

## **Assessing the environmental significance of benthic foraminiferal morpho-groups from the northern high latitudinal regions**

**R. Saraswat<sup>1\*</sup>, C. Roy<sup>2</sup>, N. Khare<sup>3</sup>, S.M. Saalim<sup>1</sup>, S.R. Kurtarkar<sup>1</sup>**

1 Micropaleontology Laboratory, National Institute of Oceanography, Goa, India

2 Oil and Natural Gas Corporation, India

3 Ministry of Earth Sciences, Prithvi Bhawan, Lodhi Road, New Delhi, India

(\* For Correspondence: rsaraswat@nio.org)

### **Abstract**

The spatial distribution of benthic foraminiferal morpho-groups has been documented from the Kongsfjorden-Krossfjorden, to assess its environmental significance. Benthic foraminiferal abundance increases from the inner-most fjord towards the mouth in Kongsfjorden. The calcareous forms dominate the benthic foraminiferal population in Kongsfjorden as compared to Krossfjorden. The agglutinated benthic foraminifera are relatively more abundant in Krossfjorden. The rounded symmetrical benthic foraminifera are the dominant morpho-group, due to the high energy conditions and generally well-oxygenated waters. A significant positive correlation between the relative abundance of rounded symmetrical benthic foraminifera and water depth, however, suggests the influence of factors other than turbulence. A more significant positive correlation is observed between the relative abundance of agglutinated rounded symmetrical benthic foraminifera and water depth. The relative abundance of calcareous angular asymmetrical benthic foraminifera is significantly negatively correlated with water depth. The significant correlation between foraminiferal parameters and water depth, suggests that melt-water and glacial calving, as well as associated changes in the sedimentation rate, grain size, pH and organic carbon, affect benthic foraminifera in high latitudinal fjords. The difference in the surface distribution of calcareous and agglutinated benthic foraminiferal morpho-groups implies their differential response to ambient conditions.

## Introduction

The high northern latitudinal region is very sensitive to climate change. A widespread ice-loss and rapidly shrinking ice-extent in the Arctic region, are a major concern. The long-term records of ice-extent, especially during distinct paleo-boundary conditions can help to constrain anthropogenic and natural contribution to the ice-sheet variability in this region. Foraminifera, being sensitive to ambient conditions, are a potential tool to reconstruct past fluctuations in ice-sheet extent and associated processes. A proper application of foraminiferal proxies, however, requires, a better understanding of the ecological preferences of foraminifera from these high latitudinal regions. Several workers documented modern distribution of benthic foraminifera from the fjords (Risdal, 1964; Alve and Nagy, 1986; Alve, 1990; Jennings and Helgadottir, 1994; Corner *et al.*, 1996; Hald and Korsun, 1997; Korsun and Hald, 2000; Gustafsson and Nordberg, 2000; 2001; Murray *et al.*, 2003; Filipsson *et al.*, 2004; Hromic *et al.*, 2006; Forwick *et al.*, 2010). The stratification of the fjords in terms of seawater temperature, salinity and organic carbon content, results in the development of distinct benthic foraminiferal assemblages (Alve and Nagy, 1986; Alve, 1990; Gustafsson and Nordberg, 2001). The seasonally changing hypoxia also affects benthic foraminiferal distribution (Gustafsson and Nordberg, 2001). The changes in dissolved oxygen, however, do not lead to a change in benthic foraminiferal population immediately, rather it is controlled by the availability of fresh food (Gustafsson and Nordberg, 1999). The distance from the glacier has also been reported as a major factor in benthic foraminiferal distribution (Korsun and Hald, 2000; Husum and Hald, 2004).

Both calcareous and agglutinated benthic foraminifera are abundant in the high latitude fjords. The depth distribution and relative abundance of calcareous and agglutinated benthic foraminifera, however, varies from fjords to fjords (Alve and Nagy, 1990; Corner *et al.*, 1996). The increased abundance of agglutinated benthic foraminifera at intermediate depths in fjords has been attributed to excessive fresh water influx, reduced bottom water renewal, high organic productivity. The absence of calcareous tests at these depths is attributed to dissolution (Murray *et al.*, 2003). The agglutinated benthic foraminifera are abundant in the glacier proximal parts of the fjords (Korsun and Hald, 2000). The abundance of agglutinated taxa close to the glaciers has been attributed to meltwater flux and sediment load. A few benthic foraminiferal species are abundant only during the particular season, which is probably controlled by the amount of organic matter produced during different seasons (Wilson *et al.*, 2008). This distinct distribution of benthic foraminifera in fjords which is controlled by the prevailing physico-chemical factors, has been used to infer past climatic

changes from fjords (Nordberg *et al.*, 2000; Majewski and Zajaczkowski, 2007; Skirbekk *et al.*, 2010).

Such studies, however, require extensive species-level identification of benthic foraminifera. A proper species identification is subject to several constraints and thus involves large error. Additionally, the restricted geological range of benthic foraminiferal species, also limits the application of species-level data across the large geological time (Murray *et al.*, 2011). Therefore, several workers have suggested application of morpho-groups for paleoclimatic studies to avoid species-level identification (Bandy 1960; Chamney 1976; Corliss and Chen, 1988; Nigam *et al.*, 1992; Murray *et al.*, 2011; Manasa *et al.*, 2016). The relative abundance and distribution of benthic foraminiferal morpho-groups is controlled by the depth (Severin, 1983), dissolved oxygen concentration (Bernhard, 1986; Kaiho, 1989; 1994; Nigam *et al.*, 2007; Manasa *et al.*, 2016) and organic matter content of sediments (Corliss, 1985; Corliss and Chen, 1988; Corliss and Emerson, 1990). The distribution of various foraminiferal morpho-groups is also influenced by salinity and proximity to the source of fresh water influx (Nigam *et al.*, 1992; Manasa *et al.*, 2016; Suokhrie *et al.*, 2017).

Although benthic foraminiferal morpho-groups have been suggested as an effective proxy for paleoclimatic reconstruction, limited attempts have been made to understand the factors affecting the distribution of benthic foraminiferal morpho-groups, in the high latitudinal fjords. In the Norwegian Sea, rounded planispiral and flattened ovoid forms of benthic foraminifera were confined to the upper 1000 m, and the milioline forms were mainly reported from the deeper waters, suggesting a clear depth influence on morphology (Corliss and Chen, 1988). The epifaunal-infaunal forms were, however, mainly influenced by the organic carbon content of the sediments (Corliss and Chen, 1988). A similar epifaunal-infaunal benthic foraminiferal distribution was also observed in the northwestern Gulf of Mexico (Corliss and Fois, 1990). The increased relative abundance of angular asymmetrical benthic foraminifera in the oxygen minimum zone of the eastern Arabian Sea, clearly suggests its application as a proxy to reconstruct past dissolved oxygen concentration (Nigam *et al.*, 2007). In view of the differential response in various regions, the environmental significance of these morpho-groups, thus has to be ascertained from the northern high latitudinal fjords.

Additionally, a majority of the workers have clubbed both the calcareous and agglutinated benthic foraminifera with specific morphology, in same morpho-groups. The ecological preferences of both the calcareous and agglutinated benthic foraminifera are, however, different. Therefore, this study was carried out to understand the factors affecting the surface distribution of rounded-symmetrical and angular-asymmetrical morpho-groups of calcareous and agglutinated benthic

foraminifera, in Kongsfjorden-Krossfjorden fjords off Svalbard, a climatically sensitive region. Previously, the combined relative abundance of both the calcareous and agglutinated angular asymmetrical foraminifera was used to infer past dissolved oxygen concentration (Nigam et al., 2007) and fresh water influx induced changes in the energy conditions (Nigam et al., 1992). Additionally, recent studies suggest that these morpho-groups are also influenced by the organic matter content ( $C_{org}$ ) of the sediments (Manasa *et al.*, 2016). All of these parameters (dissolved oxygen,  $C_{org}$ , fresh water influx) are quite relevant in the polar regions as well. Therefore, we tried to assess the factors affecting the distribution of benthic foraminiferal morpho-groups in the high latitudinal fjords.

### **The study area**

The samples were collected from Kongsfjorden–Krossfjorden region off Svalbard (Fig. 1). The Svalbard archipelago is situated in the high Arctic between 74° and 81°N latitudes. Presently, about 60% of the land is covered by glaciers and ice caps (Svendsen *et al.*, 2002). The climate of the Svalbard is modified by the West Spitsbergen Current, the northernmost extension of the North Atlantic Current as it brings heat and higher salinity water to the region (Svendsen *et al.*, 2002). In recent years, Kongsfjorden has experienced a strong inflow of Atlantic water, which has affected the winter situation in Kongsfjorden, strongly reducing the sea-ice formation in the fjord (Cottier *et al.*, 2005).

Kongsfjorden-Krossfjorden comprise of a glacial fjord system and the shelf located between 78°40' and 77°30'N and 11°3' and 13°6'E. The fjords consist of two submarine channels, converging to a deep glacial basin, the Kongsfjordrenna. The spatial orientation of Kongsfjorden is south-east to the north-west while Krossfjorden is oriented in a north-south direction. Kongsfjorden and Krossfjorden system covers a total drainage area of 3074 km<sup>2</sup>, which include 2257 km<sup>2</sup> of the land area out of which 1651 km<sup>2</sup> or 74% is covered by the glaciers, and 817 km<sup>2</sup> of the marine area (Svendsen *et al.*, 2002). The length of Kongsfjorden is 26.1 km with a width varying from 4 to 10 km. The fjord includes two distinct regions, viz. the inner shallow region (maximum depth of 94 m), with strong glacier influence, and the outer basin (up to ~350 m deep) that connects Kongsfjorden with the Greenland Sea (Elverhøi *et al.*, 1980). However, recently, based on species distribution, substrate and the overriding environmental gradient, Hop *et al.* (2002) divided Kongsfjorden into four regions, viz. 1) outer zone, 2) middle zone, 3) transitional zone, and 4) inner zone. Krossfjorden is ~30 km long with a width varying from 3 to 6 km. Its estimated volume is ~25 km<sup>3</sup> (Svendsen *et al.*, 2002). Tide-water glaciers influence both the Kongsfjorden and Krossfjorden. The summer salinity in Kongsfjorden varies from ~32 psu at shallow water stations to ~35 psu in the deepest

regions. The summer time potential temperature varies from as low as  $-2^{\circ}\text{C}$  to as high as  $8^{\circ}\text{C}$  (Svendsen et al., 2002; Promińska et al., 2017). The seawater temperature, wind direction and fresh water supply in Kongsfjorden and Krossfjorden system vary seasonally (Farmer and Freeland, 1983). There is a prominent trend of decreasing depth towards the shallower shelf, rather than a sill in the mouth.

In general, fine-grained sediments (clay+silt) dominate Kongsfjorden, suggesting deposition from water column suspensions or turbidity currents. But, the clay fraction increases with distance from the glacier. The coarse material (sand+gravel) is abundant (up to 10%) in parts of Kongsfjorden close to glacier outflow. The organic matter content in Kongsfjorden sediments increases away from the glacier (Zaborska *et al.*, 2006). The Kongsfjorden water is Arctic dominant till midsummer when Atlantic water intrudes into the fjord and continues to intrude throughout the summer (Ito and Kudoh, 1997; Cottier *et al.*, 2005).

