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On the use of sediment traps in sedimentation measurements in glaciated fjords

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ABSTRACT: Several conclusions and recommendations concerning sediment trap geometry, the technique of their deployment and interpretation of measurements results are described in this paper. Only cylindrical sediment traps are able to cope with the diverse and dynamic environment of glaciated fjords. The relation between different trap parameters shows the optimal proportion of cylinder diameter as being between 6 and 10 cm and ratio length/diameter not less than 7/1. During the peak of the melting season in Kongsfjorden (Spitsbergen) the rate of sedimentation of total matter reaches over 900 g m^{-2} d^{-1} and the velocity of brackish water current can reach 80 cm s^{-1} on the surface. Owing to the high productivity of Arctic fiords and large concentration of suspended mineral matter it is possible to collect of large samples in a short time, therefore prevention of sediment traps by swimmers is not necessary.

Key words: rate of sedimentation, sediment traps, resuspension, flocculation.

Introduction

Large international projects like the Global Ocean Flux Study or Land Ocean Interactions in the Coastal Zone have promoted in recent decades publication of a number of methodological papers dealing with the measurement of contemporary marine sedimentation rates (Smetacek *et al.* 1978, Hargrave and Burns 1979, Bloesh and Burns 1980, Butman 1986). A large part of the described activity focused on great depths and open ocean conditions. On the other hand issues concerning climate changes increase interest on sediment loaded fresh water inflow to the shelf water connected with glacial ablation and river discharge (Levin *et al.* 2001, Lisitzin 1999). Valley glaciers have meltwater streams that transport large quantities of sediment. This results in a high concentration of suspended mineral matter and a high rate of sediments accumulation in glaciated fiords (Svendsen *et al.* 2002).

Sveral important conclusions and recommendations concerning coastal processes have been drawn from these works. The author's field experience from the last 10 years of studying sedimentation in Spitsbergen fiords allows him to present a concise overview of the methodology recommended for studying sedimentation in glaciated fiords.

Geometry of sediment traps

A sediment trap is a device permitting the quantitative gathering of particles falling in the water column. According to Butman *et al.* (1986) three parameters are important for the successful design of a sediment trap:

1. Reynolds number for sediment traps $Rt = vD/\gamma$, where: v – water flow over the opening, D – the outer diameter of the trap, γ – kinematic viscosity of the fluid (viscosity/density of the fluid).
2. Size proportions $A = H/d$, where: H – height of the trap, d – inner diameter of the trap.
3. Proportion of the flow velocity to the particles sinking speed, v/W.

Since the diameter of the traps changes two of the above mentioned parameters (Rt and A), one should remember to change only one parameter during the calibration. Such experiments were performed by Butman (1986), who found the mean trapping rate at the use of A between 2.7 and 3.7 (Rt constant at 10000). A field experiment by Gardner (1980) and Blomquist and Kofoed (1981) gave best results when A was between 6 and 10. They found that the Reynolds number is the decisive factor for the selection of the size of the cylindrical trap, if one wants to keep the sediment still on the bottom of the trap. Hawley (1988) described that relation as A = 3 for Rt = 6000 (v = 6 cm/s and D = 10 cm) and A = 5 for Rt = 8000, A = 8 for Rt = 20000 (v = 20 cm/s). In oceanic water, the Rt tends to be high (> 105) and particles are common in various sizes and types, so A should be over 3. Based on the Blomquist and Kofoed (1981) studies, traps with diameters less than 3 cm should not be considered for quantitative studies on sedimentation.

Considering turbulence as the main factor responsible for the distribution and sinking of the particles ($\phi < 250$ mm), and the Reynolds number for the particles (Re) below 0.5, Bloesh and Burns (1980) and Butman (1986) formulated the equation:

$$Re = v\, d/\gamma,$$

where:
v – particles sinking velocity,
d – particles diameter,
γ – kinematic viscosity of fluid (fluid viscosity/density).

This equation leads to some basic assumptions in sediment traps design (Bloesh 1988):

- suspended matter concentration must be equal inside and outside the sediment trap,
- fallen particles may not be resuspended in the trap.

