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Climatic and hydrographic variability in the late Holocene Skagerrak as deduced from benthic foraminiferal proxies

Klimatische und hydrographische Variabilität im holozänen Sagerrak, abgeleitet aus benthischen Foraminiferen

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TABLE OF CONTENTS

2 MANUSCRIPTS

APPENDIX I

APPENDIX II Data of Core 225514

Appendix III Data of Core 225510

Appendix IV Data of Core 225521

ABSTRACT

Two Holocene sediment cores from the southern flank of the Skagerrak are investigated for the stable oxygen and carbon isotopic composition of benthic foraminiferal tests and faunal assemblages. Core 225514 was recovered from 420 m and Core 225510 from 285 m water depth.

The stable oxygen isotopic composition of *Bulimina marginata* tests in Core 225514 is demonstrated to indicate Skagerrak deep-water renewal during the last 1200 years. Since deep-water renewal is characterized by sudden drops in temperature and salinity, and since $\delta^{18}O$ values reflect both temperature and salinity changes, the influences of the two parameters have to be evaluated separately. By comparing the measured $\delta^{18}O$ variability with a salinity-$\delta^{18}O$ mixing line valid for marine to brackish Scandinavian waters, it was shown that salinity changes are responsible for maximal 9 % of the total $\delta^{18}O$ variability. Correlation of temperature monitoring data with the North Atlantic Oscillation (NAO) index reveals that Skagerrak deep-water renewal is triggered by the negative phase of the NAO. During highly negative index phases very cold and calm conditions prevail over the North Sea. Central North Sea water masses are cooled down strongly and hence reach densities, which are higher than those of the deep Skagerrak water masses. Occasionally, these dense water masses start to cascade into the Skagerrak.

The stable carbon isotopic composition of benthic foraminiferal tests is used to investigate the organic matter flux to the seafloor and the oxygen availability within the sediments as well as to approach microhabitat-corrected vital effects of four species. The $\delta^{13}C$ values of *Uvigerina mediterranea* indicate that the flux of organic matter to the seafloor was relatively constant between AD 1500 and 1950 and increased after AD 1950. We suggest that this increase in organic matter flux to the seafloor results from hydro-climatic variability within the North Sea region. A persistently high NAO index during the 1980s and 1990s enhanced the influx of nutrient-rich water masses through the English Channel. In concurrence with high temperatures, these nutrient-rich water masses allowed for increased primary productivity within the North Sea and presumably also within the Skagerrak-Kattegat region.

The comparison of reconstructed $\delta^{13}C$ gradients of dissolved inorganic carbon (DIC) within the two investigated cores indicates that organic matter remineralization due to respiration was generally enhanced in Core 225514 compared to Core 225510. Since the flux of organic matter to the seafloor was similar at both core sites and both sites were bathed by the same water mass, it is suggested that oxygen availability within the sediments is responsible for the difference. Higher sedimentation rates at Site 225510 result in enhanced carbon burial due to lower oxygen exposure times. The influence of oxygen exposure times on $\delta^{13}C$ values should be especially important in shelf environments because sedimentation rates might be very variable there. Minimum estimates of microhabitat-corrected vital effects with reference to *Globobulimina turgida* are determined for *Hyalinea balthica* (> 1.3 ‰), *Cassidulina laevigata* (> 0.7 ‰), and *Melonis barleeanus* (> 0.7 ‰). *Melonis zaandami* seems to calcify its test close to pore water $\delta^{13}C_{DIC}$.

Faunal investigations produced three clearly distinguishable assemblages for each investigated core. In Core 225514 these assemblages occur consecutively, whereas the assemblages in Core 225510 intermittently change. The chronological order of dominant species in Core 225514 reflects the lateral succession of dominant species in modern surface sediments from the basin margin to the deep Skagerrak. For each dominant seasonal-phytophagous species a Gaussian-like relationship between species frequencies and specific sedimentary total organic carbon (TOC) contents is demonstrated. We propose that the chronological species succession in Core 225514 is the result of increasing sedimentary TOC contents with time, whereas the intermittently changing assemblages in Core 225510 are attributed to the vertically changing position of the Northern Jutland Current.

ZUSAMMENFASSUNG

Zwei holozäne Sedimentkerne von der südlichen Flanke des Skagerraks wurden auf das Verhältnis der stabilen Sauerstoff- und Kohlenstoffisotope benthischer Foraminiferen sowie ihre Faunen-Zusammensetzungen hin untersucht. Kern 225514 stammt aus 420 m Wassertiefe, während Kern 225510 aus 285 m Wassertiefe geborgen wurde.

Es konnte gezeigt werden, dass das Verhältnis der stabilen Sauerstoffe-Isotope von *Bulimina marginata* aus Kern 225514 die Tiefenwasser-Erneuerung im Skagerrak während der letzten 1200 Jahre anzeigt. Da die Tiefenwasser-Erneuerung durch plötzliche Temperatur- und Salinitätsabfälle gekennzeichnet ist und δ^{18}O-Werte sowohl von Temperatur- als auch Salinitätsveränderungen beeinflußt werden, mussten diese beiden Parameter getrennt untersucht werden. Durch den Vergleich der gemessenen δ^{18}O-Variabilität mit einer Salinitäts-δ^{18}O-Mischungslinie, die für brackisch bis marine skandinavische Wassermassen Gültigkeit hat, konnte gezeigt werden, dass Salinitätsschwankungen maximal 9 % der Gesamtvariabilität der gemessenen δ^{18}O-Werte verursachen. Der Vergleich von Temperatur-Langzeitmessungen mit dem Index der Nordatlantischen Oszillation (NAO) zeigte, dass die Tiefenwasser-Erneuerung im Skagerrak von der negativen Phase der NAO ausgelöst wird. In Phasen mit stark negativem NAO-Index sind die Bedingungen über der Nordsee überwiegend ruhig und sehr kalt. Wassermassen der Zentralen Nordsee werden stark abgekühlt und erreichen so höhere Dichten als die Wassermassen im tiefen Skagerrak. Ist eine entsprechende Dichte erreicht, strömen die Wassermassen der Zentralen Nordsee kaskadenartig in die tieferen Bereiche des Skagerraks.

Das Verhältnis der stabilen Kohlenstoffisotope benthischer Foraminiferengehäuse wurde genutzt, um den Fluss organischen Materials zum Meeresboden und die Sauerstoff-Verfügbarkeit in den Sedimenten zu untersuchen. Mikrohabitat-korrigierte Vitaleffekte von vier Arten wurden angenähert. Die δ^{13}C-Werte von *Uvigerina mediterranea* zeigen, dass der Fluss von organischem Material zum Meeresboden zwischen 1500 und 1950 n.Chr. relativ konstant war und nach 1950 n.Chr. zunahm. Es wird vermutet, dass die Zunahme im Fluss von organischem Material zum Meeresboden das Ergebnis hydrographisch-klimatischer Schwankungen in der Nordsee-Region ist. Im Zeitraum der 1980er bis 1990er Jahre war der Einstrom von nährsalzreichen Wassermassen durch den Ärmelkanal in Folge eines andauernd hohen NAO-Indexes verstärkt. Zusammen mit ungewöhnlich hohen Temperaturen führten die nährsalzreichen

Wassermassen zu einer erhöhten Primärproduktion im Bereich der Nordsee und vermutlich auch im Bereich von Skagerrak und Kattegat.

Der Vergleich der rekonstruierten δ^{13}C-Gradienten des gelösten anorganischen Kohlenstoffs (DIC) der beiden untersuchten Kerne lässt vermuten, dass der Abbau organischen Materials auf Grund von Veratmung in Kern 225514 im Vergleich mit Kern 225510 grundsätzlich erhöht war. Da der Fluss von organischem Material zum Meeresboden an beiden Kernstationen vergleichbar war und beide Kernstationen von der gleichen Wassermasse überströmt werden, wird vermutet, dass die Sauerstoff-Verfügbarkeit in den Sedimenten für den Unterschied verantwortlich ist. Höhere Sedimentationsraten an Station 225510 führen zu einem geringeren Abbau von organischem Material, da sie den Zeitraum verringern, in dem dieses Material molekularem Sauerstoff ausgesetzt ist. Der Einfluss dieses zeitlichen Faktors auf den $\delta^{13}C_{DIC}$-Gradienten des Porenwassers ist vermutlich im Bereich des Schelfs besonders wichtig, da die Sedimentationsraten hier sehr variabel sein können. Schätzungen eines minimalen Vitaleffekts für *Hyalinea balthica* (> 1.3 ‰), *Cassidulina laevigata* (> 0.7 ‰) und *Melonis barleeanus* (> 0.7 ‰) werden vorgestellt. Die Kohlenstoff-isotopische Zusammensetzung der Gehäuse von *Melonis zaandami* liegt vermutlich nahe bei der Zusammensetzung des Porenwasser-$\delta^{13}C_{DIC}$.

Untersuchungen der benthischen Foraminiferen-Faunen ergaben je drei klar voneinander unterscheidbare Vergesellschaftungen für die untersuchten Kerne. In Kern 225514 erscheinen die Vergesellschaftungen zeitlich nacheinander, während sie sich in Kern 225510 mehrfach abwechseln. Die chronologische Abfolge der dominanten Arten in Kern 225514 spiegelt die laterale Abfolge dominanter Arten in rezenten Oberflächensedimenten von den Beckenrändern in den tiefen Skagerrak wider. Für jede dominante saisonal-phytophage Art konnte eine Gaußkurven-ähnliche Beziehung zwischen der Artenhäufigkeit und spezifischen gesamtorganischen Kohlenstoff (TOC)-Gehalten der Sedimente nachgewiesen werden. Es wird vermutet, dass die chronologische Artenabfolge in Kern 225514 das Resultat von mit der Zeit zunehmenden sedimentären TOC-Gehalten ist, während die sich mehrfach abwechselnden Vergesellschaftungen in Kern 225510 vermutlich durch die variable vertikale Position des Nördlichen Jutlandstroms bedingt sind.

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1 INTRODUCTION

Benthic foraminiferal research has a comparatively long tradition in marine and climate research. It provides information about a wealth of environmental variables, such as for example bottom water temperatures and circulation changes, polar ice cap coverage, and primary productivity. These environmental variables in turn are basic for the understanding of more complex relationships as for example the global carbon cycle, inter-hemispheric circulation changes or climate change. The demand for understanding what triggers climate fluctuations increased dramatically during the last years when it became evident that human action definitively influences climate. The understanding of the mechanisms involved in past climate changes provides means to estimate future climate evolution. Modelers need “hard data” to evaluate and implement their models, a process that often prompts marine climate research. It was exactly this impulse that initiated my thesis.

In this context, the Skagerrak represents an interesting investigation area, since it is the deepest part of the North Sea. High sedimentation rates and a complex hydrographic system are concentrated within a relatively small area. Therefore, it is particularly suited to gain high-resolution data and to investigate the influence of spatial patchiness as well as historic change. Furthermore, the Skagerrak is part of an area that is strongly influenced by the North Atlantic Oscillation, a weather phenomenon, which might hold responsible for smaller climate fluctuations. Especially calcareous benthic foraminifera proved to have a good fossilization potential and a long geological record. Faunal assemblages as well as the trace elemental and stable isotopic composition of their tests can be used as proxies for various environmental variables. However, correct interpretation of the proxy data requires a detailed knowledge of benthic foraminiferal ecology and of the physico-chemical link between the variable and the proxy. The high resolution of the investigated cores allows us to decipher influences that otherwise are masked or blurred by interference of changing conditions during several 10 to 1000 years. Core 225510 yields sedimentation rates of 0.8 cm/yr (AD 1500 – 1950) and of 5.2 cm/yr during the last 50 years. These high sedimentation rates together with low oxygen penetration depths (maximal 20 mm) in Skagerrak sediments ensure that samples of one centimeter thickness contain foraminifera of only 15 and 2 months, respectively. This is very close to the life cycle of benthic foraminifera and thus exceptionally valuable for deciphering the influences of different variables on benthic foraminiferal $\delta^{13}C$ values and faunal compositions: such as the microhabitat effect, the microhabitat-corrected vital effect, oxygen availability within the sediments, organic matter flux to the seafloor, and the question what determines benthic foraminiferal faunas in the Skagerrak. Benthic foraminiferal $\delta^{18}O$ values provide insight into physical processes influenced by the North Atlantic Oscillation.

1.1 INVESTIGATION AREA

The Skagerrak basin constitutes the easternmost part of the North Sea and connects the brackish Baltic Sea with the open marine conditions of the North Sea. Its shape is irregular with a gently dipping southern flank and a steep northern flank. With more than 700 m water depth the Skagerrak basin is the deepest section of the Norwegian Trench and thus the depocenter of the North Sea. A sill in 270 m water depth separates the Skagerrak from the North Sea (Rodhe, 1987) (Fig. 1).

The modern large-scale circulation system of the Skagerrak has been investigated by Svansson (1975) and Rodhe (1987; 1996; 1998) and is comprehensively

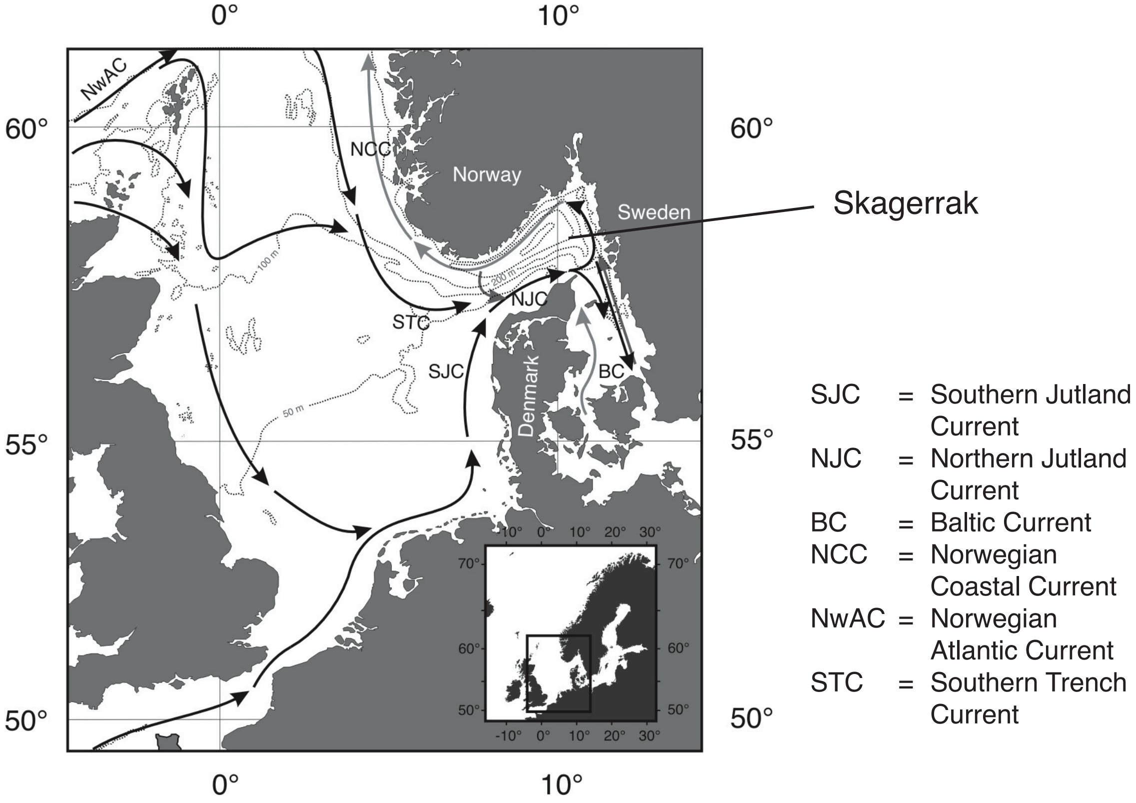

Fig. 1: Map of the investigation area, hydrography following Nordberg (1991), black arrows indicate deep currents, grey arrows indicate shallow currents.

reviewed by Otto et al. (1990). The hydrography of the Skagerrak is characterized by a counterclockwise circulation system reaching down to 400 – 500 m water depth. The Southern Jutland Current (SJC) flowing along the western Danish coast enters the Skagerrak in the southwest. The Southern Trench Current (STC), consisting of water masses from the Norwegian Atlantic Current (NwAC) and Central North Sea Waters, unites with the SJC to form the Northern Jutland Current (NJC). Further to the northeast brackish surface waters of the Baltic Current (BC) are added. The shallow Norwegian Coastal Current (NCC) exits the Skagerrak towards the northwest along the Norwegian coastline. Small amounts of NCC waters are recycled in the western part of the basin. A countercurrent within the western Norwegian Trench imports waters of the North Atlantic.

The different water masses are roughly distinguishable by their salinities. Brackish waters of the BC have salinities between 20 and 30. Deep and intermediate water masses originating from the Central North Sea and the Norwegian Atlantic Current are characterized by salinities of 31 to 35 and > 35, respectively. Stratification results from different salinities and especially from different temperatures (Rodhe, 1987).

Deep-water renewal is triggered by the negative phase of the North Atlantic Oscillation (Hagberg and Tunberg, 2000; Brückner and Mackensen, 2006). On an average, every second to third year strongly cooled Central North Sea water masses reach higher densities than Skagerrak deep waters and occasionally cascade into the basin. Accomplishment takes four to five months (Ljøen and Svansson, 1972; Ljøen, 1981).

Major parts of Skagerrak sediments and nutrients come from areas of the northern and eastern North Sea, whereas only one fourth originates from the southeast (e.g., Van Weering, 1981; Anton et al., 1993; Kuijpers et al., 1993; Lepland and Stevens, 1996; Rodhe and Holt, 1996). The Skagerrak is the main sink for suspended matter from the North Sea (e.g., Van Weering, 1981; Anton et al., 1993; Van Weering et al., 1993; Hass, 1996). Several authors estimate that up to 89% of the organic carbon accumulated in Skagerrak sediments is refractory (Van Weering and Kalf, 1987; Meyenburg and Liebezeit, 1993).

Holocene oceanographic changes have been the focus of various studies (e.g., Stabell and Thiede, 1985; Nordberg, 1991; Conradsen and Heier-Nielsen, 1995; Hass, 1996; Jiang et al., 1997; Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006). Due to different sample resolution there are discrepancies in the timing of the observed shifts. In this thesis I will refer to the timing proposed by Gyllencreutz (2005). Around 10 300 cal BP the Otteid-Stenselva outlet, which connected the Baltic Ice Lake with the Skagerrak, closed and marine waters from the eastern North Sea gained influence within the Skagerrak area (Björck, 1995). The SJC and the NCC, which are basic features of the modern circulation system, formed after the English Channel and the Danish Straits opened around 8300 cal BP. According to Gyllencreutz and Kissel (2006), hydrographic shifts after 8500 cal BP are only variations of the modern circulation system. In contrast to that, Nordberg and Bergsten (1988) and Nordberg (1991) date the onset of the modern circulation system at around 4600 cal BP based on changes in benthic foraminiferal assemblage composition and coccolith faunas. Gyllencreutz and Kissel (2006) conclude that hydrographic shifts at 6300, 4700, 4000, 1500, and 900 cal BP, which are also described elsewhere (e.g., Nordberg, 1991; Conradsen and Heier-Nielsen, 1995; Hass, 1996; Jiang et al., 1997), reflect changes in the predominance between Baltic Sea and North Sea/North Atlantic influence.

1.2 BRIEF REVIEW OF RELEVANT TOPICS

1.2.1 Benthic foraminiferal research in the Skagerrak

In general, benthic foraminiferal assemblage composition and microhabitat mainly depend on the quantity, quality and mode of organic carbon fluxes (e.g., Lutze and Coulbourn, 1984; Mackensen et al., 1985; Gooday, 1988; Corliss and Emerson, 1990; Loubere, 1991; Mackensen et al., 1995; Altenbach et al., 1999; Langezaal et al., 2003) as well as on oxygen concentrations in pore waters. Oxygen availability seems to have considerable influence on microhabitat as well as on assemblage composition and standing stocks if critical thresholds are passed (e.g., Corliss, 1985; Bernhard, 1992; Bernhard, 1993; Sen Gupta and Machain-Castillo, 1993; Jorissen et al., 1995; Loubere, 1997; Jorissen et al., 1998; Kaiho, 1999; Van der Zwaan et al., 1999; den Dulk et al., 2000; Gooday et al., 2000; Geslin et al., 2004).

Benthic foraminiferal assemblage composition in the Skagerrak is suggested to be governed by the complex hydrographic system. Current energy determines the dominant sediment grain-size, which in turn is connected to certain contents of sedimentary organic matter. Hence, prior to approximately AD 1900 assemblage composition is suggested to be related to sediment grain-size, sedimentary organic matter content, “stable” or “unstable” hydrographic conditions, but also to oxygen availability within the sediments (e.g., Nagy and Qvale, 1985; Qvale and Van Weering, 1985; Nordberg, 1991; Troelstra, 1992; Seidenkrantz, 1993; Conradsen et al., 1994; Conradsen and Heier-Nielsen, 1995; Bergsten et al., 1996). Contrary, Subrecent changes in benthic foraminiferal assemblages and standing stocks in Skagerrak and Kattegat are attributed to anthropogenic eutrophication and/or resulting oxygen depletion within bottom water masses (e.g., Moodley et al., 1993; Seidenkrantz, 1993; Alve and Murray, 1995; Alve, 1996). Hass (1997) investigated the benthic foraminiferal assemblages of the Skagerrak with regard to their connection to climate change. He concluded that (1) benthic foraminiferal assemblages are either directly or indirectly influenced by the current system, but that (2) changes in the current system are only partly the result of climate change.

1.2.2 Ratio of stable carbon isotopes in benthic foraminiferal tests

Ongoing research is engaged in the understanding and quantification of the global carbon cycle. The $\delta^{13}C$ composition of dissolved inorganic carbon (DIC) within oceanic waters was and still is subject to various studies because relative changes in the net organic carbon burial are needed to create global CO_2 balance models (according to for example Compton and Mallinson, 1996).

The $\delta^{13}C_{DIC}$ of marine waters is mainly determined by isotope fractionation due to productivity and degradation processes. The influence of carbonate dissolution and continuous ocean-atmosphere exchange are considered as minor compared to the influence of organic carbon production and degradation on $\delta^{13}C_{DIC}$ of deep ocean waters (e.g., Kroopnick, 1985; Broecker and Maier-Reimer, 1992). Primary production due to photosynthesis preferentially incorporates ^{12}C and discriminates against ^{13}C (Sackett et al., 1965; Degens et al., 1968). This fractionation results in ^{13}C enriched surface waters. Particulate organic matter sinking through the water column is continuously subject to degradation, which results in increasing enrichment of ^{12}C in deeper water masses (e.g., Kroopnick, 1985; brief overview in Rohling and Cooke, 1999). Since the degradation of organic matter within the water column consumes oxygen, the $\delta^{13}C_{DIC}$ composition parallels apparent oxygen utilization within the oceans (e.g., Kroopnick, 1980; Kroopnick, 1985). These processes provide the basis on which reconstructions of ventilation, age and circulation changes of (bottom) water masses become possible, as for example by stable isotope proxies of foraminifera.

Organic matter degradation due to respiration results in a strong $\delta^{13}C_{DIC}$ decrease within the first centimeters of the sediment (McCorkle, 1988). The $\delta^{13}C$ values of epi- and infaunal benthic foraminiferal species are suggested to reflect this pore water geochemistry gradient (e.g., Woodruff et al., 1980; Belanger et al., 1981; Grossman, 1984a; Grossman, 1984b; Grossman, 1987; McCorkle and Keigwin, 1990; Rathburn et al., 1996; McCorkle et al., 1997; Mackensen et al., 2000; Tachikawa and Elderfield, 2002; Schmiedl et al., 2004; Fontanier et al., 2006; Mackensen, 2007). Although living individuals of one species usually occur over a broader sediment depth-range, species-specific $\delta^{13}C$ values vary little at one location (e.g., McCorkle and Keigwin, 1990; Rathburn et al., 1996; McCorkle et al., 1997; Tachikawa and Elderfield, 2002; Holsten et al., 2004; Mackensen and Licari, 2004; Schmiedl et al., 2004; Mackensen, in press). Unfortunately, some or probably most benthic foraminifera do not calcify in equilibrium but show offsets to the $\delta^{13}C_{DIC}$ of the ambient waters (e.g., McCorkle and Keigwin, 1990; Rathburn et al., 1996; Schmiedl et al., 2004; Fontanier et al., 2006; Schmiedl and Mackensen, 2006; Brückner and Mackensen, submitted). Usually, these offsets are summarized as “vital effects” (Urey et al., 1951). It is suggested that growth related changes in metabolism and in kinetic fractionation during calcification are responsible for these offsets (e.g., Vinot-Bertouille and Duplessy, 1973; Berger et al., 1978; Erez, 1978; McConnaughey, 2003).

The $\delta^{13}C$ values of epifaunal or shallow infaunal foraminifera, as for example *Cibicidoides wuellerstorfi*, are commonly used to reconstruct changes in bottom water circulation, bottom water mass characteristics, and glacial-interglacial ocean chemistry shifts (e.g., Shackleton, 1977; Belanger et al., 1981; Graham et al., 1981; Broecker, 1982; Duplessy et al., 1984; Woodruff and Savin, 1985; Loubere, 1987; Curry et al., 1988; Duplessy et al., 1988; Charles and Fairbanks, 1990; Raymo et al., 1990; Mackensen et al., 1993; Lynch-Stieglitz and Fairbanks, 1994; Sarnthein et al., 1994; Bickert and Wefer, 1996; Curry and Oppo, 2005). The $\delta^{13}C$ values of shallow infaunal species or the $\delta^{13}C$ difference between epifaunal and infaunal living species were shown to reflect the organic matter flux to the seafloor (e.g., Zahn et al., 1986; Loubere, 1987; McCorkle and Keigwin, 1990; Schilman et al., 2003; Holsten et al., 2004; Fontanier et al., 2006; Schmiedl and Mackensen, 2006; Mackensen, 2007). The $\delta^{13}C$ difference between epifaunal and deep infaunal living foraminifera records most of the effect that oxygen driven organic matter decay exerts on pore water $\delta^{13}C_{DIC}$ composition (e.g., McCorkle and Keigwin, 1990; McCorkle et al., 1997; Holsten et al., 2004; Schmiedl and Mackensen, 2006). Based on the assumption that organic matter decay in oxygen limited sediments is mainly controlled by oxygenation of the overlying water mass (McCorkle and Keigwin, 1990), Schmiedl and Mackensen (2006) developed a calibration for the $\delta^{13}C$ difference between *Cibicidoides wuellerstorfi* and *Globobulimina affinis* and the bottom water oxygen content in the western Arabian Sea.

The $\delta^{13}C$ values of especially epifaunal and shallow infaunal species might be affected by the so-called carbonate ion effect (Bemis et al., 1998; Mackensen and Licari, 2004; Schmiedl et al., 2004; Schmiedl and Mackensen, 2006), an effect that is known to influence the stable isotopic composition of planktic foraminifera. Spero et al. (1997) demonstrated that planktic foraminiferal shell carbonate decreased in $\delta^{13}C$ and $\delta^{18}O$ with increasing pH and $[CO_3^{2-}]$. Mackensen and Licari (2004) proposed a threshold of about 15 % carbonate content in sediments under high productivity regimes below which benthic foraminiferal tests are enriched in ^{13}C due to a $[CO_3^{2-}]$ effect.

1.2.3 Ratio of stable oxygen isotopes in benthic foraminiferal tests

The $\delta^{18}O$ ratio in marine waters is controlled by the global water cycle, i.e. evaporation, water vapor in the atmosphere, precipitation, and the amount of water stored in global ice caps. During evaporation equilibrium and kinetic isotope fractionation result in a depletion of ^{18}O in the vapor phase. Due to a Rayleigh fractionation process precipitation increasingly enhances ^{18}O depletion within the atmospheric vapor, mainly as a result of equilibrium fractionation. During time periods in which extensive global ice sheets exist, large amounts of ^{16}O are stored as continental ice while ^{18}O is relatively enriched in the oceans. Shackleton (1967) demonstrated that the $\delta^{18}O$ variability of ocean waters mainly reflects fluctuations in the global ice volume.

Evaporation, precipitation, and climate determine the $\delta^{18}O$ value of the ocean but also its salt content. During ice ages, when global ice caps show maximum extensions and the sea level is low, $\delta^{18}O$ values of marine waters as well as the salt content of the ocean are high. This is why there is a linear relationship between the salt content and the $\delta^{18}O$ ratio of marine waters (Epstein and Mayeda, 1953). However, the slope of this relationship is regionally different, although the general connection – higher $\delta^{18}O$ values parallel higher salt contents – is mostly applicable. Mikalsen and Sejrup (2000) constructed a $\delta^{18}O$-salinity mixing line from Sognefjord waters, which they suggest to also describe $\delta^{18}O$-salinity properties of deep Skagerrak water masses:

$$\delta_w \text{ (SMOW)} = 0.31 * S - 10.68,$$

in which δ_w is the oxygen isotope composition of water and S its salinity.

The composition of stable oxygen isotopes in marine waters is discussed in detail for example in Epstein and Mayeda (1953) and Craig and Gordon (1965); overviews are given in Hoefs (1996) and Sharp (2007).

Urey et al. (1947) published that there is a temperature-dependent isotope fractionation between calcite and the water it precipitated from, in so far as at lower temperatures relatively more ^{18}O is incorporated into the precipitating carbonate. Following the first publications of temperature equations for the calcite-water system by McCrea (1950) and Epstein et al. (1951) soon tools for paleoceanographic reconstruction were developed (e.g., Emiliani, 1955; Shackleton, 1967; Shackleton and Opdyke, 1973; Shackleton, 1977; Imbrie et al., 1984; Prell et al., 1986). Emiliani (1955) compared $\delta^{18}O$ values of planktic and benthic foraminifera with insolation curves and continental records and thus demonstrated a close relationship with climate cycles. Oxygen isotope stratigraphy was developed (e.g., Emiliani, 1955; Shackleton and Opdyke, 1973; Prell et al., 1986). Meanwhile, new and more developed temperature equations were published (e.g., Epstein and Mayeda, 1953; O'Neil et al., 1969; Shackleton, 1974; Erez and Luz, 1983; review in Bemis et al., 1998). The most popular of these equations is the one Epstein et al. (1953) provided (see Wefer and Berger, 1991). Zahn and Mix (1991) and Mackensen et al. (2001) achieved best results for Recent deep and bottom water mass characterization by using the equation of Erez and Luz (1983). Bemis et al. (1998 and references herein) documented that this equation produced the best fit for temperature reconstructions derived from $\delta^{18}O$ values of *Uvigerina peregrina*. Hence, and because the equation of Erez and Luz (1983) produced a temperature range similar to Recent Skagerrak minimum and maximum temperatures, we used their equation for reconstruction:

$$t = 17.0 - 4.52\ (\delta^{18}O_c - \delta^{18}O_w) + 0.03\ (\delta^{18}O_c - \delta^{18}O_w)^2,$$

in which t is the estimated bottom water temperature, $\delta^{18}O_c$ is the $\delta^{18}O$ value of shell carbonate, and $\delta^{18}O_w$ is the $\delta^{18}O$ value of sea water.

Stable isotopic measurements on benthic foraminiferal tests in Holocene Skagerrak sediments were carried out for example by Erlenkeuser (1985), Conradsen and Heier-Nielsen (1995), and Hass (1997). Nordberg and Filipsson (2003) and

Filipsson and Nordberg (2004) published benthic foraminiferal isotope data from the Gullmar Fjord, which they correlated with the North Atlantic Oscillation Index.

1.2.4 The North Atlantic Oscillation

The North Atlantic Oscillation (NAO) describes an atmospheric variability pattern over middle and high latitudes of the Northern Hemisphere, which exerts strong influence on sea level pressure and hemispheric inter-annual temperature (e.g., Hurrell, 1996; Hurrell and van Loon, 1997; Dickson et al., 2000). The NAO index is the mathematical description of the normalized sea level pressure differences between the Icelandic low (usually Stykkisholmur or Akureyri) and the Azores high (usually Ponta del Gada) (e.g., Hurrell, 1995; Dickson et al., 1996). As it represents the strongest forcing (e.g., Hurrell, 1995), the winter index is mostly used for correlation.

The weather over northern Europe is strongly influenced by the NAO variability. During mainly positive NAO index winters strong westerlies result in stormy and relatively warm conditions over northern Europe. Contrary, during mainly negative NAO index winters the weather over northern Europe is calm and very cold. The westerlies are weaker and take a more southerly track over middle and southern Europe to the Mediterranean (e.g., Hurrell, 1995; Koslowski and Glaser, 1999; Deser, 2000; Slonosky et al., 2000; Hurrell et al., 2003; Jones et al., 2003). Hence, the NAO positively correlates with temperature and precipitation over Europe, although the quality of this correlation varies with time and region (Hurrell and van Loon, 1997; Chen and Hellström, 1999; Slonosky et al., 2000; Jones et al., 2003).

Several studies based on different proxies show that the Skagerrak and the Baltic Sea are NAO sensitive areas (e.g., Belgrano et al., 1998; Koslowski and Glaser, 1999; Hagberg and Tunberg, 2000; Nordberg et al., 2000; Filipsson and Nordberg, 2004). Koslowski and Glaser (1999) discovered a negative correlation between sea ice extension in the south-western Baltic Sea and the state of the NAO. Nordberg et al. (2000) and Filipsson and Nordberg (2004) discussed a negative correlation between bottom water oxygenation in the Gullmar Fjord and the NAO. Hagberg and Tunberg (2000) demonstrated that Skagerrak deep-water temperatures during the last 30 years positively correlate with the NAO and thus provided the basis for the deep-water renewal manuscript presented in this thesis.

1.3 AIM AND OBJECTIVES

This study is part of the IBSEN (Integrated Baltic Sea Environmental Study) project, which is aimed at the reconstruction of the two strongest climatic signals during the last 1000 years in the Baltic Sea by modeling: the Medieval Warm Period (AD 1130 – 1170) and the Little Ice Age at the sun spot Maunder Minimum (AD 1670 – 1710). Benthic foraminiferal reconstructions of environmental and hydrographic conditions bracketing the salinity gradient of the transitional area between North Sea and Baltic Sea were planned to provide the basis for correlations between climate forcing, hydrography and salinity changes. Furthermore, verification of the modeling results was intended. Unfortunately, only two out of 24 cores, Core 225514 and Core 225510, from the Skagerrak exhibited a chronological age succession, so that the plan of sampling the salinity gradient between North Sea and Baltic Sea had to be dropped. Core 225514, recovered from the southwestern flank of the Skagerrak, is 405 cm long and contains sediments of approximately the last 4000 years. Core 225510 also originates from the southern Skagerrak flank, although from further east than Core 225514. Sedimentation rates are much higher in Core 225510 than in Core 225514 so that 544 cm of core length contain sediments of the last approximately 500 years. Core 225521 from the Kattegat was investigated for its benthic foraminiferal content when it became evident that bulk foraminifera sampled for dating all indicated ages around 1200 +/- 360 AMS ^{14}C years. The data of Core 225521 is presented in the appendix. Since only two cores from the Skagerrak but no core from the transitional area between North Sea and Baltic Sea provided useful data, the objectives of this thesis had to be adjusted as follows:

- To investigate if benthic foraminiferal assemblage changes in the Skagerrak as well as changes in stable carbon and oxygen isotopes can be related to climate change and/or the North Atlantic Oscillation (NAO) being an important weather phenomenon in this area.

- To describe the processes, which mediate between climate forcing and/or the NAO and benthic foraminiferal assemblage composition, δ^{13}C, and δ^{18}O values of benthic foraminiferal tests.

- If no connection to climate forcing and/or the NAO is detectable, to investigate what determines the observed proxy values.

The above objectives are addressed in three manuscripts, one of which is published (manuscript I), whereas manuscript II is in print and manuscript III is in review.

The first manuscript, “Deep-water renewal in the Skagerrak during the last 1200 years triggered by the North Atlantic Oscillation: evidence from benthic foraminiferal $\delta^{18}O$”, aims for linking benthic foraminiferal $\delta^{18}O$ values and the NAO, since several recent publications show that the NAO influence is detectable in various environmental variables. By comparing hydrographic monitoring data of the last 50 years with the NAO index, we were able to show that positive correlations between deep-water temperature as well as salinity and the NAO exist. Benthic foraminiferal $\delta^{18}O$ is long since used to reconstruct deep-water temperatures and proved appropriate to reflect the NAO induced deep-water renewal events during historic times.

“Organic matter rain rates, oxygen availability, and vital effects from benthic foraminiferal $\delta^{13}C$ in the historic Skagerrak, North Sea” explores benthic foraminiferal $\delta^{13}C$ variability of several species during the last 500 years in the Skagerrak. The $\delta^{13}C$ values of *Uvigerina mediterranea* indicate that organic matter flux was similar at both investigated core sites. Between AD 1500 and 1950 the organic matter flux varied around a mean value and increased after AD 1950. We suggest that this increase is related to an exceptional high positive NAO index phase, which modified hydro-climatic conditions within the North Sea and resulted in enhanced primary productivity. Additionally, differences in reconstructed $\delta^{13}C$ gradients of dissolved inorganic carbon (DIC) at the two core sites are observed. Since the organic matter flux was similar at both core sites and both sites experienced the same oxygen content within the overlying water mass, the differences in $\delta^{13}C_{DIC}$ gradients were attributed to differing oxygen availabilities within the sediments. We propose that oxygen exposure times are reduced if sedimentation rates are high. Minimum estimates of microhabitat-corrected vital effects for *Hyalinea balthica* (> 1.3 ‰), *Cassidulina laevigata* and *Melonis barleeanus* (> 0.7 ‰), and *Melonis zaandami* (approx. 0 ‰) with reference to *Globobulimina turgida* are calculated.

The manuscript “Benthic foraminifera and relative organic matter contents in Holocene Skagerrak sediments, NE North Sea” links benthic foraminiferal assemblage composition to the sedimentary organic matter content. By comparing the modern spatial distribution of dominant foraminifera with surficial total organic carbon contents (TOC), we demonstrate that the dominant species prefer specific amounts of sedimentary TOC. Species frequency distribution follows a Gaussian-like curve if plotted against respective TOC contents. All dominant Holocene species, except for *Bolivina skagerrakensis*, were classified as seasonal-phytophagous species, which prefer fresh organic matter if present, but are able to cover much of their energy-demand by altered organic matter if necessary.

2.1 MANUSCRIPT I

The Holocene 16,3 (2006) pp. 331-340

Deep-water renewal in the Skagerrak during the last 1200 years triggered by the North Atlantic Oscillation: evidence from benthic foraminiferal $\delta^{18}O$

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Abstract: Benthic foraminiferal tests of a sediment core from southwestern Skagerrak (northeastern North Sea, 420 m water depth) were investigated for their ratio of stable oxygen isotopes. During modern times sudden drops in temperature and salinity of Skagerrak deep waters point to advection-induced cascades of colder and denser central North Sea waters entering the Skagerrak. These temperature drops, which are recorded in benthic foraminiferal tests via the stable oxygen isotopic composition, were used to reconstruct deep-water renewal in the Skagerrak. In a second step we will show that, at least during the last 1200 years, Skagerrak deep-water renewal is triggered by the negative phase of the North Atlantic Oscillation (NAO). The NAO exerts a strong influence on the climate of northwestern Europe. It is currently under debate if the long-term variability of the NAO is capable of influencing Northern Hemisphere climate on long timescales. The data presented here cannot reinforce these speculations. Our data show that most of the 'Little Ice Age' was dominated by comparably warm deep-water temperatures. However, we did find extraordinary strong temperature differences between central North Sea waters and North Atlantic water masses during this time interval.

