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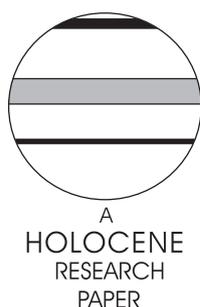
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# Diatom and stable isotope records of late-Holocene lake ontogeny at Indrepollen, Lofoten, NW Norway: a response to glacio-isostasy and Neoglacial cooling

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**Abstract:** Borg Indrepollen is a coastal lake on the island of Vestvågøy, Lofoten, NW Norway. A sedimentary sequence spanning the last 4500 cal. yr BP was analysed for diatom, C/N and stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ). The record provides clear evidence of glacio-isostatic rebound in the Lofoten region. Five distinct lithostratigraphic-geochemical zones (I–V) and four major diatom zones (A–D) were identified. The early record (I–III, A–Biii; 4500–550 cal. yr BP) contains coarse sedimentary material and diatoms indicative of more marine conditions. The correlation between the isotopic data (high  $\delta^{13}\text{C}$  and low C/N) and trends in the biological data (marine/brackish flora) suggest the marine influence on the Indrepollen basin is a controlling factor of the source of organic material. The latter part of the record (IV, C; 550 cal. yr BP–226) indicates a transitional phase from marine-dominated diatom to brackish taxa and is coincident with a section of microlaminations in the core. The youngest zone (V, D; 226 cal. yr BP–present) is indicative of an isolated basin, with the deposition of fine sediments; freshwater diatom taxa dominate the biological record and  $\delta^{13}\text{C}$  are indicative of freshwater conditions. C/N suggests a shift to a terrestrial source of organic matter. The proxies show a transition from full marine conditions, when Indrepollen was a submerged fjord, to more freshwater, lacustrine conditions in the last 200 years. The record of land uplift from Borg Indrepollen mirrors changes in sedimentary records from across Northern Norway and relative sea-level curves for the region.

**Key words:** Diatoms, stable isotopes, sea-level, lake ontogeny, land uplift, glacio-isostasy, palaeoconductivity, Lofoten, Norway, late Holocene.

## Introduction

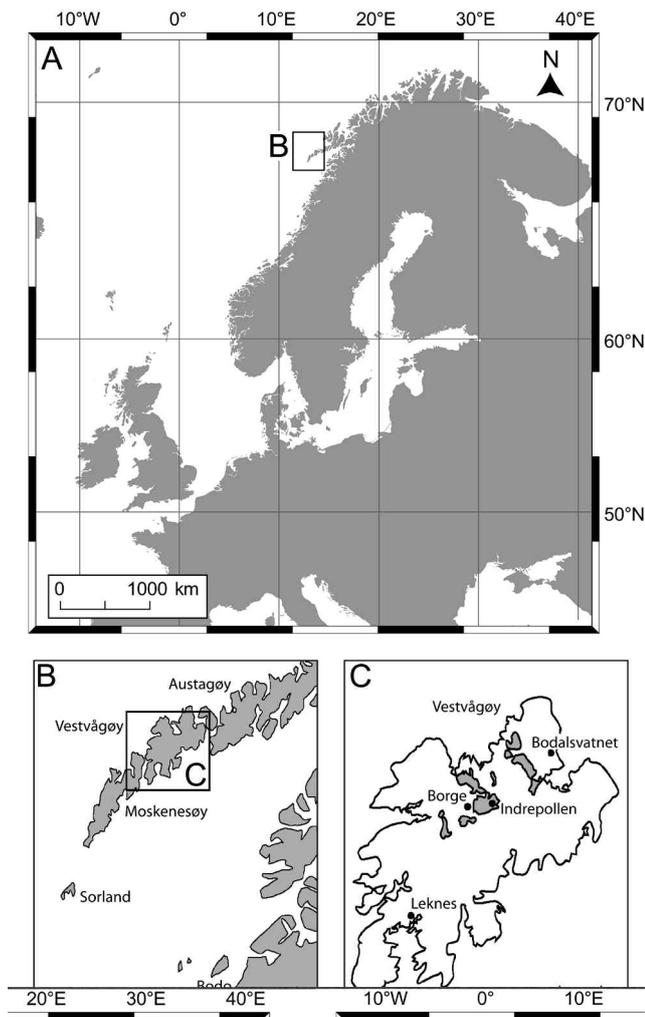
Coastal lakes, at the boundary of offshore (marine) and inland (freshwater) systems, are sensitive to changes that affect both environments including fluctuations in freshwater input, sea-level change and nutrient supply (Ryves *et al.*, 2004). As a result,

coastal sediments contain important archives of environmental change, recording signals of past changes in salinity, sea level and climate in sedimentological, geochemical and biological deposits (Cooper and Brush, 1991; Bianchi *et al.*, 2000). Although much is known about the functioning of maritime, coastal and freshwater habitats, there are still relatively few studies that use diatoms to reconstruct high-resolution Holocene environmental change from coastal sequences (Mackay *et al.*, 2003).

Climatic data from the Northern Hemisphere suggest that the last c. 4500 years is a period associated with late-Holocene cooling

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**Figure 1** (A and B) Regional location of the Lofoten archipelago and the Island of Vestvågøy, NW Norway. (C) Site map of Vestvågøy showing the location of Borg Indrepollen

(Neoglacial; Wolfe, 2002). This period includes intervals of naturally forced climates, at times colder ('Little Ice Age', *c.* AD 1350–1850) and warmer ('Mediaeval Warm Period', *c.* AD 800–1300) than present (Meeker and Mayewski, 2002). The major source of this interannual variability in atmospheric circulation is the North Atlantic Oscillation (NAO; Wallace and Gutzler, 1981), which is one of the most dominant modes of global climate variability, influencing climate variability over the eastern USA, Siberia, the Arctic and the subtropical Atlantic (Hurrell *et al.*, 2001). The NAO is not only a North Atlantic phenomenon (Hurrell, 2003), but it is the most important mode of atmospheric variability over the North Atlantic Ocean, and plays a major role in weather and climate over Northern Europe.

North Atlantic climate variability during the Holocene also involves quasiperiodic changes in the strength of the thermohaline circulation (Bianchi and McCave, 1999) which can have a direct effect on the climate of adjacent land areas. However, many of the marine sedimentary records on which such arguments are based tend to have a poor temporal resolution, though there are notable exceptions (*cf.* Birks and Koç, 2002). Coastal lake sediments may provide the opportunity to retrieve higher resolution palaeoclimate records that may shed light on changes in the nearby oceanic circulation.

The Lofoten islands, off northern Norway (Figure 1), are in a region sensitive to changes in the North Atlantic Oscillation (NAO) and oceanic circulation (Hurrell, 1995). The climatic conditions in the Lofoten archipelago during extreme phases of the

NAO range from cold and dry (negative phase) to mild and wet (positive phase). As long term changes in the NAO are linked to changes in oceanic circulation (*eg.* Rodwell *et al.*, 1999), the analysis of lake sediments from the Lofoten Islands, at a high resolution, may provide both high- and low-frequency information relevant to the understanding of climatic variations in northern Europe.

