Recent and Holocene climate change controls on vegetation and carbon accumulation in Alaskan coastal muskegs

Dorothy M. Peteet [a, b, *], Jonathan E. Nichols [b], Christopher M. Moy [c], Alicia McGeachy [d, 1], Max Perez [e]

[a] NASA Goddard Institute for Space Studies, New York, NY, USA
[b] Lamont-Doherty Earth Observatory, Palisades, NY, USA
[c] Geology Dept., University of Otago, PO Box 56, Dunedin, New Zealand
[d] Spelman College, Atlanta, GA, USA
[e] Binghamton University, Binghamton, NY, USA

ARTICLE INFO

ABSTRACT

Pollen, spore, macrofossil and carbon data from a peatland near Cordova, Alaska, reveal insights into the climate–vegetation–carbon interactions from the initiation of the Holocene, c. the last 11.5 ka, to the present (1 ka = 1000 calibrated years before present where 0 = 1950 CE). The Holocene period is characterized by early deposition of gyttja in a pond environment with aquatics such as *Nuphar polysepalum* and *Potamogeton*, and a significant regional presence of *Alnus crispa* subsp. *sinuata*. Carbon accumulation (50 g/m^2/a) was high for a short interval in the early Holocene when *Sphagnum* peat accumulated, but was followed by a major decline to 13 g/m^2/a from 7 to 3.7 ka when Cyperaceae and ericads such as *Rhododendron* (formerly *Ledum*) *groenlandicum* expanded. This shift to sedge growth is representative of many peatlands throughout the south-central region of Alaska, and indicates a drier, more evaporative environment with a large decline in carbon storage. The subsequent return to *Sphagnum* peat after 4 ka in the Neoglacial represents a widespread shift to moister, cooler conditions, which favored a resurgence of ericads, such as *Andromeda polifolia,* and increased carbon accumulation rate. The sustained *Alnus* expansion visible in the top 10 cm of the peat profile is correlative with glacial retreat and warming of the region in the last century, and suggests this colonization will continue as temperature increases and ice melts.

Published by Elsevier Ltd.

1. Introduction

Peatlands store up to one third of the global soil carbon (C) pool, are abundant at high latitudes where climate change is strongly felt, and are particularly sensitive to climate shifts (Gorham, 1991; MacDonald et al., 2006). Quantifying future shifts in C sequestration as climate warms is challenging because warmer temperatures foster both increased production and decomposition (Gorham, 1991). However, not surprisingly, biota has been shown to play a decisive role in controlling peatland C dynamics at the species, community, and ecosystem levels (Kuiper et al., 2014). Thus, exploring the relationship between carbon accumulation rate (CAR), the net storage after production and decomposition, and detailed vegetational shifts that cause these peatland C storage changes can help us to predict future carbon stores as climate-driven vegetational shifts occur. In particular, Alaska is projected to have increased precipitation in a warming world (Christensen et al., 2007), and the maritime south-central coast is a region that today already receives abundant moisture, providing a key analog as a region warmer and wetter than much of the rest of the boreal and Arctic zones. This region is also of interest because it has active glacial recession (Wiles et al., 2014), and represents a spatial gap in our southern coastal study of peatland paleovegetation and carbon (Peteet, 1986, 1991; Peteet and Mann, 1994; Jones et al., 2014; Nichols et al., 2014). In addition, the AMS C-14 dates on *Picea* and *Tsuga* macrofossils provide a robust record of conifer migration northward in a changing Holocene climate.

Paleoecological studies in maritime coastal Alaska take advantage of abundant peatlands. The Algonquins first referred to these peatlands as "muskeg," a term used extensively by Rigg (1914), Dachnowski-Stokes (1941), and Heusser (1960). These soligenous,

topogenous, and ombrogenous muskegs are adjacent to active glaciers, where processes of active glacial advance and retreat occur on human timescales (Tarr and Martin, 1914). Previous pollen and spore studies along this coastline provide a stratigraphic archive of vegetational shifts resulting from both climate change and tree migration (Heusser, 1960, 1983; Heusser et al., 1985; Peteet, 1986, 1991). Macrofossils provide detailed, site-specific records of *in situ* response to moisture that can be reliably dated and then compared with nearby lake and peatland records (Peteet, 1986, 1991).

For Corser Bog, south-central Alaska, Nichols et al. (2014) produced an independent record of hydroclimate and temperature change using the distributions and hydrogen isotope ratios of leaf wax biomarkers and the distributions of branched glycerol dialkyl glycerol tetraether lipids (brGDGTs). We found that relative changes in reconstructed temperature in the peatland are broadly correlative with changes in glacial ice extent documented for south-central Alaska. We also examined the role of carbon storage with change in peat type in Corser Bog, and found a marked increase in carbon storage when *Sphagnum* peat was present compared to sedge peat. However, more detailed vegetational history was lacking. Pollen, spores, and macrofossil identification here will reveal detailed vegetation shifts and attendant climatic inferences, which we can then compare to those made from organic geochemical data.

2. Study site

The Copper River Delta is one of the largest coastal wetlands on the Pacific coast, extending some 200 km from Hinchinbrook to Kayak Island in southeast Alaska. Sandwiched between the Delta and the Chugach Mountains, Corser Bog (Fig. 1) at 42 m asl is located in the gently sloping peatland area between Cabin Lake and Corser Lake, about 21 km east of the town of Cordova, AK. Today the peatlands are very open landscapes, dominated by *Sphagnum* moss, *Carex*, *Andromeda polifolia*, *Gentiana douglasiana*, and surrounded by the three dominant conifers − *Picea sitchensis*, *Tsuga heterophylla*, and *Tsuga mertensiana*.

Underlying the peatlands are Paleogene sedimentary rocks (Winkler and Plafker, 1993). The entire area endures repeated subsidence and uplift (Plafker et al., 1993) and was uplifted 2 m during the 1964 earthquake (Plafker, 1969). This extremely dynamic tectonic regime presents an unusual background for the vegetational and climate history of the region, as it is possible that rapid uplift of the coast might provide colonization territory for vegetational pioneers such as ferns, *Alnus viridis* subsp. *sinuata* (formerly *Alnus crispa*), and migrating conifers.

Climate of the region is maritime, with moderate temperatures (avg. 3.5 °C with −4.1 °C in January and 12.5 °C in July) and abundant precipitation in the form of rain (2.3 m) and snow (3 m) according to records from the nearby Cordova airport (Leslie, 1989; usclimatedata.com). Precipitation falls throughout the year, but September and October usually record peak values.

The modern vegetation is comprised of coastal conifers (*Picea sitchensis* (sitka spruce), *Tsuga heterophylla* (western hemlock), and *Tsuga mertensiana* (mountain hemlock) along with blanket muskeg. *Picea sitchensis* is largely coastal, *Tsuga heterophylla* prefers more organic soils, and *Tsuga mertensiana* thrives mostly farther from the coast and at timberline, with extensive growth of ferns, such as *Athyrium filix-femina* subsp. *cyclosorum*, in avalanche tracks (Heusser, 1960). A study of early successional dynamics by Lutz (1930) documents the rapid invasion of *A. crispa* var. *sinuata* along with *P. sitchensis* and *T. mertensiana* on the Sheridan glacier outwash. He mentions *Lupinus* and *Equisetum* along with mosses as early colonizers. Cooper (1942) provides a complete account of the

forelands of nearby Prince William Sound. Muskeg is interspersed there with shallow lakes and conifer forest, and the muskeg flora is comprised of *Sphagnum* moss as well as herbs such as *Scirpus caespitosus*, *Carex pauciflora*, *Cornus canadensis*, *Geum calthifolium*, *Empetrum nigrum*, *A. polifolia*, *Oxycoccus microcarpus*, and *Drosera rotundifolia*. Hollows in the muskeg support a few aquatics and emergents, such as *Nuphar polysepalum* (water lily) and *Myrica gale* var. *tomentosa*. Alpine tundra extends over a large part of the district between timberline and the glaciers, and strand-dune communities are continuous along the coast.

