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Particle transport processes at slope environments — event driven flux across the Barents Sea continental margin

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Abstract

Recent studies of the vertical flux of organic matter into the deep ocean have prompted the search for key organic compounds (biomarkers) as tracers for its production, flux and burial into the sediment.

Particulate matter was collected with sediment traps moored at the Barents Sea continental margin (75°11.78′N/12°29.21′E; water depth 2050 m) at 610, 1840 and 1950 m depth. The compositions of the organic material in the two bottoms near traps differ significantly. This difference cannot be the result of a change of the vertical sedimentation alone. A combination of biomarker analyses, quantitative microscopy and bulk parameter determinations on water and sediment trap samples is used in this study to demonstrate that a turbidity plume event at the shelf edge is a vehicle to transport organic and lithogenic particles at high velocities to the benthos of the lower continental margin. It is suggested that fine particles were advected into the trap at 1850 m, whereas the coarser fraction of higher settling velocities, passing several resuspension loops entered the lower trap.

Keywords: Biomarker; Continental margin; Plume event; Fast cross-slope particle transport; Plume event

1. Introduction

Continental margins and adjacent shelves are areas with high rates of primary productivity and large standing stocks of particulate organic carbon (POC), and therefore are important in the cycling of organic matter (Walsh, 1989; Weering et al., 1998). Following the initial suggestion by Walsh et al. (1981) there can be a net export of organic carbon from the shelf to the continental slope. The quality and the quantity of the organic matter input is strongly influenced by decomposition and physical processes dominating in the benthic boundary layer, and by microbial and benthic activity at and near the sediment–water interface and in the surface sediments (Graf et al., 1995; C. Thomsen et al., 1998). A complete investigation of a sedimentation event must therefore trace the pathways of particles from production to final geological deposition, including the assessment of the importance of lateral transport (Biscaye and Anderson, 1994; Walsh, 1989; Wollast et al., 1996).

The Barents Sea is known to export significant amounts of resuspended material mediated by cascade-like winter outflows of dense bottom water (Blaume, 1992; Blindheim, 1989). Particle flux measurements showed an annual maximum of

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sedimentation during winter with a clear dominance of lithogenic particles (Honjo, 1988, 1990). Studies of near-bottom processes (Gardner et al., 1985; Gardner and Richardson, 1992) have shown that strong gradients in vertical settling of material collected by sediment traps may occur if these traps are deployed in a turbulent near-bottom boundary layer. In the Seep II flux studies at the mid-Atlantic Bight particle fluxes due to storm-driven resuspension events on the shelf and shelf edge are described as dominant transport processes (Biscaye and Anderson, 1994).

Recent studies of the vertical flux of organic matter into the deep ocean have prompted the search for key organic compounds (biomarkers) as tracers for its production, flux and burial into the sediment. A combination of biomarker analyses, quantitative microscopy and bulk parameter determinations on water and trap samples revealed that cross-slope lateral particle export during the growth season may sweep freshly settled pelagic material from the shallow Barents Sea into the deep Norwegian Sea (von Bodungen et al., 1995; C. Thomsen et al., 1998). Sediment plume events (Fohrmann et al., 1998) are postulated as vehicles for these off-slope transport processes at high velocities.

The sediment-trap experiment described is part of the study of the of the Sonderforschungsbereich 313 of Kiel University which has one objective to understand and to link the benthic–pelagic coupling under high dynamic continental margin conditions (Schäfer et al., 1995; Schäfer et al., 2001). The aim of this investigation is to demonstrate that additionally to the vertical flux a plume event at the shelf edge can transport organic and lithogenic particles to the benthos of the lower continental margin; and that this event can be both modeled and measured.

2. Study area

The Norwegian Sea (Fig. 1) is characterized by strong east to west hydrographic gradients. Temperate and ice-covered surface waters separated by distinct oceanic gradients occur in close vicinity. Today warm saline Atlantic water moves northward on the eastern side of the Norwegian Sea in the Norwegian Current (NC), a relatively warm (6–10°C) and saline ($S > 34,9$) branch of the north Atlantic Drift (NAD) (Johannessen, 1986; Swift, 1986).

The Atlantic water masses at the continental slope at 75°N have temperatures above 3°C and extend down to depths between 600–800 m in the West Spitsbergen Current (WSC). The boundary between this branch of the Atlantic water and cold ($T < 0°C$, $S < 34.8$), polar waters entering the Barents Sea from the Arctic Basin is called the Bear Island polar front. The polar front marks the maximal extension of sea ice during winter. Due to cooling of Atlantic water by strong frontal mixing and the addition of salt by brine rejection, dense water is formed on the shelf (Blindheim, 1989; Midttun, 1985; Pfirman et al., 1994). This bottom water leaves the Barents Shelf following topographic depressions down the continental slope as dense bottom-arrested gravity plumes (Aagaard, 1989; Fohrmann et al., 1998; Jungclaus et al., 1995; Quadfasel et al., 1988).

The sedimentology in the investigation area show fine grained particles are located seaward of the glacially generated submarine Kveitehola Trough at 75°N (Fig. 1). Well-preserved layers of Holocene sediment accumulation cover an area of roughly 40 km in diameter with sediments up to four meters thick. The Holocene sediments in this area mainly consists of homogeneous fine-grained silty muds (80 wt% < 20 μm) with a minor content of sand-sized particles (<5 wt% > 63 μm) (Core 23258; Blaume, 1992). Lag sediments can be found at the upper slope (15.2°E), on the shelf edge (15.7°E), and at the western end of the Spitzbergen Banken (18.8°E) with up to 70% sand-sized particles (63–2000 μm). At the lower slope (11–13°E) the coarser particles are mainly biologically produced (Foraminifera and sponge needles). Peaks of high contents of coarse silt (20–63 μm) can be found in the area 14.7–15°E as lag sediments or early sedimentation in the inner Kveitehola (16–18°E). The maximum content of fine particles in 1400 m depth and the dominance of lag sediments at the upper slope and in the Kveitohola leads to the supposition that particles are transported from the Kveitohola across the margin (Fohrmann et al., 1998; Kämpf and Fohrmann, 2000).