A number of experiments shows that only cylindrical traps are able to cope with the above assumptions. The resuspension from the bottom of the trap is caused by the horizontal flow over the trap entrance and by consequent water movement inside the trap. The relation between different trap parameters shows the optimal diameter proportions as being between 5 and 20 cm and aspect A equal to 5:1 (Table 1).

Table 1

Relations between the maximum speed of horizontal flow (cm s^{-1}), the resuspension inside the traps, Reynolds number, and trap size proportions, according to Bloesch (1988).

Trap diameter		6.6	6.6	6.6	6.6	6.6
Aspect ratio		2.5 : 1	5 : 1	10 : 1	14 : 1	20 : 1
Re number at which resuspension starts		4 500	7 000	20 000	35 000	70 000
Mean catch [%]		5–20	65–100	100	100	100
Critical horizontal velocity [cm s^{-1}]	at 4°C	10.7	16.6	47.5	83.0	166.0
	at 4°C	8.9	13.9	39.6	69.0	139.0
	at 20°C	6.8	10.6	30.3	53.0	106.0

Spitsbergen fiords are characterised by variable physical conditions. The velocity of the brackish water current, measured in July 1999 in the constriction between the inner and middle basin, ranges from 10 to 30 cm s^{-1} in Kongsfjorden (Svendsen *et al.* 2002). In many cases maximum velocity can be affected by superimposed tidal-, freshwater- and wind-driven currents. It is worth mentioning that at the glacier fronts close to outflows of meltwater, flow of brackish layer can reach even 80 cm s^{-1} on the surface (Zajączkowski and Legeżyńska 2001). This establishes the geometric design of a sediment trap for Svalbard fiords: height/diameter ratio should not be less than 7:1 and in areas of strong currents even 10:1, and a cylinder diameter between 6 and 10 cm is optimal. An example of interpolated data of sedimentation rate in the water column at the front of Kongsbreen (NW Spitsbergen) is shown in Fig. 1. Cylindrical sediment traps (height and diameter = 100 and 10 cm, respectively) were deployed on the three stations at depths of 5, 15, 30, 50 m and 5 m over the bottom. The highest rate of sedimentation (933 g m^{-2} d^{-1}) was noted 300 m from the glacier front at the 15 m depth. This results from the decrease of meltwater velocity after it leaves the glacial tunnel and spreads out in vertical and horizontal planes. Fast sedimentation of suspended solids in brackish water caused fine sand, mud and aggregated clay to be found in this sediment trap. The relatively high rate of sedimentation

