

## Late Pleistocene-Holocene productivity record of benthic foraminifera from the Iceland Plateau (Core PS1246-2)

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### ABSTRACT

Benthic foraminiferal assemblage patterns in Core PS 1246-2 from the Iceland Plateau are examined as they relate to annual productivity and seasonal productivity changes during the Late Pleistocene glacial (23,000-11,000 yrs B.P.), Younger Dryas cool period (11,000-10,000 yrs B.P.) and Holocene (10,000-2,900 yrs B.P.). Abundance fluctuations of *Cibicides wuellerstorfi*, a suspension-feeder, are used as the proxy for annual productivity, while fluctuations of the phytodetritus-exploiting species *Epistominella exigua*, *Eponides tumidulus* and *Globocassidulina subglobosa* are used as the indicators of seasonal productivity.

These records show seasonal productivity began to increase around 22,500 yrs B.P. and experienced three subsequent peaks in the glacial, while annual productivity increased around 16,000 yrs B.P. and shows only one peak in the glacial. The Younger Dryas shows a decrease in both seasonal and annual productivity records. Seasonal productivity in the early Holocene is much higher than during the glacial, yet appears more extreme. The Holocene record of annual productivity continues to show a strong general increase in intensity.

### INTRODUCTION

The Iceland Plateau is an area which has experienced strong contrasting glacial-interglacial conditions, mainly as a function of its location in an area of the North Atlantic within close vicinity of Greenland ice sheets. Box Core PS 1246-2 (69°23.0'N, 12°55.0'W, 1861m water depth) is situated on the northern extent of the Iceland Plateau (Fig.1) and contains a Late Pleistocene glacial - Younger Dryas - early Holocene transition.

Supply of food is the deciding factor in controlling the abundance of benthic organisms, therefore both an increased organic flux (food source) from surface productivity (Altenbach & Sarnthein, 1989; Herguera & Berger, 1991; Struck, 1995) and the amount of organic carbon in the sediment (Lutze & Coulbourn, 1984) will affect the benthic foraminiferal fauna. Additionally, Herguera & Berger (1991) have determined a correlation of  $R=0.97$  between benthic foraminiferal accumulation rates and organic carbon flux rates. This means that surface productivity (as indicated from organic carbon flux rates) linearly correlates with the benthic foraminiferal accumulation rates, confirming the finding of

others that the fluctuating relative abundance or accumulation rates of benthic foraminiferal species can therefore be used as a proxy for surface water paleoproductivity (Altenbach & Sarnthein, 1989; Gooday, 1993; Smart *et al.*, 1994).

In this core, the suspension-feeding *Cibicides wuellerstorfi* (SCHWAGER, 1866) is used as the proxy for annual productivity (Lutze & Thiel, 1987; Altenbach & Sarnthein, 1989), as it is probably a long-living species (possibly several years, thus representative of the average annual productivity), fairly abundant and the distribution pattern is similar to the total benthic foraminiferal abundance curve from this core (Struck, 1992; this study).

Higher abundances of *Epistominella exigua* (BRADY, 1884), *Eponides tumidulus* (BRADY, 1884) and *Globocassidulina subglobosa* (BRADY, 1881) are used in this study to indicate periods of increased seasonal productivity, as modern specimens thrive in the phytodetritus falling on the sediment surface during periods of high surface productivity (Gooday, 1988). Such phytodetritus-exploiting foraminifera are regarded as opportunists, able to

rapidly grow and reproduce when presented with a sudden pulse of food, leading to the formation of large populations (Gooday, 1988; Graf, 1989; Gooday, 1993). Once the food source is exhausted the populations collapse, yet are able to "hibernate" until the next pulse of food (Gooday, 1988; Gooday, 1993; Smart *et al.*, 1994).

For any given year the trace of phytodetritus in the fossil record may fail to be preserved, however, the signal of increasing or decreasing phytodetritus inputs over many years should be. This would mean that inputs over significantly long periods of time would be recorded as peaks in phytodetritus-exploiting benthic foraminiferal species. The assumption of a foraminiferal abundance peak being representative of an average seasonal productivity over many years (or decades) holds true for the annual productivity peaks as well. This assumption is particularly true of Core PS 1246-2 which does not have high sedimentation rates (0.58-4.05 cm/kyear), necessarily meaning low temporal resolution.

It is a clear fact that habitat preferences of foraminifera are not rigidly set, but rather are able to tolerate fluctuating food availability and oxygen gradients (Gooday, 1993). Therefore, using the feeding habits of foraminifera more so than their respective living habitats, this study traces the changes in annual and seasonal productivity on the

Iceland Plateau using indicative benthic foraminiferal species during the late glacial, Younger Dryas and Holocene. (The reader should remember this paper's use of "annual", and especially "seasonal", productivity are therefore loosely used terms).

