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Chronology of sedimentation in Colesbukta, Spitsbergen (Svalbard Archipelago): the results of the 2018 expedition

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Abstract. This paper presents results of a study of sedimentation in Colesbukta (Isfjorden, Spitsbergen), a typical example of sedimentation in a shallow bay of the Svalbard Archipelago. We have examined sediment samples from several cores collected in Colesbukta in May 2018. To meet the goals of this study, geomorphological features of the Colesbukta catchment area have been identified and described. The lithological characteristics of bottom sediments from the study area have been described and their spatial and temporal changes analyzed. The chronology of sedimentation has been reconstructed by ^{210}Pb and ^{137}Cs. We have calculated sedimentation rates in Colesbukta and their temporal dynamics over the several latest decades. According to our estimations, the sedimentation rate has increased by 2–4 times compared to the middle of the 20th century and ranges from 0.2 to 0.46 mm/year depending on the individual conditions of sedimentation in each part of the bay. Climatic fluctuations are shown to have a direct impact on sedimentation processes in Colesbukta. We have revealed that on the periphery of the studied area the rate of sedimentation better depends on the temperature regime while in its central part it is rather a result of the amount of atmospheric precipitation.

1. Introduction

Svalbard fjords are believed to be highly susceptible to climate changes; therefore they are convenient testing sites to study how sedimentation processes respond to changing climatic conditions. Nowadays, sedimentogenesis is mostly studied in large fjords of Spitsbergen [1–6]; data from smaller and shallow fjords and bays are sparse and poorly available. Colesbukta, a tributary fjord to Isfjorden, is a good example of such a smaller fjord. This shallow bay provides good opportunities for studying sedimentation since it is rather poorly studied in this respect and easy to reach. Observations of changes of climatic parameters have long been conducted on the Svalbard Archipelago. Data from the meteorological stations at Longyearbyen and Barentsburg acquired from 1950 to the present suggest a warming of the climate in Svalbard during the latest decades [7, 8], which causes a substantial reduction of Svalbard's glaciated area [9, 10]. The findings of shells of the blue mussel *Mytilus edulis* (Linne) are of particular interest from the point of view of climatic changes. Findings of this warm-loving mollusk, which has been considered extinct in Svalbard for about the last 4 000 years, at various sites in Spitsbergen including Colesbukta [11] indicate unprecedented latest changes in climatic conditions in the study area. Although, not only abnormally warm, but also abnormally cold years have been reported for the same time period [12, 13].

The formation of bottom deposits in coastal fjords of high-latitude archipelagos is a complex process that is governed by many factors. Studying sediment cores collected in the shallow Colesbukta, a model fjord, can help reveal the main factors affecting sedimentation processes, as well as establish characteristic features of the chronology of sedimentation in the region under conditions of climate change.

2. Study area

Studies were carried out in the west part of Spitsbergen. The study area included Colesbukta and its catchment area. Colesbukta is a tributary fjord to Isfjorden, the largest fjord of the Svalbard Archipelago, and part of its hydrological system. The catchment area of Colesbukta belongs to Nordenskiöld Land (Fig. 1).

Colesbukta is 4.2 km long and 3.5 km wide at its mouth and stretches southwards and south-eastwards. The depths of the bay increase from south to north. The basin of the bay has a trough-like shape with maximum depth of 100 m at the site where Colesbukta opens to Isfjorden. One of the characteristic features of the bay is the large intertidal zone. At the western coast of the bay the littoral zone stretches for 400–500 m with the maximum of 700 m at the Kapp Laila area. At the eastern coast the littoral zone comprises 170 m and 300 m at the southern part of the bay. The largest contributing water stream is the Coles River entering the bay from the south. The western part of the Coles River delta is separated from the bay by a gravelly pebble bar that extends sublatitudinally for about 1.3 km. The south-eastern part of the bay receives the major river runoff [14].

On the east coast of Colesbukta, Colsbay Settlement is situated. It stretches from north to south along the coast of the bay for 4 km. The settlement was founded in 1934 as a trans-shipment base for coal which came from the Grumant mine by a narrow-gauge railway to be loaded into sea vessels and then shipped to the mainland. Such a transport scheme was caused by the fact that the coastline in the Grumant mine area does not allow the construction of a berth suitable for oceanic vessels. The settlement was mothballed in 1964. Nowadays it is a series of abandoned buildings, of which only one is habitable. This building is maintained in operational condition by employees of the Russian coal mining enterprise Arktikugol.

