

# Terrestrial and aquatic palynomorphs in Holocene sediments from the Chukchi–Alaskan margin, western Arctic Ocean: Implications for the history of marine circulation and climatic environments

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## Abstract

Two sediment cores from the Chukchi Sea margin north of Alaska were analyzed for palynological composition including terrestrial and aquatic palynomorphs. Based on 13 radiocarbon ages, the investigated sedimentary record represents most of the Holocene with a century to multidecadal age resolution. Three palynological zones were discriminated based on the abundance of major palynomorph groups (terrestrial and freshwater palynomorphs and dinoflagellate cysts) and composition of spore and pollen assemblages. They are interpreted in terms of depositional and paleoclimatic changes including predominance of redeposition by meltwater or sea ice in the early-Holocene, a strong input of contemporaneous material related to Pacific water advection culminating after ca. 6000 yr BP, and more subtle changes in the late-Holocene. It is concluded that depositional environments, such as current transportation and mixing, have an overall major control on palynomorph distribution. The climatic factors may have also played an important role in palynomorph abundance and composition, especially in the middle- to late-Holocene, when circulation changes were less dramatic than during the flooding of the Bering Strait and the shallow Chukchi Sea shelf. Comprehending these linkages requires a better knowledge of the Holocene vegetation history in the coastal areas of Alaska and Chukchi Peninsula.

## Keywords

Chukchi Sea, Holocene, palynomorphs, pollen, sediment cores, western Arctic

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## Introduction

The Chukchi–Alaska region of the western Arctic Ocean (Figure 1) is known to be highly sensitive to both climate variability and sea-level fluctuations, which affect its atmospheric and oceanographic linkages with the Pacific Ocean (e.g. Danielson et al., 2014; Mesquita et al., 2009; Woodgate et al., 2010). The atmospheric circulation is mainly controlled by a low-pressure system in the North Pacific (Aleutian low), which interacts with polar air masses and strongly affects meteorological conditions in the western Arctic. The oceanographic connection between the Arctic and the Pacific oceans through the Bering Strait transports Pacific waters and organisms to the Chukchi Sea shelf and adjacent basins. It is known that the shallow Chukchi Sea shelf was repeatedly subaerially exposed during low sea levels, thus bridging the easternmost Siberia (Chukotka Peninsula) and Alaska into a land region known as Beringia (Brigham-Grette and Carter, 1992; Svitoch and Taldenkova, 1994). The timing of openings and closures of the Bering Strait is essential for not only reconstructing paleoceanographic history of the Pacific sector of the Arctic, but also for understanding the history of Arctic freshwater export into the North

Atlantic (e.g. Hu et al., 2010; Ortiz et al., 2009). The most recent reopening of the Bering Strait and flooding of the Chukchi shelf occurred about 11,000–12,000 yr BP during the last deglaciation (Elias et al., 1997; Keigwin et al., 2006). The history of paleoceanographic changes at the Chukchi–Alaska margin since that event is important as a long-term perspective for present-day changes in Arctic climate and oceanic conditions.

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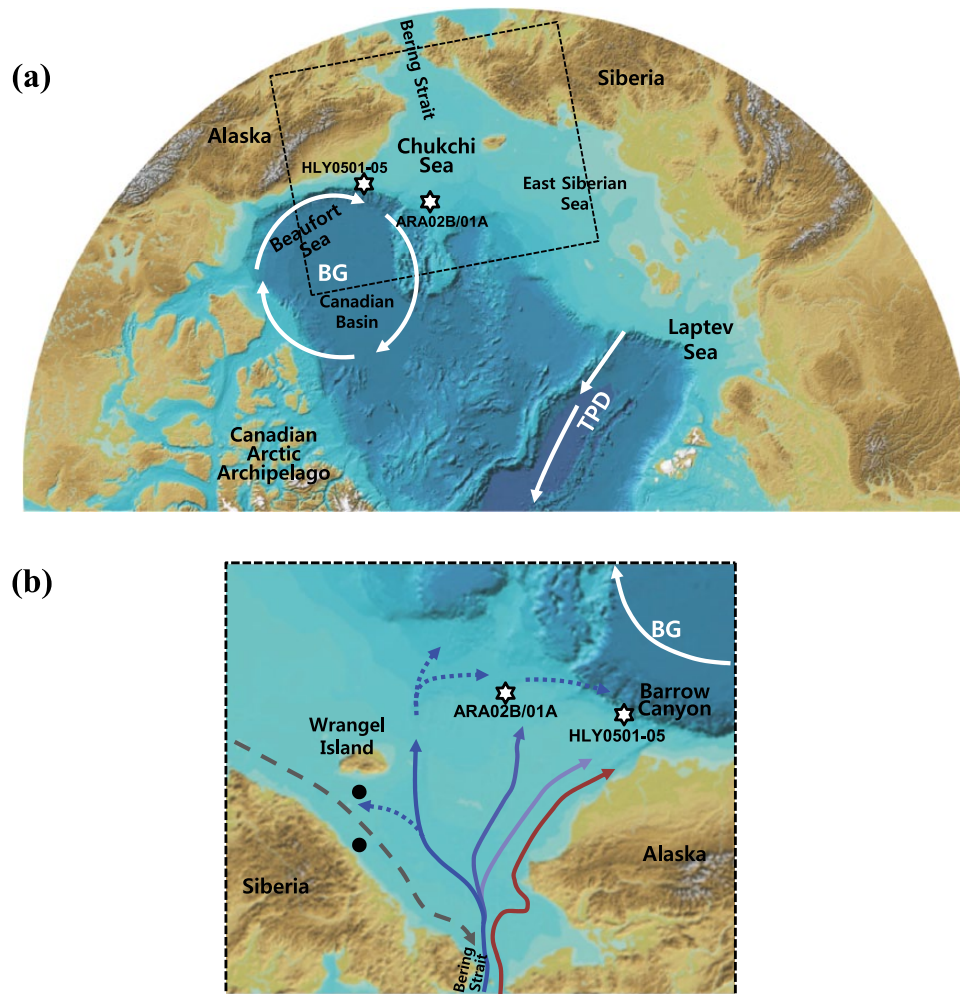
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**Figure 1.** (a) Map of the western Arctic Ocean, showing the location of sites ARA02B/01A and HLY0501-05 (ARA 01 and HLY 05 in the text). Arrows show major circulation features: Beaufort Gyre (BG), Transpolar Drift (TPD), and Pacific water inflow (dashed arrows for subsurface current). (b) Inset shows circulation in the Chukchi Sea along with the location of the study sites (white stars) and cores from Gusev et al. (2009) (black circles).