3. Methods

This investigation is based on material collected by

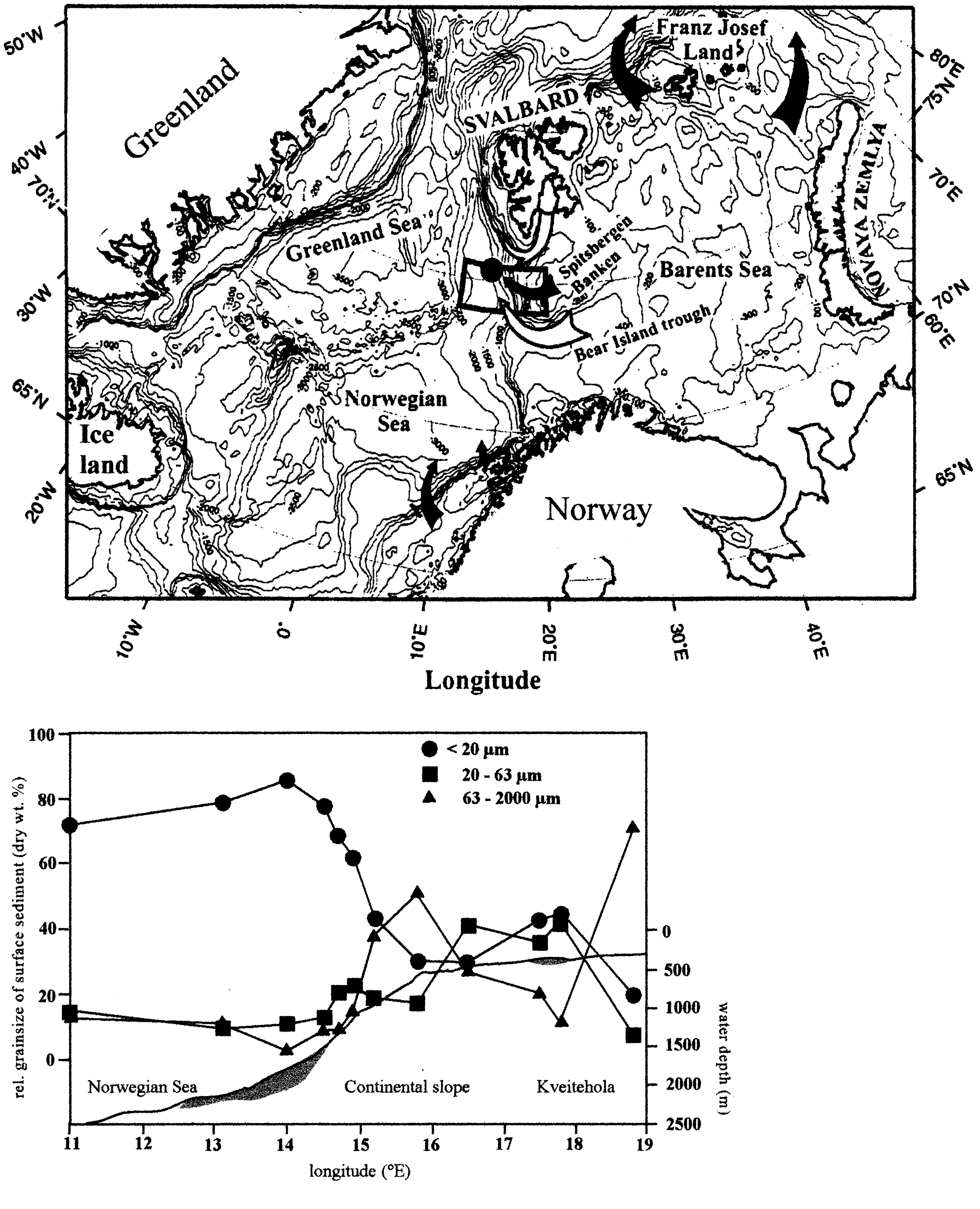

Fig. 1. (a) Map of the investigation area including position (circle) of moored sediment trap at the Barents Sea continental margin (BI-75°11.8′N;12°29.2′E; deployment March 1991–July 1991) at 610, 1840 and 1950 m. Arrows indicate areas of plume events. Black arrows: sediment plumes and white arrow: gravity plumes. (b) Relative grain-size distribution of surface sediments on a transect from the Kveitohola basin to the deep Norwegian Sea.

a sediment trap deployment combined with a transmissiometer and current meter. Water sample and sediment collections were also taken during cruises of RV *Meteor* 13 in July 1990, RV *Poseidon* cruise 181 in February 1991 and RV *Meteor* cruise 17 in July 1991.

Particulate matter was collected with automatic multi-sample sediment traps (Kiel-type, Baltec GmbH, Kremling et al., 1996) moored at the Barents Sea continental margin (75°11.78′N/12°29.21′E; water depth 2050 m) at 610, 1840 and 1950 m (March–July 1991). The temporal resolution of sampling (7 days) was high to obtain information on short time events. The sampling bottles in the traps were poisoned with HgCl2 (0.1%). After recovery the samples were splitted into aliquots by a rotating splitter. Routine analyses of collected trap material were performed on dry weight, POC, particulate biogenic silica and carbonate ($CaCO_3$) (von Bodungen et al., 1991). These data are presented as biogenic and lithogenic flux.

