Present and Past Oceanographic Controls of Sediment Formation in the North Atlantic – Arctic Gateway (A Critical Appraisal of SFB 313 Scientific Results)

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Abstract: This concluding chapter presents a critical appraisal of the research carried out within the framework of SFB 313. We will try to outline the scientific perspectives and problems as well as our approach to their solution. Moreover, we shall describe the scientific highlights of the results and define areas where we followed questionable assumptions and therefore failed to achieve what we had hoped for. A complete documentation of the various activities of SFB 313 (including an overview of research cruises, etc.) can be found in Schäfer and Schröder-Ritzrau (1999).

The Northern North Atlantic, a Key Area for Global Change

There are many indications which point to the fact that the global environment may be unstable and on the verge of drastic and rapid changes. These can be deduced from real-time measurements of climate or ocean variability (Schlosser et al. 1991), reconstructions of past climates (CLIMAP Project Members 1981), and computer simulations of present and past environments. The heated debates over this issue are driven by politicians who seek answers to their pressing needs to prepare decisions of global environmental and economical dimensions which will, in turn, have an impact on the future of all mankind. Scientists have an obligation to respond to these needs. Some do so with necessary scientific soberness, but some exploit this situation in an irresponsible eagerness to gain some political clout or at least to gain financial support for their activities.

There is no doubt that science has successfully identified compartments of the global environment for the purpose of gaining insight into the possibility of global changes in the near future. The data collected for achieving this goal must reflect global properties of the environment, such as those which can be drawn from the properties of the atmosphere or the ocean. The shells and skeletons of pelagic organisms (plankton) record the chemical and hydrographic properties of their habitats in various ocean water masses (Schott 1935). After reproduction or death the remaining biogenic particles (mostly calcareous, siliceous or organic materials) sink to the ocean floor, thus producing one of the best archives of present and past ocean properties. By recognizing this unique record of pelagic ocean floor deposits as an archive of the global environment, an entirely new discipline within the marine sciences, namely paleoceanography, has developed over the past 25 years. Today it contributes to our understanding of the earth's past environments at an ever increasing speed.

CLIMAP (1976) achieved the first comprehensive and complete quantitative reconstruction of a glacial

From *The Northern North Atlantic: A Changing Environment*, edited by P. Schäfer, W. Ritzrau, M. Schlüter, and J. Thiede, pp. 463–491, Springer, Berlin, 2000

world based almost entirely on distribution patterns of pelagic microfossils in ocean sediments and pollen records in limnetic deposits. This reconstruction also comprised the Norwegian-Greenland Sea and was based on transfer functions of planktic foraminifers, time series and time slices for the Late Quaternary (Kellogg 1977). The Deep-Sea Drilling Project (DSDP) had previously visited the northern North Atlantic during Leg 38 (Talwani and Udintsev 1976), proving that glacial paleoceanography was already established during the Pliocene, whereas later contributions from ODP (Ocean Drilling Project) Legs 104 (Eldholm, Thiede, Taylor et al. 1987), 151 (Thiede, Myhre, Firth et al. 1996) and 162 (Raymo, Jansen, Blum et al. 1999) were able to trace northern hemisphere glaciations well back into the Miocene (Fig. 1). To gain a temporal resolution of oceanic stratigraphies comparable to those of ice cores (Dansgaard et al. 1993) a relentless hunt has begun for pelagic sediment records with very high stratigraphic and, therefore, temporal resolution (Labeyrie et al. 1995). Even after the formal conclusion of SFB 313 at the end of 1998, its former members continue to be engaged in this hunt as part of the international IMAGES program. RV MARION DUFRESNE, with a newly developed, highly sophisticated ultra-long piston coring device, has sampled the Norwegian-Greenland Sea and its passages several times. The aim of these investigations is to make progress beyond the achievements of SFB 313.

The Norwegian-Greenland Sea, the main target area of SFB 313, is a small and young ocean basin which today lies on the boundary between polar and temperate environments (Schäfer et al. this volume). Its northern gateway into the Arctic Ocean is the Fram Strait, while its southern passage into the main North Atlantic Ocean lies across the Greenland-Scotland Ridge. The peculiar shape of these gateways and the properties of modern ocean circulation have given this small subbasin of the world ocean a controlling influence on climate over northwestern Europe and on the global environment. These important facts have led to intensive investigations of the processes governing the modern and historical development of the depositional environment within the Norwegian-Greenland Sea. Crucial questions investigated are: How do particle formation and particle transport occur in the modern ocean system? How do sediments on the modern seafloor reflect the present oceanography of the basin? And how can present sediment distributions be used to reconstruct paleoenvironments of the Norwegian-Greenland Sea? It is well known from historic studies and geological reconstructions that this part of the world ocean has responded quickly and dramatically to Late Quaternary climatic variations.

The Norwegian-Greenland Sea has been subject to dramatic paleoenvironmental changes due to processes which have led to the increasing glaciation of the northern hemisphere since Miocene times as well as to the rapid and dramatic changes in relationship to glacial-interglacial paleoclimatic cycles. Through DSDP and ODP sites (Figs. 1, 2), the long-term history of the Norwegian-Greenland Sea has been studied, with main emphasis placed on the Norwegian Current, the Fram Strait and the western Norwegian-Greenland Sea. Ice-covered water masses play an important role in the Greenland Sea, evident in the fact that the Greenland ice cap has existed at least as far back as the Tertiary. The glacial modes of oceanography and climate have dominated the latest part of the Neogene and the entire Quaternary, whereas interglacial interruptions seem to have been rare exceptions. The first signs of ice-rafting occurred approximately 14 to 15 million years ago (mid-Miocene). However, in the middle Pliocene, the northern hemisphere experienced a dramatic increase in ice-sheet formation, and, consequently, glaciers from Greenland and Europe shed large numbers of icebergs into the Norwegian-Greenland Sea. The Late Quaternary paleoclimatic variability of the Norwegian-Greenland Sea was dominated by glacial conditions. The entire area was frequently ice-covered, even in its eastern parts. Interglacials were relatively short (approx. 10,000 years) and variable. For instance, the Holocene seems to be more important than the Eemian. Moreover, the natures of the preceding interglacials were entirely different and, thus, not readily comparable.

Modern depositional environments of the Norwegian-Greenland Sea (cf. Schäfer et al. this volume) are under the influence of some very characteristic oceanographic regimes. Except in coastal areas along Greenland and Norway, surface-water masses are influenced by the inflowing northernmost extension of the Gulf Stream System, namely the Norwegian Current, and of the East Greenland Current on the western side (cf. Ramseier et al. this volume). This current carries cold ice-covered and brackish water masses from the Arctic Ocean through Fram Strait along the East Greenland continental margins and through Denmark Strait into the Labrador Sea. These two well-defined current systems mix their surface waters through large eddies also into the central part of the basin. The distinct Arctic water mass found in this mixing zone is characterized by cold but ice-free waters. The presence of the Norwegian and East Greenland Currents results in very

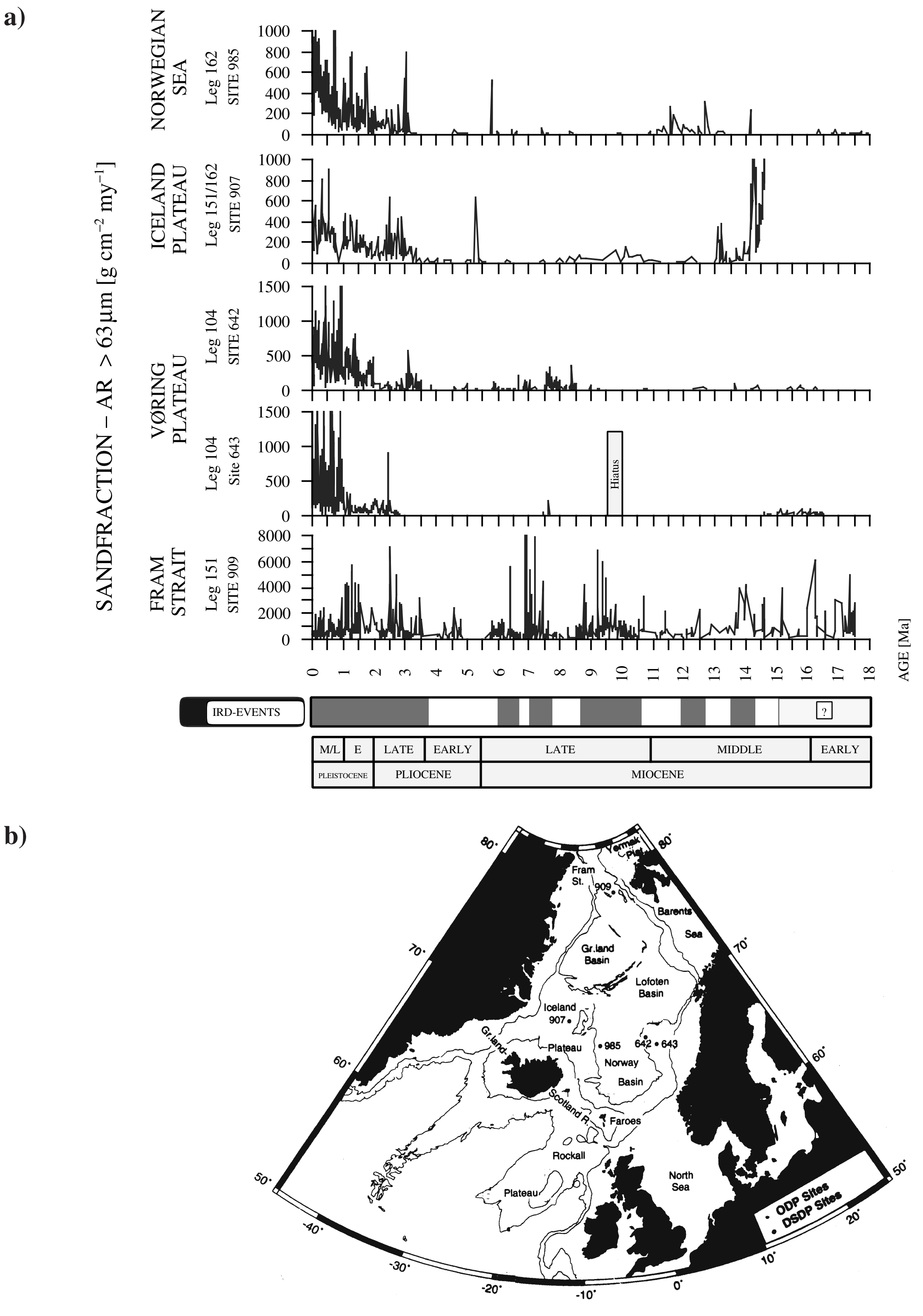

Fig. 1: a) ODP data documenting the early onset of northern hemisphere glaciation in the middle Miocene. Compiled from various sources (Thiede et al. 1998). **b)** Sampling locations

steep gradients across well-defined frontal systems (Polar Front and Arctic Front in the Norwegian-Greenland Sea). Since both current systems are relatively shallow (Norwegian Current up to 700 meters thick, East Greenland Current only 100–200 meters thick), there is a large and relatively homogeneous body of water in the deeper part of the Norwegian-Greenland Sea, which is fed through renewal processes in the upper water column (mainly Greenland Basin and Iceland Plateau) and from the rims by brine and winter-water formation. The dense, cold and saline water masses of the deep Norwegian-Greenland Sea fill this basin until they reach the sill depths of the Denmark Strait and Faeroe-Shetland Channel, from where they flow into the deep North Atlantic Ocean to feed various portions of the North Atlantic Deep Water (NADW, Meincke 1983; Koltermann 1987).

The Norwegian-Greenland Sea is one of the two most important areas within the world ocean for the renewal of bottom water masses which feed the deep-water masses of all ocean basins, keeping them cold and oxygen-rich. It was previously assumed that the dominant mode of deep-water formation occurred in the central Greenland Basin and over the Iceland Plateau, feeding the overflow of cold and oxygen-rich water masses in channels across the Greenland-Scotland Ridge (Denmark Strait, Faeroe-Shetland Channel). Modern hydrographic investigations and tracer studies (Schlosser et al. 1991) in the Norwegian-Greenland Sea seem to indicate that the mode of deep-water renewal in the central basin has slowed since the early 1980's. Investigations of winter-water formation in the shallow seas around the Norwegian Sea, and in particular off Svalbard, therefore received special attention because these cold and dense water masses sink over the shelf and the adjacent continental slope until they are advected into the oceanic water column at the depth corresponding to their density. These water masses dominantly control sediment transport from the shelf to the adjacent continental slope (Rumohr et al. this volume). However, they result in localized areas of high sedimentation rates consisting of relatively fine material which is precipitated because the transport capacity of the carrying water masses is reduced. This process seems to be important for interglacial scenarios. During glacial times, when lowered sea levels exposed much of the shelves around the Norwegian-Greenland Sea and large ice sheets dumped quantities of glacial material into the troughs across the shelves in front of former ice streams, a completely different mode of sediment influx controlled the depositional environment.