3. Methods

Two cores were extracted from the Corser peatland with a 10-cm diameter, tripod-mounted modified Livingstone piston corer in five successive drives for each. They were wrapped in plastic food wrap and aluminum foil, refrigerated, and stored at Lamont Doherty Earth Observatory (LDEO). Core B, 3.72 m in depth, was chosen for analysis. Core A showed similar stratigraphy, but was approximately 0.5 m shorter. The core was split and imaged in the LDEO respository with a Geotek linescan camera, and samples taken for loss-on-ignition (LOI) at 2-cm intervals throughout, dried at 100 °C to estimate moisture content and then burned at 550 °C for 2 h using standard procedures (Dean, 1974). LOI and bulk density measurements were multiplied to calculate ash-free bulk density. Carbon content was calculated from the ash-free bulk density by multiplying by 0.423 in *Sphagnum* peat and 0.511 in sedge peat (Loisel et al., 2014).

Samples for pollen and spore analysis (1 cm^3) were taken every 1 (upper 10 cm), 5 or 10 cm throughout the core, and extraction followed a modified Faegri and Iverson (1989) methodology involving KOH, acetolysis, ethanol and tertiary butyl alcohol washes, and immersion in silicone oil. 1 tablet of marker *Lycopodium* spores (x = 10,679) was added to each sample. Identification was performed at 400X magnification with a minimum of 300 terrestrial pollen grain counts. Fossil spores were counted in addition to the 300 pollen grain sum, and spores are plotted as percentage of the pollen and spore sum. All grains were identified using the LDEO modern reference collection from south-central Alaska as well as published pollen references (Hebda, 1979; Faegri and Iverson, 1989). Contiguous macrofossil samples were selected every 5 cm or 10 cm (20 cc), wet-sieved using screens of 125 and 500 microns, and the residue picked in water at magnification of 20-60X. Reference material from Alaska, including an extensive seed collection, aided identification. All pollen and macrofossil data were plotted in Tiliagraph (Grimm, 1992).

Statistical analyses were performed using the R statistical computing environment (R Core Team, 2014). To reduce the dimensionality of the paleoecological data and define groups of similar samples, principal components analysis by singular value decomposition was performed on the pollen and spore dataset using the function prcomp(). A hierarchical cluster analysis by Ward's method was also performed on a Euclidean distance matrix of the pollen and spore data using the functions dist() and hclust(). We chose this method of clustering our data rather than the traditional, incremental sum-of-squares, depth-constrained method (Grimm, 1992). Our goal was not necessarily to identify shifts in vegetation composition alone, but to group similar samples together, irrespective of their stratigraphic position. Our analysis thus looks for similarities rather than differences. The ecological implication of using this method is that we do not assume that the vegetational assemblage always changes to a new state and we allow the system to shift back to a vegetational assemblage whether or not that assemblage had previously occupied the site.
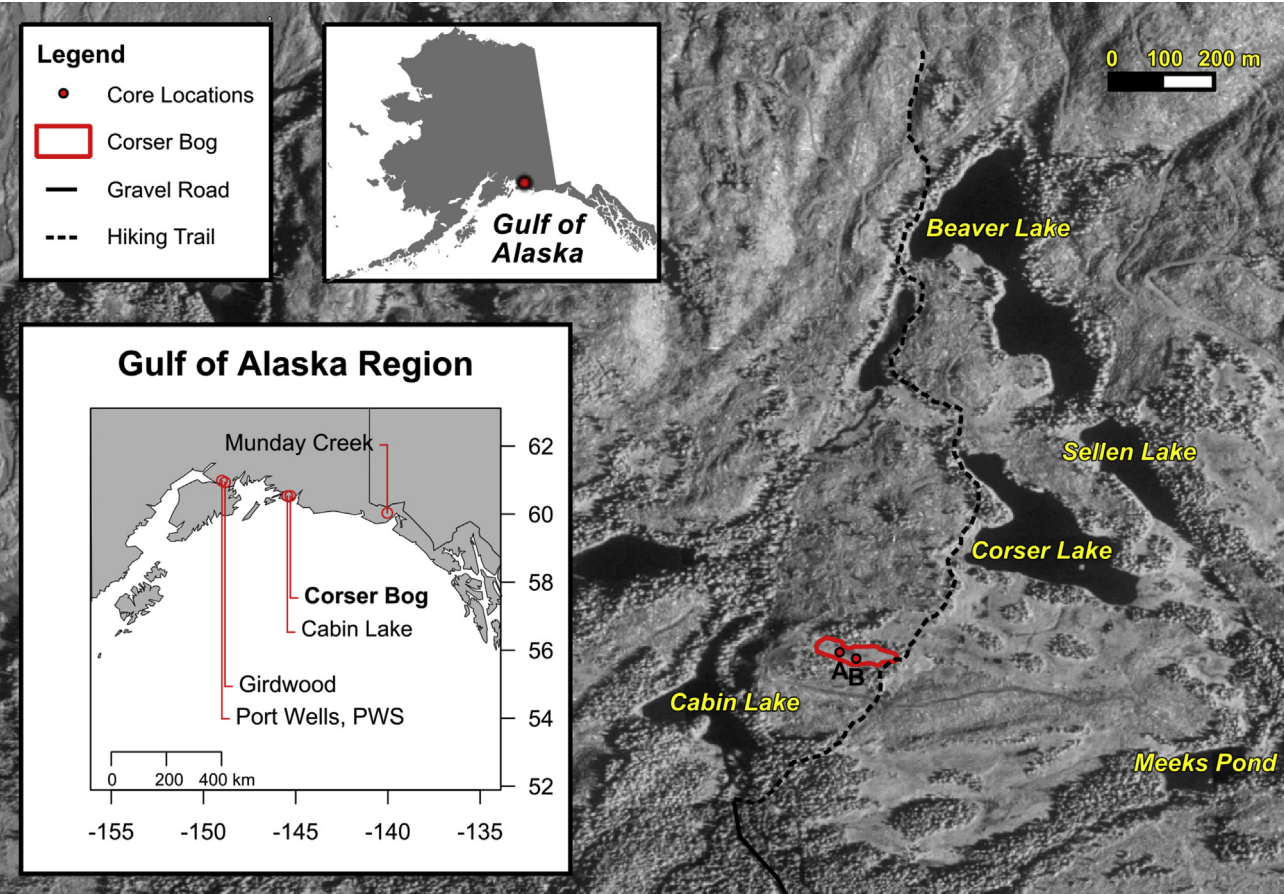
Fig. 1. Orthophoto of the region near the Sheridan Glacier containing Corser Bog. An outline of the peatland (determined by walking the perimeter with a GPS device) and hydrographic features (ADNR, 2007) are overlain on the orthophoto raster. Inset shows nearby paleoecological studies on the south-central coast of Alaska. Two cores were extracted, and Core B was used for this investigation.

3.1. Chronology and sedimentation rates

The core chronology was determined by 14 AMS radiocarbon dates on identified terrestrial macrofossils (Table 1, Fig. 2) also utilized for Nichols et al. (2014). Dated material was selected from the macrofossils and then pretreated with an Acid-Alkali-Acid chemical digestion prior to combustion, graphitization, and measurement by accelerator mass spectrometry (AMS) at the National

Table 1 AMS C-14 dates from selected macrofossils, Corser Bog, Alaska.

