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ORIGINAL PAPER

# Unusual reaction of diatom assemblage on climate changes during the last millennium: a record from Spitsbergen lake

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**Abstract** A sediment core from the Arctic Revvatnet (Hornsund area, SW Spitsbergen, Svalbard) provided data on environmental changes over the last 3100 years. Diatom analysis showing the domination of planktonic *Cyclotella* forms suggested good edaphic conditions until the middle of the nineteenth century, even during the Little Ice Age. A thermally stratified and relatively stable water column with good mixing allowed small, less heavily silicified *Cyclotella sensu lato* to develop during this time. The climate warming at the beginning of the twentieth century induced intensification of erosion processes in the catchment of the lake and caused an increase in the sedimentation rate. These processes have caused a lack of thermal stratification by disturbances in the water column and an increase of nutrients, consequently driving changes in the diatom species composition, which became dominated by benthic forms. In this period, almost all planktonic taxa disappeared or abruptly decreased in frequency. Higher temperatures accelerated the melting of nearby glaciers, which caused an increase in the activity of diatoms typical of running waters. Also a few Cladocera species appeared at the first time in the youngest samples.

**Keywords** Climate warming · High Arctic · Svalbard · Diatoms · Chrysophyceae · Isotopic data

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## Introduction

The climate changes in the last millennium have been reviewed in many papers (Jones and Mann 2004; Jones et al. 2009; Wilson et al. 2016). Today, the major climate events of this period, namely the ‘Medieval Warm Period’ (MWP), ‘Little Ice Age’ (LIA) and modern warming, are described in relative detail in the Northern Hemisphere. However, the records of these episodes are not so evident in the tropics and Southern Hemisphere (Jones and Mann 2004). Moreover, specific records can exhibit local features, e.g. caused by local geology, hydrology, human activity and differ by localities in mode, timing and magnitude.

The Arctic is changing faster than other regions of the Northern Hemisphere (Serreze and Barry 2011) and hence, lake sediments from the Arctic areas contain a unique record of the alterations occurring in their ecosystems caused by natural and/or artificial factors. The adaptation to extreme living conditions by many organisms, especially aquatic phyto- and zooplankton, means that most of environmental changes were relatively quickly mirrored in community composition due to the short life cycles of these organisms.

The Svalbard archipelago is a great place to study shifts in the environment caused by climate change and its impacts on specific water bodies, glaciers and catchment areas. The location within domain of North Atlantic Oscillation (NOA) and North Atlantic Current makes it a potentially valuable source of data on climate variation in the Northern Hemisphere (Isaksson et al. 2005). Generally, the influence of climate warming in the Arctic regions is commonly known to result in glacial retreat (Nuth et al. 2010; Małecki 2016; Martin-Moreno and Allende-Alvarez 2016), permafrost degradation (Isaksen et al. 2007; Etzelmuller et al. 2011), shorter ice-covered periods (Pienitz et al. 2004), longer growing season (Holmgren et al. 2010). Although the first permanent weather station on Svalbard to make temperature observations was founded in 1912 (Førland et al. 2011), proxy data indicate that climate warming in the Arctic began in the mid-nineteenth century (Smol et al. 2005). The largest increase in temperature was observed after the end of the Little Ice Age (LIA) at approximately the beginning of the twentieth century (Birks et al. 2004; Guilizzoni et al. 2006). The entire following century was characterized by increasing warming with a few colder periods (Isaksson et al. 2001; Perren et al. 2003).

Climate changes, among other abiotic factors such as depth, light, wind action, nutrients concentration, ice-cover duration and water pH, have great influences on aquatic organisms (Rühland et al. 2015). The relationship between water chemistry and temperature and diatom species composition is considerable (Jones and Birks 2004), as temperature affects metabolic processes and has a large influence on the growth rates of diatoms; however, the degree to which changes in temperature translate into changes in the diatom community has been problematic and controversial (Köster and Pienitz 2006).

The study purposed describes the lithology, geochemistry and diatom record from Revvatnet—the oligotrophic lake located in the Hornsund area in the southwestern part of the Spitsbergen. The obtained results will be compared with other data from the region and try to explain why the diatom record from Revvatnet reacted to climate forcing in a way opposite to that from other Spitsbergen lakes (Jones and Birks 2004).

### Study site

Revvatnet lake (77.022°N, 15.368°E) is located in the Hornsund area (SW Svalbard) 5 km northwest of the Polish Polar Station (Fig. 1). It is a moraine-dammed lake at an elevation of 30 m a.s.l. and its area is $\sim$0.9 km$^2$. The lake is composed of two basins: a smaller northern basin and the southern main basin with a maximal depth of 26 m. The lake is supplied by many streams from the west, north and east, and there is one outflow river, Revelva, which runs 2 km to the fjord. This is oligotrophic reservoir has a water pH of 7.6 and a total dissolved solid concentration of 10 mg l$^{-1}$ in the surface water (Ojala et al. 2016). The ice cover is usually 9 months per year. The mean annual temperature at the Hornsund Polish Polar Station is −4.9 °C, and the annual sum of precipitation is 434 mm, with a maximal monthly sum in the August–September period (Marsz and Styszyńska 2013). The catchment area is composed of carbonates and metamorphic rocks, and its geomorphology is characterized by many periglacial features. The catchment vegetation is typical high-Arctic tundra with peat bogs and shrubs.

## Materials and methods

### Sediment sampling and field work

A sediment core 43-cm-long was retrieved from the deepest part of the southern, larger lake basin on 29 April 2008, using a gravity corer. The lake in that location was 26.3 m deep. The core was stored in a plastic tube and transported to the laboratory in cool conditions. Then, the core was split into 1-cm-thick sections.