Scientific Highlights and Successes

The aim of SFB 313 has been to define and identify the modern and historical imprint of oceanic water masses on seafloor sediments, which are then used for quantitative reconstructions of environmental changes in areas crucial for understanding global change. The project has focused on the temporal and spatial variability of climate and environmental changes in the northern North Atlantic and their effects on the marine ecosystem in the present and the past, as documented in the living and extant communities of marine organisms and deep-sea sediments of the Upper Quaternary. The activity of SFB 313 involved numerous expeditions resulting in a dense network of stations (Fig. 2).

The activities of SFB 313 were divided into two major thematic groups. One addressed processes in the water column and at the sediment surface through a combination of biological, sedimentological and chemical methods. The other studied processes over geological time scales as documented in deep-sea sediments through radiocarbon, isotopic, sedimentological, micropaleontological and geophysical methods.

Sedimentation in Response to Ocean Water Masses and Currents

The Nordic Seas are exposed to strong variations of physical and hydrographic parameters along latitudinal and, even more directly, meridional gradients. The extreme seasonality of insolation, ice cover and nutrients, and, hence, the resulting patchiness of plankton distribution, microbial and geochemical processes as well as seasonal and episodic transport events along continental margins control a scenario responsible for the formation and distribution of paleoceanographic signals in deep-sea sediments.

Originally, this aspect of the investigations comprised several projects addressing processes in the water column, leading to discernible patterns of sediment distribution on the seafloor in relation to the oceanic water masses involved. These projects were designed to clarify the actual processes and to provide a base for the interpretation of modern and ancient sediment distributions. Investigations in the water column comprised measurements of rates and patterns of biological production in the pelagic habitat. During descent to the seafloor these particles are continuously altered and decomposed. Their composition as well as preservation are affected by a variety of biological, chemical and geological processes in the water column, on the seafloor, and in the sediment. Of fundamental in-

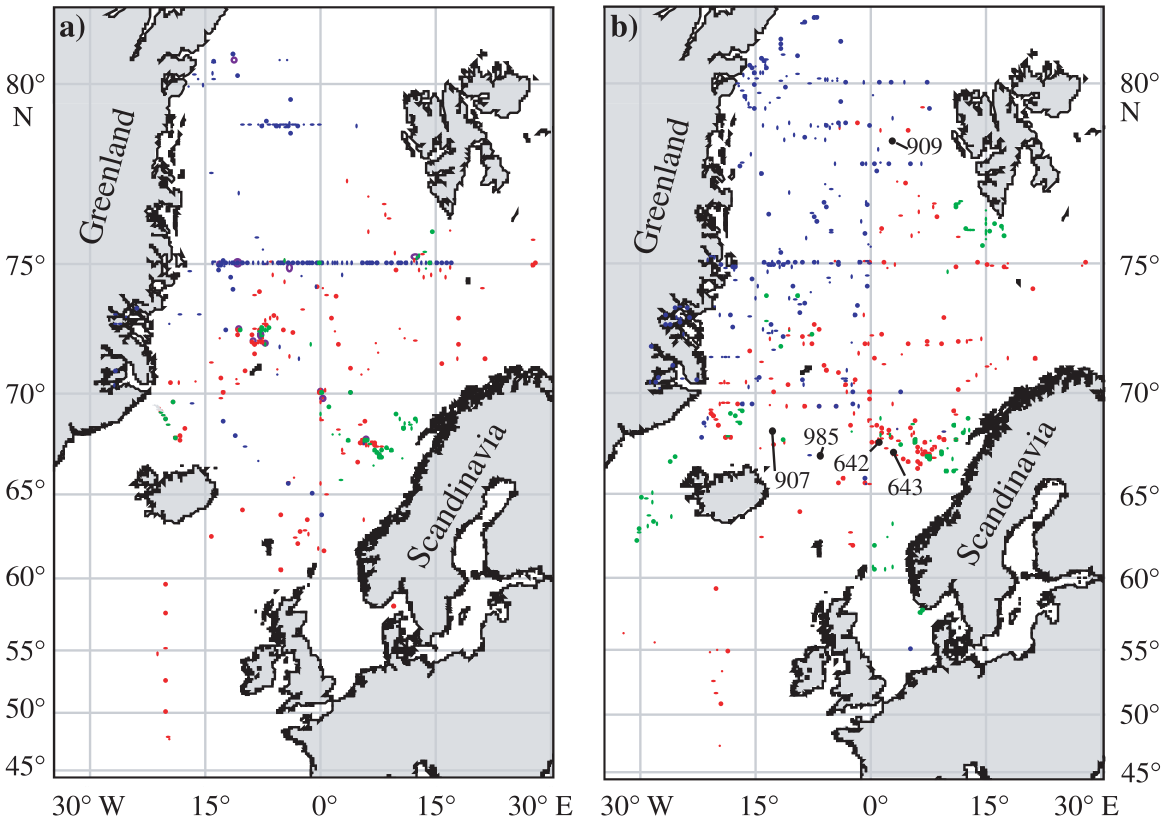

Fig. 2: Sampling locations of SFB 313 in the North Atlantic – Arctic gateway area. **a)** Distribution of plankton samples and sediment traps. **b)** Distribution of sediment sampling stations including relevant ODP sites (black circles, see also Fig. 1)

terest are observations on the influence of pelagic material fluxes on patterns and processes in the benthic habitats. Later in the history of these investigations it was also discovered that the benthic biota are not only driven by the influx of food from surface-water masses, but that at certain locations along the Norwegian continental margin and within the Barents Sea substantial amounts of "nutrients" may be expulsed from beneath the seafloor as a result to fluids originating from diagenetic or tectonic processes, and which were, therefore, a priori completely independent of the nature of surface-water masses.

Pelagic Processes and Particle Fluxes

Considerable emphasis was placed on linking the export from the upper ocean to physical and biological processes in the epipelagial (Bathmann et al. 1987, where long-term sediment trap data are available; von Bodungen et al. 1995; Boyd and Newton 1995; Fischer et al. 1996; Fischer and Wefer 1996). Within the framework of SFB 313, a decade of flux measurements and the study of pelagic processes in different provinces of the Nordic Seas aim to document the supply of food to the benthos and to provide vital information for reconstructing the paleoenvironmental record. Even though not as long as desirable and possibly in their geographic coverage not representative enough these data are unique as a time series of particle fluxes; however, their variability suggests the establishment of a substantial research program to adequately discern long-term trends and interannual variability from signal noise.

The Nordic Seas enclose two distinct provinces, separated by two north-south frontal systems and distinguished by water masses and the distribution of sea ice (Schäfer et al. this volume). Although both provinces have approximately the same solar irradiation and nutrient reserves during winter (von Bodungen et al. 1995), particle flux measurements and experiments on plankton and ice organisms show significant differences in the processes controlling particle flux in the Polar and Atlantic provinces of the Nordic Seas. At 500 m water depth, annual organic carbon exports of 1

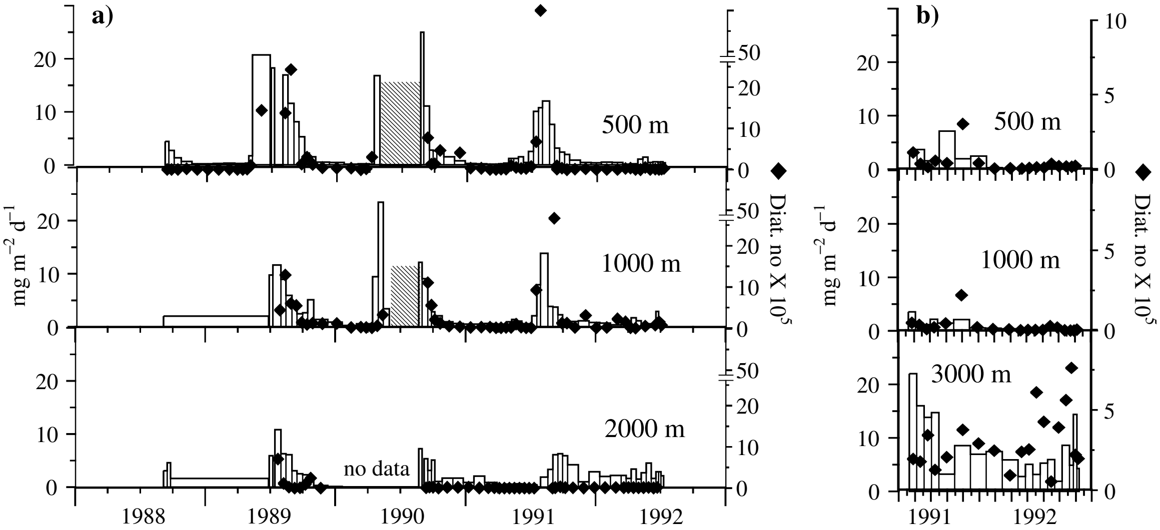

Fig. 3: Vertical fluxes of diatom cells (dots) and particulate silica (PSi, histograms) in the Polar **(a)** and Atlantic Provinces **(b)** (Peinert et al. this volume)

to 3 g m^{-2} y^{-1} are strikingly similar in both regions and represent only a few percent of annual primary production. However, the differences in pelagic primary production do not control particle fluxes but are closely related to foodweb structure (Peinert et al. 1989; von Bodungen et al. 1995). In the Polar province, ice-related physical and biological seasonality control particle flux (Peinert et al. this volume) which is dominated by autotrophic organisms (Bauerfeind et al. 1994). In the eastern Atlantic province, feeding strategies were investigated, life histories and the succession of dominant mesoplankters control vertical fluxes (Peinert et al. 1989; Bathmann et al. 1990, 1991; von Bodungen et al. 1995).

In contrast to the annual export of organic carbon, which is rather similar in both provinces, the Polar and Atlantic provinces can be distinguished by annual export in opal and carbonate at 500 m water depth (Fig. 3, Peinert et al. this volume). This is primarily due to differences in phytoplankton fluxes (Schröder-Ritzrau et al. this volume). At water depths greater than 1,000 m, secondary fluxes are often superimposed on primary pelagic fluxes, indicating lateral advection, which is most dominant in the Atlantic province (Fig. 3). Though there is no statistically significant difference between both provinces with respect to organic carbon flux at 500 and 1,000 m, near-bottom annual carbon fluxes differ substantially. This is due to resuspension and has, therefore, no relation to primary fluxes from the water column above (Peinert et al. this volume). Opal dissolution is another process which primarily affects the assemblages. This causes a shift in species composition in both provinces. The lightly silicified main flux species are strongly diminished in deep-sediment traps, while heavily silicified species dominate the sediment assemblages (Schröder-Ritzrau et al. this volume). This may have important implications for the paleorecord.

In support of the field data numerical modeling was used to investigate the processes controlling the various fluxes in both provinces. A major finding is that, in the Atlantic province, annual fluxes strongly depend on the onset of the vertical migration of zooplankton. In years when migration begins later, sedimentation can be as much as 80 % higher compared to years in which migration begins prior to spring phytoplankton growth (Haupt et al. 1999).