## METHODS

### Foraminiferal Sampling

As pointed out by Schröder *et al.* (1987), some environmentally-significant foraminifera (for example the phytodetritus-exploiting species used in this study: *Epistominella exigua*, *Eponides tumidulus* and *Globocassidulina subglobosa*) are adequately represented in only the >63µm residues. Keeping this in mind, approximately 25cc of wet bulk sediment, in 1cm thick sediment slices, was wet sieved over a 63µm mesh and the retained sediment sample was dried and sieved into the following size fractions: 63-125µm, 125-250µm, 250-500µm, 500-1000µm and 1000-2000µm.

For a given sample, the entire foraminiferal population from each size fraction was picked and counted (or the statistically valid minimum number of 300 specimens if the sample was too large to be picked in its entirety). The data presented are based on the entire fraction >63µm.

### Age Model Control

Ages used in this study are reservoir-corrected AMS  $^{14}\text{C}$  years before present. The age of the surface (2,900 yrs B.P.) was determined by correlation of planktic foraminiferal abundance patterns with Core PS 1243 from the East Iceland Sea, which has a much higher sedimentation rate and radiocarbon age control (Bauch & Weinelt, in press). Correlation between these two cores has been done in order to aid the age control for Core PS 1246-2. A distinctive rhyolitic ash (18.5 cm core depth), undoubtedly the Vedde ash which identifies the Younger Dryas cool period, occurs at a depth stratigraphically-correlated to be 10,600 yrs B.P. (terrestrially dated; Mangerud *et al.*, 1984). The beginning of the Last Glacial Maximum (LGM) is given the age of 17,700 yrs B.P. (Sarnthein *et al.*, 1995) and is plotted based on linear interpolation of age data points. The end of the LGM (better identified in this core than the beginning) is indicated by the glacial maximum in the *Neoglobobulimina pachyderma* (sin)  $\delta^{18}\text{O}$  record (see Fig. 5b(ii) this study; Bauch, 1994) and is given the age of 14,900 yrs B.P. (data from Vogelsang, 1990; age modi-

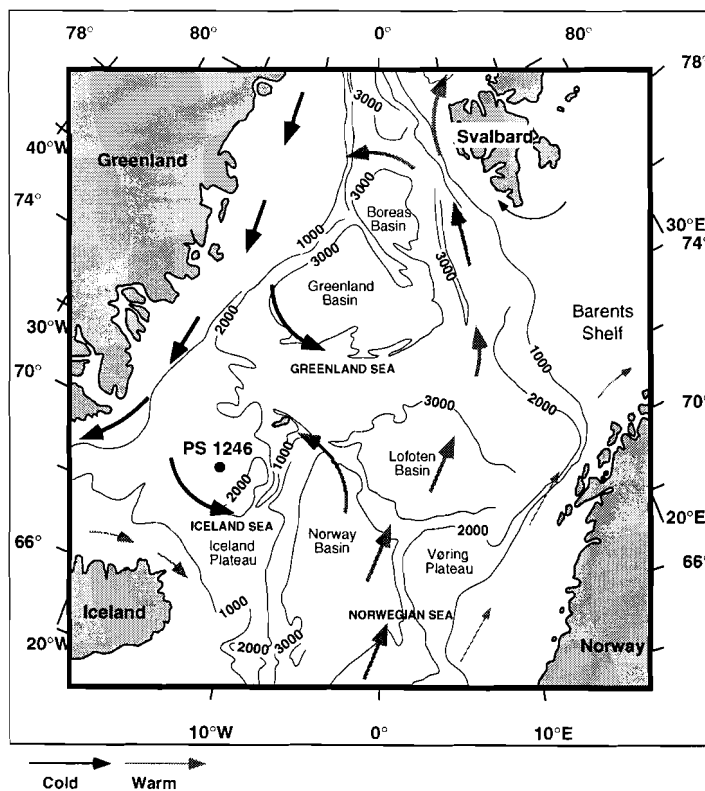


Figure 1. Locality map.

fied by Sarnthein *et al.*, 1992; Sarnthein *et al.*, 1995). The age of the bottom of the core, through correlations with Core PS 1243-2, has been assigned the age of 23,000 yrs B.P. This age estimate is confirmed by the absence of an isotope Stage 3.1 melt water spike in the planktic  $\delta^{18}\text{O}$  record and by the occurrence of *Siphotextularia rolshauseni* which also implies only isotope Stage 2 (Nees & Struck, 1994). Ages for the rest of the core were obtained by means of linear interpolation using the above four data points.