## **Materials and Methodology**

The samples were collected during Indian initiative in the Arctic and within the frameworks of two International Polar Year (IPY) projects, namely, 1) '*Arctic Natural Climate and Environmental Changes and Human Adaptation: From Science to Public awareness*' (SciencePub, IPY-39), and 2) '*Arctic Ocean warming in the Past*' (WARMFAST, IPY-786). The projects were funded by the Research Council of Norway. The cruise was also part of the collaborative project entitled '*Assessment of benthic foraminifera as environmental proxy in the Arctic*' (FORARC) between the Norwegian Polar Institute and Department of Geology, University of Tromsø, funded by the Norwegian Research Council. In the FORARC project, the overall aim was to improve the use of benthic foraminifera as environmental proxy in the Arctic by further investigations of the relationship between benthic foraminifera and the environment. The investigations were carried out in Kongsfjorden and Krossfjorden, Svalbard, during cruise NP08-16.

A total of twenty-three multicore top samples (Fig. 1, Table 1) were collected from 43 m to 383 m water depth. The core-top of the multicore samples were processed by following the standard procedure for processing of samples for foraminiferal studies (Boltovskoy and Wright, 1976). An appropriate amount (10-30 g) of sediment sample was collected in properly labeled pre-weighed glass petri-dishes and dried overnight. The dried samples were weighed and then soaked overnight. After 24 hours, the overlying water, if muddy, was decanted. The process was repeated until the overlying water became clear. The overlying water was finally decanted and the wet sediments were sieved by using a  $63\ \mu\text{m}$  sieve. The material retained on the sieve ( $>63\ \mu\text{m}$ , coarse fraction) was

transferred to small beaker for drying. The dried coarse fraction was weighed and stored in plastic vials.

An appropriate amount of coarse fraction was weighed and uniformly spread over a gridded picking tray. All benthic foraminifera (living + dead) were picked from the representative fraction. We did not differentiate between living and dead benthic foraminifera. A minimum of 300 benthic foraminifera were picked from each sample and mounted on micropaleontological slides. The picked total (living + dead) benthic foraminiferal specimens were sorted into four morpho-groups as per Nigam *et al.* (1992) and Manasa *et al.* (2016), viz. 1) Calcareous rounded-symmetrical, 2) Calcareous angular-asymmetrical, 3) Agglutinated rounded-symmetrical, 4) Agglutinated angular-asymmetrical (Fig. 2). The relative abundance of each of these four morpho-groups was calculated from the number of specimens of each of these morpho-groups in the picked specimens. The relative abundance of each of these four morpho-groups was plotted against the water depth at the respective location, to understand the influence of water depth on distribution of benthic foraminiferal morpho-groups.

## **Results**

### **Coarse Fraction (%)**

The coarse fraction varies from <2% to ~26% and is influenced by the distance from the adjacent land and glacier grounding lines (Fig. 3). The maximum coarse fraction (~26 %) is at station 8IA/N4 at the confluence of the two fjords, whereas minimum is at station 8IA/N10, towards the mouth of Kongsfjorden. The coarse fraction percentage is higher at stations close to glacial outlets. The coarse fraction is also high at a few comparatively deeper stations, located far away from the glacial outlet. The coarse fraction in Kongsfjorden fjord is higher than that in Krossfjorden fjord. The maximum coarse fraction is at the confluence of both Kongsfjorden and Krossfjorden fjords.

### **Benthic Foraminiferal Abundance**

The number of benthic foraminifera varies from 8/g sediment on the shelf (station 8IA/K3) (370 m) to 1317/g sediment at the confluence of two fjords (station 8IA/N4) (247 m) (Fig. 4). In general, the abundance increases at stations located away from the coast. The maximum benthic foraminiferal abundance is at stations located at the confluence of two fjords. In Kongsfjorden, benthic foraminiferal abundance increases from the inner fjord towards the outer fjord. An opposite trend is observed in Krossfjorden, where abundance is high in the inner fjord and decreases towards the outer fjord. The abundance, however, again increases towards the confluence of both the fjords. Out of the total benthic foraminifera, the relative abundance of agglutinated forms is higher in the inner fjord

and decreases towards the outer fjord in Kongsfjorden (Fig. 5A). The relative abundance, however, increases towards the outer fjord in the Krossfjorden. The relative abundance of calcareous benthic foraminifera is opposite to that of agglutinated, in both the Kongsfjorden and Krossfjorden (Fig. 5B). The tests were generally well preserved, with minor breakage. The agglutinated benthic foraminiferal tests were relatively more fragile than calcareous foraminifera. A few tests had predatory borings.

#### **Calcareous Rounded-Symmetrical Benthic Foraminifera (%)**

The relative abundance of calcareous rounded-symmetrical benthic foraminifera varies from being absent in the outer Kongsfjorden (station NP-08/16/11MC) (306 m), to the maximum (97.5%) at the confluence of both the fjords (station 8IA/N2) (136 m) (Fig. 6A). A majority of the calcareous benthic foraminifera are rounded symmetrical. The calcareous rounded-symmetrical benthic foraminifera are more abundant in Kongsfjorden fjord than that in Krossfjorden fjord. Additionally, the abundance is high in the inner Kongsfjorden fjord.

#### **Calcareous Angular-Asymmetrical Benthic Foraminifera (%)**

The relative abundance of calcareous angular-asymmetrical benthic foraminifera also varies from being absent in the innermost Kongsfjorden (station 8IA/N9) (115.9 m) to a maximum (~30 %) at a station (8IA/N12) in the inner fjord (80 m) (Fig. 6B). The calcareous angular-asymmetrical benthic foraminifera are also more abundant in Kongsfjorden than that in Krossfjorden fjord.

#### **Agglutinated Rounded-Symmetrical Benthic Foraminifera (%)**

The minimum relative abundance (0%) of agglutinated rounded-symmetrical benthic foraminifera is in the outermost Kongsfjorden (station 8IA/N4) (247 m) and the maximum (~86%) is at the confluence of two fjords (station NP-08/16/49MC) (303 m) (Fig. 6C). The agglutinated rounded-symmetrical benthic foraminifera are more abundant in Krossfjorden fjord as compared to that in the Kongsfjorden fjord.

#### **Agglutinated Angular-Asymmetrical Benthic Foraminifera (%)**

The relative abundance of agglutinated angular-asymmetrical benthic foraminifera varies from being absent in the outer Kongsfjorden (station 8IA/N4) (247 m), to the maximum (~91%) in the inner Kongsfjorden (station NP-08/16/63MC) (109 m) (Fig. 6D). The agglutinated angular-asymmetrical benthic foraminifera are more abundant in Krossfjorden fjord.

#### **Organic Carbon (%C<sub>org</sub>)**

The organic carbon concentration in surface sediments was compiled from previous studies (Table 2). The data points cover both the fjords as well as the area further west. The %C<sub>org</sub> is comparatively

low in Kongsfjorden, as compared to that in the Krossfjorden (Fig. 7). The highest %C<sub>org</sub> is at the confluence of two fjords.

### **Correlation Between Faunal Characteristics and Water Depth**

The relative abundance of benthic foraminiferal morpho-groups was compared with the water depth. A significant positive correlation ( $r = 0.41$ ,  $n = 23$ ) is observed between the relative abundance of rounded symmetrical benthic foraminifera and water depth (Fig. 8A). The relative abundance of angular asymmetrical benthic foraminifera is negatively correlated ( $r = 0.39$ ,  $n = 23$ ) with water depth (Fig. 8B). Out of the total population, a more significant ( $r = 0.59$ ,  $n = 23$ ), positive correlation is observed between the relative abundance of agglutinated rounded symmetrical benthic foraminifera and water depth (Fig. 8C). Similarly, the relative abundance of calcareous angular asymmetrical benthic foraminifera is significantly negatively correlated ( $r = 0.49$ ,  $n = 23$ ) with water depth (Fig. 8D). We did not find a significant relationship between water depth and calcareous rounded symmetrical benthic foraminifera, as well as agglutinated angular asymmetrical benthic foraminifera.

## **Discussion**

### **Coarse Fraction**

The coarse fraction (>63  $\mu\text{m}$ ) constitutes a small part (<25%) of the sediments in both the fjords. The coarse fraction is higher in Kongsfjorden as compared to Krossfjorden. Within the Kongsfjorden, coarse fraction is relatively abundant in the innermost fjord as well as the shallow water stations, suggesting a clear influence of glacial calving in controlling the coarse fraction abundance in the sediments. This may be attributed to the fact that a large number of glaciers including Kongsbreen, one of the most active glaciers of the Svalbard region (Lefauconier *et al.*, 1994), debouches in the Kongsfjorden. Additionally, the glacial outlets in Krossfjorden are far away from the main channel. A strong influence of depth and proximity to glacial calving on coarse fraction abundance in the sediments, is common in Arctic fjords (Gustafsson and Nordberg, 1999). The glacial calving brings a large quantity of detritus into the fjord. Earlier, Zaborska *et al* (2006) also noted that the coarse fraction is lower than the fine fraction in the Kongsfjorden sediments. A similar abundance of sand in the high glacier activity areas has been cited by many workers (Smith and Andrews, 2000; Mickelson and Winguth, 2007).

### **Benthic Foraminiferal Abundance**

Benthic foraminiferal abundance varies from 8/g sediment to 1317/g sediment. Benthic foraminiferal abundance is the lowest in the innermost Kongsfjorden and increases towards the shelf (Fig. 4). The



trend in the Krossfjorden is opposite, with the highest foraminiferal abundance being in the innermost fjord and decreasing towards the central fjord. However, here also, the abundance increases from the middle fjord to mouth. In general, benthic foraminifera are more abundant in Kongsfjorden, as compared to that in the Krossfjorden. A similar, mixed response of benthic foraminiferal abundance to the inner, middle and outer fjords, has also been reported, earlier. A decrease in benthic foraminiferal abundance was observed towards the inner part of the Hornsund as well as Smeerenburgfjorden fjord, as compared to the outer and central parts (Hald and Korsun, 1997). However, Hald and Korsun (1997), attributed higher coarse fraction and total foraminiferal abundance to the high energy conditions in the central and inner parts of the Wijdefjorden. The difference in foraminiferal distribution in the fjords suggests that several factors control foraminiferal distribution in different parts of the fjords. Here, we would like to mention that the total (living + dead) benthic foraminiferal population is influenced not only by the ecological preferences of respective species, when living, but also by the diagenetic changes (Murray, 2000). The total population may also be influenced by dissolution bias of foraminiferal tests, dilution by terrigenous sediment input, and possible post-mortem transportation of foraminiferal tests. The diagenetic changes may considerably alter the living assemblage depending upon the ambient environment (Berkeley et al., 2014). The total population, however, has also been frequently used to understand the factors affecting benthic foraminifera in a region.