Locally measured particle fluxes can be extrapolated to broader spatial scales if the export field is reasonably homogeneous (Siegel et al. 1990). In the Polar Province, Ramseier et al. (this volume) relate time-series sediment trap data to remote sensing data of ice variables. Results show a robust relationship between particle export and ambient ice regime (Fig. 4). High fluxes of pelagic particle sedimentation are primarily found in the area defined by the Biological Marginal Ice Zone (BMIZ), an 80 km-wide belt along the ice edge extending to the 64 % ice concentration isopleth. This area accounts for 88 % of ice-related particle sedimentation (Ramseier et al. 1999). The application of this approach to the Greenland Sea between Svalbard and Iceland reveals spatial patterns of flux parameters as

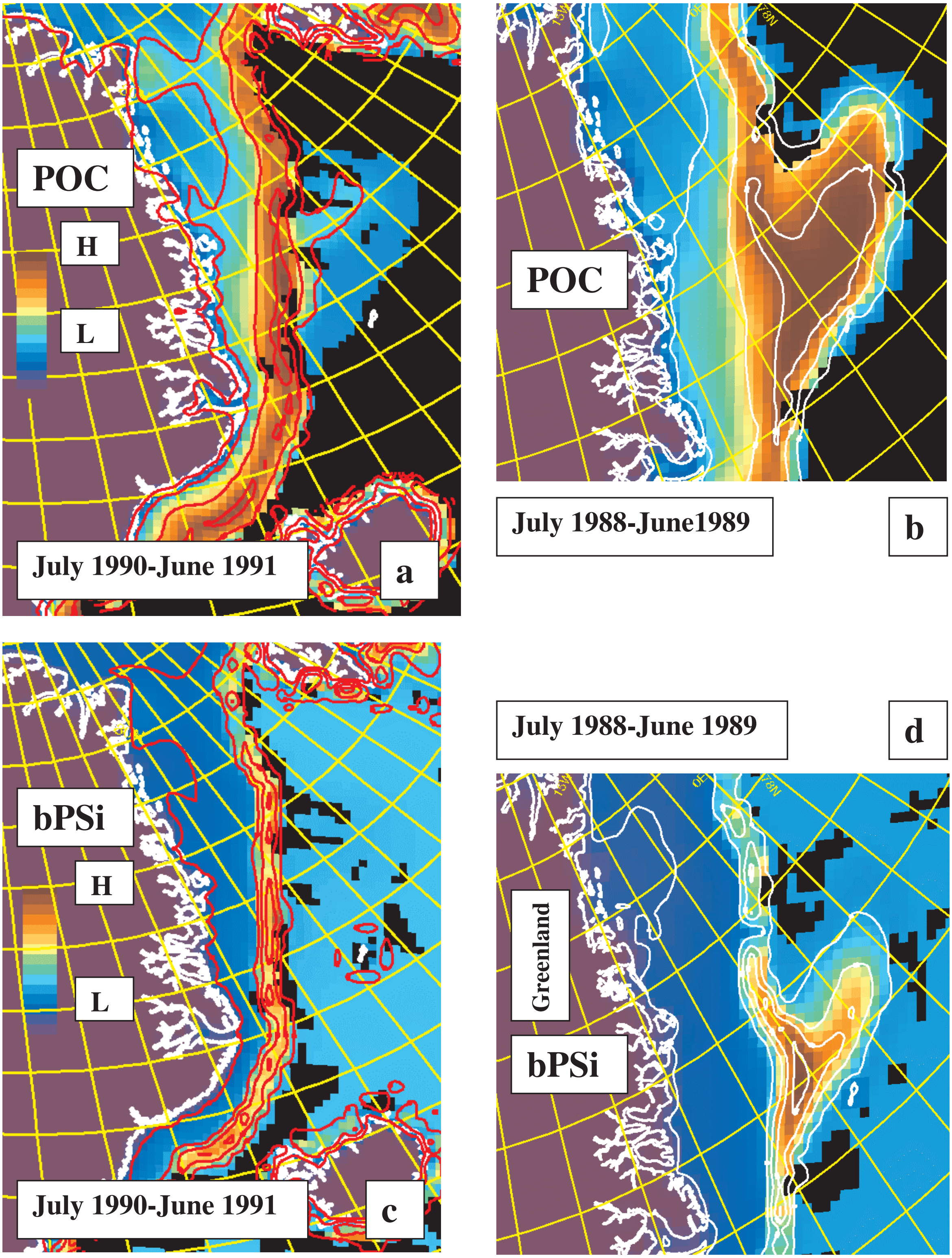

Fig. 4: Regional sedimentation pattern for POC and bPSi based on algorithms developed by Ramseier et al. (1999) for the maximum flux rate (mg m^{-2} d^{-1}) presented for the periods indicated. **a)** and **b)** show examples for POC along the Greenland Coast, while **c)** and **d)** show bPSi for the Is Odden-Nordbukta region, the area for which the algorithms were originally developed. (Ramseier et al. this volume)

particulate organic carbon (POC) or biogenic silica and intraannual variations. Spatial gradients and differences between years seem particularly intense for the mass flux of POC, but less intense for biogenic silica and weakest for total mass flux.

Processes and Models of Lateral Sediment Transport

Temporal and spatial patterns of particle sedimentation from surface-water masses are distorted by lateral transport in some areas of the Norwegian-Greenland Sea, as indicated by increasing fluxes and changing compositions of particles in the vertical series of sediment traps at a single mooring position (Peinert et al. this volume; Schröder-Ritzrau et al. this volume). In an ocean basin with wide abyssal plains also the process of turbidite sedimentation will always be important (Nilsen and Kerr 1976). For the purpose of this project, such areas have successfully been avoided when considering the sediment surface patterns (biogeography) of microfossil distributions (Matthiessen et al. this volume) and bulk sediment characteristics such as calcium carbonate concentrations (Henrich 1992, 1998), or morphological features of the seafloor surface which can be mapped by side-scan sonar technique (Mienert et al. 1993).

The lateral advection of sediment materials can occur as suspended material in the water column, as illustrated by particle trap data. It can also occur as grain transport along the ocean floor, triggered by currents as shown by the distribution of turbidites. Moreover, it can be induced by mass wasting from adjacent continental margins, as documented by large slides which carve out the morphology of the Norwegian continental margin, resulting in large fans in front of the major troughs across formerly glaciated shelves (Vorren et al. 1998). All three processes are linked to the glacial-interglacial variability of the depositional environment in the Norwegian-Greenland Sea and surrounding areas. Hence, the sequence of sediment facies observed in the cores shows regionally important and characteristic differences which can be mapped by sedimentological and geophysical methods (Henrich et al. 1989; Mienert et al. 1993).

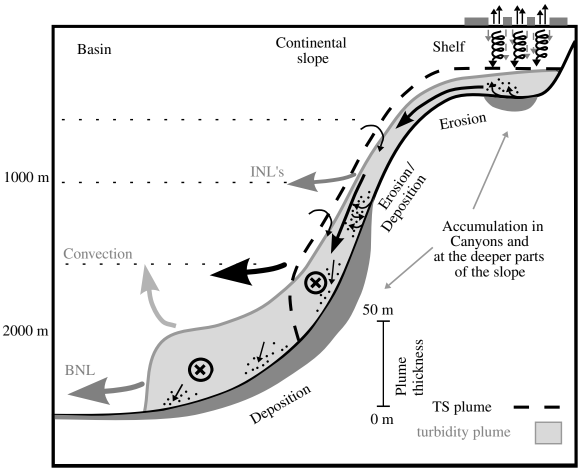

Fig. 5: Cascading of dense bottom-water masses. (TS plumes are temperature and salinity plumes, circles with cross symbols indicate flow into the figure; Fohrmann et al. this volume)

Within the framework of the project, strong attention has been paid to the transport phenomena of suspended matter in the BNL (Bottom Nepheloid Layer) along continental margins (Fig. 5) (Fohrmann et al. this volume). One potential mechanism for initiating this kind of nepheloid layers is the formation of dense winter water, resuspending large numbers of particles on shelf areas. After sedimentation, the resulting high accumulation areas provide extremely high stratigraphic resolution cores (Blaume 1992) because of the high accumulation of terrigenous clayey material, which dilutes the concentration of microfossils needed for paleoenvironmental reconstructions. A tracing of transport paths based on field measurements and numerical modeling can potentially define the source regions for these materials. The main process of this type of sediment transport is related to the formation of dense water plumes with high suspended load. Guided by morphology, they cascade over the continental margin until they are advected into deep waters of corresponding densities. These plumes develop primarily during winter, when the surface waters are cold and ice is formed, increasing salinity and consequently the density of the affected water masses (Fohrmann et al. this volume).

From regional investigations of sediment distributions, the efforts of this task group later changed to areas of high accumulation rates on shelves and along continental margins. Although such high accumulation areas are relatively small (5–50 km in diameter) they seem to catch most of the fine-grained sediment load (approx. 80–90 % of the Holocene pelagic sediment), which may partly explain generally low sedimentation during the latest part of the Quaternary over wide regions of the entire basin. Sediment transport occurred downslope in a stepwise pattern during the Holocene: first, due to the formation of dense winter waters, later by remobilization through internal waves separating waters of different densities and breaking at the upper continental slope (Fohrmann et al. this volume). During the last deglaciation, the amounts of sediment available for transport were particularly high at the shelf edge, mainly in front of the large cross-shelf troughs (Vorren et al. 1998). The main amount of reworking is also reflected in the coarse sediment fraction by the anomalous isotopic ratios in foraminiferal tests. Due to specific sedimentation processes and their influence on the geological record, the high resolution stratigraphy originally aimed for was unable to be obtained in high accumulation areas.

A special situation developed over the Vøring Plateau, where escarpments acted as obstacles to bottom currents and where topography-guided eddies dumped their sediment load over a long period of time. A large accumulation of Holocene sediments (> 1 km^3 of sediments) developed, but bioturbation of macrobenthos kept this sediment mobile. Therefore, a sediment-rich BNL was able to creep downslope, moving large amounts of fine-grained material, without affecting the coarse fraction as shown by the undisturbed stratigraphies.

Dynamics of the Benthos and its Response to Pelagic Processes

The seafloor of the deep northern North Atlantic appears to be a relatively stable environment for benthic organisms as compared to the strong temporal and spatial heterogeneity of pelagic habitats. However, in contrast to the pelagic system which is mainly determined by the dynamics of the abiotic oceanographic and nutrient regimes, nearly all processes at the seafloor are related to biological activities of endo- and epibenthic organisms. The magnitude and distribution of these activities are generally coupled to the input of organic matter by vertical sedimentation or lateral advection from the water column.

From early on, it was understood that a benthic response in terms of biogeography and benthic material fluxes to the pelagic export exists. Investigations concentrated on biogeochemical processes in the surface sediments and patterns of benthic foraminiferal activity. It was observed both on the Norwegian continental slope as well as in the Greenland Sea that benthic assemblages responded instantaneously to short pulses of the export of organic materials from the pelagic habitat (Graf 1989, 1992; Graf et al. 1995). Chlorophyll was used as an equivalent and tracer for the input of phytogenic materials, which was mixed to 10 cm depth below the seafloor within a week after arrival (Fig. 6). At the same time oxygen consumption and heat production in the sediment pointed to elevated levels of biological activity. Similar reactions were able to be substantiated through physiological and electron microscopic investigations of benthic foraminifers (Heeger 1990; Linke et al. 1995). The arrival of the labile organic materials not only "woke up" these protists physiologically, but also resulted in considerable bioproductivity. Benthic foraminifers are therefore important tools for the reconstruction of benthic paleohabitats (Altenbach et al. 1993), in particular in deep-sea sediments.

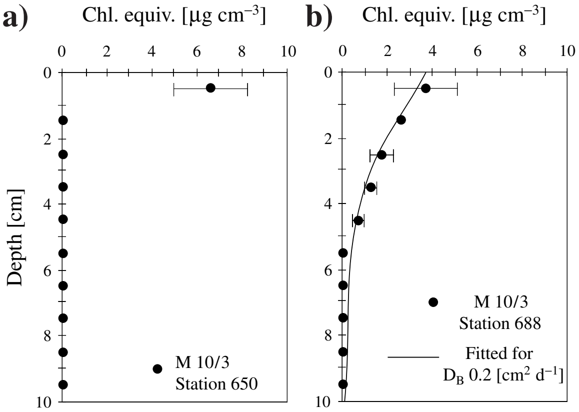

Fig. 6: Vertical profiles of chlorophyll equivalents in two sediment cores from 2530 m water depth in the East Greenland Basin. The fast response of benthic organisms via enhanced bioturbation is indicated by the difference between profiles measured immediately after settlement **(a)** and nine days after settlement **(b)** of fresh chlorophyll bearing material from the ice-edge bloom to the seafloor (Graf et al. 1995)

The unfortunate Chernobyl accident also illustrates the seasonal character and intensity of bioturbation (Balzer 1989). In this case particle associated ^{137}Cs was rapidly incorporated into the sediments of the outer Vøring Plateau through bioturbation. Even though the intensity and temporal pattern of bioturbation are difficult to assess, this example highlights the important influence of bioturbation on the burial and release of materials at the Benthic Boundary Layer (BBL). These materials can comprise dissolved as well as particulate substances and therefore result in vertical particle transport in and out of the sediments. This can potentially have enormous consequences for the burial and release of hazardous materials. Unfortunately, the intensity and temporal patterns of bioturbation are difficult to assess (Balzer 1996).