#### Calculation of Accumulation Rates

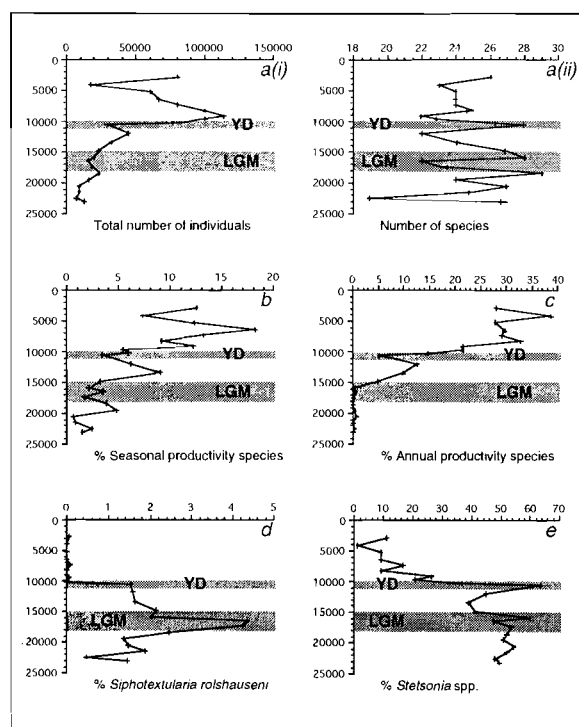
Foraminiferal counts were converted into individuals/gram (ind/g) using dry bulk sediment weight and, subsequently, into accumulation rates using the following formulas:

$$\text{AR}_{\text{Bulk}}(\text{gcm}^{-2}\text{a}^{-1}) = \text{LSR}(\text{cma}^{-1}) * \text{DBD}(\text{gcm}^{-1}) \quad (1)$$

$$\text{indg}^{-1} * \text{AR}_{\text{Bulk}}(\text{gcm}^{-2}\text{a}^{-1}) = \text{INDAR}(\text{indcm}^{-2}\text{a}^{-1}) \quad (2)$$

where:

$\text{AR}_{\text{Bulk}}$  = bulk accumulation rate



**Figure 2.** Percent abundances: (a(i)), total number of individuals (a(ii)) number of species, (b) % seasonal productivity species = % *Epistominella exigua*, % *Eponides tumidulus* and % *Globocassidulina subglobosa*, (c) % annual productivity species = % *Cibicidoides wuellerstorfi*, (d) % *Siphotextularia rolshauseni*, (e) % *Stetsonia* spp.. YD = Younger Dryas, LGM = Last Glacial Maximum. Vertical axis is age in  $^{14}\text{C}$  years before present.

a = years before present

LSR = linear sedimentation rate (partly modified from Bauch, 1993)

DBD = dry bulk density (linearly interpolated from Birgisdóttir, 1991)

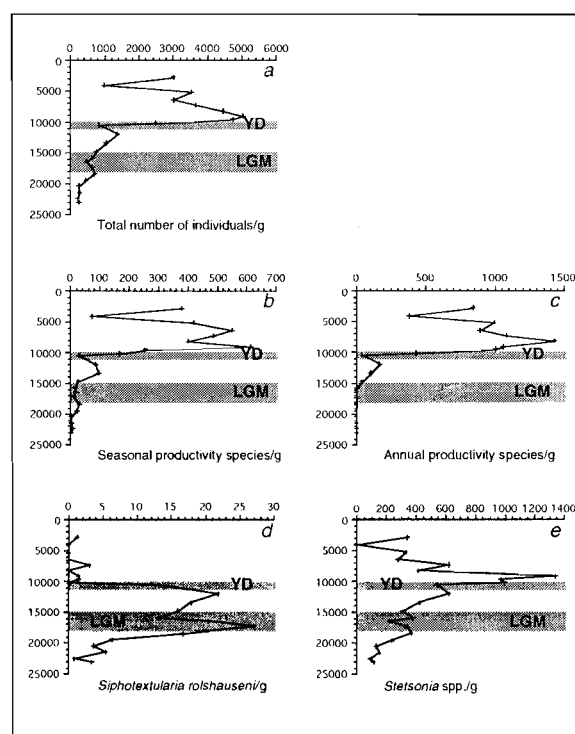
indg $^{-1}$  = individuals/g (this study)

INDAR = individual accumulation rate

#### RESULTS

Only the environmentally significant species (those showing substantial fluctuations in abundance) are discussed in this study: *Cibicidoides wuellerstorfi*, *Epistominella exigua*, *Eponides tumidulus*, *Globocassidulina subglobosa*, *Siphotextularia rolshauseni*, and *Stetsonia* spp.

General trends, as shown in Figure 2a(i), show larger numbers of foraminifera in the post-Younger Dryas and early Holocene portion of the core than during the glacial. *Stetsonia* spp. and *S. rolshauseni* are the only major exceptions. *Siphotextularia rolshauseni*, although not abundant in total number (Fig. 3d) or percent abundance (Fig. 2d), has an obvious preference for the glacial (Nees & Struck, 1994). *Stetsonia* spp. has only slightly higher total numbers (Fig. 3e) in the glacial (as compared to the