The geological structure of the Colesbukta catchment area is rather uniform. The bedrock geology of the study area is composed of Paleogene rocks blanketed by Quaternary sediments. The Paleogene rocks are presented by Eocene sandstones, mudstones and siltstones. The rocks are very susceptible to denudation processes and provide abundant material for the formation of Quaternary sediments of one size or another. The Quaternary sediments are presented mainly by Holocene formations of marine, fluvial, and hillslope genesis. Their lithological composition is very diverse and consists of boulders, cobbles, rubbles, pebbles, gravels, sands, silts, clays, and mud.

The relief of the study area demonstrates Alpine-type forms. Its characteristic features are a high degree of dissection, the presence of plateau-like mountain ranges, and corrie and valley glaciers. Peaked mountains and sawtooth crests typical for the Alpine-type relief occur in areas located to the south and east of the study area. The watersheds are presented by flat and gently sloping surfaces. They represent a partially boggy spotted tundra or stony tundra covered with fragments of Paleogene rocks. The hypsometric points of the watersheds range from 150 to 800 m. The highest point of 960 m is located in the northeastern part of the region under study on Lindströmfjellet, a mountain east of Colesbukta. The slope angles make up on average 20–28°, but in upper parts of the slopes and in erosional cuts of watercourses reach 45° and more. Within the coastal plain bordering Colesbukta, four marine terraces can be clearly identified: the first one is 5–7 m long, the second one is 10–11 m long, the third one is 25–30 m long, and the fourth one is 50–56 m long. Parts of the terraces stretching along the open shoreline of the bay represent wave-cut platforms. The thickness of their sedimentary cover, as a rule, does not exceed 0.5 m. Deep in the Colesdalen valley, there are marine-built terraces. The thickness of their sedimentary deposits reaches 4–6 meters or more.

The ice cover in the study area is insignificantly developed in comparison with other areas of the archipelago. It is mainly presented by corrie and hanging glaciers and numerous perennial snow-patches. The area of glaciers rarely exceeds 3 km². The glaciers in the study area have been actively retreating over the past 80 years. This intensifies erosion processes and as a consequence increases the input of suspended material into the catchment basin of the Coles River and its further transport into the bay.

3. Materials and methods

Sediment cores were collected from May 3 to May 5 2018 from the r/v “Dalnie Zelentsy”. In our examination we also used material acquired during land expeditions to the Colesbukta area undertaken by scientists at MMBI RAS and PMGE [14] (Fig. 1). Samples obtained from the r/v “Dalnie Zelentsy” were taken with a Van Veen bottom grab sampler and a 150 mm long plastic tube with an internal diameter of 55 mm. A sediment core was cut out with the plastic tube of the density of the sediments, previously taken by the grab sampler, without disturbing their stratigraphy. The thickness of the exposed sedimentary strata ranged from 7 to 13 cm.