These short seasonal pulses of food transport from the pelagic habitat are only able to cover part of the benthic demand. Another source of food for benthic organisms was therefore found in the BBL, with important consequences for benthic carbon dynamics (Thomsen et al. 1994; Thomsen and Graf 1995). Near-bottom lateral transport can have an important impact on the development of areas of high sediment accumulation, in particular along continental margins and with important consequences for the interaction between these areas and occurrence patterns of benthic organisms (Romero-Wetzel and Gerlach 1991). Near-bottom particle dynamics contribute substantially to our understanding of lateral transport processes, because, in principle, concentrations of particles in the lowermost 50 cm above the sediment surface are significantly higher than in middle and upper parts of the water column. They also differ in their composition. Microbial activities within the BBL have an important influence on the near-bottom dynamics of dissolved and particulate organic carbon as well as on food supply for the benthic assemblages (Ritzrau et al. 1997). In addition to field and laboratory studies on near-bottom particle dynamics, a numerical 1-D diffusion-advection model has been developed which explains interactions between various particle classes (Ritzrau and Fohrmann 1998). Simulations demonstrate that hydrodynamic sorting can generate characteristic distributions of various particles in the BBL, thus providing a basis for further considerations of particle pathways and the availability of particles for suspension-feeding benthos.

During the second phase of SFB 313, investigations were expanded to consider the influence of particle flux on community structure and on size distributions of benthic macro-and megafauna. Off Norway the relationship between near-bottom particle flux and the occurrence of echinoderms and poriferans was investigated (von Juterzenka 1994; Witte et al. 1997). Ophiuroids, in particular, are obviously able to change their feeding behavior depending upon the availability of food. The regional distribution of the assemblages is not easily related to the pelagic particle fluxes, but rather seems to be controlled by processes in the BBL (Thomsen et al. 1995). This basic pattern was later confirmed on the Kolbeinsey Ridge to the north of Iceland. Various faunal assemblages were found under different current regimes on the eastern and western flanks of the ridge (Brandt 1993). Generally, microbial investigations of surface sediments from high northern latitudes demonstrated the coupling between macrobenthos distributions and enzymatic activity (Köster and Meyer-Reil this volume).

During the last stage of SFB 313, investigations expanded into regions close to the sea-ice border along the East Greenland continental margin, with the aim of studying the influence of ice cover on bentho-pelagic coupling and benthic community patterns. The Northeast Water Polynya is maintained by a stabile anticyclonic gyre and is considered to provide a model for such experiments. Here, the specific hydrographic situation resulted in a disruption in the regional coherence of the processes controlling pelagic productivity and export from the composition and activity patterns of benthic communities (Brandt et al. 1996; Ahrens et al. 1997; Ritzrau and Thomsen 1997; Piepenburg et al. 1997). In contrast to the Norwegian continental slope, biological processes off Greenland are under the control of a seasonal ice cover and the southward-flowing East Greenland Current. The interactions between stimulated autotrophic production and related particle export in the areas of loose and frequently changing ice cover result in the formation of a broad zone of particle export, which may explain the more or less evenly distributed and rapid fluxes of phytogenic materials to sediments on the East Greenland continental margin between 400 and 3500 m water depth. The composition of epibenthic megafauna and endobenthic polychaete clusters in water-depth controlled assemblages, but the homogeneous distribution of biomass of the benthic assemblages also reflects a homogeneous food supply (Schnack 1998).

Ultimately, benthic investigations permitted the establishment of a spatial carbon budget for the Norwegian-Greenland Sea. Contrary to the conventional approach which constructs such budgets on a square meter basis, for the Norwegian-Greenland Sea the basin-wide carbon budget was assembled to avoid the fallacies of regional patterns of lateral transport (Schlüter et al. 2000). In addition to the spatial budget, a meridional gradient of benthic activity patterns was found, which seems to be related to ice cover (Ritzrau et al. this volume). In general, the largest proportion of basin-wide benthic carbon consumption occurs close to the continental margins, but in contrast to lower latitudes, only slight differences between the carbon demand were found in the deep-sea and along continental margins (Fig. 7). In the Norwegian-Greenland Sea the deep basins are more important for the carbon cycle in comparison to lower latitudes than is generally expected (Ritzrau et al. this volume). The bentho-pelagic carbon budget seems to be balanced, albeit with a small carbon deficit in the benthos. The lateral advection of allochthonous organic carbon through gateways from the adjacent ocean basins appears negligible.

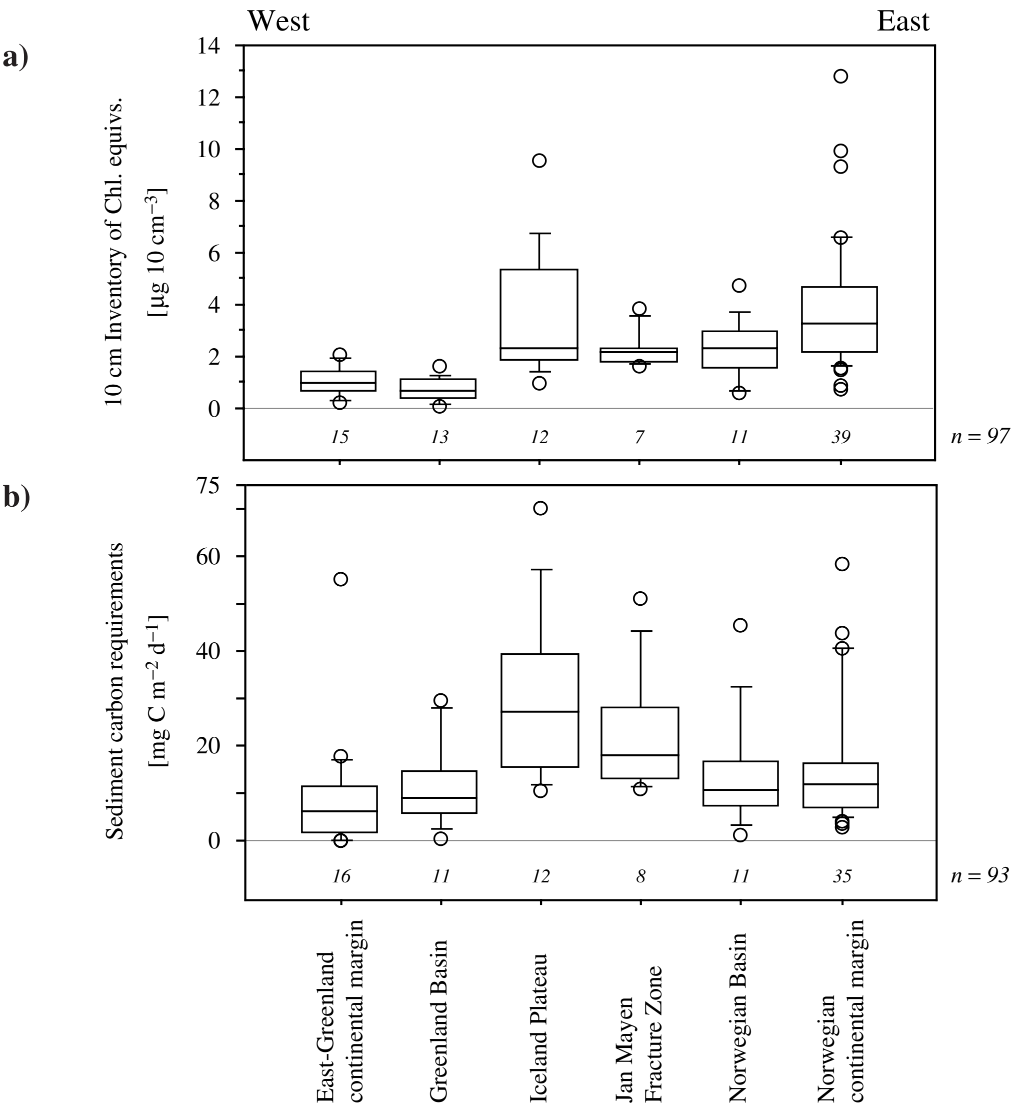

Fig. 7: Box plots of **a)** concentrations of chlorophyll equivalents (0–10 cm sediment depth) and **b)** benthic organic carbon requirements for the six biogeochemical regions of the northern North Atlantic (Ritzrau et al. this volume)

Material Fluxes through the Benthic Boundary

In the course of SFB 313 investigations, it was recognized that the BBL is not only important because of its control on the benthic habitats, but also as an important location for understanding the methane cycle, the fate of radiogenic tracers and the transformation of inorganic and organic environmental proxies due to diagenetic processes. Geochemical cycles and their spatial scales as well as process-oriented studies were conducted and evaluated. Regionally, investigations concentrated on the Norwegian and Greenland Seas, with very detailed experimental work on the Vøring Plateau, in the Barents Sea and along the continental slope off Norway.

At first, studies of geochemical fluxes through the benthic boundary concentrated on the determination of radiochemical nuclide distribution in the water column and sediments. A nuclide inventory was established and sedimentation rates were determined (Scholten et al. 1994a, 1994b). It was also demonstrated that the rates of remineralization of organic carbon in the surface sediments and the flux of dissolved nitrate through the BBL are regionally highly variable.

Microbial investigations of surface sediments from high northern latitudes demonstrate the coupling between macrobenthos distributions and enzymatic activity (Köster and Meyer-Reil this volume). The primary signals are altered by the coupled activity of macrobenthic organisms and enzymatic reactions.

Methane fluxes in the cold seep areas were surveyed on the Norwegian continental shelf and in the Barents Sea. Methane production was high in very limited regions. Therefore it can be used as a tracer for the dispersion of water masses. Relationships between the occurrence of gas hydrates and pock marks were documented (Mienert et al. 1998). The distribution and activity of methane oxidizing bacteria were determined at these localities by field and laboratory experiments. Methane oxidation rates were measured in the Barents Sea (Bussmann 1994).

A prime scientific aim was the determination of organic carbon fluxes which reached the seafloor from primary production and eventually were incorporated into the sediments. To conduct the necessary measurements, an in-situ tool was developed to determine oxygen profiles across the seafloor in ice-covered regions (Sauter 1997). For the first time it became possible to obtain in-situ measurements of the oxygen fluxes in shelf, continental slope and deep-sea deposits from the northern North Atlantic and to thereby establish benthic carbon fluxes and map regional differences in the "rain rate" of organic carbon to the seafloor. These data, in combination with satellite-derived primary production data, were used to establish a statistic relationship between benthic material fluxes, water depths and primary productivity. This was then able to be cross-checked with in-situ or sediment-trap measurements of organic carbon fluxes (Schlüter 1996; Schlüter et al. 2000). A Geoinformation System (GIS) was then employed to derive a spatial budget for carbon transfer from the photic zone to the seafloor. It was shown that $2.7 \cdot 10^6$ t a^{-1} of organic carbon from primary production reached the seafloor in the northern North Atlantic, corresponding to 1.2 % of the amount of organic carbon produced in the euphotic zone. These observations permitted the calculation of the quantity of organic carbon from primary production which is exported to depths below the winter mixing zone and is therefore removed from ocean-atmosphere-exchange for several hundred years.

In addition to organic carbon, the geochemical cycling of biogenic silicate in surface sediments was also investigated. These studies were combined with studies of similar problems in the South Atlantic and have resulted in a substantial modification of previous quantitative assumptions of silicate cycling in high southern latitudes. These studies demonstrated clearly how small silicate fluxes to the seafloor are in high northern latitudes (Fig. 8). Furthermore, only small differences exist between the northern North Atlantic and the Weddell Sea in the southern South Atlantic. The intensive dissolution of biogenic silicate in the water column and near the seafloor surface has been established as the potential cause for diminished silicate fluxes into the sediments of the Norwegian-Greenland Sea. These processes can also be elucidated by means of dissolution experiments with "Fluid Bed Reactors" (Rickert 2000), which reveal very high dissolution rates of diatom shells sampled in the northern North Atlantic.

History of Sedimentation, Ocean Circulation and Water Mass Distribution

The second suite of tasks pursued within SFB 313 considered various aspects of the historic variability of ocean circulation and distribution patterns of oceanic water masses as documented in the pelagic-hemipelagic sediment cover of the Norwegian-Greenland Sea and its gateways to the north and south. In the course of its development, SFB 313 shifted its emphasis from a pure "History of Ocean Circulation", as deduced from geophysical and sedimentological / micropaleontological data, to a comprehensive attempt to understand the "History of Global Change" through experimental and theoretical approaches. A quantitative paleoceanographic reconstruction of the history of the northernmost North Atlantic (including the Nordic Seas) during the last climatic cycles was based on excellent dating and numerous proxies. They provided a data base for deciphering the history of the pelagic biota and for modeling the dynamics of the glacial ocean.