Modern distribution of benthic foraminifera in the northern hemisphere fjords is influenced by estuarine circulation, changes in the grain size and enrichment in organic carbon (Alve and Nagy, 1986; Alve, 1990; Corner et al., 1996; Gustafsson and Nordberg, 2001; Hromic et al., 2006). While hydrographic factors control benthic faunal distribution at the shallow stations close to the glacier (except the station directly at the glacier), the sediment grain size controlled the faunal distribution in the outer deeper regions (Fetzer et al., 2002). The changes in melt-water runoff and glacial calving cause a large gradient in temperature, salinity and turbidity across the glaciomarine fjords (Elverhøi et al., 1980). Therefore, the foraminiferal abundance in the fjords can be influenced by any or a combination of several factors, including proximity to glacial calving, depth, organic matter, grain-size and others (Corner et al., 1996). Benthic foraminiferal abundance in the Kongsfjorden and Krossfjorden, increases at stations with a relatively less sand. The fine-grained sediments can store a relatively large amount of organic matter. The organic matter is used as food by foraminifera, thus leading to their increased abundance. Interestingly, both the %CF and benthic foraminiferal abundance is high towards the outer fjords, especially the confluence of the two fjords. Here, the water depth is maximum, and this region is far off from the adjacent land and calving lines. The sand

fraction is the least abundant in this region (Shetye et al., 2011). A large part of the CF at these stations comprise of foraminiferal tests, suggesting higher population. The high benthic foraminiferal population at these stations with high %CF is attributed to a combination of low sand and high %C<sub>org</sub> (Fig. 7). The %C<sub>org</sub> increases away from the glacial inlets in the inner fjord, towards the outer fjord (Kim et al., 2011; Shetye et al., 2011; Liu et al., 2015; Jernas et al., 2018) (Fig. 7).

The increase in foraminiferal population away from the coast, is also attributed to the terrigenous dilution due to variable sedimentation rate. The sedimentation affects the foraminiferal abundance in a couple of ways. The high sedimentation increases the turbidity of the ambient water, thus adversely affecting the living benthic foraminifera, resulting in reduced population. Additionally, the increased terrigenous input reduces benthic foraminiferal population by dilution. The low sedimentation rate towards the mouth of the Kongsfjorden thus contributes towards the increase in benthic foraminiferal abundance from the inner to outer fjord. The sedimentation rate close to the glacier margin in the inner fjord, is an order of magnitude higher than that in the central and outer fjord (Zaborska *et al.*, 2006).

The large salinity-temperature gradient from the inner fjord to its mouth also affects benthic foraminiferal abundance. The summer salinity in the fjord varies from ~32 psu at shallow water stations to ~35 psu in the deepest regions. The potential temperature during the summer varies from as low as -2°C to as high as 8°C (Svendsen et al., 2002; Promińska et al., 2017). A further large gradient is expected in the annual average salinity-temperature, due to the large seasonal difference in the meltwater and glacial calving. The field and laboratory culture experiments suggest that benthic foraminifera are sensitive to both the ambient salinity and temperature (Nigam et al., 2008; Kurtarkar et al., 2011; Saraswat et al., 2015). Although the species can tolerate a large range of salinity and temperature, the optimum range for reproduction is very narrow (Saraswat et al., 2015). Therefore, a large variation in temperature and salinity, such as that in the inner fjord, will adversely affect benthic foraminifera.

The decrease in benthic foraminiferal abundance in the middle of the Krossfjorden, is intriguing. The fjord is narrow in this region and the coarse fraction is also low. The decrease in foraminiferal population in middle of the Krossfjorden, can either be due to the low %C<sub>org</sub> (Fig. 7), as food availability is a major factor that influences benthic foraminiferal population (Jorissen et al., 1995) or depleted oxygen environment. The seasonal hypoxia causes low benthic foraminiferal population in a few fjords (Gustafsson and Nordberg, 2000). However, a short-term change in dissolved oxygen content does not immediately affect benthic foraminiferal population. The availability of fresh food, largely influences benthic foraminiferal population (Gustafsson and

Nordberg, 1999). Therefore, the low benthic foraminiferal population in the middle of the Krossfjorden is attributed to low food availability. The variable foraminiferal distribution in the fjords, suggests that the depth is not a significant factor controlling total benthic foraminiferal abundance in Krossfjorden-Kongsfjorden fjords.

### **Benthic Foraminiferal Morpho-groups**

A significant positive relationship is observed between water depth and relative abundance of rounded symmetrical benthic foraminifera in the fjords (Fig. 8A). The high relative abundance of rounded symmetrical benthic foraminifera is attributed to either high energy conditions or well-oxygenated waters. The rounded symmetrical forms prefer well oxygenated waters and the angular asymmetrical forms are low oxygen tolerant. The high energy environment in the shallower depths, also increases the relative abundance of rounded symmetrical benthic foraminifera. As the deeper depths are relatively calmer, the increase in rounded symmetrical forms with increasing depths in Kongsfjorden and Krossfjorden, can't be explained with the relative difference in turbulence. The high relative abundance of rounded symmetrical benthic foraminifera at deeper depths, thus suggests well oxygenated water. The inference is further supported by the inverse relationship between the relative abundance of angular asymmetrical benthic foraminifera and water depth (Fig. 8B). The high relative abundance of rounded-symmetrical benthic foraminifera in oxygenated waters has also been reported from the tropical regions (Nigam *et al.*, 2007; Manasa *et al.*, 2016). The depth distribution of rounded symmetrical benthic foraminifera in the Arctic fjords is, however, opposite to that in the riverine influx dominated tropical regions. Unlike the fjords, rounded-symmetrical benthic foraminifera are abundant in shallow water high-energy conditions, prevailing in front of the river mouths in the tropical regions (Nigam *et al.*, 1992).

As the calcareous and agglutinated benthic foraminifera prefer a different set of environment, clubbing the rounded symmetrical and angular asymmetrical specimens of both, for morpho-groups seems inappropriate. Therefore, we segregated the morpho-groups into calcareous and agglutinated specimens and calculated their relative abundance. The relative abundance of calcareous angular-asymmetrical benthic foraminifera is very low (varying from being absent to 30%), as compared to that of the calcareous rounded symmetrical benthic foraminifera (varying from being absent to 98%), especially in Kongsfjorden. Even in Krossfjorden, where agglutinated forms dominate, the calcareous rounded symmetrical forms are more abundant than the calcareous angular asymmetrical morpho-group. Based on seasonal and annual sampling, *Elphidium excavatum f. clavatum* and *Cassidulina reniforme*, both considered under the calcareous rounded symmetrical morpho-group, co-dominate the glacier-proximal fauna (Korsun and Hald, 2000). The living calcareous trochospiral-

planispiral *Nonionellina labradorica* is also comparatively more abundant in the fjord than the shelf, thus confirming the dominance of rounded benthic foraminifera in the total assemblage (Jernas et al., 2018). The low abundance of calcareous angular-asymmetrical morpho-group is attributed to the high energy and generally well oxygenated environment. The decrease in relative abundance of living calcareous angular-asymmetrical *Bolivina pseudopunctata* from the shelf station towards the innermost fjord also confirms the adverse effect of high energy conditions in the inner fjord, on angular asymmetrical morpho-group. Similarly, another living calcareous angular-asymmetrical benthic foraminifera *Stainforthia feylingi* is also abundant only in the shelf (Jernas et al., 2018). The location of glacial calving points, however, may complicate the unidirectional change in relative abundance of the benthic foraminiferal morpho-groups from the innermost fjord to its mouth. For example, in a few other fjords in the Svalbard region, *Nonionellina labradorica* and *Islandiella norcrossi* dominated foraminiferal assemblage away from the glacier (Korsun and Hald, 2000).

The factors other than turbulence, however, also seem to affect the distribution pattern, as evident from a significant negative correlation between the relative abundance of calcareous angular asymmetrical benthic foraminifera and water depth. The turbulence decreases with increasing depth and thus should facilitate increased abundance of angular asymmetrical forms at deeper depths. The relationship is, however, opposite in the fjords. The relative abundance of calcareous angular-asymmetrical morpho-group, also increases (>20%) in the middle part of the Kongsfjorden. The increased abundance of calcareous angular-asymmetrical morpho-group is attributed to the restricted circulation leading to local oxygen-deficient conditions in this region. The influence of dissolved oxygen content on benthic foraminiferal population has been summarized by Jorissen *et al* (1995). The infaunal species dominate benthic foraminiferal population in oxygen-deficient regions, often associated with high organic matter in the sediments (Chamney, 1976; Corliss, 1985; Bernhard, 1986; Corliss and Chen, 1988; Rosoff and Corliss, 1992). All the benthic foraminiferal species clubbed under angular-asymmetrical morpho-group were infaunal. Therefore, the high abundance of angular-asymmetrical benthic foraminifera in selected regions of the fjords indicates the oxygen deficient condition. Husum and Hald (2004) distinguished three benthic foraminiferal assemblages from the Malangen fjord, northern Norway. The inner fjord basin was characterized by *Bulimina marginata*–*Cassidulina reniforme*, a low oxygen tolerant assemblage, whereas outer fjord region was dominated by the *Brizalina skagerrakensis* assemblage. A distinct distribution pattern clearly suggests a strong influence of dissolved oxygen on benthic foraminifera in northern high latitudinal regions. The high relative abundance of serial forms in oxygen deficient waters has also been

reported from both the Arabian Sea (Nigam *et al.*, 2007) and the Bay of Bengal (Manasa *et al.*, 2016; Suokhrie *et al.*, 2017).

Like the calcareous forms, out of the total agglutinated benthic foraminifera, rounded-symmetrical morpho-group is relatively more abundant. However, unlike calcareous rounded symmetrical morpho-group, agglutinated rounded symmetrical morpho-group is more abundant in the Kongsfjorden. Similarly, the innermost Kongsfjorden has the lowest abundance of agglutinated rounded symmetrical morpho-group, with an increase in the middle and outer fjord. The rounded symmetrical, living agglutinated *Alveolophragmium crassimargo* is also relatively more abundant in the middle and outer fjord than the mouth and inner fjord (Jernas *et al.*, 2018). Like the calcareous angular-asymmetrical morpho-group, the agglutinated angular asymmetrical morpho-group is also abundant at a few stations in the inner fjord. A significant positive correlation between the relative abundance of agglutinated rounded symmetrical benthic foraminifera and water depth, suggests a clear influence of factors other than turbulence. In general, agglutinated benthic foraminifera are more abundant in the marginal marine environments (Boltovskoy and Wright, 1976; Schieber, 2009). On the basis of this study, it appears that the benthic foraminiferal distribution in Krossfjorden and Kongsfjorden is controlled by the distance from the land, glacial melt,  $C_{org}$  and energy conditions.