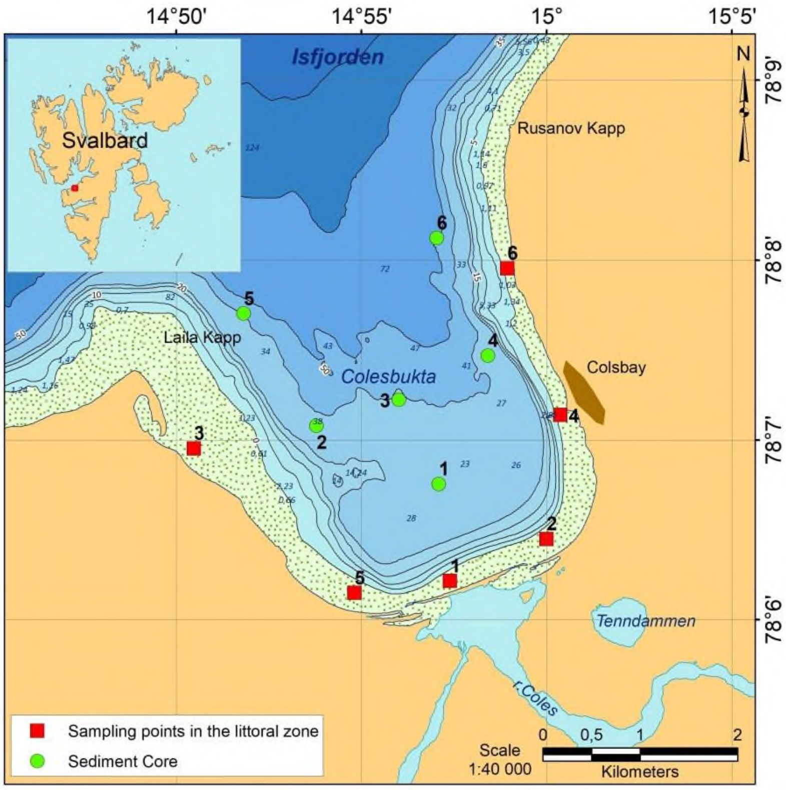

Figure 1. Sampling stations in the study area

The sediment cores taken in the basin of Colesbukta at different distances from the shore (n=6) (Table 1) and the samples of the upper sediment layer (0–2 cm) collected in the littoral zone of Colesbukta (n=6) (Table 2) were used for particle size analysis.

Table 1. Granulometric composition of sediment cores from Colesbukta in %

Layer, cm	>2	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.01	<0.01
				Core 1				
0–1	-	0.6	0.6	0.3	0.7	6.6	41.7	49.5
1–2	-	-	0.2	0.2	0.4	3.4	41.0	54.8
2–3	-	-	-	-	0.3	2.4	42.7	54.6
3–4	-	-	-	-	0.3	2.4	41.3	56.0
4–5	-	-	-	-	0.5	3.9	43.5	52.1
5–6	-	-	-	-	0.4	3.1	44.6	51.9
6–7	-	0.3	0.1	0.2	0.3	3.7	43.5	51.9
7–8	0.9	-	-	0.4	0.4	3.3	41.6	53.4
8–9	1.4	0.3	-	0.4	0.4	4.2	45.6	47.7
9–10	-	0.3	0.3	0.3	0.5	3.4	47.0	48.2
10–11	-	0.4	0.2	0.4	0.4	3.6	46.1	48.9
11–12	-	0.3	0.2	0.3	0.5	3.5	46.5	48.7
12–13	-	0.2	0.3	0.3	0.4	3.0	47.3	48.5
				Core 2				
0-1	3.7	3.7	3.7	3.6	11.0	17.5	20.0	36.8
1-2	10.1	3.9	3.1	3.9	7.4	14.8	21.8	35.0
2-3	5.3	4.3	5.6	2.8	9.0	23.8	22.9	26.3
3-4	7.8	4.9	7.2	5.2	7.8	18.6	24.6	23.9
4-5	12.0	7.8	7.8	4.9	9.4	16.2	21.2	20.7
5-6	9.7	7.3	9.2	5.7	8.2	16.0	19.5	24.4
6-7	8.2	7.9	9.1	4.7	7.5	9.1	18.1	35.4
7-8	4.1	3.4	8.6	6.8	9.4	16.5	24.4	26.8
8-9	3.5	3.2	8.2	7.0	10.5	17.2	27.4	23.0
9-10	7.1	8.2	11.0	6.6	10.4	12.6	19.2	24.9
				Core 3				
0–1	18.1	5.7	3.5	0.1	0.2	0.5	23.0	48.9
