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# Sediment supply and fluxes in glacial and outwash fjords, Kongsfjorden and Adventfjorden, Svalbard

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**Abstract**: The buoyant hypopycnal flow of brackish water and suspended sediment transport and settling were studied in two sub-polar fjords: the glacial Kongsfjorden and the outwash (non-glacial contact) Adventfjorden, Svalbard. The data presented indicates faster water mixing on the tidal flat in comparison to the englacial runoff, which leads to faster horizontal density gradients decreases in the non-glaciated fjord. The fast settling of particles in the narrow zone of the steep slope at the edge of the tidal flat leads to the removal of 25% of the surface suspended sediment. The rapid settling is due to increasing salinity, decreasing velocity, and flocculation of fine particles. The fast settling of suspended particulate matter (SPM) in the tidal flat area causes sediment redeposition and resuspension followed by sediment transport along the bottom with hyperpycnal flows. This leads to grain sorting in the fjord head. In contrast, at the glacier front, SPM is transported farther into the fjord, where tidal pumping and water mixing lead to the removal of 71% of total SPM. The fjords investigated represent two different sedimentological regimes. In the glaciated Kongsfjorden, the buoyant hypopycnal flow of brackish water is the main sediment transporting factor. In the non-glacial Adventfjorden, hyperpycnal flows transport sediment along the bottom.

Key words: Arctic, Spitsbergen, subpolar fjords, meltwater, sediment flux, turbidity currents, hypopycnal flow.

## Introduction

Due to their northern location, fjords are sensitive to changes in climate, therefore, they can provide scientists with important information on the effects of contemporary environmental changes. The sensitivity of fjord environments stems from both the interference and buffer between glaciated land and the ocean (Syvitski and Shaw 1995). Fjords are supplied intensively with turbid meltwater, which causes well-developed environmental gradients. Therefore, they can be viewed as estuaries in which additional sediment delivery from the continental shelf is less abundant in comparison to other types of estuaries (Syvitski and MacDonald 1982).

Fjords were formed during repeated glacial advances and retreats during the Quaternary, and, in many cases, they were glaciated more recently; for example, during the climate cooling of the seventeenth century. Climate warming that has been observed recently has led to renewed glacier retreat, which is especially apparent in oceanic frontal areas. One example of fast glacier retreat is the Svalbard Archipelago (European Arctic), were the western coasts of the largest island, Spitsbergen, are warmed by the West Spitsbergen Current, which forms a polar front with the cold Barents Sea water masses. This process leads to essential changes in glacier position from being tidewater to land terminating. In a glacial fjord, sediment is supplied directly from a glacier terminus by subglacial or englacial meltwater outlets. When glaciers retreat beyond the seashore, outwash sediment is partly deposited in the proglacial area and partly transported to the sea by glacifluvial rivers, which often form deltas and tidal flats at their mouths.

The purpose of this paper is twofold: (1) to define dynamics of the turbid meltwater plume and to examine factors controlling sediment spread in glacial and outwash fjords, and (2) to examine the settling of suspended sediment in relation to the turbid water plume. The present paper aims to verify the assumption that a glacier terminus shift from a tidewater position to land terminating changes the sedimentological regime in the fjords. Two Spitsbergen subpolar fjords were chosen for the study: the glacial Kongsfjorden, were most of sediment is supplied by the englacial outflow of Kongsbreen, and the non-glacial Adventfjorden, which was finally deglaciated at the beginning of the Holocene.

## Study area

**Kongsfjorden**. — Kongsfjorden is located in the northwest of Spitsbergen between 78°52' and 79°04' N and 11°20' and 12°36', and is oriented from the southeast to the northwest. The length of Kongsfjorden is about 20 km, and its width varies from 4 km in the fjord head to 10 km at the mouth between Kvadehuken and Kapp Guissez.

The inner fjord (glacial bay) is well marked by the line of the islands of Lovenoyane and Blomstrandoya with relatively shallow water less than 100 m deep and many basins and shallows. The central part of fjord consists of a submarine hollow more than 400 m deep. The bottom of the fjord mouth is less than 300 m deep and converges into the deeper basin of Kongsfjordrenna.

