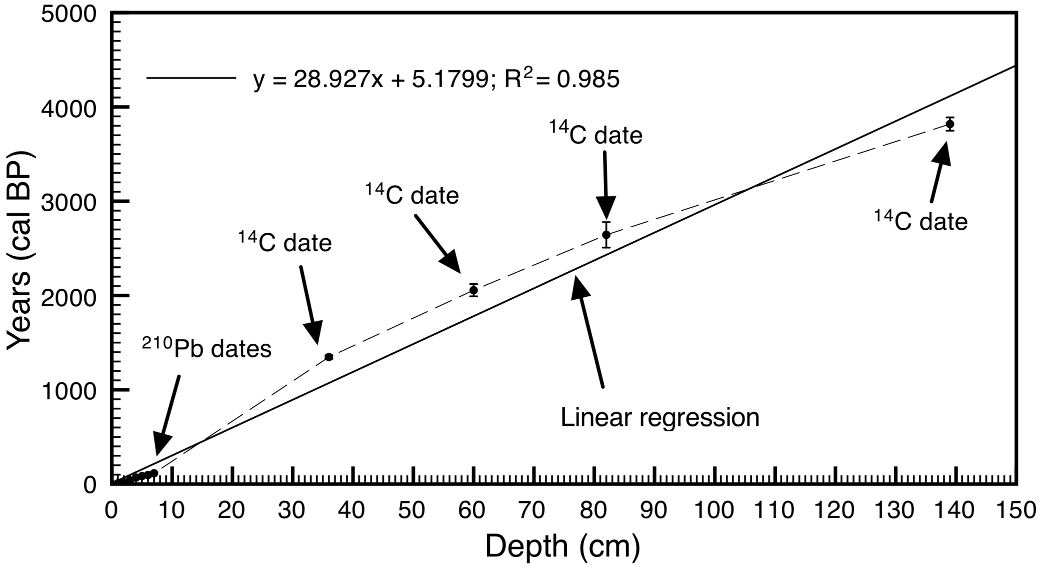

Figure 3 – Age-depth model of combined ^{210}Pb and AMS radiocarbon dates.