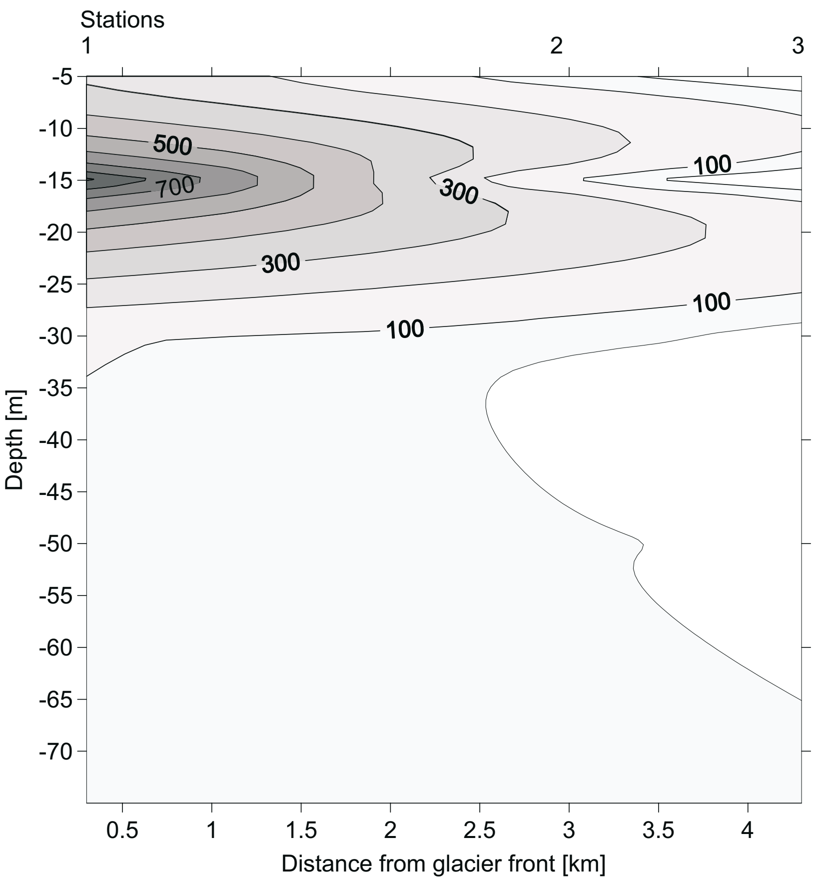

Fig. 1. An example of sedimentation rate of total suspensions in a water column at the front of a glacier (Kongsbreen, July 1996); values in g m^{-2} d^{-1}.

of solids in the near-bottom area in the distance of 4.3 km from the glacier (51 g m^{-2} d^{-1}) can be caused by both sedimentation in the upper part of the water column or resuspension of the sediment from the bottom.

Setting the sediment traps in Arctic fiords

Since fiordic suspensions can be very different even in a small area, a set of two traps per sampling station is recommended. This eliminates the errors caused by accidental ice-rafted drop stones or large phytoplankton coagulates and improves the statistical calculations of the results. The way of deploying the sediment traps which are set may have a decisive influence on the qua1ity of the measurements. Traps exposed for a longer time are conveniently deployed with a buoy and heavy anchor (Fig. 2A). Such a set works well during waving time and tidal currents,

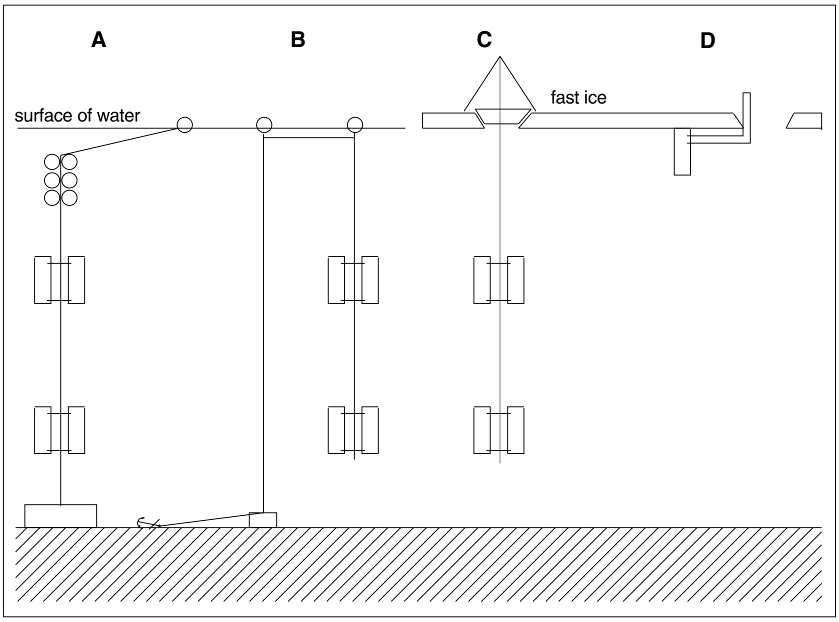

Fig. 2. Different methods of setting sediment traps. **A** and **B** during the summer, **C** and **D** during the winter and spring.

keeping a constant distance between the trap and the sea bed. The disadvantage of this method, because of the short exposure time, is need to the frequently lift the heavy anchor from the sea bed.

