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Discussions

Spatial distribution of benthic foraminiferal stable isotopes and dinocyst assemblages in surface sediments of the Trondheimsfjord, central Norway

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Spatial distribution of paleoceanographical proxies in the Trondheimsfjord

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Abstract

Instrumental records from the Norwegian Sea and the Trondheimsfjord show evidence that changes of bottom water temperature and salinity in the fjord are linked to the salinity and temperature variability of the North Atlantic Current (NAC). Changes in primary productivity and salinity in the surface and intermediate water masses in the Trondheimsfjord as well as the fjord sedimentary budget are mainly driven by changes in riverine input. In this study we use 59 surface sediment samples that are evenly distributed in the fjord to examine whether dinocyst assemblages and stable isotope ratios of benthic foraminifera reflect the present-day hydrology and can be used as paleoceanographic proxies. In general, modern benthic δ^{18}O and δ^{13}C values decrease from the fjord entrance towards the fjord head with lowest values close to river inlets. This is essentially explained by gradients in the amounts of freshwater and terrigenous organic matter delivered from the hinterland. The distribution of benthic δ^{13}C ratios across the fjord is controlled by both the origin (terrigenous vs. marine) of organic matter and local topography-induced variability in organic matter flux at the water-sediment interface. The dinocyst assemblages display the variations in hydrography with respect to the prevailing currents, the topography, and the freshwater and nutrient supply from rivers. The strength and depth of the pycnocline in the fjord strongly varies seasonally and thereby affects water mass characteristics as well as nutrient availability, temporally creating local conditions that explain the observed species distribution.

Our results prove that dinocyst assemblages and benthic foraminiferal isotopes reliably mirror the complex fjord hydrology and can therefore be used as proxies of Holocene climatic variability.

1   Introduction

The North Atlantic Current (NAC) is the prolongation of the Gulf Stream and transports warm and saline water northward along the Norwegian continental margin (Ganachaud and Wunsch, 2000). This poleward NAC flow essentially contributes to the deep water formation in the Nordic Seas and strongly affects the northern European climate (Vellinga and Wood, 2002). The hydrology of Norwegian fjords, adjoining the Norwegian Sea, is equally linked to the NAC and the Norwegian coastal current (NCC) (Wassmann et al., 1996; Aarseth, 1997; Sætre, 1999, 2007; Eilertsen and Skarðhamar, 2006). Many fjords have a bedrock threshold at the entrance causing a complex hydrology linked to the ocean currents in the adjacent sea, as well as their salinity and temperature structure, wind dynamics, and riverine input (Inall and Gillibrand, 2010 in Howe et al., 2010). As a consequence fjord sediments bear a combined signature of marine, continental and atmospheric environments and processes. Additionally, fjords are semi-enclosed basins and act as natural sediment traps with high accumulation of marine and terrigenous sediments. Norwegian fjords are therefore excellent locations for high resolution studies of the temporal variations in the physico-chemical characteristics of the NAC and NCC as well as the regional climate (Cage and Austin, 2008; Alve et al., 2011). The objective of this study is to examine if micropaleontological proxies deriving from sediments from the Trondheimsfjord reflect the main elements of present-day oceanography and hydrology. The motivation for this examination implies the question to which extent these proxies from fjord sedimentary archives can be used to determine changes in oceanographic regimes in the recent past (Holocene). In order to grasp the complex hydrological and environmental patterns of the bottom and surface waters in the Trondheimsfjord we analysed the stable isotope composition of the benthic foraminifera *Melonis barleeanus* and organic-walled dinoflagellate cysts assemblages from 59 surface sediment samples evenly distributed along the fjord's axis.

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Stable isotope ratio were analysed to determine bottom water characteristics and sediment dynamics in the fjord. Oxygen isotopes in calcite tests are conventional tools for the reconstruction of the past climate since the calcification processes are considered to occur in close equilibrium with the surrounding sea water (e.g. Urey, 1946; Shackleton and Opdyke, 1973). The foraminiferal ^{18}O/^{16}O isotope ratio (δ^{18}O) thus denotes the isotopic composition of the water linked to the salinity and temperature, in which the foraminifera has been ultimately living (e.g. Urey, 1946; Shackleton and Opdyke, 1973; Epstein et al., 1953; Bemis and Spero, 1998). The carbon isotope ratio in benthic foraminifera is mainly linked to the influence of deep water ventilation, to the origin (marine vs. terrigenous) and the amount of organic matter deposited at the sediment surface, and to remineralization processes in the sediment (e.g. Caralp, 2000; Fontanier et al., 2008). Dinoflagellate cysts are widely used proxies for the reconstruction of sea-surface conditions in marine and coastal environments (de Vernal et al., 2001a; de Vernal and Marret, 2007). They are composed of highly resistant refractory organic matter and therefore generally well preserved in sediments. Cyst assemblages in marine environments generally reflect surface water characteristics such as temperature, salinity and ice cover. Cyst assemblages in coastal environments are usually tolerant to a wide range of temperatures and salinities and reflect more distinctive ecological preferences such as oceanic versus coastal waters, nutrient availability, salinity gradients as well as stress tolerance to rapid and periodic changes (e.g. Mudie, 1992; Dale et al., 2002; Harland et al., 2004b; Radi et al., 2007; Price and Pospelova, 2011).

2 Physical settings and oceanography

The following oceanographic and hydrological overview is mainly based on Jacobson (1983) which contains a detailed description of the geomorphology and the main circulation processes affecting the hydrology of the Trondheimsfjord. Moreover, we used monthly hydrographical data and measurements from three mooring stations as

well as CTD measurements conducted in April 2011 (Fig. 2) to further illustrate the fjord hydrological context.

