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Distribution of living benthic foraminifera in the northern Chukchi Sea

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Abstract

Living (Rose Bengal stained) benthic foraminifera were studied in the topmost sediments of 5 multi- and box cores collected on the continental shelf, upper and lower slopes and of the Chukchi Sea in order to provide background information on modern benthic foraminiferal distribution, useful for future studies. Sediment cores were collected during August-September 2015, when the area is seasonally ice-free. Benthic foraminiferal contents in the 63-125 µm and >125 µm size fractions are discussed in terms of water masses distribution, sedimentological (grain size) and organic geochemical (total organic carbon, total nitrogen, C/N ratio and $\delta^{13}C_{org}$) characteristics of the surface sediments. Marine organic carbon-rich clay sediments characterize the faunal microhabitats. Despite relatively high organic carbon contents, standing stocks of living benthic foraminifera are generally low, especially for the 63–125 µm size fraction. This low living stock seems to reflect post-bloom conditions in August and September in the area. The reduced supply of fresh organic carbon also affects faunal microhabitats in the sediment with a concentration of living fauna in the upper 2 cm of the sediment. Over the Chukchi Sea shelf, a relatively mixed upper sediment layer likely due to

bioturbation or bio-structures induce a disturbed vertical distribution in the sediment. Corrosive Pacific-derived bottom water over the shelf likely explains the relative importance of agglutinated vs. calcareous fauna in this shallow setting. Our results suggest that, in a post-bloom context, the main environmental control on benthic foraminiferal assemblages in the Chukchi Sea is the nature of the bottom water masses.

Key words

Living benthic foraminifera, Chukchi Sea, water masses, primary production, sea-ice

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1. Introduction

The Arctic Ocean is the smallest and shallowest of the world's five major oceans but it plays an essential role in the global oceanic circulation and the regulation of the Earth's climate system. Since the last decades the Arctic region has undergone significant and rapid climate changes with a reduction of sea-ice cover and thickness, an increase in length of sea-ice melt season (e.g. [20, 44, 55]), as well as a rise in sea surface temperatures (SST) and temperatures of water masses flowing into the Arctic Ocean (e.g. [85, 86, 107, 109]).

Recent benthic foraminifera in the Arctic Ocean have been investigated by several authors during the last five decades [9, 37, 41, 42, 50, 64, 77, 78, 79, 94, 102, 103, 104]. The rare studies which distinguished stained (living) benthic foraminifera from fossil (dead) faunas in Arctic sediments usually demonstrate a close correlation between the distribution of foraminiferal species and bottom water masses [9, 37, 42, 64]. In the global Ocean, living benthic foraminiferal studies highlight the impact of a wide range of processes upon foraminiferal distributions among which are food supply, salinity, temperature, oxygen, tides and currents, substrate, light penetration, the presence of seagrass and macroalgae, as well as competition and predation ([61] and references therein). Of these multiple factors and in addition to bottom water mass characteristics, food availability and competition for food are thought to control to a high extent foraminiferal associations in the Arctic Ocean (e.g. [102, 103, 104]).

In this paper, we present results from living foraminiferal population collected in the northern sector of the Chukchi Sea, one of the major gateways of the Arctic Ocean. Summer sea-ice in the western Arctic, especially in the Chukchi Sea, has been rapidly declining during the last decades (e.g., [19, 20]). Recently, Yun et al. [111] have also shown that the primary production in the Chukchi Sea presents some decreasing trend for the last decades, probably associated with fresh water input related to sea-ice melting. However, there are very few studies focusing on the distribution of benthic foraminifera in this area. Osterman et al. [64] reported the distribution of benthic foraminifera in the Chukchi Sea but their study was only based on the >125 μm size fraction

and did not distinguish living from dead faunas. Here, we present the first data on the distribution of living benthic foraminifera >63 µm in the northern Chukchi Sea, from the continental shelf to the lower slope and discuss their distributional pattern in view of the local environmental setting. We believe that the present study is absolutely central for a better knowledge of Arctic foraminiferal ecology and in future efforts aiming at reconstructing past environments in the area of the Chukchi Sea.

2. Regional setting

The Chukchi Sea, one of the largest marginal sea of the Arctic Ocean, extends from the Bering Strait in the south to the edge of the Canadian basin in the north (Fig. 1). Most of the Chukchi Sea constitutes a large shallow shelf which deepens progressively towards the north (Fig. 1). To the north of the shelf system, the Chukchi Borderland includes two subsea formations that extend into the Amerasian Basin: the Chukchi Plateau and the Northwind Ridge [68].

The Chukchi Sea is strongly influenced by fresh Pacific waters entering through the Bering Strait. The annual volume transport averages about 0.8 Sv northwards [71, 105]. This inflow of fresh Pacific waters is stronger in summer and relatively weak in winter. Two water masses of Pacific origin dominate the Chukchi Sea circulation [17]: the Bering Sea Water (BSW) and the Alaskan Coastal Water (ACW). The ACW is carried by the Alaskan Coastal Current (ACC) into the Chukchi Sea, flowing northwards along the Alaskan coast with a transport volume of 0.1 Sv. It is a relatively warm, low salinity and nutrient-poor water mass [40, 106]. The remaining 0.7 Sv of Pacific waters flowing into the Chukchi Sea is made of BSW, a mixture of Anadyr Water and Bering Shelf Water [17]. These waters are saltier and richer in nutrients than the ACW [87]. In the western sector of the Chukchi Sea, the seasonal Siberian Coastal Current (SCC; 0.1 Sv) flows southwards along the coast and deflects fresh and cold waters into the central Chukchi Sea [101, 105]. Seasonal variations in Pacific water inflow and sea-ice cover lead to a seasonal cycle of water mass stratification [40, 105]. In summer, the inflow of Pacific water, especially via the ACC, transports heat into the Chukchi Sea leading to a stronger stratification of the surface layers [108]. Conversely, water column is well-mixed from fall to

spring, the inflow of Pacific water becoming cooler and denser due to brine releases during sea-ice formation [100]. To the north of the Chukchi Shelf, surface circulation is driven by the two main surface current systems of the Arctic Ocean: the Beaufort Gyre (BG) and the Transpolar Drift (TPD). Warm and salty Atlantic Intermediate Water (AIW) flows along the Chukchi slope, following the shelf break from west to east, between approximatively 200 and 900 meters below sea level, and submerges cold Arctic Deep Water (ADW) which circulates within the deep Arctic basins (Fig.1; [1, 13, 91]).

The Chukchi Sea is characterized by a first-year ice, making this area particularly sensitive to the present overall reduction in Arctic sea-ice concentration [18, 24]. Over the satellite record, the Chukchi Sea has displayed the sharpest downward trends in Arctic sea-ice extent, the September sea-ice edge being now located far north of the continental shelf break [20]. Shimada et al. [85] and more recently Serreze et al. [83] suggested that the recent reduction in sea-ice concentration was essentially triggered by the warming of the inflowing Pacific water. Atmospheric temperature and circulation may also influence the seasonal melting of ice [83].

The Chukchi Sea is generally considered as a highly productive region on the edge of the largely oligotrophic Arctic basin [57] as the result of the inflow of fresh and nutrient-rich Pacific water into the Chukchi continental shelf. However, a recent study by Yun et al. [111] has shown a decreasing trend in primary production in the Chukchi Sea during the last decades with relatively large regional variation. Spatial and temporal variations in the productivity of the Chukchi Sea are related to changes in duration, thickness and extent of seasonal sea-ice which control light availability and surface water stratification from sea-ice melting [36, 39, 98, 111]. Mean average primary productivity in the Chukchi Sea is generally higher over the shallow shelf which experiences seasonal sea-ice compared to the northern sector of the Chukchi Sea [111]. Primary production rates over the southern shallow sector of the Chukchi Sea average 80-90 g C m^{-2} y^{-1} and progressively decrease toward the slope (<50 g C m^{-2} y^{-1}) and over the deep Arctic basin (<20 g C m^{-2} y^{-1}) [36, 39, 74, 98]. Intense blooms are observed with ice edge retreat [97], in the open water of marginal ice

zone (MIZ; [65]), starting with an ice algae bloom in May followed by a strong but brief phytoplankton bloom in June [99]. A recent study also revealed intense phytoplankton blooms beneath sea-ice in the Chukchi Sea [2]. However, several studies show the negative effect of fresh water input resulting from sea-ice melting on the nutrient concentration and therefore primary production in this area [22, 110, 111].

3. Materials and methods

3.1. Sample collection

This study is based on 9.8 cm diameter multicores and push cores subsampled from boxcores collected at five stations in the Chukchi Sea during the ARA06C cruise onboard the RV ARAON, between August 25th and September 9th, 2015 (Fig. 1, table 1). Upon recovery, sediment cores were sliced onboard every 0.5 cm from the surface down to 2 cm, then every centimetre down to 5 cm. For each station, one sediment core was used for benthic foraminiferal analysis and another one for sedimentological and geochemical analyses. Temperature and salinity profiles through the whole water column, as well as chlorophyll a (Chl *a*) profiles for the upper water column were measured at Sts. 01A, 02, 03 and 04 using a conductivity temperature depth (CTD) profiler and a fluorometer sensor respectively. Sea-ice conditions (drift ice) hindered the deployment of the profiler at St. 05.