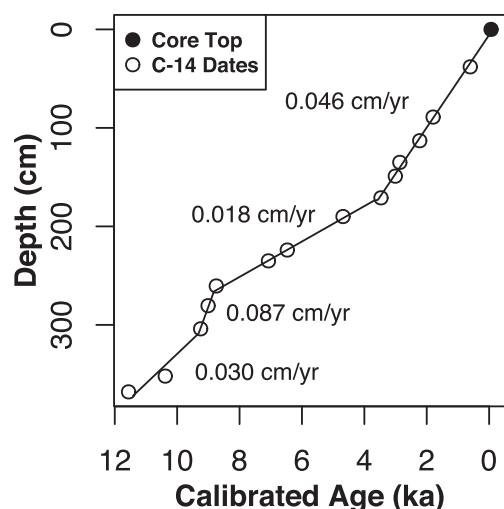| Lab code	Core depth (cm)	^{14}C date (yr BP)	Age error (yr)	Material dated	Calibrated age (cal yr BP)	2σ Calibration uncertainty lower and upper	
OS-86052	38	585	50	*Sphagnum* stems, 4 twigs	605	537	567
OS-86053	89	1860	60	*Sphagnum* stems with leaves	1796	1719	1870
UCIAMS-119399	113	2240	30	*Tsuga* twig	2224	2159	2173
OS-86051	135	2770	50	12 *Picea* needles, 15 *Tsuga m.* needles, 2 *Tsuga h.* needles	2863	2789	2928
OS-86200	149	2880	50	1x calyx, 4x *Tsuga* twig tip, 3x *Picea* needle fragments, 1x *Tsuga mertensiana* needle with base, 3x *Picea* needle tip fragments	3008	2895	2901
UCIAMS-119400	171	3255	15	Cyperaceae stems, Ericaceae twig	3467	3409	3425
OS-93485	190	4140	70	Twigs, bark	4684	4537	4541
OS-87440	224	5690	70	Twig fragments	6470	6400	6566
OS-86179	235	6170	80	Twig, twig fragment	7074	6949	7169
UCIAMS-119401	260.5	7930	40	*Sphagnum* stems	8746	8638	8793
UCIAMS-119402	280.5	8075	40	*Sphagnum* stems	9009	8988	9028
OS-86054	304	8260	80	Twig	9247	9092	9105
OS-86055	352	9220	100	*Alnus* bracts and cone scale	10,382	10,248	10,514
OS-93450	368	10,050	35	3 *Nuphar* seeds, 1 *Empetrum* leaf, 2 *Sphagnum* branches	11,558		

Fig. 2. Age-depth plot and sedimentation rates from Corser Bog, also used in Nichols et al. (2014). Four linear functions through the median calibrated ages calculated Calib 6.1.0 and Intal 13 were used to distribute age throughout the core. Changes or breaks in slope of the age depth model coincide with observed changes in peat vegetation type.

Ocean Science AMS facility (NOSAMS, Woods Hole, MA) or the facility at University of California, Irvine (UCIAMS). Dates were calibrated to the IntCal13 calendar age scale using Calib 6.1.0 (Stuiver et al., 2013), and reported as calibrated years before AD 1950. The core was collected in July 2010 and the top of the core therefore assigned an age of −60.

4. Results

The age-depth model is comprised of four linear sections (Fig. 2) and intersections of age/depth sections generally coincide with shifts in stratigraphy (Fig. 3). Highest sedimentation rates (0.087 cm/a, 0.046 cm/a) occur in the 9.2–7.6 ka and 3.7 ka to present (Fig. 2) intervals of the core, whereas lowest rates are present when the site is initially a shallow pond (0.030 cm/a) and a sedge fen (0.018 cm/a) between 7.6 and 3.7 ka.

4.1. Stratigraphy, LOI, and carbon accumulation rate, $g/m^2/yr$ (CAR) (Fig. 3)

Corser Bog sediments initially are low in organic matter, ranging from less than 40% organic in the basal pond sediments to above 80% in overlying gyttja, then consistently above 90% when the matrix is dominated by *Sphagnum* at about 300 cm depth at 9.2 ka. This *Sphagnum* peat remains very high (90–95%) in organic matter, then dips to between 80% and 90% from 245 to 175 cm, between 7.6 and 3.7 ka. The upper 175 cm of the core records LOI ranging close to 90%, but several low values suggest cryptic tephras or atmospheric dust deposition. CAR (Fig. 3) range from a median of 14 g/m^2/a in the limnic zone to highest rates (50 g/m2/a) in the overlying early Holocene *Sphagnum* zone, with the median at 27 g/m^2/a. The subsequent transition to sedge peat marks the lowest rates of the entire core at median CAR 7.5 g/m^2/a, followed by a median of 13 g/m^2/a in the overlying sedge peat. Finally, the upper *Sphagnum*-dominated upper peat has a median CAR of 20 g/m^2/a, which we note (Nichols et al., 2014) is consistent with plot studies suggesting *Sphagnum* is more efficient than sedge at storing carbon (Kuiper et al., 2014).

The role of vegetation in carbon accumulation is an intriguing one. *Sphagnum* plays an important role as an ecosystem engineer (Kuiper et al., 2014), and produces a highly decay-resistant litter,
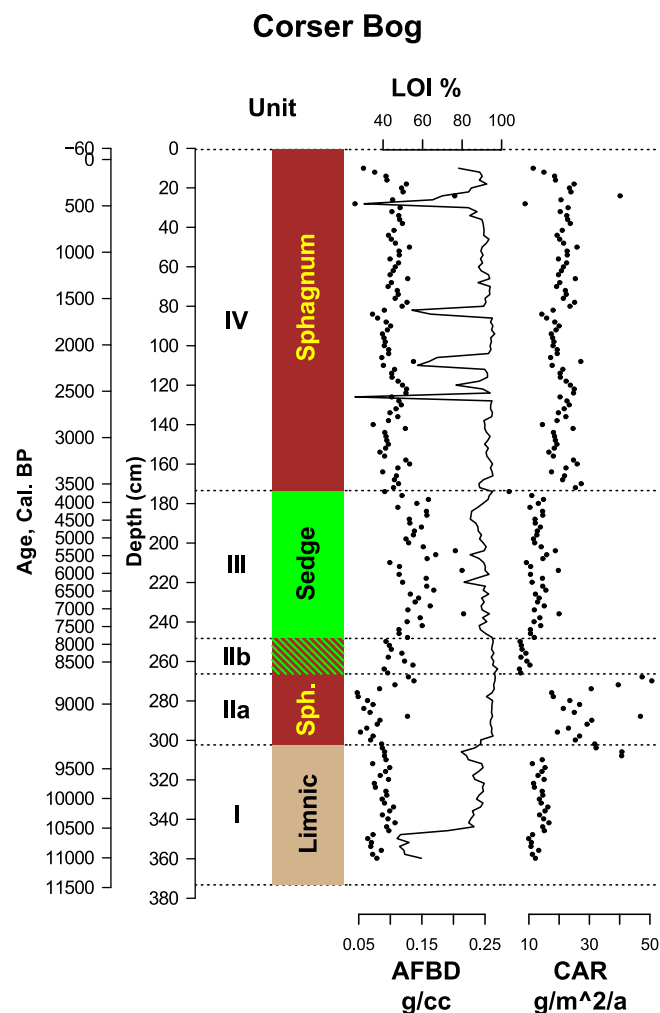

Fig. 3. Lithology, Loss-on-ignition (LOI), Ash-free bulk density (AFBD) and Carbon Accumulation Rate (CAR) (g/m^2/a) from the Corser Bog core.

rich in polyphenols (Bragazza and Freeman, 2007). While most northern peatland studies agree with our findings that *Sphagnum* peat results in higher CAR than sedge peat (e.g., Tolonen and Turunen, 1996; Jones et al., 2014), others find the opposite (e.g., Lacourse and Davies, 2015). Whether or not these exceptions are due to the *Sphagnum* and sedge species differences, or to other peat formers, such as brown mosses, deserves additional study.