The attenuation of a light beam in the water column responds mainly to the first-order effects of particle size and particle concentration (Richardson, 1987). Therefore, a temporal decrease of light transmission is taken to indicate an increase of fine suspended particulate matter (particle concentration) during events of higher current velocities with associated resuspended or advected material in the bottom nepheloid layer (BNL) (McCave, 1986; Weatherly and Kelley, 1985). The turbidity of suspended matter was determined using a Sea Tech transmissiometer (25 cm path-length) connected to a RCM 5 Aanderaa current meter deployed at 2000 m water depth equipped with a temperature and conductivity probe.

In the presented here approach a chloroplastic pigments (CPE) of primary produced material is applied for the differentiation between fresh (undegraded Chlorophyll (*a*) and degraded pigments (phaeopigments) to identify the source of sinking particles. CPE were determined with a HPLC system, equipped with a Pump Waters 600E and a Waters 990 diode array spectrophotometric detector with integration system. The pigments were analyzed by reverse-phase HPLC, using a C18 sperisorb ODS 3 um/ 40 × 125 mm) Pharmacia column and HPLC-grade solvent (Biomol). Solvent A consisted of 80% methanol and 20% acetone. Pigment concentrations were quantified based on peak areas of external standards (Peeken, 1997a, b).

Faecal pellets of mesozooplankton were picked from aliquots of sediment trap material, analyzed microscopically, separated and attributed to their respective producers. The samples were filtered on GF/F filters and dried for 24 h under 60°C. Measurement of the organic carbon content of the pellets were performed using a CHN rapid analyzer (type: Heraeus). Additionally vertical multinet hauls were sampled to trace the standing stock of the mesozooplankton (von Bodungen et al., 1995; Zeller, 1996).

The composition of the the long-chain unsaturated methyl ketones (alkenones) with 37 carbon atoms, expressed in the $U_{37}^{k'}$-index, is useful for the reconstruction of paleo-surface temperatures especially at latitudes with surface temperatures around 10–25°C (e.g. Sikes et al., 1991; Brassell, 1993; Rosell-Melé et al., 1995). In the literature several explanations for deviation in SST temperatures have been given e.g. residence time in the water column (Freeman and Wakeham, 1992), the contributions of particles from different habitats in the water column (Prahl et al., 1993; Sikes and Keigwin, 1996), genetic variations among source organisms (Conte et al., 1994, 1995), species dependency (Volkman et al., 1995) or transport due to sea-ice advection (Rosell-Melé et al., 1995). The least modification of the alkenone signal in particles on their way from surface to the near-bottom traps occurs during phases of rapid sedimentation after short residence time in the upper pelagic zone or transport via faecal pellets. In regions where a complex food web efficiently retains biogenic material in the upper pelagic layer the originally imprinted alkenone signal can be altered. Strong deviations from the surface signal occur in areas with high resuspension fluxes and nepheloid layers due to increased contributions of particles with long residence time (C. Thomsen et al., 1998). The alkenone determinations were carried out by multidimensional gas chromatography (MDGC), described by C. Thomsen et al. (1998). Alkenones were separated by a Siemens Sichromat II MDGC using a unpolar first column (Restek RTX 5, 35 m, 0.32 mm i.d., 0.25 mm film thickness) and a more polar second column (Restek RTX 200, 35 m, 0.32 mm i.d., 0.25 mm film thickness). Injection was on-column and hydrogen was used as carrier gas. With these analytical techniques the precision based on triple processing and injection was ±0.02 $U^{k'}_{37}$-units.

For this study a reduced plume model (Jungclaus and Backhaus, 1994), for the simulation of the spatial and temporal evolution of gravity plumes was coupled with a new sediment transport model including erosion, horizontal transport and deposition of two different grain size fractions (20 and 63 μm) (Fohrmann, 1996; Fohrmann et al., 1998; Jungclaus et al., 1995).

4. Results and discussion

4.1. Particle flux

4.1.1. Total mass flux

The vertical sedimentation profile of total biogenic and lithogenic flux (Fig. 2) in the present period shows a pre-bloom situation until mid-May, an increasing sedimentation with a mid-June maximum and a phase of decreased fluxes during July. Generally the total particle fluxes increase with depth. Highest particle fluxes with the lowest visible signal of distinct seasonality were determined in the deepest trap at 1950 m. The enhanced ratios of lithogenic to biogenic components with depth indicate an additional particle flux other than by vertical settling. At 1950 m two strong sedimentation events took place, one in week eight and one during week 15–16, where the particle fluxes exceeded 600 mg m^{-2} d^{-1}.

4.1.2. Chloroplastic pigments (CPE)

In order to discuss the cross slope event, the flux of CPE are presented in terms of chlorophyll *a* and the resulting ratios of Phaeopigment/Chlorophyll *a* (Fig. 3a). Similar to the flux of total mass, Chlorophyll *a* follows the seasonal trend with a phase of maximum sedimentation during weeks 14 and 15 with highest values of 73 μg m^{-2} d^{-1} in 1840 m and 60 μg m^{-2} d^{-1} in 1950 m. The Phaeopigment/Chlorophyll *a* ratio during enhanced flux was near 1 from the weeks 13–15 in both depths. A decrease in