Key words: Benthic foraminifera, NAO, $\delta^{18}O$, deep-water renewal, Holocene, Skagerrak, North Sea.

Introduction

Hurrell *et al.* (2003) describe the North Atlantic Oscillation (NAO) as the most prominent and recurrent pattern of atmospheric variability over middle and high latitudes of the Northern Hemisphere. About one-third of the total variance in sea-level pressure and of the hemispheric interannual temperature variance is explained by this large-scale variability of atmospheric masses (Hurrell, 1996; Hurrell and van Loon, 1997; Dickson *et al.*, 2000).

The NAO index is the mathematical description of the normalized sea-level pressure differences between Icelandic low (usually Stykkisholmur or Akureyri) and the Azores high (usually Ponta del Gada) (eg, Hurrell, 1995; Dickson *et al.*, 1996). Its winter index is often used for correlation as it represents the season of strongest forcing (Hurrell, 1995). During mainly positive NAO index winters the weather over northern Europe is warm and stormy due to strong westerlies bringing comparably high temperatures from over the open ocean. Mainly negative NAO index winters result in weaker westerlies taking a more southerly track over middle and southern Europe to the Mediterranean Sea while Scandinavia and northern Europe are influenced by extremely cold and calm conditions coming from the north (eg, Hurrell, 1995; Koslowski and Glaser, 1999; Deser, 2000; Slonosky *et al.*, 2000; Hurrell *et al.*, 2003; Jones *et al.*, 2003).

The NAO positively correlates with temperature and precipitation over Europe. Strongest temperature correlation generally is found over southern Scandinavia between September and March (eg, Hurrell, 1995; Chen and Hellström, 1999; Jones *et al.*, 2003). The strength of the correlation between NAO index and climate, however, varies with time and region (Hurrell and van Loon, 1997; Chen and Hellström, 1999; Slonosky *et al.*, 2000; Jones *et al.*, 2003). As recent studies prove, the Skagerrak and its surroundings seem to be a NAO

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sensitive area. Koslowski and Glaser (1999) correlate winter ice severity in the western Baltic Sea with the state of the NAO. Strong westerlies (positive NAO) cause weak ice production whereas weak westerlies (negative NAO) allow strong ice formation. Moreover, the NAO is known for influencing the marine ecosystem, as comprehensively reviewed by Drinkwater *et al.* (2003). These authors conclude that 'the impacts of the NAO are generally mediated through local changes in the physical environment, such as winds, ocean temperatures, and circulation patterns', which is also the case in the surroundings of the Skagerrak. Based on changing benthic foraminiferal faunas in the Gullmar Fjord/Swedish west coast, Nordberg *et al.* (2000) and Filipsson and Nordberg (2003) differentiated time intervals of high and low bottom-water oxygenation, which depend on the frequency of bottom-water renewal. They found a negative causal relation between the NAO and the oxygenation state of bottom waters. During positive NAO phases with prevailing westerly winds, upwelling of oxygen-rich bottom water in the Skagerrak is prevented. The upwelling, however, is a prerequisite for the deep water-exchange in the fjord. Hagberg and Tunberg (2000) demonstrated that deep-water renewal in the Skagerrak positively correlates with the NAO during the last 30 years. They found 0- to 2-year lags between NAO index and temperature evolution. We will show that the correlation between Skagerrak deep-water renewal and the NAO has existed at least for the last 50 years and presumably even for the last 1200 years.

Currently, it is speculated that the NAO remained for longer time spans in mainly one phase. These time periods, in which the NAO possibly stayed in predominantly one phase are thought to correlate with historically known climate periods, such as the 'Little Ice Age' (LIA; AD 1350–1900, following Hass, 1996) or the 'Mediaeval Warm Period' (MWP, AD 700–1350, following Hass, 1996). The climax of 'Little Ice Age' winters over northern Europe seems to be characterized by calm and extremely cold conditions, possibly a result of predominantly negative NAO index values (Koslowski and Glaser, 1999; Shindell *et al.*, 2001). The 'Mediaeval Warm Period' winters are suggested to be influenced by predominantly positive NAO index values since they were comparably warm, humid and stormy (Shindell *et al.*, 2001; Cook, 2003). Rimbu *et al.* (2003) suggested 'a continuous weakening of a Northern Hemisphere atmospheric circulation pattern similar to that of the Arctic/North Atlantic Oscillation'. They assumed that Arctic Oscillation/NAO possibly plays a role in generating millennial-scale sea-surface temperature trends, reconstructed via alkenone analysis.

The goals of this study are (1) to demonstrate that δ^{18}O values of benthic foraminiferal tests can be used to reconstruct Skagerrak deep-water renewal, (2) to present a feasible mechanism to explain the connection between the NAO and deep-water renewal in the Skagerrak, and (3) to investigate whether the NAO influences climate in the Skagerrak region on more than the short-term level. For comparison of δ^{18}O values and the NAO, we used the updated annual NAO index of Hurrell (1995), which is based on sea-level pressure differences between Stykkisholmur/Iceland and Lisbon/Portugal.

Oceanographic settings

The Skagerrak basin, more than 700 m deep, forms the deepest part of the Norwegian Trench and therefore acts as main depocentre for the North Sea (Figure 1). It has an irregular elongate shape with a steep northern and a more gently dipping southern flank. The Recent sedimentation process started after the retreat of the last glacial maximum glaciers (Stabell and Thiede, 1985). Holocene sediments overlie unconformably an eroded Mesozoic basement (eg, Stabell and Thiede, 1985; von Haugwitz and Wong, 1993).

Major parts of the sediments are injected via the Southern Jutland Current (SJC) originating from various areas of the southern and eastern North Sea (Lepland and Stevens, 1996). Sediments of the second sediment source of the Skagerrak, the northern North Sea, are transported via the Southern Trench Current (STC), which is fed by several branches of the eastern branch of the Norwegian Atlantic Current (NwAC) and northern North Sea waters (eg, Svendsen *et al.*, 1991).

The water masses of SJC and STC entering the Skagerrak in mid-to upper water depth (Rydberg *et al.*, 1996) are united in the Northern Jutland Current (NJC), which represents the southern branch of the cyclonic circulation of the Skagerrak. Continuing to the east, superficial brackish water masses of the Baltic Current (BC) mix forming the Norwegian Coastal Current (NCC). Outflowing water masses follow the morphology of the Norwegian Trench along the Norwegian coastline. Smaller amounts of NCC water masses are recycled in the western part of the Skagerrak. The cyclonic circulation of the Skagerrak reaches to 400–500 m depth, ie, far below the sill depth (270 m) of the Norwegian Trench (Rodhe, 1987).

The different currents contributing to Skagerrak water masses can be distinguished by their salinities (Rydberg *et al.*, 1996). The BC surface waters show salinities between 20 and 30 psu. The NJC, composed of a mixture of various North Sea as well as NwAC waters entering the Skagerrak from west and southwest, has values between 31 and 35 psu, whereas the deeper North Atlantic water-inflows from the counter current system of the Norwegian Trench possess salinities of > 35 psu. The salinity of Skagerrak surface waters

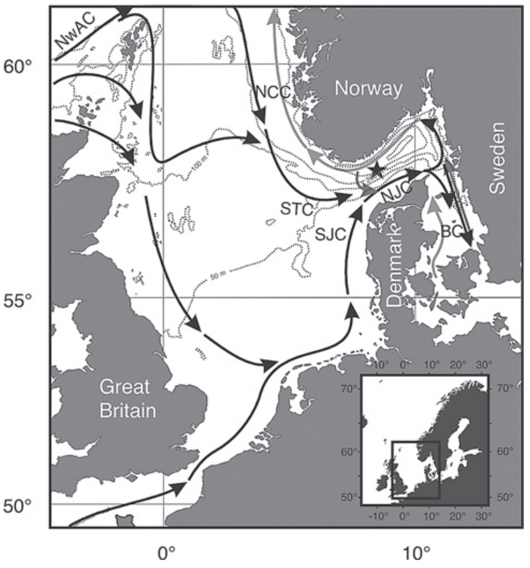

Figure 1 Map of the area of investigation, core location denoted by a star, hydrography following Nordberg (1991), solid arrows indicating deep currents, grey arrows indicating shallow currents. NwAC, Norwegian Atlantic Current; STC, Southern Trench Current; SJC, Southern Jutland Current; NJC, Northern Jutland Current; BC, Baltic Current; NCC, Norwegian Coastal Current

generally varies between 29 and 31 psu whereas the deeper water masses show values around 35 psu (Rodhe, 1987).

Deep-water renewal occurs during cold winters when the North Sea waters of the central North Sea Plateau are strongly cooled (Ljøen and Svansson, 1972). The strong cooling of central North Sea water masses results in water densities higher than in the Skagerrak and also higher than the densities of North Atlantic waters in the Norwegian Trench. Ljøen (1981) demonstrated that these high-density water masses cascade into the deeper parts of the Skagerrak, starting in January to February, on average every second to third year. A complete renewal seems to be accomplished in about four to five months.

Material and methods

Gravity core 225514 of 405 cm length was recovered with RV *Alkor* on Cruise 159. The sampling location (57°50′260″ N, 8°42′327″ E) is situated on the southern slope of the Skagerrak in 420 m water depth (Figure 1). The recovered sediments consist of olive-green clayey mud that frequently shows streaks of light grey colour (15–85 cm, 135–406 cm) throughout.

The core generally was sampled every 5 cm. To enhance the resolution of the youngest part of the core, in the uppermost 15 cm every centimetre was sampled and down to 80 cm core depth every second to third centimetre was sampled. Slices of 1-cm thickness were freeze dried and subsequently wet sieved to obtain the sediment fraction between 125 μm and 2 mm, which was used for all analyses described below. Bottom water from directly above the sediment/water interface was derived from one of the multiple corer tubes of sampling location 242940 (57°40′52″ N, 7°10′0″ E, 315 m water depth), which was sampled on RV *Poseidon* Cruise PO 282.

Isotopic investigation

The stable oxygen isotopic composition of tests of selected benthic foraminiferal species was determined with a Finnigan MAT 251 isotope ratio gas mass spectrometer directly coupled to an automatic carbonate preparation device (Kiel II). All values are given in δ-notation versus Vienna Pee Dee Belemnite (VPDB). For calibration to the VPDB scale the international standard NBS 19 was used. Overall precision of measurements based on repeated analyses of an internal laboratory standard (Solnhofen limestone) over a 1-yr period was better than 0.08‰.

For the determination of bottom water $\delta^{18}O$ of multiple corer 242940, 7 ml water were equilibrated in 13 ml headspace with CO_2 gas by using an automated Finnigan equilibration device. Isotope equilibrium in the CO_2–H_2O system was attained by shaking for 430 min at 20°C. The equilibrated gases were purified and transferred to an online-connected Finigan MAT Delta-S mass spectrometer. Isotope measurements were calibrated against Vienna Standard Mean Ocean Water (VSMOW) and Vienna Standard Light Antarctic Precipitation (VSLAP). Two replicates, including preparation and measurement, were run. Results are reported in δ-notation relative to the VSMOW scale with an external reproducibility of ±0.03‰.

Though $\delta^{18}O$ values of multiple species were measured, we only present values derived from *Bulimina marginata*, *Melonis barleeanum* and *Uvigerina mediterranea*. Individuals of these species seemed to be the least affected by carbonate dissolution and re-precipitation as inferred from microscopic and SEM investigations.

Palaeotemperature calculations were done applying the equation of Erez and Luz (1983):

$$t = 17.0 - 4.52(\delta^{18}O_c - \delta^{18}O_w + 0.03(\delta^{18}O_c - \delta^{18}O_w)^2$$

where t is the estimated bottom water temperature, $\delta^{18}O_c$ is the $\delta^{18}O$ value of shell carbonate, and $\delta^{18}O_w$ is the $\delta^{18}O$ value of sea water. Following Gonfiantini *et al.* (1995) the $\delta^{18}O$ value of bottom water (0.35‰ VSMOW) was converted to PDB scale by subtracting 0.27‰. Paleotemperatures were calculated without changing δ_w.

Though originally developed for planktic foraminifers the equation proved not only to be valid for benthic foraminifers but also as best fit to estimate palaeotemperatures of *Uvigerina peregrina* stable oxygen isotopic values (Bemis and Spero, 1998, and references herein). *Uvigerina peregrina*, which calcifies its test in equilibrium to bottom water $\delta^{18}O$ and therefore is used as approximation for equilibrium calcite, is not part of the benthic foraminiferal fauna of core 225514. Therefore we used individuals of *B. marginata*, which calcify their tests with an offset to bottom water $\delta^{18}O$, the so called 'vital effect'. Wilson-Finelli *et al.* (1998) determined an average value of 0.28‰ as being the vital effect of *B. marginata*. For determination of this vital effect these authors used the temperature equation of Shackleton (1974). Since the temperatures presented in this publication are based on the equation of Erez and Luz (1983) we recalculated the vital effect determined by Wilson-Finelli *et al.* (1998) using the equation of Erez and Luz (1983). The resulting vital effect of 0.24‰ was subtracted from measured $\delta^{18}O$ values of *B. marginata* prior to temperature calculation.

Age model

The age model for the investigated core was deduced from core III KAL (Hass, 1996) by faunal comparisons. Core III KAL originates from the southern flank of the Skagerrak and was taken only 150 m away from the location of core 225514.

Initially, it was intended to date core 225514 by AMS ^{14}C dates on bulk benthic foraminiferal tests (Table 1). Measurements were done at the Leibniz-Labor for Radiometric Dating and Isotope Research in Kiel. Measured values were corrected for the natural isotope fractionation. Calibration and transformation to calendar years was done by applying the radiocarbon calibration program Calib rev. 4.3 (Stuiver and Braziunas, 1989). We used the marine model calibration curve (Stuiver and Braziunas, 1989) together with the global reservoir age of about 400 years ($\Delta R = 0$). By comparing dominant benthic foraminiferal species of core 225514 with the dominant species described by Hass (1997), it became obvious that the faunas showed excellent co-variation if plotted against core depth (Figure 2). The corresponding age models, however,

Table 1 Conventional and to calendar years calibrated AMS ^{14}C dates on bulk benthic foraminiferal tests of core 225514

Core depth (cm)	AMS ^{14}C age	Stand. dev. AMS ^{14}C age	Cal. BP
0–3	(> AD 1954)		0
9–12	810	30	460
39–42	1155	30	690
69–72	1205	30	730
104–107	1165	30	1310
134–137	2710	+30/ − 35	2350
154–157	2755	45	2450
249–252	4280	45	4400
309–312	6400	45	6090
374–377	5680	45	6870

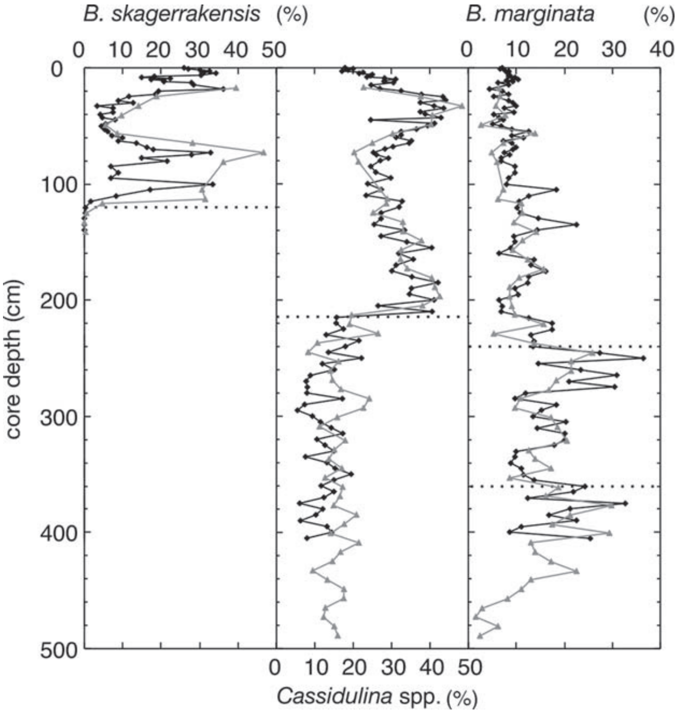

Figure 2 Core depth to frequency relation of selected species in percent of the total benthic foraminiferal fauna (solid diamonds) in comparison with frequencies Hass (1996) observed in core III KAL (grey triangles). Ordinates correspond to core 225514 since core III KAL presumably misses the top (last 17 cm)

diverged by up to 2500 years (Figure 3). There are several technical reasons why AMS ^{14}C based age models for deep Skagerrak sediments could be erroneous. Since there was not sufficient material for mono-specific dating, we were forced to use bulk benthic foraminifera. Heier-Nielsen *et al*. (1995) dated single species of benthic foraminifera as well as mollusc shells from the same depth intervals of sediment cores from the Danish Skagerrak slope. They found age discrepancies of up to 5000 years, which were attributed to re-sedimentation of single benthic foraminiferal species, as for example, species of the Miliolidae group. The conversion to calendar years could be another reason for incorrect age determinations by AMS ^{14}C measurements, since radiocarbon plateaus could cause errors of up to several centuries. One of these radiocarbon plateaus, for example, exists around 2500 cal. BP (calendar years before present) (Guilderson *et al*., 2005).

Though we only present results of the last 1000 years or 190 cm, which correspond to the time range for which NAO reconstructions exist, core 225514 spans 405 cm. To prove that faunal compositions of core III KAL and 225514 are very close and that therefore it is valid to transfer the age model of Hass (1996) to core 225514, Figures 2 and 3 show the whole core depth.

Hass (1996) determined the age model for core III KAL based on an advanced ^{210}Pb method (Erlenkeuser, 1985a), which allows dating until approximately 3500 cal. BP. Sediments younger than 160 years were dated using the 'excess ^{210}Pb' method. Older sediments were dated with help of the '^{226}Ra supported ^{210}Pb' method (^{210}Pb$_{sup}$) following Erlenkeuser (1985a). For detailed information about the method and the model see Hass (1996).

Comparisons of dominant benthic foraminiferal species were used to tie the age model of core III KAL (Hass, 1996, 1997) to core 225514. The distance between both core locations accounts for only 150 m and both cores originate from similar water depths (225514 from 420 m, III KAL from 450 m water depth). Comparisons of the most important benthic foraminiferal species revealed very similar frequencies in corresponding depth intervals (Figure 2) if the top of core III KAL was shifted down-core for 17 cm. Obviously, core III KAL misses the top, possibly because of the loss of the topmost sediments during the sampling procedure.

Control points for the correlation between both cores were chosen where major changes in the three most frequent species, *Bulimina marginata*, *Cassidulina* spp., and *Bolivina skagerrakensis* occur, that is at 120, 215, 240 and 360 cm core depth. Generally, these major changes coincide to the centimetre; the first occurrence of *B. skagerrakensis* only seems to be earlier in core III KAL (126 cm core depth) than in the investigated one (120 cm core depth). This difference can be explained by the fact that the sampling interval of Hass (1996) is larger than the one we used and therefore sample resolution is lower. The most important faunal changes, however, coincide very well. The ages of the topmost 17 cm, which are missing in core III KAL, were linearly extrapolated. For the oldest parts of the core no corresponding ages of III KAL are available, since the ^{210}Pb$_{sup}$ method is only valid until roughly 3500 cal. BP.

We chose the age model of Hass (1996) based on the ^{210}Pb$_{sup}$ method, because our temperature reconstructions did not fit to any published climate reconstruction of this area when we used the ^{14}C AMS age model. Based on AMS ^{14}C dating, reconstructed temperatures in the 'Little Ice Age', for example, would have been the warmest reconstructed temperatures of the whole core.

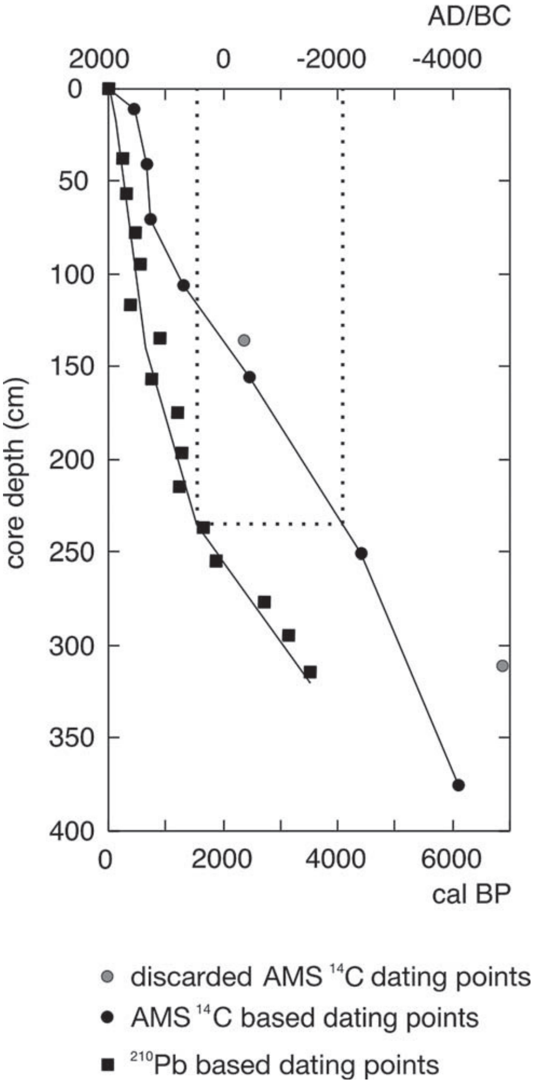

Figure 3 Age–depth relation of ^{210}Pb-based (solid squares) and ^{14}C AMS based (solid circles) age model. Grey circles denote ^{14}C AMS-based dating points, which were discarded as they were considered to show ages that were too old (see text)

Results

We present the $\delta^{18}O$ measurements of *Bulimina marginata*, *Uvigerina mediterranea* and *Melonis barleeanum* (Figure 4). In the discussion, however, we will focus on the results of *B. marginata*. The $\delta^{18}O$ values of *M. barleeanum* and *U. mediterranea* are presented to show that *B. marginata* was not subject to re-sedimentation processes. Though all curves exhibit a strong scatter and show markedly different mean values, the latter of which can be attributed to species-specific vital effects, in general they show the same evolution. Smaller differences amongst all curves can be ascribed to the sample interval of 1 cm, which comprises foraminifers of several years each. In the upper part of core 225514 (190–0 cm) investigated here the range of $\delta^{18}O$ variation accounts for 0.57‰, between a minimum value of 2.55‰, and a maximum value of 3.12‰ (Figure 4).

From 190 to 145 cm $\delta^{18}O$ values are generally comparably low but show a trend to increasing values. Between 145 and 75 cm core depth there is a trend to increasing values. The general trend is interrupted by two episodes with higher values (140–130 cm, 120 cm). Though generally regarded as a period of lower values, the depth interval 75 to 25 cm shows very variable $\delta^{18}O$ values and also highest recorded $\delta^{18}O$ values are found in this depth interval (35 cm core depth). From 25 cm core depth to the top, $\delta^{18}O$ values show a strong decrease to lower values.

The estimated temperature range is 4.2 to 7.1°C (Figure 4). The curve behaves like the $\delta^{18}O$ curve described above. Low values are translated in high temperatures, high values in low temperatures.

Discussion

Deep-water renewal in the Skagerrak

Generally, $\delta^{18}O$ values recorded in benthic foraminiferal tests are a product of two influencing parameters: (1) the temperature of the water mass in which the investigated foraminifers calcified their tests, and (2) δ_w, which corresponds to salinity and global ice volume. The global ice volume as influencing parameter can be ignored because the ascending of the sea level after the last glacial maximum was levelling out around 7000 cal. BP (Fairbanks, 1989; Bard *et al.*, 1989; Lambeck *et al.*, 2004) and therefore the general oxygen isotopic composition of the world ocean has not changed significantly (around 0.05‰ according to Fairbanks 1989) during the time interval in question.

It is difficult to distinguish the respective influence of temperature and salinity on δ^{18}O values. This is especially true for the Skagerrak area because of its complex hydrography. Water masses originating from the southern and central North Sea, the North Atlantic and the Baltic Sea enter this basin and are mixed to a certain degree. This is the reason why neither water temperatures nor salinities can be estimated easily. However, hydrographical measurements at different water depths of various regions of the Skagerrak over a time range from 1947 to 1999 do exist (ICES Oceanographic Database and Services; Ljøen, 1981; Grip *et al.*, 1993). From these data temperature variations between 3.5 and 7.5°C and salinity variations between 34.9 and 35.2 psu at 400 m water depth can be deduced.

Mikalsen and Sejrup (2000) constructed a salinity–δ^{18}O mixing line for the waters of the Sognefjorden, which they suggest to be valid for intermediate and basin waters in western Norwegian fjords. They found a 0.31‰ change in δ^{18}O values per 1 psu salinity change. Therefore, a maximum range of 0.3 psu salinity change accounts for maximum 0.09‰ of the δ^{18}O variance in modern Skagerrak deep waters. Since the total δ^{18}O variability over the whole core depth is about 1‰, the salinity changes are responsible for maximal 9% of this variability. Furthermore, temperature and salinity influence δ^{18}O values in opposite directions, so that the resulting temperature signal has to be regarded even as underestimated. Besides, the maximum δ^{18}O variability induced by salinity changes lies within the error margin of our measurements (±0.08‰). Hence, we conclude that the observed δ^{18}O variability in benthic foraminiferal tests from the deep Skagerrak mainly reflects water temperature changes.

Reconstructed palaeotemperature estimates range from 4.2 to 7.1°C. This range lies within the recorded modern temperature range between 3.5 and 7.5°C at 400 m water depth.

Sudden drops, both in temperature and salinity in the deep Skagerrak during modern times (Figure 5) point to advection-induced cascades of central North Sea waters (Ljøen and Svansson, 1972; Ljøen, 1981; Ivanov *et al.*, 2004). After deep-water renewal has been accomplished, temperatures and salinities slowly ascend over a time period of two to three years, indicating thermohaline mixing with overlying warmer and more saline North Atlantic waters.

In general, the short time intervals of two to three years are not resolvable within our sedimentary record. The average timespan between the samples accounts for 17 years. The sediment slices of 1-cm thickness used comprise foraminifers of a timespan of 4 and 9 years in the youngest 565 years and before, respectively. Consequently, the δ^{18}O values determined have to be regarded as mixed signals that underestimate the total temperature range. Nevertheless, the strongly scattered data clearly show maximum and minimum temperatures, even though masked by mixing. In summary, we suggest that high δ^{18}O values, as representing low water temperatures, mirror Skagerrak deep-water renewal in late winter to spring time as a result of advection-induced cascades of dense water masses from the central North Sea.

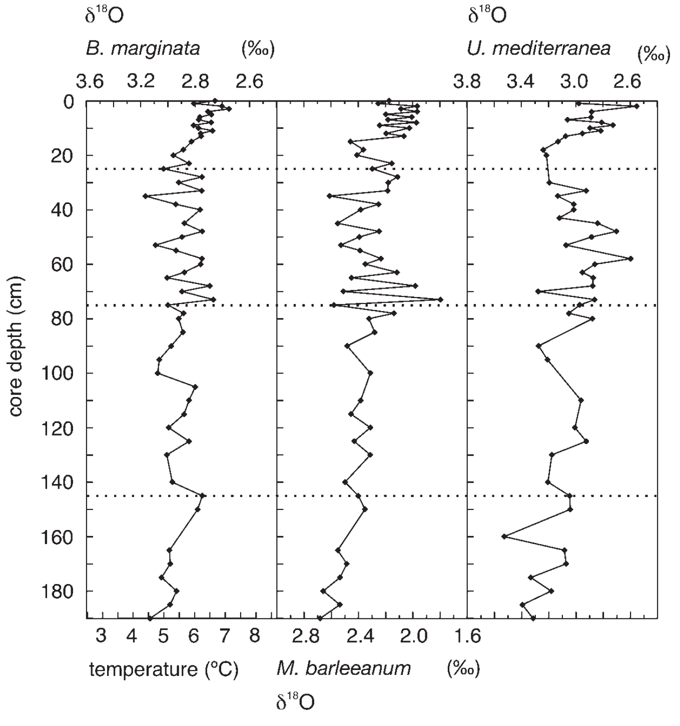

Figure 4 Measured δ^{18}O values/reconstructed temperatures as a function of core depth of *B. marginata*, *M. barleeanum* and *U. mediterranea*. Dotted lines indicate intervals of higher and lower δ^{18}O values as described in the text. Temperature estimates were calculated from vital effect-corrected δ^{18}O values of *B. marginata* according to the equation proposed by Erez and Luz (1983)

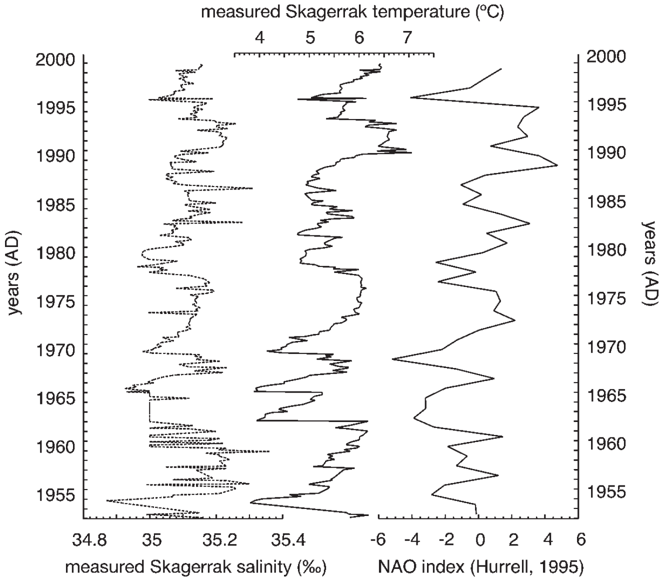

Figure 5 Evolution of Skagerrak salinity (left curve), deep-water temperature (middle curve) and annual NAO index (Hurrell, 1995) (right curve) during modern times

Relationship to the North Atlantic Oscillation

Short-term variability

Deep-water renewal in the Skagerrak usually starts in January/February and is accomplished four to five months later, ie, it is initiated during the season of strongest NAO forcing (December to March). Power spectrum analysis of the annual NAO index has revealed that dominant periods of the NAO variability are 6 to 10 years and 2 to 3 years (Hurrell and van Loon, 1997; Chen and Hellström, 1999), the latter coinciding with the modern Skagerrak deep-water renewal interval Ljøen (1981) described.

A feasible mechanism leading to Skagerrak deep-water renewal triggered by the NAO will be described as follows: During predominantly negative NAO index winters westerlies are weak and their track is shifted further to the south in a more W–E direction over central and southern Europe into the Mediterranean. Northern Europe experiences frequent blocking situations, which in turn allow severely cold and dry conditions from northern Scandinavia/Russia to take influence over northern Europe (Koslowski and Glaser, 1999). These unusually low temperatures result in a strong cooling of shallow central North Sea waters, which therefore reach higher densities than the waters of the deep Skagerrak. Advection-induced deep-water renewal in the Skagerrak follows.

During predominantly positive NAO index winters the pressure gradient between Islandic low and Azores high is unusually high, storm frequency and intensity is enhanced. The storm track shifts to a more northeasterly direction (Rogers, 1997). This results in temperatures above the average and extremely stormy winter conditions over northern Europe, not allowing central North Sea waters to reach the necessary densities (which in this case is mainly a function of temperature) to substitute Skagerrak deep waters. During these time intervals, Skagerrak deep waters successively increase in temperature and salt content by thermohaline mixing with overlying warmer and saltier North Atlantic water masses. The positive correlation between the temperature evolution of Skagerrak deep waters and the NAO during the time period AD 1970–1994 was recognized earlier by Hagberg and Tunberg (2000). Correlation analysis of the temperature and NAO index data shown in Figure 5 revealed that this relationship existed at least since AD 1950. The correlation coefficient between the annual NAO index and adjusted deep-water temperatures is 0.75. The time frame of the deep-water temperature had to be adjusted since there is a time lag of up to two years between the negative phase of the NAO and the triggered deep-water renewal (Hagberg and Tunberg, 2000). These time lags strongly affect the correlation coefficient between the NAO index (Hurrell, 1995) and modern Skagerrak deep-water temperatures. Since the NAO index always precedes the deep-water renewal, a shift of maximal two years to older ages was allowed. Subsequently, we re-sampled the data to achieve equal time intervals. Without adjustment a correlation coefficient of only 0.46 would be reached.

It has been suggested that the origin of Skagerrak deep waters lies within the NwAC, a side branch of which enters the Skagerrak via the Norwegian Trench (eg, Erlenkeuser, 1985b; Hass, 1996). There is, however, a reason why this supposition is not very probable: Orvik *et al.* (2001) found a strong coupling between the strength of the westerly winds as an expression of the state of the NAO and the inflow of North Atlantic waters via NwAC's eastern branch into the Norwegian Sea. In general, high inflow events coincide with positive NAO index values. So there actually is a correlation between the NAO and the amount of NwAC waters entering the Norwegian Sea via the eastern branch of NwAC. Renewed Skagerrak deep waters, however, are characterized by both comparably low temperatures and salinities. During modern times these low temperatures and salinities are not common in the shallow waters of the NwAC (Mork and Blindheim, 2000), which feed the side branch that enters the Skagerrak via the Norwegian Trench. Therefore, we conclude that the main source of Skagerrak deep waters is the central North Sea and not the Norwegian Sea. Consequently, temperature-induced density differences between Skagerrak deep waters and central North Sea waters provide the basis for deep-water renewal in the Skagerrak. Temperature, in turn, is also the physical property in which

NAO changes are expressed in benthic foraminiferal δ^{18}O data. Therefore, the strong scatter of δ^{18}O values mirrors the short-term variability of the NAO as it represents the temperature drops that reflect deep-water renewal.

Long-term variability

In the following we will demonstrate that the long-term variability of the data we present mirrors long-term frequencies of the NAO. Proctor *et al.* (2000) reconstructed precipitation amounts for the last 1100 years by growth rates of stalagmites from a cave in northwestern Scotland. They showed that precipitation amounts are strongly coupled to the state of NAO winter index (Hurrell, 1995), being high during positive NAO phases and *vice versa*. Their results are important because their data go further back in time than those reconstructed from tree-rings and ice cores (Appenzeller *et al.*, 1998; Cook *et al.*, 1998). The data of Proctor *et al.* (2000) explain 50% of the winter NAO's variance. This percentage of explained variance is even higher than that of tree rings (33%) and ice cores (41%).

Our temperature reconstructions from the deep Skagerrak and reconstructed precipitation amounts from northwest Scotland (Proctor *et al.*, 2000) show a close relationship regarding their long-term variability (Figure 6). Low precipitation amounts and low temperatures herein reflect negative NAO phases whereas high precipitation amounts and high temperatures are connected to positive NAO phases. Note the different time resolution of the two proxies. Precipitation amounts are recorded on an annual basis and therefore mirror NAO very precisely, whereas the data of core 225514 show mixed signals of several years.

It has been speculated if low frequency changes of the NAO could be capable of influencing climate on long timescales. It was suggested that the climax of LIA winters over northern Europe was the result of predominantly negative NAO index winters (Koslowski and Glaser, 1999; Proctor *et al.*, 2000; Shindell *et al.*, 2001), and that the MWP has a predominance of positive NAO index values (Proctor *et al.*, 2000; Shindell *et al.*, 2001; Cook, 2003).

The LIA is the best-resolved time interval of the data presented here and therefore basically will be used to investigate the above-mentioned speculation. In contrast to the speculations of Koslowski and Glaser (1999), Proctor *et al.* (2000) and Shindell *et al.* (2001) we cannot detect an indication for generally lowered temperatures, regardless of where one would like to define the climax of LIA, which could be interpreted as the NAO being in a predominantly negative phase. What we do find is a period of very unstable conditions. The range of temperature variation is higher than during the following period leading to modern conditions. Temperature differences between central North Sea winter waters and North Atlantic waters overlying Skagerrak deep waters are very high. The preceding time interval of the MWP has a much lower sample density, but shows, as during the LIA, large amplitude variations. This is why we are not able to deduce the LIA as exceptional compared with the MWP. It is exceptional however, compared with the transitional phase to modern times.

A possible explanation for these strong temperature differences during the LIA is provided by Berstad *et al.* (2003). These authors state a deepening of the NwAC during the early LIA (approximately AD 1400–1650) compared with the period AD 1750–1950. They further speculate that thermohaline circulation was decelerated in the early LIA and enhanced in the latter part. In our data, NwAC water masses are represented by the comparably warmer temperatures within the short-term variability. After a deep-water renewal event the cold and low saline deep waters mix with overlying NwAC-derived water masses, which are warmer and saltier. Our

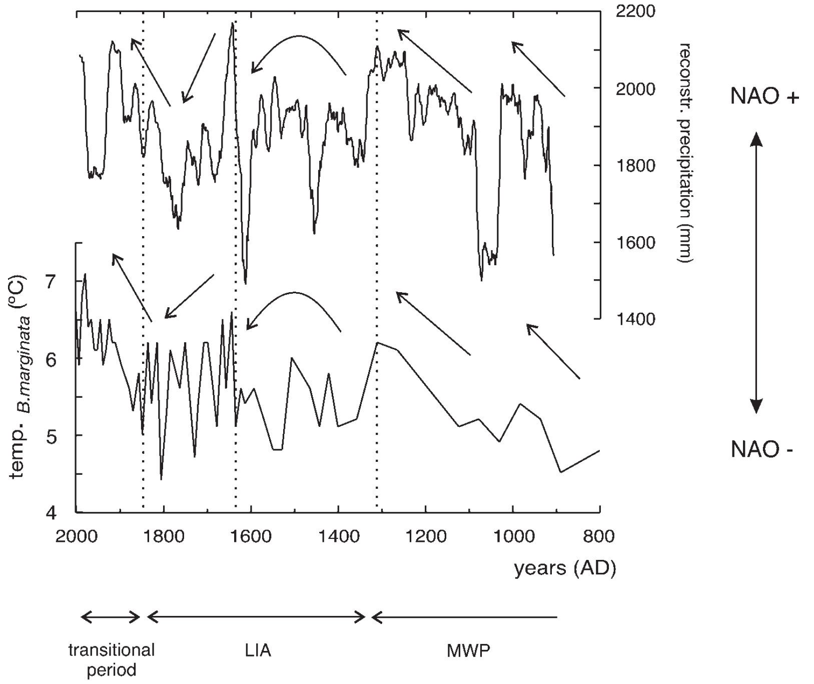

Figure 6 Temperature estimations of Skagerrak deep waters and reconstructed precipitation amounts from northwest Scotland (Proctor *et al.*, 2000). Low temperatures and little precipitation correspond to negative NAO phases and *vice versa*. Dotted lines indicate periods discussed in the text. Curved arrows indicate the general evolution during certain time intervals discussed in the text

palaeotemperature reconstructions display comparably cold conditions until AD 1630, which coincides with a decelerated thermohaline circulation, bringing less warmth to the Northern Hemisphere. The period AD 1630–1870, which is characterized by high temperature differences between North Sea winter waters and overlying warm NwAC-derived water masses, falls into the time period of accelerated thermohaline circulation. The heat transport to the Northern Hemisphere is enhanced, which explains the comparably warm North Atlantic water temperatures indicated by temperature reconstructions of core 225514. Contemporaneously recorded low temperature excursions could be the result of frequently occurring deep-water renewal episodes during strongly negative, but short-lasting NAO phases.