### **Calcareous and Agglutinated Benthic Foraminifera**

Out of the total benthic foraminiferal population, calcareous foraminifera are more abundant in the Kongsfjorden as compared to the Krossfjorden. Earlier Hald and Korsun, (1997) reported that the calcareous forms dominate and constitute >75% of the benthic foraminifera in the Krossfjorden. The living calcareous benthic foraminiferal abundance in the Kongsfjorden varies from as low as <30% to as high as >90% (Jernas *et al.*, 2018). A large inter-annual difference in relative abundance of living calcareous benthic foraminifera was also observed. The range of relative abundance of total (living + dead) calcareous benthic foraminifera in Kongsfjorden is, however much large [from being absent at one station (NP/08/16/11MC) to the entire assemblage being calcareous at another station (8IA/N4)], as compared to the living forms. The difference in relative abundance of living and total calcareous benthic foraminifera is attributed to the post-depositional diagenetic changes. The taphonomic changes considerably alter the living assemblages, due to the varying degree of dissolution/breakage susceptibility of calcareous and agglutinated benthic foraminifera (Berkeley *et al.*, 2014). Additionally, seasonal dominance of a few species that are abundantly present only during a particular season, due to the organic matter availability during different seasons, also contributes towards the difference in living and total benthic foraminiferal abundance (Wilson *et al.*, 2008).

Interestingly, there was no definite increasing or decreasing trend in the relative abundance of both the living and total calcareous benthic foraminifera, from the innermost to the outermost fjord. The trend is different than a few other Arctic fjords. The lack of definite spatial trend in relative abundance of calcareous benthic foraminifera in Kongsfjorden, suggests, that factors other than the proximity to glacial outlet, influence calcareous benthic foraminiferal abundance in the fjords. The high calcareous foraminiferal abundance in Kongsfjorden is attributed to the seasonal stratification with a stable deeper layer as well as relatively higher pH (Svendson *et al.*, 2002). Stratification of the fjords in terms of seawater temperature, salinity, organic carbon content, leads to the development of distinct benthic foraminiferal assemblages, with stable deeper water assemblages being dominated by calcareous benthic foraminifera, while the shallow seasonal layer being dominated by both calcareous and agglutinated forms. The dominance of calcareous forms in the stable deeper layer has been attributed to circulation leading to changing oxygen demand (Alve and Nagy, 1990). Earlier, a definite increase in calcareous benthic foraminifera from the outer part of Van Mijenfjorden fjord in the Svalbard, towards the inner part was reported. A similar increase in calcareous benthic foraminifera from the outer to the inner fjord was also reported from the glaciomarine Hornsund as well as Wijdefjorden fjord (Hald and Korsun, 1997). However, the calcareous benthic foraminiferal abundance decreases towards the inner parts of the Smeerenburgfjorden (Hald and Korsun, 1997).

The relative abundance of agglutinated benthic foraminifera in Krossfjorden is higher than that in Kongsfjorden. The agglutinated benthic foraminifera are almost absent at deeper stations at the confluence of both the fjords. In a few other fjords also, the regions close to the glaciers have high abundance of agglutinated benthic foraminifera (Korsun and Hald, 2000). The increased abundance of agglutinated taxa in the glacial proximity regions has been attributed to meltwater flux and sediment load. The trend is opposite to a few other fjords, wherein calcareous forms dominate the benthic foraminiferal population in the shallow water region, and the deeper water assemblage is dominated by agglutinated forms (Corner *et al.*, 1996). The maximum abundance of agglutinated benthic foraminifera was also found in the central parts of Isfjorden (Hald and Korsun, 1997). The increased abundance of agglutinated benthic foraminifera at intermediate depths in fjords has been attributed to excessive fresh water influx, reduced bottom water renewal and high organic productivity. The distinct foraminiferal assemblages were mainly attributed to the different seawater temperature and salinity in different parts of the fjords and adjacent regions.

## **Conclusions**

We report a large influence of glacial activity and  $C_{org}$ , on the granulometry and benthic foraminiferal morpho-groups' distribution in the surface sediments of the two Arctic fjord systems,

namely Kongsfjorden and Krossfjorden. The coarse fraction is more abundant in Kongsfjorden as compared to Krossfjorden as a large number of glaciers surround the Kongsfjorden. In general, benthic foraminifera are more abundant in Kongsfjorden. A general trend of increasing benthic foraminiferal abundance from the mouth towards the open end is noted in Kongsfjorden. However, in Krossfjorden, benthic foraminiferal abundance decreases in the middle part of the fjord. The maximum abundance is noted at the confluence of both the fjords. Out of the total benthic foraminiferal population, calcareous forms are more abundant in the Kongsfjorden as compared to Krossfjorden. The rounded-symmetrical forms dominate calcareous benthic foraminifera due to well-oxygenated waters and high energy conditions. Therefore, the temporal changes in the relative abundance of rounded-symmetrical benthic foraminifera morpho-group can be used to reconstruct past meltwater and glacial calving induced energy conditions as well as bottom water oxygenation. The calcareous angular-asymmetrical benthic foraminiferal abundance increases in the middle part of the Kongsfjorden, due to restricted circulation leading to local oxygen-deficient conditions in this region. The relative abundance of agglutinated benthic foraminifera is higher in Krossfjorden as compared to Kongsfjorden. The agglutinated foraminifera are almost absent at deeper stations at the confluence of both the fjords. Out of the total agglutinated benthic foraminifera, rounded-symmetrical forms are more abundant, probably due to the high energy conditions. On the basis of this study, it is inferred that the benthic foraminiferal distribution in the Krossfjorden and Kongsfjorden is controlled by the distance from the land, %C<sub>org</sub>, glacial melt and energy conditions.

### **Acknowledgements**

The authors are thankful to the Director, National Institute of Oceanography, for the permission and encouragement to publish the results. The authors also thank the Director, National Center for Antarctic and Ocean Research, Goa, for the logistic support. We are also thankful to Prof. Nalan Koç and Dr. D. Klitgaard-Kristensen for the help during sampling. Authors also thankfully acknowledge the funding from the Norwegian Research Council.

## References

- Alve, E. 1990. Variations in estuarine foraminiferal biofacies with diminishing oxygen conditions in Drammensfjord, SE Norway. In: Hemleben, C., Kaminski, M.A., Kuhnt, W., Scott, D.A. (Eds.), *Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera*. NATO ASI Series., Kluwer Academic Publishers, Dordrecht, pp. 661-694.
- Alve, E., Nagy, J. 1986. Estuarine foraminiferal distribution in Sandebukta, a branch of the Oslo Fjord. *J. Foraminiferal Res.* 16, 261-284.
- Alve, E., Nagy, J. 1990. Main features of foraminiferal distribution reflecting estuarine hydrography in Oslo Fjord. *Mar. Micropaleontol.* 16, 181-206.
- Berkeley, A., Perry, C.T., Smithers, S.G., Hoon, S. 2014. Towards a formal description of foraminiferal assemblage formation in shallow-water environments: Qualitative and quantitative concepts. *Mar. Micropaleontol.* 112, 27-38.
- Bernhard, J.M. 1986. Characteristic assemblages and morphologies of benthic foraminifera from anoxic, organic rich deposits: Jurassic through Holocene. *J. Foraminiferal Res.* 16, 207-215.
- Boltovskoy, E., Wright, R. 1976. Recent Foraminifera. Dr W. Junk b.v. Publisher. The Hague, 515 p.
- Chamney, T.P. 1976. Foraminiferal morphogroup symbol for paleoenvironmental interpretation of drill cutting samples: Arctic America, Albian continental margin. *Marit. Sediments, Spec. Publ.* 1B: 585-624.
- Corliss, B.H. 1985. Microhabitats of benthic foraminifera within deep-sea sediments. *Nature* 314, 435-438.
- Corliss, B.H., Chen, T. 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology* 16, 716-719.
- Corliss, B. H., Emerson, S. 1990. Distribution of Rose Bengal stained deep-sea benthic foraminifera from the Nova Scotian continental margin and Gulf of Maine. *Deep-Sea Res.* 37, 381-400.
- Corliss, B.H., Fois, E. 1990. Morphotype analysis of deep-sea benthic foraminifera from the Northwest Gulf of Mexico. *Palaios* 5, 589-605.
- Corner, G.D., Steinsund, P.I., Aspeli, R. 1996. Distribution of recent benthic foraminifera in a subarctic fjord-delta: Tana, Norway. *Mar. Geol.* 134, 113-125.
- Cottier, F., Tverberg, V., Inall, M.E., Svendsen, H., Nilsen, F., Griffiths, C. 2005. Water mass modification in an Arctic fjord through cross-shelf exchange: the seasonal hydrography of Kongsfjorden, Svalbard. *J. Geophys. Res. Oceans* 110, 1-18.
- Debenay, J.-P., Redois, F. 1997. Recent foraminifera of the northern continental shelf, off Senegal. *Rev. Micropaleontol.* 40, 15-38.
- Elverhøi, A., Liestol, O., Nagy, J. 1980. Glacial erosion, sedimentation and mikrofauna in the inner part of Kongsfjorden, Spitsbergen. *Norsk Polarinstitutt Skrifter.* 172, 33-61.



- Farmer, D., Freeland, H. J., 1983. The physical oceanography of fjords. In M.V. Angel & J.J. O'Brien (eds): *Prog. Oceanogr.* 12, 147-220.
- Fetzer, I., Lonne, O.J., Pearson, T. 2002. The distribution of juvenile benthic invertebrates in an arctic glacial fjord. *Polar Biol.* 25, 303-315.
- Filipsson, H.L., Nordberg, K., Gustafsson, M. 2004. Seasonal study of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  in living (stained) benthic foraminifera from two Swedish fjords. *Mar. Micropaleontol.* 53, 159-172.
- Forwick, M., Tore, O., Vorren, M. Hald, S. Korsun, Y. Roh, C. Vogt, K.-C. Yoo 2010. Spatial and temporal influence of glaciers and rivers on the sedimentary environment in Sassenfjorden and Tempelfjorden, Spitsbergen. *Geol. Soc., London, Special Publ.* 344, 163-193.
- Grotti, M., Soggia, F., Ardini, F., Bazzano, A., Moroni, B., Vivani, R., Cappelletti, D., Misic C. 2017. Trace elements in surface sediments from Kongsfjorden, Svalbard: occurrence, sources and bioavailability. *Int. J. Environ. Ana. Chem.* 97, 401-418.
- Gustafsson, M., Nordberg, K. 1999. Benthic foraminifera and their response to hydrography, periodic hypoxic conditions and primary production in the Koljo fjord on the Swedish west coast. *J. Sea Res.* 41, 163-178.
- Gustafsson, M., Nordberg, K. 2000. Living (stained) benthic foraminifera and their response to the seasonal hydrographic cycle, periodic hypoxia and to primary production in Havstens Fjord on the Swedish West Coast. *Estu. Coastal Shelf Sci.* 51, 743-761.
- Gustafsson, M., Nordberg, K. 2001. Living (stained) benthic foraminiferal response to primary production and hydrography in the deepest part of the Gullmar Fjord, Swedish west coast, with comparison to Höglund's 1927 material. *J. Foraminiferal Res.* 31, 2-11.
- Hald, M., Korsun, S. 1997. Distribution of modern benthic foraminifera from fjords of Svalbard, European Arctic. *J. Foraminiferal Res.* 27, 101-122.
- Hop, H., Pearson, T., Hegseth, E. N., Kovacs, K. M., Wes-lawski, J. M., Wiencke, C., Kwasniewski, S., Eiane, K., Leakey, R., Cochrane, S., Zajaczkowski, M., Lønne, O. J., Mehlum, F., Lydersen, C., Gulliksen, B., Falk-Petersen, S., Poltermann, M., Wängberg, S.-Å., Kendall, M., Bischof, K., Y., Voronkov, A., Kovaltchouk, N. A., Gabrielsen, G. W., Wlodarska-Kowalczyk, M., Wiktor, J., di Prisco, G., Estoppey, A., Papucci, C., Gerland, S. 2002. The marine ecosystem of Kongsfjorden, Svalbard. *Polar Res.* 21, 167-208.
- Hromic, T., Ishman, S., Silva, N. 2006. Benthic foraminiferal distributions in Chilean fjords: 47°S to 54°S. *Mar. Micropaleontol.* 59, 115-134.
- Husum, K., Hald, M. 2004. Modern foraminiferal distribution in the subarctic Malangen Fjord and adjoining shelf, northern Norway. *J. Foraminiferal Res.* 34, 34-48.
- Ito, H., Kudoh, S. 1997. Characteristics of water in Kongs-fjorden, Svalbard. Proc. NIPR Symp. *Polar Meteorol. Glaciol.* 11, 211-232.
- Jennings, A., Helgadottir, G. 1994. Foraminiferal assemblages from the fjords and shelf of eastern Greenland. *J. Foraminiferal Res.* 24, 123-144.