In Kongsfjorden, there are four fjord-locked tidewater glaciers. Kronebreen and Kongsvegen form the largest and most active front named Kongsbreen (Lefauconnier *et al.* 1994). Kongsbreen is a glacier active throughout the year with the peak meltwater season in July, when the outflow of meltwater reaches 138 $m^3$ $s^{-1}$ (Zajączkowski and Legeżyńska 2001). Kongsbreen meltwater is delivered to the fjord directly from the ice cliff by the englacial outlet. The other two glaciers,

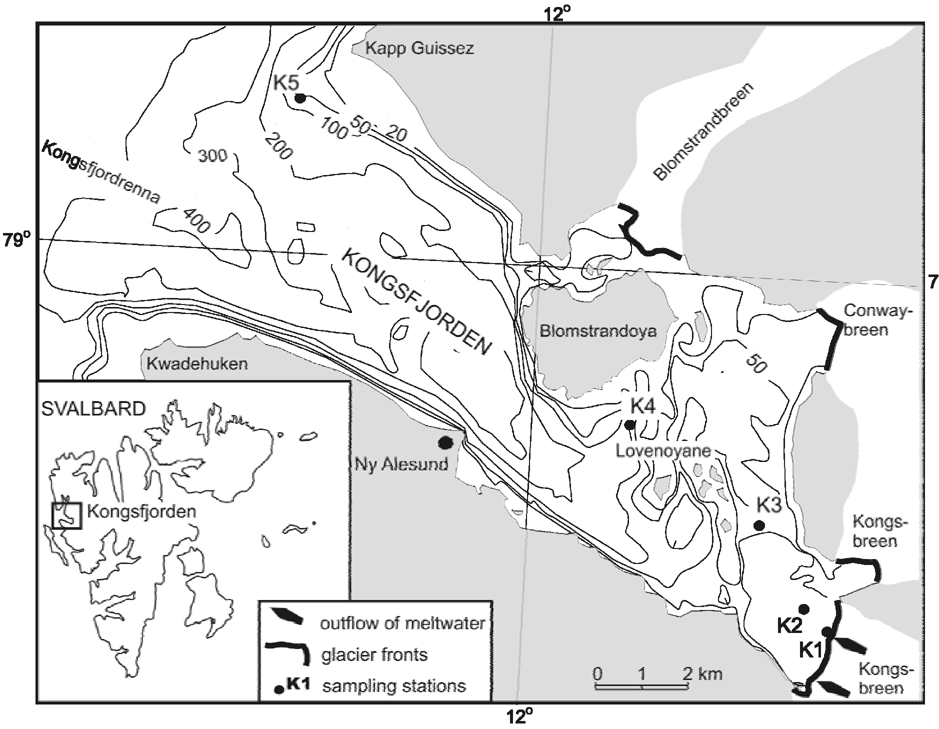

Fig. 1. Kongsfjorden study area.

Blomstranbreen and Conwaybreen, are not so active, and their outlets transport considerably less turbid meltwater (Svendsen *et al.* 2002). According to Beszczyńska-Moller *et al.* (1997), all glaciers together release 0.33 km$^3$ of meltwater per year into Kongsfjorden and the Kongsbreen calving rate reaches 0.25 km$^3$ of ice per year (Lefauconnier *et al.* 1994).

**Adventfjorden**. — Adventfjorden is one of the southern arms of Isfjorden located in the central part of the west coast of Spitsbergen. This bay is 8.3 km long and 3.4 km wide and is positioned between 78°13' and 78°17' N and 15°25' and 15°46' E, oriented southeast to northwest.

In the innermost part of Adventfjorden there is a tidal flat that is 0.7 km wide during ebb tides. The submarine steep slope ending at the tidal flat inclines at 16–18° and then descends to a depth of 70 m in the central fjord (slope inclination 7–8°) and eventually to more than 100 m in the mouth of the fjord (slope inclination 1°). The mouth of Adventfjorden is wide and open, and the bottom goes down to the central part of Isfjorden. The fjord receives turbid water from two braided rivers, the Adventelva and the Longyearbyenelva, which transport meltwater from the glaciers that retreated many km from the coast. The July freshwater discharge is 3.18 m$^3$ s$^{-1}$, with a sediment load of 131–151 mg dm$^{-3}$, which represents 40–50%