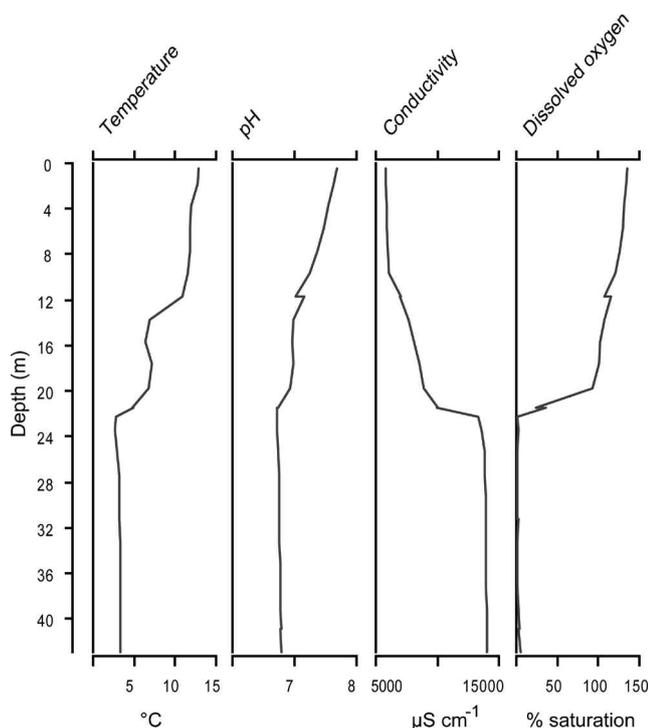
Coastal lakes also provide an opportunity to understand the timing of Holocene shoreline displacement (Marthinussen, 1962; Møller and Sollid, 1972; Møller, 1986). Since the last deglaciation, the isostatic recovery of Fennoscandia, in conjunction with eustatic variations, has resulted in the area undergoing several marine transgressions and regressions during the Holocene (*cf.* Møller, 1984; Westman and Hedenström, 2002). Microfossil analyses of isolation basin sequences from across Northwest Europe are the most common technique for reconstructing shoreline displacement and environmental changes (*cf.* Shennan *et al.*, 1995, 2000; Seppä *et al.*, 2000; Westman and Hedenström, 2002; Ryves *et al.*, 2004; Berglund *et al.*, 2005; Miettinen *et al.*, 2007). Diatoms are sensitive to changes in lake water chemistry, and in particular conductivity. When preserved in lake sediments, diatoms can provide quantitative information on past salinity changes through the application of a transfer function. These have been developed for many regions of the world including Africa (Gasse *et al.*, 1995), Spain (Reed, 1998) and North America (Fritz *et al.*, 1993), whilst the European Diatom Database Initiative (EDDI) has combined these data sets in order to reconstruct former water chemistry (Battarbee, 2000). Isotope ratios ( $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}$ ) and elemental ratios of carbon (C) and nitrogen (N) have been widely used for interpreting changes in salinity, climate, productivity and sources of organic matter from marginal marine environments (Meyers, 1994; Müller and Mathesius, 1999; Mackie *et al.*, 2005)

This paper uses diatom analysis and modelled diatom-inferred conductivity in conjunction with  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and C/N from a coastal lake sediment sequence. The aim is to reconstruct changes in the coastal palaeoenvironment and shore displacement in Northwest Norway as a response to land uplift and changing oceanic and climatic conditions over the last *c.* 4500 years.

## Indrepollen and the Lofoten Islands

The Lofoten archipelago is made up of a large number of mountainous islands that extend out into the Atlantic Ocean (Figure 1). Today, the outer Lofoten islands are bathed by the Norwegian Atlantic Current, a tongue of warm water that reaches *c.* 11°C in the summer and +5°C in winter in the vicinity of the Lofoten archipelago at ~68°N. Changes in the strength and/or position of this current are likely to have a major effect on the environment in Lofoten. Annual precipitation and SSTs are negatively correlated, although there are strong seasonal differences. During the summer months, North Atlantic SSTs are negatively correlated with precipitation; in the winter, the correlations are positive. Therefore, warm SSTs are associated with warm wet winters and warm dry summers.

In much of the area the topography is alpine with deeply eroded lake-filled cirques (tarns) and moraines, reflecting the dynamic glacial environment that once characterized the region. The islands are replete with lakes, many of which are deep and close to sea level. Borg Indrepollen (68°15'N, 13°48'E) is situated on the island of Vestvågøy, part of the Lofoten archipelago. Indrepollen is a large lake-estuary system with multiple sedimentary basins. The maximum water depth in the lake is 43 m. Very deep lakes like Indrepollen that are currently at sea level contain seawater at depth, and have a density-stratified water column.



**Figure 2** Limnological profile of Borg Indrepollen taken at 1–2 m intervals (27 July 2006). Data collected include temperature, pH, conductivity and dissolved oxygen (DO). The lake is thermally stratified (temperature difference of  $\sim 5^{\circ}\text{C}$  between the surface and deep waters). In addition, there is a strong chemocline evident at a depth of 22 m, characterized by an increase in the conductivity and a drop in the DO saturation ( $\sim 1\%$ ) indicating anoxia at depth

Limnological measurements show saline or brackish water and anoxic conditions in the deepest parts of the basin as well as strong thermal stratification below 20 m (Figure 2).

Indrepollen is the site of several important Viking-age communities and a great deal of archaeological research is being carried out in the area. Archaeological evidence suggests that Indrepollen was once a Viking stronghold and their longboats entered from the sea. Boathouses have been located and excavated a few metres above the current lake level, suggesting a sea-level regression of up to 2 m over the last 1000–1500 years. Studies of Lofoten shoreline displacement by Møller (1984, 1986, 1989) suggest that relative sea level was higher in the early to mid Holocene and has regressed, as a result of glacio-isostatic uplift, since  $\sim 6000$   $^{14}\text{C}$  yr BP (*c.* 6800 cal. yr BP).

## Materials and methods

Three cores (INDRE-A, -B and -C) of up to 107 cm in length were recovered from Borg Indrepollen in the summer of 2000 by a team from the University of Massachusetts and Queen's University of Belfast. This study is based on two percussion cores INDRE-B (102 cm) from a water depth of 28.72 m ( $68^{\circ}14'58.53''\text{N}$ ,  $13^{\circ}49'44.41''\text{E}$ ) and INDRE-C (96 cm) from a water depth of 27.09 m ( $68^{\circ}15'04.08''\text{N}$ ,  $13^{\circ}48'01.17''\text{E}$ ).

## Chronology

To establish a chronology for the cores, AMS radiocarbon dates were obtained from bulk sediments (samples were processed by the Lawrence Livermore National Laboratory).  $^{14}\text{C}$  dates were transformed into calendar ages using the calibration curve IntCal 04 in the program OxCal v. 4.0 (Bronk Ramsey, 1995, 2001). The radiocarbon dates for the age model were obtained from INDRE-B (one date) and INDRE-C (two dates). A single tephra horizon was

located in INDRE-B (26 cm) and incorporated into the Indrepollen age model. In the section analysed for tephra several occurrences were noted (Pilcher *et al.*, 2005). All tephra identifications were based on the major element chemistry. For further discussion on the tephrochronology from Indrepollen refer to Pilcher *et al.* (2005).