Palynomorphs preserved in marine sediments can provide useful proxy data for evaluating past oceanographic and climatic changes and developing land–sea connections (e.g. Mudie and McCarthy, 2006). In particular, concentrations and proportional changes of terrestrial (pollen and spores) and freshwater palynomorphs associated with changes in vegetation and fluvial inputs, respectively, have been successfully utilized in interpreting sedimentary records from Arctic continental shelves (e.g. Matthiessen et al., 2000; Naidina and Bauch, 2011; Rudenko et al., 2014). Recently, Gusev et al. (2009, 2014) used terrestrial and aquatic palynomorphs to characterize Holocene sedimentary and associated climatic environments in the southwestern part of the Chukchi Sea. Results indicate a potential usefulness of these proxies for paleoceanographic interpretation and correlation of sediment cores and the need for more studies to comprehend the regional climatic change.

In this paper, we present new terrestrial and aquatic palynomorph data from two sediment cores from the Chukchi–Alaskan margin (Figure 1) to better understand the effects of circulation changes, such as the Bering Strait opening and ensuing inputs of Pacific and riverine waters, combined with major vegetational changes in the adjacent Siberian and Alaskan regions. By using continuous, radiocarbon-dated sediment records, we track Holocene changes in palynomorph assemblages and discuss their possible source areas and transportation mechanisms along with implications for the regional climatic history.

## Environmental setting

### Hydrographic and depositional environments

The study area is located in the western Arctic Ocean at the margin of the Chukchi Sea shelf northwest of Alaska (Chukchi–Alaskan margin) (Figure 1). The overall shallow (mostly <100 m deep) Chukchi Sea is characterized by a complex system of currents originating mostly from the inflow of relatively warm and fresh Pacific waters via the Bering Strait (e.g. Weingartner et al., 1998, 2005; Winsor and Chapman, 2004; Woodgate et al., 2005). These currents cross the Chukchi Sea in three major branches, which interact with the wind-driven, clockwise Beaufort Gyre circulation at the Chukchi shelf margin (Figure 1b). In addition, the Siberian Coastal Current delivers water from the west to the southern part of the Chukchi Sea, but its influence on the northern margin is insignificant.

Extensive sea-ice formation in the Chukchi Sea is enhanced by Arctic river discharge and relatively fresh Pacific inflow providing low-salinity surface water into this region (Aagaard and Carmack, 1989; Carmack, 2000). Seasonal duration of sea-ice cover over the Chukchi shelf ranges from 6 to almost 12 months/yr, regulated by atmospheric and oceanic circulations that determine significant inter-annual fluctuations in the concentration and thickness of sea ice (Cavalieri and Martin, 1994; Roach et al., 1995). In recent years, the margin of summer sea-ice extent in this region has retreated considerably further north, which is

likely related to the increased Bering Strait Inflow (Woodgate et al., 2010).

Sediment is mostly delivered to the Chukchi shelf by currents carrying fines from the northern Bering Sea, including the discharge of large Yukon and Anadyr rivers, as well as from smaller local streams and coastal erosion (e.g. Barnes and Reimnitz, 1974; Viscosi-Shirley et al., 2003). Transport by sea ice, notably from the Alaskan coasts, may also be an important source of sediment supply (Darby, 2003; Eicken et al., 2005). Fine sediment is further redistributed by bottom erosion and redeposition, which results in the accumulation of relatively well-sorted, silty muds in seafloor depressions and on the northern slope (Barnes and Reimnitz, 1974; Darby et al., 2009; Wang et al., 2015), including both sites under study. As composition of these sediments is affected by the circulation pattern and intensity, they can be used for proxy reconstructions of circulation changes in the past. For example, some minerals associated with the North Pacific provenance, notably chlorite, can be used as a proxy of the Bering Strait Inflow (Nwaodua et al., 2014; Ortiz et al., 2009).

### Climate and vegetation

The climate over the northeastern Siberia and Alaska and Yukon Territory in northwestern North America is generally severe and continental, characterized by cold and long winters with mean temperatures of the coldest month below  $-30$  to  $-40^{\circ}\text{C}$ , and cool and short summers with mean temperatures of the warmest month less than  $+4$  to  $+9^{\circ}\text{C}$  (Lozhkin and Anderson, 1995; New et al., 2002; Tarasov et al., 2013). Over this region, summer precipitation is maximum during July (50–100 mm) because of increased radiation and warmer high-pressure systems inducing storms at most locations, while the winter climate is primarily regulated by cold and very dry air masses associated with intensive radiational cooling and a high-pressure system that is particularly dominating the northeastern Siberia (Lozhkin and Anderson, 1995; Mock et al., 1998).

Vegetation of the northeastern Siberia and the northwestern America is generally characterized by northern boreal forest and shrub tundra, reflecting harsh climatic conditions (Bigelow et al., 2003). Northeast Siberia shows a mixture of tundra and light coniferous forests, dominated by open larch (*Larix dahurica*) forest vegetations (Kozhevnikov, 1989). The understory vegetation is dominantly occupied by shrubs of dwarf stone pine (*Pinus pumila*), birch (*Betula exilis*, *B. middendorffii*), willow, and heaths. Beyond altitudinal tree limit, stone pine constitutes a belt of shrub tundra vegetation. In coastal areas, grass-sedge-*Artemisia* tundra with prostrate willow and occasional birch shrubs are dominant (Anderson and Lozhkin, 2015; Edwards et al., 2000). Vegetation of the northwestern North America predominantly comprises black and white spruce (*Picea mariana*, *P. glauca*) with an only limited distribution of larch (*Larix laricina*), in contrast to northeastern Siberia. Alder (*Alnus crispa*) often forms dense thickets on mountain slope areas, while tundra vegetation largely occupies the northern and western areas of the northwestern North America region (Lozhkin and Anderson, 1995 and references therein).

The available records of paleovegetational condition in the northeastern Siberia region during the last deglaciation and Holocene suggest an early domination of shrub *Betula* as a replacement for the herb-*Salix* tundra of the Last Glacial Maximum, followed by expansion of shrub *Alnus* ( $\sim 13,800$ – $10,500$  cal. yr BP) and eventual establishment of conifers ( $\sim 11,100$ – $8400$  cal. yr BP) (Anderson and Lozhkin, 2002; Anderson et al., 2014; Brubaker et al., 2005). During the postglacial thermal maximum ( $\sim 11,400$ – $9000$  cal. yr BP), pollen records indicate a widespread presence of deciduous trees and shrub taxa across the northeast Siberia and neighboring Alaska, followed by a shift to increased content of the evergreen needleleaf taxa after 9500 cal.

yr BP (Edwards et al., 2005). A comprehensive, state-of-the-art compilation of paleoclimatic proxies from the eastern Beringia (Alaska and adjacent territories) demonstrates a spatially consistent climatic optimum with overall relatively warm and dry conditions characterizing mid-Holocene time around  $\sim 6000$  cal. yr BP (Kaufman et al., 2016). Modern boreal vegetation communities are suggested to be established after this interval, generally consistent with paleovegetational data from adjacent regions (Anderson and Lozhkin, 2015; Edwards et al., 2005; Kaufman et al., 2004).