3.2. Sedimentological and geochemical analyses

Grain size analysis were conducted at Environnements et Paléoenvironnements Océaniques et Continentaux (EPOC, France) using a laser diffraction particle size analyser (Malvern Mastersizer 2000 hydro G). Measurements along the top 5 cm of each core were performed on freeze-dried sediment. Grain size-spectra derived from downcore measurements display a unimodal distribution at all stations. We therefore consider the median diameter of the particle size distribution D_{50} as a reliable measurement of the mean grain size in the sediment cores investigated in the present study.

Sedimentary total organic carbon (TOC) and total nitrogen (TN) contents as well as stable isotope composition of organic carbon ($\delta^{13}C_{org}$) were measured at the Korea Polar Research Institute

(KOPRI, South Korea) using an EA-IRMS system (Flash 2000-Delta V, Thermo Scientific). Total carbon (TC) and TN were measured on freeze-dried sediment. TOC and $\delta^{13}C_{org}$ were analysed on carbonate free sediment after HCl (10%) treatment. Finally, TOC was calculated using the following equation [88]: TOC (%) = [100 - (8.333 * TC)] / [(100 / TOC') - 8.333]. The analytical error was less than ± 0.1 % for TN and TOC contents and ± 0.1 ‰ for $\delta^{13}C_{org}$. TN and TOC are expressed as the mass weight of dry bulk sediment (wt. %). The C/N ratio was calculated by dividing TOC by TN.

^{210}Pb and ^{226}Ra were measured at EPOC (France) by ϒ spectrometry analytical technique on freeze-dried sediment of the first 7 cm of core 01A (St. 01A). ^{210}Pb in excess of equilibrium with ^{226}Ra, $^{210}Pb_{xs}$, was calculated as the difference between measured ^{210}Pb and ^{226}Ra.

3.3. Living (stained) benthic foraminiferal analysis

Sample treatment and faunal analysis mostly follow the FOBIMO standardized protocol [76]. Benthic foraminiferal samples were preserved in a 1.5 g L^{-1} solution of Rose Bengal in 96% ethanol in order to stain the living endoplasm of benthic foraminifera according to Murray and Bowser [60] and Walton [96]. This concentration is lower than recommended by the FOBIMO protocol (2 g L^{-1}), but has been shown to efficiently stain the living organism in many studies [e.g., 25, 28]. The samples were repeatedly homogenised immediately after staining. For more precision, the real volumes of sediment were measured [76]. Samples were wet sieved through 63 µm and 125 µm mesh screens. Benthic foraminiferal analysis was performed on both the 63-125 µm and >125 µm size fractions. All stained individuals were hand-sorted under wet condition from the surface down to 5 cm for the >125 µm fraction and from the first centimetre only for the 63-125 µm fraction. The choice of limiting the analysis of the 63-125 µm fraction to the top first centimetre stems from the extremely low abundance of living fauna in the 0-1 cm interval of this size fraction at each investigated station (precluding the existence of <125 µm fauna below the depth of 1 cm) as well as from the time consuming effort for such low gain. The coloration of Rose Bengal stained specimens considered as living at the time of sampling may vary among species from light pink to dark red or brownish violet [76]. Consequently, only specimens with all chambers coloured (except the last one) were considered

as living. Some non-transparent tests (miliolids or agglutinated taxa) were broken, after identification, to ensure that protoplasm was stained. All specimens were identified to species levels if possible following the generic classification of Loeblich and Tappan [51].

We considered as major species the ones representing at least 5% of the foraminiferal assemblages. Faunal densities were standardized for a sediment volume of 50 cm^3. Living standing stock represents the total number of living individuals counted per station in each size fraction, normalized for a 100 cm^2 sediment area according to Goineau et al. [31] and Dessandier et al. [25]. Three biodiversity indices were calculated using the PAST software [38]: the species richness (S, number of species present in a sample), the Shannon index H' [84] and the Evenness index E [12].

4. Results

4.1. Environmental, sedimentological and organic geochemical settings during the sampling period

At the end of August 2015, sea-ice was very thin and was only found north of the sampling area (Fig. 1). A continuous northward retreat of the sea-ice edge occurred until the end of September 2015. Therefore, all the investigated stations were free of ice at the time of sampling.

An upper 20 m thick low salinity (<30) surface layer characterizes all stations under the influence of sea-ice melting (Fig. 2a). Changes toward lower surface salinities (ca. 29.5 to 26.5) and lower surface temperatures (ca. 1.5 to -1°C) from St. 01A to St. 04 reflect the increasing proximity to the sea-ice edge. This surface mixed layer overlays the colder and saltier Pacific water with typical signature of -1.5°C and 33 extending down to 200-250 m over the slope and deep sectors of the Chukchi Sea (Fig. 2a). This water mass bathes the sediment-water interface at the shallow (110 m) St. 01A (Fig. 2a). The AIW with mean salinities of 35 and temperatures up to 0.8-0.9°C is observed from 200-250 m to ca. 750 m (Fig. 2a), and therefore characterizes the bottom water at the slope Sts. 05 (350 m) and 03 (750 m). The ADW occupies the deeper >750 m water column at Sts. 02 (2100 m) and 04 (2300 m) with typical temperatures <0°C and stable salinity of 35 (Fig. 2a). Chl *a* profiles within the

upper water masses of Sts. 01A, 03, 02 and 04 are given in Figure 2b. Chl *a* concentrations measured at all stations range from ca. 0.5 to 1.6 µg L^{-1} within the top 80-100 m water depth. These values are relatively low when compared to values of Chl *a* concentrations (about 1-10 µg L^{-1}) commonly measured in the study area during bloom periods in June and July [2, 65, 97]. Maximum Chl *a* concentrations over the shelf (St. 01A; 0.6-0.7 µg L^{-1}) occur in shallower depth, around 20 m water depth, than over the upper and lower slope stations (Sts. 03, 02, 04) where peak values of 0.6 to 1.6 µg L^{-1} are found deeper around 60-70 m water depth.

Sedimentological and geochemical analyses in the surface sediment are shown in Figure 3. At all stations, sediment grain size ranges from clay to fine silt (D_{50} = 8-12 µm). The shallowest St. 01A displays high TOC and TN contents (>2.5 and 0.3 wt. %, respectively) compared to other stations (≤ 1 and 0.15 wt. %). The $\delta^{13}C_{org}$ values range from -24 to -21 ‰ and agree with other evidences [36, 62, 63] for a dominant marine origin of the organic matter in sediments of the Chukchi Sea and more generally in sediments of the Amerasian Arctic. This marine origin is confirmed by the C/N ratio which, within the top 2 cm of most of the stations, ranges between 6 and 8, revealing typical signature of marine algae [70]. These ratios also indicate that this marine organic matter was subjected to limited degradation processes within the water column and the top part of the sediment layers [56]. C/N ratio values close to 9 on average at St. 01A however suggest that sediment at this shelf station might contain a terrigenous component, though with limited contribution to the total organic matter content. $^{210}Pb_{xs}$ activity profile (Fig. 4) was measured in the first 7 cm of the sediment in order to highlight possible bioturbation or bio-structures in core 01A locating on the shelf. The vertical profile of $^{210}Pb_{xs}$ shows relatively stable values down to 6 cm and a gently decrease below.

4.2. Living benthic foraminifera

4.2.1. Living standing stock and ecological indices

In total, 476 living individuals were counted representing 31 species among them 15 are calcareous and 16 are agglutinated species. Tests of benthic foraminifera, especially calcareous, don't

show any mark of alteration or dissolution. Living faunal standing stocks show extremely low values in the 63-125 µm size fraction, from 0 ind./100 cm^2 in the shallowest St. 01A to 11 ind./100 cm^2 in St. 03 (Fig. 5a and Fig. 7). For this 63-125 µm fraction, excluding St. 03 (750 m), H' therefore equals 0 and E equals 1 for all stations due to the presence of only one living species (Fig. 5c, d). Benthic foraminiferal standing stocks and diversities S are generally higher in the >125 µm size fraction, ranging from 8 to 297 ind./100 cm^2, and from 3 to 17 species, respectively, with higher values generally measured at the shallowest stations (Fig. 5a, b). Lowest standing stocks are observed at the deepest stations (8 and 18 ind./100 cm^2 at Sts. 02 and 04, respectively). H' and E values do not indicate any clear correlation with water depth (Fig. 5c, d). Both indices are minimal at the mid-depth station (St. 03, 750 m).