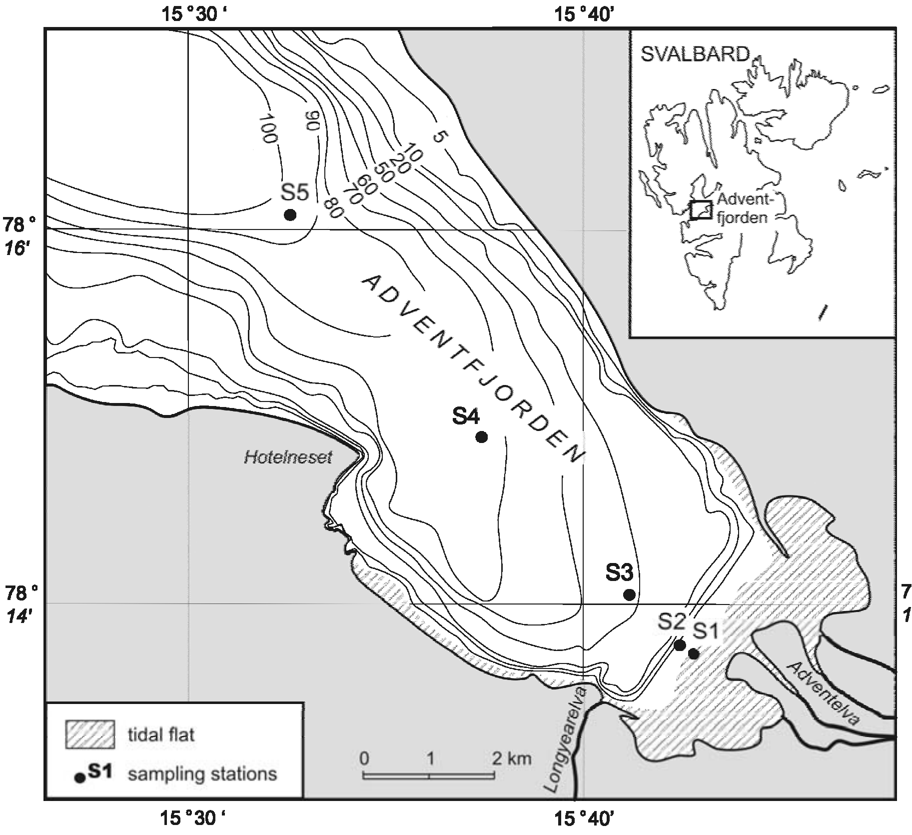

Fig. 2. Adventfjorden study area.

of the annual run off (Węsławski *et al.* 1999). During the winter when the rivers are frozen, the supply of terrigenous material to the fjord stops.

## Methods

Results presented in this paper are based on the measurements and samples collected from Kongsfjorden in July 2003 and from Adventfjorden in August 2003. Sampling stations were located on the profiles from the sources of terrigenous material (rivers and glacier fronts) to the mouths of the fjords. The water column hydrological properties were measured at anchored stations with Mini CTD Sensordata SD202 at intervals of 2 seconds. The currents (hyperpycnal flows) were measured one meter over the sea bottom with a Sensordata currentmeter Mini SD 6000 combined with a Seapoint Turbidity Meter emitting light at 880 nm at scatterance angles of 15–150°.

Ninety-seven water samples were collected with 3 $dm^3$ Niskin bottles to measure the suspended solids concentration. Sampling intervals at each station were designated at 0 m and then down every 10–15 m depth, in relationship to water salinity and temperature. Cylindrical sediment traps with diameters of 100 mm and lengths of 1000 mm (Zajączkowski 2002) were deployed at 2 m above the bottom, under the brackish water layer, and on the layers were SPM was sampled. The sedimentation rate in the water column was measured at a minimum of 24 hours, during two tidal cycles.

The volume of the sample, in relationship to the suspension load (50–500 ml), was vacuum-filtered onto pre-weighed Whatman Glass Microfibre filters GF/F 0.7 micron. These filters with samples were rinsed with freshwater to ensure that the salt was removed. Each filter was air dried at 60°C for 24 h and reweighed to determine the dry mass of the suspended particulate matter (SPM). The empirical data of the solids concentration from Adventfjorden were then used to calibrate the backscattering by plotting SPM (mg dm$^{-3}$) against FTU (Formazin Turbidity Units) recorded with a Seapoit Turbidity Meter. The derived linear regression equation SPM = 0.9986 FTU+0.6899 (determination coefficient $R^2 = 0.999$) was used to calculate the concentration of SPM.

## Results

**Buoyant hypopycnal flow**. — The meltwater delivered to Kongsfjorden can be identified by salinity-depth profiles collected at stations K1 to K4 within 0.45 km to 5.7 km from the glacier front (Fig. 3A). Station K1 shows a sharp halocline at the depth of 1 m, which is formed under the relatively well-mixed surface layer. At 2.1 to 5.7 km away from the glacier front (stations K2, K3, K4), the surface water is no longer well-mixed and salinity increases seaward and downward; however, the upper part of the water column is distinctly stratified. At a distance of over the 7 km from the glacier terminus, the stratification of the water column is weak and the salinity of the surface layer exceeds 32 PSU.

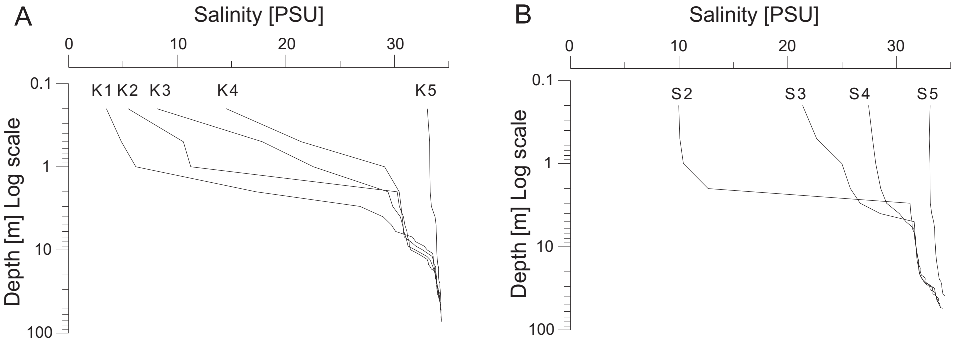

Fig. 3. Selected salinity profiles at seaward distance of the Kongsbreen meltwater outflow (**A**) and the Adventfjorden tidal flat (**B**).