### Dating methods

The sediment core was dated using a combination of lead-210 (for the topmost section) and radiocarbon methods according to the protocol described and tested by Hercman et al. (2014). Lead-210 activity was measured indirectly by alpha-spectrometry counting

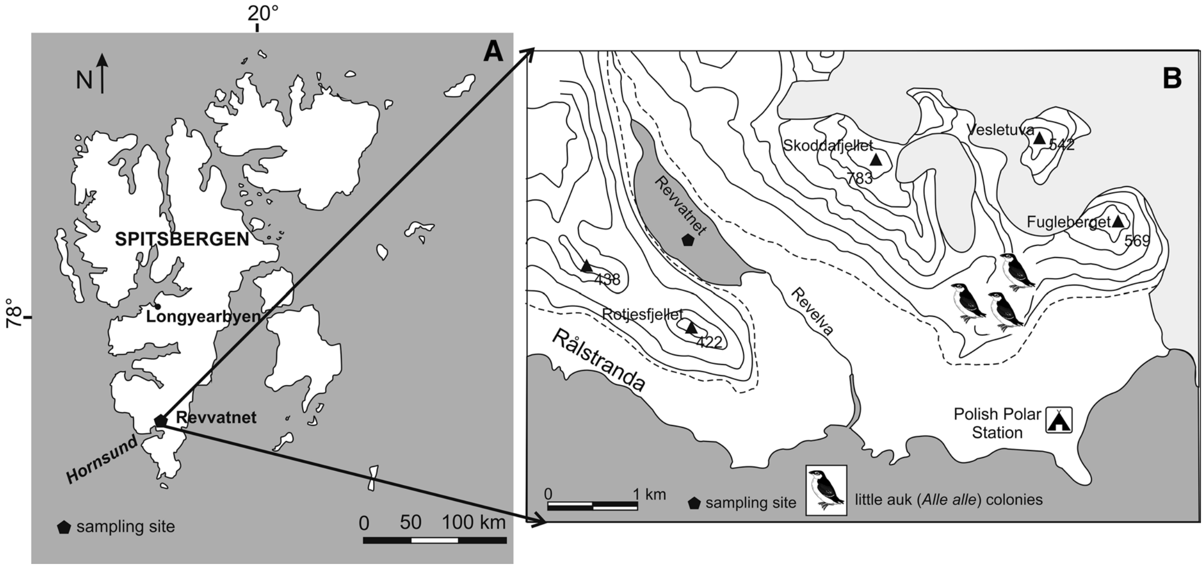


**Fig. 1** The location of Hornsund area (**a**) and Revvatnet (**b**). *Pale grey* glaciers; *grey* lakes and fjords; isohypses every 100 m

of $^{210}Po$ activity. The Constant Rate of Supply (CRS) model (Appleby 2001) was then applied for the age calculations. Terrestrial plant macrofossils from the lower part of the core were radiocarbon dated in the Radiocarbon Laboratory in Poznań (Poland) with an accelerator mass spectrometer. Conventional radiocarbon dates were calibrated with OxCal software (Bronk Ramsey 2009) using an IntCal13 calibration curve (Reimer et al. 2013). Then, the MOD-AGE algorithm was applied (Hercman and Pawlak 2012): age-depth model combining lead and radiocarbon dates was calculated using a randomization method and the LOESS algorithm was used for function fitting.

## Elemental and isotopic analyses

The sediments were pre-treated with hydrochloric acid to remove the carbonate fraction. The organic nitrate and carbon percentages were analysed with a Vario MicroCUBE elemental analyser and the isotopic composition was analysed using a Flash EA 1112 elemental analyser and a Thermo MAT 253 mass spectrometer, which was calibrated using an internal nicotinamide standard. The results are reported as per mill (‰) deviations versus atmospheric $N_2$ ($\delta^{15}N$) and the Vienna Pee Bee Belemnite ($\delta^{13}C$). The analytical errors (1 SD) for the $\delta^{13}C$ and $\delta^{15}N$ measurements were 0.17 and 0.24‰, respectively. This analysis was performed in the Laboratory for Isotope Dating and Palaeoenvironmental Studies of the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw.

## Diatom analysis

Samples for diatom analysis were prepared according to the standard methods (Battarbee 1986). Samples with a volume of 1 $cm^3$ were treated by 10% HCl to remove carbonate and were heated with 30% $H_2O_2$ until all organic material was oxidized. Permanent preparations were mounted with Naphrax® (RI = 1.75). In each sample, except in the interval of core between the depths of 80 and 20 mm where lower concentrations of diatom valves were observed (250–300 valves), approximately 400 valves were counted using an Olympus BX51 light microscope with a 100× oil immersion objective. The main publications used for diatom identification were Krammer and Lange-Bertalot (1986, 1988, 1991a, b) and Lange-Bertalot and Metzeltin (1996). The more recent nomenclature of diatoms from the AlgaeBase data was used (www.algaebase.org). The diatom assemblage zones were defined using constrained hierarchical clustering based on Euclidean distances and the significance of zones was validated with a one-way analysis of similarity (ANOSIM) using the software PAST 3.10 (Hammer et al. 2001).

### Cladocera analysis

Samples for cladoceran analysis were prepared according to the standard procedure described by Korhola and Rautio (2001). Three to six slides from each sample were scanned for remains counting. For each species, the most abundant body part was chosen to represent the number of specimens, and percentages of the sum of specimens were calculated. A stratigraphic diagram could not be assembled due to very low frequencies of remains; consequently, their abundances were only included in a diatom diagram.

## Results

### Lithology, elemental analysis, and stable C and N isotope compositions

The sediment of the studied core was composed of silt, silty clay and silty gyttja with changing concentrations of organic matter (Fig. 2). According to the lithological stratigraphy, the core can be divided into three distinct sections. The lowest section (from 430 up to 290 mm) consisted of massive grey clay with only infrequent, thin and pale lamina in the bottom part. Grey silt and clay with frequent black interbeds composed the middle section (290–75 mm) of the core. A distinct layer of fine sand was recorded at the depth of 160 mm. At the depth of 75 mm, the sediment colour changed to olive yellow, and the black laminations disappeared. A second layer of sand was found at the depth of 5 mm. The density of the sediment typically varied between 1.2 and 1.4 g $cm^{-3}$. In the middle (160 mm) and topmost (5 mm) sections of the core, two fine sand layers with a density of 1.6 g $cm^{-3}$ were observed. The total organic carbon (TOC) concentration was ~2% in the lower and middle sections of the core and decreased to ~1% in the olive yellow clay in the topmost section. Additionally, the sulfur content behaved in a same manner. The stable isotope composition changed along the core, and the most prominent change was noted at the depth of 160 mm (Fig. 2b). Below that horizon, the $\delta^{13}C$ values were −28.0‰ and, except for the depth of 330 mm, did not vary. Above the depth of 160 mm, the values systematically increased up to −25‰ in the olive yellow section. Additionally, a strong change in the C/N ratio was noted in the 160 mm horizon. In the lower section of the core, the C/N value was ~12 and increased to ~20. The nitrogen stable isotope signature did not vary much along the core, but a decreasing trend from the bottom to the top of the section can be observed.