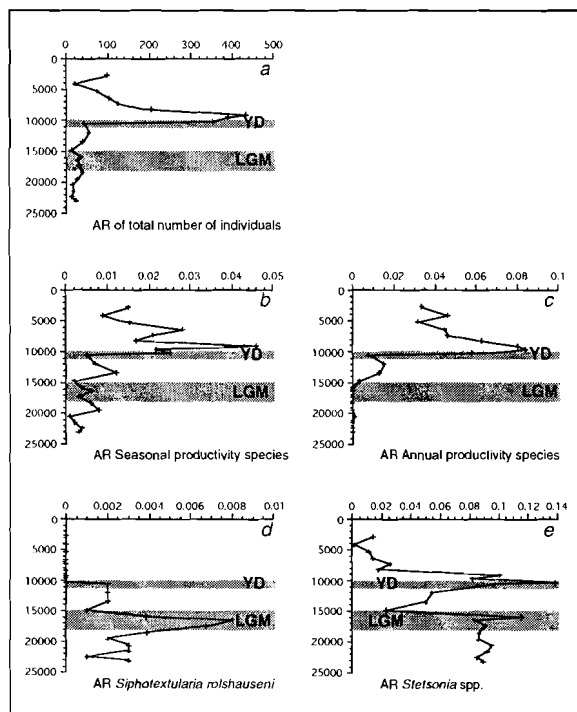


**Figure 3.** Individuals/g: (a) total number of individuals/g, (b) seasonal productivity species/g = *Epistominella exigua*/g, *Eponides tumidulus*/g and *Globocassidulina subglobosa*/g, (c) annual productivity species/g = *Cibicidoides wuellerstorfi*/g, (d) *Siphotextularia rolshauseni*/g, (e) *Stetsonia* spp./g. YD = Younger Dryas, LGM = Last Glacial Maximum. Vertical axis is age in  $^{14}\text{C}$  years before present.

Holocene) yet, as the total number of foraminifera is lower in the glacial, the percent abundance of *Stetsonia* spp. (Fig. 2e) is markedly higher. This would suggest that *Stetsonia* spp. has an obvious preference for glacial environmental conditions, as the accumulation rates of *Stetsonia* spp. (Fig. 4e) show peaks clearly associated with the LGM and the Younger Dryas. The increased percent abundance of *Stetsonia* spp. during these times is in accordance with its dominance in modern Arctic Ocean deep sea foraminiferal faunas (Scott & Vilks, 1991).

There is a pre-Younger Dryas warming as shown by increased benthic and planktic foraminiferal abundances (Fig. 5a(i) and a(ii)). During the Younger Dryas a substantial drop in the size of the foraminiferal population is recognized.

Benthic foraminiferal accumulation rates generally mimic the trend of percent abundance (Fig. 4), more so than that of ind/g, and no major deviations from this trend are observed (compare Figs. 2 and 4). The accumulation rate data give a better indication of the absolute magnitude of productivity changes, showing the strong post-Younger Dryas peak in warming of surface waters and hence, in both annual and seasonal productivity.



**Figure 4.** Accumulation rates ( $\text{ind} \cdot \text{cm}^{-2} \cdot \text{a}^{-1}$ ): (a) total individuals, (b) seasonal productivity species = *Epistominella exigua*, *Eponides tunidulus* and *Globocassidulina subglobosa*, (c) annual productivity species = *Cibicides wuellerstorfi*, (d) *Siphotextularia rolshauseni*, (e) *Stetsonia* spp.. YD = Younger Dryas, LGM = Last Glacial Maximum. Vertical axis is age in  $^{14}\text{C}$  years before present.

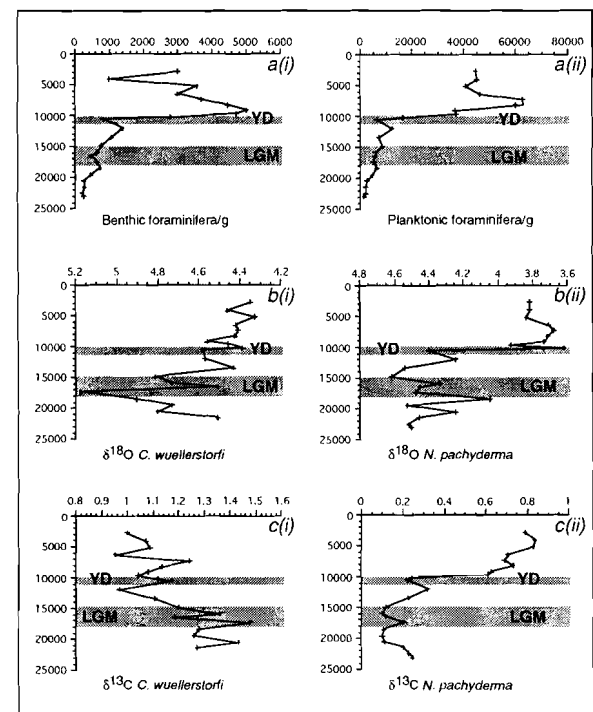
Lower  $\delta^{13}\text{C}$  values correspond to nutrient-rich waters, and higher values to nutrient-depleted waters. The  $\delta^{13}\text{C}$  *C. wuellerstorfi* record (Fig. 5c(i)), shows a general increase in productivity from low glacial levels to the higher productivity levels of the Holocene. Additionally, it agrees well with the percent abundances of the annual (Fig. 2c) and seasonal (Fig. 2b) productivity-indicating species, i.e. the peaks in percent abundance positively correlate with lower  $\delta^{13}\text{C}$  values. The general trend of the benthic  $\delta^{13}\text{C}$  curve is coeval with that of the planktic  $\delta^{13}\text{C}$  curve (Fig. 5b(ii)), further strengthening the relation of benthic foraminifera to surface productivity.