4.2. Pollen, spore and macrofossil analysis groupings and zonation (Figs. 4–8)

Zones that were first visually identified in the pollen stratigraphy (Fig. 4) were verified using PCA and cluster analysis (Fig. 5). Two subzones (Zone CB-2b, Zone CB-3b) were added based on appearance/disappearance of ecologically important but low abundance taxa. Clusters identified in Fig. 5 are shown with CAR in Fig. 6. The pollen/spore zonation was then applied to the macrofossil stratigraphy (Fig. 7) and ricaceae size (Fig. 8). Detailed descriptions of each zone follow.

We used the results of the principal component analysis (PCA) and hierarchical cluster analysis to identify groupings of samples (Fig. 5). Both analyses were used to divide samples into 5 groups, four of which were stratigraphically contiguous. Boundaries between stratigraphically contiguous groups were consistent with
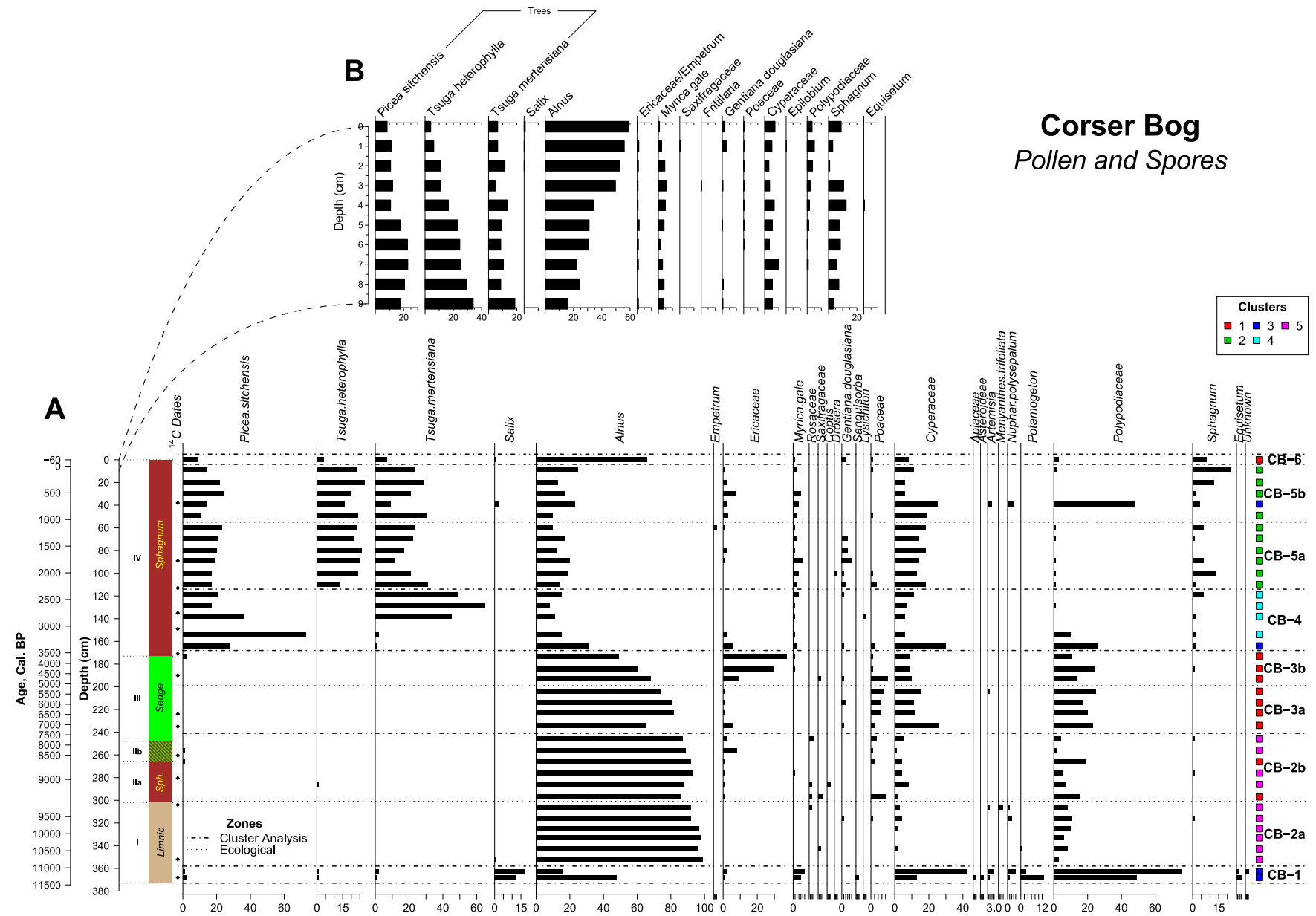
Corser Bog

Pollen and Spores

Fig. 4. A: Pollen and spore percentage diagram from Corser Bog, Alaska. Clusters resulting from PCA and hierarchical cluster analysis (Fig. 5) are noted at the right of the diagram. B: Pollen and spore percentage diagram from upper 10 cm of Corser Bog, Alaska, representing 1846 CE to present.
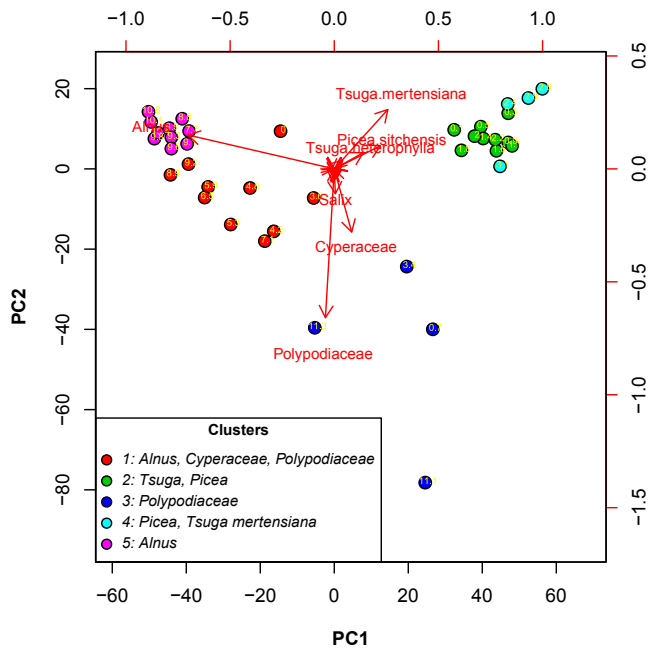
Fig. 5. PCA and hierarchical cluster analysis resulted in five clusters using Ward's method. Group 1 (red) samples are dominated by *Alnus*, Cyperaceae, and Polypodiaceae. Group 2 (green) represent those dominated by *Tsuga* and *Picea*. Group 3 (dark blue) are characterized by large percentages of Polypodiaceae. Group 4 (cyan) are domininated by *Picea* and *Tsuga mertensiana*, and Group 5 (purple) by *Alnus*. Numbers in the circles indicate the age of the sample. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
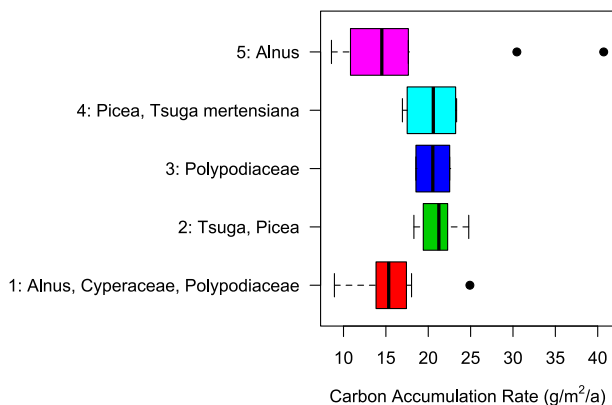

Fig. 6. Groups identified in PCA and hierarchical cluster analysis identified with CAR for each group.

visually identified pollen zones. Samples in Group 1 are dominated by *Alnus*, Cyperaceae, and Polypodiaceae and correspond with Zone CB-3, except for the uppermost sample, which is also *Alnus*-dominated. *Picea* and both species of *Tsuga* dominate Group 2 samples and fall within with Zone CB-5, while *Picea* and *Tsuga mertensiana* only dominate Group 4 samples (Zone CB-4). Group 5 is *Alnus* dominated and corresponds with Zone CB-2. Both samples in Zone CB-1 fall in this Group 3, along with two other samples where Polypodiaceae spores are dominant. Groups are shown with CAR in Fig. 6.