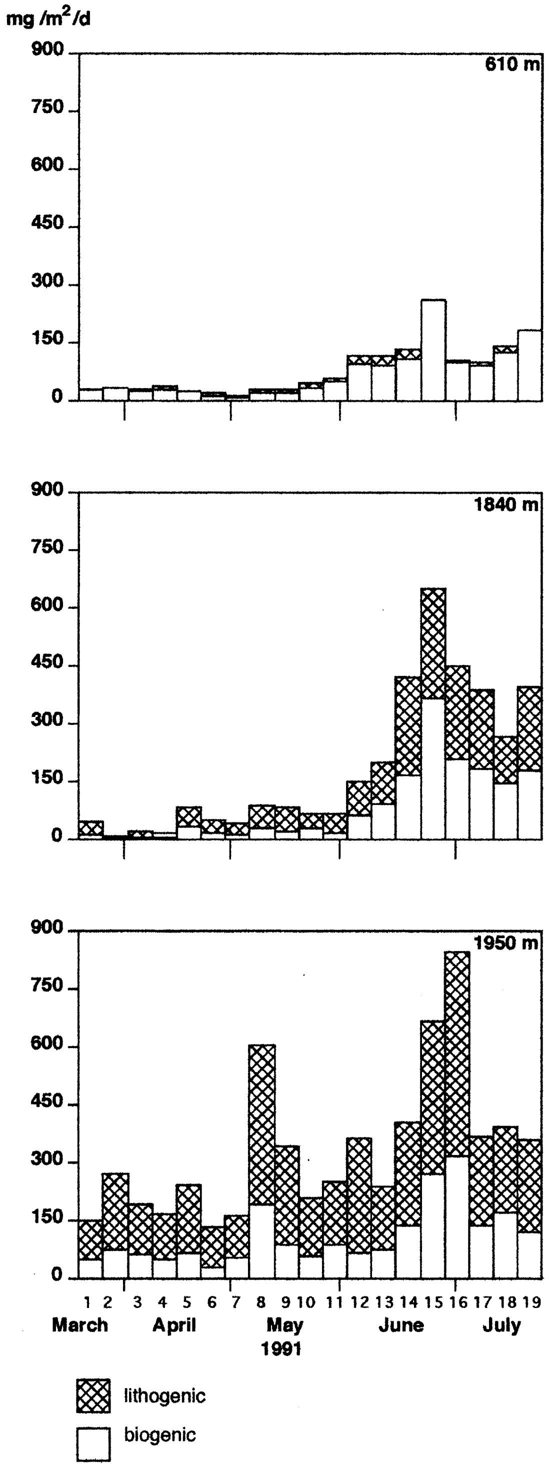

Fig. 2. Biogenic and lithogenic fluxes (in mg m^{-2} d^{-1}) at 610, 1840 and 1950 m at the Barents Sea continental margin (BI-75 11,8′N;12 29,2′E) measured in particulate matter collected with multiple sediment traps between March and July 1991.

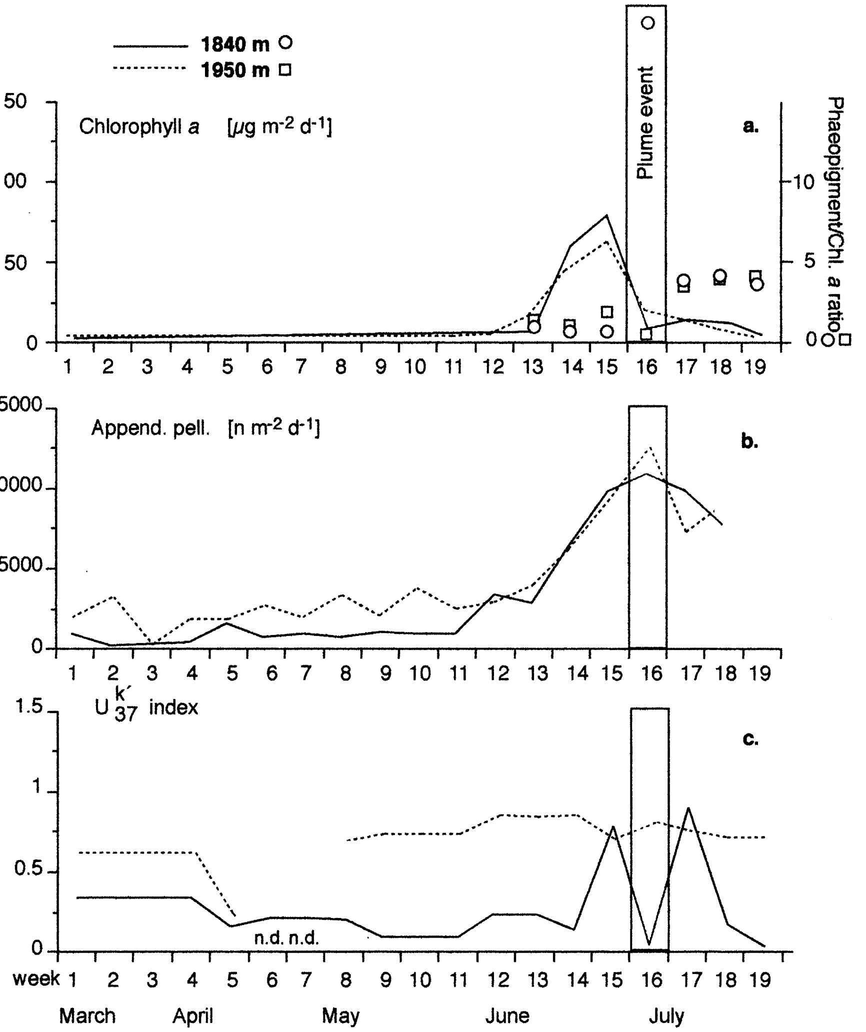

Fig. 3. Biomarker fluxes (a–c) in 1840 and 1950 m at the Barents Sea continental margin (BI-75 11,8′N;12 29,2′E) measured in particulate matter collected with multiple sediment traps between March and July 1991.

sedimentation during week 16 is accompanied with a low Phaeopigment/Chlorophyll a ratio at 1950 m while a ratio >10 was detected in the 1850 m trap. After week 16 the ratio enhanced to similar values in both traps.

4.1.3. Pellets

The number of zooplankton pellets followed the seasonal pattern and were dominated by Appendicularia (Fig. 3b). The faecal pellet production by pelagic grazers during the period of deployment had a significant impact on the vertical flux of carbon to the benthos and contributed 10–40% of the total POC flux. The pellet sedimentation show a seasonal increase starting from week 13 reaching maximum values in the week 16.

