doi:10.5697/oc.54-2.325
OCEANOLOGIA, 54 (2), 2012.
pp. 325–335.

A huge biocatalytic filter in the centre of Barents Sea shelf?*

KEYWORDS
Permeable sediments
Pelago-benthic coupling
Svalbard
European Arctic

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Received 18 October 2011, revised 6 February 2012, accepted 27 March 2012.

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* The present paper was based on the BANKMOD bilateral Norwegian – Polish projects (NFR 184719) and was completed thanks to additional financial support from the Polish Ministry of Science and Higher Education (384/W-Bankmod/2009/0 and 382/W-Akvaplan-niva/2009/0).

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Abstract

A primary production model for the Barents Sea shows a hot spot of organic carbon settlement to the sea bed over 100 km long, a shallow pile of highly permeable sediments (mainly large *Balanus*, *Mya* and *Pecten* shell fragments over 1 cm in size) of glacial origin. Hydrodynamic flow models suggest an intensive, deep flow of near-bottom waters into the sediment. Depending on wave height, water in shallow (30 m depth) places may percolate more than 5 m into the sediment. During 10 days of stormy weather as much as 4 to 8 kg wet weight pelagic biomass can be processed per square metre through this extremely permeable sediment. Analogous processes known in coastal waters lead to intense biocatalytic phenomena and metabolism of organic carbon within the seabed, estimated here as more intense than surface consumption. Spitsbergenbanken may be acting as a huge sink for organic carbon and an important source of nutrients in one of the most productive areas of the North Atlantic.

1. Introduction

The frontal zones of the subarctic North Atlantic and specifically the Barents Sea belong to the most productive marine areas in the world ocean (Sakshaug & Slagstad 1991, 1992, Sakshaug 1997). A recently developed Nordic Seas hydrodynamic model containing a primary production module (Wassmann et al. 2010) shows a large area of organic carbon sedimentation to the seabed south of Svalbard. Annual fluxes to the seabed were estimated at over 40 g C m^2 $year^{-1}$ over the entire Svalbardbanken with some locations reaching 200 g C m^2 $year^{-1}$ (Sakshaug 1997). However, this rich food supply is not reflected in the accumulation of carbon in the sediment or in the benthic biomass (Sakshaug & McClimans 2005, Renaud et al. 2007).

The post-glacial Svalbardbanken is an elongated (300 × 50 km) structure that rises from the Barents Sea bed and in places is as shallow as 30 m (Figure 1). Its surface is covered with loose carbonate material – barnacles (*Balanus balanus*) and molluscs (*Mya truncata*, *Hiatella arctica* and *Pecten* sp.) – the shell fragments being mixed with very coarse sand and gravel (Elverhøi & Solheim 1983). On the shallow Spitsbergen Bank (30–100 m depth) high-energy facies of carbonate sand and gravel were dated: the barnacle remains are 2–3 thousand years old (Bjorlykke et al. 1978). Similar calcareous sediments are also known from Troms district, Norway (Elverhøi & Solheim 1983, Freiwald 1998). The thickness of the permeable layer is not well described in the literature: it is certainly thicker than 1 m and, according to unpublished Russian sources, is more than several metres thick in some places (G. A. Tarasov, Murmansk Marine Biological Institute, personal communication).

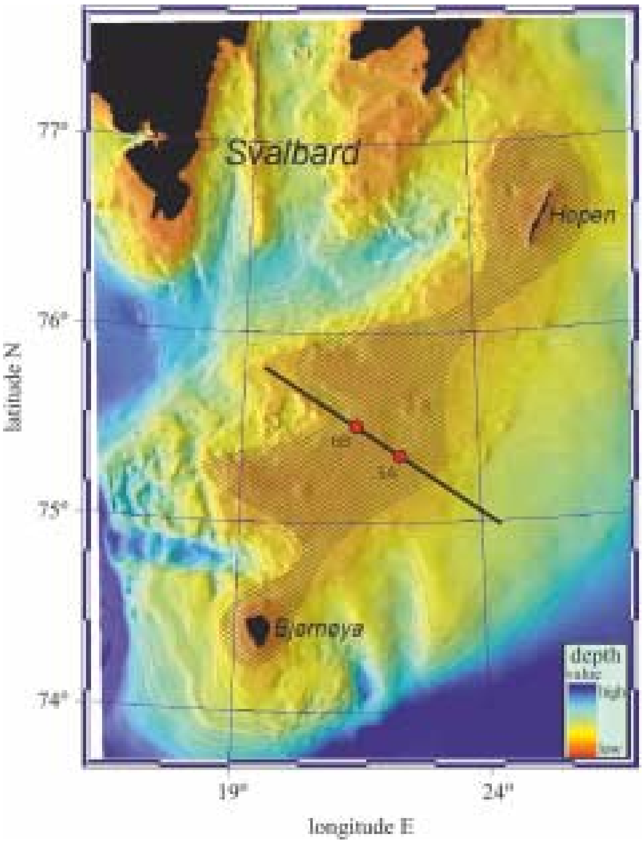

Figure 1. Svalbardbanken (Spitsbergenbanken). The shaded area shows the seabed covered with highly permeable sediments (shell and gravel areas according to the map in Elverhøi & Solheim 1983). Transect and sampling points 5a and 6b marked (Table 1)