4.3. Zone CB-1, (11.6–11 ka, 368–360 cm depth)

Zone CB-1 encompasses the earliest Holocene, which at this site

is dominated by the greatest values of *Salix* (15–20%), Cyperaceae (42%), Polypodiaceae (80%) and *Artemisia* (5%) throughout the core, along with substantial *Alnus* (above 40%) and aquatics such as *Nuphar* and *Potamogeton*. Traces of the three conifer pollen types are present.

4.4. Zone CB-2a, (c. 11–9.2 ka, 360–305 cm depth)

In this zone, *Alnus* pollen is maximal with values reaching between 90 and 98%. Polypodiaceae values average around 10%, and aquatics (*Nuphar, Potamogeton*, bryozoan statoblasts) continue to be present. Macrofossils include abundant *A. viridis* subsp. *sinuata* leaf fragments, male cones, female cone bracts, and seeds. *A. polifolia* seeds are visible, along with a single *A. polifolia* leaf, and several shrub macrofossils such as *Rubus spectabilis*.

4.5. Zone CB-2b, (9.2–7.6 ka, 305–245 cm depth)

Zone CB-2b is characterized by *Alnus* values greater than 80%, and the initiation of a record of peatland types such as large size Ericaceae (greater than 35 microns), *Myrica*, Rosaceae (possibly *Geum*), *Drosera,* and *Sanguisorba* pollen along with values of Cyperaceae up to 10%. Polypodiaceae are consistently 10–15% in this zone and pollen concentration is sometimes relatively low as indicated by large numbers of exotic marker *Lycopodium*. Macrofossils are conspicuously absent excepting *Sphagnum* leaves throughout, sparse *Viola* seeds, and *Drepanocladus* sp. at the transition from CB-2a to CB-2b.

4.6. Zone CB-3, (7.6–3.8 ka, 245–175 cm depth)

Zone CB-3a is characterized by a dense matrix of sedge stems, nodes, and roots, unique to this core. *Alnus* values begin to decline slightly (70–80%), while Cyperaceae pollen increases up to almost 0%, and Polypodiaceae increases as well. Poaceae steadily increases, while Ericaceae declines. The sole macrofossils consist of 3 *Carex* seeds and 2 *Andromeda* seeds and *Sphagnum* leaves at the transition from below.

In Zone CB-3b, Ericaceae increases to maximal values for the core (30–40%) along with declines in Cyperaceae. The small sized Ericales pollen (19–31 micron, Fig. 8) appears to be *Rhododendron* (formerly *Ledum*) *groenlandicum*, based upon Hebda's (1979) and Warner and Chinnappa (1986) size measurements for species in the region. Notably, no macrofossils are present in this zone.

4.7. Zone CB-4, (3.8–2.4 ka, 175–117 cm depth)

Picea sitchensis pollen sharply increases from about 5% at the base of the zone to over 25%, doubles to greater than 60%, then subsequently declines and remains close to 20% for the remainder of the zone. *Picea sitchensis* needles gradually increase, reaching maxima of 40 needles when pollen peaks at 70%, and then are sporadically present. *Tsuga mertensiana* pollen remains less than 5% until about 3000 ka and then dramatically increases to greater than 50%, matched by maximum numbers of needles. *T. mertensiana* pollen declines to roughly 20% as *T. heterophylla* pollen increases and remains about 20%. Cyperaceae and Polypodiaceae both decline.

4.8. Zone CB-5, (2.4–0.9 ka, 117–10 cm depth)

This zone is marked by the initial and then sustained appearance of *Tsuga heterophylla* pollen, along with *Picea* and *T. mertensiana*. Increasing percentages of Ericaceae tetrads greater
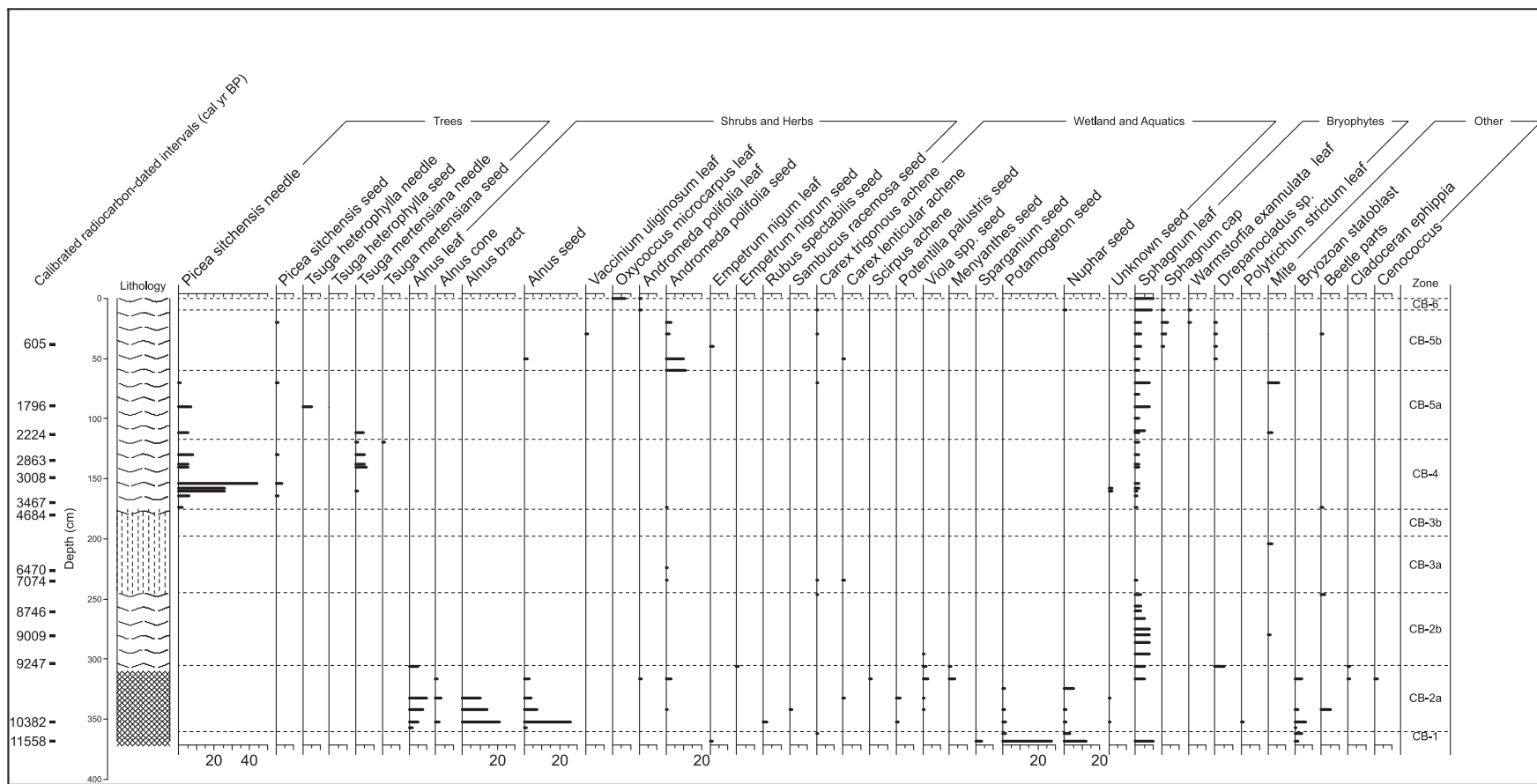
Fig. 7. Macrofossil stratigraphy from Corser Bog, Alaska, presented as macrofossils/20 cc sample.
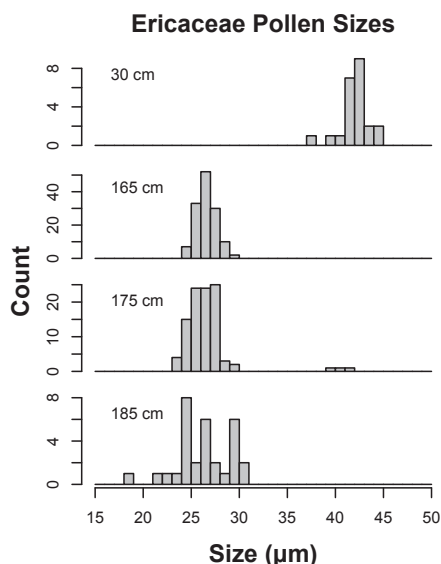
Ericaceae Pollen Sizes