4.1.4. $U^{k'}_{37}$

The mean values for the $U^{k'}_{37}$ index (during deployment) were 0.184 at 1840 m and 0.765 at 1950 m depth (Fig. 3c). This results in SST values of 8.3°C and 22.5°C respectively and can not be the result of change in vertical sedimentation alone. A strong variability of the values at 1850 m were detected

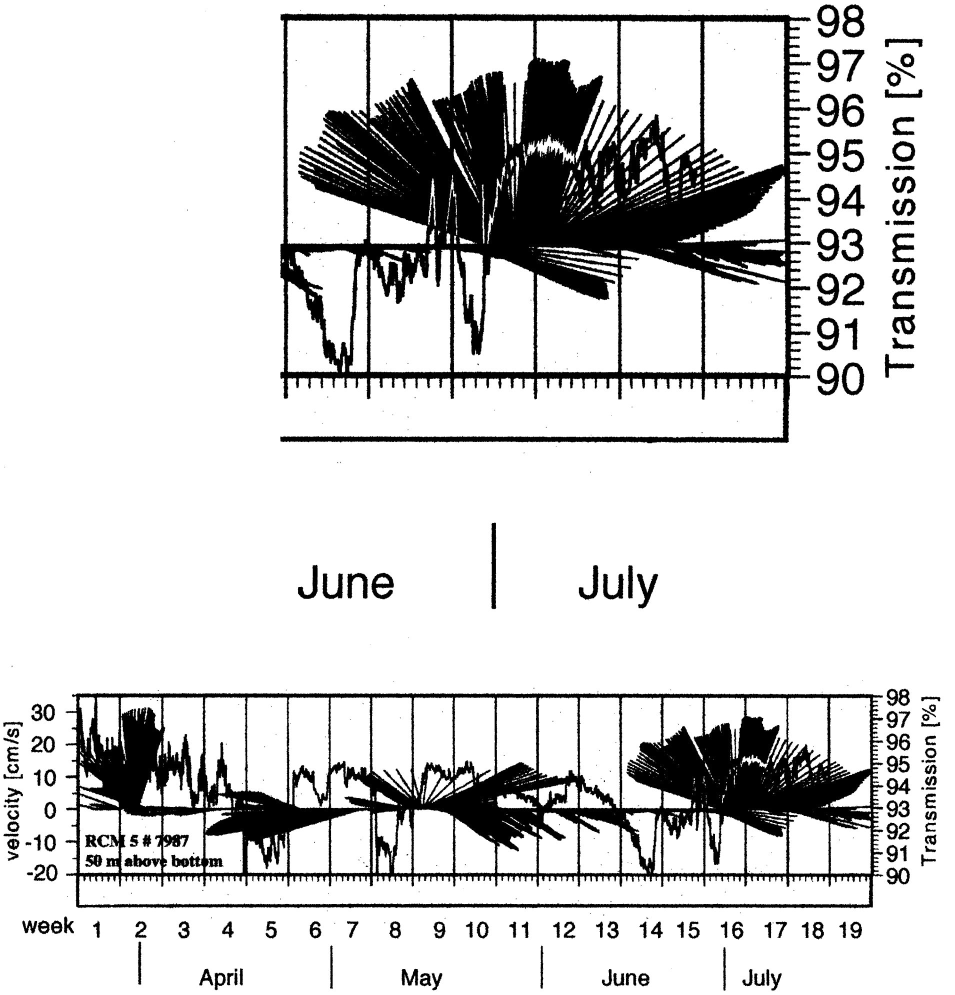

Fig. 4. The flow velocity and transmission at 2000 m water depth. Transmission is shown in % m^{-1} and current velocity in cm s^{-1}.

from the beginning of June, while at 1950 m the values remain almost constant. During the phase of enhanced fluxes of all parameters during June and July the $U^{k'}_{37}$ ratio shows an approximation of the values for both depths during week 15 and 17, interrupted by a drastic decrease to a low ratio in week 16 in 1840 m.

4.1.5. Light transmission and flow velocity

Transmission and flow velocity showed phases of high light transmission with dominant along slope currents which were interrupted by events of cross-slope transport of water-masses of mostly low light transmission (Fig. 4). During 76% of the deployment time the flow velocity was below 20 cm s^{-1}. Especially in summer (week 11–15) flow velocity was <10 cm s^{-1} and mainly directed to the south-east (i.e. parallel to the isobaths). These phases of more moderate currents were interrupted by high energy events with flow velocities 20–30 cm s^{-1}. During the events in April, May and July light transmission first decreases by 1–3% with simultaneously change in current direction. During the second half of week 16 flow direction changed from on-slope (east), off-slope (west) via along-slope (north) to on-slope (east). During these changes light transmission increases again by about 5%.

4.2. Particle flux processes

The particle fluxes at the Bear Island site can be listed in two processes:

1. The vertical seasonal input of fresh material, mainly in terms of a fast sinking pellet pulse followed by phytodetritus and,
2. Additional lateral inputs from the shelf consisting of recently settled material accumulated at the shelf edge transported via plume events.

4.2.1. The vertical seasonal input:

At the beginning of week 14 (Figs. 3 and 4) when the study site was characterized by relatively low current velocities, the decrease in transmission indicates the existence of a BNL of fine particles with low settling velocities. Linked with an increase of the lithogenic fraction all particle fluxes at all depths increased. Low Phaeopigment/Chlorophyll *a* ratios and low $U_{37}^{k'}$ suggests fast sinking aggregates, mainly in the form of pellets dominated the flux. These fast-sinking particles cleared out the water column via aggregation processes through differential settling (McCave, 1986; Hill and Nowell, 1990) resulting in an increase of light transmission close to the seafloor during at the end of week 14 (Figs. 3 and 4). At 1950 m slowly increasing values of all parameters depict the beginning of the maximum sedimentation phase, still superimposed by the BNL signal.