### Materials and methods

The palynological data used in this study were generated from two sediment cores collected from the northern margin of the Chukchi shelf (ARA02B/01A) and the Chukchi slope off the northern coast of Alaska (HLY0501-05) (Figure 1). A 546-cm-long gravity core ARA02B/01A (referred hereafter as core ARA-1) was recovered from a water depth of 111 m during the ARA02B cruise on the Icebreaker *ARAON* in 2011 ( $73^{\circ}37.9'N$ ,  $166^{\circ}31.0'W$ ). Multi-beam bathymetry survey and sub-bottom profiling performed by the shipboard echosounder system ensured a coring site with a continuous sediment accumulation not affected by downslope mass wasting. The core was split lengthways, photographed, x-rayed, and logged in detail by visual examination. Core HLY0501-05 (referred hereafter as core HLY-5) was recovered during leg HLY0501 of the USCGC Healy in 2005 (415 m water depth;  $72.69^{\circ}N$ ,  $157.52^{\circ}W$ ; Darby et al., 2005). The composite sedimentary record for this site is based on a 16.7-m-long jumbo piston core (upper 13 m analyzed for palynology) and a 2.6-m-long trigger core, with an estimated 75-cm offset due to piston-core overpenetration in soft sediment. The core material subsampled for pollen analysis has been stored in a refrigerated archival core facility of the Byrd Polar Research Center. Additional information on this core has been provided in previous studies (e.g. Barletta et al., 2008; Darby et al., 2009, 2012; Faux et al., 2011; McKay et al., 2008; Polyak et al., 2016). In particular, McKay et al. (2008) have reported data on dinoflagellate cyst assemblages along with concentrations of total pollen and spore counts, but terrestrial palynomorphs have not been investigated in detail.

Based on its relatively shallow-water depth, the ARA-1 site was exposed during the last glaciation and inundated during the postglacial transgression. In contrast, core HLY-5 was raised from the continental slope, where sediment deposition was not interrupted by sea-level changes. Sediments in the 5.5-m-long core ARA-1 mainly consist of homogeneous clayey silts indicative of open-marine environments. An admixture of sand near the core bottom may be related to shallow-water sediment reworking during the shelf flooding. In HLY-5,  $>13$  m of marine clayey silts are underlain by a partially laminated sedimentary unit with abundant coarse grains (McKay et al., 2008). These sediments in the study area were interpreted as deglacial deposits affected by the discharge of icebergs and meltwater from retreating ice sheets (Polyak et al., 2009).

Accelerator mass spectrometry (AMS)  $^{14}\text{C}$  dating for core ARA-1 was performed on bivalve mollusks (whole shells or fragments) from seven sampling horizons distributed along the core (Table 1). AMS  $^{14}\text{C}$  measurements were carried out at Center for Applied Isotope Studies (University of Georgia, USA).  $^{14}\text{C}$  ages were converted to calendar ages BP using the CALIB 7.1 program (Stuiver and Reimer, 1993). A 500-year local reservoir age correction ( $\Delta R$ ) was applied for ARA-1 in accordance with data from the coastal waters of northern Alaska (McNeely et al., 2006), while no  $\Delta R$  was used for HLY-5 as this site is washed by subsurface Atlantic water with very low residence time (Darby et al., 2012). Age constraints for core HLY-5 based

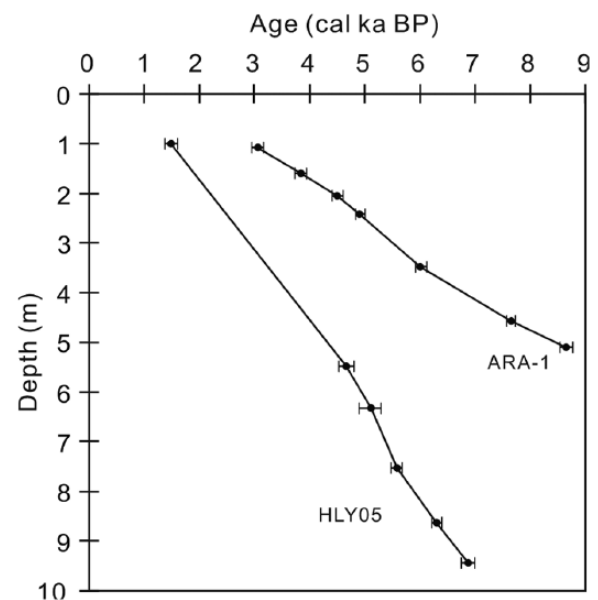
**Table 1.** Radiocarbon ages for cores ARA02B-01A-GC (this study) and HLY0501-05JPC (Darby et al., 2009).

Depth (cm)	<sup>14</sup> C age (yr BP)	CALIB 7.0 (yr BP)	ΔR	Material	UGAMS number/source
<b>ARA02B-01A-GC</b>					
107.5	3740 ± 30	3058	500	Bivalve	11825
159.5	4370 ± 30	3837	500	Bivalve	11826
204.5	4860 ± 30	4493	500	Bivalve	11827
241.5	5180 ± 30	4899	500	Bivalve	11828
347.5	6110 ± 30	5998	500	Bivalve	11829
456.5	7690 ± 30	7649	500	Bivalve	11830
509.5	8670 ± 30	8648	500	Bivalve	11831
<b>HLY0501-05JPC</b>					
100	1930 ± 45	1477	0	Bivalve	Darby et al. (2009)
547	4465 ± 40	4655	0	Bivalve	Darby et al. (2009)
632.5	4820 ± 70	5109	0	Bivalve	Darby et al. (2009)
752.5	5220 ± 40	5583	0	Bivalve	Darby et al. (2009)
863	5885 ± 40	6303	0	Bivalve	Darby et al. (2009)
943.5	6395 ± 45	6870	0	Bivalve	Darby et al. (2009)

on six AMS <sup>14</sup>C ages supplemented by paleomagnetic and <sup>210</sup>Pb analyses have been described in previous publications (Barletta et al., 2008; Darby et al., 2009, 2012; Lisé-Pronovost et al., 2009; McKay et al., 2008).

The age model was constructed by linear interpolation between the <sup>14</sup>C datings as well as the assumed modern age of the core tops; ages below the dated ranges were extrapolated. The age model for the trigger core HLY-5 was concurrently estimated from <sup>210</sup>Pb data measured in the top 15 cm (McKay et al., 2008). The best <sup>14</sup>C-based age control covers the interval of 3700–9400 yr BP in ARA-1 and 4700–6900 yr BP in HLY-5. The distribution of linear sedimentation rates shows maximal values in both cores around 5000–6000 yr BP (Figure 2).