In case of the innermost fiord basins, where waves are low and sedimentation intense (in the order of tens of grams per day per square metre) several hours of exposure is quite sufficient. In such cases one may hang the sediment trap to the floating buoy, thus avoiding the anchor deployment (Fig. 2B). This method is effective in the euphotic zone, since the distance of the trap from the sea surface remains the same regardless of the tidal phase. The same holds true for work from the fast ice cover, when the sediment traps should be kept at the same distance from the surface throughout exposure time (Fig. 2C). The opening in the ice serving for the trap deployment should be covered with an ice lid of the same thickness as the surrounding ice to prevent artificial light transmission. In measuring the sedimentation from the fast ice cover itself (Fig.2D) one should fill the trap with filtered sea water, since the organic suspensions found under the fast ice cover may disturb the ice-originated sedimentation.

When hanging the trap on a rope, one should consider the use of a gimballed link and steering blades permitting to keep the trap in a stable vertical position.

While choosing depths for trap deployment it is important to probe temperature and salinity in water column. During the winter mixing and cooling processes homogeneous water is formed, thus changes of temperature and salinity are insig-

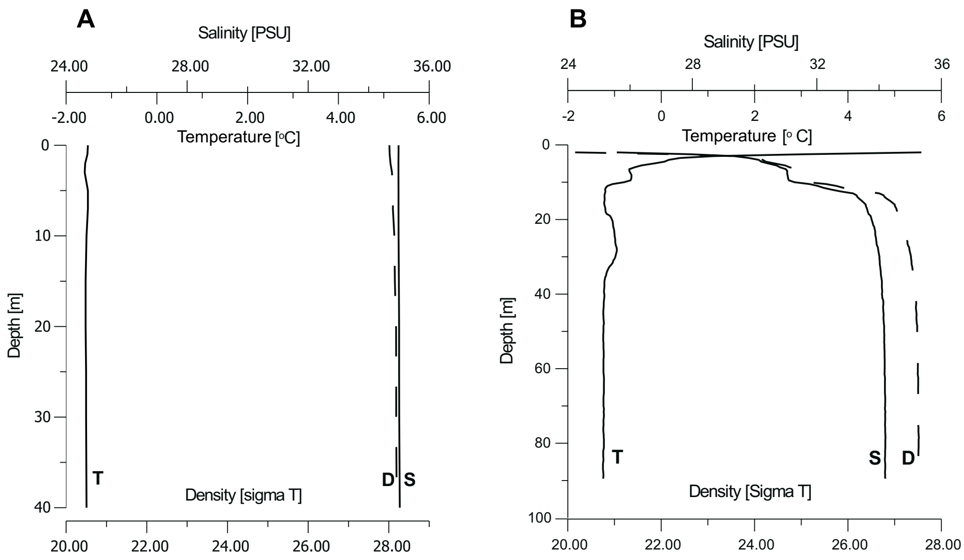

Fig. 3. An example of salinity profiles of fiord waters. **A**. Lack of stratification in Adventfjorden, April 1995. **B**. Summer stratification of Kongsfjorden water, July 1996.

nificant (Fig. 3A). The fiord water during melting season is significantly stratified and density gradients could be an obstacle to the unconstrained settling of suspended particles (Fig. 3B). Gradient of water density during the summer is caused by the inflow of melting water from the glaciers and the occurrence of dense winter water near the bottom.

Swimmers prevention

The sediment trap exposed in a water column may collect a number of items not regarded as sedimenting suspensions, such as mezozooplankton, regarded as an artefact in sediment studies but not influencing the mineralization of collected sediment (Knauer and Asper 1989). The sedimenting aggregates of organic matter often contain flagellates or ciliates, which may be considered as mineralising agents. Since it is technically impossible to separate microzooplankton from the sedimenting matter, these are included in the general sedimenting matter calculations (Silver *et al.* 1984, Taylor *et al.* 1986). Large protozoans, like Foraminifera, may actively enter the trap and leave it, however stress may diminish their mobility, and other protozoans, like Radiolaria, may feed on falling particles, causing even an 80% loss in sedimented organic matter (Knauer and Asper 1989, Gundersen 1990). To avoid disturbance by swimmers and consumers, traps exposed longer than 3 days should be contaminated with poison (like concentrated formaldehyde). The contamination of traps leads to further errors, namely the incidental zooplankton mortality which ranges from 7 to 19% of the trapped organic matter (Smetacek *et al.* 1978, Fellows *et al.* 1981, Harbinson and Glimmer 1986, Lee *et al.* 1988). Some authors recommend the installation of special crates or labyrinths on the top of a sediment trap in order to ward off swimmers (Karl and Knauer 1989, Coale 1991). Other authors recommend the use of tweezers and the mechanical removal of swimmers before the sediment analysis.