Station S2 in Adventfjorden was located 200 m from the lower edge of the tidal flat (Fig. 3B). The surface layer is over 2 m thick and is well mixed, and the extremely sharp halocline below delineates a distinct plume of surface brackish water. During the flood, the salinity of the whole water column (2.5 m deep) over the tidal flat ranged from 2 to 5 PSU. At a distance of 1.6 to 3 km from the tidal flat, the salinity of surface water increases according to river water spreading and mixing, and the thickness of the brackish water layer increases to 4 m. In this zone, the mixing rate is related to the brackish water current and tidal phase, to wind and wave activity. Salinity changes in the water column at the mouth of the fjord (station S4) are insignificant.

**Turbid overflow plume**. — The concentration of SPM was measured in the 0 to 50-cm-depth water layer on a transect from the source of terrigenous material to the mouth of the fjords (Fig. 4). The breaks between linear regression slopes suggest two changes in flow dynamics of turbid water in both fjords. The first break in the linear regression slopes indicates seaward distance where the sedimentological regime is changing. In the case of both fjords, this is consistent with changes in the hydrological condition of the water column.

In Kongsfjorden, a continuous, rapid decrease in concentration of SPM from 460 to 350 mg dm$^{-3}$ was observed. This led to the removal of 23% of the suspended SPM from the brackish layer at a distance of one km from the glacier front. According to McClimans (1978), deceleration within the surface plume resulting from lateral mixing between the plume and the surrounding water means that

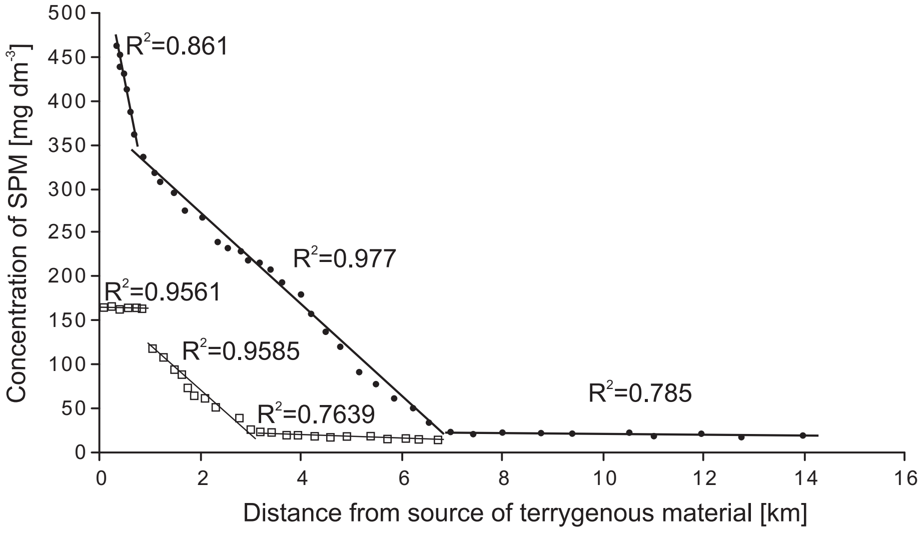

Fig. 4. Changes in concentration of suspended sediment in surface water (dots – Kongsfjorden; squares – Adventfjorden) as a function of distance from the source of terrigenous material. The position of the break in the linear regression is used to divide fjord water into individual sedimentological zones. Determination coefficients $R^2$ are given for individual best-fit linear segments.

coarser suspensions settle faster. Next, between the first and second break in linear regression, the rate of loss of SPM proceeds more slowly, but by 5 km distant this leads to the removal of an additional 71% of suspended SPM. Here, the decrease of current velocity causes the increase of sedimentation rate of SPM flocs (Syvitski 1991; Hill *et al.* 1998; Droppo *et al.* 1998).

In Adventfjorden, the SPM concentration is similar to Kongsfjorden at 160–170 mg dm$^{-3}$ in the upper 50 m. A high suspended load was observed throughout the water column over the tidal flat during the flood and the loss rate never exceeded 2%. This finding is confirmed in Blanton *et al.* (2003) who found that landward bottom stress is greater than seaward stress. The flood flow carries more suspended solids landward, and the transported material originates from both the retention of riverine material and the resuspension of the tidal flat bottom sediments. At the lower edge of the tidal flat, a sudden decrease in the surface concentration of suspended solids was observed (first break in the linear regression), which led to the removal of 25% of SPM from the fjord surface waters. The rapid settling of particles in this narrow zone (steep slope on the edge of a tidal flat) is connected with increasing salinity, decreasing velocity, and flocculation of fine particles. Next, at a distance of 3 km seaward, the steady decrease of surface suspension concentration leads to the settling of an additional 53% of the solids.