For palynological analysis, core ARA-1 was subsampled at 20- to 30-cm intervals, and the composite core HLY05 was subsampled at intervals between 30 and 100 cm. Each sample was processed for palynological analysis without oxidation according to the following procedure. Approximately 5–8 g (ARA-1) and 4–18 g (HLY05) of freeze-dried sediment per sample were used. After adding a *Lycopodium clavatum* spore tablet of batch #177745 ( $X = 18,584$  per tablet,  $\sigma = \pm 1853$ ) to each sample, they were treated with 20 mL of cold 10% hydrochloric acid (HCl) for the removal of calcium carbonate. After 20 min, the residue was rinsed with distilled water, and 20 mL of cold 40% hydrofluoric acid (HF) was added and left for 20 min to remove silicates. The HCl and HF steps were repeated 2–3 times. Afterwards, the cold HF was added to the residue, and after resting overnight and decantation, the cold HCl was added for 20 min. The final residues were washed with distilled water to neutralize the pH. In order to shorten settling time and avoid losing the residue, centrifugation was used at each step of decanting at 3000 r min<sup>-1</sup> for 10 min. Then samples were passed through a 10-μm pore sized mesh sieve and the residue was preserved in a 10-mL vessel with two to three drops of phenol added. Palynomorphs were counted in each sample under the microscope (Nikon, Eclipse 55i) at 250 and 400 times magnification. Microscopic slides were counted to at least 300 of pollen and spore grains, including arboreal (tree and shrub plants) and non-arboreal (terrestrial herb plants) pollen taxa with the accompanying pteridophyte and moss spores. Three major ecological groups (trees/shrubs, herbaceous plants, and spore vegetation) were distinguished as indicators of distinct plant communities. The percentages of pollen were calculated from a sum of tree/shrub and herb pollen with unidentifiable pollen, and spore percentages were calculated based on a total sum of all pollen and spores (Figure 4). The data diagram is divided into three pollen zones on the basis of the pollen curves calculated by Constrained Incremental Sums of



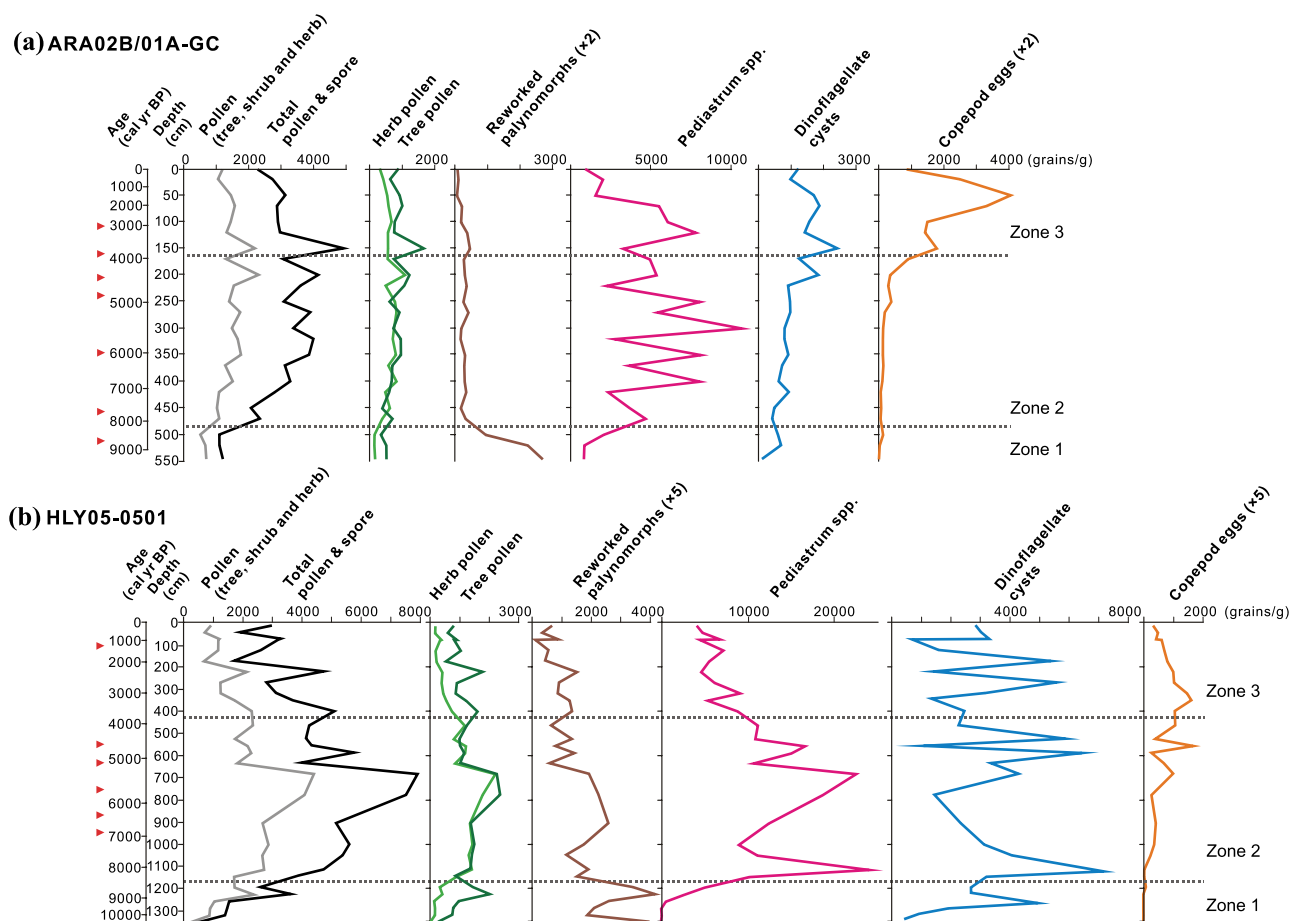
**Figure 2.** Age–depth curves for cores ARA02B/01A and HLY0501-05 with 2 sigma error ranges of the AMS <sup>14</sup>C dates (black dots). Error bars are also represented.

Squares cluster analysis (CONISS) of the TILIA program (Grimm, 1992). Concentrations of each basic sum counted are expressed as concentrations of palynomorphs per weight of dry sediment, except for the concentrations of dinoflagellate cyst sum in HLY-5 that were expressed in grains per cubic centimeter of wet sediment (McKay et al., 2009). The concentration of palynomorphs was calculated as follows (Benninghoff, 1962):

$$c(\text{grains g}^{-1} \text{dry sediment}) = \frac{g_c \times L_t \times t}{L_c \times w}$$

where  $c$  is the concentration = number of palynomorph grains per gram of dry sediment,  $g_c$  is the number of counted palynomorph grains,  $L_t$  is the number of *Lycopodium* spores/tablet,  $t$  is the number of tablets added to the sample,  $L_c$  is the number of counted *Lycopodium* spores, and  $w$  is the weight of dried sediment (g).