Conclusions

We investigated a sediment core from the southwestern flank of the deep Skagerrak (420 m water depth) for the stable isotopic composition of its benthic foraminiferal tests. We show that $\delta^{18}O$ measurements on benthic foraminiferal tests from deep Skagerrak mainly reflect temperature variations of the bottom water mass.

As stated by Hagberg and Tunberg (2000), Skagerrak deep-water temperatures of the last 30 years correlate with the NAO winter index. Deep-water renewal is triggered by the negative phase of the NAO. We show that this is the case for at least the last 50 years. The correlation between adjusted modern Skagerrak deep-water temperatures and the annual NAO is good ($r = 0.75$).

The origin of deep Skagerrak waters presumably is the central North Sea and not the Norwegian Sea. Modern temperature and salinity measurements show that winter-water densities in shallow to intermediate depths of the eastern branch of the Norwegian Atlantic Current are not high enough to replace Skagerrak deep water.

$\delta^{18}O$ values measured on benthic foraminiferal tests of the deep Skagerrak reflect the state of the NAO during the last 1200 years. A close relationship between $\delta^{18}O$-derived Skagerrak deep-water temperatures and reconstructed precipitation amounts from northwestern Scotland, which were shown earlier to closely mirror the NAO, is demonstrated.

We cannot reinforce the speculation concerning the NAO influencing climate by predominantly staying in one phase. ‘Little Ice Age’ data do not mirror constantly lowered temperatures in the Skagerrak during this time interval. However, they indicate high temperature differences between central North Sea winter waters and overlying warmer North Atlantic water masses. These temperature differences might be the result of the combination of a generally accelerated thermohaline circulation and frequently occurring deep-water renewal episodes resulting from strongly negative, but short-lasting NAO phases.

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Manuscript II

Organic matter rain rates, oxygen availability and vital effects from benthic foraminiferal δ^{13}C in the historic Skagerrak, North Sea

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Abstract

The sediment cores 225514 and 225510 were recovered from 420 and 285 m water depth, respectively. They were investigated for their benthic foraminiferal δ^{13}C during the last 500 years. Both cores were recovered from the southern flank of the Skagerrak. The δ^{13}C values of *Uvigerina mediterranea* and other shallow infaunal species in both cores indicate that organic matter rain rates to the seafloor varied around a mean value until approximately AD 1950 after which they increased. This increase might result from changes in the North Atlantic Current System and a co-occurring persistently high North Atlantic Oscillation index state in the 1980s to 1990s, rather than from anthropogenic eutrophication. Using δ^{13}C mean values of multiple species, we reconstruct δ^{13}C gradients of dissolved inorganic carbon (DIC) within pore waters for the time periods AD 1500 to 1950 and AD 1950 to 2000. The calculated $\delta^{13}C_{DIC}$ ranges, interpreted as indicating total organic matter remineralization due to respiration, are generally bigger in Core 225514 than in Core 225510. Since mean δ^{13}C values of *U. mediterranea* suggest that organic matter rain rates were similar at both locations, differences in total organic matter remineralization are attributed to differing oxygen availability. However, oxygen concentrations in the overlying bottom water masses are not likely to have differed significantly. Thus, we suggest that organic matter remineralization was controlled by oxygen availability within the sediments, reflecting strong differences in sedimentation rates at the two investigated core sites. Based on the assumptions that tests of benthic foraminiferal species inhabiting the same microhabitat depth should show equal δ^{13}C values unless they are affected by vital effects and that *Globobulimina turgida* records pore water $\delta^{13}C_{DIC}$, we estimate vital effects for several species with respect to *G. turgida*: > 0.7 ‰ for *Cassidulina laevigata*, > 1.3 ‰ for *Hyalinea balthica*, and > 0.7 ‰ for *Melonis barleeanus*. *Melonis zaandami* seems to closely record pore water $\delta^{13}C_{DIC}$.

keywords: benthic foraminifera; $\delta^{13}C$; oxygen availability; vital effect; remineralization; Skagerrak

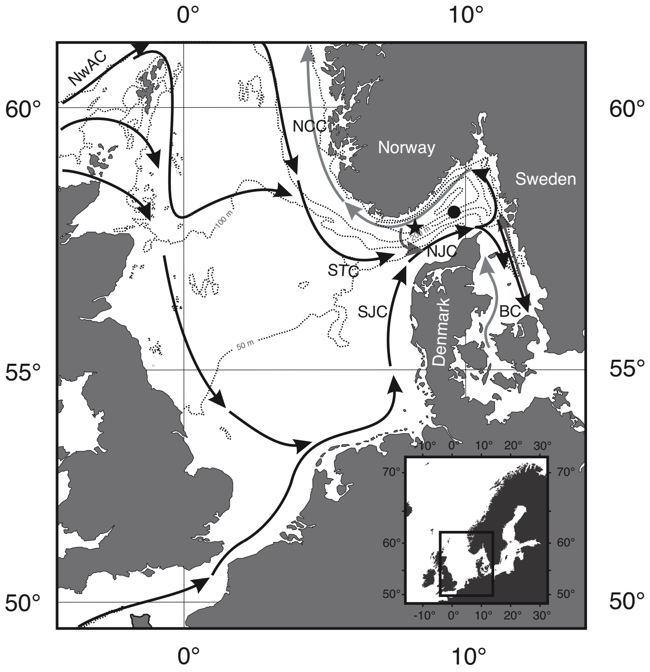
1 Introduction

The stable carbon isotopic composition of benthic foraminiferal tests provides information about deep water circulation and carbon cycling in the ocean; it is used to reconstruct organic matter fluxes to the seafloor, deep water oxygenation and organic matter remineralization rates within the sediments (e.g., Duplessy et al., 1984; McCorkle et al., 1985; Woodruff and Savin, 1985; Zahn et al., 1986; Curry et al., 1988; McCorkle and Keigwin, 1990; Mackensen et al., 1993; Mackensen et al., 2001; Berelson and Stott, 2003; Schilman et al., 2003; Holsten et al., 2004; Fontanier et al., 2006; Schmiedl and Mackensen, 2006). As these processes are important with respect to the reconstruction of global carbon budgets it is crucial to exactly determine the influences on proxies based on benthic foraminiferal $\delta^{13}C$. The Skagerrak is a complex hydro-dynamic system, which contains a variety of different sedimentation regimes in a small investigation area. Thus, it is particularly suited to study the influence of extremely different sedimentation rates on benthic foraminifera and their test $\delta^{13}C$. We will focus on organic matter rain rates to the seafloor, remineralization rates and oxygen availability within the sediments as deduced from benthic foraminiferal proxies, and the influence of sedimentation rates on these processes. Due to very high sedimentation rates resulting in relatively low remineralization rates at one investigation site we are able to approach the vital effects of some benthic foraminiferal species with respect to *Globobulimina turgida* $\delta^{13}C$ test values. We will demonstrate that vital effects can be considerable and thus must receive more attention in future investigations. Benthic foraminiferal $\delta^{13}C$ values are suggested to reflect ambient $\delta^{13}C_{DIC}$ of either bottom or pore waters, depending on the microhabitat the foraminifera occupies (e.g., Woodruff et al., 1980; Belanger et al., 1981; Grossman, 1984a; Grossman, 1984b; Grossman, 1987; McCorkle and Keigwin, 1990; Rathburn et al., 1996;McCorkle et al., 1997; Mackensen et al., 2000; Schmiedl et al., 2004; Fontanier et al., 2006; Mackensen, in press). Due to effective degradation of organic matter by respiration, pore water $\delta^{13}C_{DIC}$ values decrease strongly within the uppermost centimeters of the sediment (McCorkle and Emerson, 1988). The shape of the pore water gradient in sediments of limited oxygen penetration is determined by the rate of remineralization, which is mainly a function of oxygen availability and organic matter rain rates (e.g., McCorkle et al., 1985; McCorkle and Emerson, 1988; Sayles and Curry, 1988; Holsten et al., 2004; Schmiedl and Mackensen, 2006). McCorkle and Emerson (1988) observed that the degree of $^{13}C_{DIC}$ depletion at the sediment depth where oxygen becomes zero is correlated to the oxygenation of the overlying bottom water mass. They showed that $\Delta\delta^{13}C$ values ($\delta^{13}C_{DIC}$ difference between bottom water and pore water) increase from 1 ‰ in sediments under low oxygen bottom water masses to 4 ‰ under well-aerated bottom water masses. McCorkle and Keigwin (1990) introduced *Globobulimina* species as indicators for pore water $\delta^{13}C_{DIC}$ values at the sediment depth where oxygen becomes zero. They suggested that the $\delta^{13}C$ difference between preferentially epifaunal living *Cibicidoides* species and deep infaunal living *Globobulimina* species reflects most of the effect that oxygen driven organic matter remineralization exerts on pore water $\delta^{13}C_{DIC}$ composition. Based on this observation, Schmiedl and Mackensen (2006) developed a calibration for the $\delta^{13}C$ difference between *Cibicidoides wuellerstorfi* and *Globobulimina affinis* and the bottom water oxygen content in the western Arabian Sea. Apart from the availability of oxygen, changing organic matter rain rates influence benthic foraminiferal $\delta^{13}C$ values. In particular the difference between epifaunal and shallow infaunal or at the sediment/water interface living foraminifera and shallow infaunal dwelling species seems to be sensible to changes in organic matter remineralization rates (e.g., Zahn et al., 1986; Loubere, 1987; McCorkle and Keigwin, 1990; Mackensen et al., 2000; Schilman et al., 2003; Holsten et al., 2004; Fontanier et al., 2006; Mackensen et al., 2006; Schmiedl and Mackensen, 2006). The $\delta^{13}C$ differences increase with increasing rain rates and/or enhanced oxygen availability. Independent of the sediment depth where they were caught, live infaunal foraminifera show relatively uniform species-specific $\delta^{13}C$ values (e.g., McCorkle and Keigwin, 1990; Rathburn et al., 1996; McCorkle et al., 1997; Holsten et al., 2004; Schmiedl et al., 2004; Mackensen, in press). This is attributed either to the fact that $\delta^{13}C$ values are mean values representing the average living depth of the investigated species, or to the fact that the microhabitat in which calcification takes place is restricted to a specific sediment depth. However, most species do not calcify in equilibrium, but show offsets to the ambient water $\delta^{13}C_{DIC}$ of their microhabitat (e.g., McCorkle and Keigwin, 1990; Rathburn et al., 1996; Schmiedl et al., 2004; Fontanier et al., 2006; Schmiedl and Mackensen, 2006). These offsets, summarized under the term 'vital effect', are suggested to be caused by kinetic isotope fractionation during calcification and/or incorporation of light metabolic CO_2 into the test carbonate (e.g., Vinot-Bertouille and Duplessy, 1973; Berger et al., 1978; Erez, 1978; McConnaughey, 2003). Vital effects are difficult to quantify since they are masked especially by the $\delta^{13}C_{DIC}$ pore water gradient and other environmental influences like pH changes (e.g., McCorkle and Keigwin, 1990; McCorkle et al., 1997; Schmiedl et al., 2004; Schmiedl and Mackensen, 2006; Mackensen, in press). Further complication arises because vital effects are not constant. Dunbar and Wefer (1984) and Schmiedl et al. (2004) observed increasing $\delta^{13}C$ values with increasing test size for *Uvigerina peregrina* and *Uvigerina mediterranea*, respectively.

2 Oceanography

The Skagerrak is the deepest part of the Norwegian Trench and thus the most important depocenter of the North Sea (Fig. 1). It has the shape of an irregular formed trench with a steep northern flank and a more gently dipping southern flank. In its deepest part the Skagerrak has a depth of over 700 m. The water exchange between Skagerrak and North Sea is restricted by a sill in 270 m water depth (Rodhe, 1987). Water circulation is counterclockwise and reaches down to 400 – 500 m water depth (e.g., Rodhe, 1987).

The Southern Jutland Current (SJC) enters the Skagerrak in the southwest (Fig. 1) and after joining with the water masses of the Southern Trench Current (STC) becomes the Northern Jutland Current (NJC). The STC consists of a mixture of northern North Sea Waters and waters originating from the Norwegian Atlantic Current (NwAC). In the east of the Skagerrak superficial brackish waters (Baltic Current = BC) of the Baltic Sea and the Kattegat are added to the NJC. The outflow of Skagerrak waters via the Norwegian Coastal Current (NCC) follows the Norwegian Trench to the north. Smaller amounts of NCC water masses are recycled in the western part of the Skagerrak basin (Rodhe, 1987). The Norwegian Trench additionally holds a counter-current, delivering high saline Norwegian Atlantic Current waters into greater depths of the Skagerrak. Skagerrak deep-water is regularly renewed every two to three years by advection-induced



SJC = Southern Jutland Current
NJC = Northern Jutland Current
BC = Baltic Current
NCC = Norwegian Coastal Current
NwAC = Norwegian Atlantic Current
STC = Southern Trench Current

Fig. 1: Map of the investigation area, hydrography following Nordberg (1991), black arrows indicate deep currents, grey arrows indicate shallow currents, star marks Core Site 225514, filled circle marks Core Site 225510.

cascades of Central North Sea Waters (CNSW) (Ljøen and Svansson, 1972; Ljøen, 1981). The deep-water exchange is triggered by the negative phase of the North Atlantic Oscillation (Brückner and Mackensen, 2006).

Major parts of Skagerrak sediments and nutrients originate from areas of the southern and eastern North Sea (e.g., Van Weering, 1981; Anton et al., 1993; Kuijpers et al., 1993; Lepland and Stevens, 1996). The Skagerrak is the main sink for suspended matter from the North Sea (e.g., Van Weering, 1981; Anton et al., 1993; Van Weering et al., 1993; Hass, 1996). Several authors estimate that up to 89% of the organic carbon accumulated in Skagerrak sediments is refractory (e.g., Van Weering and Kalf, 1987; Meyenburg and Liebezeit, 1993).

3 Material and Methods

Gravity cores 225514 and 225510 investigated here come from the southern flank of the Skagerrak at 57°50.260 N, 8°42.327 E and 58°01.920 N, 9°37.172 E, respectively. They were recovered from 420 m and 285 m water depth (Fig. 1), respectively, during Cruise 159 with RV *Alkor*. Core 225514 is 405 cm long in total. For comparison purposes, however, we present only the topmost 105 cm.

The sediments consist of olive-green clayey mud, which frequently shows streaks of light grey color (15 – 85 cm). Core 225510 is 544 cm long. The sediments are colored in various shades of olive and consist of clayey mud with frequent insertions of silty or fine sandy mud. Frequent occurrences of dark grey to black striae are observed. The youngest 15 cm of Core 225514 were sampled every centimeter, down to 80 cm core depth every second to third centimeter and from 80 cm to core bottom every fifth centimeter was sampled. Core 225510 was sampled every fifth centimeter. The slices of one centimeter thickness were freeze dried and subsequently wet sieved to obtain the sediment fractions 125 μm to 2 mm and > 2 mm. The grain-size fraction > 2 mm is devoid of benthic foraminifera.

3.1 Age models

AMS ^{14}C dates of bulk calcareous benthic foraminiferal tests were used to date Core 225510 (Tab. 1). Measurements were carried out at the Leibniz-Labor for Radiometric Dating and Isotope Research in Kiel. Measured values were corrected for natural isotope fractionation. Calibration and transformation to calendar years for samples older than 400 calibrated AMS ^{14}C years (> approximately 200 cm core depth) was done by applying the radiocarbon calibration program Calib rev. 4.3 (Stuiver and Braziunas, 1989). We used the marine model calibration curve (Stuiver and Braziunas, 1989) together with the global reservoir age of about 400 years (ΔR = 0) as proposed for marine Scandinavian waters by Heier-Nielsen et al. (1995). The calibrated AMS ^{14}C date at 190 cm core depth was converted to calendar years via the program CALIBomb (http://www.calib.org) by using the NH1 dataset (Hua and Barbetti, 2004). The AMS ^{14}C measurement was carried out in AD 2001. We used the oldest suggested age in order to keep sedimentation rates as low as possible. Nevertheless, they account for 5.2 cm/year in the topmost 190 cm as opposed to 0.8 cm/year below (Fig. 2a). The AMS ^{14}C dates above 190 cm core depth delivered no meaningful results. Therefore, we assumed the top of the core to be AD 2000. The sample from 232.5 cm core depth was considered as too old and thus rejected. The age model was constructed by linear interpolation (Fig. 2a).

Tab. 1: Measured and to calendar years calibrated AMS ^{14}C dates on bulk calcareous benthic foraminifera and the standard deviation as reported from the laboratory. The date marked by the asterisk was calibrated by CALIBomb, see text for further information.

depth (cm)	AMS ^{14}C	standard deviation	years AD
20.5	-280	25	
191.5	350	35	1962*
232.5	550	30	1715
411.5	605	25	1684
520.5	740	25	1546

The age model of Core 225514 is based on the one Hass (1996) construed for Core III KAL, which was recovered only 150 m away. Dominant benthic foraminiferal species occur in both cores in the same depth ranges (Hass, 1997; Brückner and Mackensen, 2006) and thus were used to tie the age model of Core III KAL to Core 225514 (Fig. 2b). Hass (1996) used the "advanced ^{210}Pb method" (Erlenkeuser, 1985) to establish the age model for Core III KAL. This method allows dating until approximately 3500 years before present. Sediments younger than 160 years were dated using "excess ^{210}Pb" method. Older sediments were dated with help of the "^{226}Ra supported ^{210}Pb" method following Erlenkeuser (1985). For detailed information about the method and the model see Hass (1996) and Erlenkeuser (1985). For further information about the adoption of the age model of Core III KAL to Core 225514 see Brückner and Mackensen (2006).

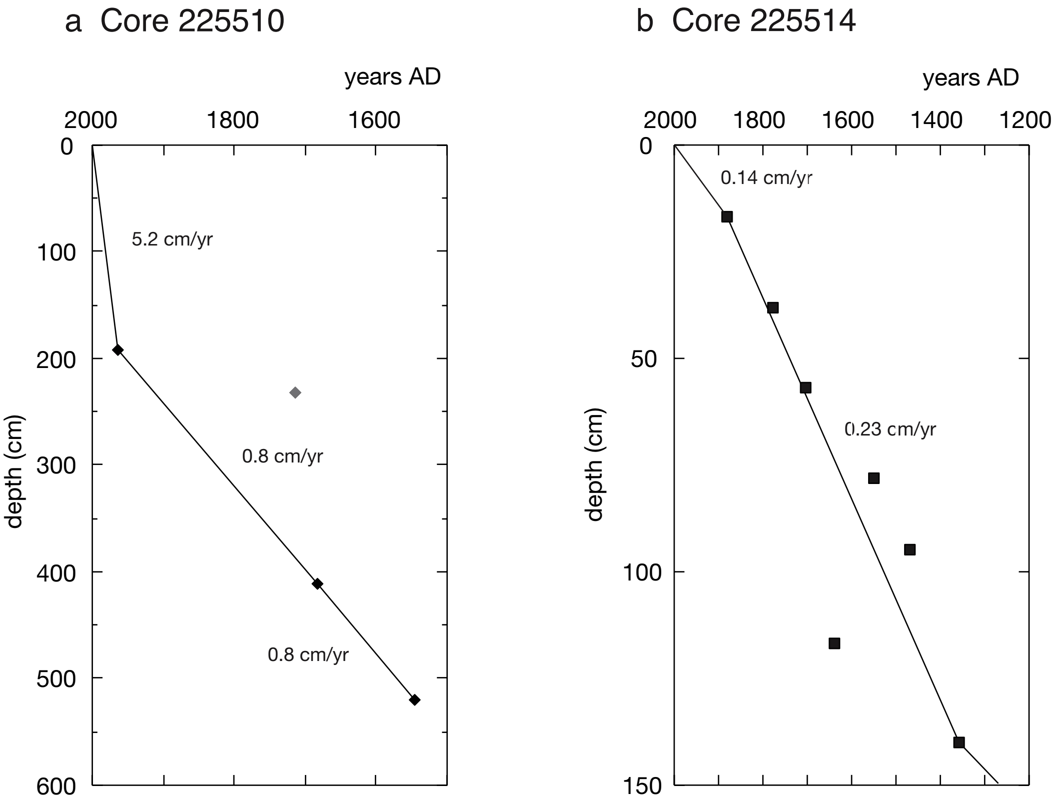


Fig. 2: a): Age model of Core 225510 basing on AMS ^{14}C dates calibrated to calendar years, black diamonds indicate dates relevant for the age model, grey diamond indicates omitted date (see text section 3.1).

b): Age model of Core 225514 basing on "advanced ^{210}Pb method", black squares indicate dating points.

In both figures sedimentation rates are indicated for each linearly interpolated time interval.

3.2 Stable carbon isotopic measurements

The stable carbon isotopic composition of foraminiferal tests was determined with a Finnigan MAT 251 isotope ratio gas mass spectrometer directly coupled to an automatic carbonate preparation device (Kiel I). Measurements were calibrated to the Vienna Pee Dee Belemnite (VPDB) scale via NIST 19 and reported in δ-notation. The overall precision of the measurements was better than 0.06 ‰, which was determined by repeated analyses of a laboratory standard (Solnhofen limestone) over a one-year period. For the determination of the dissolved inorganic carbon isotopic composition of Recent Skagerrak bottom waters, water from directly above the sediment/water interface of Multiple Core 242940 was sampled. Multiple Core 242940 (57°40.52 N, 7°10.0 E) was recovered from 315 m water depth on RV *Poseidon* Cruise PO 282. Dissolved inorganic carbon was extracted following Mook et al. (1974). The isotopic composition of the extracted CO_2 was measured with a Finigan 252 isotope gas mass spectrometer coupled to an automatic tube cracker and calibrated via NBS 19 to the VPDB scale. The presented value is the mean of two separately processed replicates. The precision of the measurements is better than 0.1 ‰. Based on different $\delta^{13}C$ mean values, the time periods AD 1500 to 1950 and AD 1950 to 2000 will be discussed separately (Tab. 2). Since the interpreted mean value differences are small, we verified the assumption by applying a Student's *t*-test. H_0, assuming that the mean values of the two investigated time periods were equal, had to be rejected in order to settle on H_1, assuming that the mean value of the period AD 1500 to 1950 was bigger than the mean value of period AD 1950 to 2000. Mean values were tested against a one-sided α of 0.5. We used the following

Tab. 2: a) Core 225514: total $\delta^{13}C$ range for the whole investigated time period, mean $\delta^{13}C$ values of all measured species for the time periods AD 1500 – 1950 and AD 1950 – 2000, the number of considered values (n), calculated *t*-value of the Student's *t*-test and the reference value for the 95 % confidence level.

a Core 225514: mean $\delta^{13}C$ values

species	range		mean AD 1500–1950	stand. dev.	n	mean AD 1950–2000	stand. dev.	n	calc. *t*-value	ref. value
B. marginata	0.01	0.72	0.42	0.15	37	0.24	0.17	8	2.771	1.833
B. skagerrakensis	-0.11	0.43	0.20	0.10	38	0.0	0.07	8	6.759	1.771
U. mediterranea	-0.58	0.29	-0.11	0.18	31	-0.33	0.27	5	1.760	2.132
C. laevigata	-0.98	-0.06	-0.54	0.22	37	-0.80	0.13	8	4.446	1.740
M. zaandami	-1.24	-0.26	-0.59	0.17	37	-0.90	0.29	7	2.741	1.943
M. barleeanus	-1.56	-0.34	-0.88	0.24	34	-1.41	0.15	8	7.895	1.746
G. turgida	-1.12	-0.30	-0.64	0.15	24	-0.99	0.15	4	4.320	2.132

Tab. 2 (continued): b) Core 22510: same as for a), asterisks indicate questionable values because of incomplete data sequences.

b Core 225510: mean δ^{13}C values

species	range		mean AD 1500–1950	stand. dev.	n	mean AD 1950–2000	stand. dev.	n	calc. *t*-value	ref. value
U. mediterranea	-0.50	0.31	0.04 *	0.18	6	-0.24	0.15	12	3.283	1.860
C. laevigata	-1.11	-0.16	-0.38	0.14	27	-0.77	0.19	16	7.142	1.714
H. balthica	-1.90	-0.50	-1.16 *	0.14	6	-1.54	0.21	13	4.657	1.753
M. zaandami	-0.69	0.02	-	-	-	-0.47 *	0.14	8	-	-
G. turgida	-0.80	0.10	-0.16	0.14	22	-0.36	0.21	18	3.460	1.699

equations to calculate *t*-values and respective degrees of freedom (Sachs, 1997):

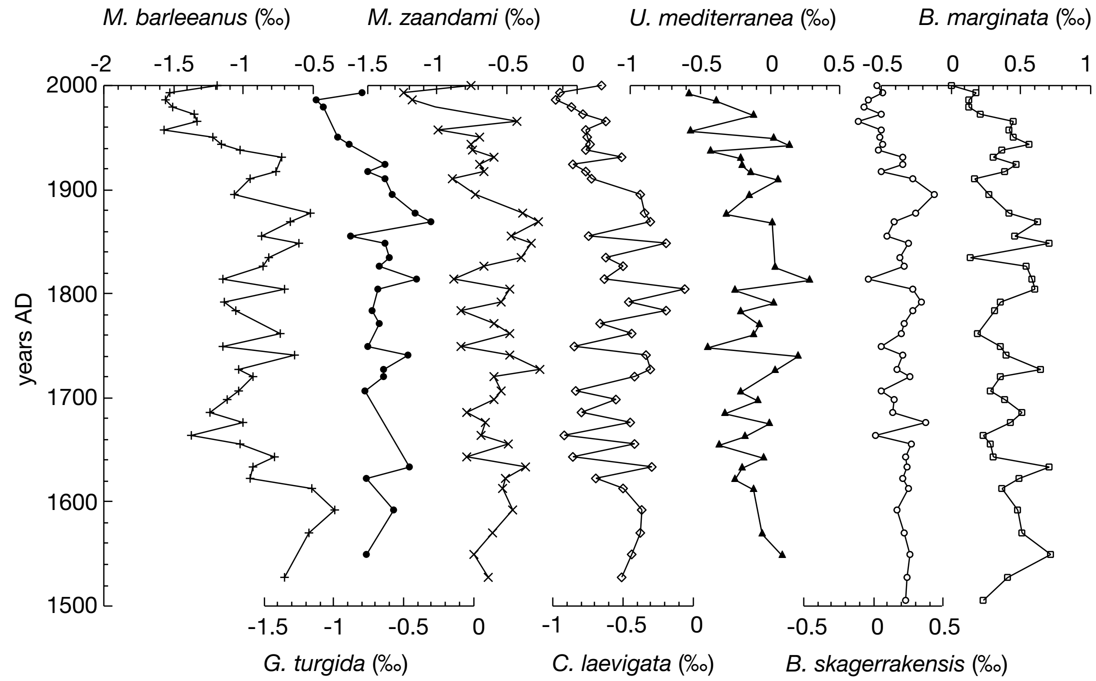
$$t = |x_1 - x_2| / \sqrt{(s_1^2 / n_1 + s_2^2 / n_2)}$$
$$n = (s_1^2 / n_1 + s_2^2 / n_2)^2 / ((s_1^2 / n_1)^2 / (n_1 - 1) + (s_2^2 / n_2)^2 / (n_2 - 1))$$

x_1 and x_2 represent the mean values of the two time periods, s_1 and s_2 represent respective standard deviations, n_1 and n_2 state the number of observations. Calculated *t*-values and reference values are listed in Tab. 2.

4. Results

4.1 Core 225514

The stable carbon isotopic composition of seven species, *Bulimina marginata*, *Bolivina skagerrakensis*, *Uvigerina mediterranea*, *Cassidulina laevigata*, *Melonis barleeanus*, *Melonis zaandami*, and *Globobulimina turgida* were determined (Fig. 3a). *Bulimina marginata* and *B. skagerrakensis* show the highest δ^{13}C values of all species, ranging from 0.0 to 0.7 ‰ and -0.1 to 0.4 ‰, respectively. Both data sequences are characterized by a trend to slightly lower values. *Uvigerina mediterranea* has lower δ^{13}C values ranging from –0.6 to 0.3 ‰. *Cassidulina laevigata* (-1.0 to 0.0 ‰), *M. zaandami* (-1.2 to -0.3 ‰), and *G. turgida* (-1.1 to -0.3 ‰) exhibit very similar δ^{13}C values, whereas *M. barleeanus* (-1.6 to -0.3 ‰) has the lowest values observed. The δ^{13}C values of *Cassidulina laevigata*, *M. barleeanus*, *M. zaandami*, and *G. turgida* each vary around a species-specific mean value until approximately AD 1950 and become lower afterwards (Fig. 3a). This shift can also be observed in δ^{13}C values of *B. marginata* and *B. skagerrakensis* a Core 225514



b Core 225510

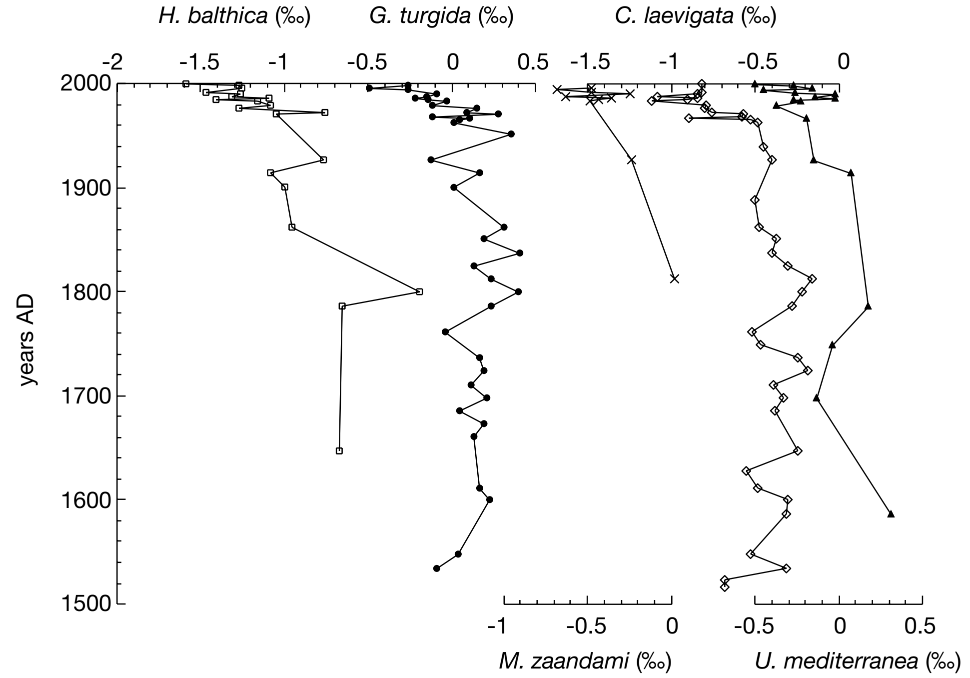


Fig. 3: a): $\delta^{13}C$ values of all measured species of Core 225514 versus age.
b): $\delta^{13}C$ values of all measured species of Core 225510 versus age.

although not as clear as in the data of the other species. Due to this shift we decided to calculate species mean values separately for the time periods AD 1500 to 1950 and AD 1950 to 2000. Mean $\delta^{13}C$ values of the time period AD 1950 to 2000 are generally lower than those of the period before (Tab. 2a). Except for *U. mediterranea* the differences are statistically significant on the 95 % confidence level. In both time periods mean $\delta^{13}C$ values of *Bulimina marginata* are the highest recorded, whereas mean values of *B. skagerrakensis*, *U. mediterranea*, *C. laevigata*, *M. zaandami*, *G. turgida*, and *M. barleeanus* are successively lower.

4.2 Core 225510

We measured the stable carbon isotopic composition of *U. mediterranea*, *C. laevigata*, *Hyalinea balthica*, *M. zaandami*, and *G. turgida* (Fig. 3b). The data sequences of *U. mediterranea*, *H. balthica*, and *M. zaandami* are incomplete since these species were not continuously present. *Uvigerina mediterranea*, *M. zaandami*, and *H. balthica* show a trend to lower values, which, however might be the result of incomplete data covering. *Cassidulina laevigata* and *G. turgida* each vary around a species-specific mean value until approximately AD 1950. Following AD 1950 all species show lowered values. *Uvigerina mediterranea* shows the highest values recorded, ranging from -0.5 to 0.3 ‰, closely followed by *M. zaandami*, ranging from -0.7 to 0.0 ‰, and *G. turgida*, ranging from -0.8 to 0.1 ‰. *Cassidulina laevigata*, ranging from -1.1 to -0.2 ‰, and *H. balthica*, ranging from -1.9 to -0.5 ‰, each are clearly offset to lower values. As in Core 225514 we calculated species mean values separately for the time periods AD 1500 to 1950 and AD 1950 to 2000 (Tab. 2b). During the time period AD 1500 to 1950 *U. mediterranea* shows the highest mean value (0.0 ‰) followed by the mean values of *G. turgida* (-0.2 ‰), *C. laevigata* (-0.4 ‰) and, clearly offset, *H. balthica* (-1.2 ‰). The mean values of *U. mediterranea* and *H. balthica* might be slightly too high since the lower values of the younger half of this period are underrepresented (Fig. 3b). Between AD 1950 and 2000 *U. mediterranea* has the highest mean value (-0.2 ‰), closely followed by *G. turgida* (-0.4 ‰) and *M. zaandami* (-0.5 ‰). For *C. laevigata* (-0.8 ‰) and especially *H. balthica* (-1.5 ‰) very low mean values are observed. The mean value of *M. zaandami* is considered as slightly too low as the data succession is complete for approximately the last 20 years, only. Generally, species mean $\delta^{13}C$ values are lower in Core 225514 than in Core 225510, and $\delta^{13}C$ values of the time period AD 1950 to 2000 are lower than from AD 1500 to 1950 (Tab. 2). The species succession from high to low mean values is different in the two investigated cores: In Core 225514 the species succession from high to low mean values is: *U. mediterranea*, *C. laevigata*, *M. zaandami*, and finally *G. turgida* (Tab. 2a). In Core 225510 *M. zaandami* and *G. turgida* show species mean values between *U. mediterranea* and *C. laevigata* (Tab. 2b).

5 Discussion

The course of benthic foraminiferal $\delta^{13}C$ with time is similar in both cores, although species $\delta^{13}C$ values are generally lower in Core 225514 than in Core 225510 (Tab. 2). Between AD 1500 and 1950 all species values vary around a species-specific mean value and become lower afterwards (Fig. 3). Student's *t*-test confirmed that on the 95 % confidence level species mean $\delta^{13}C$ values are significantly different before and after AD 1950 for all species in both cores but *Uvigerina mediterranea* in Core 225514 (Tab. 2). Thus, the two time periods will be interpreted separately.

5.1 Vital effect

Meanwhile, it is generally accepted that infaunal benthic foraminiferal $\delta^{13}C$ values bear a pore water $\delta^{13}C_{DIC}$ signal of the sediment depth in which the foraminifers calcify their tests. Consequently, it is suggested that shallow infaunal species are generally less depleted in ^{13}C than deep infaunal species, reflecting their different microhabitat preferences within the $\delta^{13}C_{DIC}$ gradient of the sediments (e.g., McCorkle and Keigwin, 1990; Rathburn et al., 1996; McCorkle et al., 1997; Mackensen et al., 2000; Mackensen and Licari, 2004). Several investigators demonstrated that $\delta^{13}C$ values are relatively homogenous for one species at one location, although living individuals of one species occur in various sediment depths (e.g., McCorkle and Keigwin, 1990; Rathburn et al., 1996; McCorkle et al., 1997; Holsten et al., 2004; Mackensen and Licari, 2004; Schmiedl et al., 2004). This implies that either test calcification occurs within very restricted conditions only, or that the foraminifer calcifies wherever it lives. In the latter case $\delta^{13}C$ test values are mean values reflecting the foraminifer's average living depth.

With the exception of *M. barleeanus*, all species of Core 225514 exhibit a $\delta^{13}C$ mean value succession from high to low in both of the two separated time periods, which is consistent with the species' microhabitat preferences (Fig. 4a). This succession of species mean values enables us to reconstruct mean $\delta^{13}C_{DIC}$ gradients for the time periods AD 1500 – 1950 and AD 1950 – 2000. Species depth distributions in figures 4 and 5 were arranged with respect to

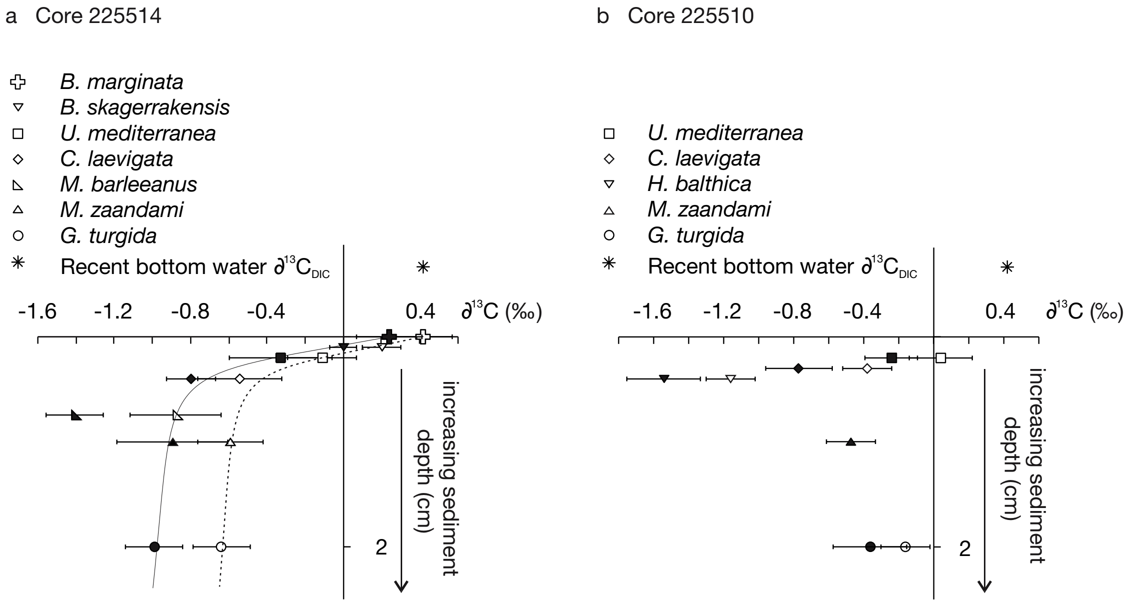


Fig. 4: a): Species-specific mean $\delta^{13}C$ values of the time period AD 1500 – 1950 (open symbols) and AD 1950 – 2000 (filled symbols) versus assumed sediment depth in Core 225514 and
b): in Core 225510.
For arrangement of species versus depth see text section 5.1. Negative depth values refer to above the sediment. Reconstructions of the $\delta^{13}C_{DIC}$ gradients within the pore waters for both time periods in Core 225514 are indicated by dotted lines. For Core 225510 no $\delta^{13}C_{DIC}$ gradients can be reconstructed, see text section 5.1.

the preferred microhabitat of the species extracted from literature (e.g., Corliss and Van Weering, 1993; Alve and Bernhard, 1995; Wollenburg and Mackensen, 1998; Fontanier et al., 2002). If several species are known to occupy the same microhabitat, species with higher $\delta^{13}C$ values were arranged slightly above those with lower $\delta^{13}C$ values, taking into account that $\delta^{13}C$ values should reflect the ambient pore water $\delta^{13}C_{DIC}$. *Globobulimina turgida*, being the species with the deepest microhabitat preference, was suggested to live two centimeters below the sediment/water interface (Fig. 4, 5), because *Globobulimina* species were observed to live close to the zero-oxygen boundary within the sediments (e.g., McCorkle and Keigwin, 1990) and oxygen penetration depth in the Skagerrak is maximal two centimeters (e.g., Bakker and Helder, 1993; Rysgaard et al., 2001). Note: species' depth distribution within their microhabitats is just a guess with the intention to visualize possible $\delta^{13}C_{DIC}$ gradient reconstructions for the presented data.