## Organic geochemistry

Elemental carbon (% organic carbon) and nitrogen content and  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  were analysed on contiguous 1  $\text{cm}^3$  samples from core INDRE-C after acid pre-treatment using an elemental analyser coupled with a Finnigan Delta-plus mass spectrometer. Isotope sample reproducibility is  $\pm 0.2\%$ . Carbon and nitrogen isotope results are presented in  $\delta$ -notation, where  $R = ^{13}\text{C}/^{12}\text{C}$  or  $^{15}\text{N}/^{14}\text{N}$ , and are expressed as per mil (‰) relative to the international standards: Vienna Peedee Belemnite (VPDB) for carbon and air (VAIR) for nitrogen.

C/N and  $\delta^{13}\text{C}$  analyses of bulk sedimentary organic matter (OM) can be powerful tools for palaeoenvironmental reconstruction (Meyers and Teranes, 2001). The C/N ratio of sedimentary organic matter can provide a method of discriminating the source of organic material (Mackie *et al.*, 2005): (i) OM originating from algae and phytoplankton, generally have C/N between 4 and 10 and (ii) organic matter produced mainly by terrestrial plants, generally have C/N  $\geq 20$  (Meyers, 1994). Thus a C/N of less than 10 may indicate the main source of organic material is algae (Meyers and Lallier-Vergès, 1999) whilst values greater than 20 are generally attributed to terrestrial sources (Meyers, 1994). In between values probably represent a mixed source.

Where C/N indicates that the organic matter source is predominantly algal, shifts in  $\delta^{13}\text{C}$  values may be related to changes in algal productivity or carbon cycling processes. Phytoplankton growing at fast rates fractionate less strongly against  $^{13}\text{C}$ , relative to times of slower growth (Laws *et al.*, 1995). In addition, the carbon pool in the lake is changed because of the preferential uptake of  $^{12}\text{C}$  by aquatic plants during photosynthesis. During periods of enhanced productivity the carbon pool in the water becomes enriched in  $^{13}\text{C}$  (Leng *et al.*, 2005). Where C/N indicates the dominance of a terrestrial carbon source,  $\delta^{13}\text{C}$  can help to determine the source of this terrestrial carbon (eg, changes in the presence of  $\text{C}_3$  or  $\text{C}_4$  plants within a lake catchment area).

## Diatom preparation and analyses

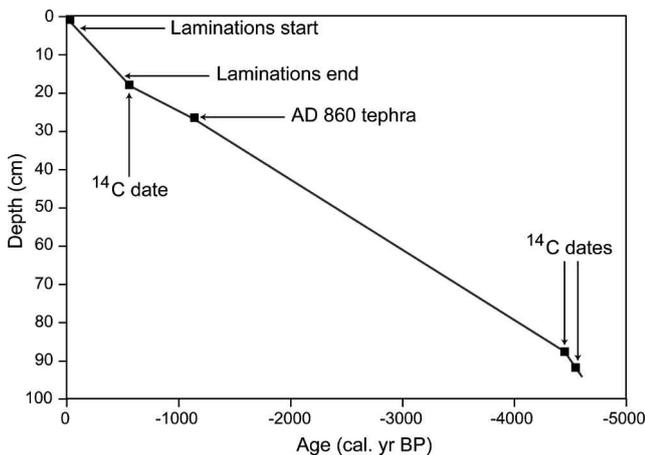
INDRE-C was subsampled at 2 cm intervals, resulting in a total of 43 samples. The samples were prepared following the methods outlined by Battarbee (1986) and Renberg (1990). All samples were treated with 30%  $\text{H}_2\text{O}_2$  to remove organic material and 10% HCl to remove calcium carbonate. After chemical treatments, the remaining acid was diluted with distilled water and centrifuged until all acid was removed. Diatom concentrations were estimated by adding a known number of inert microspheres to the samples ( $6.18 \times 10^6$ ) which were then diluted and suspensions placed on a coverslip (Battarbee and Kneen, 1982). After the suspensions had dried, the coverslips were transferred onto permanently labelled slides, mounted with Naphrax.

A Leica Axiostar microscope with phase-contrast at a magnification of  $\times 1000$  was used for identification and counting. At least 300 diatom valves were identified and counted for each sample. Diatom taxonomy and ecological affinity information followed that of Krammer and Lange-Bertalot (1986, 1988, 1991a, b) and the Baltic Sea intercalibration guides of Snoeijs and colleagues (Snoeijs, 1993; Snoeijs and Vilbaste, 1994; Snoeijs and Potapova, 1995; Snoeijs and Kasperoviciene, 1996; Snoeijs and Balashova, 1998). Diatom valve preservation was excellent throughout, with little apparent impact from dissolution processes.

**Table 1** Samples used for AMS  $^{14}\text{C}$  dating from Borg Indrepollen

Lab. code	Core	Depth (cm)	Material dated	Code	$^{14}\text{C}$ yr age (yr before AD 1950)	Calibrated age (yr BP)	Cal. age ( $\pm 1$ SD)	Cal age (AD/BC)
CAMS-84982	INDRE-B	27.0	Bulk sediment	CAMS-84982	$550 \pm 110$	558	422–695	AD 1255–1529
CAMS-84983	INDRE-C	87.5	Bulk sediment	CAMS-84983	$3930 \pm 150$	4441	4060–4823	2111–2874 BC
CAMS-84984	INDRE-C	92.0	Bulk sediment	CAMS-84984	$4070 \pm 40$	4543	4435–4650	2480–2701 BC

$^{14}\text{C}$  measurements were carried out at the Centre for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Calibrated ages were calculated using OxCal 4.0 (Bronk-Ramsey, 1995, 2001)



**Figure 3** Age model for INDRE-C constructed from three radiocarbon dates and one identified tephra layer (Pilcher *et al.*, 2005). This section analyses of the laminated section of the core identified a ‘floating chronology’ spanning ~200 years (courtesy of Pierre Francus)

### Numerical techniques

The principal gradient in the diatom data was investigated using the unimodal ordination technique of detrended correspondence analysis (DCA: using CANOCO 4.5; ter Braak and Šmilauer, 2002). DCA produced a gradient length of 2.85, indicating that the species response was unimodal (the species data used in DCA were transformed by square-root transformation and down-weighting of rare species).