### Core chronology and sedimentation rate

Dating of the sediment core based on the combination of the lead-210 activity profile (Fig. 3a) and four radiocarbon dates (Table 1) was performed. Generally, the lead-210 total activity decreased with sediment depth. However, low activities were also recorded in the topmost samples. The unsupported lead-210 activity was the highest at the depth of 30 mm (183 ± 17 Bq $kg^{-1}$) and disappeared at the depth of 80 mm. The activity of supported lead-210 was 29 ± 8 Bq $kg^{-1}$. The age-depth model indicated that the collected sediment core spans the last 3100 year (Fig. 3b). The sedimentation rate increased in the top section of the core. In fact, the sediment accumulation rate (SAR) increased from the 0.1–0.2 kg $m^{-2}$ $year^{-1}$ in the lower and middle sections of the core to almost 2 kg $m^{-2}$ $year^{-1}$ in the sediments dated to the end of the twentieth century (Fig. 3c). The highest value of SAR was recorded in the topmost sample, where it reached 4 kg $m^{-2}$ $year^{-1}$.

### Diatom stratigraphy in the sediments of Revvatnet

Altogether, 106 diatom taxa belonging to 24 genera were identified in the sediments of Revvatnet. The highest diversity was among benthic genera, such as *Navicula* sensu lato (18 taxa), *Fragilaria* (13), *Achnanthes* (12) and *Pinnularia* (10), while the highest percentage occurrences belonged to planktonic *Cyclotella* spp. (greater than 60% in one sample). In terms of pH preferences, the majority of taxa are indifferent (52.5%) or alkaliphilous (34.5%). The remaining diatoms were acidophilous (12%) or acidobiontic (1%) taxa. The diatom stratigraphy was divided into four Diatom Assemblage Zones (Fig. 4), and the significance of zonation with 10,000 permutations was statistically important ($R = 0.587$, $p = 0.0001$). $P$ values of the borders of specific zone were also significant and had the following values: DAZ 1/DAZ 2—$p = 0.014$; DAZ 2/DAZ 3—$p = 0.0004$; DAZ 3/DAZ 4—$p = 0.032$.

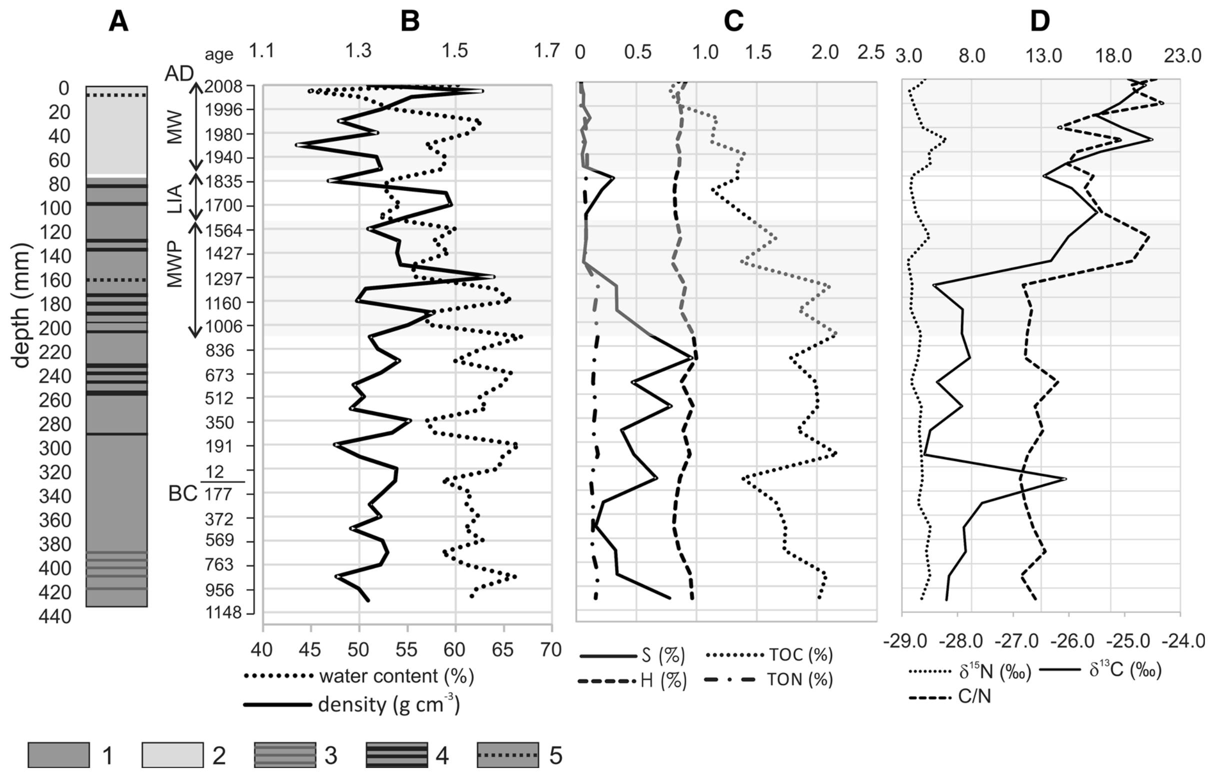


**Fig. 2** **a** Lithology; **b** water content (%), density (g cm$^{-3}$); **c** elemental analysis (C, H, N, S) of organic matter from the sediment sequence of Revvatnet and **d** stable isotope composition of carbon and nitrogen and molar C:N ratio in bulk sediment samples from the Revvatnet. Key to lithology: *1* massive grey clay; *2* olive yellow clay; *3* pale, indistinct lamination; *4* dark lamina; *5* sandy layers

Zone 1 (430–260 mm; 1052 BC–511 AD)

This zone is characterized by the occurrence of planktonic *Lindavia rossii* (Håkansson) T. Nakov et al., *Cyclotella comensis* Grunow*, C. distinguenda* var. *unipunctata* (Hust.) Håkansson & Carter and a small form of *Fragilaria* sp. Although less frequent, the benthic *Sellaphora pupula* was also present. The proportion of benthic to planktonic taxa was comparable in this period. Initially, the quantity of Chrysophyceae cysts was equal to approximately 20% in the relation to diatoms but subsequently increased in abundance by approximately 10%.