Heavier  $\delta^{18}\text{O}$  values correspond to times of increased ice volume, necessarily inferring a colder climate, thus acting as a first-order proxy for paleotemperatures. The  $\delta^{18}\text{O}$  benthic *C. wuellerstorfi* record (Fig. 5b(i)) generally corresponds with trends shown in the planktic *Neogloboquadrina pachyderma* (sin)  $\delta^{18}\text{O}$  record (Fig. 5b(ii)), both suggesting colder times during peaks in productivity.

## DISCUSSION

### Late Pleistocene Glacial (23,000-11,000 yrs B.P.)

Glacial conditions are represented by total abun-



**Figure 5.** Stable isotopes: (a) benthic and planktic foraminiferal abundances, (b) oxygen and (c) carbon stable isotope records of *Cibicides wuellerstorfi* and *Neogloboquadrina pachyderma* (s) ( $\%$  vs. PDB). YD = Younger Dryas, LGM = Last Glacial Maximum. Vertical axis is age in  $^{14}\text{C}$  years before present.

dances of about 1000 ind/g and species diversity ranging from 22 to 28 species (averaging around 26). *Siphotextularia rolshauseni* (characteristic of low organic carbon flux; Nees & Struck, 1994) ranges in abundance from 15 to 27 ind/g. This species reflects a strongly oligotrophic environment, which is supported by a near-absence (0.0125-0.25 ind/g) of high organic flux species (i.e. *Bolivina* sp., *Bulimina marginata*, *Brizalina* sp., *Pullenia bulloides* and *Uvigerina* spp.). Although *S. rolshauseni* does not constitute a large part of the foraminiferal population (1-4.5% in our core), it appears virtually only in the glacial, and strongly confirms to be stratigraphically useful in the Nordic Seas as an indicator of oxygen isotope Stage 2 (Struck & Nees, 1991; Nees & Struck, 1994). The percent abundance, ind/g and accumulation rate of *S. rolshauseni* all simultaneously reach a maximum around 16,500 yrs B.P.

*Cibicides wuellerstorfi* (used here as a first-order proxy for annual productivity) was virtually absent early in the glacial but, at approximately 16,000 yrs B.P., it began to gradually increase. In Core 1246-2, it reached its glacial peak of about 13% of the total foraminiferal population around 12,000 yrs B.P. This peak is associated with peaks in both ind/g and accumulation rate.

Seasonal productivity, as recorded by phytodetritus species such as *Epistominella exigua*, *Eponides tumidulus* and *Globocassidulina subglobosa* (Gooday, 1993), shows small peaks around 22,500 yrs B.P., 19,000 yrs B.P., 16,500 yrs B.P. and the largest glacial peak at 13,500 yrs B.P.

*Stetsonia* spp. is undoubtedly the major constituent in the glacial foraminiferal assemblage (average of 52% and 300 ind/g). At 16,000 yrs B.P. *Stetsonia* spp. increases slightly in total numbers (400 ind/g) and has a much higher percent abundance (60%), accompanied by a sharp increase in the accumulation rate. Both annual and seasonal productivity trends are similar in degree of change but seasonal productivity begins to increase some 7,000 yrs B.P. earlier and is more of a gradual change than annual productivity trends. Seasonal productivity appeared to slowly increase at about 20,000 yrs B.P., reaching a small peak before decreasing in intensity during the LGM. Percentages of both seasonal and annual productivity-indicating species show an increase around 14,000-13,000 yrs B.P., possibly indicating prolonged sea-ice free conditions, as warming of the North Atlantic was underway at this time (Veum *et al.*, 1992). At approximately 12,000 yrs B.P., there is a near-minimum in species diversity (22 species) and a slight increase in total numbers (1400 ind/g). Indicated by an increase of *C. wuellerstorfi* from 10% to 13%, annual productivity has its maximum during the late glacial, and seasonal productivity

(% phytodetritus species from 9% down to 6%) decreases at this time.