To further explore the diatom data, an online transfer function from the European Diatom Database (EDDI) was used to reconstruct the major trends in conductivity (a common proxy for salinity; Fritz *et al.*, 1999). All of the diatom data were initially included in the reconstruction; however, out of the 301 original taxa identified, only 185 could be assigned codes from the EDDI website. This is due to the EDDI data consisting of diatoms from lake systems only, thus marine species (such as *Lyrella atlantica*, *L. sulcifera* and marine *Navicula* and *Opephora* species) could not be included in the analysis. Out of the 116 diatoms omitted from the conductivity reconstruction, 25 were unknown or unidentified species. Thus the model, as applied is extremely limited and the reconstructed conductivity, especially in the lower part of the core (95–25 cm) will be skewed towards lower values (on a log scale). Nonetheless, the conductivity model provides an extremely useful tool when exploring the pattern of relative changes in the aquatic environment at Indrepollen and is used here as an aid to the understanding of the changing lake ontogeny. Ideally, future work should entail use of more appropriate data sets (eg, MOLTEN) that are currently in development.

The diatom species are expressed as relative abundances (% total diatoms) of the total number of valves counted per sample. The converted counts were plotted using C2 and sorted by their weighted average abundance. The stratigraphical data were divided into zones using the program ZONE (Juggins, 2002); based on a

numerically optimal sum-of-squares partitioning with stratigraphical constraints (Birks and Gordon, 1985). They are unbiased and are used as aids in interpretation and discussion (Birks and Koç, 2002). Four zones (A–D) and three subzones (Bi–Biii) were defined using the ZONE classification (Juggins, 2002).

## Results

### Chronology

Three calibrated AMS radiocarbon dates (Table 1) and one tephra horizon were used to construct the chronology for Borg Indrepollen. The first AMS date ( $550 \pm 110$   $^{14}\text{C}$  yr BP) was obtained from core INDRE-B (27 cm). Two bulk AMS dates ( $3930 \pm 150$   $^{14}\text{C}$  yr BP and  $4040 \pm 40$   $^{14}\text{C}$  yr BP) were taken from INDRE-C (at depths of 87.5 and 92 cm, respectively). The first (and youngest) AMS date from INDRE-B was located immediately below a counted section of laminations present in both cores and assumed to be deposited synchronously across the lake basin; the date was correlated to INDRE-C on this basis.

The tephra horizon was recovered from core INDRE-C at a depth of 26 cm. In the section analysed for tephra, two separate populations were identified (Pilcher *et al.*, 2005). The study showed the presence of the Icelandic-sourced AD 860 tephra and also Tjornuvik B, which is of a similar age.

An age–depth model based on the linear interpolation of the radiocarbon dates and the tephra date of AD 860 is shown in Figure 3.

### Lithology and geochemistry

The core lithology, C/N and stable isotope geochemistry are displayed in Figure 4. Five lithostratigraphic zones (I–V) have been identified based on a combination of the physical properties and geochemical characteristics.

#### Zone I (c. 4560–4330 cal. yr BP)

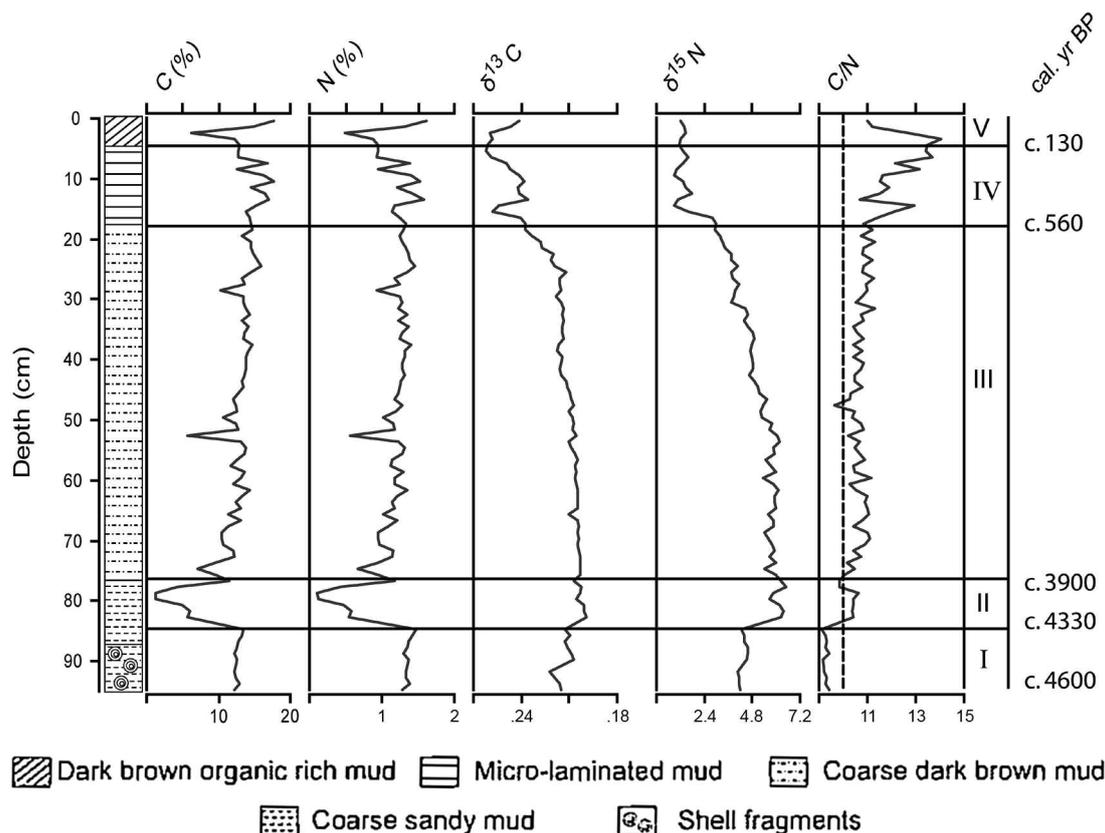
The base of the core, (87–95 cm) consists of coarse sandy mud with many shell fragments. This oldest zone is defined by low C/N (~9) and relatively high  $\delta^{13}\text{C}$  (–21‰ to –20‰). The  $\delta^{15}\text{N}$  is relatively stable throughout this zone with values around –4.2‰. The organic material in this zone is likely to be derived from algal productivity.

#### Zone II (c. 4330–3900 cal. yr BP)

The sediment in this zone (77–87 cm) consists of very coarse sandy mud, and the input of this coarse, minerogenic material is most likely responsible for the large drop in the percentages of C and N. This causes a rise in the C/N of the sediment to ~10.5, suggesting terrestrial input of some organic matter. In conjunction with this, there is also a rise in the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  to –19‰ and +7‰, respectively.

#### Zone III (c. 3900–560 cal. yr BP)

Zone III is the largest of all the lithological/geochemical units, spanning 60 cm (17–77 cm). In this zone the sediment becomes



**Figure 4** Litho-stratigraphic plot of percentage carbon and nitrogen,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and the C/N ratio from INDRE-C. The vertical dashed line (C/N ratio) indicates the boundary between algal and terrestrial dominated productivity (Meyers and Lallier-Vergès, 1999)

less sandy, though is still a relatively coarse textured, dark brown, organic-rich mud. This zone is relatively uniform with C/N fluctuating between 10 and 11, and  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  relatively constant at  $-20\text{‰}$  and  $+6\text{‰}$ , respectively. Midway through this zone (45 cm) the C/N starts to steadily increase whilst the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  decrease to  $-24\text{‰}$  and  $+3\text{‰}$ , respectively.