In both of the studied fjords, the second break in linear regression determines the beginning of the distal sedimentological zone where a decrease in the concentration of surface suspended sediment is insignificant with distance from the source of terrigenous matter.

**Dynamics of the suspended sediment plume**. — The distribution of turbid surface water over Kongsfjorden shows that the main source of suspended sediment is the central englacial outflow in front of Kongsbreen. Since the outflow is located nearly on the fjord surface (Elverhøi *et al.* 1980), the highest concentration of suspended mineral solids (more than 400 mg dm$^{-3}$) are noted at a 0–1 m depth at station K1 (Fig. 5 A). Mixing between the turbid surface water and the layer below is limited due to density differences between these water bodies. On the sides, outflow mixing within the water column is restricted largely to the breaking off of eddies at the interface between the clear, seawater, and turbid meltwater. The meltwater current, which reaches velocities of 0.8 m$^{3}$ s$^{-1}$ close to the glacier front (Zajączkowski and Legeżyńska 2001), transports suspended solids 5–6 km away from the glacier front. During transport, the concentration of suspended solids decreases on the surface and simultaneously increases in the lower part of the water column, which is related to sediment flux in the water column (Station K4). The fast settling of SPM at station K4 can be related to the numerous icebergs grounded in this area as they deliver an additional amount of fresh water and increase water mixing, and thus enhance flocculation of fine particles.

Fine suspended mineral solids are transported to a distance of several kilometers downfjord, where the flow of turbid water decreases and external agents like

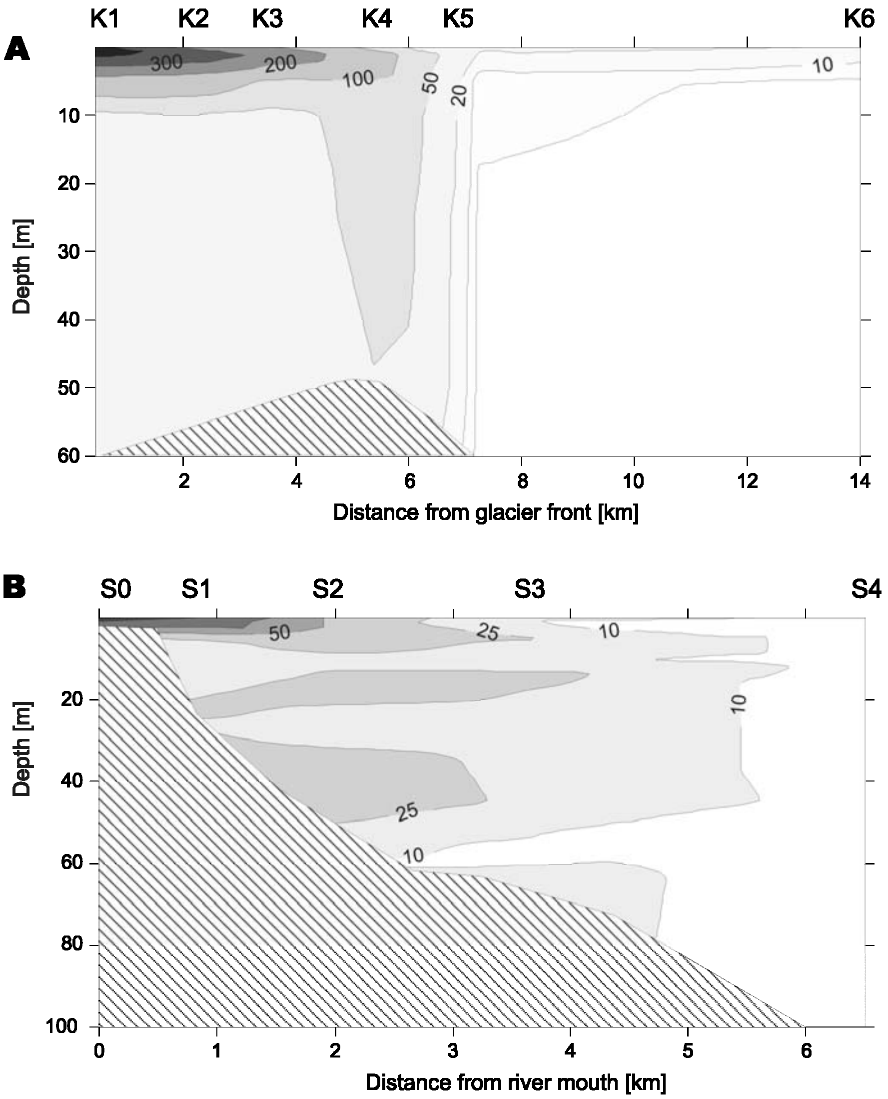

Fig. 5. Concentration of suspended mineral solids both with depth and distance seaward of Kongsbreen glacier (**A**) and Adventfjorden tidal flat (**B**). SPM data in mg dm$^{-3}$, interpolated with the linear method.

wind, waves, and tidal phase stir particles (Dowdeswell and Cromack 1991). A part of fine SPM can be transported with surface waters down to the mouth of the fjord.