The Trondheimsfjord is located at the coast of mid Norway extending with a total length of 130 km from 63° 40′ N/09° 45′ E at Ørland to 64° 45′ N/11° 30′ E at the fjord head at Verdal (Bøe et al., 2003) (Fig. 1). The Beitstadfjord adjoins the Trondheimsfjord at Skarnsund 63° 50′ N/11° 04′ E and extends until Steinkjer at 63° 00′ N/11° 28′ E. The Trondheimsfjord is divided into two basins, the Seaward basin and the Middle fjord basin, which are topographically separated from the Norwegian Sea and from each other by bedrock thresholds (Figs. 1, 2). Stjørnfjord and the Seaward basin are separated from the Norwegian Sea by a broad and shallow sill at the fjord entrance rising to 195 m water depth (Fig. 2). The Tautra sill with a minimum water depth of 98 m separates the Seaward basin from the Middle fjord (Fig. 2). The innermost fjord, the Beitstadfjord, is separated from the Trondheimsfjord by the Skarnsund sill with a minimum water depth of 140 m (Fig. 2). The deepest part in the fjord with a maximum water depth of 620 m is located in the narrow passage between the fjord entrance and Røberg in the Seaward basin. In the following, unless otherwise specified, the term "Trondheimsfjord" refers to the entire fjord area including Stjørnfjord and Beitstadfjord.

The hydrology of the Trondheimsfjord is linked to the surface current system of the Norwegian Sea which at these latitudes is dominated by the NAC and the brackish coastal waters carried poleward by the NCC. The paths of the NAC and NCC are controlled by the topography of the Norwegian shelf and are the main contributors to the fjord's hydrology (Fig. 1) (Mork, 1981; Sætre, 1999). The warm and salty poleward NAC affects the top 500 m of the water column and flows as a slope current with its main core off the shelf break. The NCC flows in the surface layers over the Norwegian shelf and is supplied with brackish water from the Baltic Sea, fjords and rivers along the Norwegian Coast (Mork, 1981; Haugan et al., 1991; Sætre, 1999). The hydrology of the Trondheimsfjord comprises several strongly contrasting hydrographic regimes due to the underlying estuarine circulation and high freshwater input from different source areas (Fig. 1). The fjord entrance and Stjørnfjord are characterized by

a more marine/coastal environment. Middle fjord and Beitstadfjord are more sheltered and largely influenced by the hydrological cycle of the surrounding hinterland resulting in larger temperature and salinity variability (Fig. 2). The bottom water renewal in the fjord is controlled by strong seasonal winds of the North Atlantic region and the variability of the pycnocline. In spring (March until June) the NCC is broader and shallower as the result of the increasing northerly winds (Sætre et al., 1988; Sætre, 2007) and increased melt water supply from rivers and fjords. The reduced vertical extension of the NCC on the inner shelf enables high salinity NAC water to pass over the sill at the fjord entrance to replace old fjord water from depths deeper than 50 m. Brackish surface water resulting from the peak spring river inputs into the Trondheimsfjord moves seaward compensating the intermediate and deep marine inflow. Starting in late summer/early autumn, south westerly winds across the Norwegian Sea induce downwelling of the surface layers causing the vertical expansion of the NCC (Sætre et al., 1988; Sætre, 2007). Marine brackish water (NCC) enters the fjord at intermediate depth (20–70 m) and is quickly mixed into the bottom water. Intense cooling and associated downwelling of the surface and intermediate layers starting in late summer contribute to the process of vertical mixing of the water column in the fjord. According to instrumental measurements, the residence time for upper low salinity surface water is approximately one month, whereas deep water is usually renewed twice a year (Jacobson, 1983).

3 Material and methods

3.1 Sample material

In total, 59 surface sediment samples, evenly distributed along the axis of the Trondheimsfjord (Fig. 4), were collected with a multicorer with 4 tubes as part of a research cruise of the RV *FF Seisma* (Geological Survey of Norway (NGU), Trondheim) in April 2011. On average, 3 to 4 cores were retrieved at each sample location for micropaleontological analysis at EPOC (CNRS/Université Bordeaux1), and geochemical analysis

accomplished at the Norwegian Geological Survey (NGU) in Trondheim. Each core was ca. 20 to 40 cm long and immediately sampled onboard. This study was performed on the top 2 cm of the sedimentary sections for both stable isotope measurements and dinoflagellate cyst census counts. Present sedimentation rates in the Trondheimsfjord largely vary 1–5 mm yr^{-1} depending on the location (Bugge et al., 1999; Bøe et al., 2003). Regarding these sedimentation rates our surface sediment samples are assumed to integrate 4 to 20 yr of sediment accumulation.

3.2 Stable isotope measurements

For each station 18–20 g of wet bulk sediment were wet-sieved using a 63 µm mesh size. The residue was ultimately flushed with distilled water and oven-dried at 40 °C. We selected pristine specimens of *Melonis barleeanus* of similar test size from the > 200 µm fraction to avoid bias caused by physiological effects due to size-related changes in growth rate on the stable isotope variability (Corliss et al., 2002). For each measurement 50–100 µg (ca. 3–4 specimens) were prepared. The samples were chemically treated by an automatic carbonate preparation device (Kiel device) and measured with a mass spectrometer type Optima hosted at EPOC (Université Bordeaux 1/CNRS). The instrumental precision yields 0.005 ‰ for $\delta^{13}C$ and 0.008 ‰ for $\delta^{18}O$. The stable isotope ratios were calibrated against the Vienna Pee Dee Belemnite (VPDB) using the international standard NBS 19 and are displayed in the δ-notation. The species-specific deviation of the oxygen isotope ratio due to equilibrium fractionation between the calcite shell and the bottom water, the so-called vital effect (e.g. Woodruff et al., 1980; McCorkle et al., 1990; Holsten et al., 2004; Schmiedl et al., 2004) was corrected by a constant value of +0.4 ‰ according to studies of *M. barleeanus* in the Norwegian Sea (e.g. Woodruff et al., 1980; Graham et al., 1981; Jansen et al., 1989). The deviation of the benthic $\delta^{13}C$ is affected by the degradation process of organic matter and strongly varies depending on the microhabitat in which the foraminifera have been living. We did not apply any correction value for the $\delta^{13}C$ as *M. barleeanus* vertically migrates in the sediment depending on the amount and quality of

organic matter complicating a precise determination of a constant correction (Fontanier et al., 2008).