Mean $\delta^{13}C$ values of shallow infaunal species, such as *B. marginata*, *U. mediterranea*, and *C. laevigata*, are comparatively low and thus reflect the species' microhabitat preferences (e.g., Corliss and Van Weering, 1993; Alve and Bernhard, 1995; Fontanier et al., 2002). According to Corliss (1993), *B. skagerrakensis* shows a bimodal depth distribution. Its $\delta^{13}C$ values, however, indicate that *B. skagerrakensis* calcifies its test in the upper part of its live distribution, i.e. close to the sediment/water interface. The $\delta^{13}C$ values of *M. zaandami*, an intermediate to deep infaunal living species and *G. turgida* preferring a deep infaunal microhabitat (e.g., Corliss and Van Weering, 1993; Wollenburg and Mackensen, 1998), are lower than $\delta^{13}C$ values of the shallower dwelling species. Only $\delta^{13}C$ values of *M. barleeanus* do not fit into the above described mean value succession. Due to its shallow to intermediate infaunal microhabitat (Fontanier et al., 2002) relatively high $\delta^{13}C$ values are expected, but $\delta^{13}C$ values of *M. barleeanus* are even lower than those of *G. turgida* in both investigated time periods. Therefore, we suggest that the $\delta^{13}C$ value of *M. barleeanus* contains a significant vital effect. This suggestion is supported by the data set of Fontanier et al. (2006), who investigated stained benthic foraminifera and reported *Globobulimina affinis* and *M. barleeanus* from the same sampling sites. *Globobulimina affinis* lived always deeper in the sediments than *M. barleeanus* but often showed up to 0.2 ‰ higher $\delta^{13}C$ values. Schmiedl et al. (2004) suggested that “vital effects may be assessed through the comparison of different species found at the same depth in the sediment”. Since *Globobulimina* species are suggested to closely record pore water $\delta^{13}C_{DIC}$ (McCorkle and Keigwin, 1990), *G. turgida* is used as reference. *Melonis barleeanus* and *G. turgida* theoretically might occupy the same sediment depth if for example the oxygen penetration depth was strongly reduced. In this case, *G. turgida* would thrive higher up within the sediment column (Jorissen et al., 1995); its $\delta^{13}C$ signal would be higher according to higher $\delta^{13}C_{DIC}$ values further up the sediments. Provided that the respirationally induced $\delta^{13}C_{DIC}$ decrease is smaller than the vital effect of *M. barleeanus*, i.e. measured $\delta^{13}C$ values of *M. barleeanus* are lower than those of *G. turgida*, the decreasing difference of the living depths of *G. turgida* and *M. barleeanus* will increase the difference between their $\delta^{13}C$ values. Thus, we can assume that the $\delta^{13}C$ difference between *G. turgida* and *M. barleeanus* would become maximal if both species occupied the same sediment depth. The maximal possible difference between these two species would then reflect the vital effect of *M. barleeanus* with reference to the $\delta^{13}C$ value of *G. turgida* (vital effect$_{Gt}$). The limitation “with reference to *G. turgida*” refers to the fact that we do not know the vital effect of *G. turgida*, although we presume that it calcifies its test close to pore water $\delta^{13}C_{DIC}$. The two biggest differences between *G. turgida* and *M. barleeanus* in all paired samples are 0.7 ‰ (Tab. 3a), so we conclude that *M. barleeanus* exhibits a vital effect$_{Gt}$ of at least this amount. The value of 0.7 ‰ is presumably underestimated since there is no indication for

Tab. 3: a) Core 225514: Paired $\delta^{13}C$ differences between *G. turgida* and *M. barleeanus*, the three biggest differences are set iterative and bold, mean value of the two biggest differences indicated at the bottom.
b) Core 225510: Paired $\delta^{13}C$ differences between *G. turgida* and *C. laevigata*, *H. balthica*, and *M. zaandami*, the three biggest differences of the paired samples are set iterative and bold, mean values of the three biggest differences indicated at the bottom.

a Core 225514

depth (cm)	**years AD**	**$\Delta\delta^{13}C_{Gturg-Mbarl}$**
0	2000	
1	1993	***0.73***
2	1986	0.43
3	1979	0.44
4	1972	
5	1965	
6	1958	
7	1951	0.25
8	1944	0.26
9	1938	
10	1931	
11	1924	
12	1917	0.01
13	1910	0.32
15	1896	***0.49***
18	1878	0.11
20	1869	0.36
23	1856	-0.02
25	1848	-0.03
28	1835	0.22
30	1827	0.18
33	1814	***0.74***
35	1805	0.02
38	1792	
40	1784	0.33
43	1771	
45	1762	
48	1750	0.39
50	1741	0.17
53	1728	0.40
55	1720	0.28
58	1707	0.25
60	1698	
63	1686	
65	1677	
68	1664	
70	1656	
73	1643	
75	1634	0.48
78	1622	0.18
80	1613	
85	1592	-0.23
90	1570	
95	1549	
100	1528	
105	1506	
mean		***0.65***

b Core 225510

depth (cm)	**years AD**	**$\Delta\delta^{13}C_{Gturg-Claev}$**	**$\Delta\delta^{13}C_{Gturg-Hbalth}$**	**$\Delta\delta^{13}C_{Gturg-Mzaan}$**
2	2000			
10	1998		1.01	
20	1996		0.76	-0.33
30	1994			***0.11***
40	1992			
50	1990	0.45	1.17	-0.15
60	1988	0.62	1.16	***0.17***
70	1986	0.32	0.88	-0.17
80	1985	0.46	***1.27***	-0.01
90	1983	***0.78***	1.13	***0.14***
100	1981			
110	1979	0.37	0.97	
120	1977	***0.64***	***1.42***	
130	1975	0.20		
140	1973	0.54	0.85	
150	1971	0.55	***1.33***	
160	1969	0.15		
170	1967	***0.69***		
180	1965	0.27		
190	1963	0.19		
200	1952			
210	1940			
220	1927	-0.04	0.64	-0.20
230	1914		1.25	
240	1901		1.01	
250	1889			
260	1876			
270	1863	0.49	1.27	
280	1851	0.26		
290	1838	0.49		
300	1825	0.13		
310	1813	0.09		-0.09
320	1800	0.31	0.59	
330	1787	0.21	0.89	
340	1775			
350	1762	0.17		
360	1749			
370	1737	0.10		
380	1724	0.07		
390	1711	0.20		
400	1699	0.22		
410	1686	0.12		
420	1673			
430	1661			
440	1648			
456	1628			
468	1612	0.35		
478	1600	0.22		
488	1587			
498	1574			
509	1561			
519	1548	0.26		
529	1535	-0.09		
539	1523			
544	1516			
mean		***0.70***	***1.34***	***0.14***

severe oxygen deficiency within Core 225514, which would be the precondition for the two species occupying the same sediment depth.

In Core 225510 no species $\delta^{13}C$ mean value succession according to the preferred microhabitat can be observed (Fig. 4 b). *Globobulimina turgida*, which is expected to show the lowest species mean $\delta^{13}C$ values, exhibits the second highest values in both time periods. *Hyalinea balthica*, which prefers a shallow to intermediate infaunal microhabitat (e.g., Corliss and Van Weering, 1993; Fontanier et al., 2002) shows the lowest values. *Uvigerina mediterranea* is the only species showing higher $\delta^{13}C$ values than *G. turgida*. Using the same hypothetic assumptions as described above for *M. barleeanus*, the vital effects$_{Gt}$ of *C. laevigata*, *H. balthica*, and *M. zaandami* can be approached. The vital effects$_{Gt}$ were calculated as the mean of the three biggest differences between paired samples and interpreted as maximal realized difference between the investigated species and *G. turgida* (Tab. 3b). They average out at 0.7 +/- 0.1 ‰ for *C. laevigata*, 1.3 +/- 0.1 ‰ for *H. balthica*, and 0.1 +/- 0 ‰ for *M. zaandami*. Note, that the same causes for uncertainty exist as for the vital effect$_{Gt}$ estimate of *M. barleeanus*. Apart from the above-described limitations, we do not know the offset of *G. turgida* $\delta^{13}C$ values from equilibrium with pore water $\delta^{13}C_{DIC}$. As far as we know, there might be a vital effect in some *Globobulimina* species, which makes their tests lighter than pore water $\delta^{13}C_{DIC}$ (McCorkle and Keigwin, 1990). The possible vital effect of *G. turgida* will therefore further increase the degree of underestimation. Furthermore, the $\delta^{13}C_{DIC}$ gradient is less pronounced in Core 225510 than in Core 225514 (Fig. 5). Thus, the slope related mismatch might be smaller in Core 225510 than in Core 225514. Therefore, the vital effect$_{Gt}$ estimate for *M. zaandami* might be more reliable than the one for *M. barleeanus*. The vital effect$_{Gt}$ estimates for *C. laevigata* and *H. balthica*, however, might be less reliable since these species are not likely to occur in the same sediment depth as *G. turgida* due to their lower tolerance for oxygen deficiency.

Despite all limitations we decided to present the estimated vital effects$_{Gt}$, because they are, although underestimated, of considerable size. Remineralization rates and organic matter rain rates deduced from $\Delta\delta^{13}C$ values of epifaunal and infaunal living species might be overestimated by far if vital effects are ignored. To our knowledge, *H. balthica*, the species exhibiting the biggest vital effect$_{Gt}$ (> 1.3 ‰) of all investigated species, has not been used for reconstruction purposes, so far. *Melonis barleeanus* (vital effect$_{Gt}$ > 0.7 ‰), however, has already been considered (Schmiedl and Mackensen, 2006), although with precautions due to its varying microhabitat preference (e.g., Mackensen et al., 2000; Schmiedl and Mackensen, 2006).

In Figure 5 vital effect$_{Gt}$ corrected $\delta^{13}C$ mean values of *C. laevigata*, *H. balthica*, *M. barleeanus*, and *M. zaandami* as well as uncorrected means measured for all other species are presented. Since $\delta^{13}C$ values of *B. marginata* and *B. skagerrakensis* are consistently higher than those of *G. turgida*, possible vital effects could not be assessed. In Core 225514, $\delta^{13}C$ values of *M. barleeanus* now reflect values expected from its microhabitat preference. Similarly, in Core 225510 vital effect$_{Gt}$ corrected $\delta^{13}C$ values now show a species mean value succession, which reflects the species microhabitat preferences. Note, that reconstructions of Figure 5 are only one possibility of many concerning the depth distribution of the species and thus the shapes of $\delta^{13}C_{DIC}$ gradients. Total $\delta^{13}C_{DIC}$ ranges, however, are fixed, since they result from measured values.

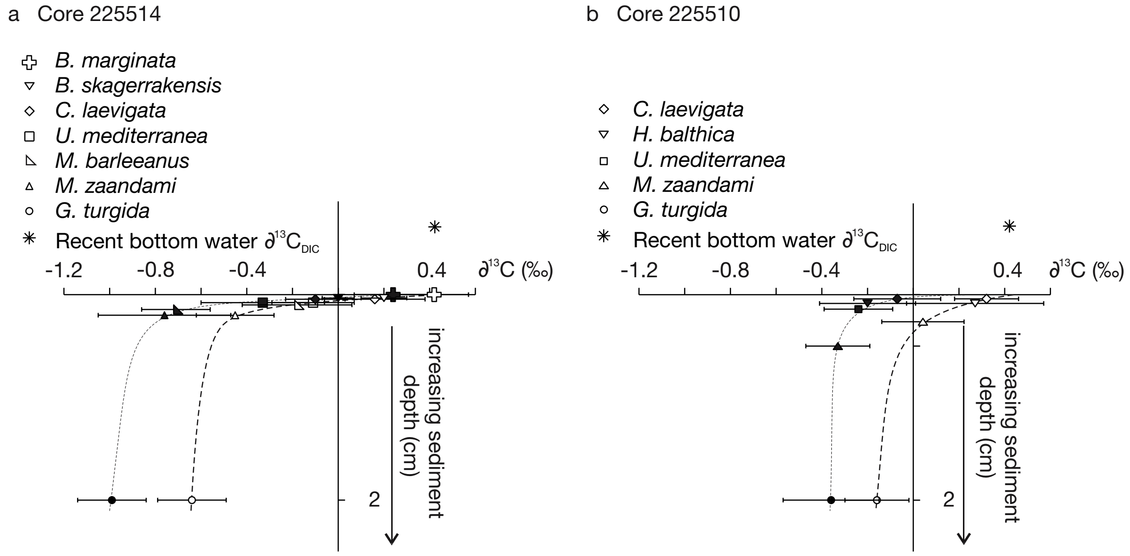


Fig. 5: (a) Vital effect corrected species-specific mean $\delta^{13}C$ values of the time period AD 1500 – 1950 (open symbols) and AD 1950 – 2000 (filled symbols) in Core 225514 and (b) in Core 225510.
For further information about the vital effect correction and arrangement of species versus depth see text section 5.1. Reconstructed $\delta^{13}C_{DIC}$ gradients for both time periods are indicated by dotted lines.

5.2 Organic matter rain rates and oxygen availability

5.2.1 Organic matter rain rates

According to Schmiedl et al. (2004) $\delta^{13}C$ values of *Uvigerina mediterranea* are reliable recorders of changes in organic matter rain rates to the seafloor in the Mediterranean Sea; higher rain rates result in lower $\delta^{13}C$ values and *vice versa*. Mean $\delta^{13}C$ values of *U. mediterranea* in both cores are > 0.2 ‰ lower between AD 1950 and 2000 than in the period before (Tab. 2) and thus would indicate increased organic matter fluxes to the seafloor since about AD 1950. The difference in *U. mediterranea* mean values in Core 225514 is not statistically significant on the 95 % confidence level (Tab. 2a) due to insufficient data covering after AD 1950. We suggest, however, that the derived interpretation of increased organic matter flux to the seafloor after AD 1950 is correct, since the mean values of all other shallow infaunal species in both cores as well as the mean values of *U. mediterranea* in Core 225510 show lowered values after AD 1950, which are significant on the 95 % confidence level (Tab. 2). Thus, we conclude that organic matter flux to the seafloor increased at both core sites after AD 1950.

During both investigated time periods differences between mean $\delta^{13}C$ values of *U. mediterranea* at the two core sites diverge by only 0.1 ‰ (Tab. 2). Since the difference of 0.1 ‰ lies within the interpretation uncertainty of +/-0.2 ‰, we suggest that the flux of organic matter to the seafloor was equal at both sites during the whole investigated time range and increased at both sites after AD 1950.

The assumption of enhanced nutrient availability in the Skagerrak-Kattegat region during the last 50 years, which is commonly attributed to large-scale human-induced eutrophication, is supported by benthic foraminiferal assemblage investigations and several other studies (e.g., Josefson, 1990; Josefson et al., 1993; Seidenkrantz, 1993; Alve and Murray, 1995; Richardson and Heilmann, 1995; Alve, 1996; Andersson, 1996; Edwards et al., 2002). Declining oxygen concentrations within the Skagerrak water masses during the second part of the 20th century are also attributed to anthropogenic eutrophication (e.g., Rosenberg, 1990; Andersson, 1996; Johannessen and Dahl, 1996; Rosenberg and Nilsson, 2005). However, Gray and Abdullah (1996) question methods, results and their interpretation. Furthermore, these investigations concern the shallow coastal areas, only. In monitoring data of Skagerrak deep waters no decline in oxygen concentrations is detectable (e.g., Dahl and Danielssen, 1992; Aure and Dahl, 1994). Investigations of shallow Swedish fjord sediments outline the importance of climate variability and suggest that anthropogenic eutrophication is of minor importance (e.g. Nordberg et al., 2000; Nordberg et al., 2001; Filipsson and Nordberg, 2004). The most recent publication investigating nutrient availability within the North Sea concludes that observed changes in all trophic levels during the late 1970s to early 1990s might be the result of changed hydro-climatic conditions rather than of anthropogenic eutrophication (Edwards et al., 2002). According to Edwards et al. (2002), the late 1980s and early 1990s were characterized by exceptional high temperatures and salinities, probably due to enhanced Atlantic inflow via the English Channel and a persistently high North Atlantic Oscillation index state. Nutrient availability and plankton abundances were very high within the North Sea and also increased in the Kattegat-Skagerrak region (Josefson, 1990; Danielssen and Dahl, 1992; Josefson et al., 1993). The late 1980s and early 1990s coincide with the time period during which lowest $\delta^{13}C$ values are recorded in most benthic foraminiferal species of the investigated Skagerrak cores (Fig. 3).

5.2.2 Oxygen availability

The $\delta^{13}C$ difference between epifaunal *Cibicidoides* species, which record bottom water $\delta^{13}C_{DIC}$ values and deep infaunal *Globobulimina* species, which reflect $\delta^{13}C_{DIC}$ values of pore waters, records most of the effect that oxygen driven organic matter decay exerts on pore water $\delta^{13}C_{DIC}$ values (McCorkle and Keigwin, 1990; Schmiedl and Mackensen, 2006). Organic matter decay, in turn, was tied to the oxygenation of the overlying bottom water mass (McCorkle and Emerson, 1988; McCorkle and Keigwin, 1990; Schmiedl and Mackensen, 2006). Bigger differences between epifaunal and deep-infaunal species are suggested to indicate higher remineralization rates within the sediments due to respiration. Higher remineralization rates are suggested to be the result of enhanced oxygen concentrations in the overlying bottom water mass. Since no truly epifaunal species was present in the investigated cores, we will rely on the comparison of the ranges of reconstructed $\delta^{13}C_{DIC}$ gradients for interpretation (Fig. 5). Since the flux of organic matter to the seafloor was similar at both core locations during each investigated time period, differences in $\delta^{13}C_{DIC}$ ranges can be quantified by comparing mean $\delta^{13}C$ values of *G. turgida*: Between AD 1500 and 1950 mean values of *G. turgida* are 0.5 ‰ lower at Site 225514 than at Site 225510; between AD 1950 and 2000 they are 0.6 ‰ lower (Tab. 2). Thus, during both investigated time periods the ranges of reconstructed $\delta^{13}C_{DIC}$ gradients are bigger at Site 225514 than at Site 225510 (Fig. 5). We suggest that 0.5 to 0.6 ‰ bigger $\delta^{13}C_{DIC}$ ranges in Core 225514 are the result of enhanced organic matter remineralization by respiration due to higher oxygen availability.

This raises the question why oxygen availability in Core 225514 is generally enhanced compared to Core 225510. Core 225510 was recovered from 285 m water depth, shortly below the sill in 270 m water depth, which separates the Skagerrak basin from the North Sea. Site 225510 is permanently bathed by waters from the Northern Jutland Current (see current cross sections by Larsson and Rodhe, 1979). Core 225514 was recovered from a site in 420 m water depth, which lies distinctly below the sill depth. Site 225514 is occasionally bathed by Northern Jutland Current water masses (Larsson and Rodhe, 1979) but also experiences regularly occurring stagnation periods and subsequent deep-water renewal events (Brückner and Mackensen, 2006). Thus, in periods during which Site 225514 is bathed in Northern Jutland Current water masses both sites would experience equal oxygen concentrations. During stagnation periods, however, oxygen concentrations in the water masses overlying Site 225514 are presumably lower than those overlying Site 225510. This is in contrast to the results of McCorkle and Emerson (1988) and Schmiedl and Mackensen (2006) who interpreted differences in $\delta^{13}C_{DIC}$ gradients as indicating different oxygen concentrations in the overlying bottom water mass. Thus, we will modify their interpretation so that oxygen availability *within* the sediments was generally enhanced at Site 225514 compared to Site 225510 without tying it to the oxygenation of the overlying bottom water mass: Hartnett et al. (1998) showed that organic carbon burial efficiencies linearly increase as oxygen exposure times logarithmically decrease. The authors argued that oxygen exposure time integrates all parameters influencing organic carbon burial: primary production rate, organic carbon rain rate, bulk sedimentation rate, and bottom water oxygenation. Carbon burial efficiency was defined as "the burial rate of OC (organic carbon) below 15 cm, expressed as a percentage of the total OC input to the seafloor". Oxygen exposure time was calculated as oxygen penetration depth divided by linear sedimentation rate and reflects the time that organic matter is exposed to molecular oxygen in sediment pore waters. Since the Recent oxygen penetration depth in the Skagerrak is maximal two centimeters (e.g., Bakker and Helder, 1993; Rysgaard et al., 2001), maximal oxygen exposure times can be calculated for both core locations (for sedimentation rates see Fig. 2): around AD 1890 they change from 8.6 to 14 years in Core 225514 and from 2.5 to 0.4 years in Core 225510 around AD 1950. This implies that due to lower sedimentation rates, organic carbon deposited at Site 225514 is much longer exposed to oxygen than organic carbon buried at Site 225510. Longer exposure times result in higher remineralization rates due to respiration at Site 225514 compared to Site 225510. We therefore suggest that oxygen exposure time, which is a function of sedimentation rate and oxygen penetration depth, determines total remineralization rates as expressed by reconstructed $\delta^{13}C_{DIC}$ ranges. This interpretation might be important for environments characterized by limited oxygen availability within the sediments and strongly variable sedimentation rates, thus, especially for shelf environments. On the other hand, total $\delta^{13}C_{DIC}$

ranges might be primarily determined by bottom water oxygenation in regions characterized by limited oxygen availability within the sediments and comparably stable sedimentation rates.

6 Conclusions

Benthic foraminiferal $\delta^{13}C$ values of two sediment cores from the southern flank of the Skagerrak were investigated. The cores 225514 and 225510 were recovered from 420 and 285 m water depth, respectively. The data presented comprise the last 500 years.

(1) We presented minimum estimates for microhabitat-corrected vital effects of *Hyalinea balthica* (> 1.3 ‰), *Melonis barleeanus* (> 0.7 ‰), and *Cassidulina laevigata* (> 0.7 ‰) with respect to $\delta^{13}C$ values of *Globobulimina turgida* (vital effect_{Gt}). The $\delta^{13}C$ value of *Melonis zaandami* seems to closely reflect pore water $\delta^{13}C_{DIC}$. Although these values assumedly contain strong mismatches, they should be discussed since they are of considerable size. To prevent strong overestimates of reconstructed remineralization rates by $\Delta\delta^{13}C$-proxies, investigations of benthic foraminiferal vital effects have to be intensified.

(2) We reconstructed $\delta^{13}C_{DIC}$ gradients for the time periods AD 1500 to 1950 and AD 1950 to 2000 for both cores by arranging vital effect_{Gt} corrected mean $\delta^{13}C$ values according to the species' microhabitat preferences.

(3) Mean $\delta^{13}C$ values of *Uvigerina mediterranea* indicate that organic matter rain rates to the seafloor increased after AD 1950 at both core sites. Enhanced nutrient availability after AD 1950 probably resulted from changes in the North Atlantic current system, which led to enhanced influx of nutrient rich Atlantic water masses into the North Sea. Simultaneously, a persisting high North Atlantic Oscillation index state resulted in generally enhanced temperatures. Exceptionally high primary production within the North Sea and presumably also in Skagerrak and Kattegat was the consequence.

(4) Comparison of mean $\delta^{13}C$ values of *U. mediterranea* from Site 225514 and Site 225510 revealed that organic matter rain rates were similar at both locations during each investigated time interval.

(5) Since the export of organic matter to the seafloor was similar at both core locations during each investigated time interval, we were able to quantify differences in reconstructed $\delta^{13}C_{DIC}$ ranges of the two core locations by

comparison of mean $\delta^{13}C$ values of *Globobulimina turgida*. We concluded that total organic matter remineralization by respiration as reflected by reconstructed $\delta^{13}C_{DIC}$ gradients was generally enhanced at Site 225514 compared to Site 225510.

(6) This implied generally enhanced oxygen availability within the sediments at Site 225514 compared to Site 225510. Bottom water oxygenation, however, was presumably similar at both sites or even reduced at Site 225514. We therefore suggested that oxygen availability within Skagerrak sediments might be explained by oxygen exposure times as proposed by Hartnett et al. (1998). In sediments with limited oxygen availability strongly varying sedimentation rates may primarily control the oxygen available for organic matter remineralization. This hypothesis might be especially valuable for shelf environments. Contrary, in sediments with limited oxygen availability and relatively constant sedimentation rates, organic matter remineralization rates may primarily be controlled by changing oxygen concentrations in the overlying bottom water mass.

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2.3 MANUSCRIPT III

Benthic foraminifera and relative organic matter contents in Holocene Skagerrak sediments, NE North Sea

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Abstract

The benthic foraminiferal assemblages of two sediment cores from the southern flank of the Skagerrak were determined and related to the amount of total organic carbon (TOC) within the sediments. Core 225514 was recovered from 420 m water depth, whereas Core 225510 was taken from from 285 m water depth. Core 225514 reveals a chronological succession of three assemblages mirroring Recent lateral faunal distribution patterns from basin margins to the deep Skagerrak: the *Hyalinea balthica* assemblage, the *Cassidulina laevigata* assemblage and the *Bolivina skagerrakensis* assemblage. Benthic foraminiferal assemblages in Core 225510 intermittently change between the *Elphidium excavatum*, the *Cassidulina laevigata*, and the *Globobulimina turgida* assemblage. Coincidence between benthic foraminiferal assemblages as well as species frequencies and specific amounts of sedimentary TOC is demonstrated for historic and modern times. We suggest that the chronological succession of seasonal-phytophagous and phytophagous faunas in Core 225514 is due to the changing hydrographic predominance from a stronger Baltic to a stronger North Sea influence around AD 700. This switch increased relative amounts of TOC within sediments imported into the Skagerrak. Variable TOC contents and accordingly changing benthic foraminiferal assemblages within Core 225510 reflect the vertically changing position of the Northern Jutland Current during last the 500 years. Similar ranges of sedimentary TOC but different dominant assemblages may result from different

qualities of sedimentary TOC as deduced from C:N values within the investigated cores.

keywords: benthic foraminifera, TOC, Skagerrak, North Sea, Holocene, seasonal-phytophagous

1 Introduction

The benthic foraminiferal fauna in Skagerrak, Kattegat and the surrounding fjords has been studied extensively, both its succession in time (e.g., Nagy and Qvale, 1985; Nordberg, 1991; Seidenkrantz, 1993b) and its spatial distribution (e.g., Höglund, 1947; Lange, 1956; Risdal, 1963; Qvale, 1985; Conradsen et al., 1994; Alve and Murray, 1995). The transitional area between North Sea and Baltic Sea seems to be promising for research on benthic foraminifera because of its rather limited extension. The hydrography and the associated sedimentary system, however, are quite complex. The counter clockwise circulation system consists of different currents. Water masses are stratified and roughly distinguishable based on temperature and salinity characteristics (Rydberg et al., 1996). Since Recent and Subrecent benthic foraminiferal distributions in the Skagerrak appear to trace the different water masses, it has been suggested that they are mainly, although probably indirectly, steered by diverging water-mass properties, current intensities and/or related sediment characteristics (e.g., Qvale and Van Weering, 1985; Conradsen et al., 1994; Bergsten et al., 1996). Seidenkrantz (1993a) reinforced these results but stated that benthic foraminiferal faunas are also influenced by water depth, relative content of organic carbon (TOC) within the sediments, and sediment grain size distributions. Seidenkrantz (1993a) described assemblage changes in Subrecent times, which she attributed to species migration, possibly due to minor hydrographical changes or occasional down-slope re-deposition.

Hass (1997) investigated the benthic foraminiferal assemblages of the Skagerrak with regard to their connection to climate change. He concluded that the composition of benthic foraminiferal faunas in the Skagerrak is influenced either directly by locations and intensities of the different currents or indirectly, because the current system also influences food supply and bottom water oxygenation. Climate change only partly explains physical changes in the current system.

Furthermore, modern eutrophication of the Skagerrak region has been suggested to influence benthic foraminiferal faunas. In the Kattegat, Seidenkrantz (1993a) found a *Hyalinea balthica* assemblage, which was substituted by a *Bulimina marginata* assemblage, most probably because of anthropogenic eutrophication and subsequent oxygen depletion within the last 20 years. Alve and Murray (1995) and Alve (1996) compared Recent and Subrecent benthic foraminiferal faunas and densities with those encountered in the Skagerrak by Höglund in 1937 (Höglund, 1947). The authors found changes in the assemblage composition and increased standing stocks in the deeper parts of the Skagerrak, which they assume to be the result of increased nutrient supplies due to anthropogenic influence.

Meanwhile, it is generally accepted that benthic foraminiferal assemblage composition and microhabitat depend mainly on the quantity, quality and mode of organic carbon fluxes (e.g., Lutze and Coulbourn, 1984; Gooday, 1988; Corliss and Emerson, 1990; Loubere, 1991; Altenbach et al., 1999; Langezaal et al., 2003). Furthermore, oxygen concentrations in pore waters seem to have considerable influence on microhabitat as well as on assemblage composition and standing stocks if critical thresholds are passed (e.g., Corliss, 1985; Bernhard, 1992; Bernhard, 1993; Sen Gupta and Machain-Castillo, 1993; Jorissen et al., 1995; Loubere, 1997; Jorissen et al., 1998; Kaiho, 1999; Van der Zwaan et al., 1999; den Dulk et al., 2000; Gooday et al., 2000; Geslin et al., 2004). We will demonstrate that benthic foraminiferal dominance in Skagerrak sediments is indeed only indirectly steered by hydrography. Relative TOC contents within the sediments and the quality of sedimentary organic matter determine the dominance of specific species. Differences in quality and relative amounts of organic matter, however, result from changes in the physical current system. The species investigated are mainly seasonal-phytophagous species. They are shown to depend on sedimentary TOC contents rather than on the flux of organic matter to the seafloor.

2 Regional setting

The Skagerrak with its over 700 m water depth is the deepest part of the Norwegian Trench and the North Sea in general and thus the most important depositional sink of the North Sea (Fig. 1). Major parts of sediments and nutrients originate from areas of the southern and eastern North Sea (e.g., Van Weering, 1981; Anton et al., 1993; Kuijpers et al., 1993; Lepland and Stevens, 1996). Several authors investigated the organic matter deposited in Skagerrak sediments and estimated that up to 89% is allochthonous and refractory (e.g., Van Weering and

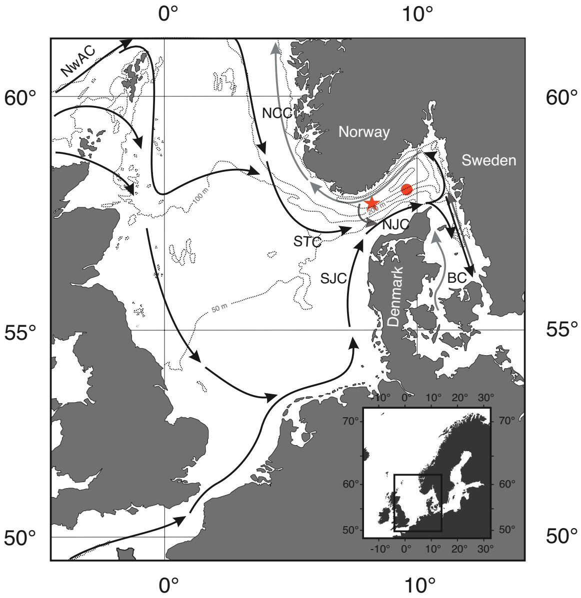

Fig. 1: Map of the area of investigation with core sites denoted by asterisk (Core 225514) and filled circle (Core 225510), hydrography following Nordberg et al. (1991), black arrows indicating deep currents, and grey arrows indicating shallow ones. NwAC = Norwegian Atlantic Current, STC = Southern Trench Current, SJC = Southern Jutland Current, NJC = Northern Jutland Current, BC = Baltic Current, NCC = Norwegian Coastal Current.

Kalf, 1987; Meyenburg and Liebezeit, 1993). Sediments and particulate organic matter enter the Skagerrak mainly via the Southern Jutland Current (SJC) but are also imported with the Southern Trench Current (STC) coming from the northeast (Fig. 1). The current system of the Skagerrak is counter clockwise and reaches down to 400 – 500 m water depth (Rodhe, 1987). A sill in 270 m water depth restricts the water exchange between Skagerrak and North Sea (Rodhe, 1987). The water masses of the SJC and the STC unite to form the Northern Jutland Current (NJC). The NJC oscillates between mid and upper water depths (Rydberg et al., 1996). Progressing to the northeast, brackish surface waters from the Baltic Current (BC) are added to form the Norwegian Coastal Current (NCC), which exits the Skagerrak in the northwest. Smaller amounts of NCC water masses are recycled in the western part of the basin (Rodhe, 1987).

The water masses of the Skagerrak are roughly distinguishable by the salt content (Rydberg et al., 1996). Brackish water masses of Baltic Sea origin have salinities between 20 and 30. Deep and intermediate waters, originating from the Central North Sea and Norwegian Atlantic Current (NwAC) show salinities between 31 to 35 and > 35, respectively (Rodhe, 1987). Skagerrak deep-water is renewed every second to third year, triggered by the negative phase of the North Atlantic Oscillation (Hagberg and Tunberg, 2000; Brückner and Mackensen, 2006). Strongly cooled Central North Sea water masses reach higher densities than deep Skagerrak water masses and occasionally cascade into the Skagerrak basin (Ljøen and Svansson, 1972; Ljøen, 1981).

3 Material and Methods

The gravity cores investigated here were recovered from the southern flank of the Skagerrak during Cruise 159 with RV *Alkor*. Core 225514 was was taken from from 420 m at 57°50.260 N and 8°42.327 E and Core 225510 from 285 m water depth at 58°01.920 N and 9°37.172 E (Fig. 1). Core 225514 is 405 cm long and consists of olive-green clayey mud, which frequently shows streaks of light grey color (15 - 85 cm, 135 - 405 cm). The sediments of Core 225510 (544 cm long) are colored in various shades of olive and consist of clayey mud with frequent insertions of silty or fine sandy mud. Frequent occurrences of dark grey to black striae are observed.

Down to 15 cm core depth Core 225514 was sampled every centimeter. Between 15 and 80 cm core depth every second to third centimeter and from 80 cm to core bottom every fifth centimeter was sampled. Sediments of Core 225510 were sampled every fifth centimeter throughout. The slices of one centimeter thickness were freeze dried and subsequently wet sieved to obtain the sediment fractions 125 μm to 2 mm and > 2 mm. The grain-size fraction > 2 mm is devoid of benthic

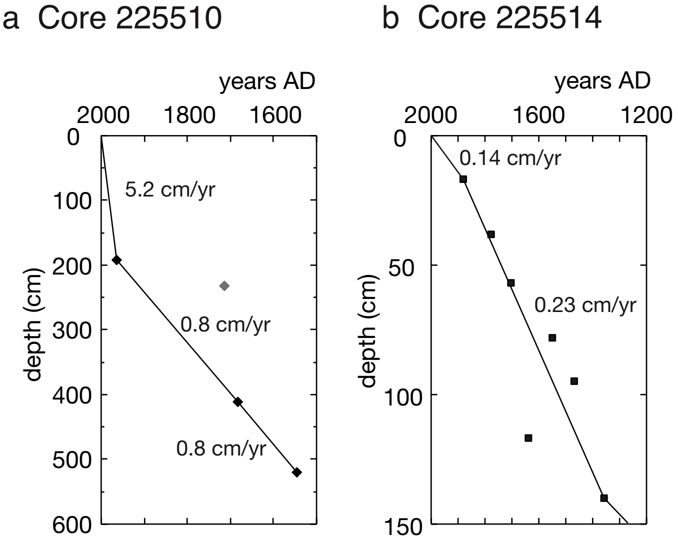

Fig. 2: (a) Age-depth relation of the AMS ^{14}C based age model of Core 225510 (black diamonds). The grey diamond marks the dating point, which was discarded as it was considered to be too old (see text section 3).
(b) Age-depth relation in Core 225514. Note different scales of x-axis.

foraminifera.

The age model of Core 225514 (Fig. 2b) relies on the age model of Core III KAL (Hass, 1996), which was recovered only 150 m away. Dominant benthic foraminiferal species and their frequencies are almost identical in both cores and occur in exactly the same depth ranges. Faunal changes and characteristic frequency features were used to tie the age model of Core III KAL to Core 225514 (see Brückner and Mackensen, 2006). Hass (1996) used the “advanced ^{210}Pb method” (Erlenkeuser, 1985) to establish the age model of Core III KAL. This method allows dating until approximately 3500 years before present (cal BP). Sediments younger than 160 years were dated using the “excess ^{210}Pb method”. Older sediments were dated with help of the “^{226}Ra supported ^{210}Pb method” following Erlenkeuser (1985). For detailed information about the method and the model see Hass (1996) and Erlenkeuser (1985). Since the “advanced ^{210}Pb method” allows dating of the youngest three core meters only, the fourth meter will be discussed against core depth. For further information about the adoption of the age model of Core III KAL to Core 225514 see Brückner and Mackensen (2006).

Bulk calcareous benthic foraminiferal tests were used to date Core 225510 via the AMS ^{14}C method (Tab. 1). Measurements were carried out at the Leibniz-Labor for Radiometric Dating and Isotope Research in Kiel/Germany, that also corrected the measurements for natural isotope fractionation. We used the radiocarbon calibration program Calib rev. 4.3 (Stuiver and Braziunas, 1989) together with the marine model calibration curve of Stuiver and Braziunas (1989) to calibrate and transform AMS ^{14}C dates to calendar years. Following Heier-Nielsen et al. (1995) the global reservoir correction of about 400 years ($\Delta R = 0$) was applied.