The highest concentration of suspended solids in Adventfjorden (112 mg dm$^{-3}$) was noted in the surface and also throughout the water column over the tidal flat during the flood tide (Fig. 5B). When surface water turbidity decreases seaward, the concentration of suspended particles increases near the bottom at the delta edge and also at a depth of 20 m and 40 m. This finding can be interpreted as the result of sediment gravity flows acting to transport sediment downslope. A similar phenomenon was described previously by Zajączkowski and Włodarska-Kowalczuk (2007) as the result of turbidity currents produced by major resuspension events at the low edge slope of the tidal flat. The numerous chutes and subsidence areas observed in this place with acoustic methods (Prior *et al*. 1981) result from the gravitational mass movement of the sediment. Resuspended sediment can flow separately from the bottom turbidity currents finally forming an interflow (Gilbert *et al*. 2002). However, at depths of 10–20 m it can be interpreted as a kind of plume connected with the fine stratification of the water column, which dies out with time (Cowan and Powell 1990; Zajączkowski and Włodarska-Kowalczuk 2007).

Figure 6 shows three peaks of very turbid water plumes that were measured during 5 hours at a depth of 1 m above the bottom. Downfjord currents lasted approximately 15 minutes and reached velocities of up to 25 cm $s^{-1}$. All of them appeared during the low tide when the stress exerted by the waves on the tidal flat bottom is the highest. The duration of the plume, water turbidity, supply of fine material due to flocculation point to hyperpycnal flow along the tidal flat and its lower edge (Smith *et al.* 1990) transporting sediment to the delta base. Prior *et al.* (1981) working with the first side-scan images of Adventfjorden sediments, iden-

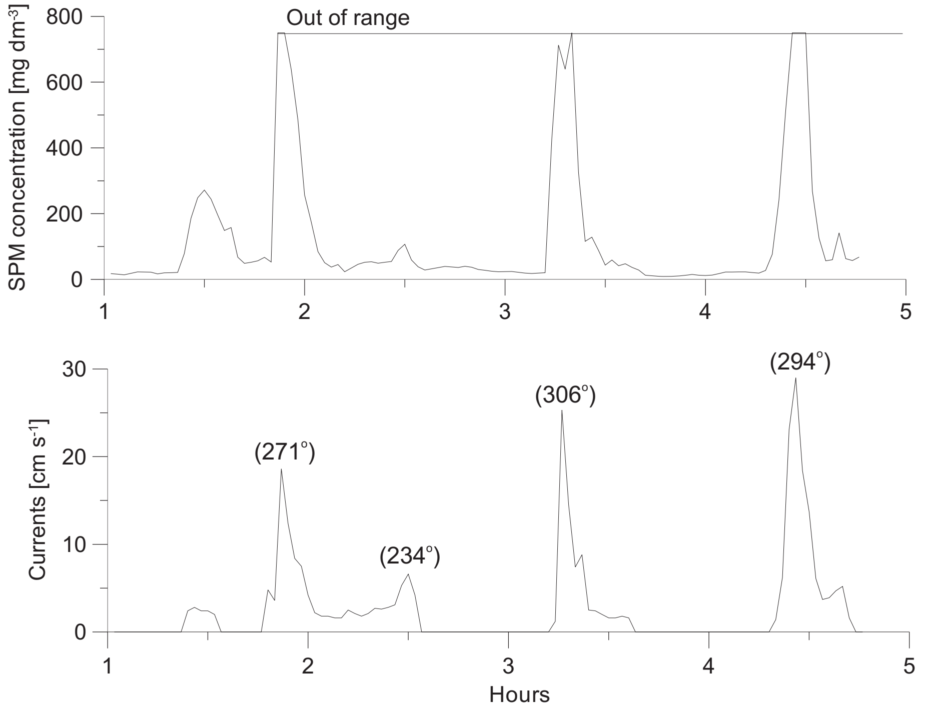

Fig. 6. Hyperpycnal flow – SPM concentration and current velocity (direction in parenthesis). The measurements were taken 1 m above the bottom at an anchored station at the front of the Adventfjorden tidal flat on August 6, 2003. The down-fjord direction was 315°.