Most pollen and spores have been identified to the generic level according to common identification keys (e.g. Hesse et al., 2009; Moore et al., 1991; Punt and Hoen, 2009; Punt et al., 2007, 1976–2009). Ecological preferences have been adopted from recent literature (e.g. Ager and Phillips, 2008; Anderson and



**Figure 3.** Concentrations of terrestrial and aquatic palynomorphs and copepod eggs (number of grains per gram of dry sediment) in cores (a) ARA02B/01A and (b) HLY0501-05. Concentration of dinoflagellate cysts in core HLY0501-05 is expressed in number of grains per cubic centimeter of wet sediment (McKay et al., 2008). Note different horizontal scales used for some of the proxies for illustrative purposes.

Lozhkin, 2015; Edwards et al., 2000; Lozhkin and Anderson, 1995, 2011, 2013; Lozhkin et al., 2007). Freshwater algae (*Pediastrum* spp.) as well as marine (dinoflagellate cysts) and reworked palynomorphs were counted as indicators of fluvial discharge, marine environments, and allochthonous sediment inputs from the adjacent landmasses. Reworked palynomorphs were identified as described in earlier studies (e.g. Lopes et al., 2014; Utting et al., 2004). As an additional marine proxy, also counted were copepod eggs, which occur in considerable numbers in many samples along with palynomorphs.

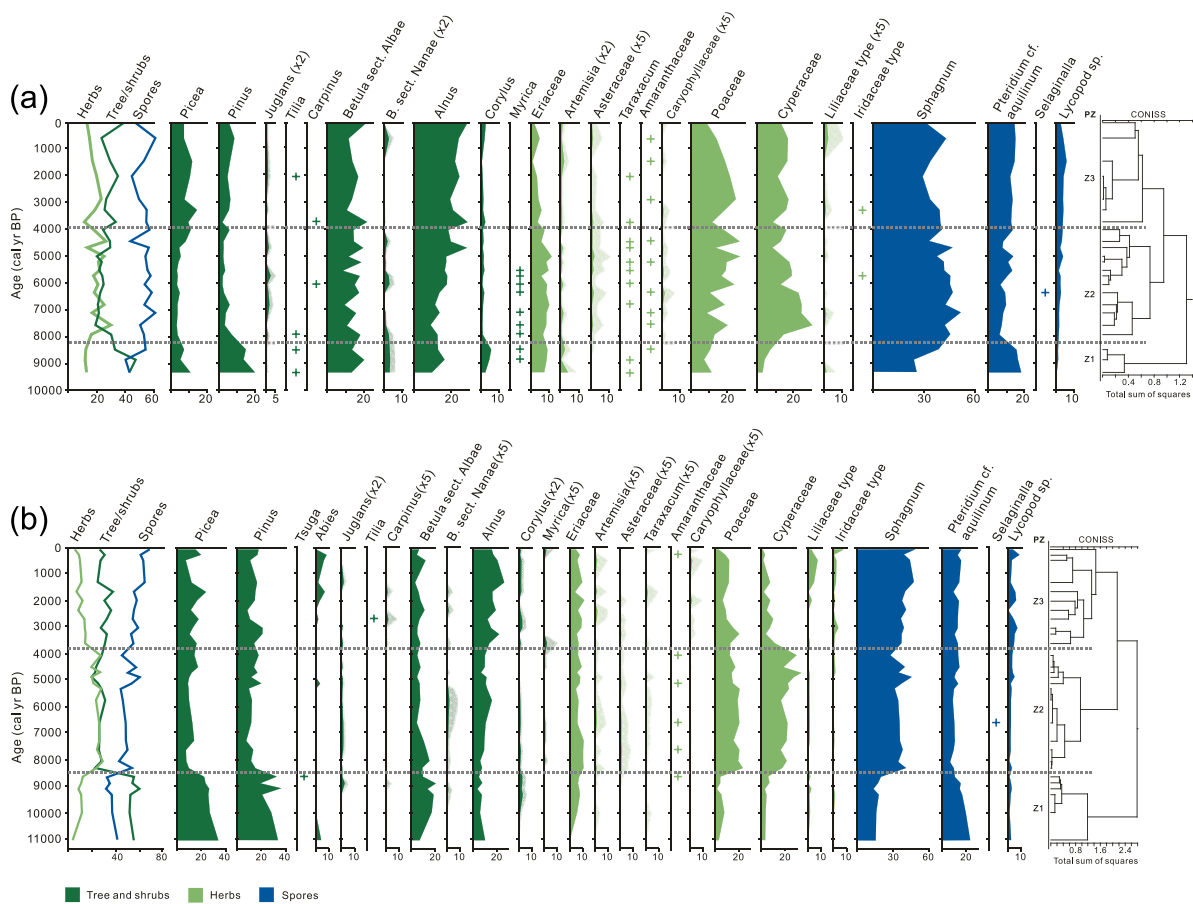
## Results

Concentrations of terrestrial pollen and spores, freshwater algae (*Pediastrum* spp.), and marine proxies (dinoflagellate cysts and copepod eggs) are shown in Figure 3. Concentrations of pollen and spores average  $\sim 3000$  and  $4000$  grains  $g^{-1}$  in ARA-1 and HLY-5, respectively. Detailed percentage diagrams of the down-core distribution of terrestrial pollen and spores are shown in Figure 4. Three palynological zones have been identified in both cores based on variability in percentages of pollen and spore taxa as well as concentrations of various groups of palynomorphs.

*Zone 1* is identified in the lower part of both cores corresponding to the early-Holocene ending at ca. 7900–8400 yr BP in ARA-1 and at somewhat older estimated age of ca. 8300–8600 yr BP in HLY-5 (Figures 3 and 4; Supplement 1, available online). This age difference may be related to uncertainties due to insufficient age control, especially in HLY-5, where  $^{14}C$  datings do not extend beyond ca. 7000 yr BP. A stratigraphically longer core HLY-5 shows that this zone is underlain by deglacial sediments, where only reworked ancient palynomorphs are present (McKay

et al., 2008). Pollen and spore concentrations in *Zone 1* are rather low in both cores with a total average of  $1000$ – $1900$  grains  $g^{-1}$ . Tree/shrub pollen contents show their highest values in this zone, up to  $\sim 50\%$  and  $60\%$  in ARA-1 and HLY-5, respectively. Most abundant are *Picea* and *Pinus* pollen reaching nearly  $30$ – $40\%$  each in HLY-5. *Betula* and *Alnus* pollen also have relatively elevated values. Spores are predominated by approximately equal percentages of *Sphagnum* mosses and *Pteridium* ferns. The bottom part of *Zone 1* is characterized by a remarkably high occurrence of reworked palynomorphs (nearly  $1500$  grains  $g^{-1}$  counted in ARA-1), which rapidly decrease in number up-core. This pattern is consistent with prior results showing  $\sim 3000$  reworked grains  $cc^{-1}$  wet sediment for deglacial sediments at  $\sim 14$  m in HLY-5 (McKay et al., 2008). Freshwater palynomorphs have very low concentrations or absent in *Zone 1* in both cores, while dinoflagellate cysts increase in abundance toward the top of the zone.