The high productivity of Spitsbergen waters (120 g of C m^{-2} y^{-1}) according to Eilertsen *et al.* (1989) and the large concentrations of mineral matter from glacial discharge (Hop *et al.* 2002) permit the collection of sufficiently large samples of sedimenting matter in a short time. In the inner basins of fiords, which act as efficient trap for suspended solids (Svendsen *et al.* 2002) 24 hours of exposure of sediment traps 10 cm in diameter resulted in a collection of few mg of sedimenting matter in winter and tens of grams in summer. Short exposure in Svalbard fiords yselds good quantitative results and does not require contamination of sediment traps.

A number of dead zooplankton items can be expected on the bottom of sediment traps while trapping close to glacier meltwater outflows (Węsławski and Legeżyńska 1998, Zajączkowski and Legeżyńska 2001). The high rate of sedimentation of dead zooplankton can remove even 15% of standing stocks in a water column (Hop *et al.* 2002). For this reason zooplankton organisms should be taken as naturally sedimenting organic matter.

Resuspension

Resuspension is a function of the diameter of particles and of the force which moves them. The moving force is a result of near bottom currents and oscillatory water movement caused by the distant action of waves on the sea surface. The oscillatory movement is partly diminished by returning bottom currents (Valeur 1995). Bottom sediment may be raised from the sea bed according to the Fredsoe (1981) formula:

$$tb = 1/2\ fw\ (Ub2 + Ud2 + 2UbUd \cos a),$$

where:

fw – wave friction factor,
Ub – horizontal mean wave orbital velocity at the sea bed,
Ud – current velocity at the top of the wave boundary layer,
a – angle between the mean current direction and the direction of wave propagation.

The smallest value tb causing the resuspension is called “critical shear stress for erosion” When tb reaches the critical level, the sea bed gets eroded according to the Partheniades (1965) formula:

$$Se = E(l\text{-}tb/tce)n,\ tb>tce,$$

where:
Se – erosion rate,
E – erosion coefficient,
tb – bed shear stress,
tce – critical shear stress for erosion
n – power of erosion

The direct influence of waves on sea bed erosion is negligible, when the depth is larger than the half of the wave length. This is because the orbital velocity of water particles diminishes exponentially in relation to the distance to the sea surface (Valuer 1995). The near-bottom sea currents are usually recorded l meter above the sea bed. Gardner *et al.* (1983) presented a formula permitting the calculation of the critical sea current velocity causing erosion for different types of sea bed:

$$Uf = C100\ 1/2 \times U100$$

where:
Uf – friction velocity,
C100 – a proportional constant for a given sea bed,
U100 – current velocity lm above the sea bed.

Fine grained sea sediments may reach the C100 coefficient between 2.5×10^{-3} and 3×10^{-3} (Bowden 1977, Gardner *et al.* 1983). The shear stress of consolidated sea bed sediments (coherent sea bed) is difficult to calculate. According to Gardner *et al.* (1983), the erosion of coherent sea bed starts at a sea current velocity between 0.5 and 1 cm s^{-1}, depending on sediment grain size. Baker *et al.* (1983) gives the sea current a value of 0.7 m s^{-1} as the minimal force causing erosion, while values above 0.95 m s^{-1} were reported by Wainright (1990). Field works in Chesapeake Bay show that resuspensions start at 1.4 m s^{-1} in early summer and at 1 cm s^{-1} at the end of the summer (Maa and Lee 1983).