Zone 2 (260–60 mm; 511–1867 AD)

In the middle part of the zone, the same diatoms as in the previous zone dominated. In the upper part of this interval, first *Pinnularia nodosa* (Ehr.) Smith increased their frequency, then *Lindavia rossii* reached maximum abundance, while quantities of *Cyclotella comensis* and *C. distinguenda* var. *unipunctata* decreased. The end of this zone is characterized by an abrupt decrease or disappearance of some planktonic species. The amount of Chrysophyceae cysts varied between approximately 20 and 40%.

Zone 3 (60–15 mm; 1867–2000 AD)

This zone is characterized by the maximal frequency of benthic diatoms. Many periphytic species, such as *Achnanthidium minutissimum* sp. group, *Encyonema silesiacum* (Bleisch) Mann, *Ceratoneis arcus* (Ehr.) Kützing, and *Navicula cincta* (Ehr.) Ralfs, appeared or increased in abundance. Benthic taxa constituted greater than 90% of the diatom population. Chrysophycean cysts increased in quantity and reached its maximum (<60%) in the upper part of the zone.

Zone 4 (15–0 mm, 2000–2008 AD)

This part of the core encompasses only three samples and corresponds to the youngest sediments. The

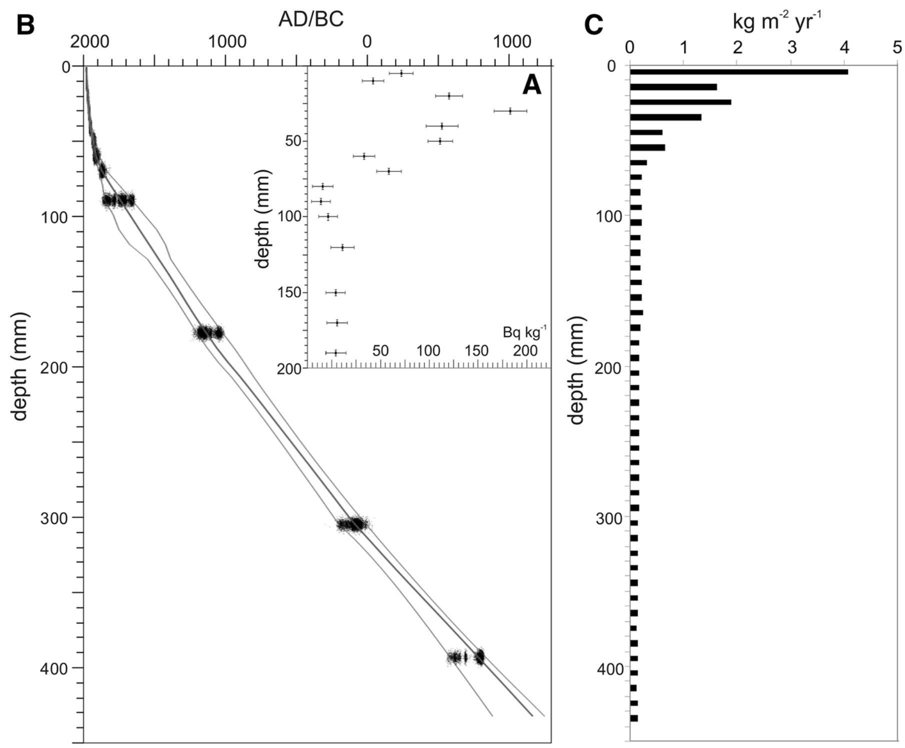


**Fig. 3** **a** (inset into panel **b**) Allochthonous specific activity of $^{210}$Pb in the sediment sequence of Revvatnet; **b** age-depth model (*bold solid line*) and its confidence bands (*fine solid lines*); probability of distribution of radiocarbon dates was indicated with *dots*; **c** changes in sediment accumulation rate (SAR) as recorded in the sediment sequence of Revvatnet

**Table 1** Radiocarbon dates from the sediments of Revvatnet. Calibration was done with OxCal ver 4.2 software (Bronk Ramsey 2009) using IntCal13 calibration curve (Reimer et al. 2013)

| Sample name | Lab. no | Depth (cm) | Dated material | $^{14}$C date BP | Calibrated range (2σ) |
|---|---|---|---|---|---|
| REV 9 | Poz-79559 | 9 | Wood | 150 ± 30 | 1667 (16.3%) 1709 calAD |
| | | | | | 1717 (31.4%) 1784 calAD |
| | | | | | 1796 (30.0%) 1890 calAD |
| | | | | | 1910 calAD (17.7%) … |
| REV 18 | Poz-79560 | 18 | Plant remain | 880 ± 30 | 1042 (27.0%) 1105 calAD |
| | | | | | 1117 (68.4%) 1222 calAD |
| REV 31 | Poz-27823 | 31 | Plant remain | 1895 ± 35 | 29 (95.4%) 220 calAD |
| REV 40 | Poz-27824 | 40 | Plant remain | 2565 ± 30 | 806 (95.4%) 556 calBC |

biggest change in diatom assemblages with respect to the previous zone is a gradual increase in planktonic taxa, especially *Lindavia rossii*. Some benthic diatoms and Chrysophyceae cysts decreased in frequency.

## Cladocera analysis

The cladoceran remains abundance was very low throughout the entire core and did not exceeded 200 individuals per 1 cm$^3$ of sediment. The concentration of remains was too low to create a stratigraphic diagram, and the presence of cladoceran remains was indicated in the diatom diagram (Fig. 4). In total, remains of 4 taxa belonging to 2 families were identified. The most abundant was *Chydorus sphaericus*, which was recorded in samples from all sections in the core. *Daphnia sp.* ephippia and carapaces were found only in samples from the lower section. *Alona affinis* and *Alonella nana* remains were found only in the two topmost samples.