- Jernas, P., Klitgaard-Kristensen, D., Husum, K., Koç, N., Tverberg, V., Loubere, P., Prins, M., Dijkstra, N., Gluchowsk, M. 2018. Annual changes in Arctic fjord environment and modern benthic foraminiferal fauna: Evidence from Kongsfjorden, Svalbard. *Glo. Pla. Cha.* 163, 119-140.
- Jorissen, F.J., De Stigter, H.C., Widmark, J.G.V. 1995. A conceptual model explaining benthic foraminiferal microhabitats. *Mar. Micropaleontol.* 26, 3-15.
- Kaiho, K. 1989. Morphotype changes of deep-sea benthic foraminifera during the Cenozoic Era and their paleoenvironmental implications. *Fossils* 47, 1-23.
- Kaiho, K. 1994. Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. *Geology* 22, 719-722.
- Kim, J.-H., Peterse, F., Willmott, V., Klitgaard Kristensen, D., Baas, M., Schouten, S., Sinninghe Damste, J.S. 2011. Large ancient organic matter contributions to Arctic marine sediments (Svalbard). *Limnol. Oceanogr.* 56, 1463-1474.
- Knies, J., Brookes, S., Schubert, C.J. 2007. Re-assessing the nitrogen signal in continental margin sediments: New insights from the high northern latitudes. *Earth Planet. Sci. Lett.* 253, 471-484.
- Korsun, S., Hald, M. 2000. Seasonal dynamics of benthic foraminifera in a glacially fed fjord of Svalbard, European Arctic. *J. Foraminiferal Res.* 30, 251-271.
- Kumar, V., Tiwari, M., Nagoji, S., Tripathi, S. 2016. Evidence of anomalously low  $\delta^{13}\text{C}$  of marine organic matter in an Arctic Fjord. *Sci. Rep.* DOI: 10.1038/srep36192.
- Kurtarkar, S. R., Nigam, R., Saraswat, R., Linshy, V.N. 2011. Regeneration and abnormality in benthic foraminifer *Rosalina leei*: implications in reconstructing past salinity changes. *Riv. Ital. Paleontol. Strat.* 117, 189-196.
- Lefauconier B., Hagen J.O., Rudant J.P. 1994. Flow speed and calving rate of Kongsbreen glacier, Svalbard, using SPOT images. *Polar Res.* 13, 59-65.
- Liu, Y., Chai, X., Hao, Y., Gao, X., Lu, Z., Zhao, Y., Zhang, J., Cai, M. 2015. Total mercury and methylmercury distributions in surface sediments from Kongsfjorden, Svalbard, Norwegian Arctic. *Environ. Sci. Pollut. Res.* 22, 8603-8610.
- Loubere, P., Jacobsen, B., Klitgaard-Kristensen, D., Husum, K., Jernas, P., Richaud, M. 2011. The structure of benthic environments and the paleochemical record of foraminifera. *Deep-Sea Research I*, 58, 535-545.
- Majewski, W., Zajaczkowski, M., 2007. Benthic foraminifera in Adventfjorden, Svalbard: Last 50 years of local hydrographic changes. *J. Foraminiferal Res.* 37, 107-124.
- Manasa, M., Saraswat, R., Nigam, R. 2016. Assessing the suitability of benthic foraminiferal morpho-groups to reconstruct past monsoon from the Bay of Bengal. *J. Earth System Sci.* 125, 571-584.
- Murray, J.W., Alve, E., Cundy, A. 2003. The origin of modern agglutinated foraminiferal assemblages: evidence from a stratified fjord. *Estu. Coastal Shelf Sci.* 58, 677-697.

- Murray, J.W., Alve, E., Jones, B.W., 2011. A new look at modern agglutinated benthic foraminiferal morphogroups: Their value in palaeoecological interpretation. *Palaeogeogra. Palaeoclimatol. Palaeoecol.* 309, 229-241.
- Nigam, R., Khare, N., Borole, D.V. 1992. Can benthic foraminiferal morpho-groups be used as indicators of paleomonsoonal precipitation?. *Estuar. Coastal Shelf Sci.* 34, 533-542.
- Nigam, R., Mazumder, A., Henriques, P.J., Saraswat, R. 2007. Benthic foraminifera as proxy for oxygen-depleted conditions off the central west coast of India. *J. Geol. Soc. India* 70, 1047-1054.
- Nigam, R., Kurtarkar, S.R., Saraswat, R., Linshy, V. N., Rana, S.S. 2008. Response of benthic foraminifera *Rosalina leei* to different temperature and salinity, under laboratory culture experiment. *J. Mar. Biol. Assoc. U.K.* 88, 699-704.
- Nordberg, K., Gustafsson, M., Krantz, A.L. 2000. Decreasing oxygen concentrations in the Gullmar Fjord, Sweden, as confirmed by benthic foraminifera, and the possible association with NAO. *J. Mar. Syst.* 23, 303-316.
- Peterse, F., Kim, J.-H., Schouten, S., Klitgaard-Kristensen, D., Koç, N., Damsté, J.S.S. 2009. Constraints on the application of the MBT/CBT palaeothermometer at high latitude environments (Svalbard, Norway). *Org. Geochem.* 40, 692-699.
- Promińska, A., Cisek, M., Walczowski, W. 2017. Kongsfjorden and Hornsund hydrography - comparative study based on a multiyear survey in fjords of west Spitsbergen. *Oceanologia* 59, 397-412.
- Risdal, D., 1964. Foraminiferfaunaenes relasjon til dybdeforholdene i Oslofjorden, med en diskusjon av de senkvartre foraminiferer. *Nor. Geol. Unders.* 226, 5-142.
- Rosoff, D.B., Corliss, B.H. 1992. An analysis of Recent deep-sea benthic foraminiferal morphotypes from the Norwegian and Greenland seas. *Palaeogeogra. Palaeoclimatol. Palaeoecol.* 91, 13-20.
- Saraswat, R., Kouthanker, M., Kurtarkar, S.R., Nigam, R., Naqvi, S.W.A., Linshy, V.N. 2015. Effect of salinity induced pH/alkalinity changes on benthic foraminifera: A laboratory culture experiment. *Estu. Coastal Shelf Sci.* 153, 96-107.
- Severin, K.P. 1983. Test morphology of benthic foraminifera as a discriminator of biofacies. *Mar. Micropaleontol.* 8, 65-76.
- Shetye, S., Mohan, R., Shukla, S.K., Maruthadu, S., Ravindra, R. 2011. Variability of *Nonionellina labradorica* Dawson in Surface Sediments from Kongsfjorden, West Spitsbergen. *Acta Geol. Sin.* 85, 549-558.
- Skirbekk, K., Klitgaard Kristensen, D., Rasmussen, T.L., Koç, N., Forwick, M. 2010. Holocene climate variations at the entrance to a warm Arctic fjord: evidence from Kongsfjorden trough, Svalbard. *Geol. Soc., London, Sp. Pub.* 344, 289-304.
- Suokhrie, T., Saalim, S.M., Saraswat, R., Nigam, R. 2017. Indian monsoon variability in the last 2000 years as inferred from benthic foraminifera. *Quat. Int.*

- Svendsen, H., Beszczynska-Møller, A., Hagen, J.O., Lefauconnier, B., Tverberg, V., Gerland, S., Ørbæk, J.B., Bischof, K., Papucci, C., Zajaczkowski, M., Azzolini, R., Bruland, O., Wiencke, C., Winther, J.-G., Dallmann, W. 2002. The physical environment of Kongsfjorden–Krossfjorden, an Arctic fjord system in Svalbard. *Polar Res.* 21, 133-166.
- Urban-Malinga, B., Wiktor, J., Jabłońska, A., Moens, T. 2005. Intertidal meiofauna of a high-latitude glacial Arctic fjord (Kongsfjorden, Svalbard) with emphasis on the structure of free-living nematode communities. *Polar Biol.* 28, 940-950.
- Wilson, L., Jernas, P., Kristensen, D., Koc, N. 2008. Annual and Seasonal Dynamics of Benthic Foraminifera and Their Sensitivity to Environmental Changes in Arctic Fjord. *Eos Trans. AGU.* 89, Fall Meet. Suppl., Abstract.
- Włodarska-Kowalczyk, M., Górska, B., Deja, K., Morata, N. 2016. Do benthic meiofaunal and macrofaunal communities respond to seasonality in pelagial processes in an Arctic fjord (Kongsfjorden, Spitsbergen)? *Polar Biol.* 39, 2115-2129.
- Zaborska, A., Pempkowiak, J., Papucci, C. 2006. Some sediment characteristics and sedimentation rates in an Arctic fjord (Kongsfjorden, Svalbard). *Ann. Environ. Prot.* 8, 79-96.
- Zhang, T., Wang, N.F., Zhang, Y.Q., Liu, H.Y., Yu, L.Y. 2015. Diversity and distribution of fungal communities in the marine sediments of Kongsfjorden, Svalbard (High Arctic). *Sci. Rep.* DOI: 10.1038/srep14524.