The large variances in the data on resuspension is explained by the influence of biological factors like bioturbation or seasonal changes in sediment microflora (Va1eur 1995). Another factor causing or enhancing resuspension is cyclic changes of pressure at the sea bed, caused by the waving of the sea surface. This causes the linear increase of pore water pressure, diminishing the grains' cohesion. Finally, the long-term effect of such pressure causes the watering of the surface layer of sediment, which starts to behave like a dense liquid (Valeur 1995). The erosion of the coherent sea bed depends on the type and mineral content of the sediment, the amount of organic matter, waving, the sea current, salinity, suspensions' concentration, the degree of sediments consolidation, *etc*.

Resuspension in Svalbard fiords is a common phenomenon, rarely caused by waving, since the fiords are sufficiently deep. More commonly the steep walls of the fiords cause the sliding of sediment followed by resuspension. In shallow, sheltered places the tidal currents are the main factor responsible for resuspension. The data presented in Fig. 4 shows concentrations of resuspended solids increasing to

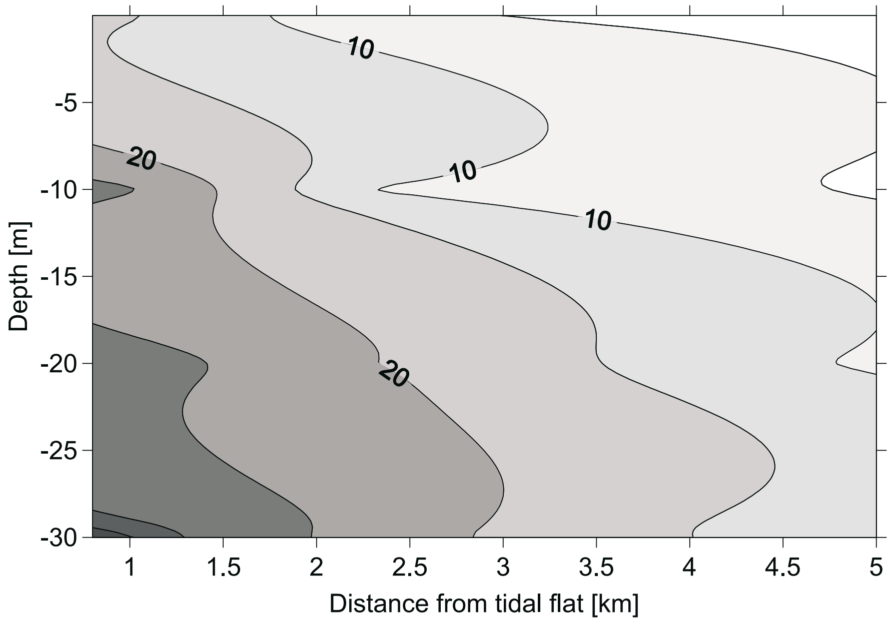

Fig. 4. Concentration of resuspended solids at the front of a tidal flat (Adventfjorden, January 1996); values in mg dm^{-3}.

the bottom in front of the tidal flat of Adventfjorden (W Spitsbergen). Also during the winter, when rivers are frozen, the influx of terrigenous material to the fiord is strongly reduced. In a shallow area of tidal flat sea-ice floats together with tides and strikes the bottom, activating the resuspension of the sediment. Thus the rate of sedimentation of suspended solids increases close to the bottom. This is why it is recommended to deploy the sediment traps not only on the sea bed but also on other levels of the water column, which may help to distinguish between the resuspended sediment and inflow of terrigenous material.

Flocculation

Flocculation is the process of small particles aggregating, caused by the Van der Waals forces. Flocculation is observed in saline water, where free kations change the charge of fine day particles, leading to the aggregating of particles in large coagulates by the electrostatic forces. Flocculation is important everywhere where sea water mixes with freshwater. Van der Waals forces may create aggregates in two cases:

- in conditions of turbulent mixing in the water column
- when particles collide attracted by larger aggregates

Organic substances like mucus (a product of bacterial degradation or phytoplankton secretion) are charged positively and this often leads to the formation of