1–2	2.5	2.0	3.0	2.0	3.7	7.5	23.7	55.6
2–3	8.0	1.1	2.2	2.0	3.8	6.9	19.2	56.8
3–4	2.0	2.0	2.3	2.0	4.6	9.6	24.5	53.0
4–5	4.6	2.8	2.8	3.0	4.9	8.9	21.4	51.6
5–6	9.5	2.7	3.2	2.3	5.0	9.5	17.2	50.6
6–7	7.5	4.7	4.7	3.3	5.3	8.6	18.7	47.2
7–8	7.3	5.8	5.8	4.0	5.4	6.2	18.5	47.0
8–9	7.6	5.7	5.9	4.0	5.3	6.0	18.4	47.1
9–10	14.0	4.3	5.0	3.1	4.3	5.0	17.1	47.2
				Core 4				
0–1	0.3	0.2	0.2	0.4	0.8	3.2	43.0	51.9
1–2	2.2	0.2	0.5	0.8	1.7	3.3	42.0	49.3
2–3	2.1	-	0.4	0.6	1.3	5.3	41.4	48.9
3–4	-	0.3	0.3	-	1.5	4.5	44.3	48.1
4–5	0.3	-	-	0.5	1.2	6.4	45.1	46.5
5–6	-	-	-	-	1.4	6.2	46.1	46.3
6–7	-	0.1	-	-	1.2	6.0	45.7	47.0
7–8	-	0.2	0.2	0.2	1.0	5.3	40.9	52.2
8–9	-	-	-	-	1.4	6.3	45.8	46.5
9–10	-	-	-	0.3	0.5	4.3	43.5	51.4
10–11	-	-	-	0.5	1.3	6.9	45.1	46.2
				Core 5				
0–1	38.9	5.3	7.3	3.6	5.1	7.0	12.2	20.6
1–2	11.1	6.0	10.0	5.4	1.6	11.4	21.4	33.1
2–3	11.0	6.1	9.8	5.6	1.4	11.6	21.0	33.5
3–4	15.0	3.0	7.6	6.1	6.1	15.3	21.2	25.7
4–5	2.4	1.8	7.2	6.0	9.0	18.0	22.5	33.1
5–6	3.6	2.7	10.4	6.4	10.9	12.7	20.0	33.3
6–7	1.2	.7	5.9	7.6	12.6	8.1	23.4	39.5
				Core 6				
0–1	1.1	1.7	0.7	0.7	2.2	9.5	25.8	58.3
1–2	4.4	0.6	0.6	0.6	2.5	7.6	13.9	69.8
2–3	3.4	1.9	0.7	0.4	1.5	7.9	26.7	57.5
3–4	2.4	0.6	0.6	0.3	1.2	6.1	23.5	65.3
4–5	2.6	0.3	0.6	0.4	1.2	6.3	29.0	59.6
5–6	-	0.7	0.8	0.4	0.9	4.6	27.8	64.8
6–7	12.4	0.8	0.8	0.5	1.0	2.0	25.1	57.4
7–8	2.0	2.8	2.4	0.1	0.3	1.6	24.1	66.7
8–9	4.4	3.3	4.9	2.9	2.7	8.8	23.8	49.2
9–10	1.0	1.3	1.9	1.3	2.6	9.4	26.2	56.3
10–11	7.7	3.4	2.6	1.3	1.7	9.0	24.3	50.0