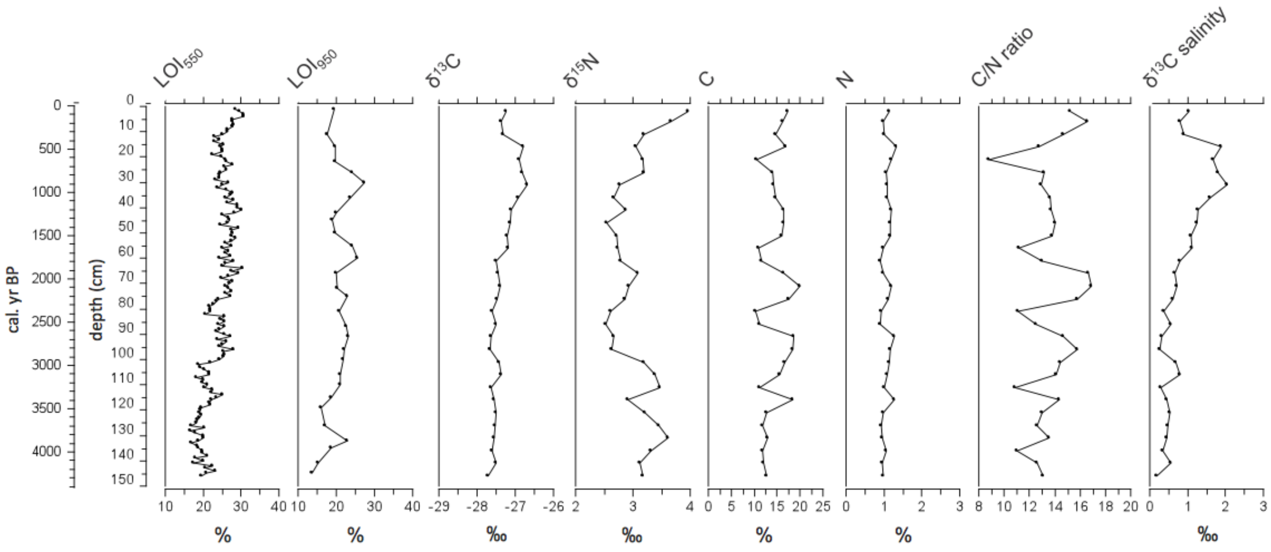

Figure 4 – LOI$_{550}$ (%), LOI$_{950}$ (%), carbon and nitrogen stable isotopes (‰), carbon and nitrogen (%), C/N ratio and δ^{13}C-inferred salinity (‰) in Furnace.

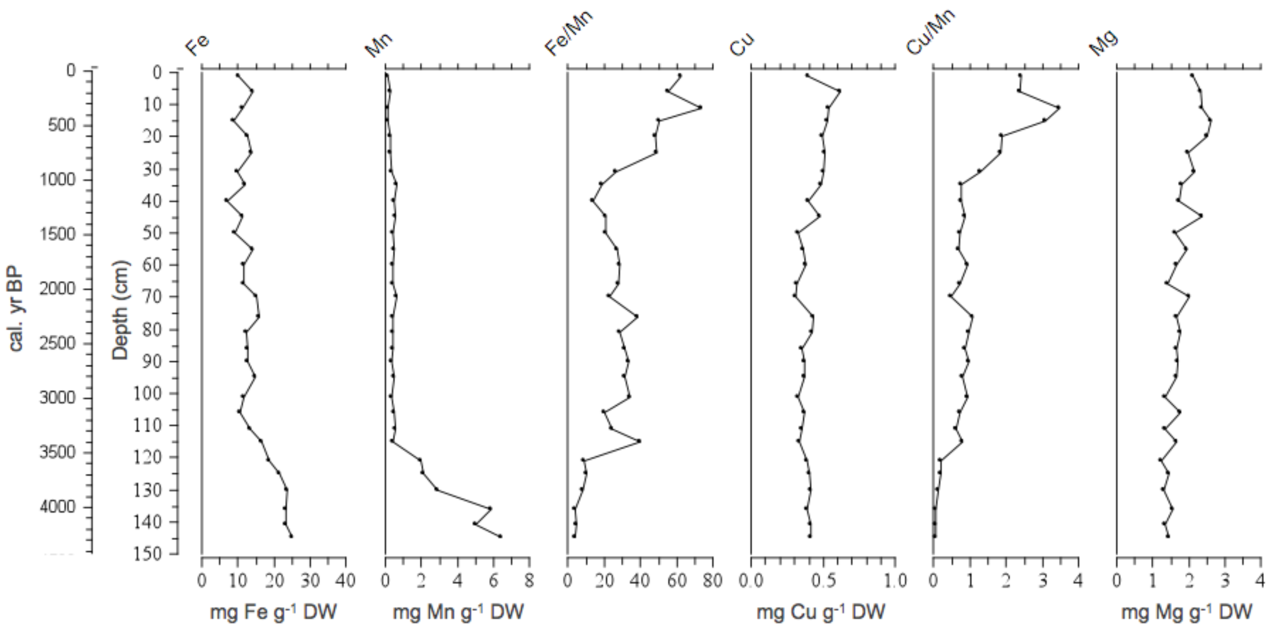

Figure 5 – Iron, manganese, Fe/Mn mass ratio, copper, Cu/Mn mass ratio and magnesium in Furnace.