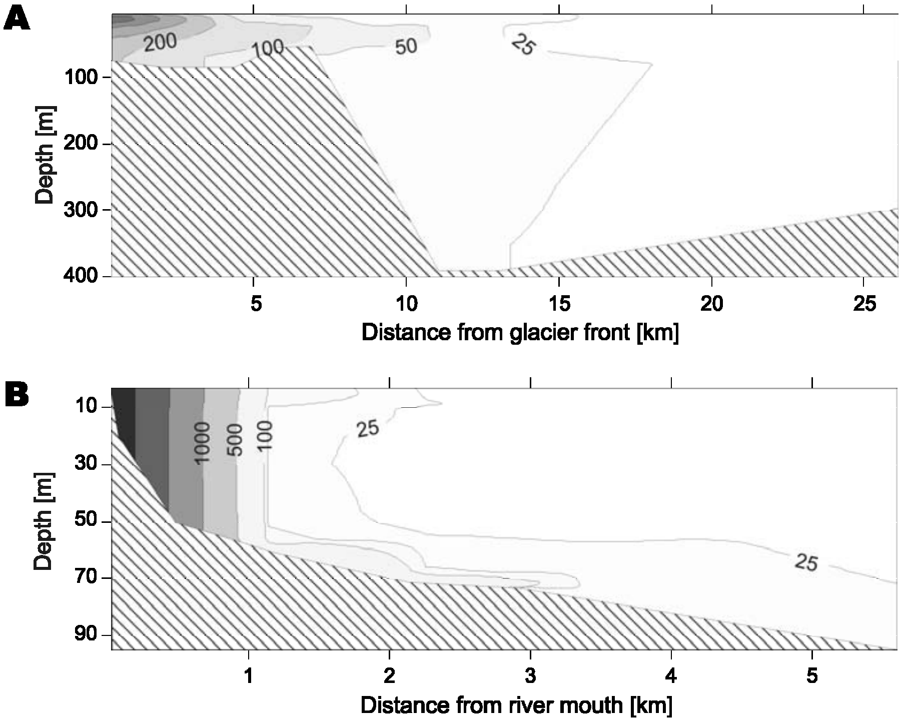

Fig. 7. SPM flux in water column of Kongsfjorden (**A**) and Adventfjorden (**B**), July 2002. Data in g $m^{-2}$ $24h^{-1}$, interpolated with a linear method.

tified numerous landslides chutes on submarine slope of tidal flat. These suggested that chutes could be produced both: by hyperpycnal flows and landslides.

An increase in the density of interstitial water ensues when flocculated fine suspension settles on the bottom and mixes with coarse material transported by traction and saltation. While the brackish water flows away from the tidal flat, it removes loose sediment to the marginal zone of the delta. Coarse grains flow down along steep slope, and fine sediment can be resuspended into the water column.

According to Stokes Law, fine particle settling can be very slow, with individual grains of less than 1 μm requiring more than 200 days to settle through 10 m of water. The same grains in the form of floccules can settle up to several hundred meters per day (Hill *et al.* 1998). Their transport can be supported by a kind of interflow often connected to fine-scale water stratification (Zajączkowski and Włodarska-Kowalczuk 2007). Examples of such interflow are presented in Fig. 5B.

**Settling of suspended solids**. — The data presented in Fig. 7 show the diverse settling rate of suspended solids in the fjords studied depending on the distance from the source of terrigenous material. The highest flux of solids (631 g $m^{-2}$ $24h^{-1}$) was observed at a depth of 10 m in front of Kongsbreen outflow, although in near-bottom area this value decreases to 207 g $m^{-2}$ $24h^{-1}$. This can be explained by the forced plume of meltwater (Powell 1990) that spreads out in horizontal and vertical planes as distance from the glacier front increases. The mixing process includes fjord water into the brackish layer that induces upwelling. Within 5 km from the glacier, SMP flux ranges from 50 g $m^{-2}$ $24h^{-1}$ in the upper part of water, to 128 g $m^{-2}$ $24h^{-1}$ at the greater depth. This finding confirms that the proximal zone exemplifies this kind of sediment trap for particles supplied with meltwater. It is in good agreement with the high accumulation rate (20 000 g $m^{-2}$ $a^{-1}$) on the sea floor, obtained by $^{210}$Pb analyses, and the short residence time of particles in the water column due to flocculation (Svendsen *et al.* 2002).

Central and outer Kongsfjorden are characterized by considerably lower vertical flux of suspended particles ranging from 31 to 7 g $m^{-2}$ $24h^{-1}$. This change results from both, the decreased concentration of suspended particles (Fig. 5) and the increased residence time of solids in the water column (Svendsen *et al.* 2002). The data presented omits the supply of iceberg-rafted debris, the rate of sedimentation of which can reach 8 mm $a^{-1}$ in the inner Kongsfjorden (Dowdeswell and Dowdeswell 1989). Iceberg-rafted debris is noted throughout the distal zone of Kongsfjorden sediment (Elverhøi *et al.* 1980).