Fig. 8. Ericaceae tetrad pollen size counts at various intervals in the Corser Bog core. Larger size tetrad pollen (40—45 micron) is likely *Andromeda polifolia*, typical of wet habitats and low pollen production, while smaller size (20—31 microns) tetrads are most likely *Rhododendron groenlandicum* (formerly *Ledum*), typical of dry habitat with high pollen production (Hebda, 1979).

than 35 microns (Fig. 8) pollen are matched by *A. polifolia* seeds in subzone CB-5b and the re-appearance of aquatic taxa pollen (*Nuphar, Potamogeton*). One sample includes relatively high *Alnus* pollen and very high Polypodiaceae spore counts. *Sphagnum* spores increase in the upper part of the zone, *Warnstorfia exannulata* and *Drepanocladus* sp.are also present.

4.9. Zone CB-6, (1921 − AD 2011, 10−0 cm depth)

A return to *Alnus* percentages of 60% characterized one point zone at the surface (AD 2011) but 9 additional counts reveal the gradual rise in the last century, concurrent with the decline of tree pollen. *Oxycoccus microcarpus* leaves are present, along with abundant *Sphagnum* leaves.

5. Discussion

5.1. Early Holocene (11.5—9.2 ka)

The LOI data and the pollen, spore, and macrofossil stratigraphy reveal major shifts in vegetation and climate throughout the Holocene. The earliest assemblages portray a shallow pond with aquatic vegetation (*Nuphar polysepalum* and *Potamogeton* sp. pollen and seeds, *Sparganium hyperboreum* seed), low organic matter, and relatively high *Salix* and *Alnus* on the newly deglaciated landscape. *Empetrum, Epilobium*, and *Artemisia* attest to the open, treeless environment, but the presence of Polypodiaceae in the region suggest some warmth and moisture in contrast to interior sites where ferns are rare (Hulten, l968). Comparative coastal sites in south-central to southeastern Alaska reveal similar representation of this Polypodiaceae pioneer in the late-glacial (Heusser, 1960, 1983; Peteet, 1991; Ager, 2007). In coastal Kodiak Island (Peteet and Mann, 1994), the late-glacial record includes some ferns, but also reveals a "fern gap" during the Younger Dryas, which is interpreted as a cooler, drier climate. Similar to the timing of our late-glacial record, nearby Cabin Lake, about 0.5 km westward, has a basal age a bit younger at 11.2 ka (Zander et al., 2013). Further to the west, Heusser's (1960, 1983) records indicate similar early Holocene pollen stratigraphy from Alaganak and Golden at Port Wells, Prince William Sound. The median CAR in the shallow pond (Fig. 2) is close to 14 g/m²/a, which is similar to the mean of gyttja in early Holocene sites on the Kenai (Jones and Yu, 2010). The depleted deuterium isotopic record (Fig. 8) from basal limnic sediments (Nichols et al., 2014) suggests that meltwater from the nearby Sheridan Glacier contributed to groundwater as climate warmed. The occurrence of trace amounts of conifer pollen and absence of conifer macrofossils in zone CB-1 may reflect the presence of *Picea sitchensis, Tsuga heterophylla*, and *Tsuga mertensiana*, along the coastline, in areas that have subsequently been inundated by sea-level rise and tectonic depression (Carrara et al., 2007; Buma et al., 2014). Pollen records from sites as far north as the Seward Peninsula suggest that conifers had reached coastal areas of southern and western Alaska by the early Holocene (Wetterich et al., 2012). However, these populations may have been extirpated due to rapid sea level rise in the early Holocene or due to tectonic depression in this very active region (Plafker, 1969).

The dominant vegetation in the early Holocene throughout south-central and southeastern Alaska is *A. viridis* subsp. *sinuata (formerly A. crispa subsp. sinuata),* which is a foundation species in this environment— defined as an abundant species that dominates community structure and moderates or stabilizes fundamental ecosystem processes (Ellison et al., 2005). *Alnus* colonizes deglaciated soils rapidly, fixing nitrogen and providing leaf litter from which a thick layer of organic matter is derived (Crocker and Major, l955). *Alnus* also has a major influence in initiating the development of microbial communities in soil by promoting microbial growth and facilitating the addition of fungal communities to the soil (Badgett and Walker, 2004). Its prolific seed production would have ensured that early Holocene environments from Yakutat northward to Prince William Sound were blanketed with *Alnus* thickets often attended with an understory of pioneer Polypodiaceae as glaciers retreated (Heusser, 1960, 1983; Peteet, 1986; Peteet, 1991). From the initiation of the pond environment to its gradual development of a bog, the wetland species such as *Myrica gale* and *Potentilla palustris* were present. Shrubs such as *R. spectabilis* and *Sambucus racemosa* probably thrived in the more mineral soils nearby, while ultimately *Sphagnum* helped to create the bog peat that *A. polifolia,* a plant of nutrient poor, ombrotrophic conditions (Malmer and Wallen, 1986), then colonized.

From 9.2 to 7.6 ka, Corser Bog was occupied by *Sphagnum* peat, though *Alnus* remained dominant on the landscape. Large-size Ericaceae tetrads are consistently present, probably reflecting *A. polifolia*, along with peatland *Drosera* and wet meadow *Fritillaria*. The assemblage suggests a warm climate because the *Alnus* signal of the recession of local glaciers is dominant in this peatland profile, and because of the absence or low percentage of cold indicators (*Salix, Artemisia, Empetrum*). The carbon accumulation rate is very high after the early Holocene shift to *Sphagnum* matrix, reaching 20−50 g/m²/a (Fig. 3) which is much higher than sites on the Kenai, and then drops back to relatively lower rates less than 20 g/m²/a until about 3.7 ka. High rates of peat accumulation during the early Holocene have been seen in other Alaskan peatlands (Jones and Yu, 2010) and in peat records from other boreal regions (Loisel et al., 2014).