Tab. 1: Conventional and to calendar years calibrated AMS ^{14}C dates on bulk benthic foraminiferal tests of Core 225510. Date with asterisk was calibrated with CALIBomb, see text section 3.

depth (cm)	AMS ^{14}C	standard deviation	years AD
20.5	-280	25	
191.5	350	35	1962*
232.5	550	30	1715
411.5	605	25	1684
520.5	740	25	1546

The AMS ^{14}C date in 192 cm core depth (< 400 years) was calibrated and transformed by using the program CALIBomb (http://www.calib.org) together with the NH1 dataset (Hua and Barbetti, 2004). The AMS ^{14}C measurement was carried out in AD 2001. The oldest suggested age was used in order to keep sedimentation rate as low as possible. Nevertheless, it accounts for 5.2 cm/year in the top 192 cm as opposed to 0.8 cm/year below (Fig. 2). AMS ^{14}C dates above this level gave no meaningful results. We therefore assumed the top of Core

225510 to be AD 2000. The sample from 232.5 cm core depth was considered as too old and thus rejected. The age model was constructed by linear interpolation (Fig. 2).

The TOC and N measurements were carried out at the Baltic Sea Research Institute in Warnemuende. The content of total carbon, total inorganic carbon and nitrogen of freeze dried and homogenized samples was analyzed in a Heraeus Elemental Analyzer. Inorganic carbon was measured with an ELTRA Metalyt CS 1000 S C/S analyzer by quantification of evolving CO_2 after treatment with phosphoric acid. Total organic carbon was calculated as the difference between total carbon and total inorganic carbon.

The benthic foraminiferal content of the sediment samples (> 125 μm) was identified and counted on species level. The taxonomic classification was carried out according to Höglund (1947), Ellis and Messina (1949), Feyling-Hanssen (1971), Qvale and Nigam (1985), Loeblich and Tappan (1988), Mackensen and Hald (1988), and Jones (1994). The samples were split when the number of enclosed benthic foraminifera exceeded the statistically necessary number of 300 specimens per sample. To simplify the interpretation of the complex matrix of depths and species, Q-mode Principle Component Analysis (PCA) with subsequent Varimax rotation was performed, using the computer program SYSTAT^{TM} 5.2.1. The original data set was reduced so that all species, which did not occur in at least two depth horizons with amounts > 1% of the total benthic foraminiferal content of the sample were rejected (Mackensen et al., 1995). *Elphidium excavatum* f. *clavata* was counted separately, whereas all other elphidiids were summarized. Since PCA resulted in an *E. excavatum* f. *clavata* assemblage accompanied by *Elphidium* spp. and the vast majority of all elphidiids consisted of *E. excavatum* f. *clavata*, we decided to summarize all elphidiids within the "*Elphidium excavatum*" group.

In figures 4 and 6 squared faunal factor values (can be read as % of total assemblage variance if multiplied by 100) or the relative frequencies of the dominant species of the respective faunal assemblage are plotted against classified TOC values. Each data point within these figures represents the average factor value (relative frequency) of the assemblage (species) encountered within the respective TOC interval. One sigma standard deviation is indicated. We defined an optimal TOC range with an upper and lower TOC boundary value for each assemblage and species. These boundary values were defined as those values of % TOC, above or below which faunas or species frequencies suddenly increase or decrease while related TOC values change only slightly.

4 Results

4.1 Core 225514

Faunal analysis of the core sediments reveals 113 benthic foraminiferal species, 91 of which are species with calcareous and 22 with agglutinated tests. Three faunal assemblages can be distinguished explaining 91.7 % of the total variance in the dataset. The *Bolivina skagerrakensis* assemblage accounts for 25.1 %, the *Hyalinea balthica* assemblage for 34.3 %, and the *Cassidulina laevigata* assemblage for 32.3 % of the total variance. Communalities range from 0.51 to 0.96; the average value is 0.92.

The oldest part of the core (405 - 210 cm, < 1044 BC – AD 700) is dominated by the *H. balthica* assemblage until approximately AD 700 (Fig. 3a). With its three dominating species it is the most evenly distributed assemblage (Fig. 3b). *Hyalinea balthica* shows the highest factor value, closely followed by *Bulimina marginata* and *Melonis barleeanus*. Around AD 700 (210 cm) this assemblage is successively replaced by the *C. laevigata* assemblage, which prevails until AD 1860 (23 cm). *Cassidulina laevigata* is accompanied by *Melonis zaandami*. The youngest faunal assemblage is characterized by *B. skagerrakensis*, which is accompanied by *C. laevigata*. The importance of this assemblage starts around AD 1450 (110 cm) when *B. skagerrakensis* suddenly becomes frequent. Until AD 1860 the *C. laevigata* assemblage and the *B. skagerrakensis* assemblage alternately dominate. Afterwards, the *B. skagerrakensis* assemblage is the only dominating fauna.

A relationship between average sedimentary TOC values and distinct faunal compositions can be observed (Fig. 3a). Slight shifts in relative TOC contents within the sediments correspond to faunal changes at AD 700 and AD 1490. The *H. balthica* assemblage dominates where sedimentary TOC values are lowest (</= 1.3 – 1.6 % TOC). The *C. laevigata* assemblage dominates where sedimentary TOC values range between 1.6 and 2.2 %, and the *B. skagerrakensis* assemblage dominates where sedimentary TOC values increase exponentially (> 2.2 % TOC)(Fig. 4a-c).

Mean TOC accumulation rates increase from 6 g C m^{-2} yr^{-1} between 1044 BC and AD 500 to 34 g C m^{-2} yr^{-1} between AD 500 and 1869 (Fig. 3a). Between AD 1878 and 2000 mean accumulation rates account for 21 g C m^{-2} yr^{-1}. No relationship between benthic foraminiferal faunas and TOC accumulation rates can be observed. The $\delta^{13}C$ values of *Uvigerina mediterranea* range from –0.61 to 0.29 ‰, and again no relationship between benthic foraminiferal faunas and this

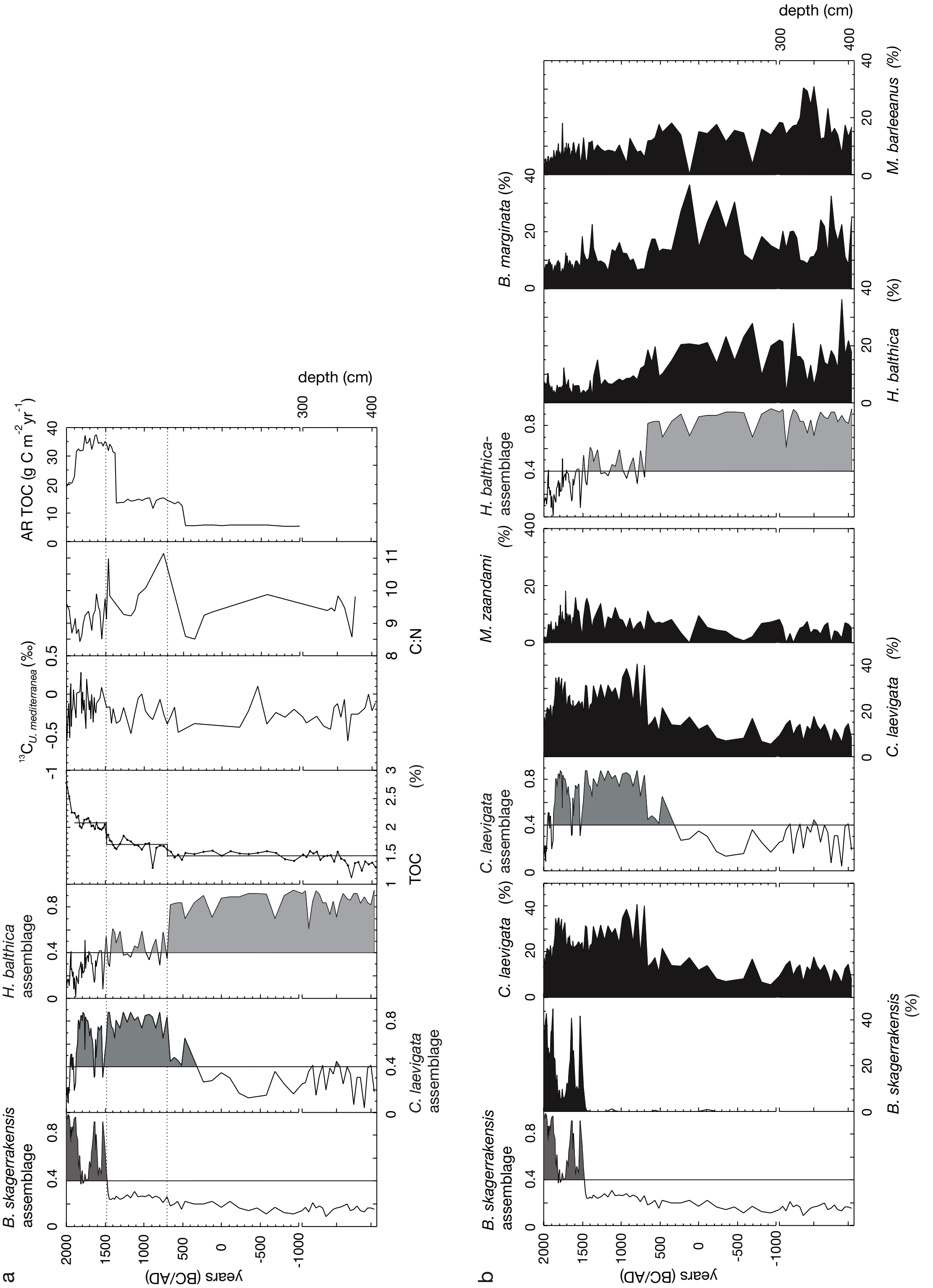

Fig. 3: Core 225514: (a) Factor loadings of assemblages, communalities, relative TOC contents, $\delta^{13}C$ values of *Uvigerina mediterranea*, C:N values and TOC accumulation rates plotted versus age model. The black, solid line within the TOC curve denotes average values for the corresponding time intervals.
(b) Relative frequencies of dominant and associated species for each assemblage plotted versus age.

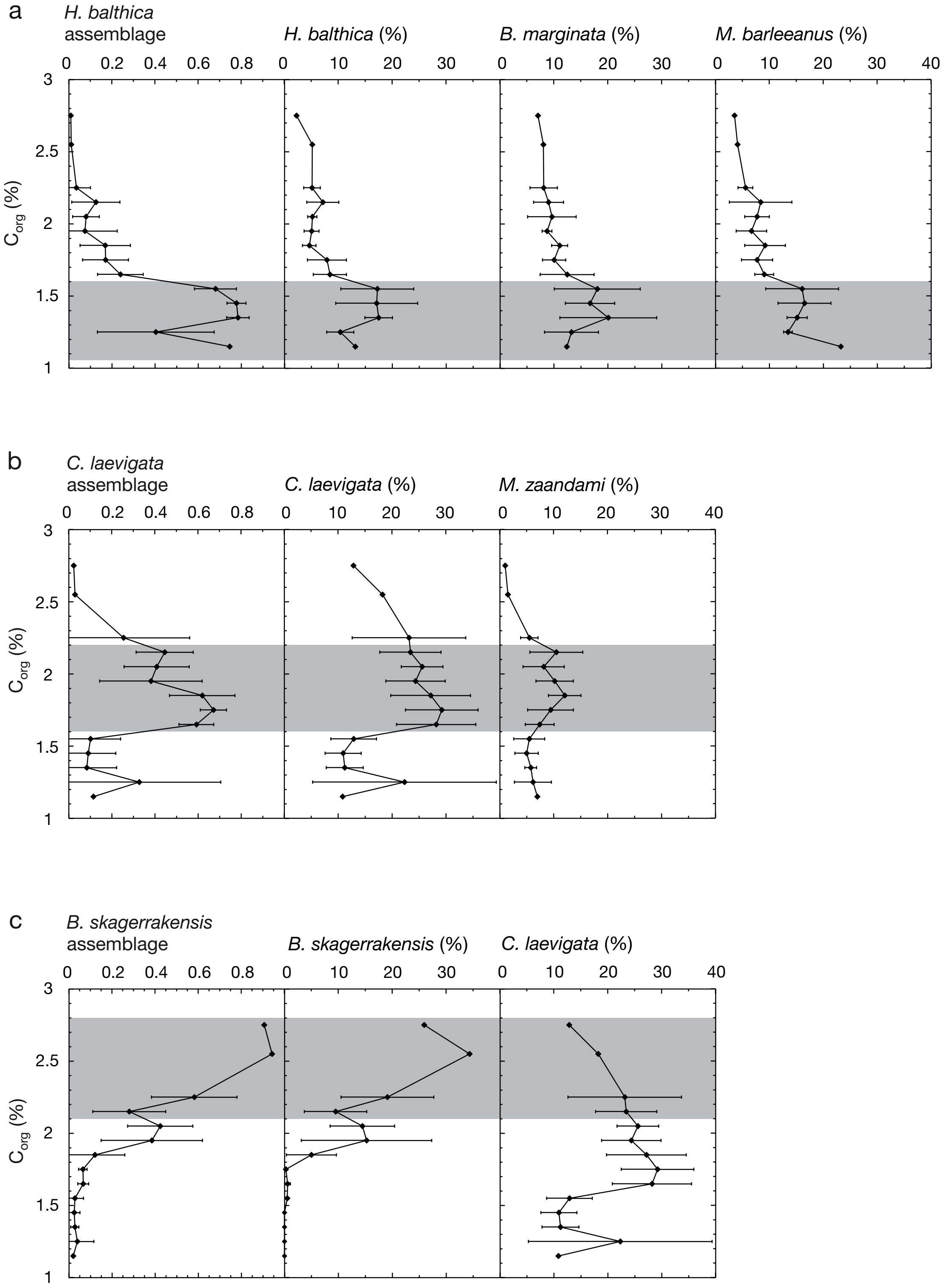

Fig. 4: Core 225514: Squared factor loadings and corresponding relative species frequencies for each assemblage plotted against classified TOC values (a - c). One standard deviation is indicated. Shaded areas highlight optimal TOC ranges for assemblages and species (see text sections 3 and 5.1).

indicator for flux of organic matter to the seafloor can be stated. The same applies to the C:N ratio, which is considered as an indicator for organic matter quality: Values range from 8.4 to 11.1, and no relationship between benthic foraminiferal faunas and C:N ratios can be observed.

4.2 Core 225510

The benthic foraminiferal investigation of Core 225510 reveals 107 taxa, 85 of which possess calcareous and 22 agglutinated tests. Principle Component Analysis allowed a subdivision into three faunal assemblages, which alternately dominate the benthic foraminiferal fauna (Fig. 5a). The faunal model explains 87.5 % of the total variance, wherein the *Elphidium excavatum* assemblage accounts for 37.6 %, the *Cassidulina laevigata* assemblage for 33.2 % and the *Globobulimina turigda* assemblage for 16.7 %. Communalities range from 0.44 to 0.98. The mean is 0.87.

The most important assemblage is dominated by *E. excavatum* and accompanied by *Planorbulina mediterranensis* (Fig. 5b). This assemblage is dominant during the intervals AD 1550 to 1590 (519 - 488 cm), AD 1710 to 1780 (390 - 340 cm), AD 1860 to 1910 (270 - 230 cm), and AD 1950 to 1980 (200 – 100 cm). The *C. laevigata* assemblage, characterized by *C. laevigata* and *Cassidulina neoteretis*, accompanied by *Hyalinea balthica*, dominates the core intervals from AD 1516 to 1550 (544 - 519 cm), AD 1590 to 1660 (488 - 430 cm), AD 1780 to 1860 (340 - 270 cm), AD 1910 to 1950 (230 - 200 cm), and AD 1980 to 1995 (100 - 20 cm). The third assemblage is dominated by *G. turgida*, which is accompanied by *C. neoteretis*. It is only occasionally important and mostly consists of single sample peaks: around AD 1670 (420 cm), AD 1700 (400 cm), AD 1790 (330 cm) and from AD 1980 to 2000 (100 – 0 cm).

Plotted against the relative TOC content of the corresponding sediments a faunal succession can be deduced (Fig. 5a and 6). The *E. excavatum* assemblage dominates where observed TOC values are lowest (< 1.95 % TOC). It is followed by the *C. laevigata* assemblage, which dominates where TOC values range between 1.95 and 2.25 % TOC. The *G. turgida* assemblage occurs when TOC values peak (> 2.25 % TOC). In contrast to Core 225514, where benthic foraminiferal assemblages dominate once and during discrete time intervals only, the predominance of faunal assemblages in Core 225510 changes quickly and assemblages re-occur intermittently.

Mean TOC accumulation rates are 135 g C m^{-2} yr^{-1} between AD 1516 and 1952 (Fig. 5a) and increase between AD 1963 and 2000 to average values of

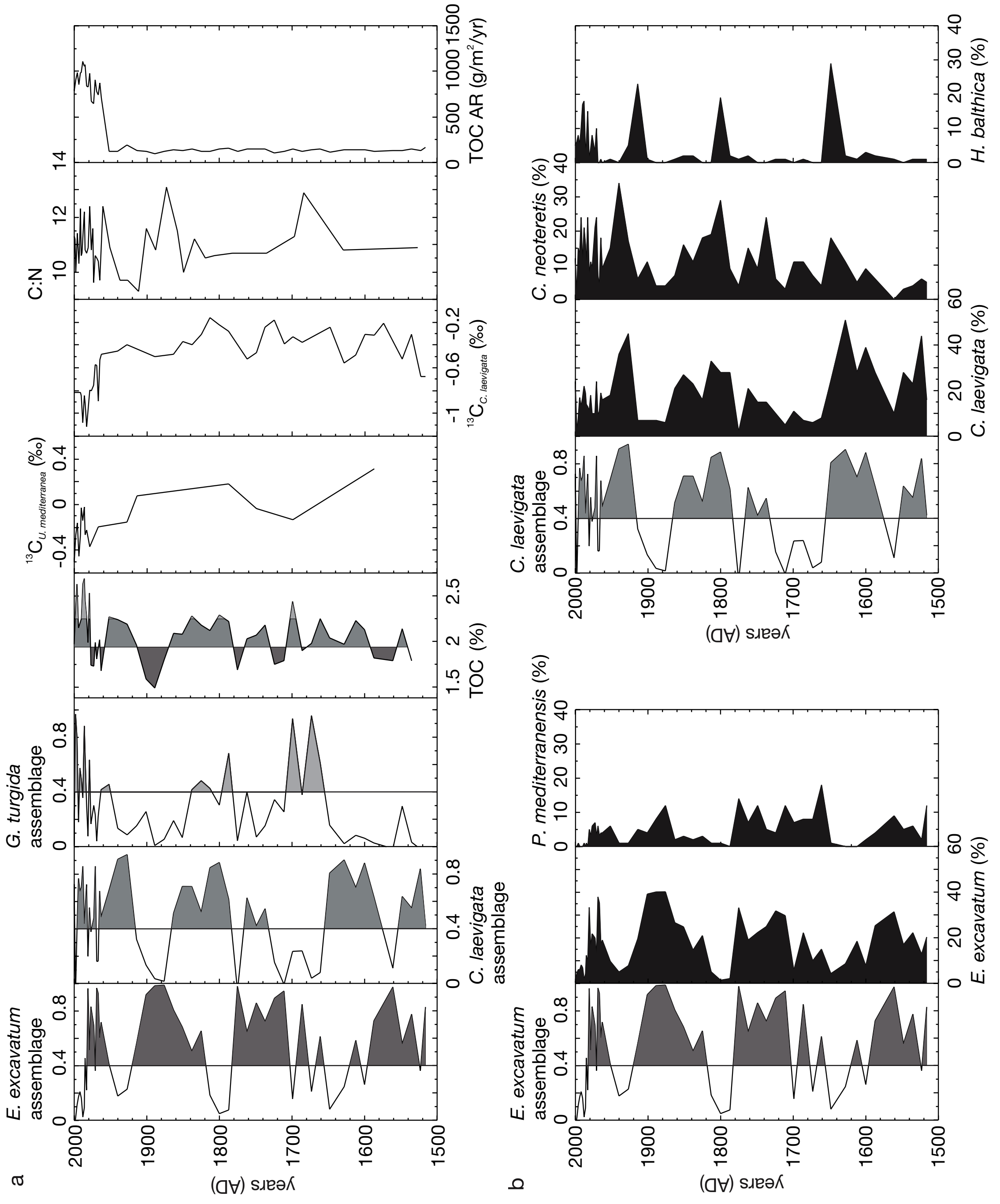

Fig. 5: Core 225510: (a) Factor loadings of assemblages, communalities, relative TOC contents, $\delta^{13}C$ values of *Uvigerina mediterranea* and *Cassidulina laevigata*, C:N values and TOC accumulation rates plotted versus age model. Shading of the TOC curve corresponds to the predominance of the different assemblages.

(b) Relative frequencies of dominant and associated species for each assemblage plotted versus age.

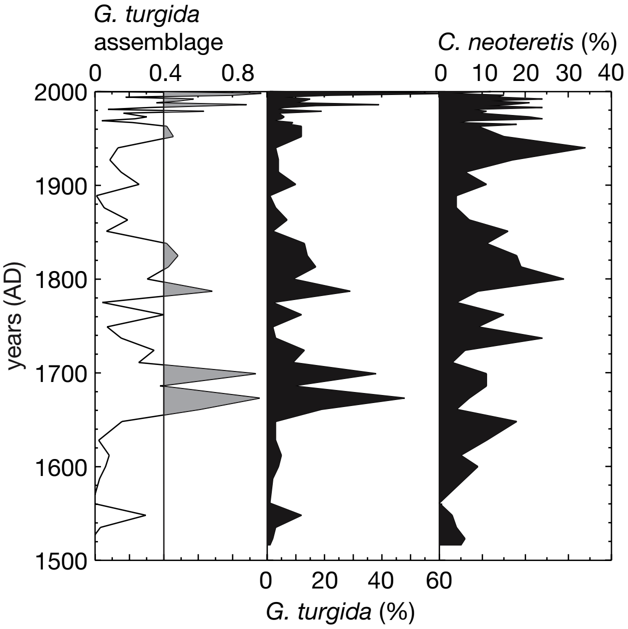

Fig. 5b (continued)

879 g C m^{-2} yr^{-1}. As in Core 225514, no coincidence between benthic foraminiferal assemblages and TOC accumulation rates is observed. The $\delta^{13}C$ values of *Uvigerina mediterranea* range from –0.5 to 0.3 ‰. Since the data sequence of *U. mediterranea* is incomplete, we complement this data set with $\delta^{13}C$ values of *C. laevigata* that range from -1.1 to –0.1 ‰. Neither $\delta^{13}C$ values nor C:N ratios (range from 9.3 to 13.1) show any relationship to benthic foraminiferal faunas.

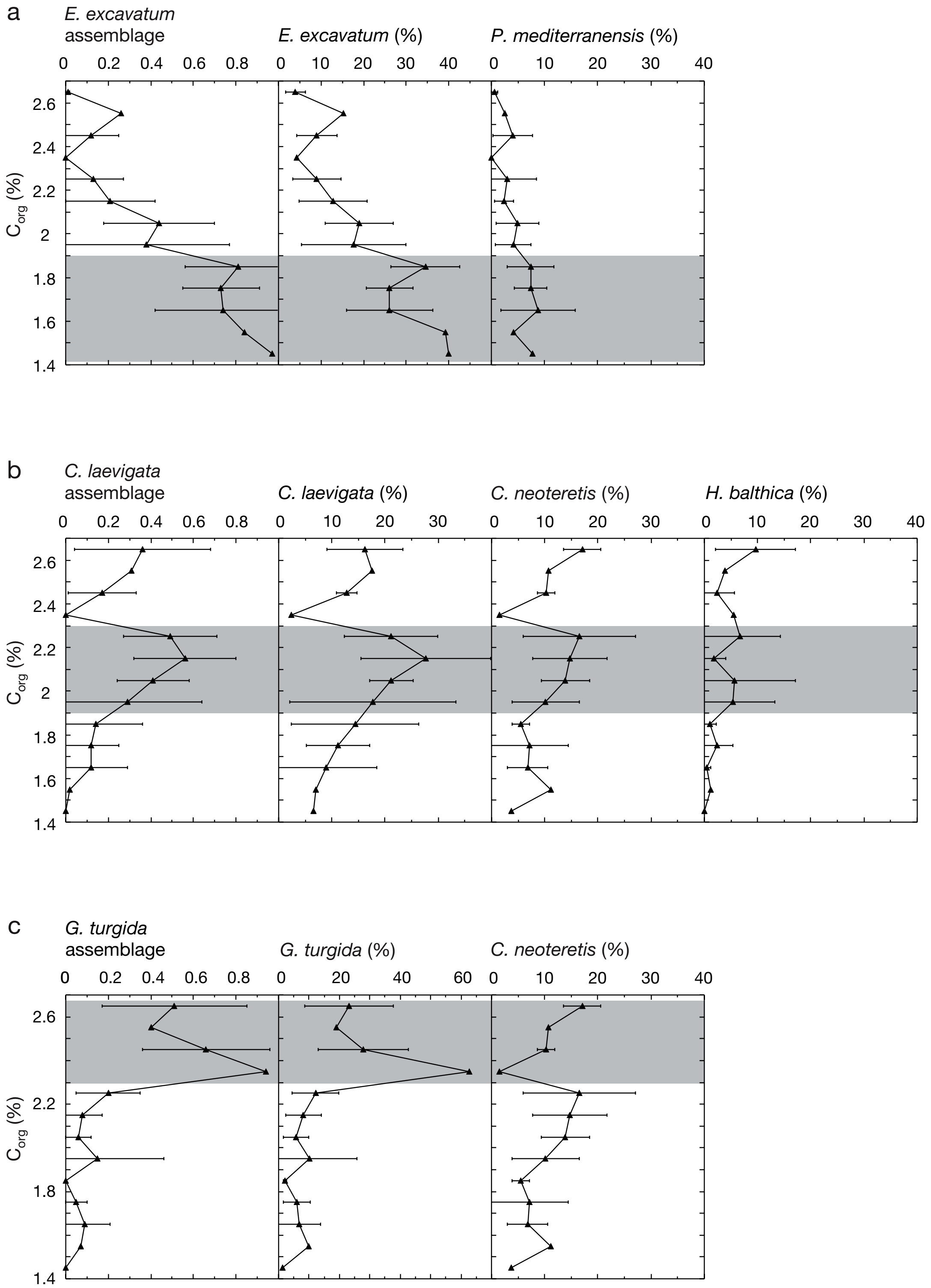

Fig. 6: Core 225510: Squared factor loadings and corresponding relative species frequencies for each assemblage plotted versus classified TOC values (a - c). One standard deviation is indicated. Shaded areas highlight optimal TOC ranges for assemblages and species (see text sections 3 and 5.1).

5 Discussion

5.1 Relationship between benthic foraminifera and sedimentary TOC values

The results show that almost all dominant species of the investigated cores 225514 and 225510 occur over entire core lengths (figs. 3 and 5) and that the dominance of single species coincides with certain ranges of sedimentary TOC (figs. 4 and 6). This finding is in accordance with the basic ecological theory that the successful existence of organisms is restricted by threshold values bracketing optimal conditions (see brief introduction in Murray, 2006). We defined the optimal TOC ranges as bordered by an upper and a lower boundary value, providing optimal nutritious and therefore optimal reproductive conditions for dominant species within Skagerrak background conditions. Altenbach et al. (2003) speculated that the abundance of distinct species within specific environmental gradients follows a Gaussian distribution curve. Frequencies of *Cassidulina laevigata* and *Melonis zaandami* (Core 225514) exhibit bell shaped curves when plotted against corresponding TOC values in a scatter diagram (Fig. 7). Since the bell-shaped frequency distribution and thus the range of optimal TOC contents is fully developed for these two species only, further investigations are necessary to confirm the general applicability of these results.

By comparing the modern spatial foraminiferal distribution in Skagerrak sediments (Conradsen et al., 1994, Fig. 8b) with surface sediment TOC values (Van Weering and Qvale, 1983, Fig. 8a) the same relationship between specific TOC ranges and dominant species as in the investigated cores is evident (figs. 4 and 6), although the suggested relationship is only based on visual comparison of the patterns, since some of the raw data is not available anymore (Van Weering written communication, 2006). Conradsen et al. (1994) identified five foraminiferal assemblages as dominant in Skagerrak and Kattegat surface sediments: *Bolivina skagerrakensis*, *C. laevigata*, *Bulimina marginata*, *Elphidium excavatum*, and *Eggerelloides scabrus*. The deepest part of the Skagerrak, which is characterized by highest sedimentary TOC values (> 3 %), holds the *B. skagerrakensis* assemblage (Fig. 8). Towards the basin margins, perpendicular to the slopes, the amount of sedimentary TOC strongly decreases. Above the *B. skagerrakensis* assemblage, where sediments contain 1.5 to 3 % TOC, *C. laevigata* and *B. marginata* dominate. Along the southern flank of the Skagerrak the distribution of *C. laevigata* is patchy, probably because the area of optimal food supply for this species is narrow, being the result of the steep inclination of this flank. In contrast to that, *C. laevigata* is widely distributed in the eastern part of the Skagerrak, following the gentle decrease

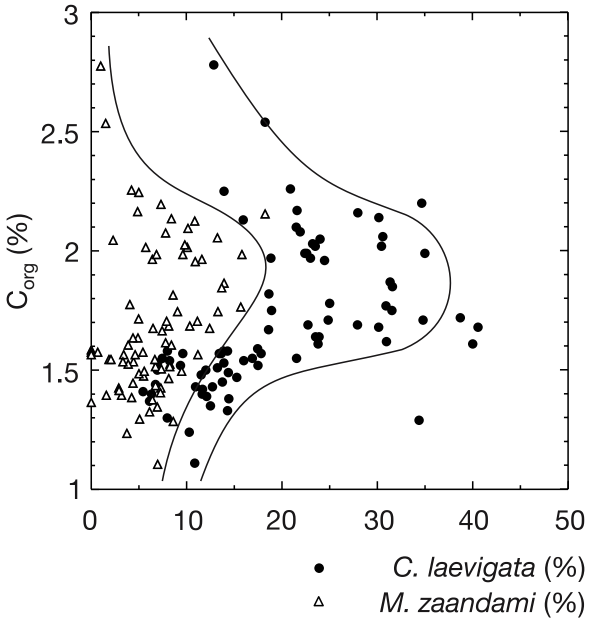

Fig. 7: Relative abundances of *C. laevigata* and *M. zaandami* of Core 225514 plotted versus corresponding TOC values. Black curves approximately indicate the bell shape of these frequency distributions (see text section 5.1).

of sedimentary TOC towards the basin margin. The *B. marginata* assemblage occurs above the *C. laevigata* assemblage along the western coast of Sweden, only. The shallow southern flank is characterized by lowest sedimentary TOC contents (< 1.5 % TOC) in the whole Skagerrak and dominated by *E. excavatum*. The *E. scabrus* assemblage, as discussed in Conradsen et al. (1994), is found in the Kattegat, only. We suggest that the most important species of the modern benthic foraminiferal fauna in the Skagerrak are closely connected to the TOC distribution within the surface sediments. A similar connection between dominant faunas/species and sedimentary TOC contents can be observed in cores 225514 and 225510: The oldest assemblage of Core 225514, consisting of *Hyalinea balthica*, *B. marginata*, and *Melonis barleeanus* is found with lowest TOC values within the sediments, followed by the *C. laevigata* assemblage and higher TOC values. The youngest assemblage, dominated by *B. skagerrakensis*, occurs where sedimentary TOC values are highest (figs. 3a and 4). The chronological benthic foraminiferal succession within Core 225514 (Fig. 3a) closely reflects the modern spatial species distribution from upper Skagerrak slopes to the deep basin, i.e. from low to high sedimentary TOC contents.

The benthic foraminiferal fauna of Core 225510 intermittently changes between the *E. excavatum*, the *C. laevigata* and the *G. turgida* assemblage (Fig. 5a). Dominance of the *E. excavatum* assemblage is restricted to lowest encountered sedimentary TOC contents. Therefore, only the upper part of the optimal TOC

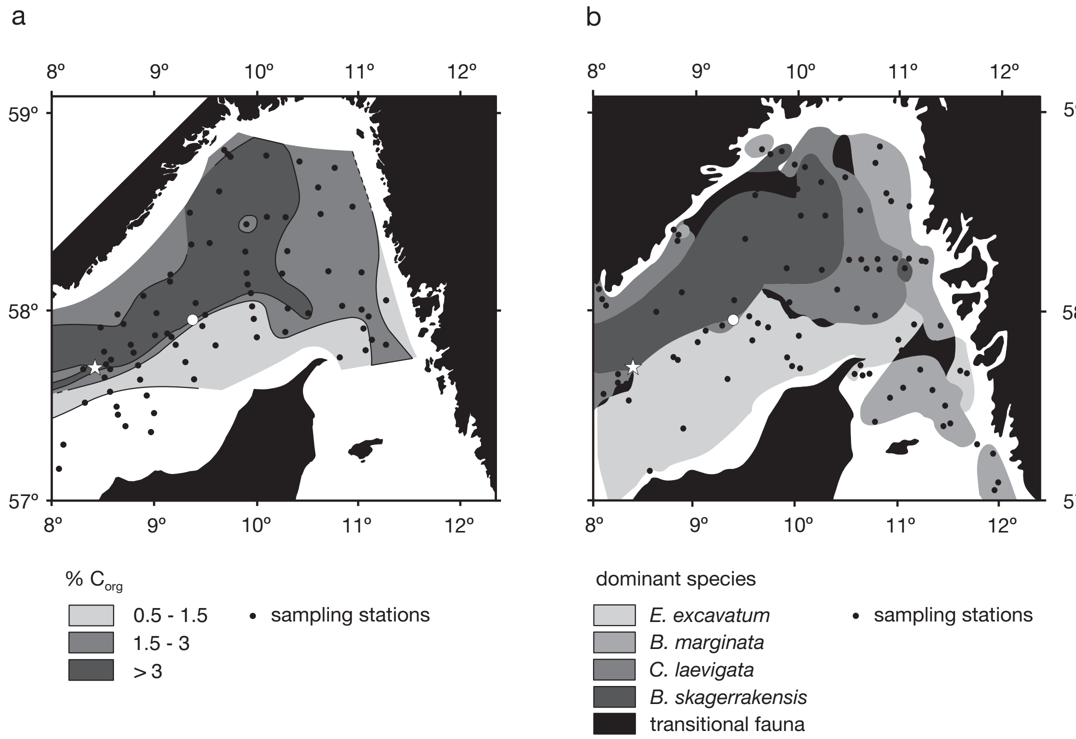

Fig. 8: (a) Distribution of relative organic carbon contents in modern Skagerrak sediments according to Van Weering and Qvale (1983).
(b) Distribution of dominant benthic foraminiferal species in the modern Skagerrak according to Conradsen et al. (1994). Areas, in which species of bordering assemblages co-occur, are denoted as “transitional fauna”.
Asterisk marks Core Site 225514, circle marks Core Site 225510.

range for this species is realized (Fig. 6). The *C. laevigata* assemblage dominates with intermediate TOC values, whereas *G. turgida* occurs only occasionally, reflecting peak TOC values within Core 225510 (Fig. 5a and 6). The frequent change of benthic foraminiferal dominance seems to be the result of TOC values varying around the boundary value, which separates the ranges of maximum success of *E. excavatum* and *C. laevigata*.

In contrast to our suggestion that the benthic foraminiferal distribution in the Skagerrak is closely connected to sedimentary TOC contents other investigators (e.g., Van Weering and Qvale, 1983; Qvale and Van Weering, 1985; Conradsen, 1993; Seidenkrantz, 1993a; Conradsen et al., 1994) did not find a clear relationship, although some demonstrated dependencies for single species. This might be explained by the fact that a linear relationship between species frequencies and TOC content was assumed, although this relationship is not linear or not linear throughout. Species and assemblages show a rather bell-shaped distribution within certain ranges of sedimentary TOC (figs. 4, 6 and 7). Other investigators (e.g., Van Weering and Qvale, 1983; Bergsten et al., 1996; Hass, 1997) interpreted the spatial and chronological distribution of benthic foraminifera in

Skagerrak sediments as an expression of hydrographical conditions or sediment characteristics. These relationships, however, might be indirect effects only. Hass (1997) already realized the analogy between the chronological species succession in Core III KAL and the spatial species distribution in the modern Skagerrak, although he interpreted this succession as reflecting the tolerance of different species towards current energy. He suggested that the *C. laevigata* assemblage indicates enhanced current strength, whereas the *B. skagerrakensis* assemblage dominates under "unstable" hydrographical conditions in the deep basin. However, Hass (1997) also speculated that varying hydrographical conditions might only mediate the availability of food and the oxygenation of the bottom water mass. Investigations of Aure and Dahl (1994) and Bakker and Helder (1993) showed that the bottom water mass of the Skagerrak is well oxygenated throughout. Skagerrak deep-waters are renewed every second to third year, triggered by the negative phase of the North Atlantic Oscillation (Ljøen, 1981; Brückner and Mackensen, 2006). We therefore suggest that the oxygenation of the bottom water mass is not a limiting factor. In contrast, oxygen penetration depth in Skagerrak sediments is limited (3 to 20 mm according to Bakker and Helder, 1993) and thus might be important for benthic habitats. *Cassidulina laevigata*, *C. neoteretis*, *B. marginata*, *H. balthica* and *E. excavatum* occupy shallow infaunal habitats (e.g., Alve and Bernhard, 1995; Wollenburg and Mackensen, 1998; Schmiedl et al., 2000; Fontanier et al., 2002; Husum and Hald, 2004). The dominance of these species indicates that there is some oxygenation at least close to the sediment/water interface (according to Jorissen et al., 1995; Jorissen et al., 1998; Kaiho, 1999). *Melonis barleeanus*, *M. zaandami*, *B. skagerrakensis*, and *G. turgida* occupy or are capable of occupying intermediate to deep infaunal habitats (Corliss and Emerson, 1990; Corliss and Van Weering, 1993; Alve and Bernhard, 1995; Jorissen et al., 1998; Wollenburg and Mackensen, 1998; Fontanier et al., 2005), which implies that they are able to cope with dysoxic or anoxic conditions within the sediments (according to Jorissen et al., 1995; Jorissen et al., 1998; Kaiho, 1999). Since most assemblages in the investigated cores are either dominated by, or at least associated with, shallow infaunal species we suggest that oxygen limitation is not an important factor determining species composition in Skagerrak sediments. Oxygen penetration depth seems to determine maximum habitat depths of benthic foraminifers (e.g., Corliss and Emerson, 1990; Jorissen, 1995) but might not be a limiting factor as long as there is no extreme deficiency (e.g., Van der Zwaan et al., 1999; Morigi et al., 2001).

Summarizing, we documented a relationship between dominant benthic foraminiferal faunas as well as individual species and certain ranges of relative TOC contents within Skagerrak sediments. We found that oxygen availability does not influence the dominance of the investigated species.