4.2.2. Relative abundances of the dominant species

Because of the extremely low living standing stock in the 63-125 µm size fraction, relative abundances and comparison between size fractions should be considered with great care. Except at St. 03, only calcareous taxa are found in the 63-125 µm fraction (Fig. 6a). In the >125 µm fraction, the contribution of agglutinated taxa is decreasing with increasing water depth, ranging from 40 % at St. 01A to 0 at Sts.02 and 04 (Fig. 6b). With the exception of the deepest St. 04 where *Oridorsalis tenerus* shows high relative abundances in both size fractions, species assemblages are drastically different between size fractions (Fig. 7). Some species observed in the small size fraction are however worth mentioning: *Parafissurina tectulostoma* and *O. tenerus* are found on the upper slope (Sts. 05 and 03) and in the lower slope (Sts. 02 and 04). Higher standing stocks in the >125 µm fraction support a more robust description of the species assemblages. *Elphidium excavatum subsp. clavatum* and *Nonionellina labradorica*, both calcareous species, are the dominant taxa (45 and 13 %, respectively) in shelf sediments (St. 01A, Fig. 7b). Subordinate agglutinated species consist of *Saccammina* sp., *Labrospira crassimargo*, *Nonionina scapha var. arenacea* and *Recurvoïdes contorta*. Upper and lower slope stations are characterized by distinct foraminiferal populations. Foraminiferal assemblages at upper slope stations are both overwhelmingly (>60 %) dominated by *Cassidulina neoteretis*.

Elphidium excavatum subsp. clavatum and *Lagenammina arenulata* are present (27 % and 7 %, respectively), at St. 05 (350m) though both species are absent in the other upper slope St. 03 (750 m). In both deepest Sts. 02 and 04, *Ioanella tumidula* and *Triloculina oblonga* are common to abundant (Fig. 7b). *Oridorsalis tenerus* is dominant (64 %) at the deepest station (St. 04) but not observed at St. 02.

4.2.3. Vertical distribution

The vertical distribution (0 to 5 cm) of living foraminifera was analysed for the >125 µm size fraction only (Fig. 8). Benthic foraminifera are generally concentrated in the upper 2 cm of the sediment with density reaching up to 133 and 386 ind./50 cm^3 in the top-most layer (0-0.5 cm) of Sts. 03 and 05, respectively. At the shallowest St. 01A, the highest faunal density is also observed in the top-most layer with 47 ind./50 cm^3 and abundant agglutinated species, among which *L. crassimargo* and *N. scapha var. arenacea*. However, contrary to other stations, living faunas are found down to 5 cm, with *E. excavatum subsp. clavatum* reaching up to 28 ind./50 cm^3 in the 4-5 cm layer. *Nonionellina labradorica* shows its higher abundances between 1 and 2 cm (12 ind./50 cm^3).

5. Discussion

In most studies where benthic foraminifera from 63-125 µm and >125 µm size fractions are analysed, the standing stocks are generally much higher (e.g. [33]). In the Arctic, particularly under permanent sea-ice cover, most of the benthic foraminifera are smaller than 125 µm [78, 102, 103]. However, in this study, the living standing stock in the 63-125 µm size fraction is extremely low and always much lower than in the >125 µm size fraction. This might be due to either a methodological bias related to the staining of the living foraminifera or to environmental conditions. At all stations, the sediment is extremely fine (Fig. 3) and therefore very cohesive which might prevent the good penetration of Rose Bengal staining in the sediment. Although we cannot completely rule out this hypothesis, the occurrence of well stained individuals in the >125 µm size fraction suggests that the extremely low density in the 63-125 µm fraction is a consequence of environmental conditions rather

than a methodological bias. Density of dead fauna was assessed on the top centimetre (0-1cm) of the sediment for the 63-125 and >125 µm fractions in order to test whether the distribution of living fauna according to the size fractions is representative of mean average conditions in the studied area. Living and dead faunal densities are shown for both fractions in Figure 9. Not surprisingly given the time interval represented by the accumulation of dead fauna (25 years at least considering a minimal sedimentation rate of 0.4mm/yr [23]), the density of the dead fauna is much higher than that of the living fauna, especially for the 63-125 µm size fraction. Furthermore, the density of the dead fauna shows highest values in the lower slope Sts. 02 and 04 while the living fauna are more abundant in the upper slope Sts. 03 and 05. The remobilization and transport of dead fauna by active currents from shallow to deep settings [23] as well as taphonomical processes leading to the dissolution of calcareous forms that dominate the living assemblage at shallow stations [e.g., 89] might in part explain the observed discrepancy. More presumably, we consider that the sampling period (late August to early September 2015) is not typical of normal late summer environmental conditions in the Chukchi Sea and/or that the peak production of benthic foraminiferal species which contribute to the 63-125 µm fraction does not occur over late summer. Our data does not permit us to deal further with this issue. Therefore, and despite the relatively high proportion of dead foraminifera in the 63-125 µm fraction, most of the following discussion on the distribution of the living benthic foraminifera will be based on the >125 µm fraction only.

5.1. Density and diversity of living benthic foraminifera related to primary production

Except at St. 01A, where bottom temperature and salinity are -1.5°C and 33.1 respectively, these two parameters display similar values at all other stations, ranging from 0.2 to -0.5°C and close to 35.0 (Fig. 2a). Wollenburg and Mackensen [102, 103] have shown that among the various factors controlling the distribution of benthic foraminifera in the Arctic, bottom water mass characteristics are of minor importance. Likewise, given the equivalent grain size measured at all stations (clay to fine silt), we do not consider this sedimentological parameter as influential in explaining the

observed heterogeneities in species assemblages among stations (Fig. 3). The distribution of living benthic foraminifera is well known to be influenced by biotic and abiotic factors, among which the oxygen concentration and food supply are the most important [45, 102, 103]. TOC values in the studied upper and lower slope stations are fairly stable, ranging from 0.6 to 1.2 %, and agree with values found by Husum et al. [41] for the central Arctic. Over the shelf (St. 01A), TOC reaches 2.6 %. However, the standing stock at St. 01A is not particularly high compared with other stations, pointing out the influence of other parameters than organic matter content alone. Recent studies suggest that the quality and origin of the organic matter delivered to the seabed play a major role in controlling benthic foraminiferal ecology [25, 28, 29, 32, 46, 75]. The major food source for benthic foraminifera in the open ocean is organic matter derived from primary production. In the Arctic Ocean, food availability and benthic foraminiferal standing stock, composition and vertical distribution in sediments will greatly depend on sea-ice seasonality (e.g., [41, 102, 103]). In the Chukchi area, the marine primary production, and thus the export of organic matter to bottom sediments, is essentially controlled by nutrients availability, seasonal sea-ice extent (e.g., [93]), light penetration and fresh water input variability [22, 111], these parameters being strongly related. Many studies suggest that nitrogen availability through nitrate supply tends to control and limit primary productivity in seasonally ice-covered waters of the Arctic Ocean [58, 74, 92]. Tremblay et al. [93] showed a clear difference between the Chukchi shelf and Chukchi borderlands in terms of nitrate maximum at the surface due to perennial stratification in the interior sector. Yun et al. [111] also showed that primary production is highest in the southern Chukchi Sea and decreases northward as a result of sea-ice cover and meltwater input mainly. In this study, abundance and diversity are lower in the deepest stations (Sts. 02 and 04) that in the shelf and upper slope stations (Sts. 01A, 05 and 03). The living foraminiferal density in the >125 µm size fraction at all stations (Fig. 8) remains however low (from 4 ind./50cm^3 at St. 02 to 454 ind./50cm^3 at St. 05 for the upper centimetre) in comparison to other studies in Arctic environments. Wollenburg and Mackensen [103] reported living benthic foraminiferal densities in the same size fraction ranging from 18 ind./50cm^3 in

the deep Nansen Basin to 1044 ind./50cm^3 on the Yermak Plateau. Husum et al. [41] using a slightly smaller size fraction (100 µm-1 mm) provided density values of 0 ind./50cm^3 on the Alpha and Gakkel Ridge and more than 6300 ind./50cm^3 on the Kara Sea continental margin. The north of the Chukchi Sea is covered by sea-ice 8 months a year from November to June [e.g., 82, 90]. Long sea-ice cover leads to a generally low primary productivity and organic matter flux reducing the living benthic foraminiferal standing stock and the faunal habitat depths in the sediment [11, 69]. Although the sea-ice cover at the time of sampling was scarce for the northernmost deep stations, this may, at least partly, explain the standing stock differences between the relatively rich outer-shelf, upper slope stations and the very poor lower slope stations (Fig. 7). During summer in the Chukchi Sea, heterotrophic processes take over autotrophic processes following nutrient depletion by the spring bloom [39, 99]. This feature induces a seasonal shift in the quantity and the quality of the vertically exported biogenic matter. The biogenic matter exported is high and fresh in spring while it becomes lower and more degraded (faecal pellets, aggregates, detritus) in summer, especially during August and September [99]. Chlorophyll data measured at the deepest stations of the Chukchi Sea, however, show a relatively well-developed subsurface Chlorophyll maximum (SCM) centred around 60 m with chl *a* values reaching 1.6 µg L^{-1}. The depth and values of this SCM agree with the results of Coupel et al. [22] for the Chukchi area and Martin et al. [54] for other Arctic seas. Therefore, surface or subsurface productivity might not be the only limiting factor there.