5.2. Mid-Holocene 7.6—3.7 ka

The shift from *Sphagnum* peat to a sedge peat at 7.6 ka is clearly visible in the lithology and LOI decrease. While *Alnus* pollen percentages decline, they remain between 50 and 70%. Increases in grass and sedge pollen, along with Polypodiaceae spores characterize the mid-Holocene between 7.6 and 5 ka. This shift suggests a
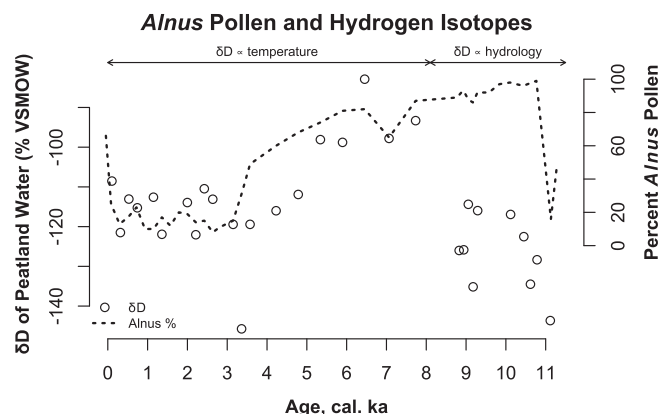
Fig. 9. *Alnus* pollen percentages (dotted line) compared with hydrogen isotopes of peatland water (circles) from 11 ka to present illustrated in Nichols et al. (2014). Depleted isotopes in the early Holocene reflect the influence of groundwater, which may have some amount of glacial meltwater, but from 8 ka to present parallel the *Alnus* pollen percentages indicating the strong influence of temperature on both hydrogen isotope ratios and *Alnus* pollen abundance.

drier climate with continual glacial retreat as evidenced by the presence of substantial pioneer *Alnus* and fern. The poor macro-fossil preservation is consistent with reduced paludification which likely increased decomposition. The upper portion of the sedge peat from 5 to 3.7 ka records a remarkable increase in Ericaceae pollen tetrads between 30 and 40%, which are very small in size (less than 30 microns), probably *Rhododendron (*formerly *Ledum) groenlandicum* (Hebda, 1979) which is the sole Ericaceae type in the region which matches this pollen type. Hebda's modern ecological study from British Columbia shows that small pollen tetrads such as *Ledum* indicated a drier habitat and that pollen productivity in this dry habitat was relatively high. This ecological shift lends further support to the interpretation of a drier climate. To evaluate the evaporation occurring at the surface of Corser Bog using the δD of leaf wax n-alkanes, Nichols et al. (2014) found that groundwater strongly influences the hydrogen isotope ratios of peatland water during the limnic phase of the site (Fig. 9). The warmer conditions during this early Holocene are not reflected in the δD because the signal is dominated by cold meltwater. In the leaf wax δD-derived record of evaporation, the most evaporative part of the record occurred at about 8 ka. This increased evaporation then lowered the water table and favored sedge growth rather than *Sphagnum*. The sedge dominance was then favored until less evaporative conditions resumed in the Neoglacial. While carbon accumulation declines and averages 13 g/m^2/a in this sedge-dominated zone, it is higher than in other mid-Holocene peat sediments such as those on the Kenai Peninsula (Jones and Yu, 2010).

The nearby stratigraphic record from Cabin Lake (Zander et al., 2013) records a hiatus (dry phase) from 8.8 to 3.4 ka and is consistent with our stratigraphic shift from *Sphagnum* peat through a dry sedge phase and back to *Sphagnum* peat. In several sites where peat cores were analyzed from Port Wells, Prince William Sound (Heusser, 1983), the sediment shifted from limnic to fibrous (sedge peat) between 9 and 3 ka, and extremely low sedimentation rates are recorded, supporting the regional interpretation of sedge peat characteristic of muskegs and drier conditions. To the south-east at Icy Bay, the Munday Creek record indicates dominance of sedge as well until about 4 ka (Peteet, 1986).

5.3. Neoglacial 3.7-present

At about 3.7 ka, an abrupt shift to a *Sphagnum* peatland takes

place, along with the arrival of *Picea sitchensis* and *Tsuga mertensiana* on the landscape. A single *Andromeda* seed is preserved as Ericaceae abundance declines, probably due to wetter climate (Hebda, 1979), and *Alnus* and Polypodiaceae record minimal values. Clearly a major regional shift in climate takes place, as the peatland lithologic shift from sedge to *Sphagnum* is similar in timing and nature to that observed at Munday Creek, Icy Cape, about 180 km to the southeast (Peteet, 1986). *Picea sitchensis* expansion requires abundant moisture and lack of a pronounced summer drought (Farr and Harris, 1979). The arrival of *Picea sitchensis* at this time may indicate that conditions prior to 4 ka were not favorable for its development along the coastline, particularly if summers were dry. Alternatively, a migration lag across the Bering Glacier area (probably an embayment) may have been present, as *Picea* was present at Munday Creek about a millennium earlier, and even further to the southeast trees were already present early in the Holocene (Ager and Rosenbaum, 2009). The presence of *Tsuga mertensiana* attests to the cool conditions that must have been present − *T. mertensiana* favors colder environments with deep winter snows (Viereck and Little, 1972). *Tsuga heterophylla* favors mature soils (Heusser, 1960), so its subsequent arrival may reflect the more advanced soil development with time. Stormier weather with higher winds may have contributed to the migration of trees northwestward (Heusser, 1983). A cooler, wetter climate has been inferred throughout the region, extending southward to British Columbia (Heusser, 1960; Heusser et al., 1985; Ager et al., 2010), and agrees with the more depleted deuterium data and low *Alnus* values (Fig. 9). The carbon accumulation in the Neoglacial upper portion of the core is about 20 g/m^2/a, which is substantially higher than the mean on the Kenai and is similar to the increase in C storage for circumboreal peatlands at this time (Loisel et al., 2014). It is noteworthy that this extensive compilation (Loisel et al., 2014) also indicates that 40−60% of sites are dominated by *Sphagnum* in the Neoglacial, suggesting a climatic forcing.
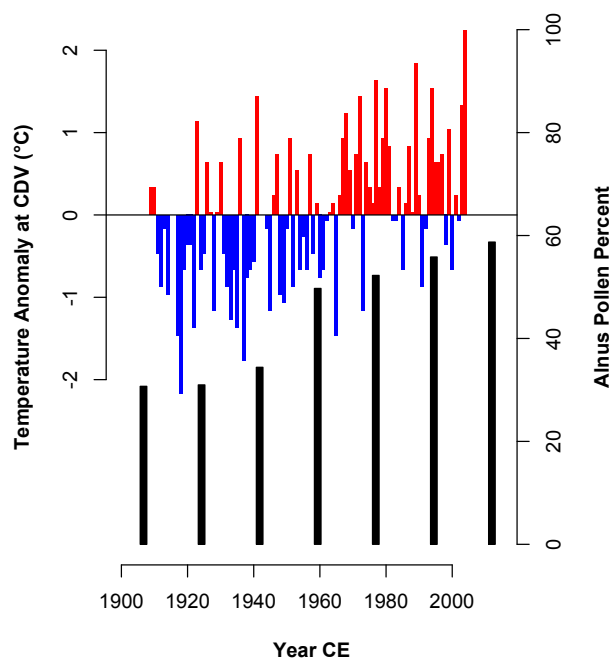

Fig. 10. Temperature anomaly, Cordova Airport and *Alnus* pollen percentages reveal a 20% *Alnus* increase paralleling a 2 °C increase in temperature over the last 60 years, calculated from sedimentation rate in Fig. 2.

Neoglacial advances in southern Alaskan as early as 4 ka have been noted (Tuthill et al., 1968; Denton and Karlen, 1977; Mann and Hamilton, 1995; Wiles et al., 2002), and Barclay et al. (2009) summarize the data for advances beginning at 4 ka and major advances at 3 ka with perhaps 2 distinct expansions occurring from 3.3 to 2.9 ka and from 2.2 to 2.0 ka. Focusing on the last two millennia, tree ring studies from four adjacent valley glacier-killed stumps and logs demonstrate the Sheridan Glacier advances at 530 to 640 CE, then 1240s—1280s CE, and in the Little Ice Age from 1510 to 1700's and 1810s—1860s CE (Barclay et al., 2013).

About 0.8 ka (1208 CE), slight declines in all tree pollen coincide with slight increases in *Alnus* and the preservation of abundant *A. polifolia* seeds, as well as the preservation of leaves of other ericads such as *Vaccinium uliginosum* and *Oxycoccus microcarpus*. An anomalously high abundance of ferns and *Equisetum* suggests disturbance, and may represent a retreat of the nearby Sheridan Glacier during the Medieval Warming Period (MWP). On the broader regional scale, *Tsuga mertensiana* tree ring records (Wiles et al., 2014) demonstrate two significant periods of warmth - between 910 and 1000 CE, as well as the most recent century from 1880 to 2010 CE. The most recent 10 pollen samples spanning 165 years (1846—2011) (Fig. 10) with up to 20% expansion of *Alnus* pollen percentage is quite intriguing, and is correlative with the 1—2 °C temperature increase recorded at the airport in Cordova, AK. We suggest that this *Alnus* expansion is indicative of recent glacial recession providing new mineral soils available for pioneer colonization. Further study could exploit this pollen type as a warming signal along this coastline.