Table 2. Granulometric composition of the upper layer of bottom sediments from the littoral zone of Colesbukta in % [14]

Sampling sites	>2	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.01	<0.01
1	31.0	27.0	25.4	7.8	2.0	0.8	0.7	5.3
2	21.7	13.0	11.3	7.3	16.8	13.5	9.3	7.1
3	14.6	25.9	21.1	12.1	22.0	0.7	0.6	3.0
4	0.8	0.5	0.4	0.4	59.7	19.5	5.7	9.3
5	56.8	15.8	21.0	4.4	1.0	0.4	0.3	0.3
6	54.9	36.2	4.5	1.1	0.9	0.9	0.5	1.0

Dating of the bottom sediment layers by contents of excess ^{210}Pb and indicator radionuclide ^{137}Cs was performed in cores sampled in the deep layers (Fig. 2). A sediment core was divided into segments, each 1 cm long. Each segment was analysed for granulometry and concentrations of ^{210}Pb, ^{226}Ra, and ^{137}Cs. Grain size analysis was performed using the Baturin–Osborne method. In order to identify the types of bottom sediments, we used Klenova's classification [15].

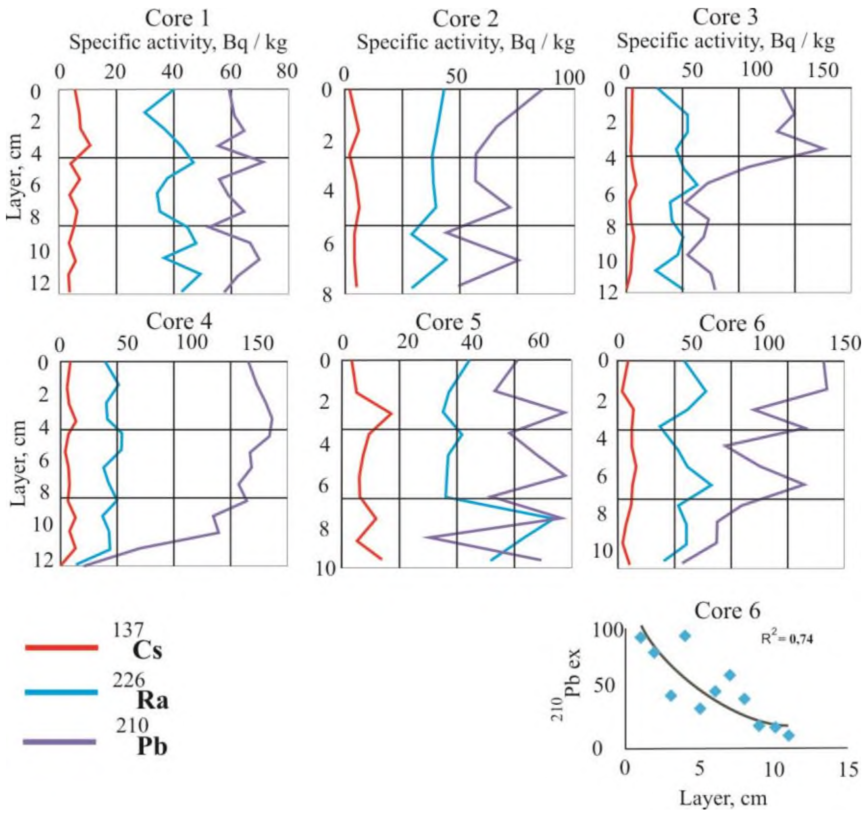

Figure 2. Specific activities of ^{137}Cs, ^{226}Ra, and ^{210}Pb, Bq/kg dry weight

To date the sediment cores, we used the method of dating modern sediments by non-equilibrium ^{210}Pb based on disequilibrium in a series of ^{238}U decay products [16]. The sedimentation rate was calculated using the Constant Flux model (CF) recommended for sedimentation basins with a variable vertical flux of suspended particles [17]. The specific activity of ^{137}Cs was used as a tool to refine the age of sedimentary strata.

Data on the temperature regime and precipitation amount were acquired from the Norwegian Meteorological Institute–NRK database.

4. Results and discussion

4.1. Modern bottom sediments

Sand is reported to be the main type of sediments in the littoral zone of Colesbukta [14]. This type of sediments is distributed in shallow areas of the bay and in the wide intertidal zone with the exception of the southeastern part of Colesbukta. Silty sand dominates the area affected by the runoff of the Coles River. Coarse-grained material brought by storm events accumulates in the upper part of the littoral zone (Fig. 3).