5.2. Species distribution as a proxy of environmental changes

In the 5 studied cores, distinct living benthic foraminiferal assemblages are observed according to the following bathymetric ranges as: outer shelf (110 m water depth), upper slope (350-750 m) and lower slope (2100-2300 m). The outer shelf assemblage is found where organic matter content is the highest (Fig. 3). The most abundant species in this assemblage are *E. excavatum subsp. clavatum, N. labradorica*, *L. crassimargo* and *R. contorta*. *Elphidium excavatum subsp. clavatum* is a typical shelf species [61] and was found abundant in surface sediment over the Chukchi shelf [64] although this cited study did not distinguish living from dead fauna. Other species in this assemblage

such as *N. labradorica* are either linked to elevated fluxes of fresh phytodetritus [14, 21, 67] or associated to high contents of buried organic matter [21]. Phytoplankton bloom in this area typically occurs in late June-early July [2], two months before the sampling period. High TOC (Fig. 3) and the vertical distribution of *N. labradorica* at this station (Fig. 8) rather suggest the latter case in the present study. From a study conducted over the Kamchatka slope, Bubenshchikova et al. [11] described *N. labradorica* as an abundant intermediate infaunal species in the sea-ice free mesotrophic zone. The benthic foraminiferal population observed at the shelf St. 01A is made of 40 % of agglutinated specimens, peaking to 70 % in the topmost centimetre (Fig. 8). This calcareous/agglutinated assemblage is typical of shallow Arctic and subarctic environments [41, 49, 50, 64, 104]. In the Chukchi Sea, several authors observed undersaturated seawater *p*CO2 during the sea-ice free period across the shelf [3, 4, 5, 15, 16, 30, 59, 66, 81]. In contrast, subsurface seawater *p*CO2 values were highly oversaturated [3, 6]. These observations are indicative of an efficient organic carbon remineralization in the subsurface waters and into the sediment of the Chukchi continental shelf. Organic carbon remineralization increases *p*CO2 and decreases the pH. This process contributes to the acidification of interstitial waters making them further corrosive and leading to partial carbonate dissolution [7, 8] which could explain the recorded high abundance of agglutinated species on the shelf sediment of the Chukchi Sea.

The upper slope assemblage is highly dominated by *C. neoteretis*. *Elphidium excavatum subsp. clavatum* is dominant only on the upper slope St. 05. *Cassidulina neoteretis* is a shallow infaunal species associated to AIW in the Arctic [41, 42, 64] and typically related to fresh input of phytodetritus [34, 53]. Additionnaly, and although based only on quick visual examination of dead faunas, we notice that *C. neoteretis* that is dominating the living fauna at Sts. 03 and 05 is completely absent in the dead fauna. *Cassidulina*, a typically opportunistic genus, is however generally more abundant in dead assemblages than in living populations in various settings of the world ocean as a consequence of high production rates and short living time [26]. Our paradoxical observations may be related to dissolution in sediment by corrosive interstitial water or active transport by bottom

currents directly after the death of the organisms as already suggested earlier to explain higher density of the dead fauna at deep stations. The presence of this species, indicator of modified Atlantic Water/Arctic Intermediate Water [43], in the living fauna only may also suggests very recent changes in the local hydrology. *Elphidium excavatum subsp. clavatum* was observed by Korsun and Hald [47] in the Tempelfjorden in Svalbard and seems to be related to increasing glacier meltwater discharge. It is a widespread species in Arctic shelves with ability to colonize harsh environments (e.g., [21]). Its presence in the living fauna (Fig. 7b and 8 may therefore suggest high meltwater supply from sea-ice at the location of Sts.01A and 05.

The deep assemblage is essentially made of the surface infaunal species *O. tenerus* and *I. tumidula*. *Ioanella tumidula* dominates St. 02 at 2100 m while *O. tenerus* is absent. *Oridorsalis tenerus* is overwhelmingly dominant at the deepest St. 04. Note that *O. tenerus* is the only species found at both Sts. 02 and 04 in the 63-125 µm fraction. *Oridorsalis tenerus* and *I. tumidula* (as *Eponides tumidulus*) were found in the same biofacies by Ishman and Foley [42] at water depths greater than 1300 m in the Canada Basin. Husum et al. [41] also found these species in the 1300-3700 m water depth interval, on the permanently ice-covered Lomosov Ridge and Alpha Ridge in addition to the seasonally ice-free Nansen Basin. They are therefore referred as typically oligotrophic species. Wollenburg and Mackensen [102] however suggest that *O. tenerus* is better adapted to more oligotrophic conditions. Lower TOC values at St. 04, where *O. tenerus* is dominant, compared to St. 02 well supports this idea.

The vertical distribution of the living fauna (Fig. 8) shows sharp decrease below the first centimetre with the topmost layer being normally the richest, except at St. 02 where no living individuals where found in this upper layer. This is very consistent with other studies on the distribution of living benthic foraminifera in the Arctic. Wollenburg and Mackensen [103] found living individuals down to 8 cm while in the central Arctic most of the fauna was concentrated in the upper 2 cm according to the very low flux of organic matter in this permanently ice-covered area. The sampling period during post-bloom conditions, as well as the relatively low TOC values measured in

sediments of the upper and lower slope stations suggest that a weak input of labile organic matter in this sector of the Chukchi Sea induced the observed shallow (upper 2 cm) habitat of benthic foraminifera. The shallow St. 01A is characterized by a subsurface peak in foraminiferal density between 1 and 3 cm with *N. labradorica*, an intermediate infaunal species [61] as the dominant taxa. The presence of *E. excavatum subsp. clavatum*, a shallow infaunal species between 3 and 5 cm at St. 01A suggests local bioturbation or bio-structures. The occurrence at this station of several macro-organisms such as bivalves and echinoderms as well as a homogeneous $^{210}Pb_{xs}$ activity profile (Fig. 4) showing relatively stable values down to 6 cm confirms the possible bioturbation or bio-structure systems created by the activity of macro-/meio-fauna. On one hand, bioturbation might explain the unusual occurrence of *E. excavatum subsp. clavatum* deeper than expected. On the other hand, the presence of bio-structures leads to particular biochemical conditions and biotic associations which offer microhabitats favourable for the development of benthic foraminifera traditionally found in another range of sediment depth [52] such as *E. excavatum subsp. clavatum*.

6. Conclusions

This study aims to describe and understand the distribution of living benthic foraminifera in the northern Chukchi Sea continental shelf, upper and lower slope, an Arctic environment strongly impacted by recent climate changes. According to our observations, various environmental factors may influence the benthic foraminiferal abundance, composition and vertical distribution in the Chukchi Sea.

(1) The distributional patterns of living faunal assemblages seems to reflect the nature of the bottom water masses according to the three bathymetric sectors of the Chukchi Sea investigated in the present study. Over the shelf bathed by the corrosive Pacific water agglutinated specimens are abundant. Here, the assemblage is dominated by the calcareous species *E. excavatum subsp. clavatum* and *N. labradorica* and the agglutinated species *L. crassimargo* and *R. contortus*. Over the Chukchi slope, under the influence of Atlantic waters,

the assemblage is overwhelmingly dominated by *C. neoteretis*. Benthic foraminiferal populations in deep stations bathed by Arctic water are dominated by *I. tumidula* and *O. tenerus*.

(2) The overall low faunal diversity and standing stock at all stations may reflect post-bloom conditions in late August and early September in the area, and hence reduced supply of fresh organic matter to the sea floor. Living standing stocks are much lower in the 63-125 µm size fraction than in the >125 µm fraction. Although a methodological bias cannot be completely excluded, we believe that the conditions at the time of sampling were oligotrophic with highly degraded organic matter that does not favour the presence of opportunistic species often found in the small fraction.

(3) Our results suggest that in the context of post-bloom conditions, the lower quality of exported organic matter might also explain the observed, exclusively shallow (topmost centimetre) habitat of living benthic foraminifera in sediments of the upper and lower slope. The apparently deepest habitat (down to 5 cm) found over the shelf is probably related to intense bioturbation or bio-structures in this shallow setting, as evidenced by the presence of typical surface dwellers down in the sediment column.

Our study brings several hypothesis on the ecology and preservation of benthic foraminiferal fauna in the northern Chukchi Sea, confirming the key information that this species group can provide about modern and past changes in Arctic circulation and climate.