5.2 Feeding preferences

Nomaki et al. (2006) investigated feeding strategies of several benthic foraminiferal species from Sagami Bay by feeding them with ^{13}C-labeled bacteria and algae. The authors differentiated (1) phytophagous species, feeding only on fresh phytodetritus, (2) seasonal-phytophagous species, selectively feeding on fresh phytodetritus but also on sedimentary organic matter if fresh food is absent, and (3) deposit feeders, which ingest sedimentary organic matter at random. *Uvigerina akitaensis*, *Bolivina spissa*, and *Bolivina pacifica* were classified as phytophagous species, whereas *Bulimina aculeata* and *Globobulimina affinis* show seasonal-phytophagous feeding preferences. *Cyclammina cancellata* and *Chilostomella ovoidea* were classified as deposit feeders. According to Nomaki et al. (2006) we classified the dominant species of both cores into these categories on genus basis. We suggest that *Bolivina skagerrakensis* is a phytophagous species, whereas *Bulimina marginata* and *Globobulimina turgida* are seasonal-phytophagous species. Unfortunately, Nomaki et al. (2006) did not investigate species of the genus *Hyalinea*, *Melonis*, *Cassidulina* and *Elphidium*, so that we are not able to place the other dominant species on genus basis into one of those categories. However, since *H. balthica*, *C. laevigata*, and *E. excavatum* were shown to feed on fresh phytodetritus (e.g., Mackensen and Hald, 1988; Gooday and Lambshead, 1989; Altenbach, 1992; De Rijk et al., 2000; Eberwein and Mackensen, 2006) they presumably fit into the phytophagous or seasonal-phytophagous category. *Melonis barleeanus* is generally suggested to prefer altered food, mainly based on the publications of Caralp (1989a; 1989b). By investigating the nutritive quality of available organic matter, Caralp (1989a; 1989b) suggested that *M. barleeanus* prefers ‘more altered’ fresh organic material than *Bulimina exilis*. In contrast to deposit feeders in the sense of Nomaki et al. (2006), *M. barleeanus* does feed on fresh food, although of lower quality (see also Heinz et al., 2002). Thus, all dominant species occurring within the investigated cores apparently prefer fresh organic matter; however, probably most of them are also able to make their living on sedimentary organic matter.

5.3 Relative amount and quality of food available in the Skagerrak

We are aware of the fact that decreasing TOC contents from top to bottom in Core 225514 first and foremost are the result of organic matter decay over time. Anton and Liebezeit (1993) and Meyenburg and Liebezeit (1993) showed that the relative amount of organic matter in Skagerrak sediments decreases exponentially downcore, which is clearly visible in our data (Fig. 3a). This exponential decrease, though, is not uniform and exhibits shifts, which coincide with faunal boundaries. It is difficult to explain these shifts in view of a continuous decay. Instead, it is reasonable to interpret these shifts as sudden increases in the relative amounts of deposited organic matter. Core 225510 does not show the typical exponential TOC decrease with increasing core depth, but is characterized by varying TOC values around a mean of 2 % (Fig. 5a). This pattern cannot be attributed to organic matter decay over time.

TOC accumulation rates (TOC AR), $\delta^{13}C$ values of shallow infaunal benthic foraminifers and C:N ratios are commonly used to reconstruct relative amounts and quality of organic matter deposited on the seafloor. Neither in Core 225514 nor in Core 225510 these three parameters do show any correlation with each other, or with sedimentary TOC contents (figs. 3a and 5a). Since up to 90 % of organic matter deposited within Skagerrak sediments is allochthonous and refractory (e.g., Van Weering and Kalf, 1987; Meyenburg and Liebezeit, 1993; de Haas and Van Weering, 1997), TOC AR are not likely to show any correlation with organic matter fluxes to the seafloor as reconstructed by $\delta^{13}C$ values of *Uvigerina mediterranea* or *Cassidulina laevigata*. The TOC AR rather reflect sedimentation rates since the sediments deposited in the Skagerrak and the North Sea in general contain specific background amounts of allochthonous organic material depending on the dominant grain size (Wiesner et al., 1990). Furthermore, no correlation is observed between TOC AR and benthic foraminiferal assemblages.

Following Schmiedl et al. (2004), $\delta^{13}C$ values of *U. mediterranea* or *C. laevigata* are used to reconstruct organic matter flux to the seafloor (Brückner and Mackensen, in press). Since we interpreted the dominant species of the two investigated cores as phytophagous or seasonal-phytophagous species, a correlation between $\delta^{13}C$ values of *U. mediterranea* and benthic foraminiferal faunas and species might be expected. However, no such relationship can be observed (figs. 3a and 5a). Likewise, the C:N ratios of sediments in the two investigated cores, which are thought to reflect the quality of organic matter deposited within the sediments, are very variable, but show no obvious trends. However, their mean values are different: In Core 225514 the C:N mean value is 9.3 +/- 0.6, whereas the mean value in Core 225510 is 11.0 +/- 0.9. Since higher C:N ratios indicate marine organic matter of lower quality or a higher content of terrestrial organic matter (e.g., Hedges et al., 1988; Ståhl et al., 2004), Core 225510 probably received organic matter of lower quality than Core 225514; but no correlation between C:N ratios and benthic foraminiferal faunas or species can be observed.

We summarize: (1) dominant benthic foraminiferal assemblages/species of both cores are connected to specific sedimentary TOC ranges; (2) they show no correlation with the total amount of organic matter deposited; (3) they show no correlation with the flux of fresh organic matter to the seafloor; (4) there is no correlation between benthic foraminiferal faunas or species and the quality of organic matter deposited. We thus suggest that benthic foraminiferal species in the Skagerrak depend directly on relative TOC contents within the sediments. The dilution of deposited TOC by inorganic sediment particles seems to determine benthic foraminiferal faunas rather than the total amount of deposited TOC or fresh organic matter. This is especially surprising since about 90 % of deposited organic matter has to be regarded as refractory, but all dominant species were interpreted as preferring fresh organic matter. However, seasonal-phytophagous species are also able to feed on sedimentary organic matter.

Nomaki et al. (2006) demonstrated that, although only two of the investigated eight different species are considered as deposit feeders and although substantial amounts of fresh organic matter were accessible, the amount of sedimentary organic matter ingested by benthic foraminifera was more than three times higher than the amount of fresh organic matter. Among all investigated species *Globobulimina affinis* assimilated the highest amount of sedimentary TOC: 6.5 +/- 7.8 mg C m^{-2} d^{-1}. This matches our observation that *Globobulimina turgida* dominates the fauna in Core 225510 if sedimentary TOC values peak. We suggest that relative amounts of sedimentary organic matter determine species' dominance and that TOC ranges of maximum success are species-specific. Since all dominant species are known to prefer fresh food, we speculate that reproduction is linked to the availability of fresh organic matter as proposed by Heinz et al. (2002). The amount of available fresh food, however, seems neither to be limiting nor to be determining.

5.4 Similar TOC ranges but different dominant species

Although sedimentary TOC ranges are similar in both cores, the dominant species are partly different. In Core 225510 *Globobulimina turgida* dominates sediments with highest sedimentary TOC values, whereas *Bolivina skagerrakensis* dominates these sediments in Core 225514. Similarly, *Elphidium excavatum* dominates sediments with lowest TOC values in Core 225510, whereas these sediments are dominated by *Hyalinea balthica*, *Bulimina marginata*, and *Melonis barleeanus* in Core 225514.

Core 225514 comes from an area, which today is typically occupied by the *B. skagerrakensis* assemblage (Fig. 8b, Fig. f of Conradsen et al., 1994). This area receives highest input of particulate organic matter in the Skagerrak (Fig. 8 of Alve and Murray, 1997). Core 225510 is from the border area between modern *B. skagerrakensis* and *C. laevigata* assemblages (Fig. 8b, Fig. f of Conradsen et al., 1994). Alve and Murray (1997) connect the dominance of *G. turgida* to the deficit of abundant particulate organic matter. This interpretation is consistent with the interpretation of C:N ratios in the investigated cores, which suggest that Core 225510 received organic matter of lower quality than Core 225514. Although there is no correlation between foraminiferal frequency distribution and C:N ratios, different levels of food quality might be crucial. We therefore suggest that *G. turgida*, which probably is a seasonal-phytophagous species, dominates sediments containing organic matter of low quality. *Bolivina skagerrakensis*, which was classified as phytophagous species and thus depends on supply of fresh organic matter is probably not connected with sedimentary TOC contents at all. The relationship between frequencies of *B. skagerrakensis* and sedimentary TOC contents hence would be due to coincidence, only. A difference in feeding preferences, however, does not explain why *H. balthica*, *B. marginata*, and *M. barleeanus* are substituted by *E. excavatum* in Core 225510, since they are presumably all seasonal-phytophagous species. *Elphidium excavatum* probably is able to exploit refractory organic matter, whereas *H. balthica*, *B. marginata*, and *M. barleeanus* might depend on food of higher quality as indicated by different mean C:N ratios in the investigated cores. However, on the basis of the presented data, this suggestion is purely speculative.

Alve and Murray (1997) consider *E. excavatum* and *Planorbulina mediterranensis* on the Danish Skagerrak slope as “exotic” species, i.e. as imported from the North Sea. Regarding *E. excavatum*, we are not convinced that this is the case. Although Core 225510 originates from the southern slope, it is from an area, which, after Alve and Murray (1997), receives 4 % of transported tests at most. *Elphidium excavatum*, however, contributes up to 40 % to total benthic foraminiferal tests. Moreover, investigations of modern and historic sediments of fractions > 100 or > 125 μm found *E. excavatum* dominating considerable areas on the southern slope (e.g., Van Weering and Qvale, 1983; Seidenkrantz, 1993a; Conradsen et al., 1994; Bergsten et al., 1996). It seems unlikely that all these individuals are imported. Furthermore, these reworked and therefore older specimens should have influenced the dated samples containing between 17 and 22 % *E. excavatum* tests. If these tests were all reworked and therefore too old, the age model of Core 225510 would give anomalously old ages. However, we observed unusual high sedimentation rates and thus rather low ages.

5.5 Benthic foraminiferal fauna and hydrography

Gyllencreutz and Kissel (2006) investigated grain size distributions within Holocene Skagerrak sediments. They documented that the predominant current system switched several times between a Baltic Sea and a North Sea dominated system. Around AD 700 one of those switches coincided with the faunal change from *Hyalinea balthica*, *Bulimina marginata*, and *Melonis barleeanus* to a *Cassidulina laevigata* dominated fauna in Core 225514. The current system switched from a predominant Baltic Sea to a predominant North Sea influence. We therefore suggest that North Sea sediments contained relatively more organic material than Baltic Sea sediments around this time. Higher relative organic matter content within Skagerrak sediments, however, resulted in competitive advantage of *C. laevigata*, since *C. laevigata* prefers higher contents of sedimentary organic matter than *H. balthica*, *B. marginata*, and *M. barleeanus*. The substitution of *C. laevigata* by *B. skagerrakensis* around AD 1450 and the shift to higher sedimentary TOC contents cannot be connected to such a hydrographic shift.

However, if the suggestion holds that *B. skagerrakensis* is a phytophagous species, which selectively feeds on fresh organic matter, its immigration and subsequent dominance is most probably not connected to sedimentary TOC contents. We would expect a connection between the frequency of *B. skagerrakensis* and the flux of organic matter to the seafloor, but no relationship can be observed. We are not able to explain the dominance of *B. skagerrakensis* on basis of the available data.

In Core 225510 benthic foraminiferal faunas frequently change between the *E. excavatum* and the *C. laevigata* assemblage according to the TOC range realized. *Globobulimina turgida* occasionally becomes important when sedimentary TOC values are highest. Seidenkrantz (1993a) describes two cores (BC 55, GC 59), which show the same repeated changes between an *E. excavatum* and a *C. laevigata* assemblage during the last approximately two centuries. These two cores were recovered from 98 m and approximately 200 m water depth, whereas Core 225510 originates from 285 m water depth. All cores were recovered from the southern slope of the Skagerrak. Thus, repeatedly changing *E. excavatum* and *C. laevigata* assemblages, which are supposedly the result of repeatedly changing sedimentary TOC contents, occur in a considerable area on the southern slope and over at least 200 m water depth. The covered area is influenced by the Northern Jutland Current, the core of which moves up and down the southern Skagerrak slope (Rodhe, 1987; Rodhe, 1996). Therefore, variable benthic foraminiferal assemblages in Core 225510 probably are the result of the vertically changing position of the Northern Jutland Current, which induces varying grain sizes at the sampling site. Varying grain sizes, however, result in varying sedimentary TOC values, since the TOC content is negatively correlated to grain size in general (e.g., Van Weering, 1981; Wiesner et al., 1990; Anton et al., 1993; Conradsen, 1993).

6 Conclusions

The sediments of Core 225514 recorded environmental conditions over more than the last 3000 years. The oldest part of Core 225514 is dominated by *Hyalinea balthica*, *Bulimina marginata* and *Melonis barleeanus*. Around AD 700 this assemblage is replaced by the *Cassidulina laevigata* assemblage. The youngest assemblage is dominated by *Bolivina skagerrakensis*, being important since around AD 1450. Sediments of Core 225510 comprise the last 500 years. The benthic foraminiferal fauna is characterized by intermittently changing assemblages of *Elphidium excavatum*, *C. laevigata* and *Globobulimina turgida*.

We demonstrated a close relationship between the dominance of benthic foraminiferal assemblages as well as species and specific ranges of sedimentary TOC within the investigated cores. *Bolivina skagerrakensis* or *G. turgida* dominate if sedimentary TOC values are highest, *C. laevigata* dominates with intermediate TOC values, whereas *H. balthica*, *B. marginata*, and *M. barleeanus* or *E. excavatum* dominate with lowest sedimentary TOC contents.

According to Nomaki et al. (2006) we suggested that all dominant species are phytophagous (*B. skagerrakensis*) or seasonal-phytophagous species (all other species). We concluded that benthic foraminiferal dominance in Skagerrak sediments is determined by relative organic matter contents within the sediments.

Although sedimentary TOC ranges are similar in both investigated cores, dominant assemblages and species are partly different. We suggested that *H. balthica*, *B. marginata*, and *M. barleeanus* dominate the fauna instead of *E. excavatum* if the quality of sedimentary organic matter is high. Similarly, *G. turgida* dominates the fauna if the relative amount of sedimentary organic matter is high but of comparably low quality. *Bolivina skagerrakensis* dominates in sediments with high organic matter contents, which is of comparably high quality. Since *B. skagerrakensis* is probably a phytophagous species although no connection to the flux of fresh organic matter to the seafloor was observed, we suggested that the link between high sedimentary organic matter contents and high frequencies of this species presumably is due to coincidence, only.

Our data further suggest that hydrography controlls the amount of organic matter within the sediments. In Core 225514 the *H. balthica* assemblage is replaced by the *C. laevigata* assemblage around AD 700, which coincides with a shift from a Baltic Sea dominated to a North Sea dominated hydrography. Core 225510 is characterized by intermittently changing benthic foraminiferal faunas. Varying amounts of organic matter in connection with the dominance of different benthic foraminiferal faunas, were interpreted as reflecting changing sedimentation regimes, caused by the changing position of the Northern Jutland Current.

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3 CONCLUSIONS AND FUTURE PERSPECTIVES

This thesis deals with three different proxies based on benthic foraminifera of Holocene Skagerrak sediments: the benthic foraminiferal assemblage composition as well as ratios of stable carbon and oxygen isotopes in benthic foraminiferal tests. Since the results of these investigations concern different topics, conclusions and suggestions for future research will be presented step-by-step.

The oxygen isotopic composition of benthic foraminiferal tests from the deeper Skagerrak basin was investigated with regard to the North Atlantic Oscillation (NAO) and climate change. The $\delta^{18}O$ values of *Bulimina marginata* were shown to reflect deep-water renewal events, which are triggered by the negative phase of the NAO. During mainly negative phases of the NAO relatively calm and very cold conditions prevail over the North Sea, resulting in a strong cooling down of Central North Sea Waters. The strongly cooled down Central North Sea waters reach densities, which are higher than those of the Skagerrak water masses and occasionally start to cascade into the deepest basin of the North Sea. After accomplishment of the deep-water renewal, thermohaline mixing with overlying water masses of North Atlantic origin results in increasing temperatures and salinities. The $\delta^{18}O$ long-term evolution was suggested to reflect both the temperature evolution of the Norwegian Atlantic Current and the local state of the NAO.

Deep-water renewal events are characterized by sudden temperature and salinity drops, which are recorded in monitoring data of the last approximately 50 years. Since the $\delta^{18}O$ values of *B. marginata* are influenced by temperature but also by salinity changes, it was necessary to separate these effects. By comparing modern monitoring data with the $\delta^{18}O$-salinity mixing line valid for Skagerrak water masses, we demonstrated that salinity changes are responsible for only 9 % of the total $\delta^{18}O$ variability. Since the influences of temperature and salinity changes on $\delta^{18}O$ values during deep-water renewal events additionally counteract each other, we interpreted the remaining benthic foraminiferal $\delta^{18}O$ changes as entirely resulting from temperature changes.

The conclusion that $\delta^{18}O$ values of *B. marginata* reflect deep-water renewal events triggered by the NAO is based on: (1) the good correlation between deep-water temperatures recorded in monitoring data of the last 50 years and the NAO, (2) the assumption that $\delta^{18}O$ values of *B. marginata* mainly reflect temperature changes of the deep water. Unfortunately, the sample resolution was too low to directly determine the correlation coefficient between $\delta^{18}O$ values and the NAO index. Time series analysis failed because of the same problem. I am convinced that the NAO proves to be responsible not only for deep-water renewal but also strongly influences the current regime. High-resolution investigations of benthic foraminiferal $\delta^{18}O$ and possibly sediment grain-sizes will enable us to demonstrate this influence.

The carbon isotopic composition of benthic foraminiferal tests of two cores comprising the last 500 years was investigated. The $\delta^{13}C$ values of *Uvigerina mediterranea* indicated that organic matter rain rates to the seafloor increased after AD 1950 at both core locations. We suggested that the increase in organic matter rain rates was the result of simultaneously changing hydrographic and climatic features. The flux of nutrient rich Atlantic water masses into the North Sea increased after AD 1950, while a persistent high North Atlantic Oscillation index state led to generally enhanced temperatures. Exceptionally high primary production within the North Sea and probably also in Skagerrak and Kattegat followed.

The flux of organic matter to the seafloor as reconstructed from $\delta^{13}C$ values of *U. mediterranea* was similar at both core locations, however, $\delta^{13}C$ values of *Globobulimina turgida* differed by up to 0.6 ‰. We concluded that this discrepancy reflects differences in organic matter remineralization rates due to respiration, which implies differences in oxygen availabilities at the two core sites. Since both core sites were bathed by the same water mass, this difference could not be explained by diverging oxygen contents in the overlying water mass. We proposed that oxygen exposure times *within* the sediments differed, which might result from different sedimentation rates. This phenomenon should be especially important in shelf regions, where sedimentation rates are very variable.

Vital effect estimates, with respect to $\delta^{13}C$ values of *G. turgida*, for *Hyalinea balthica* (> 1.3 ‰), *Cassidulina laevigata* and *Melonis barleeanus* (each > 0.7 ‰) were determined. *Melonis zaandami* seems to calcify its test $\delta^{13}C$ close to pore water $\delta^{13}C_{DIC}$ values. The presented values are only minimum estimates and presumably contain mismatches. However, since the mismatches in $\Delta\delta^{13}C$ reconstructions resulting from uncorrected vital effects are probably bigger than mismatches in the here estimated vital effects, we decided to present these data despite their limitations.

Further investigations are necessary to support the suggestion that differences in oxygen exposure times are indeed reflected in $\delta^{13}C$ values of deep-infaunal benthic foraminiferal tests. Vital effects in benthic foraminiferal $\delta^{13}C$ values, once again, have to receive more attention, since the here presented dimensions proved to be crucial, especially with regard to reconstructions of organic matter remineralization rates from $\Delta\delta^{13}C$ values.

By Principle Component Analysis three benthic foraminiferal assemblages in each of the two investigated cores were distinguished. The dominant species were shown to mainly depend on species-specific amounts of sedimentary organic matter, exhibiting a Gaussian-like frequency distribution if plotted versus respective TOC contents. This outcome was surprising, since modern research focuses on quantity and quality of the organic matter flux to the seafloor and oxygen availability as the prime limiting factors for infaunal foraminifera. However, research on benthic foraminifera in the Skagerrak was always concerned with sedimentary organic matter contents. Due to the fact that researchers supposed a linear relationship between foraminiferal frequencies and TOC contents, a bell-shaped relationship was not observed. A Gaussian frequency distribution, however, corresponds with basic expectations from the biological point of view (Murray, 2006). Nomaki et al. (2006) demonstrated that distinct benthic foraminiferal species that are closely related to typical Skagerrak species are able to gain large amounts of their energy from sedimentary organic matter. Based on close species relationships as well as on feeding preferences extracted from literature, we suggested that the observed dominant Skagerrak species, except for *Bolivina skagerrakensis*, are seasonal-phytophagous species, which flourish if certain well-defined amounts of sedimentary TOC are available. Sedimentary TOC contents are connected to the sediment grain size, which in turn is the result of the Skagerrak current regime. These findings confirm earlier suggestions that there is a link between benthic foraminiferal assemblage composition and the hydrographic system in the Skagerrak.

Future investigations should address the following topics: (1) The Gaussian relationship between species frequencies and sedimentary organic matter content has to be further investigated, because TOC ranges enabling the plot of a complete frequency bell are only realized for *Cassidulina laevigata* and *Melonis zaandami*. For all other species upper (*G. turgida*) or lower (*B. marginata*, *H. balthica*, *M. barleeanus*, *Elphidium excavatum*) TOC ranges are not realized in our samples. (2) The classification of the dominant species as seasonal-phytophagous or phytophagous species has to be confirmed by culture experiments. (3) In both investigated cores TOC ranges are similar, but the dominating species are partly different. We suggested that this discrepancy is due to the lower organic matter quality in Core 225510, which has to be verified.

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Appendix I

1 Taxonomic list of important species

Order **Foraminiferida** Eichwald 1830

Suborder **Rotaliina** Delage & Hérouard 1896

Bolivina skagerrakensis Qvale & Nigam Plate: Fig. 5
1947 *B.* cf. *robusta* Brady - Höglund, Pl. 24, figs. 8 - 9, Pl. 32, figs. 16 - 18
1956 *B.* cf. *robusta* Brady - Lange, Pl. 10, Fig. 6
1964 *B.* cf. *robusta* Brady - Feyling-Hanssen, Pl. 16, Fig. 9
* 1985 *B. skagerrakensis* Qvale & Nigam, Pl. 1, figs. 1 - 10, Pl. 2, figs. 1 - 10

Bulimina marginata D'Orbigny 1826 Plate: Fig. 1
* 1826 *B. marginata* D'Orbigny
1953 *B. marginata* D'Orbigny - Phleger et al., Pl. 6, figs. 25 - 26
1960 *B. marginata* D'Orbigny - Barker, Pl. 51, figs. 3 - 5
1989 *B. marginata* D'Orbigny - Van Leeuwen, Pl. 8, Fig. 6
1997 *B. marginata* D'Orbigny - Schmiedl et al., Pl. 2, Fig. 10

Cassidulina laevigata D'Orbigny 1826 Plate: figs. 7 - 8
* 1826 *C. laevigata* D'Orbigny
1960 *C. carinata* Silvestri 1896 - Barker, Pl., 54, figs. 2 - 3
1988 *C. laevigata* D'Orbigny - Mackensen & Hald, Pl. 1, figs. 1-7
1997 *C. laevigata* D'Orbigny - Schmiedl et al., Pl. 1, figs. 13 - 14

Cassidulina neoteretis Seidenkrantz 1995 Plate: figs. 9 - 10
1951 *C. teretis* Tappan
1988 *C. teretis* Tappan - Mackensen & Hald, Pl. 1, figs. 8 - 15
1994 *C. teretis* Tappan - Jones, Pl. 54, Fig. 1
* 1995 *C. neoteretis* Seidenkrantz - Seidenkrantz, Pl. 1, figs. 1 - 6, 14, Pl. 2, figs. 1 - 14, Pl. 3, figs. 1 - 8
1997 *C. teretis* Tappan - Schmiedl et al., Pl. 1, figs. 13-14
1998b *C. teretis* Tappan - Wollenburg & Mackensen, Pl. 3, figs. 12 - 13

APPENDIX I.1 (continued)

Globobulimina turgida (BAILEY 1951)

* 1851 *Bulimina turgida* BAILEY
1947 *G. turgida* (BAILEY) - Höglund, Pl. 20, Fig. 5, Pl. 21, figs. 4, 8, Pl. 22, Fig. 5
1953 *G.* cf. *turgida* (BAILEY) - Phleger et al., Pl. 6, figs. 33 - 34
1997 *G. turgida* (BAILEY) - Schmiedl et al., Pl. 2, figs. 17 - 18

Hyalinea balthica (SCHRÖTER 1783) Plate: Fig. 4

* 1783 *Nautilus balthicus* SCHRÖTER
1960 *H. balthica* (SCHRÖTER) - Barker, Pl. 112, figs. 1 - 2
1971 *H. balthica* (SCHRÖTER) - Feyling-Hanssen et al., Pl. 9, figs. 7 - 9
1994 *H. balthica* (SCHRÖTER) - Jones, Pl. 112, figs. 1 - 2

Melonis barleeanus (WILLIAMSON 1858) Plate: figs. 2 - 3

* 1858 *Nonionina barleeanum* WILLIAMSON
1979 *M. barleeanum* (WILLIAMSON) - Corliss, Pl. 5, figs. 7 - 8
1988 *M. barleeanum* (WILLIAMSON) - Loeblich & Tappan, Pl. 696, figs. 5 - 6
1989 *M. barleeanum* (WILLIAMSON) - Caralp, pl. 1 - 3
1997 *M. barleeanum* (WILLIAMSON) - Schmiedl et al., Pl. 2, figs. 10 -11
2001 *M. barleeanum* (WILLIAMSON) - Schumacher, Pl. 9, figs. 7 - 8

Melonis zaandami (VAN VOORTHUYSEN 1952)

* 1952 *Anomalinoides barleeanum* (WILLIAMSON) var. *zaandamae* VAN VOORTHUYSEN
1989 *M. sphaeroides* VOLOSHINOVA - Van Leeuwen, Pl. 13, figs. 5 - 8
1993b *M. zaandamae* (VAN VOORTHUYSEN) - Mackensen et al., Pl. 3, figs. 4 - 5
1997 *M. zaandamae* (VAN VOORTHUYSEN) - Schmiedl et al., Pl. 2, figs. 12 - 13
1998 *M. zaandami* (VAN VOORTHUYSEN) - Wollenburg & Mackensen, Pl. 5, figs. 11 - 12

Uvigerina mediterranea HOFKER 1932

* 1932 *U. mediterranea* HOFKER
1952 *U. finisterrensis* COLOM, Fig. 4
1960 *Euuvigerina peregrina* (CUSHMAN) - Barker, Pl. 74, figs. 11 - 12
1986 *U. mediterranea* (HOFKER) - Lutze, Pl. 5, figs. 1 - 7

APPENDIX I.1 (continued)

1994 *U. mediterranea* (HOFKER) - Jones, Pl. 74, figs. 11 - 12

Elphidium excavatum (TERQUEM) f. *clavata* CUSHMAN 1930 Plate: Fig. 6

* 1930 *E. incertum* (WILLIAMSON) var. *clavatum* CUSHMAN - Cushman, Pl. 7, Fig. 10

1971 *E. excavatum* (TERQUEM) - Knudsen., Pl. 20, figs. 7 - 8

1972 *E. excavatum* (TERQUEM) f. *clavata* - Feyling-Hanssen, Pl. 1, figs. 1- 9, Pl. 2, figs. 1 - 9

Planorbulina mediterranensis D'ORBIGNY 1826

* 1826 *P. mediterranensis* D'ORBIGNY

1960 *P. mediterranensis* D'ORBIGNY - Barker, Pl. 92, figs. 1 - 3

1994 *P. mediterranensis* D'ORBIGNY - Jones, Pl. 92, figs. 2 - 3

APPENDIX I

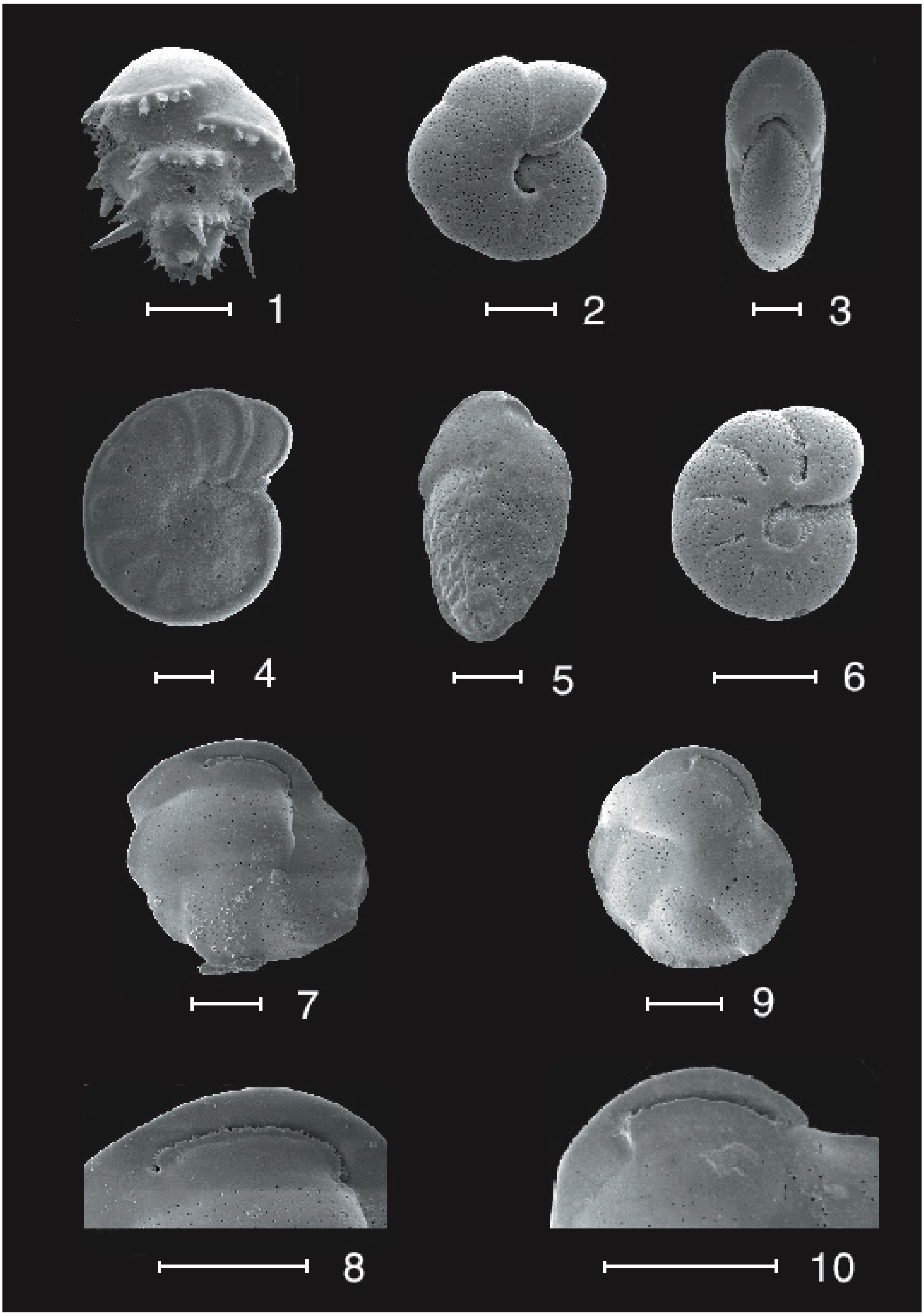
2 Plate of some important species

1 *Bulimina marginata* D'ORBIGNY
    Core 225514, 4 - 5 cm depth
2 *Melonis barleeanus* (WILLIAMSON) (side view)
    Core 225514, 4 - 5 cm depth
3 *M. barleeanus* (WILLIAMSON) (apertural view)
    Core 225514, 4 - 5 cm depth
4 *Hyalinea balthica* (SCHRÖTER)
    Core 225514, 4 - 5 cm depth
5 *Bolivina skagerrankensis* QVALE & NIGAM
    Core 225514, 4 - 5 cm depth
6 *Elphidium excavatum* (TERQUEM) f. *clavata* CUSHMAN
    Core 225510, 10 - 11 cm depth
7 *Cassidulina laevigata* D'ORBIGNY
    Core 225514, 5 - 6 cm depth
8 *C. laevigata* D'ORBIGNY (close-up of apertura)
    Core 225514, 5 - 6 cm depth
9 *Cassidulina neoteretis* SEIDENKRANTZ
    Core 225510, 5 - 6 cm depth
10 *C. neoteretis* SEIDENKRANTZ (close-up of apertura)
    Core 225510, 5 - 6 cm depth

scale bar = 100 μm

APPENDIX I

Plate



APPENDIX II Data of Core 225514

1 Relative frequencies of counted species

Nonionella turgida		0.1	0.2		0.1	0.2	0.1	0.3					0.4				0.2				0.3		0.2
Melonis spp.		0.7	0.3	0.3	0.4	0.5	0.8	0.5	1.0	0.3	0.2	1.3	1.3			2.0	1.0	1.5		2.1		1.4	
Melonis zaandami	1.0	2.2	1.6	1.5	1.9	1.5	2.3	4.4	6.6	5.3	4.2	6.5	3.9	7.4	5.0	3.7	4.9	3.3	7.3	4.5	5.7	5.5	9.6
Melonis barleeanus	3.5	2.3	5.6	3.9	5.5	4.1	3.6	6.4	6.6	5.9	4.0	4.7	6.1	4.0	6.2	4.7	8.6	5.1	6.5	8.6	6.3	10.9	3.7
Lobatula lobatula		1.6	1.3	1.0	0.9	1.5	1.4	1.1	1.0	0.3	1.1		1.1	0.5	1.2	0.5	0.2	0.6	0.3	1.1	0.5	0.2	1.0
Lenticulina spp.		0.1																0.3					
Lagena spp.	1.3	1.5	0.8	1.6	1.1	1.7	1.2	0.4	1.4	1.8	0.4	1.3	0.9	1.3	0.2	0.7	0.7	2.7		1.3	1.6	1.4	1.5
Hyalinea balthica	2.3	7.3	6.5	6.8	6.7	5.2	8.5	10.5	9.3	7.6	6.2	6.0	5.0	4.8	5.8	2.5	4.4	3.3	3.4	4.8	6.3	4.5	5.7
Globobulimina turgida	1.3	2.0	1.3	2.1	1.3	0.8	0.8	1.7	1.7	0.8	1.8	1.5	1.1	1.6	2.5	2.0	2.1	2.7	4.5	1.6	2.4	2.1	2.0
Globobulimina hoeglundi							0.1	0.2			0.2	0.2			0.2	0.2	0.3		1.7		0.3	0.5	
Globobulimina auriculata	0.5	1.1	0.6	0.2	1.1	0.8	0.9	1.5	2.1	1.3	1.3	1.9	1.1	1.3	0.2	2.7	0.7	1.8	1.4	0.3	1.1	1.9	1.2
Glandulina ovula		0.1	0.3		0.4		0.1				0.2	0.2								0.5			0.2
Fursenkoina spp.	0.5	0.5	0.5	1.1	0.1	0.6	0.6	0.3	0.2		0.2	0.2		0.3				0.6			0.3	0.5	0.7
Fissurina spp.	0.8	0.3		0.2	0.5	1.1	0.1	0.2		0.3	0.9	0.2	1.1	0.3		0.2	0.2	0.3	0.3			0.7	0.2
Elphidium spp.		1.0	1.0	2.1	1.1	0.9	1.3	2.4	2.1	2.8	1.6	1.3	1.3	2.4	1.2	1.2	3.4	2.1	2.3	2.1	2.4	2.4	2.0
Discorbina spp.																	0.2						
Cibicidoides wuellerstorfi																	0.2						
Cibicidoides refulgens																					0.3	0.2	0.7
Cassidulina neoteretis	5.0	2.9	4.1	3.2	3.7	3.3	3.6	3.1	4.3	8.1	10.2	12.3	5.5	9.3	10.8	5.0	10.9	10.9	8.7	11.0	7.1	6.4	8.6
Cassidulina laevigata	12.8	17.1	14.6	13.8	18.8	18.2	21.4	21.4	19.2	20.1	20.9	15.9	22.6	21.2	13.9	22.0	21.6	26.9	34.6	33.2	30.4	34.7	35.0
Cassidulina crassa		0.2		0.3	0.1	0.2	0.4	0.5	0.2		0.4				0.2	0.5	1.0	0.3		0.5		1.0	
Bulimina marginata	7.1	6.7	7.6	8.5	8.3	8.1	8.7	8.4	9.7	9.2	10.4	8.0	9.2	6.1	8.5	4.5	7.0	8.5	5.4	8.3	9.2	10.0	7.6
Bolivina skagerrakensis	25.9	27.2	30.2	32.5	31.1	34.3	30.3	18.3	14.9	22.4	17.3	20.7	20.6	27.9	28.5	36.1	19.2	18.4	11.6	8.8	12.8	3.3	7.4
Astrononion gallowayi	0.3	0.1				0.2					0.2					0.2	0.7	0.6	0.6	0.3	0.3	0.2	0.7
Angulogerina angulosa	0.3	0.3		0.6	0.4	0.6	0.5	0.6	0.6	1.0	0.9	0.6	0.4	0.3	1.0	0.5	1.3	0.9	1.4	1.1	1.9	0.2	0.7
age AD/BC	2000	1993	1986	1979	1972	1965	1958	1951	1944	1938	1931	1924	1917	1910	1896	1878	1869	1856	1848	1835	1827	1814	1805
core depth (cm)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	15	18	20	23	25	28	30	33	35

APPENDIX II.1 (continued)