3.3 Dinocyst assemblages

Dinoflagellate cysts were retrieved from the < 150 µm fraction. The preparation technique follows a classical sample preparation procedure (e.g. Stockmarr, 1971; de Vernal et al., 1996) slightly modified at EPOC/Université Bordeaux1. For the purpose of quantification and calculation of the cyst concentrations, spores of *Lycopodium clavatum* were added prior to the sample treatment. The samples were successively treated with cold 10, 25 and 50 % hydrochloric acid (HCl) and cold 40 and 70 % hydrogen fluoride (HF) and again with 25 % HCl. The residue was sieved through 10 mm nylon mesh screens. Since high amounts of amorphous organic material (AOM) concealed the cysts as well as their spines and processes we carefully removed any resistant AOM by centrifugation and swirling in a large watch glass. The method relies on density differences between the cysts and the AOM (Riding and Kyffin-Hughes, 2004; L. Londeix, personal communication, 2012). Cyst counts of various samples before and after the treatment show only minor discrepancies: counting of the untreated samples yield lower amounts of the smaller species *Pentapharsodinium dalei* and randomly a stronger presence of *Selenopemphix quanta* due to the different dimensions of the cyst bodies. We assume that the relative amount of the dominant species *P. dalei* masked by AOM causes a stronger permanent variation of the cyst assemblages than randomly higher amounts of *S. quanta*. Still, we keep in mind a potential increase of certain species characterized by larger cyst bodies.

The residue containing the dinocysts was mounted between slide and coverslip with glycerine jelly. An average amount of 300 cysts per slide was counted using a Zeiss Axioscope light microscope at 40 × magnification. The identification of the cysts is based on the nomenclature of Rochon et al. (1999) and Head et al. (2001). *Operculodinium centrocarpum* s.l. includes both, long-process and short-process forms of *O. centrocarpum* sensu (Wall and Dale, 1967) and *O. centrocarpum* – Arctic morphotype

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(de Vernal et al., 2001). Dinoflagellate species within the Spiniferites group were grouped according to Marret and Zonneveld (2003). Hence, *Spiniferites elongatus* s.l. includes *Spiniferites elongatus* and *Spiniferites frigidus*, and *Spiniferites membranaceus* includes *Spiniferites belerius*. *Spiniferites ramosus* comprises species of *Spiniferites bulloides*, and *Spiniferites hyperacanthus* is grouped together with species of *Spiniferites mirabilis*. *Spiniferites* spp. refers to every cyst that was clearly recognized as species of the Spiniferites assemblage but was not identified beyond the genus level. *S. quanta* includes *Selenopemphix nephroides*, *Islandinium minutum* includes *Islandinium cezare* and *Brigantedinium* spp. includes *Brigantedinium simplex* and *Brigantedinium caracoense*. *Impagidinium* spp. includes the species *Impagidinium Patulum*, *Impagidinim aceulatum* and *Impagidinium sphaericum*. Census counts of the cysts are expressed as both, relative (%) and absolute abundances (cysts cm^{-3}).

The cysts counts were statistically evaluated using nonmetric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarities and visualization in a two-dimensional space to check for any groupings within the study area. We accomplished the analysis using the free software package R 2.15.1 (http://cran.r-project.org). Before running the NMDS the data set was square root transformed and submitted to Wisconsin double standardization due to the large range of data values.

4 Results and discussion

4.1 Benthic oxygen isotopes

Oxygen isotope ratios of *M. barleeanus* range between 0.39 and 2.14 ‰ with an average of 1.2 ‰ (Figs. 3a and 4). Overall, the foraminiferal δ^{18}O values decrease along the Trondheimsfjord from the fjord entrance (2.1 ‰) to the fjord head (0.6 ‰). δ^{18}O values in the Seaward basin are higher than in the Middle fjord (Fig. 3a). At the Tautra sill, which separates the two basins, δ^{18}O markedly increases by 0.5 ‰ as compared to the values inwards and seawards of this bedrock threshold. The strongest deviations

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from the mean value of 1.2 ‰ were determined for samples recovered from the side branch southeast of the Tautra sill (M304: 0.56 ‰, M305: 0.48 ‰) and the shallow bay in the central Middle fjord (M214: 0.39 ‰) (Fig. 3a). Oxygen isotopes from the southernmost part of the fjord, where the rivers Orkla and Gaula discharge freshwater, do not deviate remarkably from the mean, in contrast to other sites close to the mouths of the Stjørdal River and the Nidelva River (Fig. 3a).

The δ^{18}O ratio in foraminiferal calcite shells is predominantly controlled by the temperature and δ^{18}O of the ambient seawater (e.g. Urey, 1946; Shackleton and Opdyke, 1973). Measurements from the Sognefjord, located some 400 km south of the Trondheimsfjord, show that the δ^{18}O of the water (δ^{18}O$_w$) is positively related to salinity as both, δ^{18}O$_w$ and salinity, are mainly controlled by the admixture of ^{18}O-depleted freshwater supplied by rivers and groundwater (Mikalsen and Sejrup, 2000). Sognefjord, like the Trondheimsfjord, is separated from the Norwegian shelf by sills, largely controlled by the NAC and NCC, and is supplied with large amounts of ^{18}O-depleted river water and groundwater from the Norwegian hinterland (Jacobson, 1983; Mikalsen and Sejrup, 2000).

Bottom water temperatures and salinities recorded along the Trondheimsfjord tend to increase from the fjord head towards the fjord entrance as documented by our own measurements during the sampling cruise in April 2011 and the 43 yr long monthly to bimonthly records of three mooring stations located in each basin (Fig. 2). This spatial pattern in temperature and salinity is independent from season or year (Fig. 2). If temperature was the predominant factor controlling the foraminiferal δ^{18}O in the Trondheimsfjord, a decrease towards the fjord entrance would be expected because of the inverse relationship between temperature and δ^{18}O$_{calcite}$ (e.g. Shackleton and Opdyke, 1973; Bemis and Spero, 1998; Mulitza et al., 2003). This is clearly at odds with our data (Figs. 3a, 4). We therefore assume that the spatial distribution of benthic foraminiferal δ^{18}O primarily reflects the decrease in salinity and δ^{18}O$_w$ with increasing distance from the fjord entrance as a consequence of increasing brackish water supply towards the fjord head.