#### Younger Dryas (11,000-10,000 yrs B.P.)

A decrease in total numbers of individuals (850 ind/g), as well as a corresponding decrease in the total number of each individual species, occurred during the Younger Dryas. This is understandable, as there was a return to glacial conditions, with an associated decrease in temperature (Fig. 5b(i)) and productivity (Fig. 5c(i)). Oddly, there exists a near-maximum in species diversity (Fig. 2a(ii)), resembling the peak in species at 15,000 yrs B.P. *Siphotextularia rolshauseni* comprises only 1.5% of the total population. Despite the low relative abundance, it maintains a glacial level, thereby indicating low organic carbon flux. The decrease in % *C. wuellerstorfi* as a suspension feeding species suggests a decrease in annual productivity (Fig. 2c), as well as a possible weakening of lateral advection of nutrients. This may be a manifestation of the slight decrease in NADW production in the Nordic Seas as suggested by Boyle & Rosener (1990). Seasonal productivity is also reduced during the Younger Dryas, as indicated by the lower percent abundance of phytodetritus species (Fig. 2b).

Most trends during the Younger Dryas seem to indicate environmental conditions similar to those indicated at 15,000 yrs B.P., during the last glacial. At both times, the total numbers of each species decrease and percent abundances are slightly lower. The lower percent abundances result from the relatively small decrease in total numbers of *S. rolshauseni* and especially *Stetsonia* spp. (Figs. 2e and 4e). In fact, this similarity between the Younger Dryas and conditions indicated at 15,000 yrs B.P. is evident in nearly all proxy indicators.

The abrupt decrease of *S. rolshauseni* at the end of the Younger Dryas may have resulted from a marked increase in organic carbon flux at this time which, in turn, may help explain the quick environmental recovery immediately following the Younger Dryas as shown by the sudden and dramatic increase in foraminiferal abundances.

#### Holocene (10,000-2,900 yrs B.P.)

Early Holocene conditions are represented by a post-Younger Dryas 4-fold increase (as compared to early- to mid-Younger Dryas levels) in total number of individuals (approximately 5000 ind/g) as well as a slight decrease in species diversity (average of about 24 species). Annual productivity, as indicated by % *C. wuellerstorfi*, increases rapidly from the Younger Dryas level to the early post-Younger Dryas level between 9,000 and 8,000 yrs B.P. Seasonal productivity (% phytodetritus species) slightly decreases immediately after the

Younger Dryas, then increases to the Holocene average. Though seasonal productivity fluctuates, there appears to be a period of high (Fig. 2b with a maximum of 18% phytodetritus species abundance) seasonal productivity from 7,000 to 5,000 yrs B.P. At 4,000 yrs B.P. there is a noticeably sharp decrease in the foraminiferal population, accompanied by a slight decrease in species diversity (Figs. 2a(i) and a(ii)). The relative abundance of *C. wuellerstorfi* is higher at this time, while all others decrease. This is interpreted not as an increase in annual productivity but, rather, as a change in environmental conditions that was detrimental to all species. As *C. wuellerstorfi* was the most numerous at the time (about 1000 ind/g), its higher percent abundance is a result of the greater loss to the remaining species.

### CONCLUSIONS

Our study of benthic foraminifera (percent abundances, ind/g, and accumulation rates) support the following observations concerning late Pleistocene-Holocene productivity changes:

(1) During the glacial period (23,000 to 15,000 yrs B.P.) seasonal productivity increased some 7,000 yrs B.P. before any comparable increase in annual productivity. Seasonal productivity peaked at 22,500 yrs B.P., 19,000 yrs B.P., 16,500 yrs B.P. and 13,500 yrs B.P., while annual productivity had a peak at only 12,000 yrs B.P.

(2) The Younger Dryas is marked by a noticeable decrease in the total number of foraminifera and a near-maximum in species diversity. Foraminiferal evidence points to conditions similar to those present at 15,000 yrs B.P. The abrupt decrease of *S. rolshauseni* at the end of the Younger Dryas possibly indicates a substantial increase in organic carbon flux, which may account for the post-Younger Dryas explosion in total numbers.

(3) Most species exhibit an abundance maximum during the early Holocene, reflecting highest seasonal productivity from 7,000 to 5,000 yrs B.P. The major exception being *S. rolshauseni*, which almost disappeared. At 4,000 yrs B.P. there was a substantial change in environmental conditions on the Iceland Plateau, which caused total numbers to drastically decrease.