#### Zone IV (c. 560–130 cal. yr BP)

Unit IV (4–17 cm) encompasses a section of microlaminations and is a distinct feature of the unit. Preliminary thin section analysis indicates that these laminations are extremely regular in structure and may be varved; if so, lamination counts indicate they could span an interval of  $\sim 200$  years (P. Francus, personal communication, 2001). At the start of this laminated unit,  $\delta^{13}\text{C}$  ( $-26\text{‰}$ ) reaches its lowest value before increasing to  $-24\text{‰}$  and then steadily decreasing once again to values of  $-26.5\text{‰}$ . The  $\delta^{15}\text{N}$  follows a similar pattern with values in the range of  $-2.4$  and  $-1.2\text{‰}$ . The C/N ratios fluctuate between 10 and 14 in this zone, with the highest C/N ratios corresponding with the lowest  $\delta^{13}\text{C}$  values.

#### Zone V (c. 130 cal. yr BP–present)

The uppermost Unit (0–4 cm) consists of very fine, dark brown, organic rich, lake mud. The start of this zone bears similarities to the top of the underlying unit, with a high C/N of 14, which decreases to  $\sim 11$  at the top of the zone. The  $\delta^{13}\text{C}$  values start off low ( $-26.5\text{‰}$ ) and increase to  $-24\text{‰}$  at the core top;  $\delta^{15}\text{N}$  values remain low ( $+1.2\text{‰}$ ) across the zone (as seen at the top of zone IV).

### Diatom flora and numerical analyses

In total, 301 taxa of both marine and lacustrine origin were identified in the analyses. However, only 31 of these taxa, with relative abundances  $>5\%$  were used in the ordination analyses.

The stratigraphic data was divided into assemblages using ZONE (Juggins, 2002) as an aid to interpretation and discussion. There are four main diatom zones (A–D; Figure 5). Diatom zone A encompasses the lithological and geochemical units I and II, all other units and zones are comparable (diatom zone B = lithological/geochemical unit III; zone C = unit IV and zone D = Unit V).

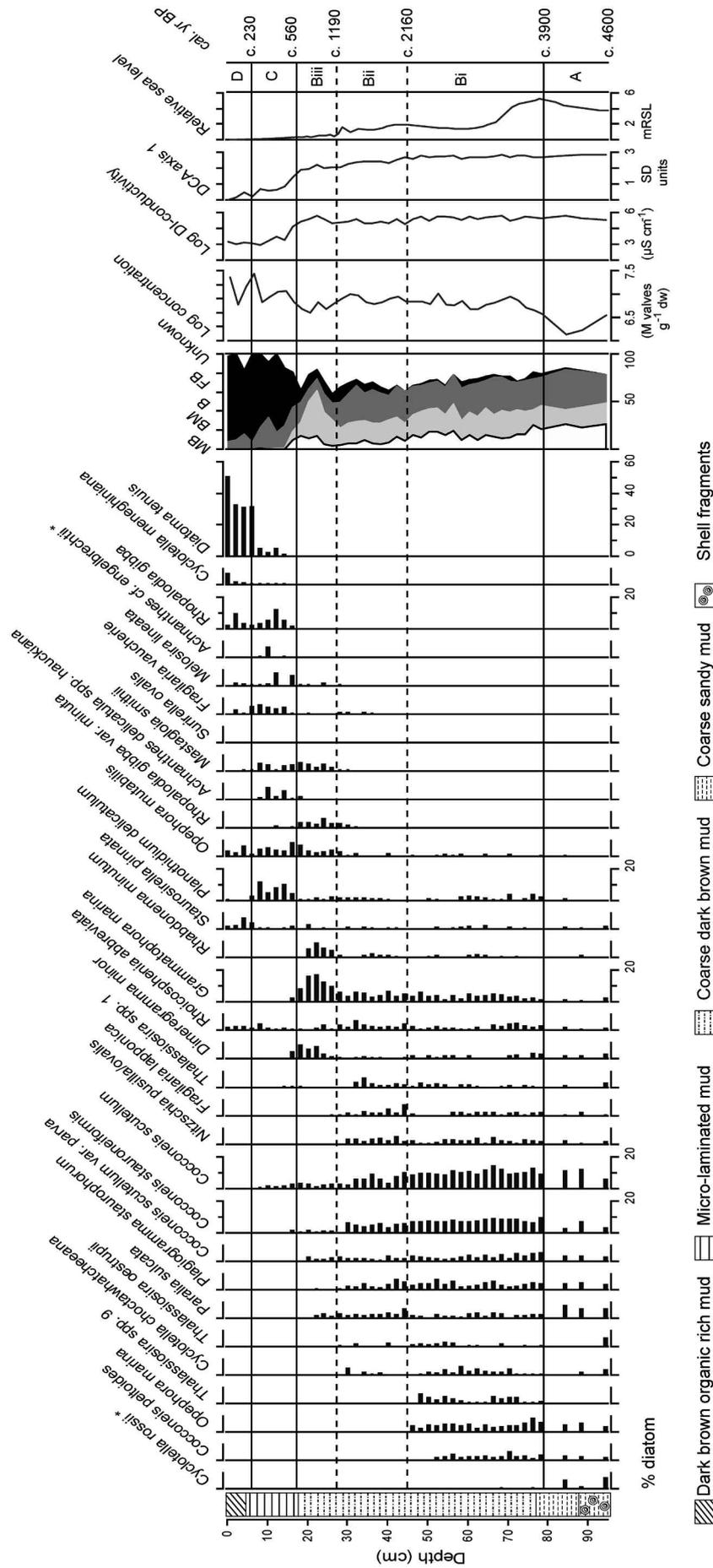
All of the diatoms are described in terms of their salinity preference (McQuoid, 1999) using the following criteria:

- (1) Marine-brackish (MB) – diatoms that are widespread in marine habitats but which demonstrate an affinity to brackish water (eg, *Plagiogramma staurophorum*, *Opephora marina*).
- (2) Brackish-marine (BM) – diatoms that are widespread in brackish environments but which demonstrate an affinity to marine waters (eg, *Cocconeis stauroneiformis*, *C. peltoides*).
- (3) Brackish – diatoms with a strong preference for brackish water environments (eg, *Tabularia fasciculata*, *Thalassiosira oestrupii*).
- (4) Freshwater-brackish (FB) – diatoms widespread in brackish environments, but which demonstrate an affinity to freshwater (eg, *Diatoma tenuis*, *Cyclotella meneghiniana*).