Adventfjorden presents a decidedly different sedimentological regime. The maximum vertical flux of SPM (2348 g $m^{-2}$ $24h^{-1}$) was noted at a depth of 4 m and 2497 g $m^{-2}$ $24h^{-1}$ at a depth of 20 m on the delta front beyond the tidal flat on the delta plain. In the central and outer fjord, the highest rate of sedimentation in the water column was noted in the near-bottom layer (62–41 g $m^{-2}$ $24h^{-1}$). In the tidal flat area, the river water mixes with fjord water throughout the column that causes settling of both fine particles due to flocculation, and coarser grains due to decreased transport velocity. This process leads to temporary deposition of loose sediment on the surface of the tidal flat during the flood. The redeposition of loose sediment from tidal flat described by Smith *et al.* (1990) and landslides on the delta margin reported by Prior *et al.* (1981) transport material to the base of delta slope.

## Discussion

In models of the dynamics of buoyant hypopycnal flow, two zones are usually distinguished in the fjords: the near or proximal zone where the energy of flow controls transport and mixing of the plume; and the far (distal) zone where external agents control transport and mixing of brackish water (McClimans 1978; Dowdeswell and Cromack 1991). The data presented indicates that the dynamics of buoyant hypopycnal flow and the turbid water plume in the fjords occurs in three stages. Very close to the source of terrigenous material (marginal zone), the most important is the sediment load and concentration in meltwater and current velocity/mixing processes. In the case of the glacier front, small decreases of meltwater velocity cause settling of coarser particles; however, fine particles are transported to the next part of the fjord in brackish water. Tidal flats are an example of a kind of natural sediment trap, where most sediment delivered by rivers settles on the bottom of the marginal zone. This zone includes intertidal area during the flood and slope ending the tidal flat during the ebb. Further, sediment transport depends on redeposition and resuspension. In the case of Adventfjorden, the near bottom transport by turbidity currents leads to sediment sorting and the removal of the finest particles from the fjord head (Zajączkowski and Włodarska-Kowalczuk 2007). At the front of tidewater glaciers, tides influence the sediment flux and causes deposition of cyclically interlaminated sediments. Each low water period produces a couplet lamina: sorted, coarser grained and finer grained flocculated particles (Cowan and Powell 1990). It has been reported that particle transport and release from the plume are controlled predominantly by semidiurnal tidal fluctuations throughout the proximal zone of Kongsfjorden (O'Cofaigh and Dowdeswell 2001). In Adventfjorden such laminated sediments were observed only in the tidal flat. The sediment in the proximal zone, but also partially in the distal zone, are formed by turbidity currents (Zajączkowski and Włodarska-Kowalczuk 2007). In the glaciated Kongsfjorden, sedimentation from suspension was even observed in the central fjord.

These differences influence the lithofacies of the sediment, the particle size composition, and structures. They should be taken into consideration when calculating the sediment deposition rate in the fjords, as well as in studies of the environment of benthic fauna. The comparison of the studied fjords leads to the conclusion that in the case of tidewater glacial fjords, ice-rafted debris as well as that which settles from suspension sediment (including the finest fraction) form clay zones throughout the fjord. When the sediment is transported via a tidal flat, the role of turbidity currents increases, which leads to sediment sorting and the inner part of the fjord plays the role of a transitional zone for the finest particles.

Notable climate warming over the past century has caused the Svalbard glaciers to retreat significantly (Nordli *et al.* 1996; Ziaja 2001), a consequence of which has been the increase of terrigenous material supply to the fjords (Elverhøi *et al.* 1995; Svendsen *et al.* 2002; Zajaczkowski *et al.* 2004). According to Syvitski (2002) and Syvitski and Andrews (1994), further increases in sediment flux over the next 200 years is predicted. Increased concentrations of suspended solids in surface water decreases the extension of the euphotic zone in the fjords. On the other hand, the data presented indicate that after glaciers shift from tidewater to land terminating, most sediment is trapped in the narrow marginal zone of the tidal flat. This should result in higher fjord productivity and increased organic-matter delivery to the fjords and shelf sediments.

The differences presented are intended to assist in the interpretation of Quaternary and older sediments in the geological record. They can also support predictions of the result of further climate warming and fjord deglaciation.

## Conclusions

- The hydrological data presented indicate faster water mixing on the tidal flat in comparison to the englacial runoff, and this leads to a more rapid decrease in horizontal gradients of water density in the outwash fjord.
- Sedimentological regime in both fjords is consistent with changes in the hydrological condition of the water column. It allows definition of three sedimentological zones in the fjords; however, turbid water advection and sediment flux is different in glacial and outwash fjords.
- Tidal flats are natural sediment traps for wide size spectrum of terrigenous material delivered by meltwater. Continued sediment transport into the fjord is related to sediment redeposition and resuspension by hyperpycnal flows.
- In glacial fjords, buoyant hypopycnal flows of meltwater allow terrigenous matter to be transported several kilometers from the glacier front.

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