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Table and figure captions

Table 1 Station numbers, types, locations and water depths

Fig.1 Bathymetric map of the Chukchi Sea with sampling locations, main features of the surface and intermediate circulation, and mean sea-ice extent in August 2015 (white line) and September 2015 (white dotted line). The circulation is adapted from Rudels and al. [73]. For the surface waters, low-salinity currents derived from Pacific water are indicated by green arrows and cold polar and arctic currents by blue arrows. Circulation of intermediate waters is shown by black dotted arrows. AC: Anadyr Current; ACC: Alaskan Coastal Current; BG: Beaufort Gyre; BSW: Bering Sea Water; SCC: Siberian Coastal Current; TPD: Transpolar Drift. Monthly sea-ice extent is from NSIDC [27] and bathymetry is from IBCAO, WGS84

Fig.2 Water column profiles of temperature, salinity (a) and chlorophyll a (b) at Sts. 01A, 03, 02 and 04. Pacific water mass is underlined in green, Atlantic Intermediate Water in red and Artic Deep Water in blue

Fig.3 Downcore (topmost 2 cm) profiles of median sediment grain size D_{50} (µm), total organic carbon content (TOC, wt. %), total nitrogen content (TN, wt. %), $\delta^{13}C_{org}$ (‰ VPDB) and C/N ratio at all stations

Fig.4 Downcore $^{210}Pb_{xs}$ profile measured at St. 01A

Fig.5 Ecological indices describing foraminiferal assemblages at all stations for the 63-150 µm (topmost centimetre, grey bars) and >125 µm size fractions (topmost 5 cm, black bars). (a) Foraminiferal abundances; (b) Number of species S; (c–d) Shannon (H') and Evenness (E) indices

Fig.6 Proportion of agglutinated versus calcareous species at all stations for the 63-125 µm size fraction (a) and the >125 µm size fraction (b)

Fig.7 Foraminiferal relative abundances of major species (>5% of the total living benthic foraminifera assemblage) for the 63-125 µm (a) and the >125 µm (b) size fractions. Living standing stock (number in the central area of the pie charts) are standardized for a surface area of 100cm². Species representing less than 5 % are grouped in the category "others"

Fig.8 Vertical distribution of major species of living benthic foraminifera (>125 μm) in terms of faunal density (ind./50cm^3) in the topmost 5 cm

Fig.9 Density of living (blue) and dead (orange) benthic foraminifera in the first centimetre of sediment for each station and each size fraction.

Table Click here to access/download;Table;Table.docx

Table 1 Station numbers, types, locations and water depths

Cruise	Sample station	Sampling device	Longitude	Latitude	Water depth (m)
ARA06C	01A	Multicorer	-166.44	73.62	110
ARA06C	02	Boxcorer	-161.17	76.60	2100
ARA06C	03	Multicorer	181.01	76.33	750
ARA06C	04	Multicorer	-173.23	78.84	2300
ARA06C	05	Boxcorer	179.50	75.60	350

Figure

Click here to access/download;Figure;revised_figures2.pptx

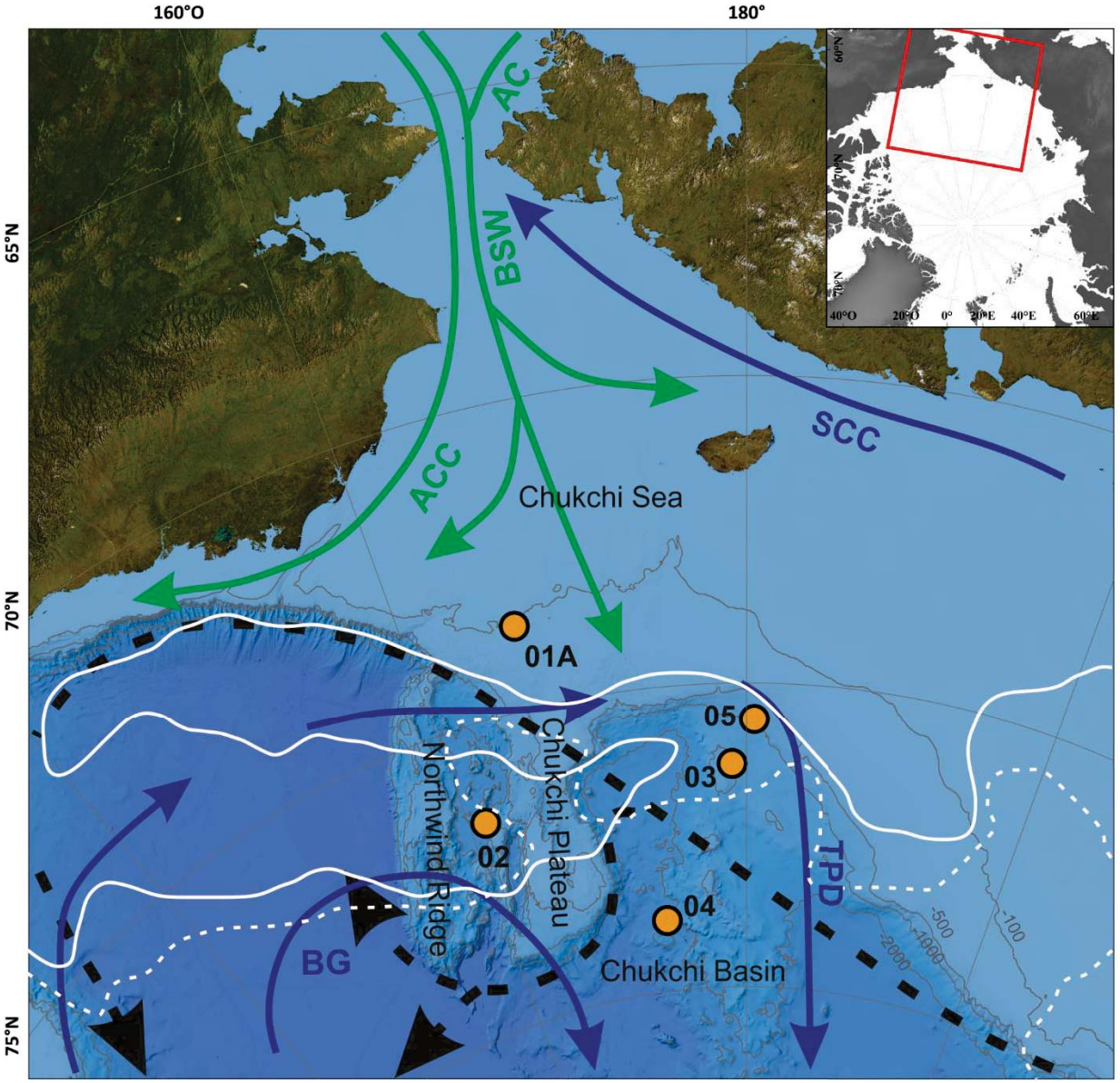

Fig1

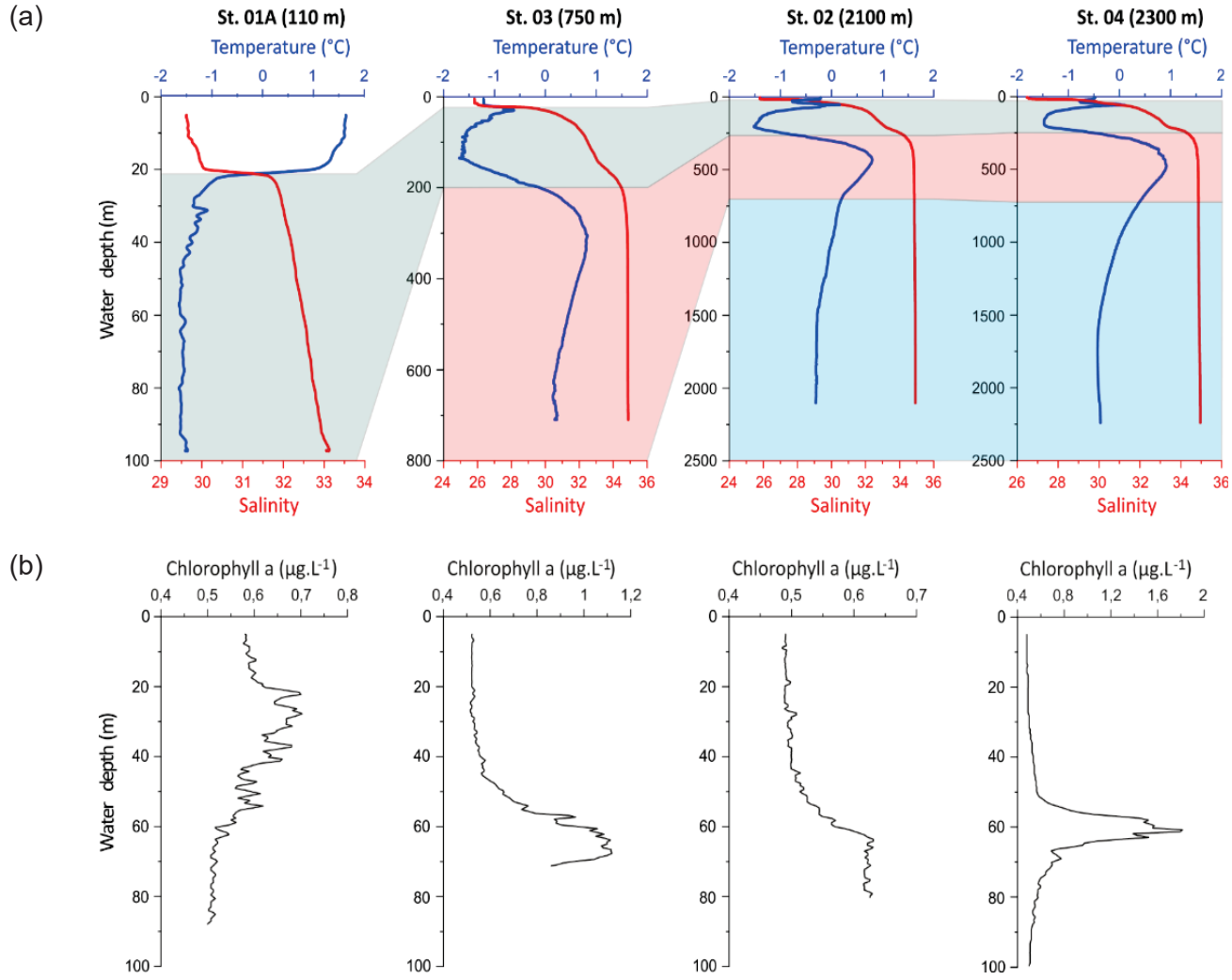
(a)
St. 01A (110 m)
St. 03 (750 m)
St. 02 (2100 m)
St. 04 (2300 m)
Temperature (°C)
Salinity
Water depth (m)
(b)
Chlorophyll a (µg.L-1)
Water depth (m)