Seismic Expressions of Sediment Distributions and Geophysical Signals in Seafloor Deposits

Originally, seismics were primarily used to map areas of undisturbed sedimentation (Meissner et al. 1988). Later, specific phenomena were traced using geophysical methods to characterize the entire sediment section or to map their geometry. A variety of methods was used for the geophysical characterization of subseafloor structure, namely, wide-angle side-scan sonar (GLORIA), reflection seismic profiling, high-frequency ocean bottom hydrophones and physical properties of core sediments. The results permitted the comparison of seafloor properties and large-scale sediment distributions on the two continental margins in response to the different climatic evolution of these areas during the Pleistocene. The occurrence of gas hydrate zones was

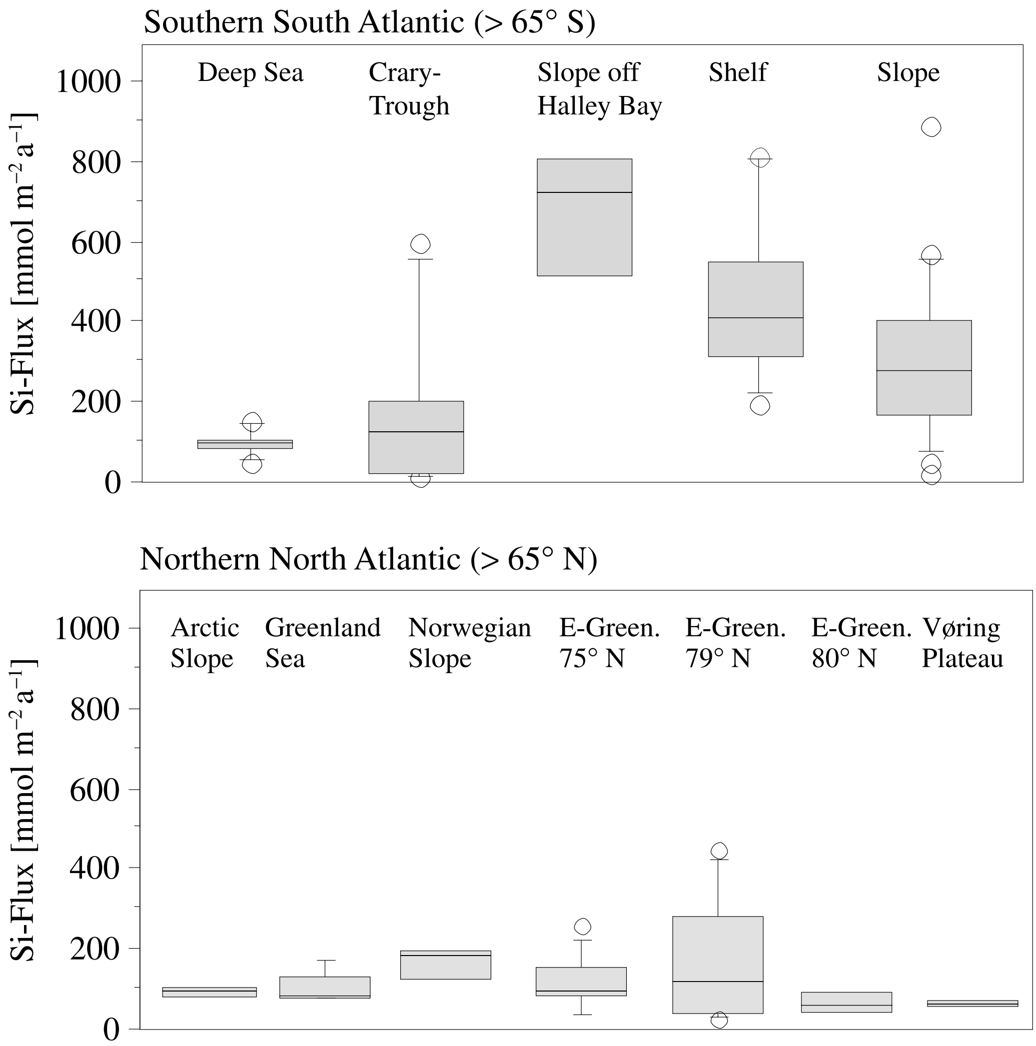

Fig. 8: Fluxes of biogenic silica to the seafloor of the Weddell Sea (southern South Atlantic) and northern North Atlantic (Schlüter et al. this volume)

established, their influence on the stability of sediment layering evaluated and their relationship to slope failure documented.

The Norwegian continental slope shows many examples of large-scale slope failure and the displacement of enormous quantities of sediments. Wasted slides, which have a very characteristic geophysical signal, can be traced far into the adjacent abyssal plains. Similar phenomena have not been observed along the Greenland continental margin (Mienert et al. 1998). Despite their similar geological structures both continental margins have developed substantial differences. The reasons for these differences are not fully understood. One substantial difference is the occurrence of gas hydrates off Norway as observed in the upper 300 m of the sediment column between 500–1800 m water depth. Such gas hydrates seem to be lacking on the Greenland side. Their instability may have contributed to the origin of numerous slide scars off Norway. Beyond the general characteristics of the areas investigated, geophysical studies have been used to highlight three specific phenomena, namely the dynamics of the hydrate stability zone, the evolution of turbidite channels in the deep sea and paleoclimatic evolution as traced in cyclic variations (Milankovitch Frequencies) of the physical properties of cored sediment.

Seismic data revealed a spotty occurrence of hydrates and free gas in the sediment cover off Norway. The lower boundary of the Hydrate Stability Zone (HSZ) can be traced through the occurrence of a Bottom

Simulating Reflector (BSR). In some seismic sections a BSR was traced over 300 km from the upper slope to the deep sea. Velocity analyses resulted in 1930 m s^{-1} for hydrate-cemented sediments. It was possible to resolve the upper and lower limits of the hydrate zones. They can be as thick as 300 m and generally do not outcrop at the seafloor. The velocities of gas-bearing deposits below the hydrate zone are considerably lower (approx. only 1200–1400 m s^{-1}, cf. Mienert and Posewang 1997, 1999). Along the Norwegian continental margin, several BSRs were found on top of each other. The upper BSR corresponds to the sliding layer of the Storegga Slide, thus pointing to a relation of the occurrence of slide events and the stability of gas hydrates (Mienert and Bryn 1997). Modeling has shown that the lower BSR can be considered a relict from the last glacial maximum (LGM), therefore establishing the immediate correlation between paleoclimatic changes, sea-level fluctuations and the stability of gas hydrates. The retreat of the HSZ resulted in the dissolution of gas hydrates at their base and the liberation of large quantities of free gas in the pore volume of the sediments, resulting in the instability of sediment layering and mass wasting along the slopes.

The use of the deep-tow wide-angle side-scan sonar (GLORIA) permitted the mapping of an area of 250,000 km^2 off East Greenland, including substantial sections of the Boreas and Greenland Basins (Mienert et al. 1993). The reflectivity of the mapped sediment cover shows substantial differences for both basins due to different grain sizes and transport processes. In the Greenland Basin, meandering turbidite channels were able to be traced over distances of as much as 300 km. These channels are several kilometers wide and up to 100 m deep, connecting the upper part of the continental margin to the deeper part of the basin in the north. In addition, the Greenland Basin can be subdivided into several morphological provinces, with fields of sediment waves generated by contour and turbidity currents. The combination of GLORIA and PARASOUND data permitted the establishment of a southward bottom current direction, which changed substantially on the southern part of the region investigated.

The application of the multi-sensor core logger to sediment cores permitted various physical properties, such as bulk density, compression wave velocity, magnetic susceptibility and clay mineral composition, to be measured. Some of these properties showed cyclic variations which, through stratigraphic studies, were able to be linked to orbital parameters (Mienert and Chi 1995). Magnetic susceptibility records on the Rockall Plateau seem to reflect a 100,000 year frequency linked to eccentricity changes, but this type of cyclicity cannot be easily identified in the Norwegian-Greenland Sea. Therefore, substantial research efforts are required in the future to decipher the processes controlling the cyclic variations of physical properties on a regional basis.

Short- and Long-Term Changes in Ocean Circulation, Chronostratigraphy and Quantitative Paleoceanography

The first attempts of SFB 313 to produce a Late Quaternary paleoceanography of the Norwegian-Greenland Sea were limited in scope. However, they were able to build on earlier experiences by the CLIMAP Project (Kellogg 1980). CLIMAP used planktic foraminifers for the first quantitative reconstructions of Nordic Sea paleoenvironments based on the transfer function technique (Imbrie and Kipp 1971). They had two major results: Kellogg (1977) showed that the surface waters of the Norwegian-Greenland Sea were cold and probably ice-covered during most of the last two climatic cycles. These cold intervals were interrupted only by two major warming events, namely the last interglacial (Eemian or oxygen-isotope stage 5e) and by the Holocene. He showed that the two interglacials resemble each other in many ways but that they also have some fundamental differences. By including an analysis of ODP Leg 104 drill sites on the Vøring Plateau, SFB 313 considered a much longer time scale than CLIMAP did. Furthermore, younger history was studied in much greater detail and at a higher resolution than ever done before. Later, this part of SFB 313 experienced substantial growth by allowing three subtasks to pursue paleoenvironmental aspects of the entire problem through: 1) isotope-based paleoceanographic reconstructions, 2) the SYNPAL project (see below), and 3) modeling efforts devoted to the glacial ocean (see below). All three approaches were aided by the enormous growth in dating capacities and by the increase in precision through the routine application of AMS dating (for many additional details see Sarnthein et al. this volume).

A multiple proxy approach was pursued to establish a quantitative paleoceanography of the Nordic Seas. Ocean circulation models were derived from reconstructions of sea-surface temperatures, sea-surface salinities and ice cover as well as hydrographic properties of the bottom water masses derived by a multiple proxy approach (Weinelt et al. this volume). While the basic sequence of events established by Kellogg (1977) seemed valid enough, the question as to whether glacial sea-ice cover or at least seasonally open waters existed remained enigmatic.

Several modes of deep-water renewal have been proposed (Sarnthein et al. this volume). During modern and Holocene times, intensive deep-water renewal occurred in the Nordic Seas and continued to feed the NADW, being coupled with strong heat and moisture fluxes, in particular over northwestern Europe. During the last glacial, this process slowed down considerably, probably about 50 %, thus advecting less heat to northwestern Europe. The polar front moved southwards to the area off West Ireland and transported cold, sometimes iceberg-laden waters off the Iberian peninsula and further south (Molina-Cruz and Thiede 1978). Meltwater events, sometimes linked to Heinrich events, were clearly different from the two previous scenarios and potentially led to a reversal of the main circulation pattern. They may have triggered some of the major short-term paleoclimatic fluctuations during the last deglaciation (Spielhagen et al. 1997).

The successful collection of sediment cores from high accumulation areas permitted the establishment of a variability in major water-mass properties which resembled Dansgaard-Oeschger cycles in their frequencies (Sarnthein et al. this volume), documenting the near-isochronous variability of atmospheric and oceanic circulation. However, the causal relationship of these high frequency changes and their potential response on the southern hemisphere have remained enigmatic and will be an exciting research target for the years to come.

The main results of paleoceanographic reconstructions are based on time series which have been dated with ever-increasing precision and detail, despite major differences in sediment composition observed between the eastern and western parts of the Norwegian-Greenland Sea (Henrich et al. 1989). The main changes in the oceanography in this ocean basin were restricted to its eastern subbasins, whereas the region off Greenland remained cold regardless of the fact that is was either glacial or interglacial. This provides a major argument for the long-term stability of the Greenland ice sheet which produced icebergs and ice-rafted material throughout the entire time span of the past climatic cycles – though often with a variable intensity. Reconstructed time slices (Sarnthein et al. this volume) document the various modes of surface-water circulation. It is clear that the nature of the waters feeding the major current systems (today North Atlantic Drift/Norwegian Current in the east and East Greenland Current in the west) had a controlling influence on the surface-water oceanography of the Atlantic (Fig. 9).

Paleoceanographic proxies also permit the assessment of the export of organic carbon in the Norwegian-Greenland Sea. For example, there are important contributions of organic material of fossil terrigenous origin (Wagner 1993) to the mass accumulation of total organic carbon preserved in the sediment. As Weinelt et al. (this volume) show, it is possible to reconstruct the ventilation rates of the deep Norwegian-Greenland Sea based on the mapping of the $\delta^{13}C$ signal of epibenthic foraminifers. In contrast, the species composition of benthic foraminiferal assemblages seems to reflect the flux of organic carbon and, therefore, paleoproductivity.