During week 15 the maximum vertical sedimentation took place. Fine particle scavenging in the BNL appeared and a distinct signal of fresh phytodetritus derived from the euphotic zone arriving at 1840 m is shown by the maximum Chlorophyll *a* values. The particle scavenging under low flow conditions results in further increasing light transmission (Hill and Nowell, 1990) again with the low ratio of Phaeopigments/Chlorophyll *a*. During weeks 14 and 15, the maximum vertical summer signal arrived at greater depth.

4.2.2. The lateral particle flux during events

The current velocity -and light-transmission data show times of enhanced off slope currents. Many of these events show no visible change in the flux monitored with the sediment trap deployment. Even the cross slope event during spring (week 5, 6 and 7) is only prefaced of a strong drop of the $U_{37}^{k'}$ signal in 1950 m. During that time off-slope currents $>20\ \mathrm{cm\,s^{-1}}$ combined with light transmission data around 95% $\mathrm{m^{-1}}$ coincide. Even though for the period of May small coccolithophorid blooms have been reported for the Barents Sea Shelf (Samtleben et al., 1995) the fluxes of the bulk parameters are low during deployment and neither CPE nor Appendicularia pellets showed higher values. Due to the low fluxes at the 1950 m trap, it is therefore suggested that the event during weeks 5, 6 and 7 refers to a cold water cascade entering the Norwegian Sea as reported by Honjo et al. (1988, 1990).

The event at the end of the main sedimentation in June/July is different from the smaller event in the spring.

In July (weeks 14, 15) low flow velocities and increase of light transmission is coupled with maximum sedimentation in the bottom near traps followed by low light transmission/low current velocities to increased light transmission/high flow velocities during the postulated plume event at week 16. Focused on these three weeks (Figs. 3 and 4) the following course of events appeared:

During week 14 the light transmission decreased from 94 to 90% $\mathrm{m^{-1}}$. At that time the flow was east–south–east directed with flow velocities $\ll 10\ \mathrm{cm\,s^{-1}}$. At the 1840 m trap CPE flux increase intensively along with a decrease of the $U_{37}^{k'}$. At 1950 m depth values of all parameters started to increase.

During week 15 moderate light transmission of 93% $\mathrm{m^{-1}}$ and flow velocities below $<10\ \mathrm{cm\,s^{-1}}$ were coupled with maximum sedimentation of the bulk parameters at all depths (Fig. 2). The ratio of Phaeopigments/Chlorophyll *a* showed minimum values. At 1840 m the ratio of Phaeopigments/Chlorophyll *a* changed to values below one, indicating the arrival of fresh and labile organic carbon. The $U_{37}^{k'}$ value at 1840 m showed increased values, coupled with a decrease in 1950 m resulting in a similar $U_{37}^{k'}$ value in vertical flux material in both traps.

During week 16 an intense event of down-slope transport of fine material took place. The flow velocity exceeded 30 $\mathrm{cm\,s^{-1}}$, while the flow direction changed by nearly 180° from west–north–west to east–south–east. Simultaneously the light transmission was

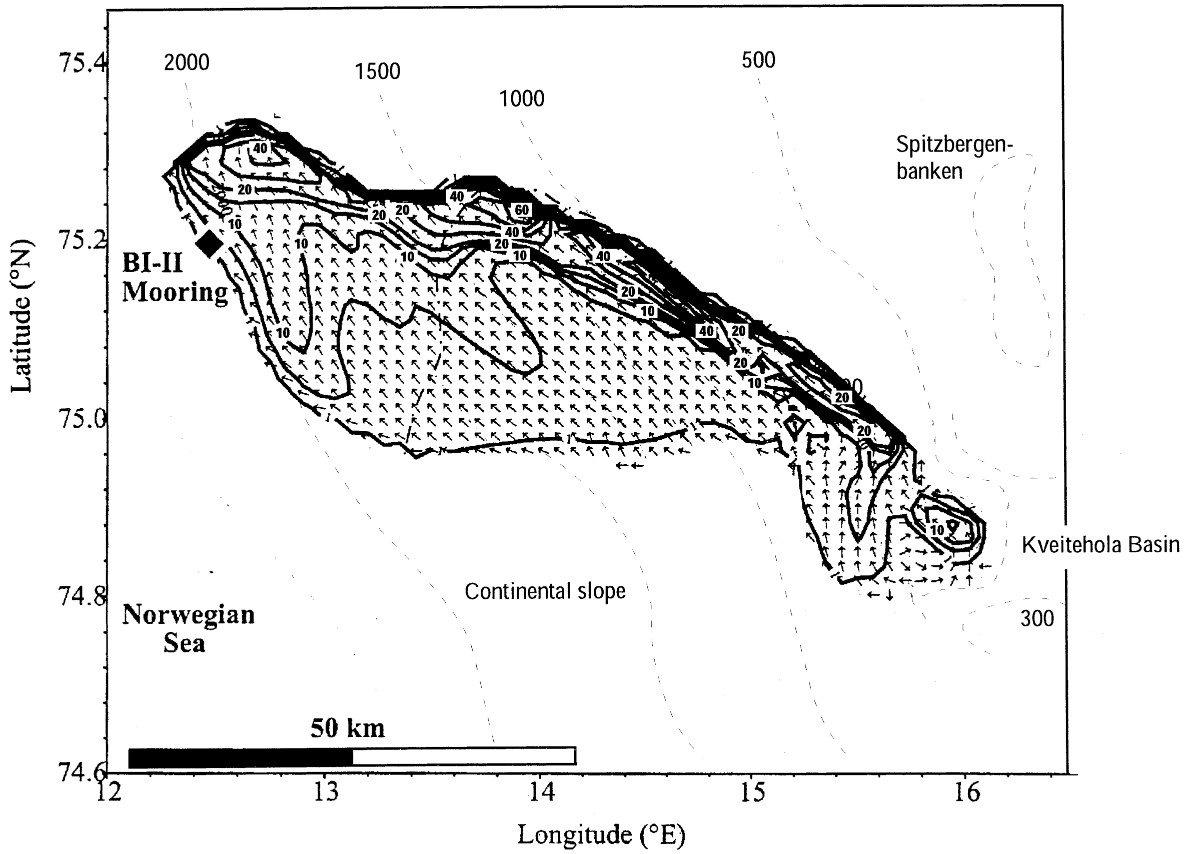

Fig. 5. Simulation of plume event. Plume height (m) is given with contour interval 1, 5, 5–20, 10–60 m. Arrows indicate flow direction relative to the slope. Additionally area of fine grained particles accumulation is marked.