Fig2

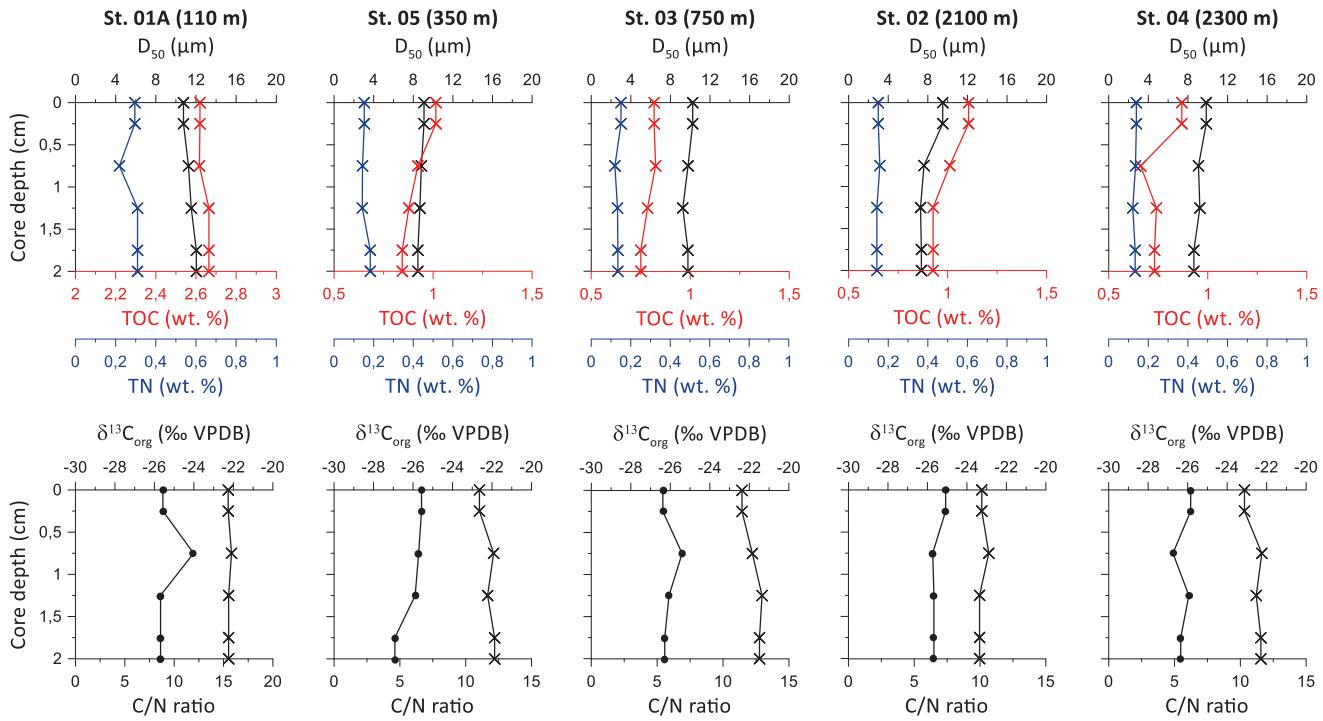
St. 01A (110 m)
St. 05 (350 m)
St. 03 (750 m)
St. 02 (2100 m)
St. 04 (2300 m)
D50 (µm)
Core depth (cm)
TOC (wt. %)
TN (wt. %)
δ13Corg (‰ VPDB)
C/N ratio

Fig3

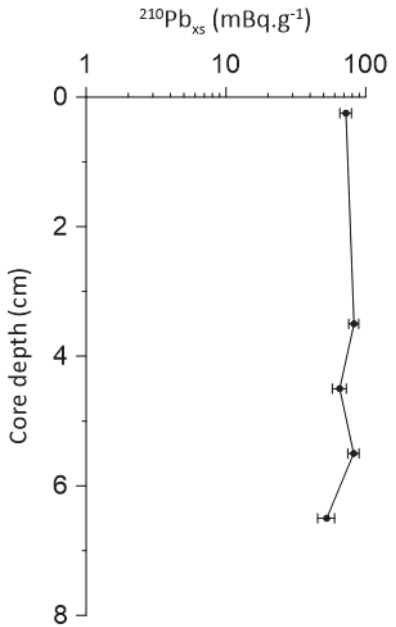

Fig4

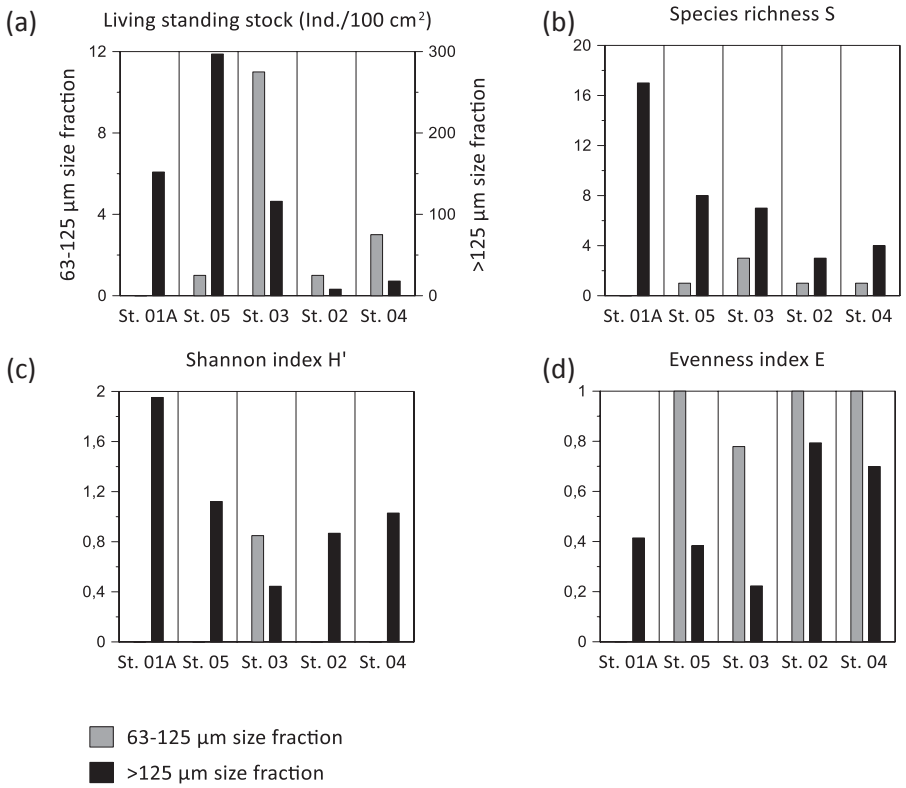
(a)
Living standing stock (Ind./100 cm²)
63-125 µm size fraction
>125 µm size fraction
12
8
4
0
300
200
100
0
St. 01A St. 05 St. 03 St. 02 St. 04
(b)
Species richness S
20
16
12
8
4
0
St. 01A St. 05 St. 03 St. 02 St. 04
(c)
Shannon index H'
2
1,6
1,2
0,8
0,4
0
St. 01A St. 05 St. 03 St. 02 St. 04
(d)
Evenness index E
1
0,8
0,6
0,4
0,2
0
St. 01A St. 05 St. 03 St. 02 St. 04
63-125 µm size fraction
>125 µm size fraction

Fig5

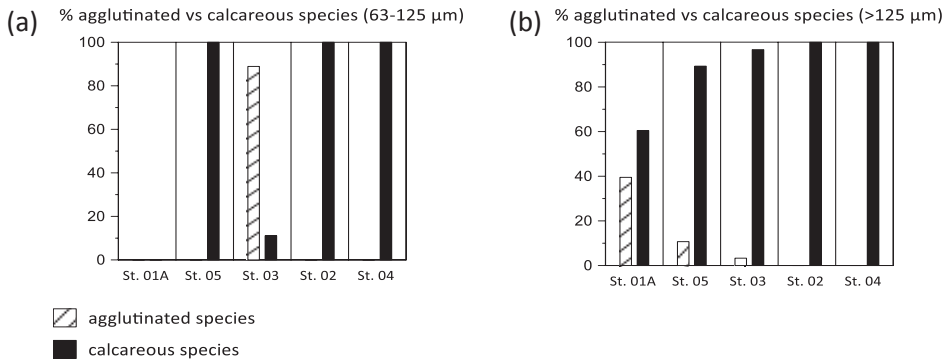
(a)
% agglutinated vs calcareous species (63-125 µm)
100
80
60
40
20
0
St. 01A
St. 05
St. 03
St. 02
St. 04
agglutinated species
calcareous species
(b)
% agglutinated vs calcareous species (>125 µm)
100
80
60
40
20
0
St. 01A
St. 05
St. 03
St. 02
St. 04