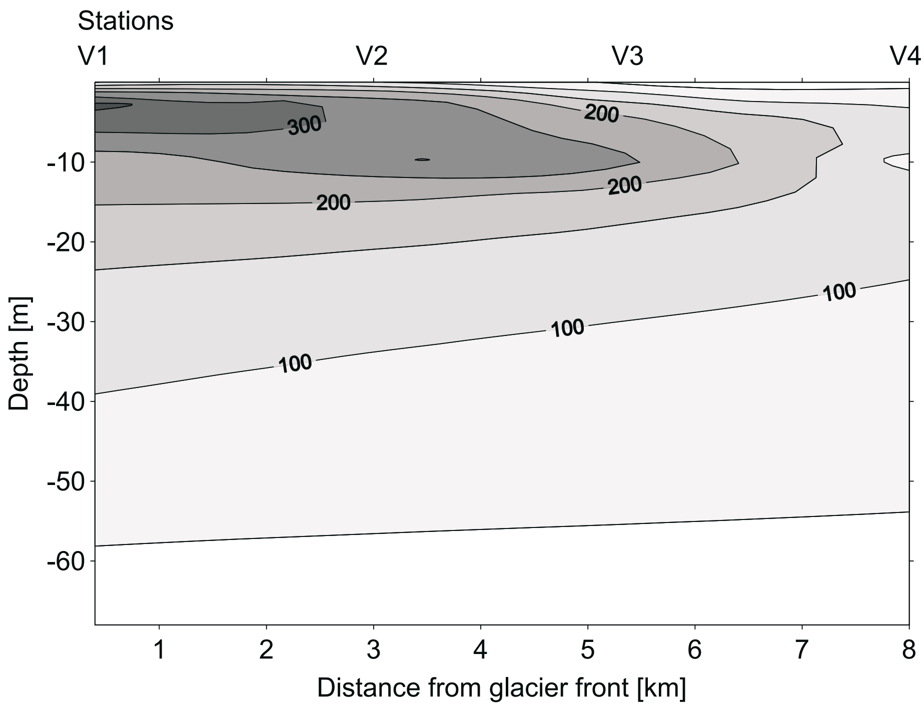

Fig. 5. Concentration of suspended solids at the front of a glacier Kongsbreen, July 1998; values in mg dm^{-3}.

coagulates (Heiskanen 1988). This process is of primary importance during the blooming of phytoplankton. Organic aggregation is weak and new aggregates are constantly formed and disintegrated. These aggregates can be divided into macroagregates (mm in size) and microagregates (10 to 20 mm in size). The macroagreagates disintegrate easily into microagregates (Glasgow and Luecke 1980) due to turbulence forces. While the microagregates are more resistant, they may be disintegrated and reflocculated again, depending on the distance from the water mixing area (Eisma 1986). The sinking velocity of particles with a Reynolds number below 0.5 theoretically should be calculated according to Stoke's law (Smayda 1970). The sedimentation of fine particles is determined by the size and density of aggregates (Dyer 1989).

Sedimentation rate of solids in Spitsbergen fiords is largely determined by:
- thermo-haline stratification
- exchange rate of surface waters in the glaciers' bays
- concentration of organic matter

The freshwater outflow from the glaciers carry large amounts of mineral sediment, reaching even 2500 mg dm^{-3} (Elverhoi *et al.* 1980). The meltwater does not mix instantly with the sea water because of the density gradient. First the gravel and sand suspensions are deposited, usually within 200–300 m from the glacier