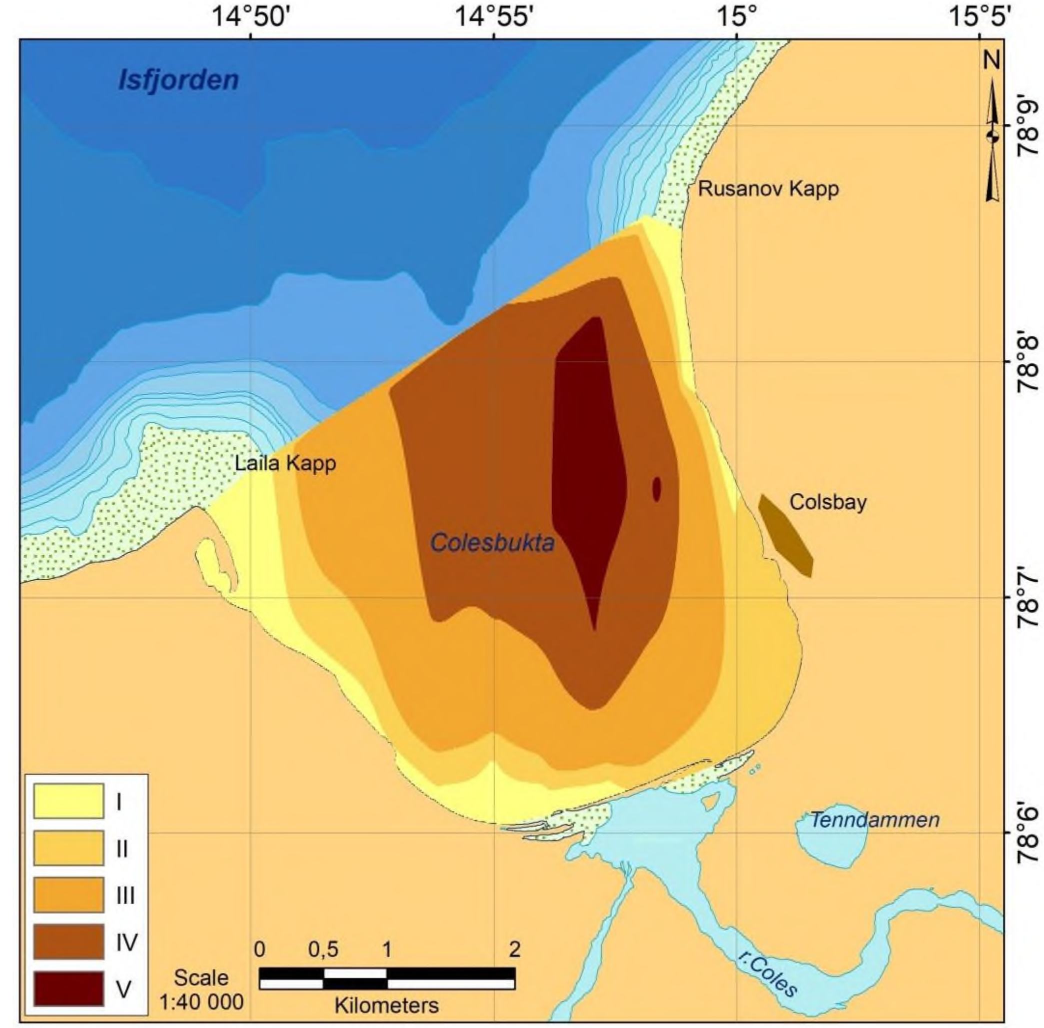

Figure 3. Types of bottom sediments in Colesbukta: I – sand (content of particles <0.01 mm ranges from 0 to 5 %); II – silty sand (content of particle <0.01 mm ranges from 5 to 10 %); III – sandy mud (content of particle <0.01 mm ranges from 10 to 30 %); IV – mud (content of particles <0.01 mm ranges from 30 to 50 %); V – clayey mud (content of particles <0.01 mm above 50 %)

The share of fine-grained material in the sediments increases with depth and the type of bottom sediments changes from sand to silty sand. At sites of the zone affected by Isfjorden, sediments turn into sandy mud and in the deeper central part of the bay into mud. Along the eastern coast of the bay, due to the hydrodynamic features of the distribution of the river runoff over the basin, clayey mud dominates the sediments despite shallow depths.

4.2 Age and type of examined bottom sediments

We found man-made radionuclide ^{137}Cs in all layers of the sediment cores (Table 1). Therefore, the formation of the sedimentary deposits examined in the course of this study happened during the input of this marker into the environment.

In cores 3 and 4 in layers below 11 cm we determined a sharp decrease of the specific activity of ^{137}Cs. We infer that these layers were formed before the 1950s. The results of measurements of ^{210}Pb and ^{226}Ra showed that only core 6 was suitable for dating and calculating the sedimentation rate. The rest of the cores used in the calculations showed an uneven decrease of excess ^{210}Pb with depth. Layers located in zones with an intensified hydrodynamic regime might have been reworked, which hampered the determination of the sedimentation chronology in the basin. For example, at sampling stations 1, 3, and 4 located in the southeastern part of the bay types of bottom sediments were determined to be forming to a greater extent under the influence of the river runoff than as a result of oceanological processes [14]. The granulometric analysis of the cores collected in the bay showed that the sedimentation proceeded evenly and uniformly during the calculated period of time, presumably from 1950 to 2018. The types of sediments formed without significant changes in the fraction content <0.01 (Table 2).