Below we present for the first time an assessment of the part played by a permeable sediment bank in pelago-benthic coupling in the Barents Sea.

2. Material and methods

Material was collected in August 2009 during a cruise of r/v 'Oceania' to Svalbardbanken as part of the BANKMOD project. Hydrographic measurements were performed with a towed Seabird FastCAT SBE49 CTD system. Sediment and benthos samples were collected with a Van Veen grab and a triangular dredge. Table 1 presents the sediment characteristics from two stations where permeability was measured. The epifaunal wet weight exceeded 150 g m^{-2} at each site, and sediment organic matter content (loss on ignition) was $< 0.3\%$. Permeability was measured on

Table 1. Svalbardbanken, August 2009, sediment sample characteristics. The mean surface sediment grain (broken shells) diameter was 20 mm at both sites

Station No. Longitude Latitude	Depth [m]	Sediment type	Dominant benthic fauna	Porosity (void fraction)
5A 75.35.000 N, 22.35.000 E	66	shells, stones and gravel	*Strongylocentrotus*, *Hydrallmania falcata*	39%
6B 75.50.239 N, 21.44.679 E	42	shells, stones and gravel	*Alcyonidium*, *Eucratea*	39%

sediment samples from the grab, according to the method described in Kluke & Dirksen (1986), on board and then again under laboratory conditions. For comparison, we measured the permeability of Baltic clean quartz sands (fine – 0.1 mm, medium – 0.4 mm and coarse-grained 0.6 mm) on the same equipment. The hydrodynamic benthic boundary flow was modelled on the basis of formulas by Massel (1999) and Massel et al. (2004, 2005), and was run for assumed permeable layer thicknesses of 5 and 20 m, as well as two grain sizes (0.9 and 20 mm) for a horizontal seabed.

3. Results and discussion

The permeability of the sediments was measured (Figure 2); its values (4.28×10^{-10} m^{-2}) are well above the permeability of comparable Baltic sands and well-studied sands from European waters or the Mid-Atlantic Bight (MAB) (Rush et al. 2006). The hydrodynamic (Slagstad & McClimans 2005) and tidal (Kowalik & Proshutinsky 1995) models show very intense dynamics and important atmospheric drivers (waves, surface

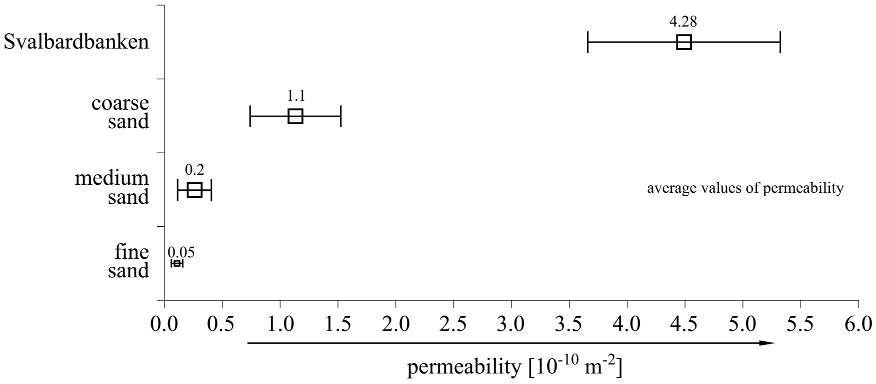

Figure 2. Mean values, SD and ranges of measurements of permeability of porous sediments – Baltic quartz sands and Svalbardbanken carbonates. Permeability expressed in 10^{-10} m^{-2}