Nonionella turgida	0.8					0.3			0.5		0.5			0.2	0.2	0.2	0.5		1.4	1.3	0.7	0.3	0.6	0.9	1.0
Melonis spp.	2.0		2.0	3.6	2.2		1.0		2.3		2.2	1.8	1.2	1.1	1.4	1.2	2.5	2.0	2.0	2.0	1.7	3.3	1.7	1.5	2.5
Melonis zaandami	4.2	13.2	4.3	10.9	7.2	8.4	5.5	18.2	8.8	10.1	7.8	10.1	7.9	9.8	5.3	6.4	8.8	7.8	15.8	11.6	10.9	6.9	2.3	8.6	13.9
Melonis barleeanus	8.2	6.2	8.3	18.1	9.9	5.4	9.6	3.0	11.2	6.8	11.0	9.0	9.2	5.4	8.4	7.0	10.8	11.5	6.4	8.5	10.9	3.6	8.0	13.0	5.5
Lobatula lobatula	2.8	0.5	1.7	1.1	1.1	1.1	4.2	1.8	2.3	0.2	1.7	0.3	1.7	0.7	1.2	0.6	1.6	0.2	1.0	2.0	1.7	1.5	0.6	0.6	3.2
Lenticulina spp.									0.3						0.2						0.5				
Lagena spp.	0.8	1.1	0.4	0.7	1.3	1.6	2.6	2.1	0.8	2.7	2.4	0.5	1.2	0.9	1.2	1.2	2.0	1.3	2.2	2.5	0.5	1.0	0.6	1.8	1.2
Hyalinea balthica	4.4	5.5	5.2	6.2	5.2	12.2	8.3	6.4	6.2	6.5	8.1	5.2	5.0	4.5	3.4	3.7	6.7	5.9	6.0	6.0	6.1	2.9	4.0	4.4	3.5
Globobulimina turgida	1.8	4.8	1.5	1.1	2.3	2.4	2.9	1.8	2.9	0.7	1.7	2.1	2.3	0.9	1.1	1.9	2.2	0.9	1.2	0.9	1.5	1.4		1.2	0.7
Globobulimina hoeglundi		0.5		0.7	0.4	0.5	0.3	1.8	0.8	3.1		1.8		3.8		0.2	0.5	0.4	2.0	1.1	1.0	1.4		0.6	0.7
Globobulimina auriculata	0.6	0.5	1.5	1.5	1.8	0.5	1.6		1.8	0.2	1.5	0.5	1.3	0.2	0.2	1.0	0.4	0.9	1.8	1.1	1.2	0.3		0.6	
Glandulina ovula			0.2		0.2		0.3															0.2			
Fursenkoina spp.		0.2	0.2			0.3	1.6	0.9	0.3	1.0	0.2	0.5		0.7	0.4	0.4	0.2		0.6	0.7		0.7	1.1		0.7
Fissurina spp.	0.4	1.6	1.1		0.2			0.9	0.3	0.5	0.2		0.8	0.9	0.5				0.6	0.2					0.5
Elphidium spp.	4.6	3.7	4.3	4.3	1.3	2.4	0.3	1.2	1.0	0.5	0.5	1.0	1.3	1.1	1.2	0.4	0.9	1.7	0.8	0.2	0.7	0.7	2.3	1.5	2.0
Discorbina spp.																		0.2	0.6				0.6	0.3	
Cibicidoides wuellerstorfi												0.3				1.2		0.4			0.2			0.3	
Cibicidoides refulgens		0.2		0.4		1.1				0.7				0.4		0.2		0.2	0.4	0.4	0.2	0.2			0.2
Cassidulina neoteretis	7.2	8.2	8.5	8.7	11.7	9.2	3.6	4.6	9.1	9.7	8.8	11.1	3.5	5.1	2.9	7.2	4.5	5.2	2.2	2.9	5.3	1.2	3.4	4.7	1.5
Cassidulina laevigata	30.3	30.6	34.3	15.9	29.4	30.2	32.8	28.0	23.4	21.5	26.4	23.5	26.9	23.2	22.5	18.8	24.7	21.9	22.4	23.0	24.5	22.6	24.0	18.6	31.3
Cassidulina crassa	1.2	0.2	2.0	1.1	1.3	0.8					0.5		0.4	0.2	0.5	0.2	0.9	0.7	1.2	0.9	1.5	0.5	0.6	1.5	0.2
Bulimina marginata	9.4	5.3	6.3	7.2	5.1	6.8	9.1	12.5	9.1	11.6	7.3	9.0	10.0	9.2	7.5	8.7	6.8	6.9	9.8	9.8	8.5	8.1	18.3	12.7	10.7
Bolivina skagerrakensis	7.4	4.1	4.6	8.0	5.4	4.3	5.2	6.1	7.3	9.9	8.8	13.4	16.3	17.9	32.8	28.0	15.0	21.5	6.8	8.9	7.0	33.4	17.1	8.3	1.7
Astrononion gallowayi	0.6		0.2						0.3		0.2		0.2				0.4	0.4	0.6	0.2			0.6		
Angulogerina angulosa	0.8	1.1	1.1	1.1	1.6	0.3	1.0	0.6	1.0	1.2	0.7		1.0	1.1	1.1	1.0	1.8	0.7	1.2	1.6	1.7	1.0	3.4	1.5	4.0
age AD/BC	1792	1784	1771	1762	1750	1741	1728	1720	1707	1698	1686	1677	1664	1656	1643	1634	1622	1613	1592	1570	1549	1528	1506	1485	1464
core depth (cm)	38	40	43	45	48	50	53	55	58	60	63	65	68	70	73	75	78	80	85	90	95	100	105	110	115

APPENDIX II.1 (continued)

Nonionella turgida	1.9	0.7	1.7	2.0	1.3	0.7	1.1	0.7	0.3		0.6	1.0	1.0	0.1	0.6		0.3	0.5	1.8		1.9	0.9	0.5	1.0	0.5
Melonis spp.	3.9	2.7	2.1	5.9	1.8	1.9		2.7	1.7	1.0	1.8	1.8	2.0	1.1	1.1	0.8	1.4	0.5	1.5		1.9	1.8	1.0	2.6	1.5
Melonis zaandami	15.7	13.3	10.3	4.9	7.8	11.1	13.7	4.1	9.1	8.1	12.4	8.4	7.9	5.0	8.6	4.4	6.5	7.4	3.9	11.2	8.1	6.7	7.3	6.7	8.2
Melonis barleeanus	3.9	11.5	11.2	11.8	8.0	10.4	9.1	8.1	8.7	8.4	7.9	10.4	7.4	4.2	12.9	10.4	7.9	8.4	6.3	11.9	12.0	13.0	17.7	14.9	18.0
Lobatula lobatula	0.6	2.5	2.9	1.0		2.0	0.7	2.0	1.7	1.6	0.2	1.5	0.7	1.2	0.9	3.6	0.6	6.5	0.9	4.5	2.9	2.2	6.8	2.6	3.1
Lenticulina spp.									0.3												0.3				
Lagena spp.	3.0	0.7	0.4	1.0	2.9	1.7	2.1	2.7	2.0	1.3	1.6	1.6	2.0	0.9	0.6	0.8	1.4	1.4	2.7	0.7	1.9	1.8	2.6	2.6	1.5
Hyalinea balthica	4.1	5.0	7.9	2.0	9.4	15.2	6.0	8.1	6.7	6.5	7.5	8.4	7.7	8.6	8.6	9.6	8.2	12.1	13.1	18.7	14.3	19.7	9.4	10.3	14.9
Globobulimina turgida	1.9	1.8	1.2		0.9	2.2	2.8	0.7	1.7	1.3	1.2	1.6	1.0	0.1	0.3	0.4	0.8		0.3	2.2	1.0	1.3	0.5		0.5
Globobulimina hoeglundi	0.9	0.7			0.2	0.4	1.1		0.7	1.0	1.0	0.3	0.2		0.3	0.4			0.3	1.5	0.7	0.4			1.0
Globobulimina auriculata			0.8		0.7	0.7	0.4		1.0	0.7	0.2	0.5	1.0	0.1	0.3	0.8	0.6	0.9	0.3	2.2	1.3	0.4	0.5	0.5	
Glandulina ovula	0.2													0.1				0.5			0.3			0.5	
Fursenkoina spp.	0.4	0.2		1.0	0.2			0.7	0.3					0.1		0.4		0.5			0.3		0.5	0.5	
Fissurina spp.	0.6	0.5				0.2	0.4			0.7	0.4	0.6	0.2	0.8	0.3		0.6				0.7	0.4		1.0	
Elphidium spp.	1.7	0.9	2.1		1.1		1.1	2.7	1.3	0.7	1.6	1.5	1.2	0.9	0.3		0.6		0.3		0.3		0.5	0.5	1.5
Discorbina spp.		0.7	0.4								0.2	0.2	0.2	0.7	0.3						0.3		2.6		
Cibicidoides wuellerstorfi		0.5			2.5	2.2	1.1		0.7		2.2	0.2	1.5	0.8	0.6		5.4		2.4		2.3	1.3		2.6	
Cibicidoides refulgens	0.6												0.2												
Cassidulina neoteretis	1.1	8.3	4.5	2.0	2.5	2.4	2.5	15.5	0.3	7.8	1.0	6.3	0.5	3.4	0.9	10.8	0.6	7.9	0.6	2.2	0.3		2.1		4.1
Cassidulina laevigata	30.9	18.9	22.7	23.5	31.0	24.9	31.6	25.0	31.5	27.9	30.1	23.8	34.8	38.7	34.4	23.9	40.6	18.6	40.0	13.4	15.3	17.5	10.9	21.5	13.9
Cassidulina crassa	0.6	0.7	0.4	1.0				2.0	0.3			1.0	0.2	0.5							0.3			0.5	0.5
Bulimina marginata	10.1	10.8	14.5	22.6	14.3	9.5	9.8	8.8	6.4	13.6	13.0	16.2	12.6	12.4	9.7	10.4	6.5	7.0	6.9	12.7	17.5	17.5	13.0	13.8	13.4
Bolivina skagerrakensis	0.2	0.2							0.3	1.0	0.2											0.4			
Astrononion gallowayi	0.4		0.4		0.7	0.2					0.8			0.1	0.3		0.8	0.5		1.5	1.0	0.9	0.5		0.5
Angulogerina angulosa	3.4	3.2	0.8	3.9	2.2	1.9	1.1	0.7	3.4	1.0	2.0	2.3	0.7	2.6	0.6	0.4	1.4	0.9	0.9	1.5	1.3	0.4	0.5		
age AD/BC	1442	1421	1400	1378	1357	1310	1264	1217	1170	1123	1077	1030	983	936	890	843	796	749	703	656	609	562	516	469	353
core depth (cm)	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200	205	210	215	220	225	230	235	240

APPENDIX II.1 (continued)

Nonionella turgida								0.7	0.3						0.7		0.6								
Melonis spp.	0.8		1.9	0.6	1.9	1.6			0.7	0.6	1.8	0.8	0.6	3.6	0.7	1.0	0.6		2.1		2.1	1.2	1.3	0.8	1.4
Melonis zaandami	3.4		9.5	5.4	4.4	3.9	1.9	0.7	2.1	6.7	7.3	8.2	5.5		3.3		2.9	5.0	5.6	7.4	3.2	4.6	4.4	2.9	6.1
Melonis barleeanus	14.0		15.2	14.5	17.7	11.6	15.5	14.7	3.8	16.0	13.9	18.4	18.1	14.3	16.0	17.3	17.3	20.0	30.6	29.4	24.3	31.0	22.5	12.5	12.9
Lobatula lobatula	1.9	1.6	1.9	3.0	1.9	2.3	5.6	4.7	3.4	3.7	5.5	5.6	3.3	21.4	8.0	2.9	6.4	7.5	4.2	5.9	6.9	8.1	5.0	2.5	4.1
Lenticulina spp.			0.6	0.6						1.2		0.4							0.7		0.5				2.7
Lagena spp.	1.5	4.8	2.5	0.6	3.2	4.7		1.3	1.7	5.5	1.2	1.1	1.6	3.6	2.7		1.2	1.9	1.4		1.1		2.5	1.7	0.7
Hyalinea balthica	20.5	20.6	20.3	21.1	13.9	23.3	14.9	23.3	27.9	9.8	20.0	22.1	21.4	3.6	14.0	27.9	16.2	16.3	14.6	7.4	13.2	6.3	11.3	20.4	14.3
Globobulimina turgida	0.4		1.3			0.8		0.7	0.7		0.6	3.0			1.3		1.2	0.6	1.4		0.5				
Globobulimina hoeglundi			0.6						0.7			0.4	1.1				1.7		0.7						
Globobulimina auriculata	0.4		0.6		0.6				0.3								0.6						0.6		
Glandulina ovula			0.6	0.6	0.6			0.7	1.0		0.6						0.6	1.3							
Fursenkoina spp.	1.1					0.8		1.3	1.0	0.6	0.6			3.6						1.5					
Fissurina spp.	0.4							1.3			0.6	1.5									0.5				
Elphidium spp.	0.4	1.6	1.3	0.6			1.2	0.7	1.0	0.6	1.2	0.8	1.6	3.6					1.4	1.5	0.5	2.3	0.6	0.8	2.0
Discorbina spp.							0.6		0.7	1.2		0.4					0.6								
Cibicidoides wuellerstorfi	1.9		1.9		3.2	4.7		5.3		0.6															
Cibicidoides refulgens						0.8															0.5				1.4
Cassidulina neoteretis		4.8		1.2	0.6	0.8	0.6		0.3	0.6					1.3	1.0		0.6	0.7		3.7	1.7	1.3		0.7
Cassidulina laevigata	13.6	17.5	12.0	13.9	8.2	7.0	7.5	8.0	16.9	6.7	5.5	9.4	11.5	14.3	16.0	9.6	12.7	14.4	6.9	13.2	11.6	17.8	13.8	11.7	14.3
Cassidulina crassa						0.8			0.3	0.6									0.7				0.6	0.4	
Bulimina marginata	27.3	36.5	14.6	23.5	31.0	20.9	30.4	12.0	9.7	18.4	15.2	13.5	20.3	14.3	20.0	20.2	17.9	10.0	9.7	8.8	11.1	11.5	13.8	24.2	21.8
Bolivina skagerrakensis				0.6																					
Astrononion gallowayi			0.6					0.7		0.6		0.4	0.6		0.7		1.2	1.3					0.6	0.4	
Angulogerina angulosa	0.4		0.6	0.6	1.3		1.2		0.3	2.5	0.6	1.1			0.7	1.0		1.3		2.9	1.6		1.3		1.4
age AD/BC	236	120	3	-113	-229	-346	-462	-579	-695	-812	-928	-1044													
core depth (cm)	245	250	255	260	265	270	275	280	285	290	295	300	305	310	315	320	325	330	335	340	345	350	355	360	365

APPENDIX II.1 (continued)

Nonionella turgida							0.5	
Melonis spp.		4.1	2.4	1.9	1.1	1.4	4.3	
Melonis zaandami	7.0		4.2	3.7	1.6	6.9	6.4	5.1
Melonis barleeanus	23.3	14.3	16.4	14.0	7.4	17.4	13.4	16.7
Lobatula lobatula	6.2	6.1	3.6	3.7	6.3	1.4	5.9	4.3
Lenticulina spp.						0.7		
Lagena spp.		2.0	2.4	0.9		1.4	1.6	0.7
Hyalinea balthica	13.2	18.4	16.4	12.2	36.3	16.7	21.9	17.4
Globobulimina turgida				0.9			0.5	
Globobulimina hoeglundi						0.7		
Globobulimina auriculata			0.6					0.7
Glandulina ovula								
Fursenkoina spp.						0.7		
Fissurina spp.					1.1			
Elphidium spp.				2.8	1.1	3.5	1.6	0.7
Discorbina spp.								
Cibicidoides wuellerstorfi								
Cibicidoides refulgens	0.8							
Cassidulina neoteretis	1.6					0.7		
Cassidulina laevigata	10.9	6.1	12.1	10.3	6.3	12.5	14.4	8.0
Cassidulina crassa			0.6					
Bulimina marginata	12.4	32.7	21.2	16.8	22.6	11.1	8.6	25.4
Bolivina skagerrakensis								
Astrononion gallowayi	1.6			1.9		0.7		
Angulogerina angulosa	1.6					1.4		
age AD/BC								
core depth (cm)	370	375	380	385	390	395	400	405

APPENDIX II.1 (continued)

Sigmoilopsis schlumbergeri	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.5	0.0	0.0	0.2	0.3	0.0	0.0	0.5	0.0	0.0	0.3	0.0	0.2	0.0	0.8
Eratidus foliaceus		0.4	0.8	1.1	0.4	0.6	0.6	1.2	2.7	1.3	2.7	1.7	1.8	1.9		0.5				0.5		0.5	0.2	
Eggerelloides scabrus	8.1	9.2	9.2	5.6	4.4	3.2	3.1	4.4	3.7	2.3	2.7	5.0	3.9	1.6	1.0	2.0	1.0	2.1	0.3	0.8		0.7		0.6
Cribrostomoides wiesneri		1.0	1.7	1.9	0.4	0.8	0.3	0.4					0.7											
Cribrostomoides subglobosus	1.8	0.5	0.6	1.0	0.4	0.3	0.6								0.6						0.5			
Valvulineria minuta		0.7				0.2			0.2				0.2											
Uvigerina mediterranea	1.3	2.0	1.1	1.5	1.2	0.8	1.5	1.7	2.1	1.5	2.7	1.7	2.4	1.6	2.3	2.0	1.6	0.9	2.0	1.3	3.3	2.9	0.2	2.8
Triloculina spp.					0.1					0.3														
Triloculina sp. 4																								
Triloculina sp. 3					0.1		0.1										0.3							0.2
Triloculina sp. 2			0.2					0.1			0.2													
Triloculina sp. 1																							0.2	
Steinfortia fusiformis																								
Quinqueloculina spp.			0.3			0.2		0.1			0.2	0.2												0.2
Quinqueloculina seminulum	0.8				0.3	0.3	0.1	0.2						0.5		0.2							0.2	
Pyrgo sp. 2																	0.2							
Pyrgo sp. 1	0.3	0.1	0.2														0.2						0.2	
Pyrgo cf. *laevis*	0.8	0.2	0.2			0.3				0.3		0.2		0.5	0.2								0.2	
Pullenia quinqueloba	0.3	1.7	0.8	1.1	0.8	0.8	0.9	1.8	1.4	0.8	0.2	0.4	0.7	0.3	1.0	0.2	0.8	0.3	2.3	0.3	0.8	1.2		2.0
Pullenia bulloides	7.3	3.3	4.4	3.2	3.7	3.6	3.2	2.8	4.1	2.5	4.0	3.0	2.6	1.3	2.3	3.0	1.5	2.7	0.3	3.5	1.9	2.6	1.5	3.2
Nonion labradoricum	0.3					0.2		0.1											0.6		0.3	0.2	0.2	
age AD/BC	2000	1993	1986	1979	1972	1965	1958	1951	1944	1938	1931	1924	1917	1910	1896	1878	1869	1856	1848	1835	1827	1814	1805	1792
core depth (cm)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	15	18	20	23	25	28	30	33	35	38

APPENDIX II.1 (continued)

Sigmoilopsis schlumbergeri	0.0	0.2	0.0	0.0	0.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.2	0.2	0.2	0.0	0.0	0.2	0.0	0.6	0.0
Eratidus foliaceus		0.4					0.3		0.8				0.2		0.4		0.4							
Eggerelloides scabrus	0.5	0.4			0.7																0.2			0.3
Cribrostomoides wiesneri																								
Cribrostomoides subglobosus																								
Valvulineria minuta		0.6	0.4	0.4			0.5					0.3					0.2	0.7				1.0		
Uvigerina mediterranea	1.8	2.8	3.6	3.6	3.3	3.3	1.8	1.5	1.8	4.1	2.4	2.8	3.1	3.3	2.7	3.5	2.7	3.5	3.0	2.7	2.9	0.3	4.0	2.7
Triloculina spp.																								
Triloculina sp. 4									0.3					0.4					0.2					
Triloculina sp. 3					0.2							0.3		0.4										
Triloculina sp. 2																								
Triloculina sp. 1																						0.2		
Steinfortia fusiformis										0.2		0.3		0.2		0.2					0.7	0.3		0.6
Quinqueloculina spp.			0.7	0.7	0.2				0.3								0.2					0.3		
Quinqueloculina seminulum	0.5				0.2		0.3																0.6	
Pyrgo sp. 2																								
Pyrgo sp. 1												0.3										0.2		
Pyrgo cf. *laevis*									0.5	0.7		0.3		0.4					0.2			0.2		
Pullenia quinqueloba	0.7	0.7	0.4	0.4	1.1	0.8	0.8	0.3	0.8	1.2	0.7	0.8	0.8	0.9	0.7	0.8	1.1		1.0	1.3	1.5	0.2	0.6	3.0
Pullenia bulloides	2.7	3.0	1.8	1.8	2.7	3.0	2.9	5.2	3.1	4.6	3.7	3.6	2.7	3.8	2.5	3.3	2.9	2.6	5.6	7.1	5.6	3.8	2.3	7.7
Nonion labradoricum			0.4	0.4	0.2								0.4										1.1	0.3
age AD/BC	1784	1771	1762	1762	1750	1741	1728	1720	1707	1698	1686	1677	1664	1656	1643	1634	1622	1613	1592	1570	1549	1528	1506	1485
core depth (cm)	40	43	45	45	48	50	53	55	58	60	63	65	68	70	73	75	78	80	85	90	95	100	105	110

APPENDIX II.1 (continued)

Sigmoilopsis schlumbergeri	0.0	0.0	0.0	0.4	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.8	0.0	0.9	0.0	0.0	0.3	0.0	0.0
Eratidus foliaceus																								
Eggerelloides scabrus																								
Cribrostomoides wiesneri																								
Cribrostomoides subglobosus																								
Valvulineria minuta	0.2	0.2			1.0				0.7			0.4	0.3	0.2	0.1		0.4							
Uvigerina mediterranea	3.2	1.3	2.7	4.1	2.9	3.3	2.8	4.6	4.7	7.1	5.2	2.9	2.9	3.7	4.4	4.6	6.8	5.4	13.5	5.4	3.7	5.2	3.1	5.2
Triloculina spp.																								
Triloculina sp. 4						0.4									0.1		0.4							
Triloculina sp. 3					1.0	0.2					0.3	0.2			0.7	0.6	1.2	0.6					0.4	0.5
Triloculina sp. 2			0.5				0.4					0.2		0.2	0.1	0.3								
Triloculina sp. 1																	0.8		0.5	0.3				
Steinfortia fusiformis													0.2	0.2		0.3	0.4		0.5					
Quinqueloculina spp.					1.0					0.3														
Quinqueloculina seminulum			0.5				0.4			1.0	1.0		0.2	0.2	0.3		1.2							
Pyrgo sp. 2																							0.4	
Pyrgo sp. 1																								
Pyrgo cf. *laevis*				0.4		0.4		0.4			0.3	0.2		0.2	0.1	0.6	0.8		0.5	0.3				0.5
Pullenia quinqueloba	2.5	2.4	4.1	1.7	1.0	1.1	1.7	2.8	2.7	2.7	1.6	2.9	1.5	3.0	1.7	4.0	5.2	2.0	1.4	1.5	3.7	1.9	3.1	2.1
Pullenia bulloides	5.7	7.3	5.4	7.0	5.9	5.3	6.5	6.7	4.1	5.0	7.1	5.5	6.1	7.7	7.5	5.7	2.8	5.1	7.0	6.3	6.0	4.9	3.6	9.9
Nonion labradoricum								0.4					0.2							0.3	0.7			
age AD/BC	1464	1442	1421	1400	1378	1357	1310	1264	1217	1170	1123	1077	1030	983	936	890	843	796	749	703	656	609	562	516
core depth (cm)	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200	205	210	215	220	225	230

APPENDIX II.1 (continued)

Sigmoilopsis schlumbergeri	0.0	0.0	0.0	0.0	0.0	1.2	0.6	0.8	0.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.5	0.0	0.6
Eratidus foliaceus																								
Eggerelloides scabrus																								
Cribrostomoides wiesneri																								
Cribrostomoides subglobosus																								
Valvulineria minuta										0.7						2.7		0.6		0.7		0.5	0.6	
Uvigerina mediterranea	1.5	3.1	3.8		3.8	1.8	3.8	3.9	9.3	10.7	8.0	6.7	5.2	3.3	3.6	3.3	7.7	3.5	5.6	1.4	8.8	4.8	2.3	5.0
Triloculina spp.						0.6								0.6							1.5			
Triloculina sp. 4						0.6				0.7		2.4		0.6	3.6	0.7	1.0					0.5		1.3
Triloculina sp. 3	0.5	0.5		4.8		1.2	1.3	1.6	0.7	1.0	0.6	0.6						0.6	0.6			0.5		0.6
Triloculina sp. 2						0.6				0.3						1.3						0.5	0.6	
Triloculina sp. 1	1.0				0.6			2.3													1.5			
Steinfortia fusiformis										0.3										1.4				
Quinqueloculina spp.	0.5				1.3				0.7							0.7		0.6	0.6	0.7		0.5		0.6
Quinqueloculina seminulum		1.5	0.8			0.6	0.6	1.6	0.7	2.1				1.1	3.6			1.7	1.3	0.7	1.5		1.2	
Pyrgo sp. 2							0.6	0.8	1.3			0.6												
Pyrgo sp. 1				1.6	0.6	1.8			1.3									0.6	0.6			0.5		
Pyrgo cf. *laevis*	0.5	1.0	0.4		0.6			0.8		2.1		0.6		0.6			1.9	1.2	1.3			0.5		1.3
Pullenia quinqueloba	2.6	0.5	1.5		0.6		1.9	0.8	3.3	2.1	6.1	4.2	2.6			0.7	1.9	3.5	1.3	2.8	1.5	0.5		
Pullenia bulloides	7.7	7.2	3.4	6.4	2.5	0.6		0.8	4.0	2.4	6.7	5.5	3.4	6.0	3.6	2.7	3.8	4.1	5.0	11.1	5.9	6.9	7.5	10.0
Nonion labradoricum																	1.0							
age AD/BC	469	353	236	120	3	-113	-229	-346	-579	-695	-812	-928	-1044											
core depth (cm)	235	240	245	250	255	260	265	270	280	285	290	295	300	305	310	315	320	325	330	335	340	345	350	355

APPENDIX II.1 (continued)

Sigmoilopsis schlumbergeri	0.0	0.7	0.0	0.0	0.0	0.0	0.5	0.0	0.0	1.5
Eratidus foliaceus										
Eggerelloides scabrus										
Cribrostomoides wiesneri										
Cribrostomoides subglobosus										
Valvulineria minuta										
Uvigerina mediterranea	2.5	4.1	3.9	4.1	3.6	4.7	4.2	5.6	4.8	8.0
Triloculina spp.	0.4		0.8				0.5			
Triloculina sp. 4	0.8						0.5		0.5	
Triloculina sp. 3	1.7		0.8				1.1			1.5
Triloculina sp. 2	0.4		0.8							1.5
Triloculina sp. 1										
Steinfortia fusiformis										
Quinqueloculina spp.				2.0	0.6					
Quinqueloculina seminulum	2.5			2.0	1.2	0.9	1.1		0.5	
Pyrgo sp. 2	0.4				0.6					
Pyrgo sp. 1	0.4									
Pyrgo cf. *laevis*	0.4				1.2		0.5			0.7
Pullenia quinqueloba	1.7	1.4	2.3	2.0	0.6	3.7		2.1	2.1	0.7
Pullenia bulloides	7.5	9.5	9.3	4.1	9.7	18.7	7.4	13.9	6.4	5.1
Nonion labradoricum										
age AD/BC										
core depth (cm)	360	365	370	375	380	385	390	395	400	405

APPENDIX II Core 225514

2 Faunal assemblages and factor loadings

species	F1	F2	F3
Angulogerina angulosa	-0.291	-0.317	0.116
Astrononion gallowayi	-0.312	-0.292	-0.188
Bolivina skagerrakensis	**6.131**	-0.978	-1.84
Bulimina marginata	0.822	**3.678**	-0.248
Cassidulina crassa	-0.277	-0.379	-0.103
Cassidulina laevigata	**1.67**	-0.1	**5.945**
Cassidulina neoteretis	0.772	-0.724	0.882
Cibicides refulgens	-0.308	-0.366	-0.186
Cibicidoides cf. *wuellerstorfi*	-0.369	-0.24	-0.138
Discorbina sp. 1	-0.318	-0.332	-0.206
Elphidium excavatum	-0.08	-0.304	0.032
Fissurina spp.	-0.261	-0.362	-0.16
Fursenkoina spp.	-0.248	-0.326	-0.189
Glandulina ovula	-0.3	-0.335	-0.224
Globobulimina auriculata	-0.124	-0.39	-0.091
Globobulimina hoeglundi	-0.281	-0.369	-0.075
Globobulimina turgida	-0.057	-0.41	0.083
Hyalinea balthica	0.338	**3.718**	-0.739
Lagena spp.	-0.182	-0.059	-0.036
Lenticulina spp.	-0.31	-0.324	-0.228
Lobatula lobatula	-0.345	0.74	-0.284
Melonis barleeanus	0.078	**3.261**	0.193
Melonis zaandami	-0.129	0.143	**1.735**
Melonis spp.	-0.256	-0.164	0.069
Nonionella turgida	-0.353	-0.363	-0.054
Nonion labradoricum	-0.296	-0.37	-0.207
Pullenia bulloides	-0.099	0.871	0.322
Pullenia quinqueloba	-0.338	0.001	0.031
Pyrgo cf. *laevis*	-0.288	-0.259	-0.245
Pyrgo sp. 1	-0.297	-0.327	-0.242
Pyrgo sp. 2	-0.305	-0.336	-0.24
Quinqueloculina seminulum	-0.304	-0.203	-0.261
Quinqueloculina spp.	-0.298	-0.31	-0.239
Stainforthia sp.	-0.306	-0.367	-0.204
Triloculina sp. 1	-0.316	-0.342	-0.216
Triloculina sp. 2	-0.312	-0.337	-0.221
Triloculina sp. 3	-0.313	-0.246	-0.246
Triloculina sp. 4	-0.314	-0.287	-0.243
Triloculina spp.	-0.306	-0.349	-0.228
Uvigerina mediterranea	-0.253	0.641	0.151
Valvulineria minuta	-0.296	-0.349	-0.199

APPENDIX II.2 (continued)

species	F1	F2	F3
Cribrostomoides subglobosus	-0.231	-0.374	-0.258
Cribrostomoides wiesneri	-0.221	-0.372	-0.266
Eggerelloides scabrus	0.513	-0.388	-0.581
Eratidus foliaceus	-0.132	-0.389	-0.26
Sigmoilopsis schlumbergeri	-0.297	-0.316	-0.214

APPENDIX II Core 225514

3 Stable isotope measurements

		$\delta^{18}O$ (‰ VPDB)							$\delta^{13}C$ (‰ VPDB)						
core depth (cm)	AD/BC	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*
0	2000	2.89	2.65	2.77		2.17	1.89		0.02	0.01	-0.65		-1.19	-0.75	
1	1993	2.95	2.81	2.65	3.25	2.26	1.81	2.98	0.07	0.18	-0.95	-0.80	-1.53	-1.24	-0.58
2	1986	2.76	2.60	1.65	2.98	1.97	1.44	2.55	-0.04	0.13	-0.98	-1.12	-1.56	-1.18	-0.39
3	1979	2.68	2.55	1.90	3.12	2.09	1.70		-0.06	0.13	-0.87	-1.07	-1.51	-1.01	
4	1972	2.74	2.71	2.10		1.97		2.89	0.06	0.21	-0.79		-1.35		-0.12
5	1965	2.76	2.68	2.15		2.20	2.03		-0.11	0.44	-0.62		-1.33	-0.42	
6	1958	2.91	2.77	2.71		2.01	1.84	2.89	0.05	0.41	-0.76		-1.56	-0.99	-0.57
7	1951	2.83	2.77	2.34	3.37	2.18	1.89	3.06	0.04	0.45	-0.76	-0.97	-1.22	-0.70	0.03
8	1945	2.76	2.68	2.25	3.34	1.97	1.89	2.81	0.07	0.56	-0.74	-0.90	-1.16	-0.76	0.14
9	1938	2.78	2.81	2.47		2.24	1.99	2.73	0.04	0.37	-0.76		-1.03	-0.75	-0.43
10	1931	2.84	2.78	2.49		2.02	1.79	2.90	0.21	0.30	-0.51		-0.73	-0.60	-0.21
11	1924	2.56	2.67	1.58	3.50		1.90	2.82	0.21	0.46	-0.86	-0.64		-0.70	-0.20
12	1917	2.89	2.76	2.01	3.11	2.20	1.95	2.95	0.06	0.39	-0.77	-0.76	-0.77	-0.66	-0.14
13	1910	2.95	2.76	2.61	2.87	2.07	2.04	3.08	0.28	0.17	-0.72	-0.63	-0.95	-0.89	0.06
15	1896	2.97	2.83	2.98	3.45	2.46	2.11	3.13	0.43	0.27	-0.38	-0.58	-1.07	-0.72	-0.15
18	1878	3.06	2.89	2.99	3.48	2.36	2.14	3.24	0.30	0.41	-0.35	-0.42	-0.52	-0.39	-0.31
20	1869	3.02	2.96	2.95	3.43	2.41	2.13	3.22	0.15	0.62	-0.30	-0.30	-0.66	-0.27	0.01
23	1856	2.80	2.85	2.02	3.35	2.15	1.83		0.01	0.46	-0.75	-0.88	-0.87	-0.47	
25	1848	2.99	3.03	3.17	3.57	2.30	2.18		0.25	0.70	-0.20	-0.63	-0.61	-0.32	
28	1835	2.95	2.75	2.38	3.41	2.11	1.96		0.18	0.14	-0.62	-0.60	-0.82	-0.39	
30	1827	3.00	2.92	2.88	3.47	2.18	2.09	3.20	0.22	0.54	-0.50	-0.67	-0.85	-0.66	0.03
33	1814	2.68	2.75	2.07	3.24	2.19	1.70	2.93	-0.04	0.58	-0.63	-0.41	-1.15	-0.88	0.29
35	1805	3.20	3.17	3.53	3.63	2.61	2.35	3.13	0.28	0.60	-0.06	-0.68	-0.70	-0.48	-0.26
38	1792	2.91	2.94	2.53		2.25	2.05	3.02	0.35	0.35	-0.46		-1.14	-0.54	0.03
40	1784	2.79	2.76	2.89	3.56	2.38	2.24	3.02	0.28	0.32	-0.19	-0.72	-1.05	-0.83	-0.22
43	1771	2.69		2.07	3.40		1.91	3.12	0.22		-0.67	-0.67		-0.60	-0.08
45	1763	2.95	2.88	3.20		2.55	2.37	2.84	0.20	0.19	-0.44		-0.74	-0.48	-0.12
48	1750	2.68	2.75	2.10	3.39	2.25	1.99	2.70	0.06	0.35	-0.85	-0.76	-1.14	-0.83	-0.45
50	1741	2.72	2.90	2.69	3.13	2.39	2.15	2.89	0.21	0.40	-0.33	-0.47	-0.64	-0.48	0.20
53	1728	3.03	3.09	3.27	3.40	2.53	2.11	3.07	0.17	0.64	-0.31	-0.64	-1.04	-0.26	0.03
55	1720	2.65	2.94	2.83	3.22	2.39	2.17		0.26	0.35	-0.42	-0.65	-0.93	-0.60	
58	1707	2.44	2.75	1.72	3.53	2.23	1.93	2.60	0.05	0.28	-0.84	-0.78	-1.03	-0.54	-0.21
60	1699	2.64	2.76	2.61		2.35	2.06	2.86	0.15	0.39	-0.55		-1.12	-0.59	-0.09

APPENDIX II.3 (continued)

		$\delta^{18}O$ (‰ VPDB)							$\delta^{13}C$ (‰ VPDB)						
core depth (cm)	AD/BC	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*
63	1686	2.66	2.88	1.98		2.12	1.71	2.95	0.14	0.50	-0.80		-1.24	-0.79	-0.33
65	1677	2.79	3.01	3.12		2.45	2.36	2.87	0.37	0.42	-0.45		-1.00	-0.65	-0.00
68	1664	2.55	2.69	1.54		1.98	1.76	2.88	0.01	0.23	-0.92		-1.37	-0.69	-0.18
70	1656	2.96	2.90	3.50		2.51	2.04	3.28	0.27	0.28	-0.41		-1.03	-0.49	-0.37
73	1643	2.74	2.67	1.67		1.80	1.56	2.86	0.23	0.30	-0.86		-0.77	-0.79	-0.05
75	1634	2.71	3.00	3.12	3.19	2.58	2.24	2.97	0.24	0.70	-0.29	-0.45	-0.93	-0.37	-0.21
78	1622	2.91	2.89	2.48	3.17	2.14	2.02	3.05	0.21	0.48	-0.69	-0.77	-0.95	-0.51	-0.25
80	1613	2.74	2.92	2.87		2.32	2.26	2.88	0.26	0.37	-0.50		-0.51	-0.53	-0.12
85	1592	2.65	2.89	3.25	3.45	2.28	2.19		0.17	0.48	-0.37	-0.57	-0.34	-0.46	
90	1570	3.08	2.98	3.49		2.48	2.25	3.27	0.22	0.50	-0.37		-0.53	-0.60	-0.06
95	1549	3.10	3.06	3.43	3.35		2.19	3.21	0.26	0.72	-0.44	-0.77		-0.73	0.09
100	1528	3.16	3.08	3.14		2.31	2.36		0.24	0.40	-0.51		-0.70	-0.63	
105	1506	3.04	2.80						0.23	0.23					
110	1485	2.95	2.85	2.88		2.38	1.99	2.96	0.13	0.41	-0.37		-1.01	-0.75	-0.17
115	1464		2.88	3.24		2.45	2.10			0.38	-0.31		-0.71	-0.53	
120	1442		3.00	2.90	3.41	2.31	2.04	3.01		0.62	-0.42	-0.64	-0.87	-0.71	-0.17
125	1421		2.85	2.86	3.52	2.43	2.06	2.92		0.52	-0.42	-0.84	-1.19	-0.62	-0.38
130	1400		3.01	3.08		2.31		3.18		0.64	-0.44		-1.11		-0.19
135	1378														
140	1357		2.97	3.15		2.50	2.11	3.21		0.44	-0.57		-1.18	-0.95	-0.38
145	1310		2.75	2.89		2.40	2.09	3.05		0.48	-0.50		-1.27	-0.91	-0.35
150	1264		2.78	2.88	3.43	2.35	1.86	3.04		0.16	-0.67	-0.99	-1.01	-0.76	-0.18
155	1217			3.30							-0.57				
160	1170			4.03			2.37	3.53			-0.70			-0.87	-0.52
165	1123		2.99	3.01		2.55	2.10	3.08		0.57	-0.51		-1.23	-0.89	-0.27
170	1077		2.98	3.25		2.49	2.21	3.07		0.37	-0.48		-1.14	-0.59	-0.05
175	1030		3.05	3.22		2.54	2.17	3.33		0.59	-0.38		-0.92	-0.74	0.00
180	983		2.94	3.66		2.66	2.26	3.18		0.36	-0.54		-1.09	-1.04	-0.22
185	936		2.99	3.72		2.54	2.25	3.39		0.47	-0.57		-1.39	-0.80	-0.29

APPENDIX II.3 (continued)