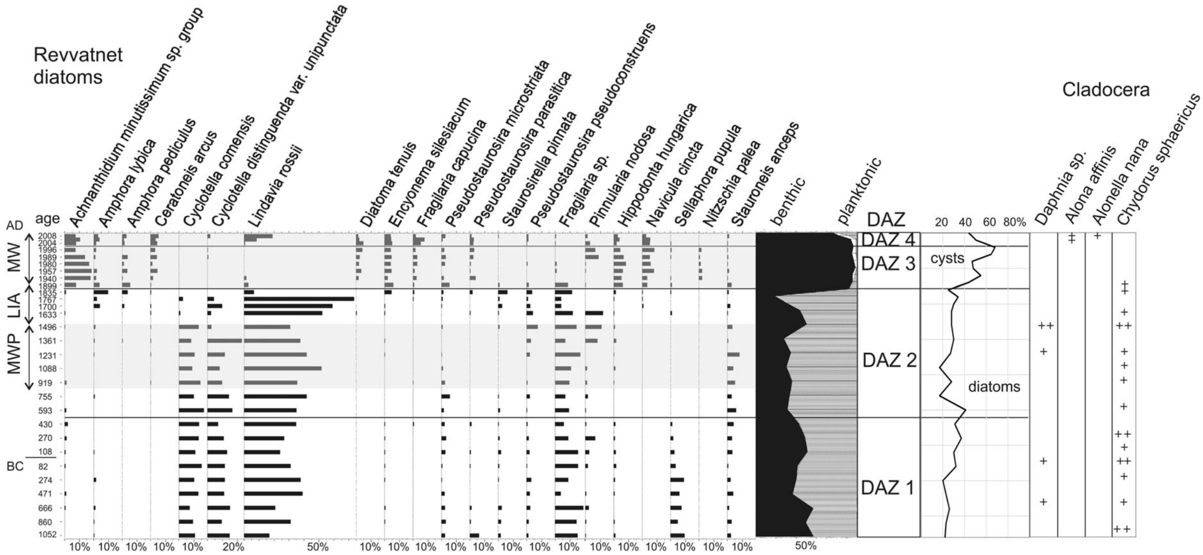


**Fig. 4** Relative frequency diagram of the most dominant diatom taxa (>5% in any one sample), the ratio of diatom frustules to chrysophycean cysts and Cladocera remains recorded in the sediments of Revvatnet

## Discussion

During the last millennium the main climatic events observed in Northern Hemisphere were Medieval Warm Period (MWP, 900–1500 AD), Little Ice Age (LIA, 1500–1900) and modern warming (1900 to present) (Spielhagen et al. 2011; Jernas et al. 2013). In the European Arctic the alterations in climate are link with the transport of warm and saline Atlantic Water (AW) by the West Spitsbergen Current (WSC). The most inflow of AW into the Arctic Ocean is observed in the last thirty years. On Svalbard the environmental conditions in the MWP and the early LIA were relatively stable (Pawłowska et al. 2016). Even during the LIA, the summers at this area were not particularly cold although glaciers occupied their maximum Holocene extent. The presence of glaciers was rather connected with high winter precipitations than low temperatures (D'Andrea et al. 2012). The end of the LIA resulted in the gradual increase in temperature, which caused the retreat of glaciers and substantial transformations in unstable glacigenic sediments. The most spectacular climate changes in the Arctic took place before the 1940s and is often called "early twentieth century warming" (Førland et al. 2011). In the consequence the majority of the glaciers on Svalbard withdrew by up to 2 km. An increase in temperature caused a negative glacier mass balance, i.e., the difference between accumulation and ablation, and a significant increase of SAR in the lake. Since then, extreme precipitation events have destabilized and reactivated sediment delivery to the coast and water bodies, forming debris flows, slush avalanches and solifluction tongues. Sometimes, huge sediment inputs created new landforms, such as barriers, deltas, spits and tidal flats (Strzelecki et al. 2015). Further climate warming will likely result in increases in the SAR and a negative glacier mass balance in the future.

Enhanced sediment input from the catchment is associated with a higher concentration of nutrients. However, in the Arctic regions, poor vegetation density and diversity caused by low temperature and the type of bedrock are responsible for common nutrient limitations in the catchment areas. Vegetation cover consists mainly of mosses, lichens, vascular plants of low stature and low productivity (Zmudczyńska-Skarbek et al. 2013). In the polar desert zone, the formation of soil is mainly determined by temperature and permafrost regimes. Soils are usually very shallow and deficient in available phosphorus and nitrogen. Thus, many lakes located on the Svalbard archipelago remain oligotrophic despite substantial deliveries of allochthonous material. On the other hand, warmer temperatures accelerate litter and soil organic matter decomposition and nutrient mineralization what caused an increase in algal biomass as a result of higher nutrient inputs to aquatic ecosystem (Jonasson et al. 1999). Other important factor influencing the nutrient budget of these ecosystems is connected with the presence of seabird colonies on the island. The amount of biogenic compounds generated by colony of polar coastal birds is much larger than that originating from other sources such as atmospheric N deposition from fossil fuel combustions, sea spray, biogenic N fixation by some species of cyanobacteria (Cocks et al. 1998; Zmudczyńska-Skarbek et al. 2013). Seabirds feed both at the ocean's surface and below it, but breed on land, often many kilometres from the sea shores and most of them nest in colonies, which can vary in size from a few dozen birds to millions. Vegetation developing around colonies is called 'ornithogenic tundra' rich in biogenic compounds. Due to the tonnes of excrement deposited in this area, the trophic status of lakes located close to seabird colonies increases by nutrient influx transported to the water bodies. So, changes in the Arctic aquatic ecosystems are caused by many biotic and abiotic factors. An influence of these alterations is recorded in the sediments of Revvatnet located in the south-western part of Spitsbergen. The most spectacular shift in the lake evolution was marked at the end of the LIA, which was mirrored in the diatom assemblages. These changes were surprising due to the near-complete disappearance of planktonic diatoms in the post-1900 sediments—the indicators of climate warming, although they were dominated in the earlier colder periods.