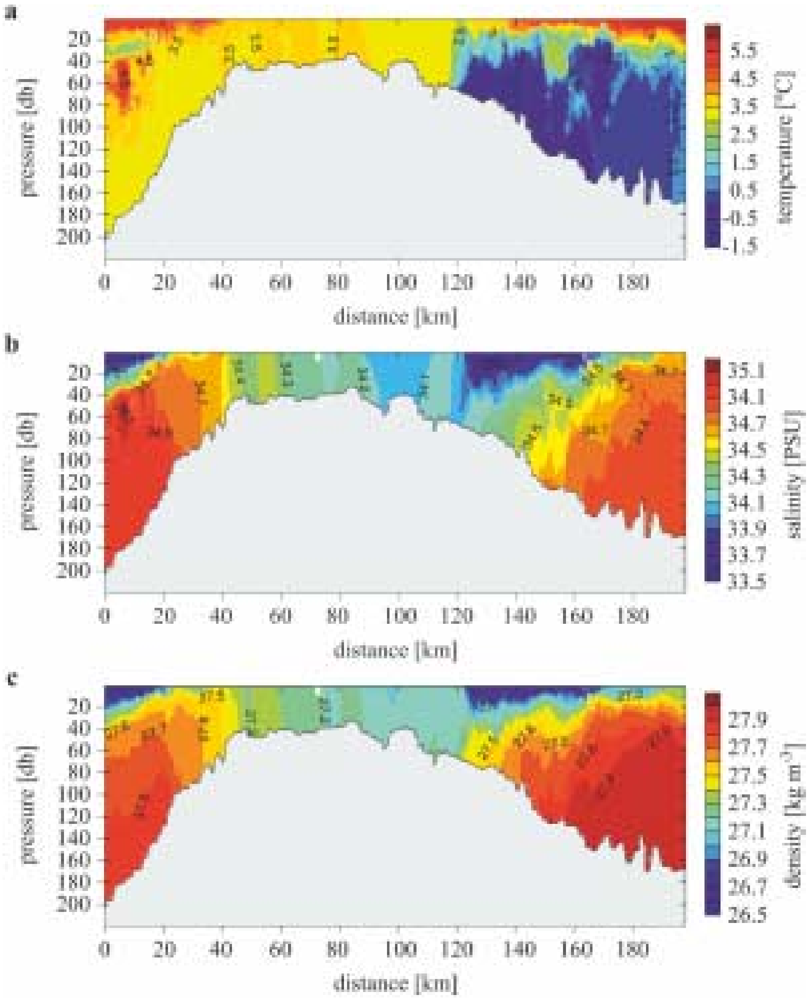

Figure 3. Hydrological cross section (as in Figure 1) over Svalbardbanken, August 2009; temperature (a), salinity (b), density (c)

and tidal currents, eddies and oceanic fronts) dominating the top of Svalbardbanken. The circulation over Svalbardbanken was previously modelled by Adlandsvik & Hansen (1998). In situ hydrological measurements taken in August 2009 showed typical settings with warmer, transformed Atlantic Water washing the NW part of Svalbardbanken and cold, Barents Sea Arctic waters on its SE side. On the top, well mixed, relatively warm and less saline local waters predominate (Figure 3), much like the situation known from the literature (e.g. Sakshaug & McClimans 2005).

The benthic boundary model shows that during average storms, water percolates through the coarse sediment to a depth of a few metres (depending on the assumed thickness of the permeable layer). Our estimate shows that during stormy weather as much as 8160 to 15 912 m^3 m^{-2} day^{-1} of water passes through the upper 5 metres of the shell pit at respective water depths of 50 and 30 m (Table 2). This downward flow makes possible the deep aeration of sediment and the transport of fine particles deep into the seabed. An equal volume of water leaves the sediment as compensation for the downward flow. In effect, each surface sediment layer is washed twice in a cycle, unless this flow washes the sides of the bank. A particle movement model through a permeable sediment was described by Huettel et al. (1996) and Rush et al. (2006). Besides the hydraulic pressure of waves, the second mechanism that may be responsible for circulation in the porous layer in Svalbardbanken involves tidal currents and bottom Ekman layer formation. Tidal forcing was modelled by Kowalik & Proshutinsky (1995), who found residual currents of 8 cm s^{-1} over Spitsbergenbanken. The model by Massel et al. (2004, 2005) was constructed for a uniform, geostrophic flow in a homogeneous fluid over a flat porous bottom. An additional effect may be sea bed roughness, which increases turbulent mixing; according to Reidenbach et al. (2010), a cobble bed increases mixing and downstream transport 7.5 times compared to a smooth surface. Other models of water flux forced by gravity waves were produced by King et al. (2009); they show a ca 0.3 m deep penetration of water into the sediment, which is consistent with the data obtained for fine coastal sands in the Baltic Sea (Massel et al. 2004).