The influence of temperature and salinity on the δ^{18}O in the calcite shell, however, depends on the species (vital effect and habitat effect) (e.g. Shackleton and Opdyke, 1973; Bemis and Spero, 1998) and the seasonal effect, particularly in coastal environments (Cage and Austin, 2008). According to several previous studies (Caralp, 2000; Mackensen et al., 2000; Alve, 2010; Alve et al., 2011;), *M. barleeanus* is not an opportunistic species and does not calcify during a certain time in the year. Still, our interpretation of the benthic δ^{18}O distribution in the Trondheimsfjord does not take into consideration any effect on the foraminiferal δ^{18}O due to the topographic settings, tidal currents, erosion or remobilization of the sediment, induced by strong currents (Bøe et al., 2003) and the age variability of surface samples. Nevertheless, regarding the relatively stable physico-chemical conditions in the Trondheimsfjord (Fig. 2) the spatial trend of the benthic δ^{18}O along the fjord axis (Figs. 3a, 4) can be certainly adressed to the decrease of salinity with increasing distance from the fjord's entrance.

4.2 Benthic carbon isotopes

Overall, the carbon isotope ratios of the infaunal benthic foraminifera *M. barleeanus* show a decreasing trend from the fjord entrance to the fjord head, ranging between -0.28 and -2.65‰ with an average value of -1.37‰ (Figs. 3b, 4). Beside the δ^{13}C ratios at the fjord entrance highest ratios were measured in samples close to the Tautra sill. The δ^{13}C within the fjord basins are lower with an average ratio of -1.6‰.

Several studies on the ecological preferences of *M. barleeanus* have shown that the occurrence of this species is linked to the quality of organic matter deposited in the sediments (Caralp, 2000; Schmiedl and Mackensen, 2006; Alve, 2010; Alve et al., 2011). The species prefers organic matter in a more altered form and migrates in the sediment depending on the organic matter supply (Caralp, 2000; Mackensen et al., 2000; Schmiedl and Mackensen, 2006). Moreover, δ^{13}C in living *M. barleeanus* decreases with increasing sediment depth which is assumed to be related to the pore water δ^{13}C$_{\text{DIC}}$ (dissolved inorganic carbon) that exponentially decreases within the

uppermost sediment (McCorkle et al., 1985; Grossmann, 1987; Mackensen et al., 2000). Hence, δ^{13}C deriving from *M. barleeanus* is strongly related to the amount and origin of organic matter deposited at the sample sites as well as to deep water ventilation that considerably affects the δ^{13}C of the bottom water and the pore water making a straightforward interpretation of potential forcing factors difficult.

Regardless of species-specific microhabitat and ecological preferences, benthic foraminiferal δ^{13}C in coastal and/estuarine settings is used as a tracer of the relative influence of marine vs. fresh waters, especially in high latitude regions which are affected by strong seasonal changes in river runoff (Polyak et al., 2003; Bauch et al., 2004). Dissolved inorganic carbon in rivers originates mainly from the degradation of ^{12}C-enriched organic matter from continental soils resulting in generally lower δ^{13}C values as compared to marine water. Regarding the large amounts of freshwater and terrigenous material being temporally discharged into the Trondheimsfjord the overall decreasing trend in benthic foraminiferal δ^{13}C along the Trondheimsfjord axis (Fig. 4) and in the side branches (Fig. 3b) is likely to reflect the δ^{13}C$_{DIC}$ gradient between river and marine-derived waters. However, the measured foraminiferal δ^{13}C gradient of ca. 1 ‰ between the fjord entrance and the fjord head (Fig. 4) is 5 times larger than the estimated δ^{13}C$_{DIC}$ gradient per ca. 1 PSU bottom salinity difference for this high latitude setting (Erlenkeuser et al., 1999 in Polyak et al., 2003). Hence, additionally to the freshwater supply, enhanced terrigenous organic matter flux and remineralization close to river inlets in the side branches of the fjord basins and at the fjord head clearly affect the δ^{13}C$_{DIC}$ of the bottom water and may explain the observed benthic foraminiferal δ^{13}C gradient in the Trondheimsfjord. Measured ratios of total organic carbon vs. organic nitrogen (C/N) in the fjord surface sediments confirm the progressivelly enhanced contribution of terrigenous vs. marine organic matter with distance from the sea and with proximity to major river inlets (J. Faust, personal communication, 2012).

We explain the observed peak δ^{13}C excursions in surface sediments close to the Tautra sill (Fig. 4) by differences in sediment accumulation between shallow and deep settings. As summarized by Jacobson (1983), prevalent (tidal) currents in the

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subsurface layers at the sills in the Trondheimsfjord reach maximum velocities up to 100 cm s^{-1}. The strength of these tidal currents impedes the accumulation of fine sediments ($< 63\,\mu m$) and organic matter on the sills. Instead the fine grained sediment deposits in the deep and more sheltered areas of the fjord basins (Dale, 1976). Low organic matter concentrations in the sediments of the shallow Tautra sill result in reduced release of isotopically depleted CO_2 during organic matter degradation and account for the observed high benthic foraminiferal $\delta^{13}C$ excursions. The same process might explain the observed heavy benthic $\delta^{13}C$ at the relatively shallow fjord entrance (Stjørnfjord) and at the sill (Fig. 3b), in addition to the dominant influence of marine waters and thus enhanced $\delta^{13}C_{DIC}$ (Polyak et al., 2003; Bauch et al., 2004; Filipsson et al., 2004).

Our results indicate that the distribution of benthic foraminiferal $\delta^{13}C$ in the Trondheimsfjord reflects the $\delta^{13}C_{DIC}$ gradient between marine and river-derived waters and the associated differences in $\delta^{13}C$ of continental vs. marine organic matter. Deviations from this pattern are caused by local, topographically-related variations in the amount of organic matter accumulation and degradation in bottom sediments.

4.3 Dinocyst assemblages

The dinocyst concentration slightly increases from the fjord entrance towards the Beitstadfjord (Figs. 5 and 6). According to several previous investigations (e.g. Wall, 1971; Dale, 1976; de Vernal et al., 2000, 2007; Marret and Zonneveld, 2003b) bulk dinocyst concentrations in sediments are related to several biotic and abiotic factors among which the most important are sea-surface conditions during production phases of the cysts (modulated by the cyst preservation ability in dependence of sedimentary and diagenetic processes) and the species-specific organic wall composition. Dinocyst concentrations in surface sediments of the Trondheimsfjord (Fig. 6) show a high degree of spatial heterogeneity reflecting the complex and seasonally variable surface hydrology, and more likely, the topographically-steered sediment dynamics (sediment

redistribution) as well as sediment dilution by terrigenous material from nearby river inlets. Topographically induced prevalent currents cause a redistribution of fine sediments from shallow settings to the deeper fjord basins. Hence, the low cyst concentration at the fjord entrance and the sills might be explained by the strong currents caus-
ing a gradation and thus redistribution of the sediments and the incorporated cysts. As a result of winnowing and sediment remobilization cyst concentrations in the more sheltered and deep fjord basins as well as in Beitstadfjord are relatively high. Further investigation on sedimentary processes such as local debris and turbidity flows on slopes in the fjord basins (Bøe et al., 2003) supports our observations on the apparent het-
erogeneity of cyst accumulation in the Seaward and Middle fjord basin. Furthermore, strong seasonal stratification of the brackish mixed layer in the fjord basins favors the spring production of cyst-forming dinoflagellates.