The coupling of pelagic and benthic habitats can be illustrated through accumulation rates of planktic and benthic foraminifers (Bauch et al. this volume). High accumulation rates of planktic and benthic foraminifers during interglacials and low rates during glacials indicate that productivity followed climate-induced cycles. Hence, high accumulation rates of these organisms were related to the advection of relatively warm Atlantic waters as an extension of the Gulf Stream system. However, it seems particularly noteworthy that distinct differences in species composition characterize the various interglacials, with no modern analog during the present Holocene interglacial. This suggests that they result from oceanographic conditions different than those which prevail today in the Norwegian-Greenland Sea. Since interglacials seem to have ended rather abruptly in the past, the fate of the modern interglacial remains speculative.

SYNPAL and the Fate of Pelagic Biota during the Late Quaternary

During the early years of SFB 313, the formation of sediment particles by organisms within the pelagic ecosystem of the Norwegian-Greenland Sea was either studied as a biological process or as a tool for dating and reconstructing paleoenvironments, usually focusing on one particular group of available microfossils (generally coccolithophores, diatoms, radiolarians, planktic foraminifers, dinoflagellates and other palynomorphs). Later the desire arose to study shells and skeletons of these organisms as tracers for the entire pelagic ecosystem and to follow their fate from the moment of origin to their final burial as sediment particles, provided that they survived the long and complicated sequence of destructive processes in the water column, at the seafloor and within the sediment column (Fig. 10). In 1991 the

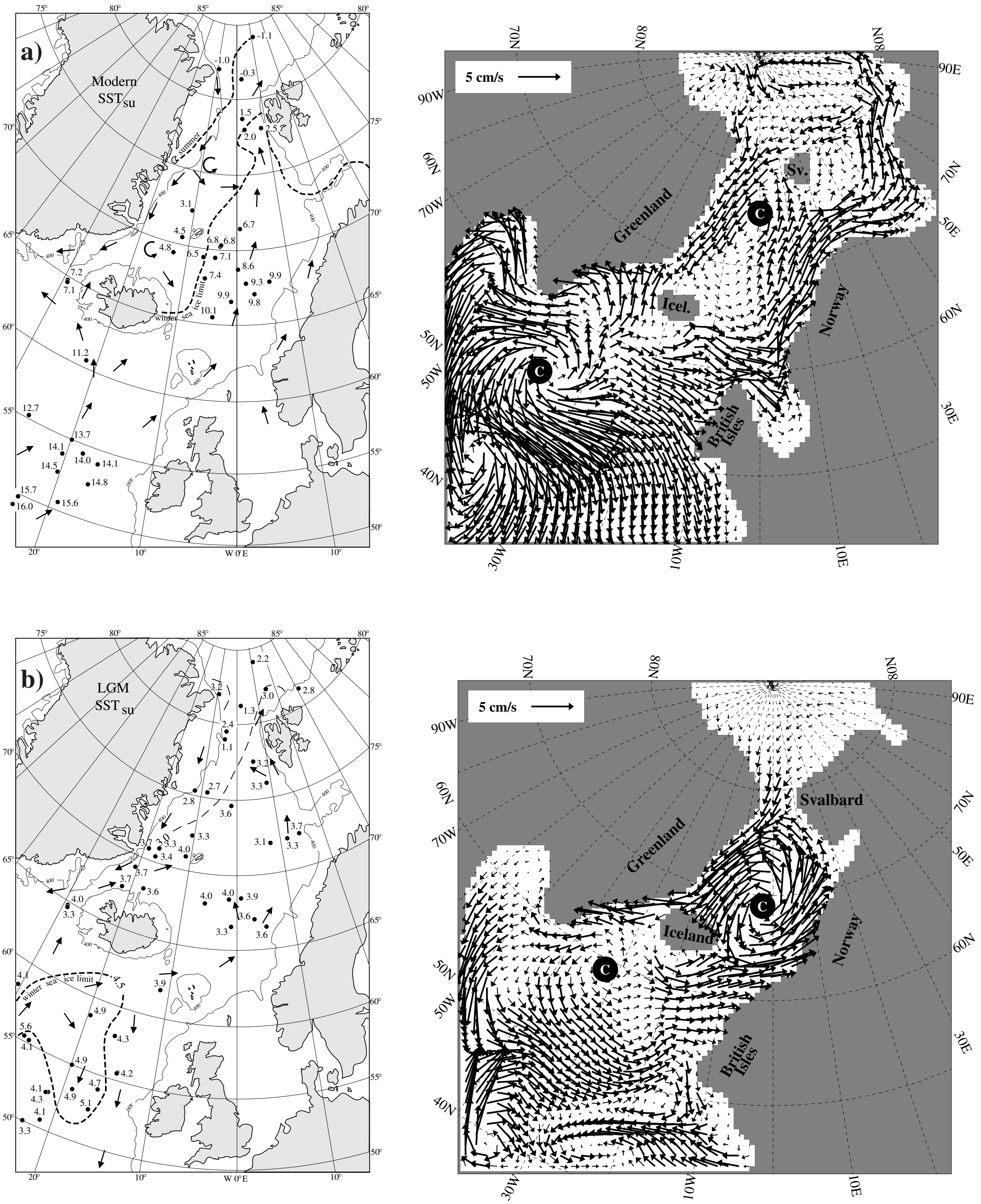

Fig. 9: Summer sea-surface temperatures (left col., in °C) for **a)** modern and **b)** Last Glacial Maximum (LGM). Note ice-free Nordic Seas during glacial summer. Arrows indicate surface currents. Modeled near-surface velocities (right col.) for **a)** today and **b)** LGM summer. For details see Sarnthein et al. (this volume) and Schäfer-Neth and Paul (this volume)

SYNPAL project (SYNoptic PALeontology) was defined (Samtleben et al. 1995), which combined the efforts of a group of marine biologists and micropaleontologists to achieve precisely this by studying the skeletal materials and remains of pelagic organisms, applying the same methods and using the same samples in as synoptic a manner as possible. The study concentrated on plankton groups with fossilizable remains (coccolithophorids, diatoms, radiolarians, foraminifers, dinoflagellate cysts).

Plankton occurrences are patchy, both on small and large scales. For example, it was possible to characterize the main water masses of the Norwegian-Greenland Sea by identifying coccolithophorid assemblages there (Baumann et al. 1997), but large seasonal fluctuations led to a temporary regional dominance of *Emiliania huxleyi*. The depth distribution of living planktic foraminifers and radiolarians has been established primarily in the relatively poorly known Greenland Sea. Arctic surface waters are inhabited only by *Amphimelissa setosa*, whereas other species such as *Pseudodictyophimus gracilipes* and *Actinomma ex gr. borealis/leptodermum* live in deeper waters with Atlantic properties. Siliceous plankton dominates the export of skeletal materials in the Greenland Sea, calcareous plankton is dominant in the Norwegian Sea. This is particularly well-expressed in the phytoplankton, since assemblages settling through the water column reveal characteristic differences for various regions (Schröder-Ritzrau et al. 1997). All plankton groups show some interannual variability (best developed in diatoms) with respect to both the species composition and vertical fluxes of their skeletal materials.

Quantitative differences in the export of skeletal materials from the water column to the seafloor can only be documented for calcareous plankton groups, but not for siliceous plankton, probably due to intensive opal dissolution (Kohly 1998; Schlüter and Sauter 2000). Reconstructions based on the occurrence of siliceous microfossils and opal accumulations rates are therefore highly dubious. The composition of diatom assemblages is affected by opal dissolution. Production assemblages make up approximately 90 % of the annual export, but only fall production assemblages are found in sediments. Although they represent only a few percent of annual flux, fall assemblages are preserved due to the robustness of their valves. In contrast, radiolarians are only minimally affected by selective dissolution.

Differences in production and grazing in various regions have an important impact on regional export patterns. An index of the relationship of the two most frequent coccolithophorid species, *Emiliania huxleyi* and *Coccolithus pelagicus*, permits a regional characterization of surface sediments despite strong changes during sedimentation and accumulation (Andruleit 1995). This index can also be used for interpreting Late Quaternary paleoclimate.

Investigations of samples from deep-sediment traps in the Norwegian-Greenland Sea have substantiated the importance of lateral advection to the sedimentation and preservation of plankton skeletal materials; these observations are also supported by long chain alkenone flux studies (Thomsen et al. 1998). Diverse diatom and radiolarian assemblages have helped to identify the source areas for advected materials. For example, advected material in the Norwegian Basin stems primarily from the Norwegian Shelf and the Jan Mayen Fracture Zone. The Greenland Sea traps were contaminated by material originating from the Barents Sea.

The analysis of fossil assemblages shows that their composition reflects the distribution of water masses (Fig. 11), the principal climatic and oceanographic events and development of the past 15,000 years (Fig. 12). In the past, different ecological requirements of various fossil groups frequently resulted in controversial reconstructions of the paleoenvironment (Baumann and Matthiessen 1992). However, the synoptic approach has permitted the identification of similarities as well as dissimilarities in habitat demands of individual plankton groups and the bridging of gaps in the records due to dissolution or other destructive processes. Despite the important differential preservation potential of individual plankton groups, it was possible to identify "cold", "warm", "transitional" and relict assemblages. Their occurrence in cores (Fig. 12) is closely related to environmental conditions during the Bølling/Allerød, Younger Dryas, Termination IB and Holocene, and can be used to characterize these stages better than was previously possible.

Modern living plankton assemblages (Hass et al. this volume) have adapted to hydrographic conditions in a time-transgressive mode, from south to north and with some delay, from east to west. They appeared at approx. 10,000 y BP on the Rockall Plateau, but they followed the Atlantic waters and reached the Barents slope only at 6,500 y BP. Stable plankton communities developed in the Atlantic domain only after the cold spell at 8,200 y BP. On the contrary, such stable conditions were unable to develop in the Greenland Sea, probably due to the differing amount of inflowing Atlantic waters. Dinoflagellates suggest a maximum inflow of Atlantic waters to the Greenland Sea at approx. 5,500 y BP, during the Holocene climatic optimum.

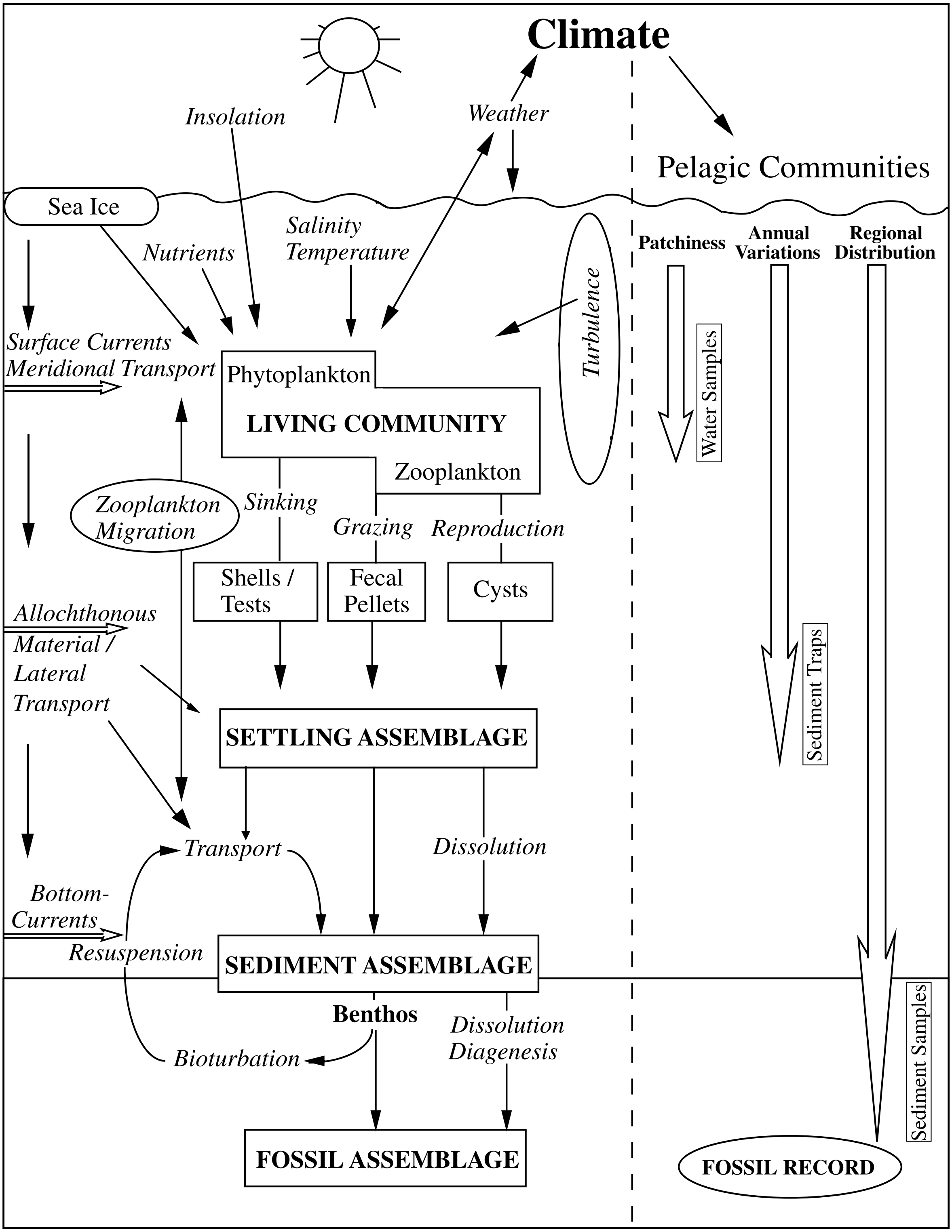

Fig. 10: Formation of fossil sediment assemblages via successive stages during the settlement and burial of plankton (Samtleben et al. 1995)