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### REFERENCES

- Altenbach, A.V. & Samthein, M. 1989. Productivity record in benthic foraminifera. In: W.H. Berger, V.S. Smetacek & G. Wefer (eds.), *Productivity of the Ocean: Present and Past*, 255-269, John Wiley.
- Bauch, H. 1993. Planktische Foraminiferen im Europäischen Nordmeer - ihre Bedeutung für die paläo-ozeanographische Interpretation während der letzten 600.000 Jahre. *Berichte aus dem Sonderforschungsbereich 313*, **40**, 1-108.
- Bauch, H. 1994. Significance of variability in *Turborotalita quinqueloba* (Natland) test size and abundance for paleoceanographic interpretations in the Norwegian-Greenland Sea. *Marine Geology*, **121**, 129-141.
- Bauch, H. & Weinelt, M. (in press). Surface water changes in the Norwegian Sea during last deglacial and Holocene times. *Quaternary Science Reviews*.
- Birgisdóttir, L. 1991. Die paläo-ozeanographische Entwicklung der Islandsee in den letzten 550 000 Jahren. *Berichte aus dem Sonderforschungsbereich 313*, **34**, 1-186.
- Boyle, E.A. & Rosener, P. 1990. Further evidence for a link between late Pleistocene North Atlantic surface temperatures and North Atlantic deep-water production. *Palaeogeography, Palaeoclimatology, Palaeoecology* (Global and Planetary Change Section), **89**, 113-124.
- Gooday, A.J. 1988. A response by benthic foraminifera to the deposition of phytodetritus in the deep sea. *Nature*, **332**, 70-73.
- Gooday, A.J. 1993. Deep-sea benthic foraminiferal species which exploit phytodetritus: Characteristic features and controls on distribution. *Marine Micropaleontology*, **22**, 187-205.
- Graf, G. 1989. Benthic-pelagic coupling in a deep-sea benthic community. *Nature*, **341**, 437-439.
- Herguera, J.C. & Berger, W.H. 1991. Paleoproductivity from benthic foraminifera abundance: Glacial to post-glacial change in the west-equatorial Pacific. *Geology*, **19**, 1173-1176.
- Lutze, G.F. & Coulbourn, W.T. 1984. Recent benthic foraminifera from the continental margin of northwest Africa: community structure and distribution. *Marine Micropaleontology*, **8**, 361-401.
- Lutze, G.F. & Thiel, H. 1987. *Cibicidoides wuellerstorfi* and *Planulina ariminensis*, elevated epibenthic foraminifera. *Berichte aus dem Sonderforschungsbereich 313*, **6**, 17-30.
- Mangerud, J., Lie, S.E., Furnes, H., Kristiansen, I.L. & Lomo, L. 1984. A Younger Dryas ash bed in western Norway, and its possible correlations with tephra in cores from the Norwegian Sea and the North Atlantic. *Quaternary Research*, **21**, 85-104.
- Nees, S. & Struck, U. 1994. The biostratigraphic and paleoceanographic significance of *Siphonotextularia rolshauseni* Phleger and Parker in Norwegian-Greenland Sea sediments. *Journal of Foraminiferal Research*, **24**, 233-240.
- Samthein, M., Jansen, E., Duplessy, J.C., Erlenkeuser, H., Flåtøy, A., Veum, T., Vogelsang, E. & Weinelt, M. 1992.  $\delta^{18}\text{O}$  time-slice reconstructions of meltwater anomalies at Termination I in the North Atlantic between 50 and 80°N. In: E. Bard & W.S. Broecker (eds.), *The Last Deglaciation: Absolute and Radiocarbon Chronologies*, 183-200, NATO ASI Series, I, 2.
- Samthein, M., Jansen, E., Weinelt, M. & 12 others. 1995. Variations in Atlantic surface ocean paleoceanography, 50°-80°N: A time-slice record of the last 30,000 years. *Paleoceanography*, **10**, 1063-1094.
- Schröder, C.J., Scott, D.B. & Medioli, F.S. 1987. Can smaller benthic foraminifera be ignored in paleoenvironmental analysis? *Journal of Foraminiferal Research*, **17**, 101-105.
- Scott, D.B. & Vilks, G. 1991. Benthonic foraminifera in the

- surface sediments of the deep-sea Arctic Ocean. *Journal of Foraminiferal Research*, **21**, 20-38.
- Smart, C.W., King, S.C., Gooday, A.J., Murray, J.W. & Thomas, E. 1994. A benthic foraminiferal proxy of pulsed organic matter paleofluxes. *Marine Micropaleontology*, **23**, 89-99.
- Struck, U. 1995. Stepwise postglacial migration of benthic foraminifera into the abyssal northeastern Norwegian Sea. *Marine Micropaleontology*, **26**, 207-213.
- Struck, U. & Nees, S. 1991. Die Stratigraphische Verbreitung von *Siphotextularia rolshauseni* (Phleger and Parker) in Sedimentkernen aus dem Europäischen Nordmeer. *Geologisches Jahrbuch*, **A128**, 243-249.
- Veum, T., Jansen, E., Arnold, M., Beyer, I. & Duplessy, J.C. 1992. Water mass exchange between the North Atlantic and the Norwegian Sea during the past 28,000 years. *Nature*, **356**, 783-785.
- Vogelsang, E. 1990. Paläo-Ozeanographie des Europäischen Nordmeeres an Hand stabiler Kohlenstoff- und Sauerstoffisotope. *Berichte aus dem Sonderforschungsbereich 313*, **23**, 1-136.



## Appendix 1: SYSTEMATIC TAXONOMY

### *Adercotryma glomerata* (BRADY 1878)

*Lituola glomerata* BRADY, 1878, p. 433, Plate 20, Fig. 1

### *Bolivina* spp.

### *Brizalina* spp.

### *Bulimina marginata* (D'ORBIGNY 1826)

*Bulimina marginata* D'ORBIGNY, 1826, p. 269, Plate 12, Fig. 10-12

### *Bulimina* spp.

### *Buliminoides williamsonianus* (BRADY 1881)

*Bulimina williamsoniana* BRADY, 1881, p.56.