reduced to values $<91\%\ \mathrm{m}^{-1}$, follwed by an increase above $95\%\ \mathrm{m}^{-1}$. The mass fluxes at 610 and 1840 m decreased considerably, indicating the final stage of the spring/summer vertical mass flux. However, via the plume event an additional lateral particle flux of resuspended material from the shelf occurred, resulting in peak fluxes of particulate matter in the 1950 m trap. The Appendicularia pellets peaked at both depths (Fig. 3c). The maximum amount of Appendicularia pellets in the 1950 trap despite low bulk fluxes (Figs. 2 and 3) is a first indicator for the additional source of the incoming lateral signal. The compositions of the $U^{k'}_{37}$ distributions and Phaeopigments/Chlorophyll *a* ratio in the two bottom near traps differ significantly. This difference cannot be the result of a change of the vertical sedimentation alone.

4.3. The lateral input via a turbidity plume event

It is postulated that the lateral transport process during summer took place via a turbidity plume event.

In the following, the numerical plume model of Fohrmann et al. (1998) for 20 and 63 (m particles was applied for the prognosis of the plume event in week 16. In contrast to a pure TS plume (Jungclaus and Backhaus, 1994), a sediment transport turbidity plume is by virtue of its particle load more energetic, even at comparatively low concentrations of suspended sediments (Fohrmann et al., 1998; Kämpf and Fohrmann, 2000). In the numerical model prognostic equations for the vertically integrated height of the flow, the velocity compounds *u*, *v*, temperature *T*, salinity *S* and the concentration of suspended particles

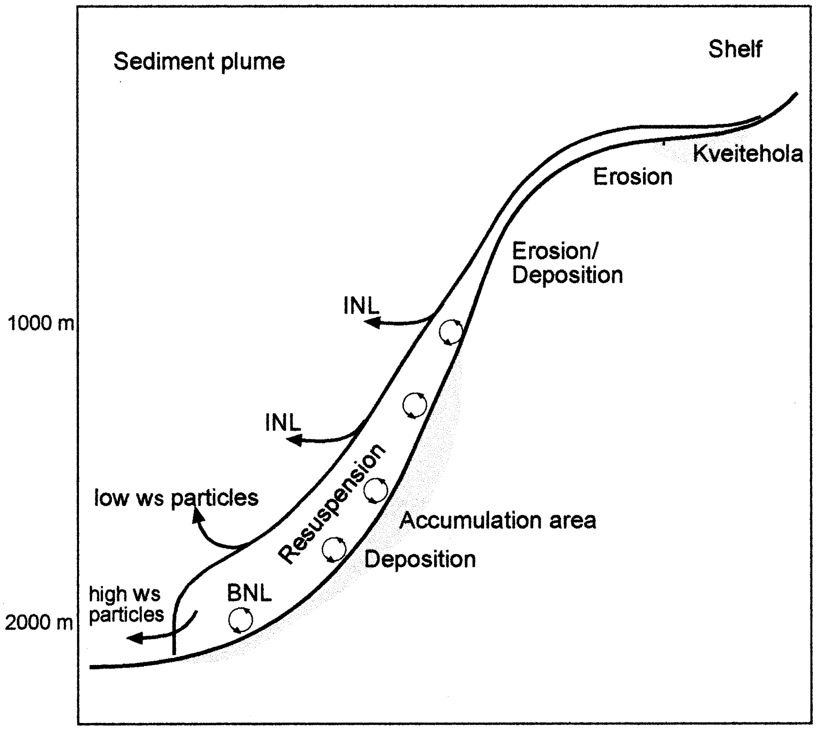

Fig. 6. Postulated hydrodynamic sorting of material during the plume event.

C_i of the respective grain sizes were solved. Depending on the flow velocity, particles can be eroded, transported and differentially deposited. The critical velocities for erosion and deposition of the two different sediment types were taken from laboratory experiments (Unsöld, 1984). The settling velocities of the particles were calculated after Stokes, but the deposition rates include concentrations, flow height and the mean settling distance, depending on the probability of the particles to settle. The sediment distribution at the seafloor and the initial particle concentration at the inflow ($C = 0.03\ \mathrm{kg\,m^{-3}}$, density contrast $(S, T, P, C) = 0.01\ \mathrm{kg\,m^{-3}}$, flow height $H = 20$ m and velocity $0.1\ \mathrm{m\,s^{-1}}$) were chosen following measurements, bathymetry, and numerical experiments from the study site as a result of 5 yr observations (Fohrmann et al., 1998).