## Evolution of Revvatnet

### *Changes in the lake until the second half of the nineteenth century*

Previous studies (Karczewski et al. 1981) suggested that Revelva valley was covered with ice approximately 2400 yrs BP. The presented age-depth model indicates that the age of the bottom sample from the study core is 3100 ± 80 yrs BP. The differences between former and present datings of lake age are a result of indirect age estimation in former studies based on radiocarbon datings of marine terraces from other localities in the region. Present datings of terrestrial plant macrofossils from the bottom section of the studied core are more reliable. Therefore, the lake existed before the glaciers' advance 2500–2400 cal. BP (Svendsen and Mangerud 1997). There is no lithological, elemental, isotopic or biological evidence that the lake basin was covered by a glacier during the cooling around 1700 cal. yr. BP (Røthe et al. 2015) and during LIA. The similar interpretation of lacustrine record from the lake was given by Ojala et al. (2016). From the beginning of the lake sediment record to the second half of the nineteenth century, the changes in diatom community were relatively slight. Some minor changes in species composition of benthic forms (e.g. decline of *Sellaphora*) were recorded around 500 AD. In the majority of the samples, the frequency of planktonic diatoms exceeded 50%. The diatom assemblages were characteristic for deep, circumneutral oligotrophic lakes. The lake was dominated by small planktonic *Cyclotella sensu lato*, including *Lindavia rossii, C. comensis* and *C. distinguenda* var. *unipunctata*, with small forms of benthic *Fragilaria* sp. The beginning of *Cyclotella* blooming during the vegetation period starts when lake is still partly ice covered and when there is a sufficient amount of light for photosynthesis. The main bloom of *Cyclotella* occurs under open water conditions in the summer months (Lotter and Bigler 2000). Small *Cyclotella* forms have less heavily silicified cells, which suggests a thermally stratified and stable water column with little mixing. Their occurrence points to warmer temperature and a longer growing season. Even during the Little Ice Age with more ice sheet, shorter open water season and late-winter anoxia, lake water conditions were good enough for development of planktonic diatoms. Probably, it was an effect of not very low summer temperatures (D'Andrea et al. 2012) and the lack of glaciation of the lake in the LIA period (Ojala et al. 2016). The amount of chrysophycean cysts in this period varied between approximately 20 and 40%. The predominance of diatoms over Chrysophyceae suggests a longer growing season and relatively good availability of light and nutrients (Smol 1985). From the beginning of lake sediment record until approximately 1230 AD (at depth 17 cm), the $\delta^{13}C$ values were relatively stable (approximately −28‰) except one sample at the depth of 330 mm, where the value increased to −26‰ (Fig. 2). In contrast, the $\delta^{15}N$ curve exhibited a slightly decreasing trend. In the same period, the C/N ratio indicated the source of organic matter was phytoplankton with a small component of terrestrial plants. At the beginning of the LIA, the C/N ratio and isotopic values reached relatively high values (depth 120 mm; ~1500 AD), but during the LIA their values generally decreased. Surprisingly, during the LIA, the quantity of chrysophycean cysts indicated a short growing season, only slightly increased, while the frequency of benthic diatoms decreased. This could be due to relatively good conditions for the development of primary production occurring in the lake located in the southern part of Spitsbergen.

*Changes in the lake sediments since the second half of the nineteenth century to the end of the twentieth century*

Abrupt changes in diatom communities have occurred since the second half of the nineteenth century. In that time, the frequency of benthic species has increased above 90%. In contrast to earlier years, there were no strongly dominant taxa, but the highest abundance belongs to the *Achanthidum minutissimum* sp. group. These taxa are widespread and abundant in different types of life environments, common in circumneutral and alkaline waters with low or moderate concentrations of nutrients and organic pollution. Changes in the lake ecosystem could be an effect of various processes associated with the end of the Little Ice Age, which on Svalbard ended at approximately 1900 AD (Szczuciński et al. 2009). The rapid deglaciation caused an increase in the sediment accumulation rate (SAR) due to the glacial erosion and the increase in the erosion of terrestrial sediments (Szczuciński et al. 2009). In the sediments of Revvatnet, a clear increase in SAR occurred after 1899 AD (at 70 mm depth) (Fig. 3c). The glaciological changes in the catchment and terrain evolution surrounding Revvatnet, which resulted in a huge sediment flux to the lake, likely influenced the changes in the lake ecosystem at the end of the nineteenth and throughout the twentieth century. Although, higher temperatures usually contribute the growth of phytoplankton, in the case of Revvatnet, it seems that the intensive physical and chemical alterations in the lake caused higher development of benthic diatom assemblages. Climate-derived catchment processes, such as high minerogenic turbidity, hindered light penetration into the water column and in consequence, the expansion of planktonic diatoms. The disappearance of small *Cyclotella* could also be caused by much higher energy in the water environment (i.e. disturbances of thermal stratification and water transparency) as a result of the post-LIA processes. Such environmental conditions are more favourable for chrysophycean cysts because they are heavier silicified than diatom frustules (Smol 1985). During this time in Revvatnet, cysts of golden algae reached their maximum abundance (Fig. 4) what suggests a high-energy lake's environment. Despite the globally increasing temperature since the end of the LIA, two or three colder periods occurred in the last century on Svalbard (Guilizzoni et al. 2006). Lower temperatures, shorter growing season and more oligotrophic conditions have also been confirmed by an increase of chrysophycean cysts in Revvatnet in the 1940s and 1980–1990s, which coincided with the colder episodes noted in other lakes on Svalbard (Isaksson et al. 2003; Perren et al. 2003; Guilizzoni et al. 2006). Moreover, the relative abundance of diatom frustules noticeably decreased compared to the previous periods. Poor preservation of diatoms, especially less silicified ones, could be related to higher alkalinity and dissolution.

At the end of the LIA, diatoms typical of rivers and streams, such as *Ceratoneis arcus* and *Navicula cincta*, appeared or relatively increased in frequency, i.e. the lake received large minerogenic inputs from running waters. Their occurrence is an effect of the increase in running waters caused by the higher-temperature-related melting of the nearby glaciers. The delivery of allochthonous organic matter was also visible earlier, before the Little Ice Age (at depth 150 mm, 1360 AD), which was confirmed by an increase in the C/N value (to a value of approximately 20), and this tendency has been maintained to the recent times. A high C/N ratio indicates the intensity of the processes occurring inside and outside the lake (Meyers and Laillier-Vergés 1999).