The dominant species in the Trondheimsfjord are *P. dalei* with an average relative abundance of 49 % and *O. centrocarpum* (34 %), followed by the two subordinate
species *Brigantedinium* spp. and *S. quanta* (4.83 and 6.02 %, respectively) (Fig. 7). All other species contribute less than 2 % to the total assemblage (Fig. 7). Other palynomorphs like *Halodinium minor*, *Hexasteria problematica* and *Radiosperma corbiferum* were identified in surface sediments with mean absolute concentrations of 474 cysts cm^{-3}, 234 cysts cm^{-3} and 71 cysts cm^{-3}, respectively. The composition of
cyst assemblages in the present study is similar to the one described by Dale (1976) from a limited set of sediment samples in the Trondheimsfjord, and to other investigations performed in fjords and shelf environments along the Norwegian coast (e.g. Grøsfjeld et al., 1999; Grøsfjeld and Harland, 2001; Rørvik et al., 2009). Cyst assemblages in fjords are supposed to reflect the ecological niches of dinoflagellate cysts based on
their preferred habitat and feeding strategies. The NMDS method was applied to check for any groupings and (dis)similarities within the study area. The output confirms our observations of a great homogeneity of the data set (stress = 0.26) impeding any reliable statistically-based structuring of the surface sediment dinocyst assemblages in the fjord.

The most abundant species in our data set are adapted to a wide range of temperature and salinity. *Pentapharsodinium dalei* and *O. centrocarpum* are autotrophic species tolerating large temperature and salinity ranges of ca. −2 °C to 30 °C and 16 (21 PSU for *P. dalei*) to 36.7 PSU, respectively. Cysts of *Brigantedinium* spp. and *S. quanta* belong to the heterotrophic species, both of them tolerating temperatures between −2.1 °C and 30 °C and salinities between 17 and 37 PSU (Matthiessen, 1995; Marret and Zonneveld, 2003; de Vernal and Marret, 2007). The following discussion will be focused on these species since the in situ production of species with highest abundances is most likely and may be related to recurrent dynamics rather than sporadic events.

The dominance of *P. dalei* in the Trondheimsfjord is probably linked to the high turbidity of the water column and the prevailing surface currents. This relatively small cyst is supposed to get easily stuck on biogenic and lithogenic particles in the water column, leading to a more rapid deposition at the sediment surface than bigger cysts (Dale, 1976). The highest abundance of *P. dalei* was observed in the central Seaward basin, the Middle fjord and the Beitstadfjord with decreasing abundance towards the fjord entrance (Fig. 8). We assume that the reduced abundance of *P. dalei* at the fjord entrance is caused by the weaker stratification of the water column due to stronger currents and limited riverine input. Moreover, the transport of living and dead cysts over large distances by strong currents at the fjord entrance and in the narrow passage between the entrance and the Seaward basin (Bøe et al., 2003) constitutes unfavorable conditions for the production and sedimentation of *P. dalei* in this area. *Operculodinium centrocarpum* shows the opposite distribution with highest abundance at the fjord entrance and in the narrow passage, and lower amounts in the other fjord basins (Fig. 8). This species is considered to be an ubiquitous species that preferentially thrives in warm and saline waters (Matthiessen, 1995; Marret and Zonneveld, 2003; de Vernal and Marret, 2007). The contrary distributions of *P. dalei* and *O. centrocarpum* in spite of similar habitat preferences might be related to their individual stress tolerance and ecological survival strategies. Experimental studies (e.g. Lewis et al., 1985; Sullivan

and Swift, 2003) have shown that cyst production is highly dependent of the water column stratification triggering photosyntetic activity. The stratification of the water column varies seasonally depending on wind patterns, temperature and salinity changes, and river discharge. After the bottom water renewal in late winter/early spring the pycnocline deepens. This triggers the internal mixing of deep bottom water with intermediate waters and increases the availability of nutrients for the dinoflagellates in the upper water layers. Increased temperatures and sunlight intensity in spring and early summer establishes the required conditions for autotrophic species and triggers a phytoplankton bloom (Harland et al., 2004; Bagøien et al., 2012). The hydrographic conditions tend to remain stable until early autumn when northwesterly winds trigger another bottom water renewal. Such a general seasonal relationship of the two dinocyst species in fjord environments is confirmed by Dale (1976, 1977) from the Oslofjord and in the Trondheimsfjord. Moreover, Head et al. (2001) and Harland et al. (2004b) observed a strong presence of both thecate cells and cysts of the autotrophic species *P. dalei* and *O. centrocarpum* in topographically similar settings during spring.

Brigantedinium spp. was observed in maximum amounts in the southernmost side branch of the Seaward basin at the mouth of the rivers Orkla and Gaula, and at the fjord head close to the island of Ytterøy (Fig. 8). *Selenopemphix quanta* occurs preferentially close to river inlets and slightly increases at the fjord entrance (Fig. 8). In areas of relatively low temperature and salinity variability of the surface and intermediate waters the distribution of these two species is considered to be largely controlled by their food requirements linked to the amount of nutrients in the water column, and the presence of diatoms for *Brigantedinium* spp. Cysts of *S. quanta* have been reported from temperate to subpolar latitudes with highest abundances in upwelling areas where nutrients from deeper water masses are mixed into the surface water layers (Dale and Fjellsafi, 1994; Marret and Zonneveld, 2003). Obviously, these heterotrophic species thrive best in high-nutrient waters close to river mouths and upwelling areas (Harland et al., 2006). However, other factors also influence their growth rate and preservation ability. For instance, the low amounts of *Brigantedinium* spp. at the fjord entrance indicate the

sensibility of this species to diagenetic and aerobic decay which in turn is linked to the strength of primary productivity that determines the oxygen concentration in the water column and the sediment pore water (Dale, 1976; Matthiessen, 1995; Zonneveld et al., 2001; Marret and Zonneveld, 2003b).