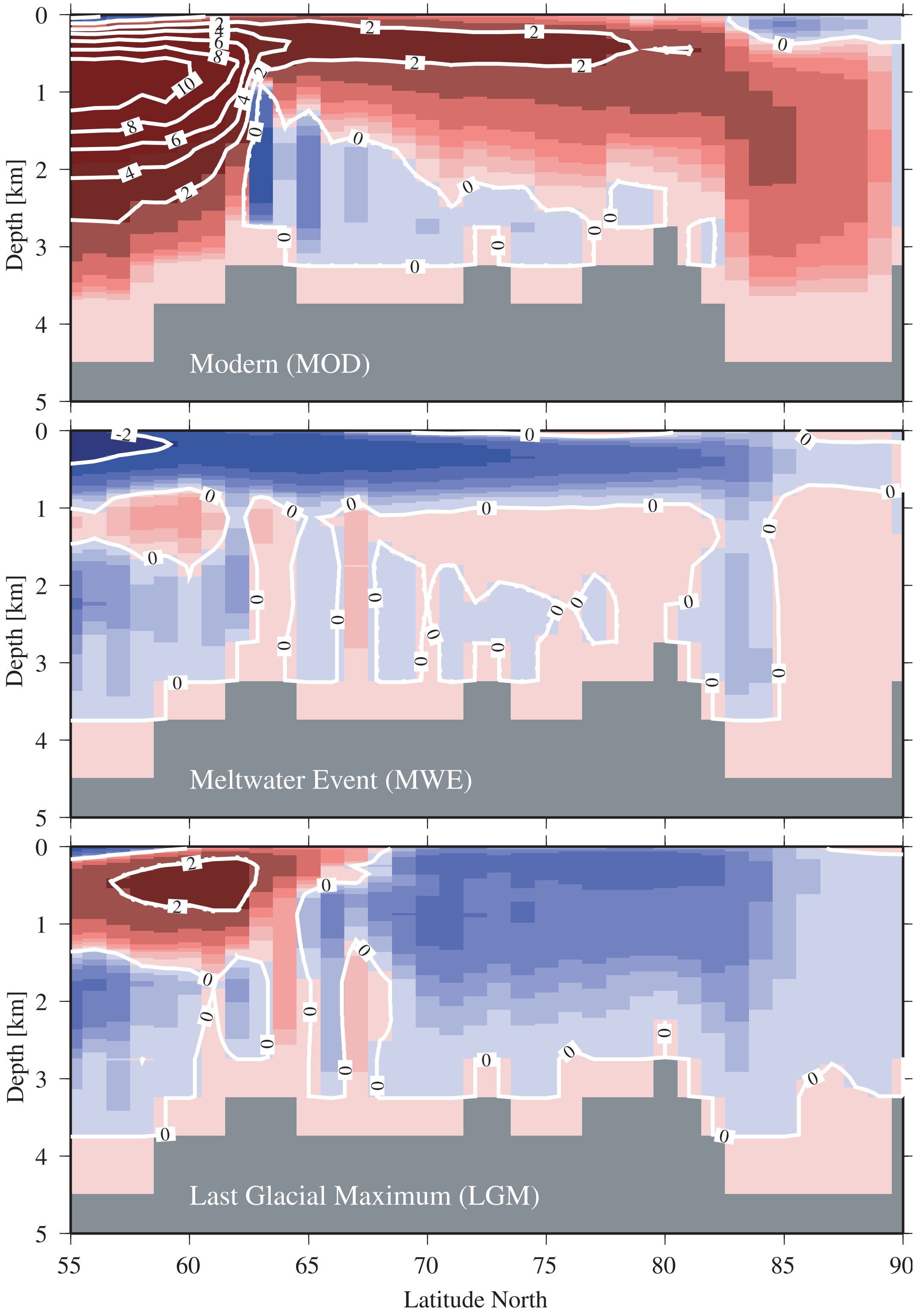

Fig. 11: Meridional transport of water masses (mio t / s) in the North Atlantic modeled for the Late Glacial Maximum (LGM), the Melt Water Event (MWE) and the modern ocean (MOD); red: currents clockwise, blue: anti-clockwise (from Schäfer and Schröder-Ritzrau 1999)

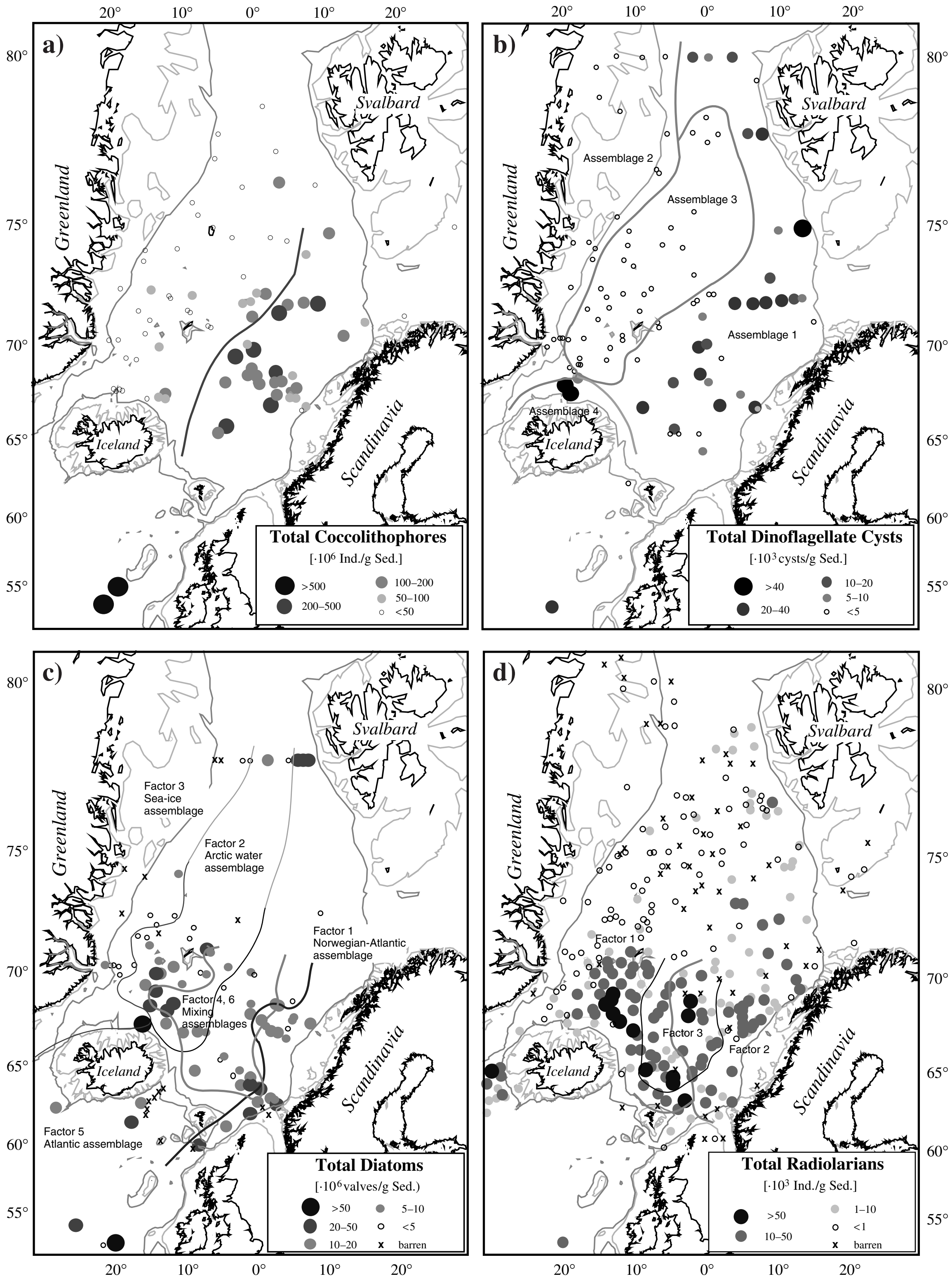

Fig. 12: Absolute abundances of planktic microfossils (1 / g dry sediment) and distribution of main assemblages **a)** coccolithophores (from Baumann et al. 2000); **b)** dinoflagellate cysts (from Matthiessen 1995; Baumann, unpubl.); **c)** diatoms (from Koç-Karpuz and Schrader 1990; additional data from Kohly 1994); **d)** radiolarians (from Bjørklund et al. 1998). (Matthiessen et al. this volume)

Modeling the Glacial Ocean

After six years of field studies it became obvious that simulation techniques would be critical for a further understanding of the spatial and temporal changes of environments. Modeling was used by the biological working groups from early on, later the modeling approach was also taken up by paleoceanographers, but with sufficient emphasis to consider historic scenarios only during the late stage of SFB 313. The Norwegian-Greenland Sea covers locations of intense deep-water renewal which have fed the overflow across the Greenland-Scotland Ridge and the North Atlantic Deep Water (NADW) during recent times (Meincke 1983). Even though a modest warming of the deep Norwegian-Greenland Sea has been observed since the early 1980's (Schlosser et al. 1991), it is presently unclear how this is balanced from other sources. However, the central role of the Norwegian-Greenland Sea for the thermohaline circulation of the entire world ocean has led to repeated attempts to establish a quantitative and theoretical basis for an understanding of these processes. The historic reconstruction of the evolution of Norwegian-Greenland Sea deep waters has demonstrated that three stages can be defined, namely 1) the modern stage with a relatively intense deep-water renewal, 2) the last glacial maximum with a reduced, but continued deep-water renewal, and 3) melt-water events generating brackish lids in the uppermost layers of the water column and preventing deep-water renewal as it is known today (Sarnthein et al. this volume).

To acquire a detailed and quantitative understanding of these scenarios, a hierarchy of numerical models has been developed consisting of 3-dimensional ocean circulation models of variable resolution, with coupled sedimentation and carbon cycle models. The models (Fig. 11) were driven with boundary conditions from paleoceanographic reconstructions and modeled wind fields (Seidov and Prien 1996; Seidov 1998; Schäfer-Neth 1998; Seidov and Haupt 1999). Maximal meridional overturning of approx. 10 Sv, which induces the strong inflow of Atlantic waters traceable to 80° N, has been reached under modern conditions. Melt-water events, such as Heinrich Event 1, can result in the reversal of the entire circulation regime above 1,000 m water depth, with a cessation of deep-water renewal at the same time. Reduced, but modest, deep-water renewal seems to have occurred during the Last Glacial Maximum, and regions of down-welling seem to have been relocated approx. 10° latitude further south than today (Schäfer-Neth and Stattegger 1998).

Experience as a Basis for Future Studies

In this chapter a brief, but critical evaluation of the approach and results of SFB 313 will be presented. In sequencing the arguments of this chapter (as well as of the contributions to this book) the organizational structure of the entire project has generally been followed, though many other approaches could have been used. They are thought to build on each other and, therefore, to guide the reader through the contents of this volume.