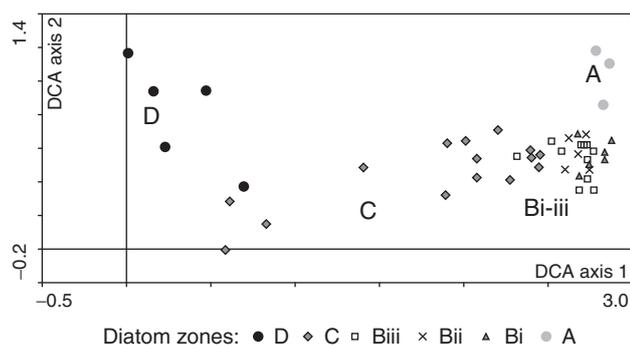
#### Zone A (c. 4600–3900 cal. yr BP)

Diatom zone A encompasses both zones I and II, as defined by the lithological and geochemical properties. The concentration of diatoms in this zone was generally low ( $3 \times 10^6$  valves/g). The diatoms that occur in zone A are those with a preference for marine and/or brackish habitats. One diatom species *Cyclotella rosii* (B) declines significantly in this zone, almost disappearing completely from the record. All other brackish and marine species are continuously

Borg Indrepollen, Vestvågøy, Lofoten



**Figure 5** Litho-stratigraphical plot of selected diatom taxa from INDRE-C plotted as relative abundance (%). All taxa (>5% abundance) are shown. The diatoms have been ordered according to their weighted averaging distribution (descending) and are split into assemblage zones (A–D). A summary of the diatom habitats (MB, Marine-Brackish; B, Brackish; BF/FB, Brackish-Freshwater/Freshwater-Brackish; Unknown) is shown alongside the diatom-inferred (DI) conductivity (European Diatom Database (EDDI)), DCA axis 1 sample scores and a relative sea-level curve, displayed as relative sea-level in metres (mRSL; the model is based on the shoreline relation principle; Andrews, 1970) for the Lofoten region (produced using Sealevel32; Møller, 2003)



**Figure 6** DCA of the core diatom samples in the > 5% data set. The ordination plot of samples from Indrepollen shows a clear division in the data set, with the samples indicative of a marine environment (diatom zones A–C) clustering to the right, and those indicative of the transitional phase and modern day freshwater conditions (C–D) to the left

**Table 2** Summary of results from the detrended correspondence analysis (DCA) on the reduced dataset (31 taxa, > 5% as shown in Figure 5)

Axes	1	2	3	4
Eigenvalues	0.470	0.038	0.025	0.019
Gradient length	2.859	1.182	1.077	1.172
Cum. % variance of species data	49.4	53.3	56.0	58.0

present and maintain abundances above ~3%. The boundary between diatoms zone A and B corresponds to the lithostratigraphic boundary between zones II and III, where the sediment changes from coarse sandy material, to a dark brown mud.

#### Zone B (c. 3900–560 cal. yr BP)

Zone B (17–77 cm) in the diatom data corresponds to Zone III in the lithostratigraphic and geochemical data. However, in the diatom data three subzones (Bi, Bii and Biii) have also been identified.

#### Zone Bi (c. 3900–2160 cal. yr BP)

The diatom concentrations increased through the zone (~4–8 × 10<sup>6</sup> valves/g), and the lithology suggests finer sedimentation. This zone is dominated by diatoms with a preference for marine and/or brackish habitats. Three species disappear before the zone boundary at or before 2150 yr BP: *Cocconeis peltoides* (BM), *Opephora marina* (MB) and *Thalassiosira* spp. 9 (MB), all other brackish and marine species are continuously present in relatively high abundances.

#### Zone Bii (c. 2160–1190 cal. yr BP)

The second subzone of B is characterized by the presence of diatoms with marine and/or brackish habitat preferences. In this zone, several of the brackish species begin to disappear (*Cyclotella choctowhatcheeana*, *Nitzschia pusilla* and *Plagiogramma staurorophorum*). The transition between Zones Bi and Bii (45 cm) in the diatom data corresponds closely with the increases of  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and C/N midway through Unit III of the lithostratigraphic data.

#### Zone Biii (c. 1190–560 cal. yr BP)

Several brackish species with a marine affinity (*Grammatophora marina*, *Rhabdonema minutum*) and marine species with a brackish affinity (*Dimeregramma minor*) peak in this zone before disappearing completely from the record. It is in this zone that the first brackish species with a preference for more freshwater

habitats appear (eg, *Mastogloia smithii* and *Melosira lineata*). The brackish species with a freshwater affinity occur with abundances of < 10%. The boundary between lithostratigraphic units III and IV, where laminated sedimentation begins, corresponds with the boundary between diatom zones Biii and C.

#### Zone C (c. 560–230 cal. yr BP)

Brackish species with a freshwater affinity peak in abundance in this zone. This follows the peak and decline of the brackish-marine (BM) species in Zone Biii. It is apparent that the species composition within this zone changes from an assemblage in which species have an affinity for marine waters to species that have a greater affinity to freshwater conditions. It is within this zone that any major marine influence on Borg Indrepollen appears to cease. The transitional boundary between diatom zones C and D is close to the transition into lithostratigraphic unit V, where laminated sedimentation ends.

#### Zone D (c. 230 cal. yr BP–present)

The uppermost zone (0–7 cm) is dominated by brackish species with an affinity for more freshwater conditions. In this zone, it is apparent that there is very little marine influence and Indrepollen is becoming a more freshwater environment. In the top few centimetres of the core, most of the species appear to decline and species diversity reduces. This in part is due to the overwhelming abundance of *Diatoma tenuis* (60–75%) in the uppermost samples. This final diatom zone corresponds to the uppermost lithostratigraphic unit (V).

### Numerical analysis

The DCA (Figure 6) revealed a gradient length of 2.85 and showed that 49.4% of the variance in the diatom data could be explained by the first axis (Table 2). An EDDI conductivity reconstruction (as a proxy for salinity) was applied down core; a weighted-averaging (WA) technique was chosen as the data were compositional, with some species absent in many of the samples (Hill and Gauch, 1980; ter Braak and Prentice, 1988).

There is a clear division in the reconstructed conductivity of Indrepollen (Figure 5 and 6). In the lower 70 cm of the core (c. 4500–680 yr BP), there is relatively little change in the diatom inferred conductivity, with the values almost constant at the higher end of the log scale. At ~15 cm (c. 450 yr BP) there is a significant drop in the log conductivity. This change in the inferred conductivity is mirrored by the axis one sample scores (correlation coefficient of 0.951).

### Discussion

Lake isolation studies provide an ideal method for reconstructing shore displacement history of areas affected by postglacial isostatic land uplift (Seppä *et al.*, 2000). Many studies across Northwest Europe have documented relative sea-level changes using sedimentary and biological proxy data. In many of these studies, the isolation process is very clear and is seen in both the lithostratigraphy and the diatom stratigraphy, usually as a decrease in marine influence (Shennan, 1982; Zong, 1998; Miettinen, 2004; Miettinen *et al.*, 2007). Diatom analysis in particular has proven a very practical method in understanding the isolation process. Diatoms show a clear progression from an assemblage dominated by pelagic, marine species, through brackish taxa, to those species with a more freshwater affinity once isolation is reached (Shennan *et al.*, 1995, 2000; Zong, 1998; Seppä *et al.*, 2000; Miettinen, 2004; Berglund *et al.*, 2005; Miettinen *et al.*, 2007). However, the precise nature, timing and character of these changes are local and site-dependent (Shennan *et al.*, 1983; Long, 1992; Plater and Shennan, 1992).