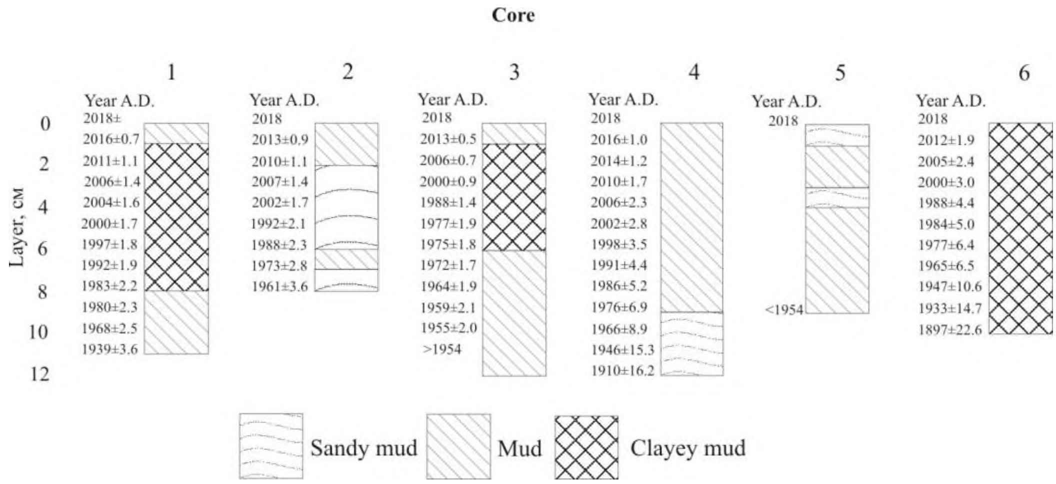

Figure 4. Types and age of bottom sediments from Colesbukta

Sampling stations 2 and 5 are located along the western edge of the trough-like basin of the bay in the zone of tidal currents. The types of bottom sediments in these areas of the bay periodically changed from sandy mud to mud (Fig. 4). Station 6 is located in the northeastern part of the bay and is characterized by the accumulation of extremely fine-grained clayey mud.

4.3 Sedimentation rate

Calculations of the sedimentation rate in Colesbukta show that its values have been increasing since the 1950s. Thus, according to our estimations, in the 1950s the sedimentation rate in all parts of the bay did not exceed 0.1 mm/year. In the 1980s, it varied from 0.1 to 0.2 mm/year. In the early 2000s, values of the sedimentation rate in Colesbukta ranged from 0.15 to 0.4 mm/year. By 2017 they increased to 0.2–0.46 mm/year (Fig. 5). The maximum sedimentation rates were discovered in the southern part of the bay close to the Coles River mouth. In the northern part of the bay, the sedimentation rate is minimal.