*Zone 2* has the largest sediment thickness in both cores, extending from the top of *Zone 1* to ca. 3600–3700 yr BP (Figures 3 and 4). Pollen and spore concentrations show a large increase in comparison to *Zone 1*, with a total average of  $3000$  and  $5000$  grains  $g^{-1}$  in cores ARA-1 and HLY-5, respectively. The highest numbers are mostly attained in the middle part of *Zone 2*, reaching nearly  $8000$  grains  $g^{-1}$  around  $7$  m (ca. 5000–6000 yr BP) in HLY-5. The increase in concentrations affects all groups of pollen and spores, but is especially prominent in grasses as expressed in their percentages rising to  $20$ – $30\%$ , approximately equal to tree/shrub pollen numbers, which become more abundant near the zone top. Major tree taxa are *Alnus* and *Betula* in both cores, with an addition of somewhat elevated contents of *Pinus* and *Picea* in HLY-5. Herb pollen are characterized by relatively high abundance of Poaceae and Cyperaceae, reaching  $20$ – $30\%$  each.



**Figure 4.** Pollen and spore percentage diagram for cores (a) ARA02B/01A and (b) HLY0501-05. Note percentage exaggeration used for some species for illustrative purposes.

*Sphagnum* mosses account for most of the increase in spore contents, while percentages of *Pteridium* ferns decline in comparison with Zone 1. Concentrations of reworked palynomorphs decrease radically in both cores to  $\sim 150$  grains  $g^{-1}$  in ARA-1 and  $\sim 300$  grains  $g^{-1}$  in HLY-5 on average, with slightly higher numbers in the lower part of the zone in HLY-5. Zone 2 is also characterized by a pronounced increase in concentrations of freshwater algae *Pediastrum* spp. that remain high and variable in both cores averaging at  $>5000$  and  $>14,000$  grains  $g^{-1}$  in ARA-1 and HLY-5, respectively. Dinoflagellate cyst numbers are strongly variable in HLY-5 (between  $\sim 1000$  and  $7000$  grains  $cc^{-1}$  wet sediment), but show a more gradual increase towards the zone top in ARA-1 from  $\sim 600$  to  $>1200$  grains  $g^{-1}$ . Copepod eggs increase up-core in both cores to  $\sim 400$  and  $\sim 300$  grains  $g^{-1}$  in ARA-1 and HLY-5, respectively.

Zone 3 extends from the top of Zone 2 to the core tops, corresponding to the last  $\sim 3600$  yr BP (Figures 3 and 4). Pollen and spore concentrations in both cores decrease in comparison with Zone 2 to a total average of  $\sim 3100$  and  $\sim 3200$  grains  $g^{-1}$  in ARA-1 and HLY-5, respectively. This decrease is especially expressed in concentrations of grass pollen. At the same time, changes in terrestrial palynomorphs composition are relatively subtle. Tree/shrub pollen has a somewhat higher content than herbs, with *Alnus* and *Betula* most abundant in ARA-1, and *Alnus*, *Picea*, and *Pinus* in HLY-5. Poaceae and Cyperaceae are still relatively abundant in ARA-1, and *Sphagnum* moss spores remain predominant in both cores. Reworked palynomorphs keep low numbers, with the lowest concentrations near the core tops. *Pediastrum* spp. concentrations also decrease notably in ARA-1 to  $<1000$  grains  $g^{-1}$ , while being consistently low in HLY-5 decreasing to  $\sim 4000$  grains  $g^{-1}$ . Dinoflagellate cyst concentrations are variable with an overall decreasing trend towards the core top. Copepod egg numbers

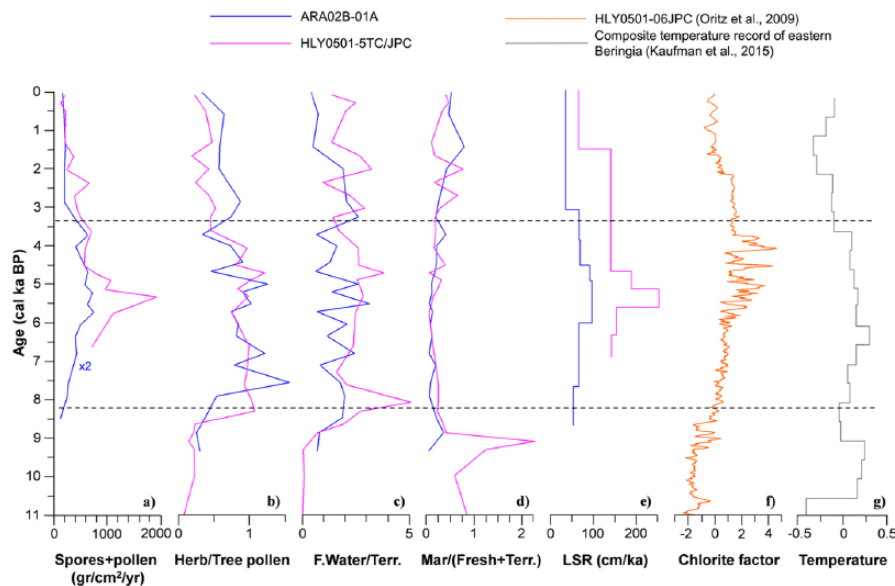
show an even more pronounced decline, preceded by a sharp increase to  $\sim 2000$  grains  $g^{-1}$  until 50 cm in ARA-1.

## Discussion

### General approach

Marine palynological data may render information on a combination of vegetational changes on adjacent lands and oceanic and/or atmospheric circulation history. For example, a record from the Laptev Sea margin, west of our study area (Figure 1), was interpreted in terms of changes in inputs from the large Siberian rivers and Holocene climatic variability (Rudenko et al., 2014).