Halodinium minor and _R. corbifera_ are chlorophycean algae (Price and Pospelova, 2011). _Halodinium minor_ has been previously reported from polar environments by Mudie (1992) and from warm to temperate environments in Australian estuaries by McMinn (1991). Matthiessen (1995) found high relative abundances at the Greenland and Iceland shelf with a random occurrence in the central Greenland Sea and the Norwegian Sea. _Radiosperma corbiferus_ has been recorded in high concentrations from the Baltic Sea, the Barents Sea (Meunier, 1910; Leegard, 1920; Sorrel et al., 2006) and the Laptev Sea (Matthiessen, 1995; Kunz-Pirrung, 1998, 1999; Sorrel et al., 2006; Price and Pospelova, 2011). _Hexasteria problematica_ is a Prasinophyceae species (Parke and Dixon, 1964 in Price and Pospelova, 2011) and has been recorded from Baffin Bay fjords by Mudie (1992) and in the North Sea region by Cleve (1900). These palynomorphs are linked to low saline/brackish cold surface waters in a marine environment with proximity to river inlets and/or melt water plumes (Matthiessen, 1995; Kunz-Pirrung, 1998, 1999; Sorrel et al., 2006; Price and Pospelova, 2011).

The assemblage of palynomorphs in the Trondheimsfjord mirrors the large seasonal range in hydrological conditions and implies a high stress tolerance and fast adaptation of the dominant species. Recent studies (Smayda and Reynolds, 2003) group the species according to their survival strategies with regard of their tolerance to physical disturbance, light stress and nutrient availability into competitors, stress tolerant species and disturbance tolerant species (Harland et al., 2006). At this stage, even though this hypothesis seems to be applicable to the Trondheimsfjord, the data set does not provide enough information to evaluate survival strategies of the dinoflagellates and their cysts.

5   Implications and conclusions

Based on an extensive and evenly distributed set of surface sediment samples we show that the potential proxy indicators analysed in this study reliably record the complex modern hydrological and environmental setting of the Trondheimsfjord. Both the benthic stable isotope ratios and the dinocyst assemblages very well indicate the spatial variations in marine and fresh water influence across the entire fjord.

The spatial variability of foraminiferal δ^{18}O reflects the complex combination of the temperature and salinity structure of the prevalent water masses. Contrary to the dominant role of temperature on the distribution of benthic foraminiferal oxygen isotopic ratios in most open marine surface sediments, our observations indicate that the present-day δ^{18}O in the Trondheimsfjord mainly follows the salinity gradient along the fjord axis and essentially records the influence of increasing supply of brackish river water towards the fjord head.

The spatial variability of benthic δ^{13}C in the Trondheimsfjord mainly reflects the marine vs. terrigenous origin of the organic matter at the sediment surface which tends to have an increasingly continental proportion towards the fjord head. Local deviations from this overall trend are related to the complex fjord topography and associated current dynamics. Winnowing and remobilization of fine-grained organic-rich sediment over topographic highs limit the accumulation of organic matter and explain the difference in benthic δ^{13}C between deep and shallow sites.

The cyst assemblages record the hydrographic changes of the Trondheimsfjord that is dominated by a strong seasonality and the decreasing influence of the NAC towards the fjord head. The recurrent bottom water renewal, fluvial input and seasonal stratification of the water column affect the nutrient availability and trigger the production of dinoflagellate cysts depending on their feeding strategy.

In summary, the hydrology of the Trondheimsfjord underlies strong seasonal variations that affect the benthic foraminiferal isotope ratios and the production of dinoflagellate cysts. Even though a seasonal sampling strategy would be most appropriate to

determine specific forcing factors in detail, this study proves that benthic foraminifera and dinocysts are suitable tools to study the Holocene climate variability from sediment cores in this fjord environment.

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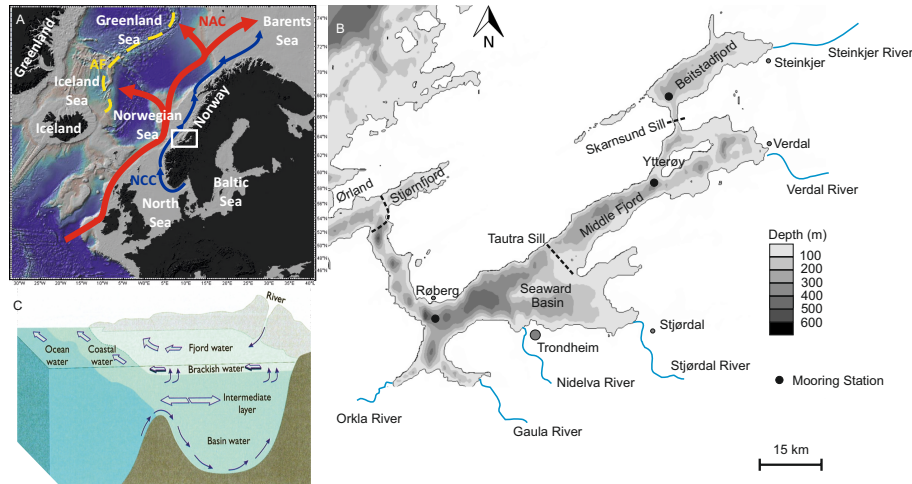
Fig. 1. (A) Surface circulation in the Surface circulation in the Norwegian Sea; **(B)** bathymetric map of the Trondheimsfjord. Black dots in the fjord indicate the location of the fixed mooring stations Røberg, Ytterøy and Beitstad referred to in the text; **(C)** main elements of the surface, intermediate and deep water circulation in Norwegian fjords (from Sætre, 2007).
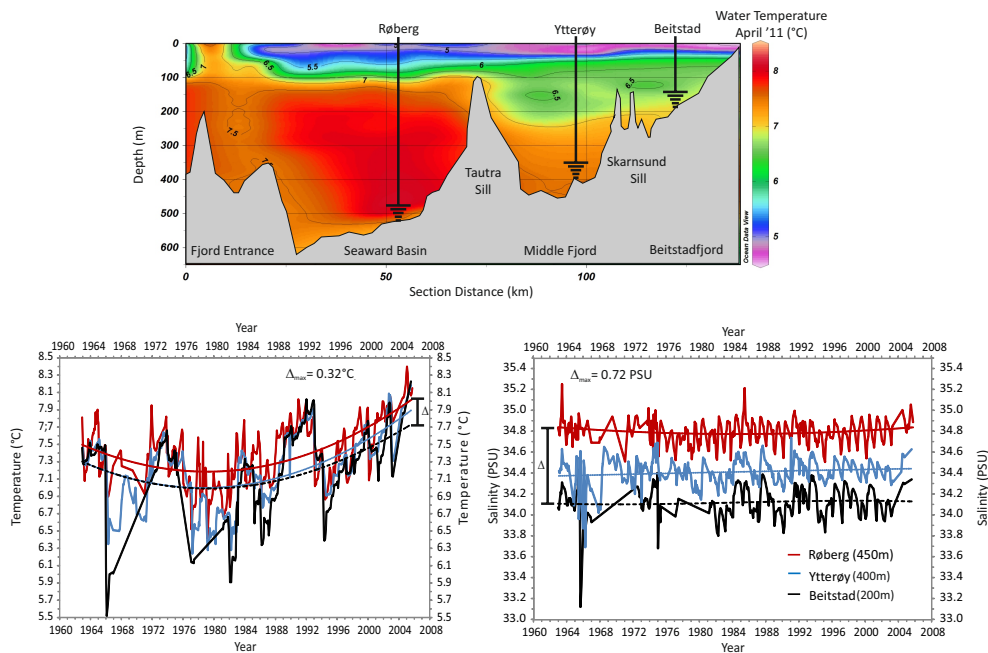
Fig. 2. Top: Water column temperature structure along the fjord axis in April 2011 based on CTD measurements conducted during the sampling cruise of the RV *FF Seisma*. Bottom: Monthly to bimonthly instrumental temperature and salinity measurements from the fixed mooring stations Røberg, Ytterøy and Beitstad in the Trondheimsfjord between 1963 and 2005 (data from Trondheim Biological Station of the Norwegian University of Science and Technology in Trondheim: http://www.ntnu.edu).