Fig6

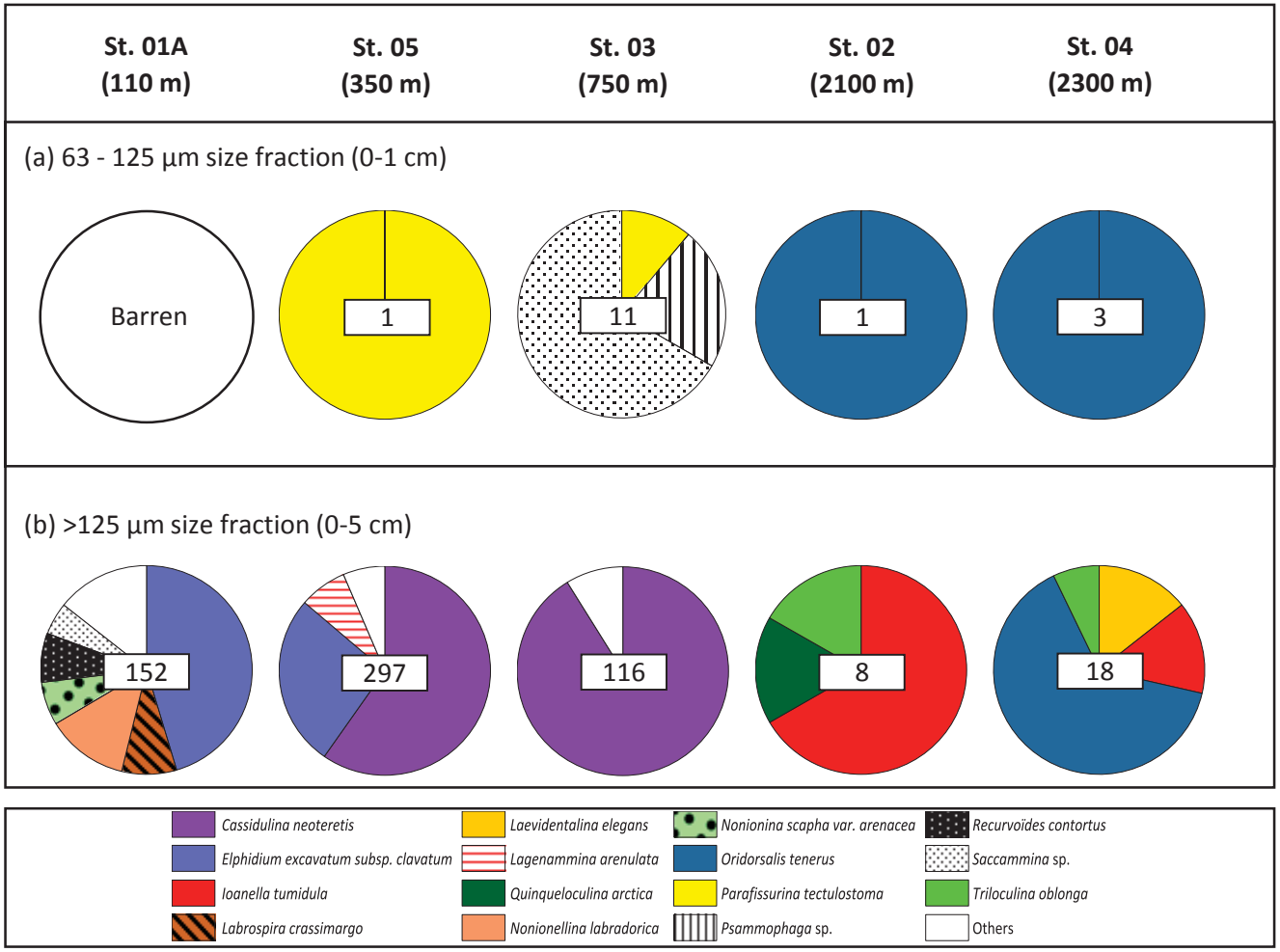
St. 01A (110 m)
St. 05 (350 m)
St. 03 (750 m)
St. 02 (2100 m)
St. 04 (2300 m)
(a) 63 - 125 µm size fraction (0-1 cm)
Barren
1
11
1
3
(b) >125 µm size fraction (0-5 cm)
152
297
116
8
18
Cassidulina neoteretis
Elphidium excavatum subsp. clavatum
Ioanella tumidula
Labrospira crassimargo
Laevidentalina elegans
Lagenammina arenulata
Quinqueloculina arctica
Nonionellina labradorica
Nonionina scapha var. arenacea
Oridorsalis tenerus
Parafissurina tectulostoma
Psammophaga sp.
Recurvoïdes contortus
Saccammina sp.
Triloculina oblonga
Others

Fig7

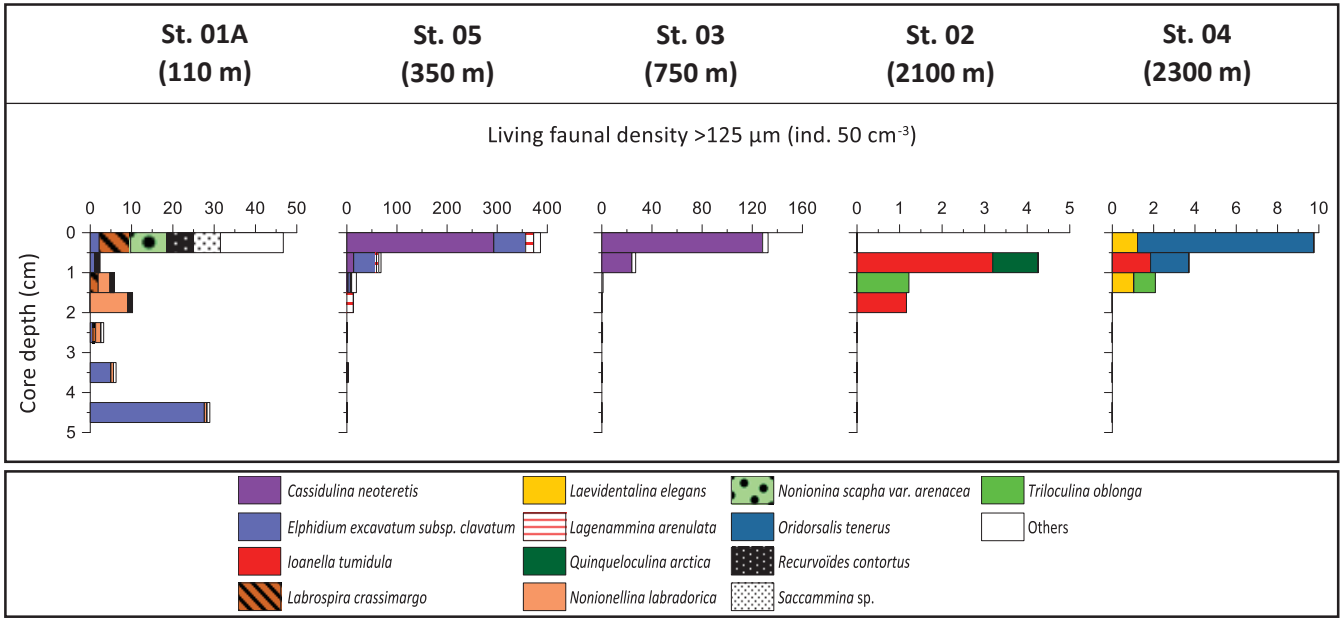
St. 01A
(110 m)
St. 05
(350 m)
St. 03
(750 m)
St. 02
(2100 m)
St. 04
(2300 m)
Living faunal density >125 µm (ind. 50 cm-3)
Core depth (cm)
0 10 20 30 40 50
0 100 200 300 400
0 40 80 120 160
0 1 2 3 4 5
0 2 4 6 8 10
0 1 2 3 4 5
Cassidulina neoteretis
Elphidium excavatum subsp. clavatum
Ioanella tumidula
Labrospira crassimargo
Laevidentalina elegans
Lagenammina arenulata
Quinqueloculina arctica
Nonionellina labradorica
Nonionina scapha var. arenacea
Oridorsalis tenerus
Recurvoides contortus
Saccammina sp.
Triloculina oblonga
Others