The studies of peat sediments collected from the Hornsund area in 2008 and located in the vicinity of little auk (*Alle alle*) colonies showed that the highest $\delta^{15}N$ value was up to +15‰ (Gąsiorowski and Sienkiewicz unpublished data). Approximately one kilometre away from Revvatnet, the population of little auks breeding (Fig. 1) and their activity also affects the environment close to the nesting. Minerals and biogenic compounds including guano, dead chicks, adult birds and eggs, occur between the feeding place at the ocean and the breeding place on land, and are delivered to the lake along with eroded material from the catchment and running waters. In the sediments of Revvatnet, the $\delta^{15}N$ value reached its maximum value of +6.20‰ in the middle half of the twentieth century. It was higher than typical pollution of nitrate and ammonium fertilizers, which values of $\delta^{15}N$ varied between −3 and +3‰ (Wolfe et al. 2003) which suggests an influence of seabird colonies on the lake ecosystem. On the other hand, the amount of nutrients available for phyto- and zooplankton has not become excessive because Revvatnet is still an oligotrophic lake (Ojala et al. 2016). In the second half of the twentieth century, the isotopic signal of nitrogen decreased but still maintained relatively high values. The $\delta^{13}C$ curve follows a comparable trend as the $\delta^{15}N$ curve. Initially, the values of the carbon isotopic composition increased; then, in the second half of the twentieth century, the values decreased by approximately 1.5‰. During this time, the $\delta^{13}C$ values were the highest of the entire record, which suggests that the main source of organic carbon was from freshwater aquatic plants with some input from terrestrial plants (Zong et al. 2006). This finding was also confirmed by high C/N ratios (14–22). This was likely connected to different types of mass movement, unstable physical and chemical conditions, and intensification of erosion and slope processes that occurred in the post-LIA period. The curve of total organic carbon (TOC) indicates a decreasing trend (1.34–0.87%), but the low values of sulfur, total organic nitrogen (TON) and hydrogen were relatively constant.

### *Changes in the lake sediments during the twenty-first century*

Although sediments deposited during the twenty-first century were recorded only in three samples, changes in diatom community and chrysophycean statospores were observed. The main shifts in these two groups of algae were associated with the gradual development of planktonic taxa and the decrease in the frequency of Chrysophyceae cysts. These shifts were likely an effect of the continuous increase in temperature. The global change-induced warming of the Arctic has been observed since the end of the 1990s (Serreze et al. 2009; Lang et al. 2015). For two to three decades warm Atlantic Water (AW) inflow in the Arctic Ocean is anomalous and unique during the last 2000 years (Spielhagen et al. 2011). In the sediments of Revvatnet, the re-appearance of *Lindavia rossii* and the decrease in the relative abundance of chrysophytes confirmed increases in both temperature and trophic level. The occurrence of planktonic taxa suggests open water conditions and a longer growing season, i.e., an increase of primary production. Also, the cladoceran remains indicated that the last decade was an extraordinary period because, during this time, two cladoceran taxa (*Alona affinis* and *Alonella nana*) never recorded before in the core were identified. The amount of TOC also follows this trend but to a minimal extent (Fig. 2). During the approximately 8 years (~2000–2008 AD), the $\delta^{15}N$ values increased by more than 1‰, while the values of $\delta^{13}C$, sulfur, hydrogen and total organic nitrogen remained almost the same. The C/N ratio indicates that the organic matter was, as in previous years, an admixture of phytoplankton and vascular plants.

### Comparison with other lakes located on Svalbard and other Arctic regions

Many studies of sediment cores collected from lakes and their surrounding areas on Svalbard and other Arctic regions have shown striking changes in the sediments accumulated at the end of the nineteenth century (Rühland et al. 2003; Jones and Birks 2004; Birks et al. 2004; Smol et al. 2005; Guilizzoni et al. 2006; Lim et al. 2008; Szczuciński et al. 2009; Holmgren et al. 2010; Strzelecki et al. 2015). Research has been conducted on the biotic communities living in lakes and the sedimentology and geochemistry of lake sediments to study the evolution of the Svalbard coastal zone. The main factor responsible for these alterations (i.e. an increase in the sediment accumulation rate, changes in biota community, retreat of glaciers) is the twentieth century climate warming following the end of the Little Ice Age. However, these environmental changes do not reflect to a similar extent in an earlier warming episode i.e., in the Medieval Warm Period (MWP). In the MWP and at the beginning of LIA, the environmental conditions were relatively stable with a low SAR (Pawłowska et al. 2016). In the diatom record of Revvatnet, a relatively high frequency of *Cyclotella sensu lato* was observed, what confirms favourable conditions to phytoplankton development (Fig. 4). However, similar taxa occurred in the earlier colder period with a slightly higher amount of benthic diatoms in comparison to the MWP. Sediment accumulation rates indicate stable conditions in the lake environment without a huge delivery of eroded material from the catchment up to the end of the nineteenth century (Fig. 3c). The lack of rapid processes and the small alterations in diatom record in the MWP, contrary to the modern warming period, probably could be explained by two periods of relative summer warmth (1010–1060 AD and 1160–1250 AD were 2 and 2.5 °C colder, respectively), than temperatures since the second half of the twentieth century (D'Andrea et al. 2012) and a lacustrine response to climate change which was not so evident. In many investigations from Northern Europe no clear peak in temperature and fossil record was observed at these times (Bradley et al. 2003; Bjune et al. 2009; Pawłowska et al. 2016). Seppä et al. (2009) consider the MWP as a part of a longer warm period before the onset of the LIA. The crucial conditions for stable percentages of planktonic *Cyclotella*,regardless of climate fluctuation, was a stable lightly turbid condition and water stratification. The sediment lithology indicates stable conditions until the beginning of the twentieth century (Fig. 2). The higher energy of the environment, caused probably by exceptional volume of melting water and inorganic particles supplying the lake basin, crushed the *Cyclotella* population.

One of the factors confirming the effects of modern climate warming in the Arctic lakes is the shift in the diatom community from benthic to planktonic (Rühland et al. 2003; Smol et al. 2005; Hobbs et al. 2010). Higher temperatures have caused ice cover to be less extensive, the growing season to be longer with greater production, and the zone of open water (needed for the development of planktonic taxa) to be greater. However, many lakes on Svalbard are not deep enough for colonization by planktonic diatoms; thus, their absence cannot be used as an indicator of climate change and is instead the result of the local geology. In the post-1900 period in some high-elevation mountain lakes of the northern Canadian Cordillera, a rapid eroded processes, an increase of SAR, inwash of soil, turbidity, and an easily-weathering sedimentary bedrock generated external inputs of carbonate and base cations to the lakes during open water season. It caused lakes to become more productive with diverse assemblage of periphytic diatoms and higher alkaline lake water conditions (Karst-Riddoch et al. 2005). On the other hand, in some regions, including northern Quebec and Labrador, an increase in temperature was not observed and no considerable changes in algal assemblages have occurred (Joynt and Wolfe 2001; Smol et al. 2005) and they have a potentially higher exposure to anthropogenic impacts than remote Arctic lakes (Hausmann and Pienitz 2009). In some Canadian High Arctic relatively shallow water bodies, the benthic diatom community dominated the pre-1850 period was replaced by different, more diverse also benthic assemblages in recent sediments (Antoniades et al. 2005; Lim et al. 2008).