In view of measured and modelled spring and summer concentrations of microplankton biomass (0.05 g ww m^{-3} – Piwosz et al. 2009) and a flow rate into the sediment of between 8160 and 15 912 m^3 m^{-2} day^{-1} (Table 2), it is estimated that during 10 days of stormy weather as much

Table 2. Total discharge of flow in the porous layer due to wave motion, for the assumed values of porous layer thickness, wind velocity and grain size. The mean volume of water circulating in the porous layer was modelled according to Massel et al. (2004, 2005)

Depth [m]	Thickness of porous layer [m]	Wind velocity [m s^{-1}]	Fetch [km]	Flow through 0–5 m thick porous layer [m^3 $hour^{-1}$ m^{-2}]; in parentheses [m^3 day^{-1} m^{-2}]	Grain size [mm]
30	5	15	200	663 (15912)	20
30	20	15	200	3.8 (91.2)	1
50	5	15	200	340 (8160)	20
50	20	15	200	0.015 (0.36)	1

as 4 to 8 kg of pelagic biomass wet weight passes through each m^2 of Svalbardbanken sediment (Table 2). The figures suggest that the site under examination is an extremely active filter system, important for recycling nutrients and sustaining regional primary production rates. A similar role of permeable shallows was postulated for temperate shelf environments (Huettel et al. 1996, Ehrenhauss et al. 2004). A number of studies on the mineralization of organic matter in permeable sediments have been performed in coastal and very shallow waters (Huettel et al. 1996, Rush et al. 2003, 2006): all of them indicate that the intensity of organic matter metabolism depends on the intensity of oxygen flow through porous media. Apart from building up the biomass of interstitial organisms, organic carbon processing in the sediments provides the surrounding waters with regenerated nutrients (Huettel et al. 1996). Flow through the permeable sediment in the offshore banks of the Gulf of Mexico is an important source of nutrients and bioavailable iron for the whole region (Gibbes et al. 2008). There are three main pathways along which organic matter can be oxidized in the sediment – abiotic, microbial, and indirectly through meiofauna (Opaliński et al. 2010). In cold water (in the Baltic in winter) the abiotic oxygen consumption drops to near zero, whereas in summer it is ca 50% with the microbial part being ca 8% (Opaliński et al. 2010). Piepenburg et al. (1995) found that over the Barents Sea shelf, as much as 68% of oxygen is attributable to sediment microbes, and that the benthic requirement for carbon ranges from 10 to 40% of that of local primary production. The carbon requirement of shelf sediments in the Arctic Beaufort Sea was estimated at 60% of new production (Renaud et al. 2007).

The importance of the microbial oxidation of organic matter in permeable sediments is emphasized by many authors (e.g. Gihring et al. 2009). In the coarse sediments of the North Sea, the meiofauna responds rapidly to the organic supply, yet bacteria dominate respiration (Franco et al. 2008, 2010). In sands, low standing stocks mean a rapid turnover due to advective interfacial flow and microbial populations (Rocha 2008). Respiration and denitrification rates in MAB aerobic denitrifiers (Rao et al. 2008) were 34 times faster than molecular diffusion, and up to 17% of the integrated mid-shelf water column production is recycled annually below the sediment surface there (Jahnke et al. 2005). Algal cells were present to a depth of 11 cm in MAB sediments and were metabolized as intensely as in coastal waters (Rusch et al. 2003). An estimated volume of 1 m^3 m^{-2} day^{-1} was pumped through the top 10 cm of sands in MAB (Reimers et al. 2004), which was calculated by Rush et al. (2006) as contributing 'significantly to the cycling of carbon and nutrients in the shelf environment'.

Part of the primary production that falls to the Svalbardbanken seabed goes through the high biomass of large, erect filter feeders (bryozoans, sponges, sea squirts and bivalves) that are able to capture food above the seabed (Idelson 1930). The species composition, distribution and density (present authors, in prep.) was almost identical to the previous study by Idelson (1930) from this area nearly 80 years ago. That author also noted that the abundance of epifauna and filter feeders on Svalbardbanken was the result of strong currents and the amount of detritus available.

In summary we suggest that sediment coarseness and flow intensity most likely create the opportunity for the intensive metabolism of organic carbon within the Svalbardbanken sediments. This particular area (ca 16 000 km^2) acts as a huge, three-dimensional converter, probably capable of processing a significant part of the primary production below the seabed surface and enriching the surrounding waters with regenerated nutrients. Direct measurements of flow in local sediments and of metabolic activity in pore waters are needed, although it has to be borne in mind that this may be technically difficult, as no conventional sampler is capable of penetrating the shell/gravel sediment to this depth in order to collect the interstitial water intact.

Acknowledgements

We thank W. Ambrose, P. Kukliński, P. Bałazy and the officers and crew of the r/v 'Oceania' for their assistance at sea. We thank especially Prof. Stanisław Massel, who provided numerical simulations, and Dr K. W. Opaliński helped a lot in the final shaping of the discussion and the present version of the manuscript.

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