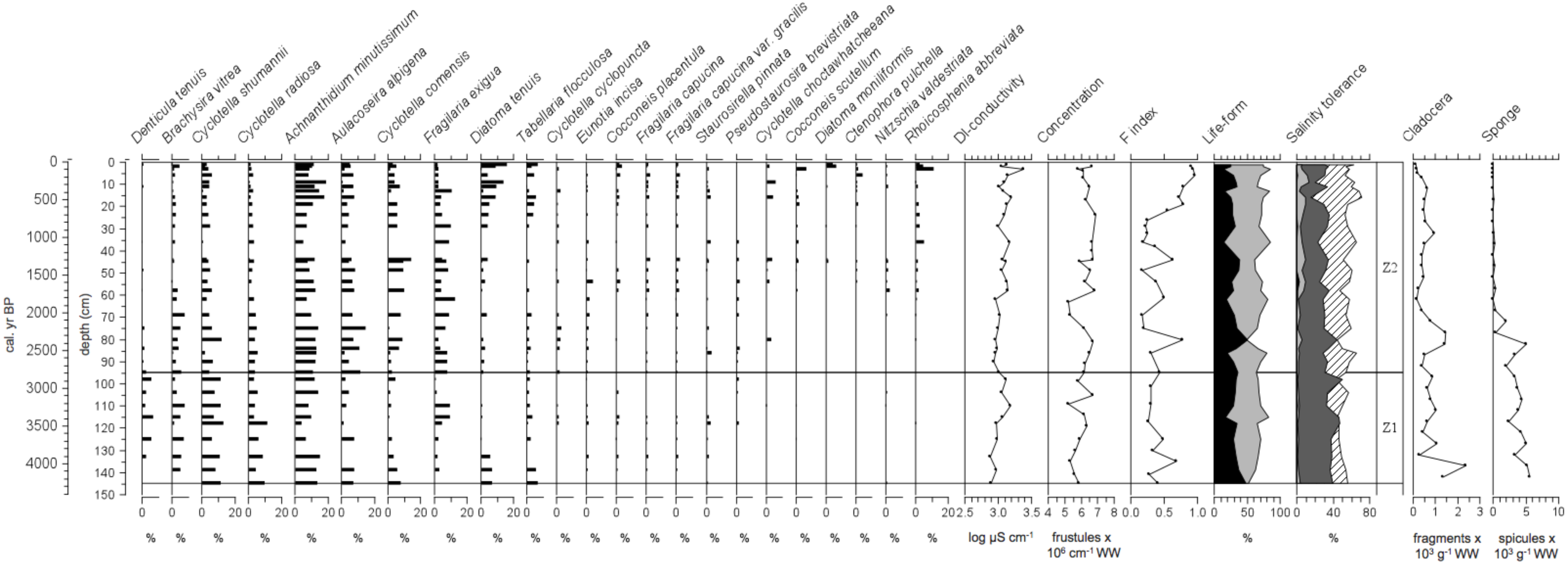
Denticula tenuis
Brachysira vitrea
Cyclotella shumannii
Cyclotella radiosa
Achnanthidium minutissimum
Aulacoseira alpigena
Cyclotella comensis
Fragilaria exigua
Diatoma tenuis
Tabellaria flocculosa
Cyclotella cyclopuncta
Eunotia incisa
Cocconeis placentula
Fragilaria capucina
Fragilaria capucina var. gracilis
Staurosirella pinnata
Pseudostaurosira brevistriata
Cyclotella choctawhatcheeana
Cocconeis scutellum
Diatoma moniliformis
Ctenophora pulchella
Nitzschia valdestriata
Rhoicosphenia abbreviata
DI-conductivity
Concentration
F index
Life-form
Salinity tolerance
Cladocera
Sponge
cal. yr BP
depth (cm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Z2
Z1
%
log µS cm-1
frustules x 10^6 cm-1 WW
fragments x 10^3 g-1 WW
spicules x 10^3 g-1 WW

Figure 6 – Summary of the most abundant (>2%) diatom taxa (n=23), DI-conductivity (WA; log μS cm^{-1}), diatom concentration (frustules x 10^6 g^{-1} WW), diatom dissolution index (F index), diatom life-form (black=planktic; gray=benthic), salinity tolerance (black=marine; light gray=brackish; dark grey=freshwater; black pattern=fresh-brackish), cladocera (total fragments x 10^3 g^{-1} WW) and sponge spicule (spicules x 10^3 g^{-1} WW) concentration in Furnace. Zones were calculated by means of CONISS and the broken stick model (Bennet, 1996).