### Legend to Figures and Table:

- Figure 1: The multi-corer samples collected from Kongsfjorden and Krossfjorden. The serial numbers of the stations are same as in Table 1. The inset map shows the Svalbard region. The location of Kongsfjorden and Krossfjorden in the inset map is marked by white arrow.
- Figure 2: The representative genera of calcareous rounded-symmetrical (A-D), angular-asymmetrical (E-I), agglutinated-rounded symmetrical (J-M), and angular-asymmetrical (N-Q) benthic foraminiferal morpho-group. A. *Cibicides*, B. *Elphidium*, C. *Cassidulina*, D. *Nonionellina*, E. *Trifarina*, F. *Stainforthia*, G. *Bolivina*, H. *Globobulimina*, I. *Buliminella*, J. *Labrospira*, K. *Labrospira*, L. *Haplophragmoides*, M. *Adercotryma*, N. *Textularia*, O. *Spiroplectammina*, P. *Textularia*, Q. *Textularia*. The scale bar is 50  $\mu\text{m}$ , unless otherwise mentioned.
- Figure 3: The distribution of coarse fraction in Kongsfjorden and Krossfjorden.
- Figure 4: The distribution of the absolute abundance of benthic foraminifera (individual/g dry sediment) in Kongsfjorden and Krossfjorden.
- Figure 5: The relative abundance (%) of (A) agglutinated and (B) calcareous benthic foraminifera in the surface sediments of Kongsfjorden and Krossfjorden.
- Figure 6: The surface distribution of relative abundance (%) of calcareous rounded-symmetrical benthic foraminifera (A), calcareous angular-asymmetrical benthic foraminifera (B), agglutinated rounded-symmetrical benthic foraminifera (C) and agglutinated angular-asymmetrical benthic foraminifera (D), in Kongsfjorden and Krossfjorden.
- Figure 7: The surface distribution of %C<sub>org</sub> in Kongsfjorden-Krossfjorden, based on the published data (Urban-Malinga et al., 2005; Knies et al., 2007; Peterse et al., 2009; Shetye et al., 2011; Liu et al., 2015; Włodarska-Kowalczyk et al., 2016; Zhang et al., 2015; Kumar et al., 2016; Grotti et al., 2017). The black filled circles denote the station locations used to compile the %C<sub>org</sub> distribution.
- Figure 8: The relationship between water depth and rounded symmetrical benthic foraminifera (A), angular asymmetrical benthic foraminifera (B), agglutinated rounded symmetrical benthic foraminifera (C) and calcareous angular asymmetrical benthic foraminifera (D). The 'r' is the correlation coefficient.
- Table 1: The details of the surface sediment samples collected from Kongsfjorden and Krossfjorden.

**Table 1**

<b>Serial No.</b>	<b>Station</b>	<b>Longitude (°E)</b>	<b>Latitude (°N)</b>	<b>Water Depth (m)</b>
1.	8IA/N1	11.27.930	78.59.924	383.0
2.	8IA/N2	11.34.990	79.02.450	136.0
3.	8IA/N3	11.40.650	79.01.365	235.0
4.	8IA/N4	11.37.226	78.59.548	247.0
5.	8IA/N5	11.47.621	78.57.956	254.0
6.	8IA/N7	12.00.374	78.57.353	162.6
7.	8IA/N8	12.09.357	78.56.538	167.5
8.	8IA/N9	12.26.920	78.58.888	115.9
9.	8IA/N10	12.20.910	78.56.927	53.6
10.	8IA/N11	12.21.445	78.55.047	43.1
11.	8IA/N12	12.10.370	78.55.033	80.0
12.	8IA/N13	12.00.210	78.55.780	162.0
13.	8IA/K1	11.20.843	79.02.668	347.2
14.	8IA/K2	11.37.562	79.07.013	67.2
15.	8IA/K3	11.46.364	79.11.529	369.8
16.	8IA/K4	11.43.643	79.12.994	268.3
17.	NP-08/16/49MC	11.22.100	79.04.350	303.0
18.	NP-08/16/63MC	12.15.790	78.55.180	109.0
19.	NP-08/16/11MC	11.39.380	79.07.080	306.0
20.	NP-08/16/40MC	11.50.220	78.59.170	319.0
21.	NP-08/16/41MC	11.52.640	79.00.210	161.0
22.	NP-08/16/35MC	10.51.510	79.00.760	328.0
23.	NP-08/16/44MC	11.39.450	78.59.170	278.0