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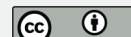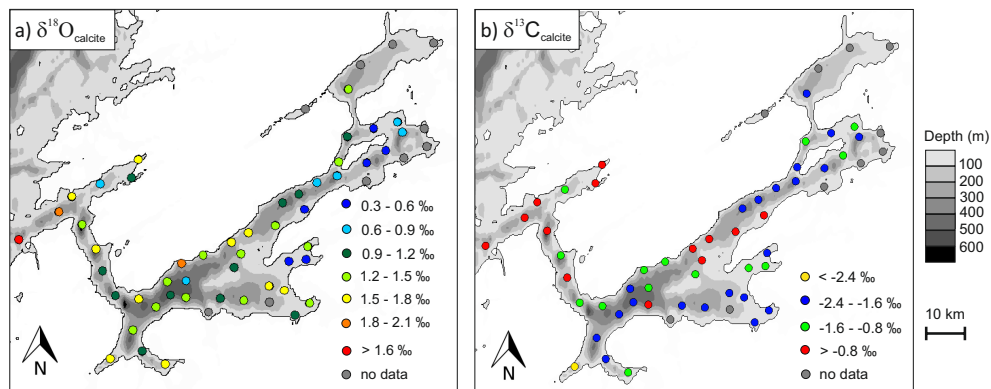
Fig. 3. Benthic foraminiferal (*M. barleeanus*) stable isotope distribution in the Trondheimsfjord: **(a)**: δ^{18}O; **(b)**: δ^{13}C.