Fig8

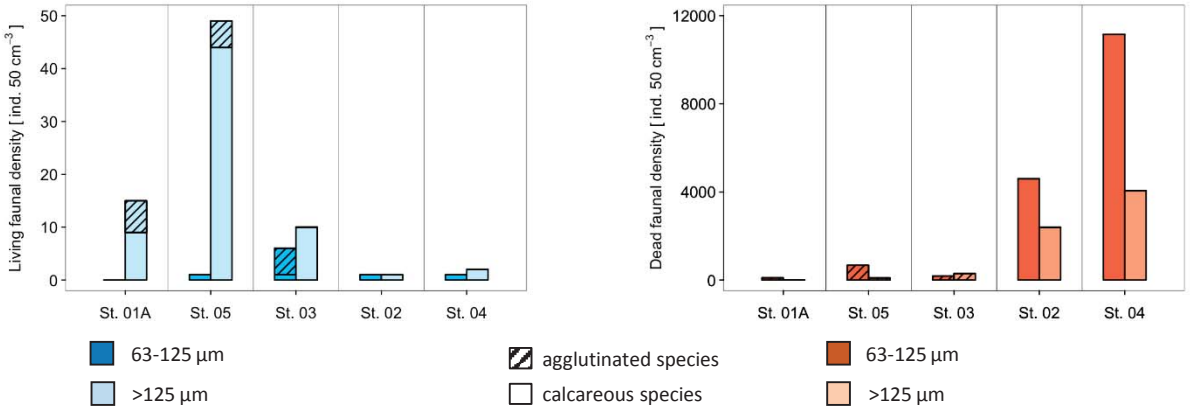
Living faunal density [ind. 50 cm^{-3}]
50
40
30
20
10
0
St. 01A
St. 05
St. 03
St. 02
St. 04
Dead faunal density [ind. 50 cm^{-3}]
12000
8000
4000
0
St. 01A
St. 05
St. 03
St. 02
St. 04
63-125 µm
>125 µm
agglutinated species
calcareous species
63-125 µm
>125 µm

Fig9

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Appendices

Appendix 1 Taxonomic reference list of major taxa

Cassidulina neoteretis Seidenkrantz, 1995

Elphidium excavatum subsp. clavatum Cushman, 1930

Ioanella tumidula (Brady, 1884)

Labrospira crassimargo (Norman, 1892)

Laevidentalina elegans (d'Orbigny, 1846)

Lagenammina arenulata (Skinner, 1961)

Quinqueloculina arctica Cushman, 1933

Nonionellina labradorica (Dawson, 1860)

Nonionina scapha var. arenacea Heron-Allen and Earland, 1922

Oridorsalis tenerus (Brady, 1884)

Parafissurina tectulostoma Loeblich and Tappan, 1953

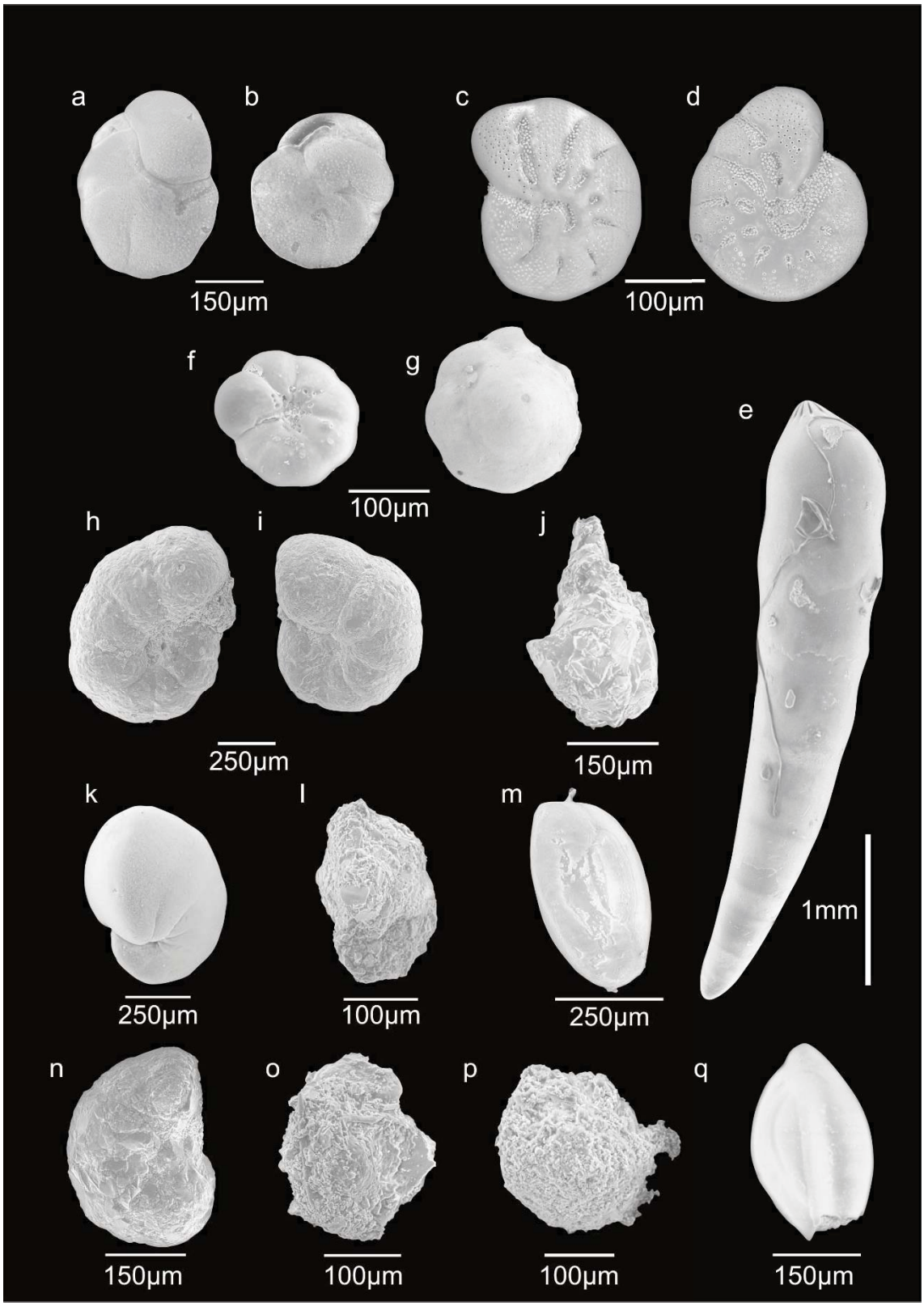
Psammophaga sp. Arnold, 1982

Recurvoides contortus Earland, 1934

Saccammina sp. Sars, 1869

Triloculina oblonga (Montagu, 1803)

Appendix 2 Plate with SEM pictures of major species (>125 µm)



a-b : *Cassidulina neoteretis*; **c-d** : *Elphidium excavatum subsp. clavatum*; **e** : *Laevidentalina elegans*; **f** : *Ioanella tumidula* (ombilical side); **g** : *Ioanella tumidula* (spiral side); **h-l** : *Labrospira crassimargo*; **j** : *Lagenammina arenulata*; **k** : *Nonionellina labradorica*; **l** : *Nonionina scapha var. arenacea*; **m** : *Triloculina oblonga*; **n** : *Recurvoïdes contortus*; **o-p** : *Saccammina* sp.; **q** : *Quinqueloculina arctica*

Appendix 3

Table 2. Number of major living (stained) benthic foraminiferal species (representing >5% in at least one sample), number and densities of total living and dead fauna for each station and each size fraction.

Station	**01A**		**02**		**03**		**04**		**05**	
Size fraction	63-125 µm	>125 µm	63-125 µm	>125 µm	63-125 µm	>125 µm	63-125 µm	>125 µm	63-125 µm	>125 µm
Cassidulina neoteretis	0	0	0	0	0	83	0	0	0	139
Elphidium excavatum subsp. clavatum	0	54	0	0	0	0	0	0	0	62
Ioanella tumidula	0	0	0	4	0	0	0	2	0	0
Labrospira crassimargo	0	10	0	0	0	0	0	0	0	0
Laevidentalina elegans	0	0	0	0	0	0	0	2	0	0
Lagenammina arenulata	0	0	0	0	0	1	0	0	0	17
Quinqueloculina arctica	0	0	0	1	0	0	0	0	0	0
Nonionellina labradorica	0	15	0	0	0	0	0	0	0	0
Nonionina scapha var. arenacea	0	8	0	0	0	0	0	0	0	0
Oridorsalis tenerus	0	0	1	0	0	0	2	9	0	0
Parafissurina tectulostoma	0	0	0	0	1	0	0	0	1	0
***Psammophaga* sp.**	0	0	0	0	2	0	0	0	0	0
Recurvoïdes contortus	0	9	0	0	0	0	0	0	0	0
***Saccammina* sp.**	0	6	0	0	6	0	0	0	0	0
Triloculina oblonga	0	0	0	1	0	1	0	1	0	0
Others	0	17	0	0	0	6	0	0	0	15
No of living specimens counted	0	119	1	6	9	91	2	14	1	233
Living specimens/50cm^3	0	14	0.5	1	6	11	1	2	0.9	50
No of dead specimens counted	186	54	8552	19056	266	2526	21184	34576	298	470
Dead specimens/50 cm^3	103	6	4598	2394	182	294	11149	4058	677	100