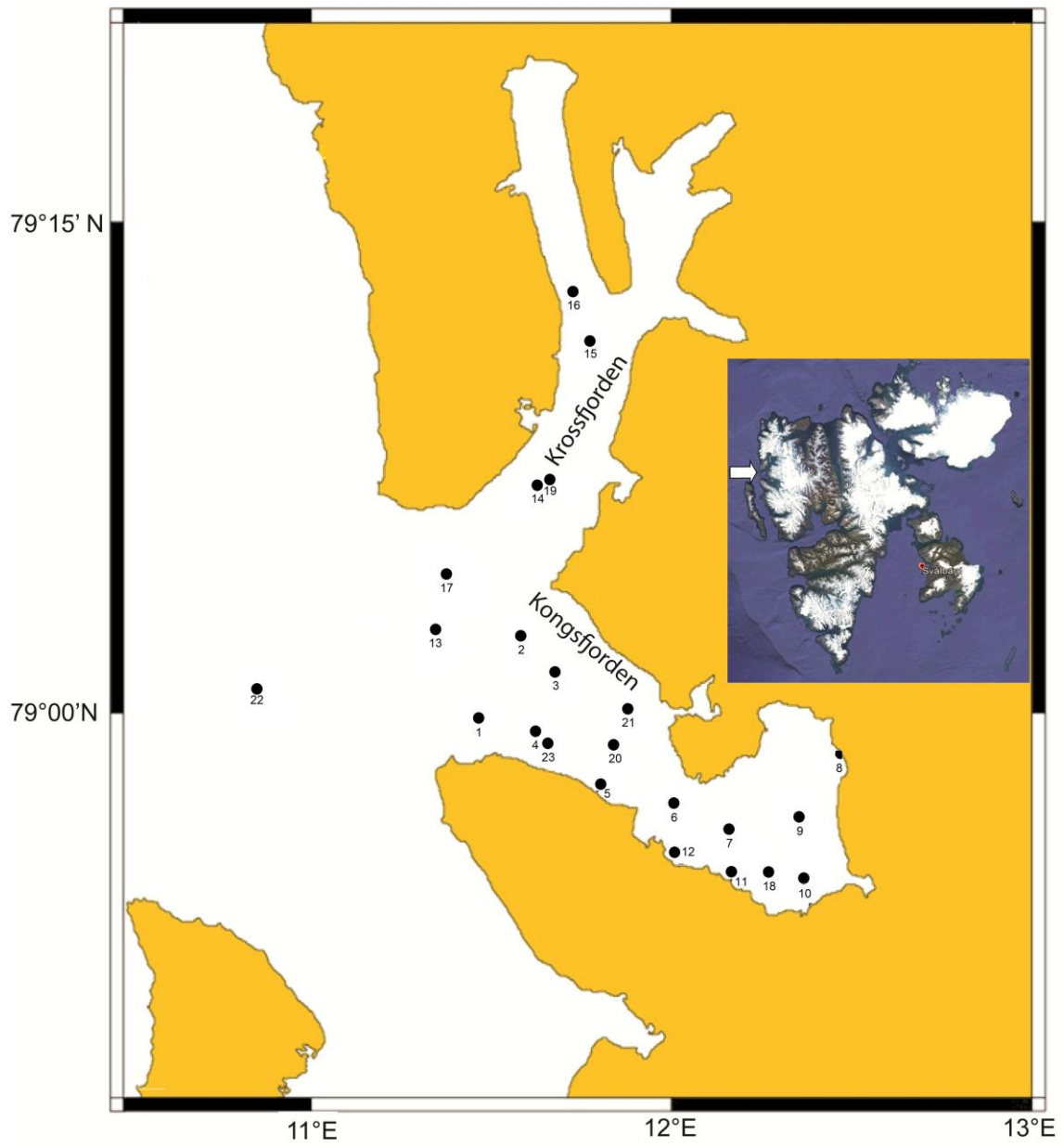


Figure 1

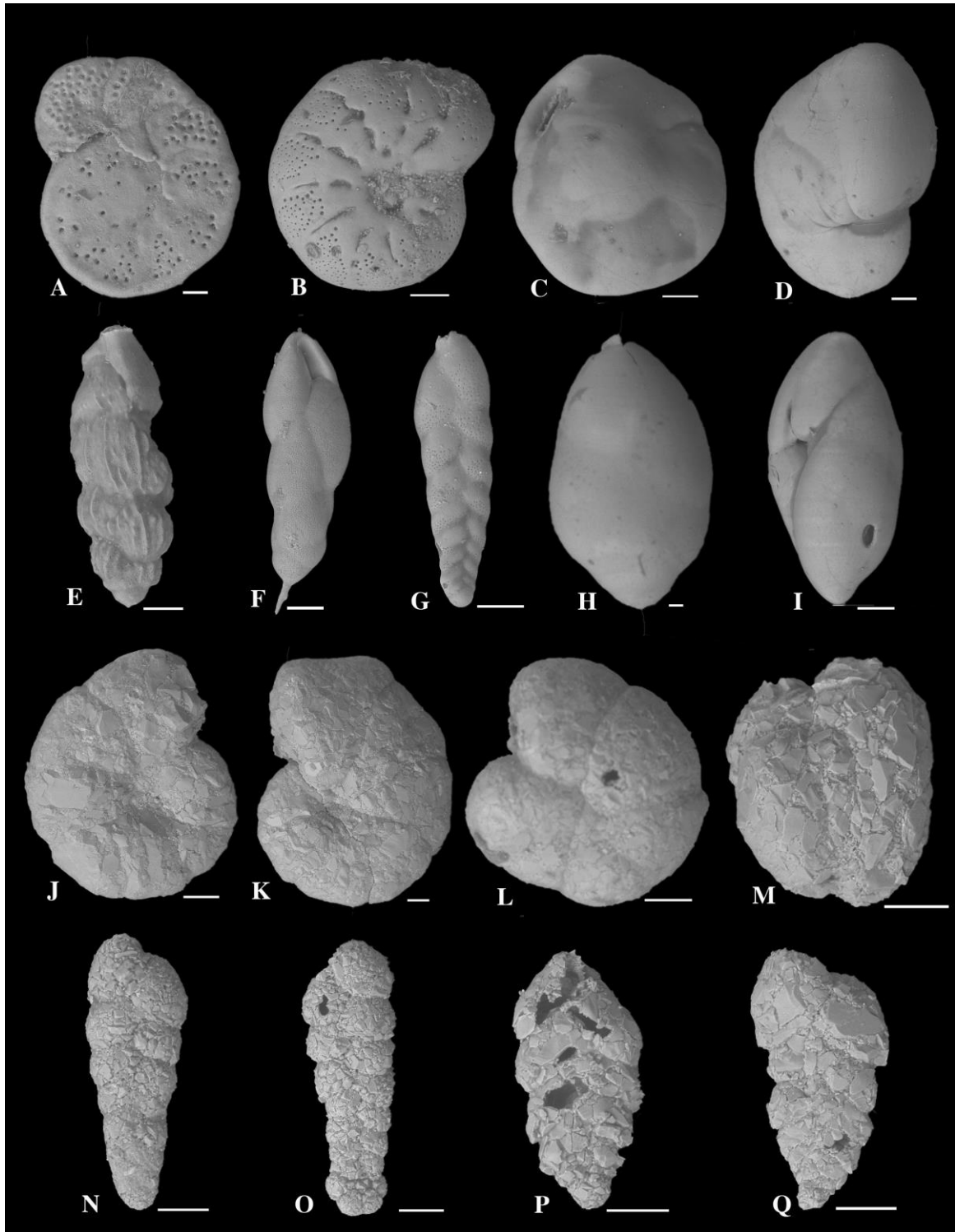


Figure 2



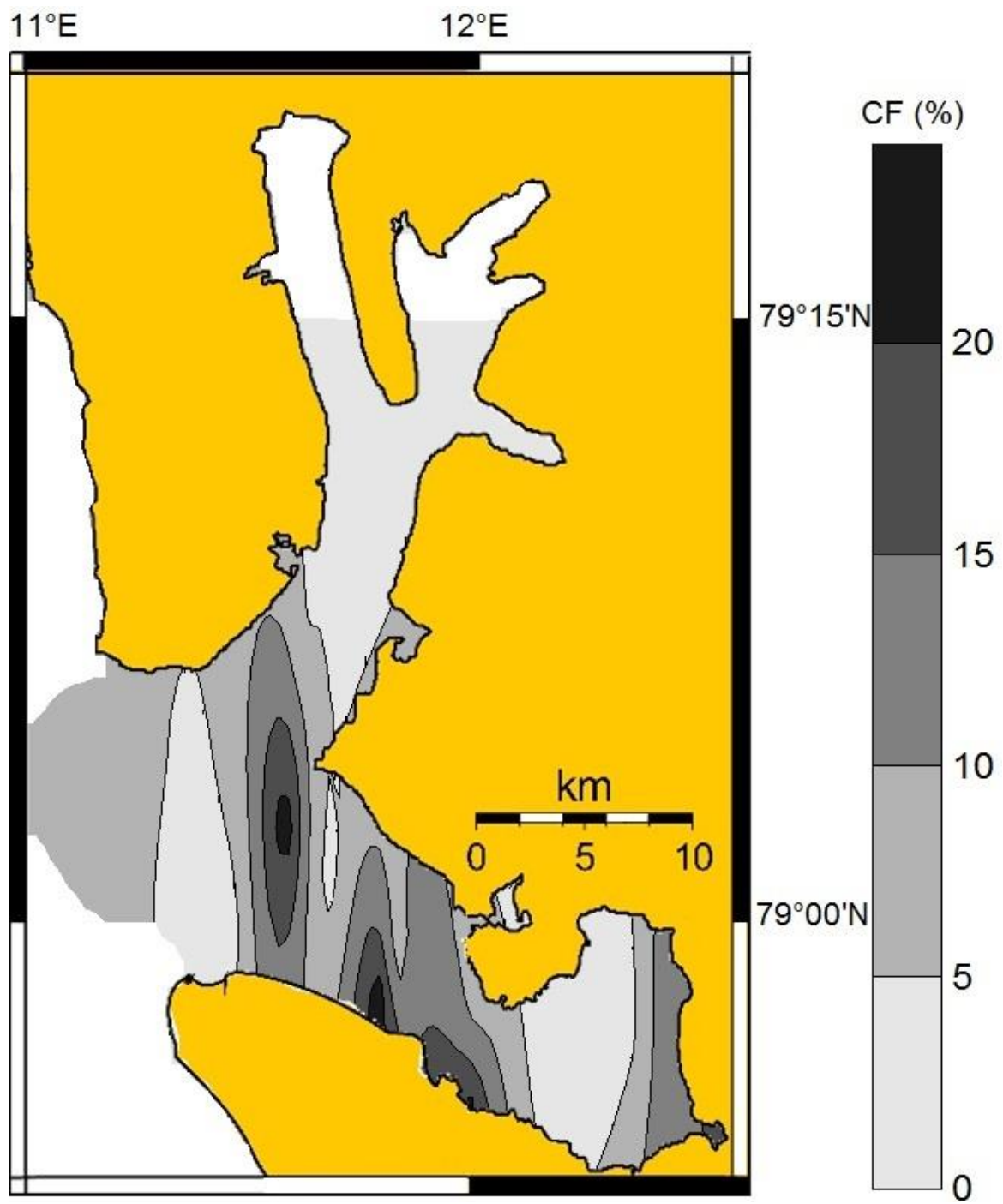


Figure 3

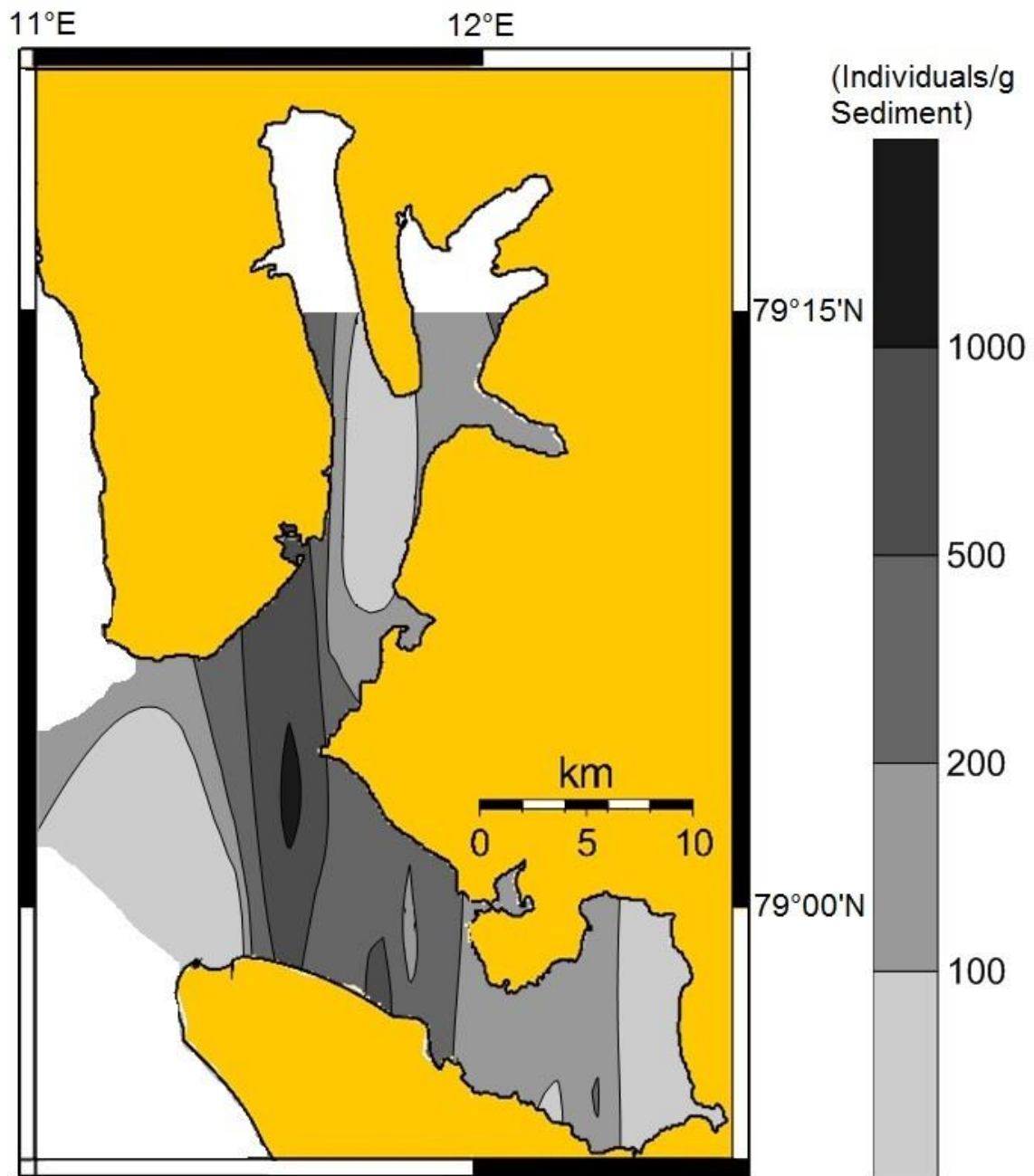


Figure 4