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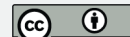
Fig. 4. Top: Bathymetric overview with sample locations and fixed mooring stations at Røberg, Ytterøy and Beitstad. The dashed frame marks the sample locations which are displayed below. Bottom: Cross section of the benthic foraminiferal stable isotope ratios along the fjord axis, top: δ^{18}O; bottom: δ^{13}C.
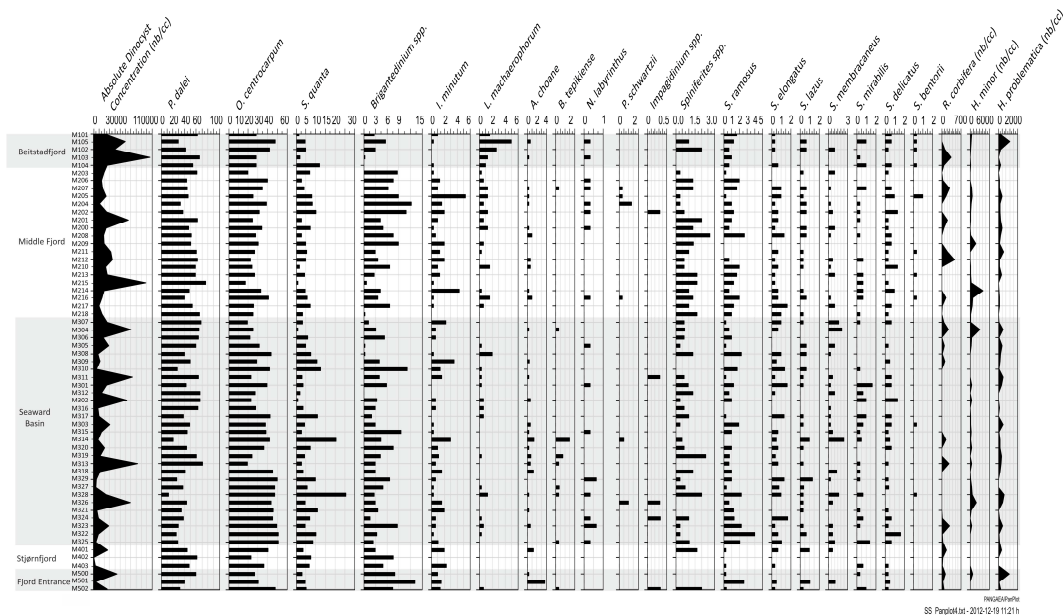
Fig. 5. Dinocyst assemblages in the Trondheimsfjord; relative abundances of cysts are given in %, total abundance of cysts per sample and other palynomorphs are displayed as concentration in cysts cm^{-3}.
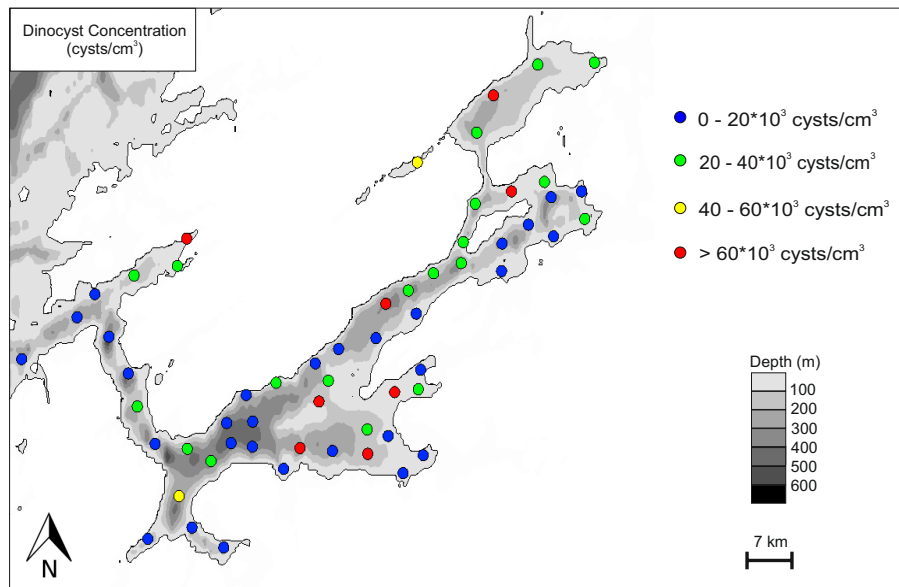
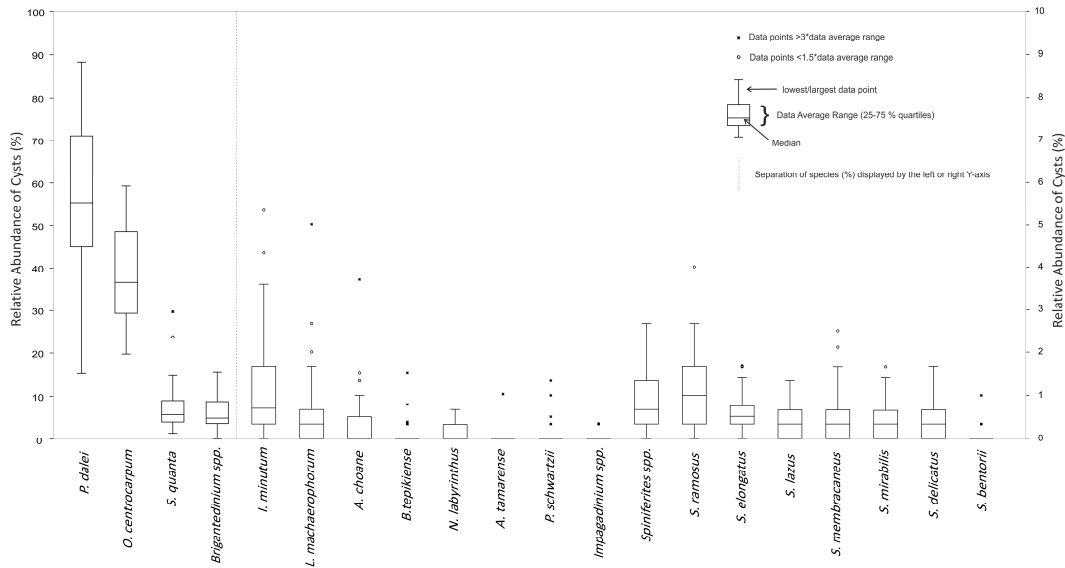**Fig. 6.** Dinocyst concentrations ($\mathrm{cysts\,cm^{-3}}$) in surface samples in the Trondheimsfjord.

Fig. 7. Distributional ranges of the dinocyst species counted in the Trondheimsfjord (%) using the software package PAST by (Hammer et al., 2001).
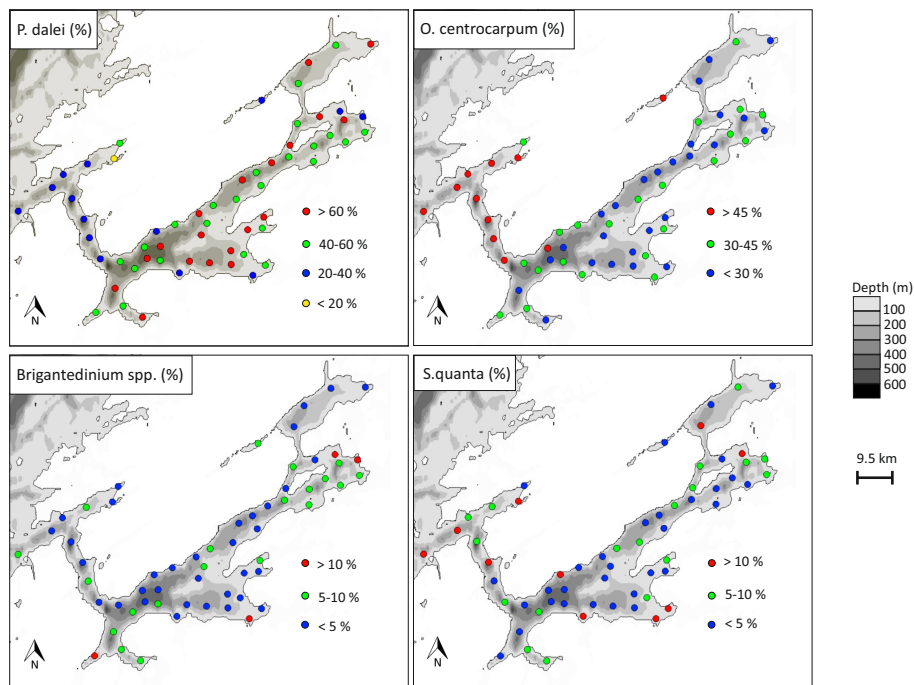
Fig. 8. Relative distribution of the dominant and subordinate cysts in the Trondheimsfjord.