The analyses from Indrepollen show a clear record of lake ontogeny over the last 4600 years, with major changes occurring in the last 550 years in particular. The lake ecosystem appears to be responding to a combination of land uplift and changing climatic conditions associated with neoglacial cooling and recent warming trends.

The diatom, isotope and reconstructed conductivity from Indrepollen all suggest that in the lower part of the core (c. 4600–560 cal. yr BP) conditions are relatively stable. The diatoms indicate a marine environment. The diatom-inferred conductivity suggests a stable, high-salinity environment and the isotope and C/N data indicate an environment dominated by algal productivity. The most dramatic change in the sediment, geochemical and diatom stratigraphy from Indrepollen occurs from ~550 cal. yr BP, when the marine-dominated fjord becomes increasingly isolated and a more freshwater, lake environment prevails.

### c. 4600–1190 cal. yr BP

The glacio-isostatic rebound of Vestvågøy over the late Holocene is the main controlling factor on the environment of Borg Indrepollen. The diatom flora indicates a major shift in habitat from a marine-influenced environment to that of a brackish/freshwater ecosystem. It has long been recognized that many diatom taxa thrive in water of a particular salinity and some are indifferent to this environmental factor (Palmer and Abbott, 1986). In coastal lakes, fossil diatom assemblages reflect the prevailing salinity of their habitat. For sea-level studies, the most useful historical reconstructions are ones in which a substantial change is found in the proportions of fresh, brackish and marine diatoms (Palmer and Abbott, 1986).

The main control on the salinity of Indrepollen is sill geometry, a result of the isostatic rebound of Scandinavia (Møller, 2003) and influences of freshwater inflow (Emeis *et al.*, 2003). Indrepollen is an emerging fjord; the area once provided an embayment for Viking longboats that entered from the sea, but today as a result of the glacio-isostatic uplift, the connection to the sea is very shallow. The sill at Indrepollen provided a critical threshold for marine influence in the basin. Approximately 1000 cal. yr BP, land uplift reached a point at which the sill prevented a constant marine influx into the basin. Now at sea level, only the highest tides breach the sill, greatly reducing the marine influence and making Indrepollen quasi-tidal in character. Without the constant marine influence, Indrepollen has become strongly stratified; limnological measurements indicate saline or brackish water and anoxic conditions at depth with a distinct freshwater layer overlying cool, saline waters. The contemporary analyses of the water column show that these major changes occur at depth (12 m depth); specific conductivity (SPC) increases, temperature drops and dissolved oxygen (DO) becomes extremely low.

The presence of *Paralia sulcata*, a common coastal diatom (Snoeijs, 1993) in the earlier record is an indicator of high productivity (McQuoid and Nordberg, 2003) and a degree of mixing within the water column. *Paralia sulcata* also favours a sandy substrate; between 78 and 95 cm the sediment is extremely coarse and sandy, and *P. sulcata* is at its greatest abundance. As there is an increase in the deposition of finer, organic sediment, the taxon begins to decrease before disappearing completely from the record, even though marine conditions appear to prevail. This species disappears at the onset of the laminated section of core, and the diatom flora shifts to a more brackish assemblage.

There is a possibility of locating the Trænadjupet tsunami within the Indrepollen stratigraphy. Laberg *et al.* (2002) suggest that this mid-Holocene landslide and associated tsunami event occurred immediately prior to 4000 <sup>14</sup>C years. At this time in the Indrepollen geochemical and lithological record (85–80 cm) there is a large drop in carbon and nitrogen per-

centages, suggesting a drop in productivity or dilution as a result of a substantial minerogenic influx. This section of the core also coincides with coarser-grained sediment.

### 1190 cal. yr BP–present

The water of Indrepollen is closely connected to the water mass of the Norwegian Atlantic current and the thermohaline circulation. The presence of the marine species *Thalassiosira oestrupii* in the earlier part of the record suggests a warming of SSTs and a reduction in seasonal ice cover, as this species prefers warmer conditions and a higher salinity than those found in Arctic conditions (Birks and Koç, 2001). At ~560 cal. yr BP both marine and brackish species are present in the assemblage, but there is also the introduction of species with a freshwater affinity (eg, *Melosira lineata*), suggesting that there is a trend towards a more freshwater environment. This marks the beginning of a forced regression event as a result of land uplift, causing a sill-threshold to be passed and so reducing marine exchange. This is further supported by a decline in species such as *T. oestrupii*, an indicator species of marine waters (Hasle and Syvertsen, 1997; Birks and Koç, 2002). *T. oestrupii* is the main species of the warm Atlantic assemblage in the Nordic seas (Jiang *et al.*, 2001; Birks and Koç, 2002). The disappearance of this species indicates the declining influence of Atlantic marine waters on the environment at Indrepollen and a possible cooling of SST temperatures in this region (Jiang *et al.*, 2001; Birks and Koç, 2002).

The correlation between the isotopic data (high  $\delta^{13}\text{C}$  and low C/N) and the trends in the biological data (which indicate a marine/brackish flora) suggest the marine influence on the Indrepollen basin, represented by the reconstructed conductivity, is a controlling factor of the source of organic material. The high  $\delta^{13}\text{C}$  is unlikely to be as a result of input from C<sub>4</sub> plants as they constitute a minor fraction of land plants in temperate regions (Raven *et al.*, 1992) and because of the low C/N ratios. The higher  $\delta^{13}\text{C}$  may be due to an increase in the marine organic matter (which has high  $\delta^{13}\text{C}$ ), but could also be attributed to an increased primary production (as reflected in the high  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) as a result of decreased fractionation and CO<sub>2</sub> drawdown (Laws *et al.*, 1995; Peterson and Fry, 1987).

Indrepollen begins to experience isolation (owing to glacio-isostasy) from the influence of the marine waters at around 550 cal. yr BP. This zone is characterized by a distinct change in sediment characteristics from coarser-grained sediments, to a section of finely laminated sediment. Studies of shoreline displacement at Lyngen and Vana, north Norway also demonstrate sections of laminated sediments (either laminated gyttja or sand/silt laminae). These are interpreted as a transitional stage from marine to brackish/freshwater, supported by diatom analyses which show the appearance of diatoms with a FB/BF affinity (classified according to Hustedt, 1957; Corner and Haugane, 1993).

In many studies from the isolation basins of Scotland and the Baltic Sea region (ie, Finland), at the point of isolation, the diatom assemblages are dominated by *Fragilaria* spp. (up to ~50% abundance; eg, Eronen, 1974; Shennan *et al.*, 1993; Seppä *et al.*, 2000; Miettinen, 2002, 2004; Miettinen *et al.*, 2007). This particular assemblage is often related to the onset of isolation of the lake (eg, Stabell, 1985) and is attributed not only to the salinity changes, but also to changes in the water chemistry during the isolation process (Miettinen, 2004; Miettinen *et al.*, 2007). Interestingly, despite its commonality in many other isolation studies, although *Fragilaria* spp. do occur, this phenomenon is not seen in the record from Indrepollen.