Several distinctive palynological features can be identified in cores under study and provide insight on the nature of palynomorph assemblages and their depositional history. The composition of pollen and spores is overall fairly consistent throughout most of the record in both cores, while concentrations of various groups of palynomorphs change considerably (Figures 3 and 4). Furthermore, pollen and spore assemblages in these cores are much less diverse than in records from adjacent land areas (e.g. Anderson and Lozhkin, 2015; Lozhkin et al., 2001) or even from the Laptev Sea (Rudenko et al., 2014). In addition, a large part of the record (after ca. 8500 yr BP) is characterized by high numbers of freshwater algae *Pediastrum* spp., which is unusual for sites remote from large rivers. These features suggest that this palynological record reflects aggregation of palynomorphs from broad area including distant locations. This interpretation is consistent with the depositional environment in the Chukchi Sea that is primarily controlled by currents providing long-range transportation of fine particles, tracking as far back as the Bering Sea, and their considerable mixing prior to deposition (e.g. Darby et al., 2009; Faux et al., 2011; Polyak et al., 2016). Sea ice may also play a



**Figure 5.** Paleoclimatic and sedimentological context for palynomorphs in cores under study: (a) influx of terrestrial palynomorphs estimated from grain concentrations, linear sedimentation rates, and average wet sediment bulk density and water content (variations of the latter parameters are minor in the Holocene sediments); the curve for ARA02B/01A is exaggerated by a factor of 2 for illustrative purposes; (b) herb/tree pollen ratio; (c) freshwater/terrestrial palynomorph ratio; (d) marine/(freshwater + terrestrial) palynomorph ratio; (e) linear sedimentation rates; (f) percentages of chlorite in the mineral composition in core HLY0501-06JPC, indicating the Bering Strait Inflow strength (from Ortiz et al., 2009); (g) multi-proxy reconstruction of air temperature for the Alaskan region (standardized anomaly from the long-term average; from Kaufman et al., 2016).

significant role in transporting sediment from coastal areas along a considerable stretch of northern Alaska (Eicken et al., 2005). Input of material from the Siberian coast by way of the Siberian Coastal Current is possible, but its delivery to the northern Chukchi margin is unlikely. We note, however, that circulation patterns may have been different in the past because of changing paleogeographic settings such as glaciations and sea-level rise. Pollen transport by winds also cannot be excluded, particularly for the interval with high percentages of wind-blown pollen (e.g. *Picea* and *Pinus*) at the transition to the early-Holocene (Figure 4), which could have potentially originated from the taiga vegetation in the eastern Siberia and/or the North America (Martin, 1958; Tarasov et al., 2000). However, considering abundant freshwater palynomorphs and an overall low content of the coniferous-type pollen, a direct delivery of the palynomorphs by wind was unlikely significant.

In this depositional context, the interpretation of the palynological record under study must consider not only composition of vegetation, but also changes between palynomorph groups from different types of environment (terrestrial, freshwater, and marine), and a comparison with non-palynological features reflecting the history of sedimentation. To facilitate the interpretation along these lines, we show the downcore distribution of several palynological indices including the ratio of herb to tree pollen, freshwater to terrestrial palynomorphs, and marine to non-marine (freshwater plus terrestrial) palynomorphs (Figure 5; Supplement 1, available online). With some variations, similar characteristics have been used in marine palynological studies, such as a freshwater to marine palynomorph ratio, also known as a CD (chlorophycean to dinoflagellate cyst) index (Gusev et al., 2014; Matthiessen et al., 2000). In addition to concentrations per gram sediment shown in Figure 3, we estimated influx of terrestrial palynomorphs (spores and pollen) for both cores based on grain concentrations, linear sedimentation rates between the  $^{14}\text{C}$  age points, and average Holocene wet sediment bulk density and water content (Figure 5a). We also compare the distribution of palynomorphs with a mineral provenance record that has been interpreted as a proxy for the Bering Strait Inflow (chlorite factor; Ortiz et al., 2009). This proxy

record, developed on a core HLY0503-06JPC proximal to HLY-5, is now established also for both ARA-1 and HLY-5 (Yamamoto et al., 2015, personal communication; Yamamoto et al., 2016). To account for climatic factors affecting palynological composition at source areas, we use an air temperature curve from the state-of-the-art, multi-proxy paleoclimatic synthesis covering the Alaskan region (Kaufman et al., 2016). A similar proxy compilation yet needs to be developed for northeastern Siberia.

### Early-Holocene

The most prominent features of the early-Holocene (palynological Zone 1, prior to ca. 8000–8500 yr BP) is a very low abundance of terrestrial and freshwater palynomorphs, except for reworked, and a high relative content of tree pollen, not only spruce and pine trees, but also deciduous trees such as birches and hazel (Figures 3–5). This interval appears to broadly correspond to a variable but overall relatively warm period in Beringia during the late deglaciation to the earliest Holocene, ca. 13,000–9000 yr BP, with birch stumps dated to ca. 13,000 yr BP found as far north as the Wrangel Island (Anderson and Lozhkin, 2015; Kaufman et al., 2016 and references therein). However, there is no evidence for forests expanding close to the Beringian Arctic coasts since the early Pleistocene (Brigham-Grette and Carter, 1992). Furthermore, the expansion of trees to the coast would be expected to come along with an overall increased pollen numbers in sediments. Therefore, we infer that palynological composition in Zone 1 hardly represents natural changes in vegetation in adjacent land areas, but rather indicates enhanced redeposition associated with the late phases of the Laurentide ice sheet retreat and/or sea-level rise and the flooding of the Bering land bridge. This interpretation is consistent with very high numbers of clearly reworked palynomorphs, decreasing fast towards the top of Zone 1 (Figure 3). Even higher concentrations of reworked, pre-Quaternary palynomorphs characterize pre-Holocene, deglacial sediments in HLY-5 (McKay et al., 2008). Pollen assemblage with a high content of spruce and pine was also found in the bottom layers of two cores from the southern Chukchi Sea, interpreted as early Pleistocene deposits,

partially in-situ and partially redeposited during the postglacial flooding of the shallow shelf (Gusev et al., 2009).

Specific mechanism(s) of redeposition to the study sites could involve transport by meltwater, sea ice, or reworking of seafloor sediments. The absence of *Larix* pollen indicates a higher probability of North American and North Siberian sources over East Siberian (which could be potentially transported via the Anadyr River), while nearly absent freshwater palynomorphs make riverine inputs, such as from the Mackenzie River, unlikely. We note that Zone 1 formed during an incomplete sea-level rise and, thus, not fully open Bering Strait, combined with a possibility of meltwater accumulation on the Arctic side of the strait. This resulted in a likely diminutive inflow of Pacific waters, consistent with sedimentary proxy records (Figure 5) (Ortiz et al., 2009), and a high contribution of more local Arctic provenance including terrestrial material, such as from soils (Faux et al., 2011; McKay et al., 2008; Polyak et al., 2016).

The top part of Zone 1, after ca. 9000 yr BP, is characterized by a pronounced increase in the concentrations of terrestrial and freshwater palynomorphs (Figure 3) that is reflected notably in a sharp decline in a relative content of dinoflagellate cysts in core HLY-5 (marine to non-marine palynomorph ratio, Figure 5). This pattern, which continues into Zone 2 and is consistent with the trend of a chlorite factor, possibly indicates an intensification of the Bering Strait Inflow and an associated advection of material transported from the northern Bering Sea and/or winnowed from the shallow Chukchi shelf. The lack of a marine to non-marine ratio peak at the bottom of core ARA-1 may be related to spatial hydrographic differences or an imperfect correlation due to age uncertainties. We note that the age control for the bottom part of HLY-5, below the lowermost age point at ca. 7000 yr BP, is very tentative.