In Figs. 5 and 6 the results of a simulated plume event are shown:

Originated from the existence of high density bottom-water masses due to high particle concentrations in the Kveitehola trough at the shelf edge around week 16, which suddenly is released across the shelf edge, the plume cascades from the Kveitehola valley into the deep Norwegian sea. Within the first two days of this simulated event, the plume descends the continental slope to a depth of about 2000 m with velocities up to $1\ \mathrm{m\,s^{-1}}$. At a water depth of about 1400 m the sediment is dominated by the particle size fraction 20–63 μm and indications for high resuspension load in the BNL is given due to attenuation measurements (Fohrmann et al., 1998). Crossing this area the plume can deposit its suspended load or resuspended particles. During the measured velocities up to $30\ \mathrm{cm\,s^{-1}}$, the plume reaches the position of the sediment trap mooring. The central part of the plume has a height of approximately 60 m and the flow velocities are in the order of 10–20 $\mathrm{cm\,s^{-1}}$. In this part of the plume mainly resuspended sediments are transported with a high $U^{k'}_{37}$ signal. However in the upper part of the plume fine particles of low settling velocities are transported reaching more than 100 m into the water column. Overall it is a lower flux of particles (Fig. 3) entering the sediment trap in this height above seafloor, but the material has the imprint of shelf material carrying coccoliths as reported for upwelling areas by Dickson and McCave (1986). The flow direction within the plume, modeled and verified with the current meter of the mooring; shortly before and during the time when the front of the plume-head passes the mooring the flow is upward directed. While the main plume passes the mooring, the flow is generally parallel to the slope. At the end, the back part of the plume moves in an up slope direction.

HPLC pigment measurements show similar degradation stages (low Phaeopigment /Chlorophyll *a* ratio) of the surface sediments chlorophyll signal in August 1991 in 1400 and 2050 m depth. The supply of phytodetritus on a similar time scale again indicates the existence and discussed progress of the plume event (L. Thomsen et al., 1995; Walsh, 1989).

The numerical plume in comparison with the biomarker flux proves the theoretical proceeding of the turbidity plume.

Highest particle fluxes with highest lithogene content of the total mass flux at 1950 m (Fig. 2) after the major bloom sedimentation are strong indicators for the plume event. A sharp decrease of the Phaeopigments/Chlorophyll *a* ratio below 1 and the maximum particle flux at 1950 m water depth indicate an incoming signal of rebound labile carbon of high settling velocities (L. Thomsen and van Weering, 1998). Additional evidence for that is given by the processes occurring at 1840 m. At that depth the total mass flux has decreased again but the peak Phaeopigment/Chlorophyll *a* ratio indicates the input of material of already advanced decomposition and is consequently different from the trap below. The lowest $U_{37}^{k'}$ signal of the material settled during deployment in contrast to the high signal in 1950 m reveals that the material originates from water masses of water temperature below of 6°C, as reported for the Kveitehola area east of the Bear island front. The progression of the plume with its upward directed flow components would transport material of low settling velocities at this height above sea floor. It is therefore suggested that fine, resuspended and disaggregated phytodetritus including coccolithophores have been transported on the upper side of the plume by hydrodynamic sorting and settled into the 1840 m trap. Indications are given that due to hydrodynamic sorting (Middleton and Southard, 1984; Ritzrau and Fohrmann, 1998) during the plume event (Fig. 6). Fine particles were advected into the trap at 1850 m, whereas the coarser fraction of higher settling velocities, passing several resuspension loops entered the lower trap.

C. Thomsen et al. (1998) assume that within particles undergoing long residence time in resuspension loops the originally imprinted SST signal can be altered. In addition the signal depends on the origin of the particle. Rosell-Melé and Comes (1999) discuss that the occurrence of anomalously high $U_{37}^{k'}$ SST estimations at the study site might be influenced by the organic-rich sediments of pre-Quaternary origin in the Barents Sea. These sediments would be transported down slope via the here discussed plume event.

There is evidence that the described mid slope area with high contents of fine particles (Fohrmann et al., 1998) acted as an additional source for the further progression of the turbidity plume which transported material down-slope into the Norwegian Sea. Further important processes are scavenging (Biscaye and Anderson, 1994) and aggregation (McCave, 1984; L. Thomsen and McCave, 2000). Fast down-slope transport of organic carbon at continental margins has been postulated for the mid Atlantic Bight by Biscaye and Anderson (1994); Walsh and Gardner (1992), for the Celtic Sea by Pingree and LeCann (1989) and L. Thomsen and van Weering (1998) and for the western Mediterranean by Monaco et al. (1990).

5. Conclusion

Aim of the study was to demonstrate first evidence that cross-slope lateral particle export during the growth season of phytoplankton can sweep freshly settled pelagic material from the shallow Barents Sea into the deep Norwegian Sea during a plume event. This data interpretation was accomplished by a combined study on biomarker analyses, quantitative microscopy and bulk parameter determinations on water and sediment trap samples.

During the deployment a pre-phytoplankton bloom situation was detected until mid-May, followed by an increasing sedimentation with a mid-June maximum and a phase of decreased fluxes during July.

Turbidity and flow velocity showed phases of high light transmission with dominant along slope currents which were interrupted by events of cross-slope transport of water masses of mostly low light transmission.

In July (weeks 14, 15) low flow velocities and an increase of light transmission was coupled with maximum sedimentation in the bottom near traps followed by low light transmission/low current velocities to increased light transmission/high flow velocities during the postulated plume event at week 16.

Originated from the existence of high density bottom-water masses due to high particle concentrations in the Kveitehola trough at the shelf edge around week 16, which suddenly was released across the shelf edge, a plume cascaded down the continental slope to a depth of about 2000 m with velocities up to 1 m s^{-1}. During this event fine particles were advected into the trap at 1840 m, whereas the coarser fraction of higher settling velocities, passing several resuspension loops entered the lower trap at 1950 m.

The data and discussion presented here should be noted as an approach to understand distinct processes acting at high dynamic continental margins. The importance of lateral advection at these sites, especially for ocean-margin exchange processes has already been discussed in the literature, but could not been directly proofed. Almost all continental slopes display abundant evidence of slope failure and mass movement in debris flows. It is likely that such slope failure leads to formation of sediment flows, which become turbidity currents and which in turn erode gullies like the Kveitehola, which may later grow into a canyon. These trough and canyon systems form an extreme environment, seen in the fact that an actual transfer of particles from the shelf and shelf edge most likely takes place during short duration events. Numerous troughs and canyons dissect the European upper slope and shelf edge. These features will be studied in much greater detail in the future.

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