In the case of the relatively deep Revvatnet, located in an area where climate warming was confirmed by instrumental records and other proxies, the diatom compositional turned during the twentieth century. Since the greatest increase in temperature after the LIA, benthic taxa have represented more than 90% of the diatom flora population, by comparison with earlier periods, when the lake was generally dominated by phytoplankton. A similar situation was observed in Kongressvatnet, but the predominance of benthic diatoms was only episodic and corresponded to the coldest periods of the twentieth century (Guilizzoni et al. 2006). In the sediments of Revvatnet, the frequency of benthic taxa remained almost unchanged, but the coldest years of the last century were mirrored in an increase of chrysophycean cysts. In two other deep lakes located on Svalbard (Birgervatnet and Arresjøen), planktonic *Cyclotella sensu lato* also occurred (Jones and Birks 2004). In the latter lake, diatom plankton disappeared before the beginning of the twentieth century, which can be explained by a change in the light regime related to an increase in turbidity caused by catchment erosion and inwash of allochthonous material to the lake. A significant increase in planktonic taxa in the sediments of Birgervatnet was observed after ca. 1950 AD, which was connected with the recent climate warming (Jones and Birks 2004). However, temperature is only one of the factors controlling the distribution of *Cyclotella sensu lato*. In southwestern Greenland, increases in *Cyclotella* were associated with neoglacial cooling in some lakes but with the twentieth century warming in others (Perren et al. 2012). An important factor is also wind strength, which determines the thickness of mixed surface water modified by inputs of dissolved organic carbon (DOC) from the catchment. Higher values of DOC are associated with lower light availability (Saros and Anderson 2015). The next driver impacting *Cyclotella* communities is thermal stratification. Nevertheless, high frequencies of these diatom taxa were observed prior to lake stratification (Thackeray et al. 2008) and when water column stability was high (Saros et al. 2012). These observations were made in Arctic, alpine, boreal and temperate lakes.

The main basin of Revvatnet was definitely not glaciated during the LIA. At the end of the nineteenth century and beginning of the twentieth century, higher temperatures activated processes that could cause faster and much more intensely than in glaciated areas. The sediment accumulation rate in Revvatnet lake varied between 0.21 and 1.89 kg $m^{-2}$ $year^{-1}$ during the twentieth century. The highest value of SAR was observed in the twenty-first century and equalled 4.06 kg $m^{-2}$ $year^{-1}$, which can be considered as slump event. Much lower sediment accumulation rates were observed in other lakes located to the north of Revvatnet, ranging from 0.02 to 0.50 kg $m^{-2}$ $year^{-1}$ (Appleby 2004). Episodes of higher sediment accumulation rates affect the mixed water and light conditions of the lake. Processes causing alterations in the availability of light (e.g. changes in water column stability and water clarity) and nutrient concentrations are responsible for changes in the small *Cyclotella* succession in the Arctic (Saros et al. 2014). Moreover, the increasing input of inorganic matter during the twentieth century may have diluted the concentration of diatoms. It was detected in the decline in $^{210}Pb$ activity that was observed in the upper part of the Revvatnet sediments. Similar events are known from other Arctic lakes (Appleby 2004; Holmgren et al. 2010). Low concentrations or lack of diatoms could also be the result of strong dissolution of the valves. Moreover, there is activity of anaerobic sulfur photosynthetic bacteria, which would indicate that a long ice-covered period with a scarcity of light and nutrients, precluded extensive algal growth (Guilizzoni et al. 2006). Additionally, in the sediment of Revvatnet diatoms typical for running waters could cause a dilution of planktonic taxa and the relative increase in benthic diatoms from the littoral zone to central part of the lake. Moreover, the lengthening of the vegetation period could cause enhanced growth of aquatic plants and increased availability of benthic habitat for the growth of periphytic diatoms (Karst-Riddoch et al. 2005).

## Conclusions

1. The age-depth model indicated that the lake basin has not been covered by glaciers since at least 3100 BP. Therefore, the present lake is at least 600 years older than previously estimated.
2. From the beginning of the lake sediment record, including the MWP and LIA, to the end of the nineteenth century, Revvatnet was dominated by small planktonic *Cyclotella* and a small form of *Fragilaria* sp. The dominance of less heavily silicified cells of planktonic species suggest thermally stratified and relatively stable water column conditions with little mixing. The relatively low ratio chrysophycean cysts to diatoms indicate good edaphic conditions and a high water level.
3. At the end of the nineteenth century and during the twentieth century (post-LIA period), climate warming caused an increase in the sediment accumulation rate (SAR), which affected the thermal stratification, amount of nutrients (an increase of $\delta^{15}N$) and significant changes in diatom assemblages (almost a complete disappearance of *Cyclotella sensu lato*). The lake was dominated by periphytic diatoms with a conspicuous increase in species typical of running waters. A high-energy water environment caused an increase in turbidity and a decrease in light availability, i.e., more unfavourable conditions for the development of planktonic taxa. Mass input to the lake and an increase of running water diatoms could also dilute the concentration of planktonic diatoms and the $^{210}Pb$ activity in the upper part of the core.
4. Generally, sediment accumulation rates were higher at the more southerly location of Svalbard archipelago. In Revvatnet, the SAR and different processes initiated by climate change, especially during the twentieth century, caused more rapid and intense changes in the diatom community than in lakes located in the northern part of Svalbard.
5. Atmospheric contamination did not affect the diatom community in the study lake, but an increase in $\delta^{15}N$ values at the beginning of the twentieth century was caused by the influence of a

little auk colony in the vicinity of Revvatnet and in some extent of the fossil fuels combustion.

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