### *Cassidulina* spp.

### *Cassidulina laevigata* (D'ORBIGNY 1826)

*Cassidulina laevigata* D'ORBIGNY, 1826, p. 282, Plate 15, Fig. 4-5

### *Cibicides robertsonianus* (BRADY 1881)

*Truncatulina robertsoniana* BRADY, 1881, p. 65

### *Cibicides* spp.

### *Cibicidoides wuellerstorfi* (SCHWAGER 1866)

*Anomalina wuellerstorfi* SCHWAGER, 1866, p. 258, Plate 7, Fig. 105, 107

### *Cribo stomoides subglobosum* (SARS 1872)

*Lituola subglobosa* SARS, 1872, p. 252

### *Cyclammina* spp.

### *Dentalina pauperata* (D'ORBIGNY 1846)

*Dentalina pauperata* D'ORBIGNY, 1846, p. 46, Plate 1, Fig. 57-58

### *Dentalina* spp.

### *Elphidium* spp.

### *Epistominella exigua* (BRADY 1884)

*Pulvulinina exigua* BRADY, 1884, p. 696, Plate 103, Fig. 13, 14

### *Eponides tumidulus* (BRADY 1884)

*Truncatulina tumidulus* BRADY, 1884, p. 666, Plate 95, Fig. 8

### *Eponides* spp.

### *Fissurina* spp.

### *Fursenkoina fusiformis* (WILLIAMSON 1858)

*Bulimina pupoides* var. *fusiformis* WILLIAMSON, 1858, p. 63, Plate 5, Fig. 129-130

### *Globocassidulina subglobosa* (BRADY 1881)

*Cassidulina subglobosa* BRADY, 1881, p. 60

### *Glomospira gordialis* (JONES & PARKER 1860)

*Trochammina squamata* JONES & PARKER var. *gordialis* JONES & PARKER, 1860, p. 304

### *Gyroidina* spp.

### *Hormosina* spp. (infilled)

### *Islandiella norcrossi* (CUSHMAN 1988)

*Islandiella norcrossi* (CUSHMAN) - Loeblich & Tappan, p. 506, Plate 559, Fig. 3-7

### *Lagena* spp.

### *Lenticulina gibba* (D'ORBIGNY 1839)

*Cristellaria gibba* D'ORBIGNY, 1839, p. 40, Plate 7, Fig. 20-21

### *Marginulina glabra* (D'ORBIGNY 1826)

*Marginulina glabra* D'ORBIGNY, 1826, p. 259, no. 6

### *Neolenticulina peregrina* (SCHWAGER 1866)

*Cristellaria peregrina* SCHWAGER, 1866, p. 245, Plate 7, Fig. 89

### *Nonionellina labradorica* (DAWSON 1860)

*Nonionina labradorica* DAWSON, 1860, p. 191, Fig. 4

### *Nonionella* spp.

### *Oolina* spp.

### *Oridorsalis umbonatus* (REUSS 1851)

*Rotalina umbonata* REUSS, 1851, p. 75, Plate 5, Fig. 35a-c

### *Pullenia bulloides* (D'ORBIGNY 1846)

*Nonionina bulloides* D'ORBIGNY, 1826, p. 293, Plate 5, Fig. 9-10

### *Pyrgo rotalaria* (LOEBLICH & TAPPAN 1953)

*Pyrgo rotalaria* LOEBLICH & TAPPAN, 1953, p. 47, Plate 6, Fig. 5-6

### *Pyrgo* spp.

### *Quinqueloculina seminula* (LINNÉ 1758)

*Serpula seminulum* LINNÉ, 1758, p. 786

**Quinqueloculina spp.**

***Reophax nodulosa* (BRADY 1879)**

*Reophax nodulosa* BRADY, 1879, p. 52, Plate 1, Fig. 9

***Rhizammina algaeformis* (BRADY 1879)**

*Rhizammina algaeformis* BRADY, 1879, p. 39, Plate 4, Fig. 16-17

***Sigmoilopsis schlumbergeri* (BRADY 1884)**

*Planispirina celata* (Costa) - BRADY, 1884, p. 197, Plate 8, Fig. 1-4

***Siphotextularia rolshauseni* (PHLEGER & PARKER 1951)**

*Siphotextularia rolshauseni* PHLEGER & PARKER, 1951, p.4, Plate 1, Fig. 23, 24a-b

***Stetsonia* spp.**

***Subreophax guttifer* (BRADY 1881)**

*Reophax guttifera* BRADY, 1881, p. 49

***Textularia* spp.**

***Triloculina tricarinata* (D'ORBIGNY 1826)**

*Triloculina tricarinata* D'ORBIGNY, 1826, p. 299, Plate 7, Fig. 94

***Trochammina* spp.**

***Uvigerina* spp.**

**agglutinated tube fragments (unidentified)**