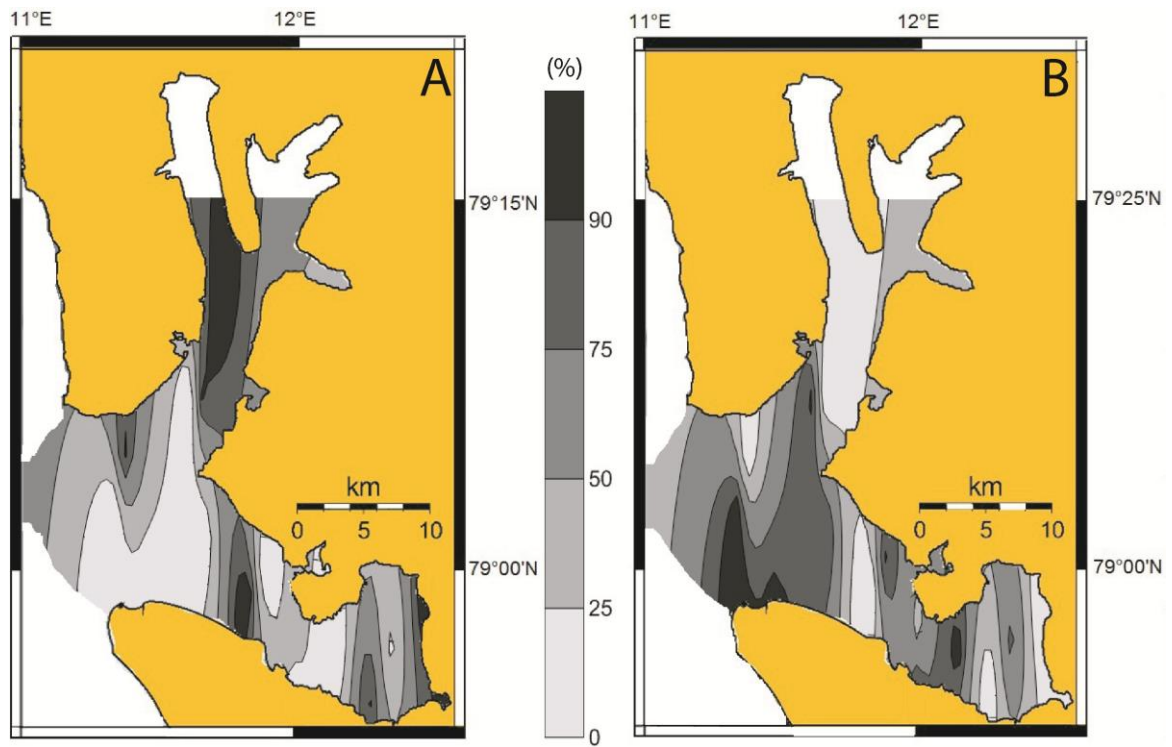


Figure 5

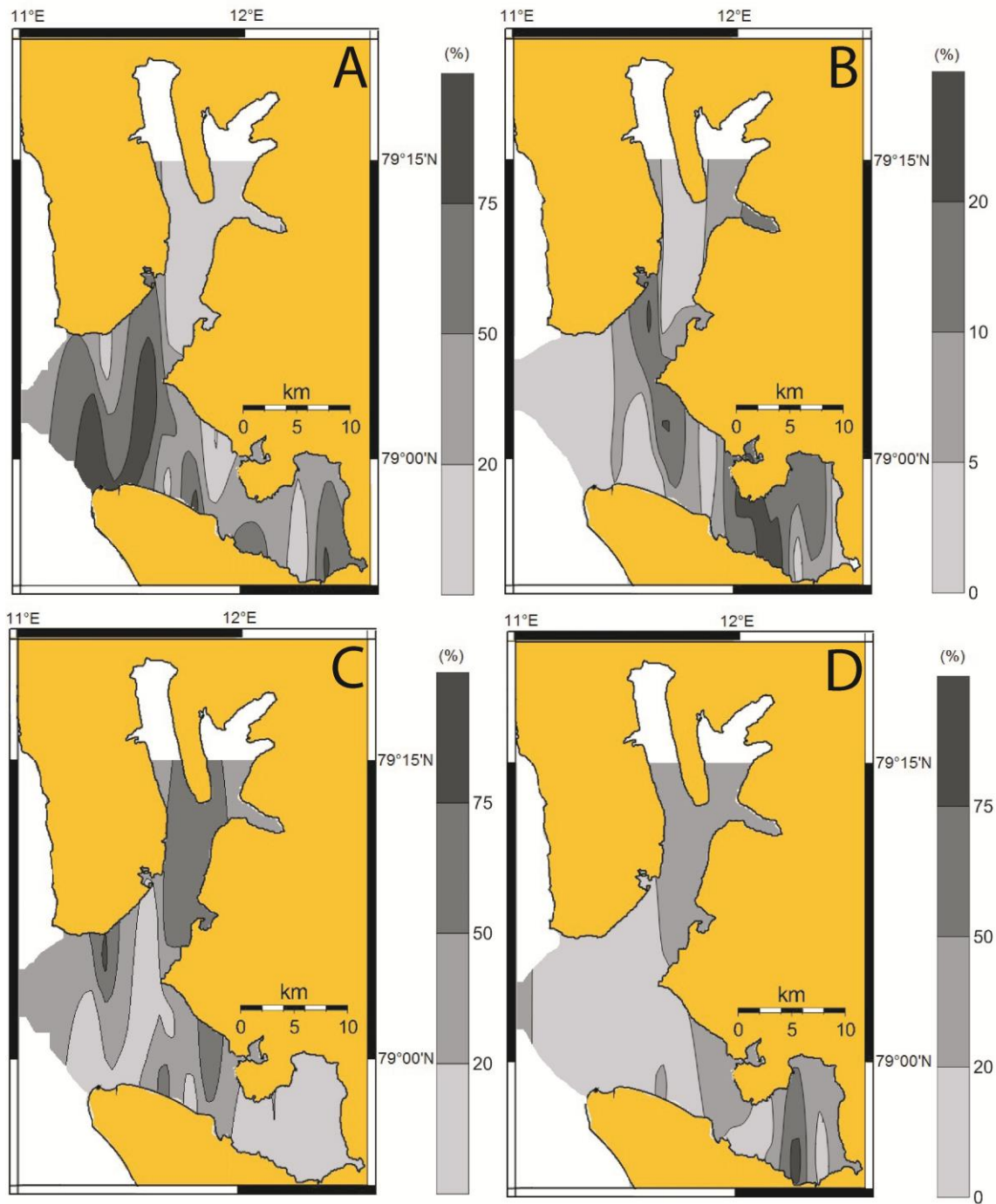


Figure 6

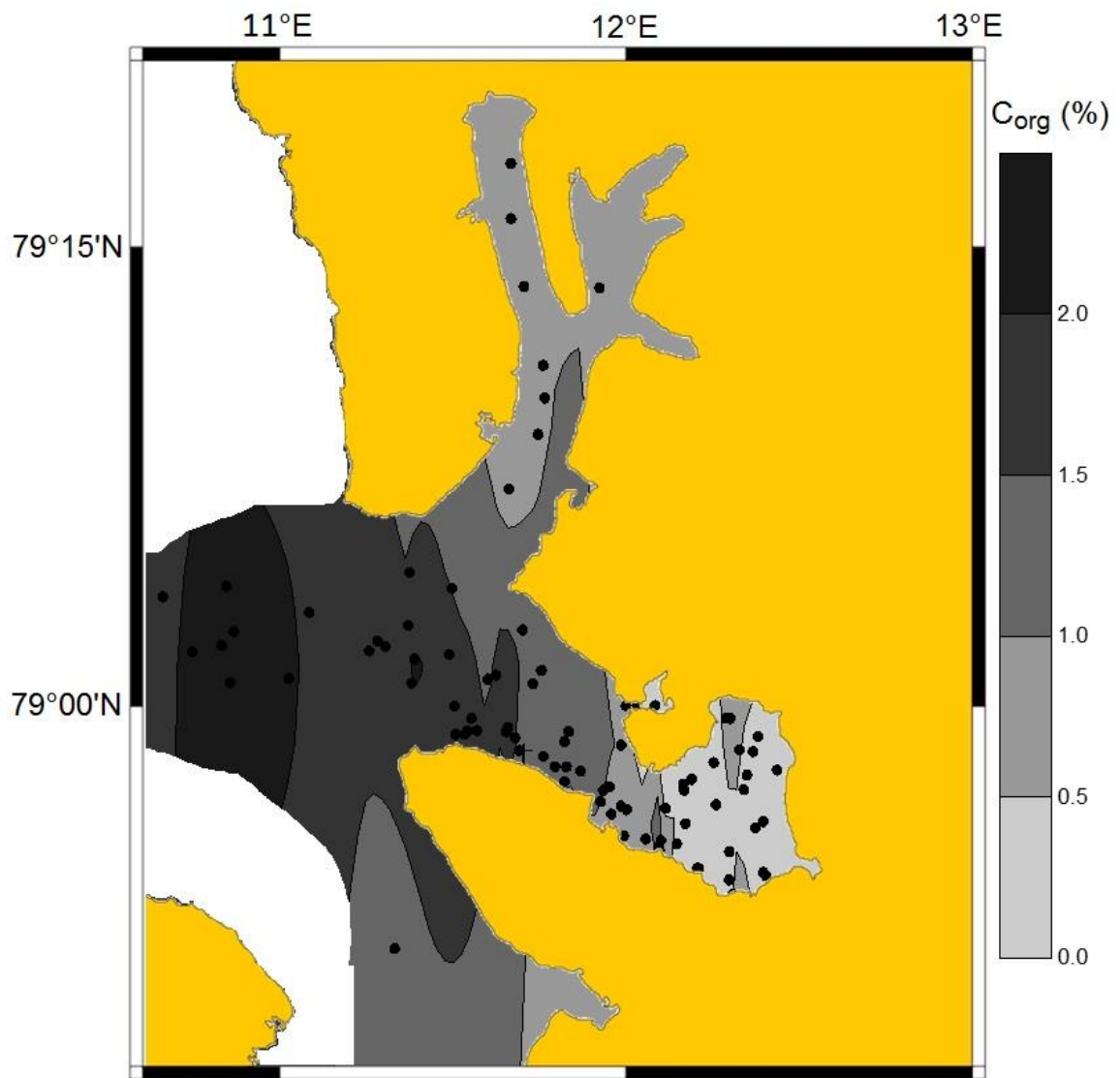


Figure 7

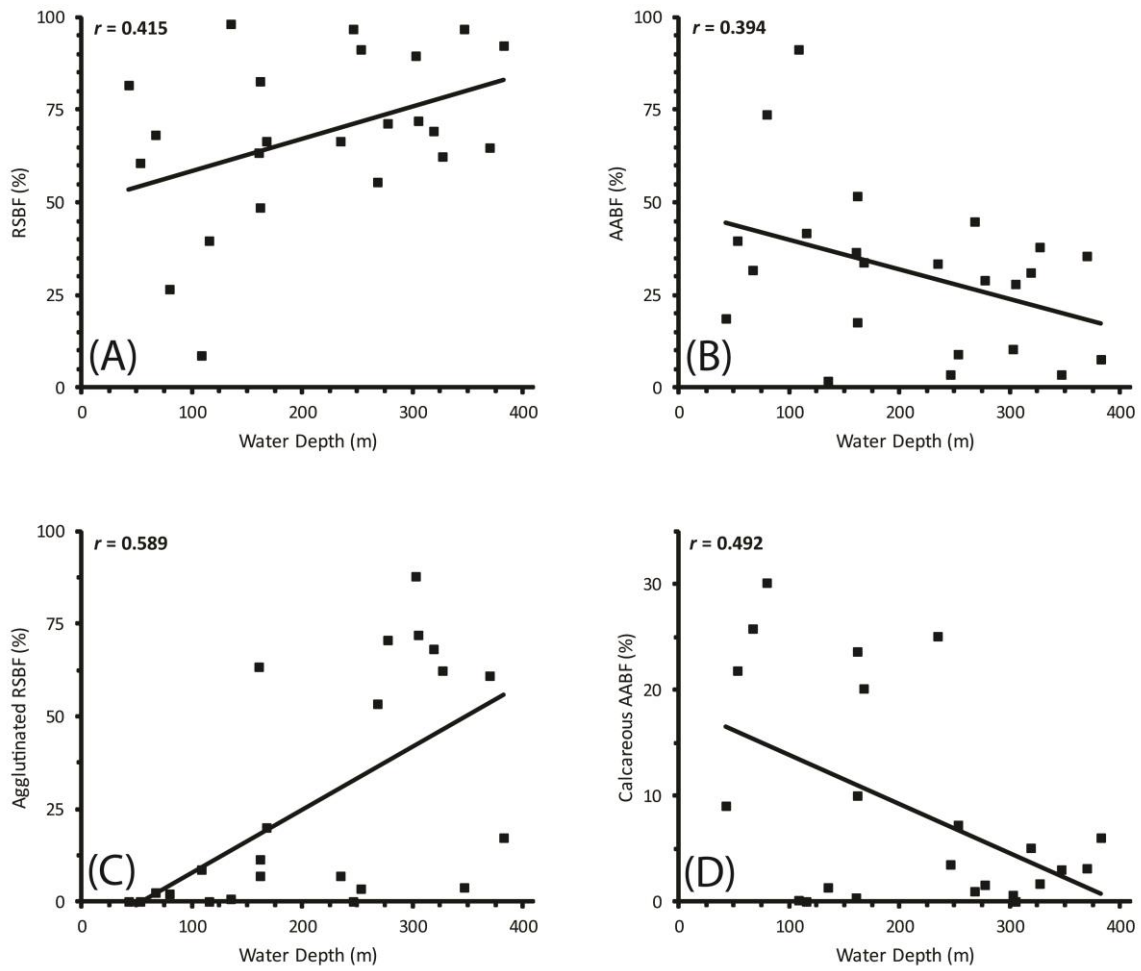


Figure 8