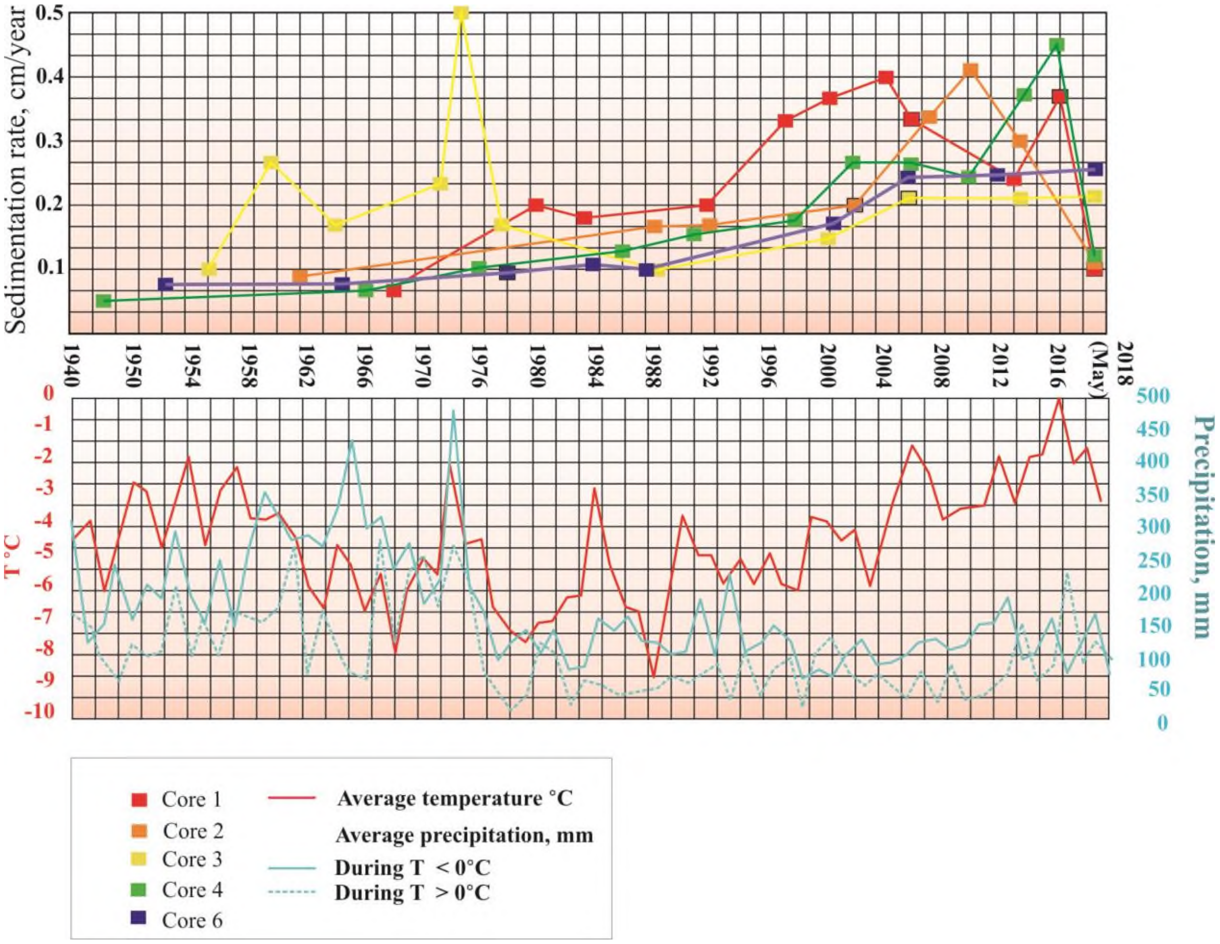

Figure 5. Sediment accumulation rates in Colesbukta and climatic conditions in the Colesbukta area (Norwegian Meteorological Institute and NRK, Longyearbyen station) from 1950 to 2018

We have revealed the correlation between the sedimentation rates determined in cores at all sampling stations in Colesbukta and the changes in air temperature and atmospheric precipitation in the area.

Cores 1, 2, 4, and 6 demonstrate an increase in the sedimentation rate during warm years with increased air temperatures. On the contrary, in abnormally cold years the rate of sedimentation decreased throughout the basin.

An exception is the area of station 3 in the central part of Colesbukta. We have found out that the maximum rates of sedimentation in this area occur during abundant atmospheric precipitation on the catchment area. The geological structure and geomorphological features of the investigated area result in that an increased meltwater and rainwater input into the catchment area of the bay serves as the main driving factor intensifying the outwash of terrigenous material from the catchment area and its transport into Colesbukta.

5. Conclusions

Bottom deposits in Colesbukta are presented by a wide range of different types of sediments, from sand and sandy mud in the littoral to mud in the central part of the bay and clayey mud in its northeastern part. Geomorphological features of the Colesbukta area and the hydrological regime of the bay, as well as the river runoff, are the main factors that influence the formation of bottom sediments. The sedimentation rate has increased 2–4 times over the latest years compared to the middle of the last century and ranges from 0.2 to 0.46 mm/year depending on the part of the basin. At some sites of the bay we have noted the replacement of bottom sediment types by interbedded sediments. The main driving forces affecting the rate of sedimentation in the bay are air temperature and precipitation. An increase in air temperature and the amount of atmospheric precipitation intensifies the influence of geomorphological processes (slumping, crumbling, solifluction, washout, etc.) on the destruction and transport of material from the area of removal to the area of accumulation and deposition. With fluctuations in the mean annual temperature and the amount of precipitation, the values of the sedimentation rate in Colesbukta can change by several times. The most significant factor at the periphery of the sedimentation basin is temperature, while in its central part the leading role belongs to atmospheric precipitation.

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