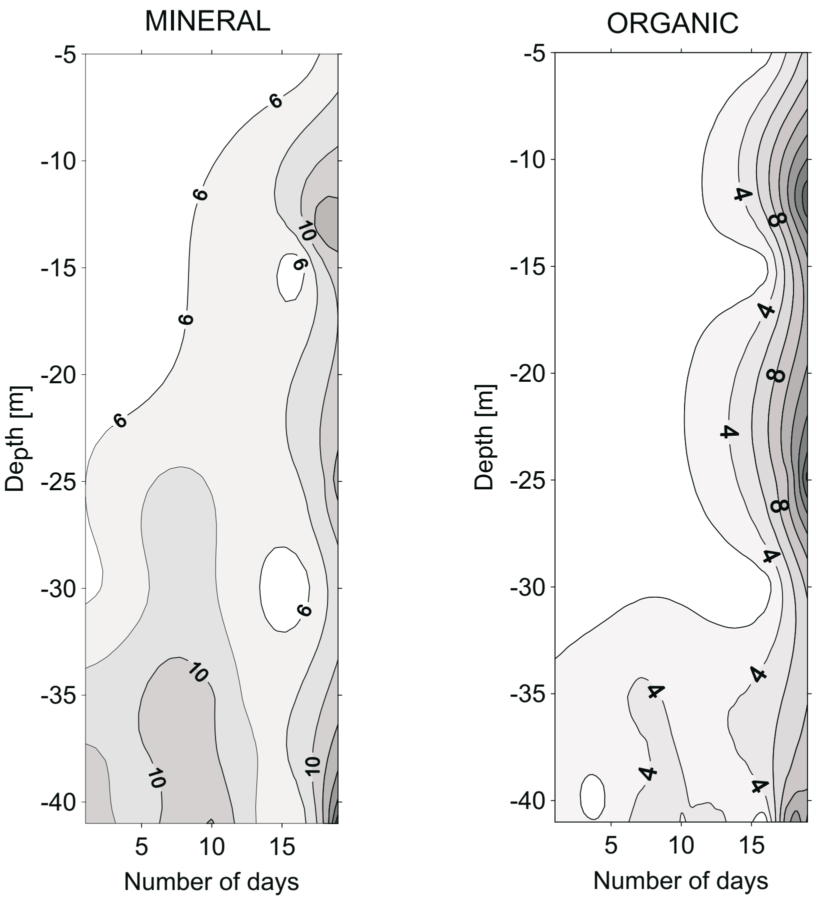

Fig. 6. Rate of sedimentation of mineral and organic particles during the spring bloom of phytoplankton; Adventfjorden (Spitsbergen), 23rd of April – 3rd of May, 1995; values in g m^{-2} d^{-1}.

cliff (Elverhoi *et al.* 1983). The rate of sedimentation under the meltwater outflow can reach over 800 g m^{-2} d^{-1}, but due to water circulation only part of this material reaches the bottom under the glacier gate (author's unpublished data).

Fine particles are concentrated on the lower part of the brackish water layer (on the salinity gradient) and may be transported even some kilometres from the glacier front (Fig. 5).

In the case of Kongsbreen bay the velocity of outflowing brackish water reaches 0.36 m s^{-1} (Zajączkowski and Legeżyńska 2001), which causes turbulent mixing of the surface layer. When the brackish layer starts to mix with the more saline fiord water fine particles start to sediment due to flocculation (Gilbert 1983), especially when the suspensions consist of large amounts of uniform material (Görlich 1986, Görlich *et al.* 1987). As an consequence, mud and clay bottom sediment is formed (Svendsen *et al*. 2002).

For these reasons sedimentation studies in glaciated fiords require knowledge of the density stratification and flocculation phenomenon.

The spring bloom of phytoplankton is connected with light appearing under the fast ice, which causes an increase in the concentration of organic particles and products of its degradation (mucus) (Wiktor 1999) in the euphotic zone. Fig. 6 shows how organic flocculation causes increases in the sedimentation rates of both organic and mineral solids (days 16 to 19). In this case, mineral particles originated from resuspended sediment from tidal flat (see days 6 to11), while organic particles were advected from the outside fiord.

Conclusions

To study the process of sedimentation in Svalbard fiords the following procedures are recommended:

- background measurements of STD and suspensions' concentrations are compulsory;
- cylindrical, double traps of the size of 10 × 70 cm, without swimmers' prevention are recommended;
- exposure time should range from 12 to 48 hours;
- sediment traps should be deployed at appropriate depths in the water column in order to distinguish between resuspended sediment and setting of particles from terrigenous and autochtonous material;
- knowledge of the flocculation phenomenon is also required.

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