SFB 313 was a large and ambitious interdisciplinary research project, combining a number of diverse disciplines within the marine sciences. It was some time before the members of the various groups developed a common language, but through joint experiments, expeditions and combining various disciplines into the same tasks, results were achieved, which with their successes and shortcomings, can offer some guidance for future studies. Selected highlights of the scientific results of SFB 313 have been outlined above; in the following the approaches through which these results were achieved will be evaluated.

It was highly important that SFB 313 was able to use the final two years of its existence as a phase to synthesize collected data and to evaluate its scientific approach, with the result that substantial proposals for future work are now possible. In this context it should be mentioned that several international groups of researchers have demonstrated that the Norwegian-Greenland Sea is presently the subject of major changes (Broecker 1999), as it has been in the past.

One of the major shortcomings of the structure and scientific profile of this research project were several unsuccessful attempts to motivate a larger segment of physical oceanographers to contribute to SFB 313. Despite many tasks which could not be properly addressed without the participation of hydrographers, obligations to other projects prevented the participation of such specialists from bridging the gap in many of the seagoing operations and in the generation of data relevant to the characterization of the hydrographic properties of Norwegian-Greenland Sea water masses.

The Norwegian-Greenland Sea is a small ocean basin, with an importance for the dynamics of the global environment far exceeding its size. It is one of the most intensively studied subbasins of the world ocean, yet the complexity of the investigations required cannot be handled by the researchers from one nation alone. In the future a large-scale international and interdisciplinary research effort must be devoted to trace the early onset of global changes and their impact on the environment of the Norwegian-Greenland Sea. It is now clear that the

Norwegian-Greenland Sea should be used as a natural laboratory to detect early indications of global changes; this will require the interdisciplinary collaboration of a wide range of marine disciplines as well as the employment of remote sensing techniques.

After improved understanding of pelagic processes based on data obtained by long-term mooring deployments at different locations in the Norwegian and Greenland Seas, the next logical step was to extrapolate these results with respect to the spatial distribution of, for example, the ice edge or ice coverage. Recent advances in remote sensing technology appeared to be the best method for this approach. Instead of initiating a new group in SFB 313, leading colleagues were invited to cooperate on this topic at sea as well as in the subsequent analysis and integration of the data. To compensate for the lack of sufficient remote sensing data, SFB 313 made multifold efforts to involve guest scientists from other European and North American institutions, both through invitations to participate in research cruises and extended visits to Kiel.

One of the basic ideas of the combination of remote sensing techniques, particle trap deployments and benthic investigations was to reach a detailed knowledge of present-day processes controlling sediment formation and distribution, then to apply this understanding to resolve the depositional history of the region, that is, to compare modern and ancient variabilities despite large differences in scales of space and time. This was not able to be completely achieved, primarily because various glacial scenarios have no modern analog. In the present interglacial mode, the modern glaciated parts of our planet have even higher eustatic sea levels. Moreover, the interglacials observed and compared were obviously quite different despite their apparent similarities.

The early as well as the later portions of the SFB 313 research program tried to consider the fate of skeletal biogenic materials from their production to their resting place in sediments. Remarkable progress has been achieved, but the collaboration between various biological oceanographers and micropaleontologists evolved slowly due to the different scientific cultures in both disciplines. The primary focus of the SFB 313 plankton group was to understand the entire process of the sedimentation of biogenic particles primarily based on biological and chemical measurements such as chlorophyll, macro- or micronutrients such as nitrate or silica. In contrast micropaleontologists cultivate their field by meticulously establishing the species composition of selected, preserved microfossil groups. At the end of SFB 313 the result of this cooperation resulted in new conceptual approaches for both disciplines.

After understanding the magnitude and distribution of bulk fluxes, planktologists must return to the study of the ecology of communities by integrating information from the physical and chemical environment and from the detailed temporal and spatial development of the species composition of communities, both experimentally in the laboratory and in the field and by numerical simulation. In close cooperation micropaleontologists were able to engage in experimental work to understand the ranges of the preferred environmental conditions of their key microfossils, also in the laboratory and in the field. Furthermore, studying alteration processes of their key microfossils before final burial opens a wide field of experimental micropaleontology, similar to the very successful approach for benthic foraminifers in SFB 313.

Recent oceanographic scenarios can be related to regionally high rates of sediment accumulation. Since this primarily affects surface sediments, it is difficult to detect regional reworking. Modeling mesoscale gravity-driven turbidity plumes is an effective tool for simulating exceptionally high-energy sediment transport events under recent conditions and for reconstructing paleoceanographic scenarios. While deciphering these processes successfully, it was not possible to obtain sufficient and systematic small-scale bathymetric data and sufficiently high sediment sampling density to resolve the mesoscale sediment transport events affecting continental margins and their geological records.

In the well-oxygenated surface sediments of the Norwegian-Greenland Sea (Sauter 1997) biological activities on the seafloor modify sedimentary structure, thus potentially influencing the geological record. Particularly bioturbation, the reworking of sediments by benthic organisms, may influence stratigraphy, putting some restrictions on the resolution of the exact dating of sediment layers. Even though the understanding of this process was primarily enhanced separately by experiments of this benthos group and numerical statistical simulations of the paleoceanographers, a joined comprehensive solution was unfortunately not achieved in SFB 313. Particularly the effect of selective transport or the relocation of relevant microfossils, such as diatoms, on paleontological interpretations was not addressed. Similarly, suspension feeding, the process of selective biodeposition of specific grain sizes or allochthonous microfossils from the benthic boundary layer into the sediment, may lead to high accumulation areas, which then do not necessarily represent local geological history. Building on the present, a closer cooperation between the geological and biological disciplines would significantly enhance our understanding of the present and the past.

The challenge of future benthos research will be to combine community structures and biogeochemical fluxes in a quantitative manner. Experimental and field work as well as numerical modeling must go hand in hand towards a better understanding of the role of biological activities at the sediment-water interface, which also represents the boundary between the present and the past.

SFB 313 later recognized that fluids and materials cross the BBL not only from above but also from below. Discoveries regarding the methane cycle, the fate of radiogenic tracers and the transformation of organic and inorganic particulate and dissolved carbon contributed substantially to the success of SFB 313. In some areas methane production seems to control the settling pattern of large benthic assemblages and many properties of sediment cover. Microbiologists showed the important enzymatic reactions and coupled activities of benthic organisms. It was possible to establish and understand the balance of carbon fluxes for the entire Norwegian-Greenland Sea, both in terms of field measurements and models. The geochemical cycling of silicate at the sediment surface in the northern North Atlantic is quite similar to that observed in the South Atlantic and the Weddell Sea, with the result that only very little silicate is preserved in the sediments.

Geophysical mapping established a wide range of differences of sedimentary provinces. Particular emphasis was paid to the sediment cover of the continental margin off Norway, where substantial gas hydrates were found, and off Greenland, where they seem to be absent for unknown reasons. Instabilities in gas hydrates related to climate change and sea-level fluctuations seem to have generated an environment favorable for large-scale sediment failures along the Norwegian continental margin. Deep-towed wide-angle side-scan sonar profiling established the occurrence of a meandering deep-sea channel system, probably due to the flow of turbidity-driven currents. In the future such large-scale surveys should be conducted early on to provide an impression of the general features of the area investigated, to discern large- and small-scale features in their various geographic contexts and to guide the definition of locations for the completion of in-situ experiments as well as to establish the sampling program.

No clear picture emerged from the continuous measurements of physical properties in sediment cores. Whereas elsewhere numerous examples of fully developed cyclic variations of the properties could be related to orbital parameters, observations from the Norwegian-Greenland Sea have remained spotty and inconclusive. The progress that had been hoped for in relating these variations to their driving forces was unable to be achieved. Part of this deficit has to do with the relatively short sediment cores able to be collected with available research vessels. In the meantime, the IMAGES program has taken up the task of hunting for longer sediment cores with higher stratigraphic resolution, and members of the former SFB 313 are an integral part of the scientific groups conducting the IMAGES expeditions to the Norwegian-Greenland Sea and adjacent deep-sea basins.

One of the basic assumptions of SFB 313 in its entirety was linked to the use of modern processes to explain past oceanographic or climatic scenarios. However, even modern ice sheets or ice-covered parts of the Arctic Ocean and of waters east of Greenland are in an interglacial state today. It is now clear that glacial scenarios have basically no proper modern analogies. Even records from various interglacials differed from each other despite their apparent superficial similarities. Hence, the present has not provided a key to the past, neither has the past done so for the present. Nevertheless, the quantification of the modern processes controlling sediment formation in the Norwegian-Greenland Sea and the comparison of modern and past records has helped to establish a better understanding of the rates and range of climatic changes.

One of the most intriguing enigmas is the fossil record of sea ice and icebergs in Arctic Ocean and Norwegian-Greenland Sea Quaternary sediments. Today sea ice transports large amounts of relatively fine-grained terrigenous sediments from the shallow Arctic Eurasian shelf seas into the Arctic Ocean and into the Greenland Sea through the Fram Strait. Icebergs are virtually absent. However, glacials and, in particular, the record of terminations are full of coarse, obviously ice-rafted debris brought in by melting icebergs. SFB 313 has succeeded in defining characteristic structures and a certain stratigraphy of ice-rafted debris in the Norwegian Sea, but has failed to link them quantitatively and in detail to the dynamics of ice sheets on adjacent continents.

Following the CLIMAP approach, SFB 313 succeeded in refining methods of formulating paleoecological equations for quantitative estimates of physical and chemical properties in past environments. The Norwegian-Greenland Sea, with its extreme environment and marginal occurrence of many plankton groups, has proven difficult for such attempts. Despite wide-spread records of ice-rafting, temperature reconstructions show relatively high surface temperatures even during glacial maxima (several degrees centigrade above zero!). It remains to be seen whether these results will withstand critical scrutiny in the future.

Modeling past oceanographic scenarios in the Norwegian-Greenland Sea and in the entire North Atlantic Ocean has proven to be of invaluable help in defining areas of potential major change. SFB 313 was too slow in adopting various modeling approaches. Much more intense efforts should have been devoted to interaction with modeling communities.

Over the past few climatic cycles, the North Atlantic seems to have been instrumental in contributing to the driving forces of global climate. SFB 313 made strong efforts towards establishing a quantitative understanding of paleoenvironmental change. This was supported by extensive studies with data sets from chemical, biological and theoretical paleoceanography. Much progress has been made toward the establishment of a base of well-dated undisturbed sediment cores from the Norwegian-Greenland Sea obtained with important contributions from the international IMAGES project and from investigations in the Arctic Ocean. Modeling the glacial Norwegian-Greenland Sea began rather late in the history of SFB 313, but has produced important progress in our understanding of how this small but important ocean basin has responded to rapid and slow climate changes.

Data management was in its infancy in the early days of SFB 313 but it has improved substantially over the years. All core data are stored in the PANGAEA data base maintained at the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven. All data revealed from sediment trap studies are stored in the JGOFS data base at the Fachbereich für Geowissenschaften, Bremen University. However, even now – only 2 years following the existence of SFB 313 – it is difficult to trace certain meta-data which are not published but only stored in various institutional archives. Therefore, great care and substantial resources should be devoted to securing such valuable data collections in the future.

Conclusions

The Norwegian-Greenland Sea is the centerpiece of the gateway between the Arctic and the main basin of the North Atlantic Ocean, allowing for the exchange of surface- and deep-water masses across climatic zones. The advection of large quantities of relatively warm water masses from the Gulf Stream system to very high northern latitudes is of eminent importance for the modern climate over Europe, whereas the renewal of deep-water in the Norwegian-Greenland Sea feeds the NADW, thus giving the oceanic processes in these deep-sea basins a global scope. Since it was hoped that sediment accumulations would hold the key to the historic variability of this system, the interdisciplinary investigations of SFB 313. in addressing the mode of sediment formation and distribution under modern conditions as well as the historic reconstructions of various depositional environments, represent an important scientific contribution. In the course of the development of SFB 313, emphasis shifted from a pure “History of Ocean Circulation” as deduced from geophysical and sedimentological / micropaleontological data to a comprehensive attempt to understand the “History of Global Change” through experimental and theoretical approaches. The evaluation of the results of SFB 313 has not been concluded, but will continue into the foreseeable future. In this volume a first comprehensive and interdisciplinary synthesis of our understanding of short- and long-term changes in the environment of the Norwegian-Greenland Sea is presented. As a result of these investigations and the efforts of a number of other groups, primarily from the Scandinavian countries, this small subbasin, which was poorly known a short while ago, has probably become the best known basin compared to the remainder of the world ocean. There is no question that these latter results could only be achieved because stable and long-term funding was available for more than a decade to the group of scientists under the frame of SFB 313.

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