		$\delta^{18}O$ (‰ VPDB)							$\delta^{13}C$ (‰ VPDB)						
core depth (cm)	AD/BC	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*
190	890		3.13	3.72		2.68	2.19	3.32		0.33	-0.57		-1.22	-0.77	-0.33
195	843							3.63							-0.21
200	796		3.07	3.23		2.57	2.31	3.27		0.44	-0.60		-1.28	-0.76	-0.07
205	749		3.05	3.64			2.30	3.34		0.03	-0.58			-0.69	-0.26
210	703		3.16	3.52		2.50		3.17		0.35	-0.47		-0.87		-0.39
215	656		2.98	3.30		2.48	2.25	3.09		0.44	-0.33		-1.04	-0.50	-0.29
220	609		3.21	3.20		2.59		3.26		0.55	-0.58		-1.19		-0.17
225	563		2.89	3.01		2.47	2.26	3.06		0.48	-0.61		-1.10	-0.90	-0.50
230	516														
235	469		2.84	2.85		2.58	2.25			-0.01	-0.52		-0.91	-0.88	
240	353		2.85			2.49	2.22	3.20		0.17			-1.26	-0.91	-0.39
245	236		3.10	3.28		2.56	2.16			0.37	-0.62		-1.25	-0.62	
250	120		2.94							0.09					
255	3		2.88			2.64	2.28			0.48			-1.28	-0.85	
260	-113		2.92			2.43				0.30			-1.05		
265	-230		2.81			2.38		2.97		0.51			-1.20		-0.44
270	-346		3.22			2.65		3.08		0.08			-1.51		-0.22
275	-462		3.12			2.56		3.09		0.29			-1.21		0.10
280	-579		2.88			2.49		3.21		0.01			-1.17		-0.39
285	-695		3.09	3.24		2.50		3.05		0.01	-0.46		-1.19		-0.24
290	-812		2.88			2.43	2.16	3.02		0.19			-1.32	-0.97	-0.30
295	-928		2.78			2.33	2.01	3.02		0.27			-1.43	-0.73	-0.20
300	-1044		2.99	2.83		2.49	2.22	3.06		0.31	-1.04		-1.17	-0.65	-0.30
305			2.89			2.38	2.23	3.04		0.23			-1.40	-0.75	-0.38
310															
315			2.87	2.64		2.40				0.27	-0.92		-1.47		
320								3.35							-0.29
325			2.90	2.93		2.38	2.17			0.38	-0.75		-1.53	-0.88	
330			3.01	3.49		2.66	2.25	3.20		0.30	-0.89		-1.32	-0.99	-0.42

APPENDIX II.3 (continued)

		$\delta^{18}O$ (‰ VPDB)							$\delta^{13}C$ (‰ VPDB)						
core depth (cm)	AD/BC	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*	*Bolivina skagerrakensis*	*Bulimina marginata*	*Cassidulina laevigata*	*Globobulimina turgida*	*Melonis barleeanus*	*Melonis zaandami*	*Uvigerina mediterranea*
335			2.82			2.58	2.24			0.39			-1.24	-0.69	
340						2.62		3.23					-0.92		-0.46
345			2.79			2.43	2.05	2.95		0.20			-1.20	-0.81	-0.17
350			2.98	3.64		2.60		3.24		0.30	-1.26		-1.29		-0.12
355			3.01			2.49		3.11		0.22			-1.26		-0.30
360			3.07	3.24		2.58	2.29	3.06		0.38	-0.75		-1.16	-0.63	-0.07
365			2.87			2.47	2.34	3.08		0.30			-1.42	-1.11	-0.61
370			3.01			2.50		2.95		0.01			-0.99		-0.26
375															
380								3.51		0.44			-0.89		-0.26
385			2.64			2.07				0.14			-1.23		
390			2.79			2.05		3.03		0.31			-1.17		-0.18
395			2.82			2.12	1.85	2.97		0.49			-0.96	-0.78	0.00
400			2.73			2.01		2.78		0.11			-0.82		-0.22
405			2.90			2.41		3.05		0.50			-0.98		-0.12

APPENDIX III Data of Core 225510

1 Relative frequencies of counted species

Nonion labradoricum	0.5	2.0	0.3	0.5	0.3	2.3	0.8		1.5	0.4			0.2		0.3								0.3	0.3
Melonis zaandami	2.7	1.2	4.7	2.3	4.5	4.8	3.5	1.4	3.6	8.8	0.1	0.8	0.3									2.3		
Melonis barleeanus	1.1		0.7	3.7	0.9	1.0		0.3	1.1	1.9			0.2		0.3							0.9	0.9	
Lobatula lobatula	2.1	1.5	1.4	5.6	2.7	2.1	1.2	1.1	4.0	2.4	4.4	1.3	5.8	3.0	2.0	5.6	2.6	4.1	3.3	3.3	3.9	0.3	0.9	3.6
Lagena spp.	1.6	0.3	0.3		0.8	0.4	0.4	0.9	0.4	0.7	0.9	0.8	0.6	0.7	0.3	1.2	3.3	1.5	0.9	0.7	2.5	0.3		0.3
Hyalinea balthica	5.3	5.5	7.8	4.7	10.2	17.3	17.9	3.1	4.7	14.6	0.7	3.8	8.1	3.0	9.5	0.3	0.4	1.1		0.7	0.4	4.9	23.3	1.2
Haynesina nivea						0.8			1.1		1.2	0.3	0.5		2.0	2.5		1.1	0.5				0.9	
Globobulimina turgida	0.5	62.6	21.6	3.7	14.8	12.7	9.3	38.5	17.4	6.3	3.3	18.9	4.2	6.3	5.3	1.6	9.3	8.5	11.8	11.5	2.5	3.8	3.7	9.9
Globobulimina auriculata	0.5	7.0	2.4		1.1	1.5		0.6				0.5	0.2											
Fursenkoina spp.											0.3						0.7	0.4		0.7	0.4			0.6
Fursenkoina cf. *complanata*			1.0	0.9	1.5	0.2	0.8	0.3	1.1	0.2		1.8				0.3	0.4							
Fissurina spp.	0.5			0.9	0.5	0.2	0.4	0.3	0.7	0.2	0.4		0.6			0.9	1.1		0.5		0.7		0.3	0.6
Elphidium sp. 2		0.9	3.0	1.4	2.8		0.8																	
Elphidium sp.1						0.6		1.7	1.5	1.5	2.2	2.0	1.7	8.9	3.0	9.6	13.4	8.1	6.6	3.7	0.7	1.7	3.2	3.0
Elphidium excavatum f. *clavata*	0.5	0.6	2.0	1.9	2.7	4.0	0.8	0.9	8.7	6.7	30.8	12.8	18.7	10.6	8.2	25.2	20.4	6.6	10.9	5.2	3.9	6.1	14.7	36.1
Elphidium albiumbilicatum		2.9	1.0	2.8	2.5	2.3		1.7	2.2	0.9	0.4	0.5	1.4	0.3	0.7	3.1	1.5	2.2	1.4	0.7	0.4		1.7	
Cassidulina neoteretis	12.2	1.5	14.5	13.0	23.8	10.0	21.0	15.6	9.1	24.3	6.5	10.7	9.0	20.9	24.0	7.1	3.7	17.7	9.5	14.9	34.0	16.5	6.3	11.1
Cassidulina laevigata	24.5	2.3	8.1	16.7	13.2	16.6	21.8	18.7	14.1	13.3	10.5	17.6	10.3	9.9	24.3	9.3	10.8	19.1	15.6	17.8	35.7	45.2	6.9	6.9
Cassidulina crassa	0.5		0.3		0.2		0.4	0.3		0.2	0.6	0.3	0.5	0.7		0.9	0.7	0.4						
Bulimina marginata	3.2	0.3	1.7	3.3	0.3	2.1	0.8	0.3	0.4	0.3	1.0	0.8	1.6	0.3										0.3
Bucella cf. *frigida*									0.4															
Bolivina skagerrakensis	4.8	2.0	11.8	13.0	3.3	5.4	3.9	0.3	1.1	0.3			0.3	0.3	0.3				0.5			0.3		
Angulogerina angulosa	1.6	0.3		1.4	0.3	0.2			1.1	0.2	0.3	0.3		0.3	0.3									
Ammonia falsobeccarii											0.4	1.8	1.2	0.3		0.6	0.7		0.5			0.3	0.6	
Ammonia beccarii					0.3	0.4		0.3	1.5	0.4	2.5	0.3	0.8	1.3	0.7	0.3	1.5	0.4		0.4		0.3	0.9	7.2
AD	2000	1998	1996	1994	1992	1990	1988	1986	1985	1983	1981	1979	1977	1973	1971	1969	1967	1965	1963	1952	1940	1927	1914	1901
core depth (cm)	2	10	20	30	40	50	60	70	80	90	100	110	120	140	150	160	170	180	190	200	210	220	230	240

APPENDIX III.1 (continued)

Nonion labradoricum					0.4			0.1																
Melonis zaandami				0.3	0.4	0.4	1.5						0.2			0.5				0.9		3.1	0.3	0.7
Melonis barleeanus			0.2			0.4		0.4							0.7		0.7			0.9	1.1	2.3	1.6	0.2
Lobatula lobatula	2.5	1.9	2.9	3.8	1.1	1.9	1.5	0.5	0.3	3.6	1.6	3.8	2.7	0.9	1.7	1.4	3.0	0.7	0.8	1.4	3.0	1.9	1.6	1.8
Lagena spp.	1.2	0.2	2.9	1.3	0.4	2.7	1.2	0.6	0.3	2.1	1.6	2.5	0.9	2.7	3.4	3.3	2.7	0.3	1.6	0.5	0.4	3.1	0.6	1.1
Hyalinea balthica		0.3	1.0	1.6	2.5		0.3	18.6	1.8	1.0	1.6		0.2	0.6	1.0		1.0			28.9	2.2	1.2	2.6	2.4
Haynesina nivea	1.2	1.4	1.6	0.3	0.7					1.3	2.4	2.0	2.7	1.8	2.4		2.0	1.0	2.4		1.5	1.2	0.3	1.1
Globobulimina turgida	1.2	2.6	7.1	1.6	12.8	14.4	16.6	8.8	28.6	1.8	12.2	2.0	2.7	12.8	9.0	38.4	9.4	47.6	18.9	3.3	2.6	4.6	4.2	2.2
Globobulimina auriculata								0.1																
Fursenkoina spp.	0.3		0.8	0.3	0.4	2.3	0.6			0.5	0.3	0.3	0.2		2.1		0.3	0.3	0.8				6.7	1.3
Fursenkoina cf. *complanata*								0.4							0.3		1.0							
Fissurina spp.	0.9	0.2	1.4	0.3	0.4				0.3	0.5	0.8	0.5	0.2	1.5		0.5		0.3	1.6		0.4	0.4	0.3	0.2
Elphidium sp. 2																								
Elphidium sp.1	6.5	4.5	5.9	5.0	5.7	6.6	1.8		0.9	10.3	4.2	7.1	13.6	7.4	15.5	1.4	7.4	1.7	3.9	3.3		1.5	3.8	14.5
Elphidium excavatum f. *clavata*	32.0	35.8	19.6	18.8	8.9	14.4	3.3	0.5	1.2	22.7	14.6	15.2	11.3	24.4	14.1	4.3	14.8	8.2	11.0	0.9	8.2	14.6	2.9	6.8
Elphidium albiumbilicatum	1.6		1.2	0.9				0.9		0.3	0.3										0.4	2.3	1.0	4.0
Cassidulina neoteretis	3.7	3.9	7.4	15.7	11.0	18.3	19.3	29.2	9.0	4.1	15.1	9.1	23.8	6.3	2.8	11.4	10.8	6.9	3.9	18.5	10.8	5.0	8.7	5.5
Cassidulina laevigata	6.5	5.8	20.7	27.3	23.1	15.6	33.4	27.7	27.7	2.3	20.9	15.2	15.3	9.5	4.8	11.4	7.1	6.2	7.9	23.7	51.5	28.1	39.4	28.0
Cassidulina crassa	1.2	0.3	0.2		0.4	0.4				0.8								0.3	0.8		0.4	0.4	0.3	
Bulimina marginata	0.6	0.5	0.4			0.4	0.3	0.1		0.3	0.3	0.5	0.2	0.9	0.3	0.9	0.3		0.8		1.1			
Bucella cf. *frigida*	0.3					0.8	0.6			0.3	0.8		0.9	0.3	0.3	0.5				0.5	0.7	1.5	0.3	0.9
Bolivina skagerrakensis																			0.8	0.5				
Angulogerina angulosa		0.3			0.4		1.2	0.4					0.2	0.3							1.1		0.6	1.1
Ammonia falsobeccarii	0.3	0.2	0.4									0.3												
Ammonia beccarii	4.7	2.7	0.8		2.8	0.4	0.9		0.3	3.6	2.1	3.3	2.2	8.3	3.1	0.5	2.0	0.3	1.6		0.4	2.3	0.3	0.9
AD	1889	1876	1863	1851	1838	1825	1813	1800	1787	1775	1762	1749	1737	1724	1711	1699	1686	1673	1661	1648	1628	1612	1600	1587
core depth (cm)	250	260	270	280	290	300	310	320	330	340	350	360	370	380	390	400	410	420	430	440	456	468	478	488

APPENDIX III.1 (continued)

Nonion labradoricum					
Melonis zaandami			0.6		0.6
Melonis barleeanus		1.0	0.9	0.4	0.3
Lobatula lobatula	3.1	0.7	1.8	1.1	3.5
Lagena spp.	2.8	1.7	3.0	2.3	1.2
Hyalinea baltica	0.7	0.3	0.6	0.8	1.5
Haynesina nivea	0.7		1.5	2.3	1.7
Globobulimina turgida	1.1	12.2	2.7	1.5	0.9
Globobulimina auriculata	0.7				
Fursenkoina spp.	3.5	1.4	3.0	3.4	0.6
Fursenkoina cf. *complanata*		1.0			0.6
Fissurina spp.	1.1	0.3	0.3	0.4	1.5
Elphidium sp. 2					
Elphidium sp.1	11.9	8.0	8.4	3.4	10.8
Elphidium excavatum f. *clavata*	14.6	6.3	7.8	7.5	6.4
Elphidium albiumbilicatum	4.9	2.8	6.0	1.9	3.2
Cassidulina neoteretis	0.3	3.1	3.6	6.0	5.2
Cassidulina laevigata	9.8	28.1	22.5	44.0	16.3
Cassidulina crassa	1.1		0.3	1.1	0.6
Bulimina marginata	0.3	0.3			
Bucella cf. *frigida*	1.4	3.5	1.5	2.3	0.9
Bolivina skagerrakensis					
Angulogerina angulosa		0.7	0.3	0.4	0.3
Ammonia falsobeccarii					
Ammonia beccarii	2.1	1.0	2.4	1.5	2.6
AD	1561	1548	1535	1523	1516
core depth (cm)	509	519	529	539	544

APPENDIX III.1 (continued)

Trochammina ochracea					0.8	0.4	0.4		1.8	0.4	0.3	0.3	0.2		1.0		1.1		
Trochammina labiosa					0.3				0.4		0.3						0.4		
Textularia sp. 1											4.4	1.0	4.7	1.3	0.3	2.8	1.5	0.4	2.4
Reophax spp.							0.4					0.3	0.2					0.4	1.4
Reophax subfusiformis																			0.5
Eggerelloides scabrus		0.3	0.3		0.3	0.6	4.7	3.7	1.8	1.9	0.6	2.0	1.2		3.9	0.3	0.7	1.1	5.7
Cribrostomoides jeffreysii					1.2	0.6	0.4		2.2		1.0	1.3	0.8	1.0	0.7	1.6	3.3	1.5	1.9
Uvigerina mediterranea	29.3	4.1	3.0	9.8	3.1	1.7	1.9	2.0	1.1	3.0	0.4	1.8	0.5	0.3	0.3	0.3	1.9	0.4	
Stainforthia fusiformis	0.5	2.0	6.4	1.4	0.9	2.5	0.4	1.4	2.9	1.3	1.8	0.8		4.6	1.3	2.5	0.4	1.8	0.5
Rosalina sp. 5											0.4					0.9	0.4		
Rosalina sp. 4											2.4	1.0	2.2	0.7		0.6	1.5	2.2	0.5
Rosalina sp. 3										0.2	2.1		2.0	0.7	0.3	1.2	1.1	1.8	
Rosalina sp. 2										0.4	5.8	1.5	6.7	4.0	1.0	2.5	1.5	2.9	5.7
Rosalina sp. 1		0.6	1.4	1.9	3.1		0.8	0.6	4.3	0.7	3.8	1.8	4.4	2.0	2.0	5.0	3.3	1.8	1.4
Rosalina spp.						2.7			0.7	0.4		1.3	0.6	1.0	0.7	0.9	0.4	1.1	0.9
Quinqueloculina spp.	0.5				0.2			0.3		0.2	0.3		0.2	0.7	1.0		1.1	0.4	0.9
Quinqueloculina stalkeri											0.6		0.9	0.7		1.6	0.7	0.4	0.9
Quinqueloculina seminulum			0.3	0.5	0.2	0.6	0.4					0.8		1.3			1.5	4.8	0.9
Pyrgo cf. *laevis*			0.7	0.5							0.3	0.3		0.7			0.7		1.9
Pullenia cf. *bulloides*		0.3	0.3		1.2	2.1	0.8	2.0	0.4	4.9	0.7	1.0	2.0	3.0	1.6	1.2	1.1	0.7	2.8
Polymorphina concava											0.3						0.7	0.4	
Planorbulina mediterranensis			0.7	0.5	0.3	0.2	1.2		1.5	0.2	5.5	2.6	5.6	7.0	2.6	5.9	3.0	4.4	3.8
AD	2000	1998	1996	1994	1992	1990	1988	1986	1985	1983	1981	1979	1977	1973	1971	1969	1967	1965	1963
core depth (cm)	2	10	20	30	40	50	60	70	80	90	100	110	120	140	150	160	170	180	190

APPENDIX III.1 (continued)

Trochammina ochracea	0.7	0.7		0.6	0.3	1.6	0.7	1.8	0.9	1.1	0.4	3.0		3.0	1.3	0.8	2.3	1.8
Trochammina labiosa				0.6		0.3		0.4		0.4	0.4	1.2		0.6	0.5	1.1	1.8	0.7
Textularia sp. 1				0.6	3.3	5.6	5.1	0.4		0.7		0.3			2.3	0.5		0.2
Reophax spp.	0.4	0.4	0.9	0.3	0.3		0.3	0.4		2.1			0.1					
Reophax subfusiformis	1.1		2.0	1.2	0.3		0.2	0.2	0.3					3.9	0.8			
Eggerelloides scabrus	6.7	0.4	0.6	3.7	1.2		0.3	1.8	3.8	2.5	0.4	3.6	0.8	4.2	0.3	0.3	0.3	0.2
Cribrostomoides jeffreysii	1.9	2.5	0.9	0.9		0.3	0.5	0.8	2.5	0.4	0.8			0.3	0.5		0.5	1.6
Uvigerina mediterranea	0.7		3.5	4.0				0.2	0.3	0.4		0.6	0.6	1.8	0.3		1.0	0.2
Stainforthia fusiformis	1.5	1.1			0.3	0.3	0.5	1.4	0.3	2.5	1.6	0.9		0.9	1.8	1.1	1.3	1.3
Rosalina sp. 5	0.4					0.3	0.9	0.2	0.3	0.7	0.8			0.3	1.0	1.3	0.8	0.9
Rosalina sp. 4	1.1			0.3	0.6	1.2	1.5		0.3	0.7	1.6				2.3		1.5	1.3
Rosalina sp. 3	0.4			0.3		0.6	2.9	1.2	1.6		1.2	0.6		0.6	3.9	1.9	4.1	1.3
Rosalina sp. 2	1.5		0.3	4.9	2.7	7.8	4.5	0.6	0.3	0.7	1.9				5.4	1.1	2.3	2.7
Rosalina sp. 1	1.5	0.4		2.3	0.3	4.3	2.7	2.5	1.6	1.4	1.6	0.3	0.4		4.6	2.9	5.8	3.3
Rosalina spp.		0.4		0.6		0.3	0.9	0.4	0.3	0.4	0.4	0.6		0.3	0.8	0.3	0.5	0.2
Quinqueloculina spp.	0.7	0.4	0.6	0.9	0.3	0.9	0.5						0.3					
Quinqueloculina stalkeri	3.0	2.5		2.6	0.6	0.6	1.2	2.0	1.9	0.7	1.2	0.6				0.3		0.4
Quinqueloculina seminulum	3.3		2.9	0.3					0.3	1.4	0.4	0.3	0.6			0.3		0.2
Pyrgo cf. *laevis*			0.3		1.2		0.2				0.4		0.5	0.3	0.8		0.3	
Pullenia cf. *bulloides*	6.7	2.1	0.6	2.0			0.5	2.2	0.9	6.4	1.2	0.9	0.8	8.4	0.5	1.1	1.0	0.2
Polymorphina concava		0.4				0.3	0.2	0.4		0.4	0.4	0.3			0.8		0.3	
Planorbulina mediterranensis	5.9	1.1	1.5	5.2	4.2	7.8	12.3	2.3	2.8	2.1	3.1	0.6	0.8		13.7	6.9	11.9	4.7
AD	1952	1940	1927	1914	1901	1889	1876	1863	1851	1838	1825	1813	1800	1787	1775	1762	1749	1737
core depth (cm)	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360	370

APPENDIX III.1 (continued)

Trochammina ochracea	0.6	2.1	0.9	0.7	2.1	2.4	1.9	1.1	5.0	3.5	2.6	1.7	0.3	2.4	1.5	2.6
Trochammina labiosa		0.7		0.7	0.3			1.9	2.7	4.2	0.7	0.3	1.7	0.6	1.5	2.3
Textularia sp. 1	1.5	0.7		0.3												
Reophax spp.	0.3	0.7	0.5	0.7	0.7		0.5						0.3			
Reophax subfusiformis	1.5	0.3	1.4	2.7	1.4											
Eggerelloides scabrus	0.3		0.9	3.4	0.3			0.4		0.3	0.2	0.3	0.3			
Cribrostomoides jeffreysii	0.3	1.0	0.9	1.0	0.7	2.4	0.5		3.5	1.9	2.9	2.8	0.3	0.3	0.4	5.5
Uvigerina mediterranea			1.9	0.3			0.5	0.7	0.4	0.3	1.1	0.3	0.7	1.5		0.6
Stainforthia fusiformis	0.9	3.4	0.5	1.3	1.4			1.5	5.0	2.9	1.5	3.5	3.1	2.1	1.5	2.3
Rosalina sp. 5	1.2	1.7			0.3	0.8			0.4	0.3	0.9	0.7		0.6	0.4	0.9
Rosalina sp. 4		1.0		0.3		3.9		0.4			0.4	0.7			0.4	0.9
Rosalina sp. 3	2.4	3.1	0.5	3.4	1.4	3.9		0.7	0.4	0.3	1.8	1.1	3.5	3.3	2.3	2.9
Rosalina sp. 2	1.8	1.0		1.3	0.7	3.2	0.5	1.1	2.3	0.3	0.9	4.5		4.5	0.8	7.6
Rosalina sp. 1	2.7	3.1	1.4	1.7	1.0			1.5	0.4	1.3	2.9	3.8	3.5	1.2	1.1	0.6
Rosalina spp.	0.3	0.7	0.5	0.3	0.7	1.6		0.7	1.2		0.2	1.4	1.0	0.6	0.8	0.6
Quinqueloculina spp.	0.3		1.9													
Quinqueloculina stalkeri	0.3	0.7			1.7	0.8	0.5				0.2	1.1	0.7	0.3		
Quinqueloculina seminulum		0.7	1.9	2.7			3.3			0.3	0.4	0.3	0.7	0.6	1.1	
Pyrgo cf. *laevis*				0.3										0.3		
Pullenia cf. *bulloides*	0.6	0.3	1.4	4.0	1.4			1.9	1.5	3.2	3.7	0.7	2.4	3.3	3.0	
Polymorphina concava	0.9	1.4					0.5		0.4	0.3	0.2	1.1		0.6		0.3
Planorbulina mediterranensis	4.2	12.4	6.6	8.4	8.2	18.1	0.9		0.4	1.6	4.0	9.4	4.5	5.7	1.5	11.9
AD	1724	1711	1699	1686	1673	1661	1648	1628	1612	1600	1587	1561	1548	1535	1523	1516
core depth (cm)	380	390	400	410	420	430	440	456	468	478	488	509	519	529	539	544

APPENDIX III Core 225510

2 Faunal assemblages and factor loadings

species	F1	F2	F3
Ammonia beccarii	**1.082**	0.032	0.331
Ammonia falsobeccarii	0.086	0.016	-0.006
Angulogerina angulosa	-0.134	0.047	0.078
Bolivina skagerrakensis	-0.526	0.115	-1.055
Bucella cf. *frigida*	-0.028	0.007	0.339
Bulimina marginata	-0.055	0.059	-0.192
Cassidulina crassa	0.125	0.023	0.08
Cassidulina laevigata	-8.361	**3.383**	**6.579**
Cassidulina neoteretis	-4.197	**3.033**	-2.964
Elphidium spp.	**10.472**	**1.546**	**3.175**
Fissurina spp.	0.161	-0.004	0.087
Fursenkoina cf. *complanata*	-0.035	-0.013	-0.117
Fursenkoina spp.	0.014	0.039	0.57
Globobulimina auriculata	-0.113	-0.554	-0.313
Globobulimina turgida	-2.785	-11.441	-3.541
Haynesina nivea	0.389	0.079	0.27
Hyalinea balthica	-2.169	**2.332**	-4.181
Lagena spp.	0.309	-0.042	0.353
Lobatula lobatula	0.517	0.444	-0.022
Melonis barleeanus	-0.212	0.181	-0.046
Melonis zaandami	-0.558	0.205	-0.774
Nonion labradoricum	-0.083	-0.104	-0.195
Planorbulina mediterranensis	**2.935**	-0.309	0.303
Polymorphina concava	0.131	0.025	0.064
Pullenia bulloides	-0.46	-0.133	0.311
Pyrgo cf. *laevis*	0.081	0.006	-0.026
Quinqueloculina seminulum	-0.167	0.099	-0.031
Quinqueloculina cf. *stalkeri*	0.175	0.053	0.008
Quinqueloculina spp.	0.031	-0.01	-0.054
Rosalina spp.	0.105	-0.02	0.057
Rosalina sp. 1	0.958	0.184	0.151
Rosalina sp. 2	**1.501**	0.411	0.184
Rosalina sp. 3	0.673	-0.033	0.429
Rosalina sp. 4	0.46	0.033	0.049
Rosalina sp. 5	0.234	-0.004	0.127
Stainforthia fusiformis	0.087	-0.155	0.112
Uvigerina mediterranea	-1.023	0.421	-0.857
Cribrostomoides jeffreysii	0.236	0.123	0.283
Eggerelloides scabrus	-0.082	-0.011	-0.158
Reophax cf. *subfusiformis*	-0.04	-0.212	0.024
Reophax spp.	-0.015	-0.037	0.006
Textularia sp. 1	0.948	0.15	0.042
Trochammina labiosa	-0.109	0.046	0.468
Trochammina ochracea	-0.002	-0.06	0.477

APPENDIX III Core 225510

3 Stable isotope measurements

		$\delta^{18}O$ (‰ VPDB)					$\delta^{13}C$ (‰ VPDB)				
core detph (cm)	AD	*Cassidulina laevigata*	*Globobulimina turgida*	*Hyalinea balthica*	*Melonis zaandami*	*Uvigerina mediterranea*	*Cassidulina laevigata*	*Globobulimina turgida*	*Hyalinea balthica*	*Melonis zaandami*	*Uvigerina mediterranea*
2	2000	2.2		1.7		2.5	-0.8		-1.9		-0.5
10	1998		3.2	1.9		2.7		-0.6	-1.6		-0.3
20	1996		3.1	1.9	1.6	2.8		-0.8	-1.6	-0.5	-0.2
30	1994		3.2		1.5	2.9		-0.6		-0.7	-0.5
40	1992	2.4		1.9	1.7	2.8	-0.8		-1.8	-0.5	-0.3
50	1990	2.3	3.2	1.9	1.6	2.9	-0.8	-0.4	-1.6	-0.2	-0.0
60	1988	2.4	3.3	1.9	1.4	2.7	-1.1	-0.5	-1.6	-0.6	-0.1
70	1986	2.4	3.2	2.0	1.7	2.9	-0.8	-0.5	-1.4	-0.4	-0.0
80	1985	2.4	3.2	1.7	1.5	3.0	-0.9	-0.4	-1.7	-0.4	-0.3
90	1983	2.2	3.3	2.0	1.5	2.8	-1.1	-0.3	-1.5	-0.5	-0.2
110	1979	2.3	3.2	1.9		2.5	-0.8	-0.4	-1.4		-0.4
120	1977	2.5	3.3	1.9			-0.8	-0.2	-1.6		
130	1975	2.8	3.3				-0.5	-0.3			
140	1973	2.5	3.2	2.0			-0.8	-0.2	-1.1		
150	1971	2.7	3.3	1.9			-0.6	-0.0	-1.4		
160	1969	2.6	3.3				-0.6	-0.4			
170	1967	2.0	3.2			2.9	-0.9	-0.2			-0.2
180	1965	2.7	3.3				-0.5	-0.3			
190	1963	2.7	3.3				-0.5	-0.3			
200	1952	2.9	3.4				0.4	0.1			
210	1940	3.0					-0.5				
220	1927	2.9	3.2	2.2	1.7	3.0	-0.4	-0.4	-1.1	-0.2	-0.2
230	1914		3.3	2.0		2.9		-0.1	-1.4		0.1
240	1901		3.3	2.2				-0.3	-1.3		
250	1889	2.6					-0.5				
270	1863	3.0	3.5	2.5			-0.5	0.0	-1.3		
280	1851	2.7	3.5				-0.4	-0.1			
290	1838	2.7	3.3				-0.4	0.1			
300	1825	2.8	3.4				-0.3	-0.2			
310	1813	3.1	3.4		2.2		-0.2	-0.1		0.0	
320	1800	2.7	3.3	2.2			-0.2	0.1	-0.5		
330	1787	3.0	3.4	2.3		2.9	-0.3	-0.1	-1.0		0.2
350	1762	2.8	3.3				-0.5	-0.3			
360	1749	2.9				2.9	-0.5				-0.0
370	1737	2.8	3.4				-0.2	-0.1			
380	1724	2.7	3.2				-0.2	-0.1			
390	1711	2.6	3.1				-0.4	-0.2			

Appendix III.3 (continued)

		$\delta^{18}O$ (‰ VPDB)					$\delta^{13}C$ (‰ VPDB)				
core detph (cm)	AD	*Cassidulina laevigata*	*Globobulimina turgida*	*Hyalinea balthica*	*Melonis zaandami*	*Uvigerina mediterranea*	*Cassidulina laevigata*	*Globobulimina turgida*	*Hyalinea balthica*	*Melonis zaandami*	*Uvigerina mediterranea*
400	1699	2.6	3.1			2.6	-0.3	-0.1			-0.1
410	1686	2.6	3.2				-0.4	-0.3			
420	1673		3.4					-0.1			
430	1661		3.4					-0.2			
440	1648	2.8		2.2			-0.2		-1.0		
456	1628	2.5					-0.6				
468	1612	2.4	3.3				-0.5	-0.1			
478	1600	3.0	3.4				-0.3	-0.1			
488	1587	2.9				3.1	-0.3				0.3
498	1574	2.8					-0.2				
509	1561	1.9					-1.0				
519	1548	2.7	3.3				-0.5	-0.3			
529	1535	2.6	3.2				-0.3	-0.4			
539	1523	2.2					-0.7				
544	1516	2.5					-0.7				

APPENDIX IV Data of Core 225521

1 Relative frequencies of counted species

Lagena spp.			0.4	0.4	0.5		0.2	0.2	0.6		0.9	1.0	0.8			0.3		0.9	0.5	0.1	1.0	0.5	0.8	0.3
Hyalinea balthica	7.0	10.7	7.5	4.8	12.7	4.6	7.6	13.7	21.4	18.8	10.8	7.5	11.1	7.7	17.2	7.2	5.9	7.3	5.5	4.1	7.9	9.1	21.6	16.4
Globobulimina spp.															0.3							0.3		
Globobulimina turgida			0.4		0.5	0.5	0.2	0.6		1.7	0.9	0.2	0.8	0.7	0.8	2.4	2.2	2.4	3.1	6.2	1.9	1.0	1.0	0.7
Globobulimina auriculata	0.3		0.4					0.2					0.3					0.4	0.2				0.2	
Glandulina ovula																								
Fursenkoina spp.	0.6																					0.8		
Fissurina spp.		0.2	0.8	0.4	0.2	0.5	0.2		0.3	0.4	0.2	0.6		0.4		0.2	0.6				0.2	0.8	0.8	
Elphidium spp.												0.2						0.2		0.1				0.3
Elphidium sp. 2		0.2					0.2	0.2																
Elphidium subarcticum																	0.3							
Elphidium excavatum f. *clavata*	6.7	9.0	7.8	12.5	15.3	5.4	6.0	5.4	5.8	8.4	1.5	2.3	4.3	17.6	8.0	9.1	5.3	5.6	8.2	23.3	6.6	5.6	3.9	7.2
Elphidium excavatum f. *alba*	1.0																							
Elphidium albiumbilicatum		1.1	0.8					0.2	0.3	0.6	0.2		0.3	0.7	0.6	0.6		0.7		1.0	1.0	0.5	0.2	0.7
Cornuspira involvens			0.4																					
Cibicides refulgens																								
Cassidulina neoteretis	0.3	1.1		2.4	0.2		0.2			0.2	2.6	0.6		0.4	0.3	1.1	4.3	0.4			1.9	2.0	0.8	
Cassidulina laevigata	1.6	10.5	7.8	36.7	21.6	34.0	11.5	18.8	27.2	17.3	36.8	6.1	11.6	8.1	19.4	24.8	26.6	14.7	15.9	14.1	9.1	13.7	13.5	6.9
Cassidulina crassa							0.2															0.3		0.3
Bulimina marginata	3.5	7.5	3.5	2.0	2.8	8.5	4.4	6.2	3.2	2.7	2.2	6.3	5.0	7.0	1.9	0.7	4.6	5.0	5.5	3.4	5.6	3.0	5.7	15.8
Bulimina aculeata	50.3	32.7	9.0	6.1	9.2	22.2	10.6	22.2	12.9	16.1	9.2	21.3	14.1	19.8	5.8	3.1	3.1	19.9	11.8	7.6	14.8	24.3	13.7	16.8
Bolivina sp.	0.3																							
Bolivina skagerrakensis	0.3			0.4		0.3	0.5	0.4	1.0	0.2	0.2		0.3											
Astrononion gallowayi																						0.3		
Ammonia beccarii (inner lining)		0.9	3.9	3.6	3.5	0.3	4.6	2.1	0.3	3.0	2.6	4.2	5.3	4.4	6.4	2.2	3.7	2.4	11.5	2.2	1.0		1.4	1.6
Ammonia beccarii	0.3	0.9	2.0	0.4	1.2	0.3	1.6	0.8	0.6	0.6	0.2	1.7	0.8	0.4	0.8	0.3	0.6	1.3	0.5	1.1	0.8	0.3	1.8	2.6
depth (cm)	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230

APPENDIX IV.1 (continued)

Lagena spp.	1.5	1.0	1.3	0.6	0.5	0.8		0.7		1.0	0.3	0.3		0.3	0.4	1.6	0.5	1.0
Hyalinea balthica	15.3	14.1	15.0	10.6	8.9	2.3	6.4	3.7	10.5	12.3	19.3	7.0	11.1	22.2	9.6	25.1	14.8	9.9
Globobulimina spp.																		
Globobulimina turgida				0.8	0.3				1.0			2.0			2.0	1.3	2.2	3.4
Globobulimina auriculata				0.2								0.3						
Glandulina ovula									2.9									
Fursenkoina spp.					0.3			0.7						1.6				0.2
Fissurina spp.	0.5	1.3	0.4	0.4	0.8				2.9	0.3	0.3			1.0	0.9	0.3	0.2	
Elphidium spp.								0.7								0.3		
Elphidium sp. 2					0.3													
Elphidium subarcticum																		
Elphidium excavatum f. *clavata*	3.0	15.1	5.0	6.8	10.2	1.5	5.8		5.7	4.9	6.8	10.6	3.5	2.6	5.8	5.9	5.7	10.2
Elphidium excavatum f. *alba*																		
Elphidium albiumbilicatum			0.4	0.6			0.6								0.2		0.5	0.5
Cornuspira involvens																		
Cibicides refulgens			0.4		0.3													
Cassidulina neoteretis			0.4		2.1		1.3	0.7	2.9	1.0	0.6		1.2	2.6	1.1	0.5	1.2	0.5
Cassidulina laevigata	8.4	6.1	7.1	15.7	13.9	10.8	19.2	12.7	15.2	15.9	14.9	14.3	7.0	13.7	11.8	13.1	29.3	17.7
Cassidulina crassa																0.3		
Bulimina marginata	9.9	5.8	8.3	6.0	4.5	3.1	3.2	8.2	7.6	16.8	12.2	7.8	18.0	4.2	12.0	8.3	3.2	1.7
Bulimina aculeata	8.4	4.8	6.7	9.4	9.4	2.3	5.1	12.7	7.6	17.5	9.2	10.9	19.8	24.8	17.6	4.0	1.7	4.4
Bolivina sp.																		
Bolivina skagerrakensis								1.5	1.0	0.3	0.3	0.6			0.2		0.2	
Astrononion gallowayi																		
Ammonia beccarii (inner lining)		5.1	1.3	1.4	2.4	1.5	1.3	2.2	1.9	2.9	1.5	0.8	2.3		1.6	2.7	0.5	1.9
Ammonia beccarii	1.5	1.6	0.4	0.6	0.5	1.5			1.0	0.6	1.2	1.4	3.5	0.7	1.8	2.4	3.2	1.0
depth (cm)	240	250	260	270-280	290	300	310	320	330	340	350	360	370	380	390	400	410	420

APPENDIX IV.1 (continued)

Lagena spp.	1.3	0.9	0.6	0.3	1.3	
Hyalinea balthica	18.1	26.5	30.4	14.2	18.3	15.6
Globobulimina spp.						
Globobulimina turgida	5.6	2.1		0.5	1.3	6.9
Globobulimina auriculata						
Glandulina ovula						
Fursenkoina spp.				0.5		
Fissurina spp.	0.4				1.8	1.2
Elphidium spp.		0.2				
Elphidium sp. 2	0.4					
Elphidium subarcticum						
Elphidium excavatum f. *clavata*	10.3	4.1	5.3	3.4	5.4	8.7
Elphidium excavatum f. *alba*						
Elphidium albiumbilicatum						
Cornuspira involvens	0.4	0.2				
Cibicides refulgens						
Cassidulina neoteretis	0.4	0.4	1.8	0.8	0.9	
Cassidulina laevigata	2.2	14.1	21.6	8.2	15.2	13.3
Cassidulina crassa		0.2				0.6
Bulimina marginata	4.3	8.3	7.0	17.8	7.6	9.2
Bulimina aculeata	3.0	3.6	4.1	11.6	6.3	8.7
Bolivina sp.						
Bolivina skagerrakensis				0.3	0.4	1.7
Astrononion gallowayi						
Ammonia beccarii (inner lining)	2.2	1.1	1.2	1.5	7.6	
Ammonia beccarii	0.9	1.9	0.6	1.3		2.3
depth (cm)	430	440	450	460	470	480

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