#### Middle- to late-Holocene

The continuing increase in terrestrial and freshwater palynomorphs resulted in a maximal content of *Pediastrum* in the lower to middle part of Zone 2, along with a pronounced increase in the percentages of herb pollen in the terrestrial spectra (Figures 3–5). The overall concentrations and influx of terrestrial palynomorphs also rise to maximum numbers after ca. 7000 yr BP, with an especially distinct peak in HLY-5 (Figures 3 and 5). These changes correspond to an increase in sedimentation rates in both cores, culminating at ca. 5000–6000 yr BP, and in chlorite content that shows the highest values between ca. 4000 and 6000 yr BP (Figure 5). Both sedimentation rates and the chlorite content have been shown to be related to the intensity of the Bering Strait Inflow and ensuing currents (Darby et al., 2009; Ortiz et al., 2009; Polyak et al., 2016). The concerted development of palynological and sedimentary proxies indicates that the palynomorph abundances could have also been controlled by changes in marine circulation. Accordingly, the characteristic composition of the palynomorph assemblage with high contents of *Pediastrum*, herbaceous pollen, and sphagnum spores may primarily reflect the southern Alaska provenance, including the Yukon River impact, and transportation via the Alaskan coastal current and the Bering Strait Inflow. Contribution from the Anadyr River on the Siberian side of the Bering Sea is unlikely because of the absence of *Larix* or Siberian pine pollen, which is consistent with the circulation pattern as the Yukon outflow is deflected eastwards after passing the Bering Strait. While *Larix* is generally rare in marine sediments because of its fragility, pollen assemblages in cores from the southwestern Chukchi shelf contain small amounts of Siberian pine, for a comparison (Gusev et al., 2009, 2014). The transport of material from the Yukon River discharge to the Chukchi–Alaskan margin is corroborated by the composition of organic matter in surficial sediment from this area that has a high

content of terrestrial biomarkers indicative of higher plants, as opposed to mostly soil-derived terrestrial component of high-Arctic rivers (Goñi et al., 2013).

The composition of terrestrial pollen and spores is common for forested or shrub tundra, but not for the tundra proper that presently occupies the high-Arctic coasts including the Chukchi Sea (e.g. Anderson and Lozhkin, 2015). This composition could indicate not only the long-distance transportation, presumably from southern Alaska and adjacent areas, but also simultaneous general increase in pollen and spore productivity because of more favorable climatic conditions for plant growth. Notably, a relative increase in herb pollen over trees suggests a probability of climatic amelioration, as herbs are generally less productive than trees. This inference is consistent with the synthesis of paleoclimatic proxy data from the Alaskan region that reveals a well-defined climatic optimum with overall relatively warm and dry conditions at ca. 4000–7000 yr BP (Figure 5; Kaufman et al., 2016). It is possible that by mid-Holocene time, after stabilization of sea level, and thus marine circulation, climatic factors started to play a bigger role in controlling palynomorph abundance and composition in sediments under study. However, our data cannot provide conclusive evidence regarding the relative contribution of hydrographic versus climatic factors.

The transition from Zone 2 to 3 is overall subtle but includes some visible changes that appear to be consistent between various palynological proxies. They include an overall decrease in terrestrial and freshwater palynomorph concentrations, a relative decrease of herb pollen, and an increase in dinoflagellate cyst numbers (Figures 3–5). The composition of terrestrial palynomorph assemblages in Zone 3, with relatively diminished content of herbs and elevated elder, is closer to the shrub tundra vegetation common for the Arctic coasts today, and could be related to cooler regional climate established after ca. 5000 yr BP (Kaufman et al., 2016). However, the changes between Zones 2 and 3 also co-occur with a decrease in sedimentation rates and in the chlorite factor load, possibly indicating a decrease in the strength of the Bering Strait Inflow and related currents affecting the study sites. Higher dinoflagellate cyst abundances may also reflect changes in the hydrographic structure, which could affect biological production. Accompanying changes in dinoflagellate cyst assemblages in HLY-5, such as an increase in the content of *Pentaparsodinium dalei* cysts starting from ca. 5000 yr BP, have been tentatively associated with warmer temperatures (McKay et al., 2008). However, this inference is inconsistent with a contemporaneous climatic cooling (Kaufman et al., 2016) and a decrease in Pacific water inflow (Ortiz et al., 2009). An alternative interpretation may invoke increased primary production, but this issue requires further investigation. Copepod eggs also reach highest numbers in Zone 3 but then decrease in abundance after a peak at ~3000 yr BP in HLY-5 and ~1000–1500 yr BP in ARA-1, but the controls on their distribution are unknown.

## Summary and conclusion

Two sediment cores providing a century to multidecadal Holocene record from the Chukchi–Alaskan margin, from water depths of 111 and 415 m, were analyzed for palynomorph composition. Both cores have a similar pattern of palynomorph distribution with relatively little variability, which suggests a strong impact of sediment mixing prior to deposition. Long-term changes in marine and terrestrial palynomorph assemblages show a distinct pattern, potentially controlled by sediment transport and redistribution by cross-shelf currents originating from the Bering Sea, combined with climatic changes in the Chukchi–Alaskan region. Palynological Zone 1 identified in the lower part of the Holocene record (older than ca. 8000–8600 yr BP) is characterized by very low inputs of contemporaneous



palynomorphs, but enhanced redeposition, probably associated with the late phases of the Laurentide ice sheet retreat and/or sea-level rise. A lack of freshwater palynomorphs indicates a prevalence of terrestrial sources, such as soils distributed by meltwater or sea ice, over riverine supply. In contrast, Palynological Zone 2 shows high numbers of both terrestrial and freshwater palynomorphs culminating at ca. 5000–6000 yr BP, along with a maximum in sedimentation rates. This increase in sediment inputs is related to the intensification of the Pacific water inflow via the Bering Strait, consistent with mineral provenance data (Ortiz et al., 2009, 2012). In addition to marine circulation factors, high numbers of palynomorphs along with a high relative content of herb pollen may be related to mid-Holocene climatic amelioration, consistent with paleoclimatic data from the Alaskan region (Kaufman et al., 2016). The transition to Palynological Zone 3 at ca. 4000 yr BP is characterized by relatively subtle changes in terrestrial palynomorph composition and increase in the number of dinoflagellate cysts, possibly reflecting changes in the hydrographic structure and, thus, biological production. Terrestrial spore/pollen assemblages in the late-Holocene are quite similar to the shrub tundra vegetation common for the Arctic coasts today, but the linkage of palynomorph changes in the sediment record to climate is not clear. Overall, we infer that sediment transport and redistribution played the primary role in shaping the palynomorph assemblages in sediments under study. Climatic conditions may have also affected palynomorph abundance and composition, especially in the middle- to late-Holocene, when the effects of marine circulation on sediment deposition at the Chukchi–Alaskan margin were not as dramatic as during the flooding of the Bering Strait and adjacent shallow Chukchi Sea shelf.

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