At ~450 yr BP (~15 cm) there is a decline in saline/brackish taxa, which may be a response to cooler climate during the 'Little Ice Age'. As a result of a high pressure zone over Scandinavia, the flow of cold Arctic air predominated from the east (Emeis *et al.*,

2003). During this period, winter precipitation increased steadily whilst summer temperatures cooled, North Atlantic deep water formation reduced and the climate across much of western Europe became cooler (Stuiver *et al.*, 1995; Emeis *et al.*, 2003); the advance of Norwegian glaciers at this time also suggests advection of moisture during the winter, resulting in more freshwater (brackish) conditions.

The abundance of freshwater diatoms in the most recent part of the record may be as a result of full isolation, or could be due to cooler and wetter conditions across the region, or a combination of these factors. It is interesting that the major change in inferred conductivity corresponds to a period of very minor change in sea level (Figure 5). The conductivity change could be a result of a transition across a threshold sill depth controlling water exchange. Alternatively, it could be postulated that an increase in the input of freshwater caused by climate change during the 'Little Ice Age' resulted in the periodic development of a freshwater surface layer. Such a layer would result in a density contrast between the deeper saline waters and surface water, causing anoxic conditions at depth and allowing a section of fine laminations to be recorded in the sediment sequence.

In conjunction with this at *c.* 450 cal. yr BP, there are low  $\delta^{13}\text{C}$  and high C/N and it is likely that these data represent freshwater aquatic and terrestrial inputs. The high C/N suggests that some of the organic material is sourced from terrestrial plants. The reduction in  $\delta^{15}\text{N}$  at this time could be a result of the increasing input of terrestrial material (which tends to have lower  $\delta^{15}\text{N}$  values). This is also consistent with increased precipitation, and increased delivery of terrestrial materials via enhanced erosion and runoff. This is in accordance with the sea-level curve for this area of Lofoten; at this time the relative sea-level (modelled on the shoreline relation principle), as a result of isostasy, appears to drop to almost 0 m (ie, present apparent isostatic uplift at Indrepollen is 0 mm/yr), thus the marine influence at Indrepollen was greatly reduced. The immediate decrease of C/N that follows and an increase in  $\delta^{13}\text{C}$  suggests a reduced input from organic terrestrial matter and an increase in lake productivity (Mackie *et al.*, 2005). Following this excursion in the isotope and C/N record, C/N increases steadily, whilst  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  generally decrease.

From ~230 cal. yr BP to present, Indrepollen is most likely an isolated lake. The dominance of more brackish/freshwater affiliated diatom species (eg, *Diatoma* spp. and low  $\delta^{13}\text{C}$  values are indicative of a freshwater environment where the carbon is not fully utilized (Schelske and Hodell, 1995). However, the increased C/N ratio (the highest in the record), the low  $\delta^{13}\text{C}$  (−26.5‰; the lowest in the record) and low  $\delta^{15}\text{N}$  suggests that these signatures could also result from an increase in organic material derived from terrestrial plants. This, together with lower organic carbon could be due to dilution but also due to a decrease in primary productivity, or again due to the input of material from terrestrial sources (Talbot and Johannesssen, 1992; Bianchi *et al.*, 2000).

The dominance of *Diatoma* spp. in the most recent record at Indrepollen may indicate a transient influx of brackish water to the lake, perhaps as a result of periodic breaches of the sill threshold during storm related excursions (Eronen, 1974; Seppä *et al.*, 2000). Alternatively, given the chemical stratification of Indrepollen (with a freshwater lens overlying more saline waters; cf. Figure 2), periodic overturn of the lake would result in the mixing of the underlying saline water with the freshwater hypolimnion, could be responsible for the dominance of *Diatoma* spp. It is however common for post-isolation lakes to contain a brackish diatom assemblage, especially as coastal zones are diverse habitats for diatoms and the change from a saline/brackish environment is seldom sudden and clear (Palmer and Abbott, 1986; Corner and Haugane, 1993; Seppä *et al.*, 2000).

The increasing influence of terrestrial organic matter on the lake geochemical stratigraphy can be attributed to several causes, the

reduced influence of the marine realm and a drop in the lake productivity would allow terrestrial influxes to dominate. In addition to this, many land-use changes were occurring in this period as a result of Viking activity, especially in terms of clearance of natural vegetation for farming practices, which could also account for a larger input of terrestrial material into the lake sediments. Decreasing  $\delta^{13}\text{C}$  and increasing C/N (which begins in zone III at ~45 cm, *c.* 2160 cal. yr BP and continues to the top of the core) is likely to be a consequence of a gradually increasing influx of terrestrial organic matter to the lake, which could be attributed to increasing land-use changes in the catchment by Viking cultures. In support of this, a pollen study by Johansen and Vorren (1986) across 'Arctic' Norway, and particularly from a site 'Bøstad', Lofoten, suggests a decrease in forest cover (arboreal pollen) and grassland pastures becoming more common (increase in grass and cereal pollen) from *c.* 2500 cal. yr BP, which coincides with archaeological evidence suggesting the establishment of more permanent settlements and a heavier reliance on farming in the Lofoten region.

## Conclusions

Diatom analysis provides an effective tool for the reconstruction of conductivity in dynamic environments as they respond rapidly to changes in salinity. Diatom-conductivity models have proven to be useful tools in the study of the response of coastal areas to hydrographic and climatic transitions (Holm and Bager, 2001; MacKenzie *et al.*, 2002; Ryves *et al.*, 2004).

Through the comparison of new sedimentary data (lithological, geochemical and biological) to the existing shoreline displacement curve for the Lofoten region, it can be seen that the results from Indrepollen are in agreement, showing an apparent marine regression as a result of glacio-isostatic rebound over the time frame represented by the sediment core (Møller, 2003; Møller, personal communication, 2005). The diatom analyses from Indrepollen provide an insight into the relative sea-level changes at Vestvågøy. Variations in the  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$  and C/N from Indrepollen track and strengthen the diatom-based palaeoconductivity reconstructions.

The proxy data from Borg Indrepollen provide clear evidence of isolation as a result of the glacio-isostatic rebound of Fennoscandia over the late Holocene. The diatom and numerical analyses alongside the reconstructed conductivity shows a clear change of habitat. Prior to *c.* 550 cal. yr BP, the evidence suggests that Indrepollen is a marine inundated fjord, connected to the North Atlantic and its associated influences. After *c.* 560 cal. yr BP Indrepollen begins to experience isolation, most likely that the sill-threshold is passed and marine exchange is greatly reduced. There may also be evidence for increasing precipitation in the Lofoten region at ~450 yr BP. The observed freshening of the lake could have been exacerbated by the combination of the sill-threshold being passed and changing climatic conditions across the area, at a time coincident with the 'Little Ice Age'. This decline in marine influence continues, and the lake reaches full isolation (*c.* 230 cal. yr BP).

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