6. Conclusions

Climate-driven vegetational change appears to direct carbon storage in this Alaskan coastal muskeg. Shallow pond deposition followed deglaciation at 11.5 ka, and records regional warmth with the pioneers *A. crispa* subsp. *sinuata*, *Salix*, and *Polypodiaceae* colonizing the fresh, mineral soils on the landscape. Carbon accumulation in the pond environments is 14 g/m^2/a—similar to mean regional values of gyttja on the Kenai (Jones and Yu, 2010). Continued early Holocene warming and melting of glaciers led to the dominance of the foundation species *Alnus* on mineral soils and peatland formation in wetter sites with species such as *Myrica gale* and *P. palustris*. As *Sphagnum* peat accumulated, the highest rates of carbon accumulation (50 g/m^2/a) last for a few centuries. This rate is similar in magnitude to very high short-term rates in the early Holocene throughout the circumboreal region (Jones and Yu, 2010), but timing of these short bursts of high accumulation rate vary within the early Holocene due to development of local wet, bryophytic environments. A more evaporative, drier climate ensued along the south-central Alaskan coast 7.6—3.7 ka resulting in a shift from *Sphagnum* to sedge peat with lower rates of carbon accumulation (13 g/m^2/a), and minimal macrofossil preservation. This type of deposition is paralleled regionally in coastal muskegs both to the northwest (Heusser, 1960, 1983; Ager et al., 2010) and southeast and by a hiatus in the nearby Cabin Lake record (Zander et al., 2013). A cooler, moister climate is evident in Corser Bog with the shift back to *Sphagnum* peat at 3.7 ka, which mirrors regional shifts from sedge to *Sphagnum* peat throughout the entire coastline from Yakutat to Girdwood, AK (Heusser, 1960; Heusser, 1983; Peteet, 1986, 1991; Ager et al., 2010) and is consistent with the demonstrated glacial advances in the region (Barclay et al., 2009, 2013). The last century is characterized by rapid *Alnus* expansion, concurrent with a 2 °C warming at Cordova.

References

Ager, T.A., Rosenbaum, J.G., 2009. Late Glacial-Holocene Pollen-based Vegetation History from Pass Lake, Prince of Wales Island, Southeastern Alaska. USGS Professional Paper 1760-G.

Ager, T.A., Carrara, P.E., McGeehin, J.P., 2010. Ecosystem development in the Girdwood area, south-central Alaska, following late Wisconsin glaciation. Can. J. Earth Sci. 47, 971—985.

Barclay, D.J., Wiles, G.C., Calkin, P.E., 2009. Holocene glacier fluctuations in Alaska. Quat. Sci. Rev. 28, 2034—2048.

Barclay, D.J., Yager, E.M., Graves, J., Klozko, M., Calkin, P., 2013. Late Holocene glacial history of the Copper River Delta, coastal south-central Alaska, and controls on valley glacier fluctuations. Quat. Sci. Rev. 81, 74—89.

Bardgett, R.D., Walker, L.R., 2004. Impact of coloniser plant species on the development of decomposer microbial communities following deglaciation. Soil Biol. Biochem. 36, 555—559.

Bragazza, L., Freeman, C., 2007. High nitrogen availability reduces polyphenol content in Sphagnum peat. Sci. Total Environ. 377, 439—443.

Buma, B., Hennon, P., Bidlack, A.L., Baichtal, A.F., Ager, T.A., Streveler, G., 2014. Correspondence regarding "The problem of conifer species migration lag in the Pacific Northwest region since the last glaciation" by Elias SA (2013), Quaternary Science Reviews 77: 55—69. Quat. Sci. Rev. 93, 167—169.

Carrara, P.E., Ager, T.A., Baichtal, J.R., 2007. Possible refugia in the Alexander Archipelago of southeastern Alaska during the late Wisconsin glaciation. Can. J. Earth Sci. 44, 229—244.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, R., Jones, R., Kolli, R.K., KwonW, K., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Räisänen, J., Rinke, A., Sarr, A., Whetton, P., Arritt, R., Benestad, R., Beniston, M., Bromwich, D., Caya, D., Comiso, J., de Elia, R., Dethloff, K., 2007. Regional Climate Projections, Climate Change: the Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. University Press, Cambridge, ISBN 978-0-521-88009-1 (Chapter 11).

Cooper, W.S., 1942. Vegetation of the Prince William Sound region, Alaska, with a brief excursion into post-Pleistocene history. Ecol. Monogr. 12, 1—22.

Crocker, R.L., Major, J., 1955. Soil development in relation to vegetation and surface age at Glacier Bay Alaska. J. Ecol. 43, 427—448.

Dachnowski-Stokes, A.P., 1941. Peat Resources in Alaska. US Dept. Agriculture Tech. Bull, p. 769.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sediment. Petrol. 44, 242—248.

Denton, G., Karlen, W., 1977. Holocene glacial and treeline variation in the White River Valley and the Skolai Pass Alaska and Yukon territory. Quat. Res. 7, 63—111.

Ellison, A.M., Bank, B.D., Clinton, E.A., Colburn, K., Elliott, C.R., Ford, D.R., Foster, B.D., Kloeppel, J.D., Knoepp, Lovett, G.M., Mohan, J., Orwig, D.A., Rodenhouse, N.L., Sobczak, W.V., Stinson, K.A., Stone, J.K., Swan, C.W., Thompson, J., Von Holle, B., Webster, J.R., 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. Front. Ecol. Environ. 3, 479—486.

Faegri, K., Iverson, J., 1989. Textbook of Pollen Analysis. John Wiley and Sons, Chichester.

Farr, W.A., Harris, A.S., 1979. Site index of Sitka spruce along the Pacific coast related to latitude and temperature. For. Sci. 25, 145—153.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1, 182—195.

Grimm, E.C., 1992. Tilia and Tilia-graph Software, Version 2.0. Illinois State University.

Hebda, R.J., 1979. Size, productivity, and paleoecological implications of ericaceous pollen from Burns Bog, southern Fraser River Delta, British Columbia. Can. J. Bot. 57, 1712—1717.

Heusser, C.J., 1960. Late Pleistocene environments of North Pacific North America. Am. Geogr. Soc. Spcl. Publ. 35.

Heusser, C.J., 1983. The Holocene vegetation history of the Prince William sound region, South-Central Alaska. Quat. Res. 19, 337—355.

Heusser, C.J., Heusser, L., Peteet, D., 1985. Late Quaternary climatic change on the American North Pacific Coast. Nature 315 (6019), 485—487.

Hulten, E., 1968. Flora of Alaska and Yukon. Gleerup, Lund.

Jones, M., Yu, Z., 2010. Rapid deglacial and early Holocene expansion of peatlands in Alaska. Proc. Natl. Acad. Sci. 107, 7347—7352.

Jones, M., Wooler, Peteet, D.M., 2014. A deglacial and Holocene record of climate variability in south-central Alaska from stable oxygen isotopes and plant macrofossils in peat. Quat. Sci. Rev. 87, 1–11.

Kuiper, J.J., Mooij, W.M., Bragazza, L., Robroek, B., 2014. Plant functional types define magnitude of drought response in peatland CO_2 exchange. Ecology 95 (1), 123–131.

Lacourse, T., Davies, M., 2015. A multi-proxy record of Holocene vegetation history, bog development, and carbon accumulation on northern Vancouver Island, Pacific Coast of Canada. Holocene 25 (7), 1165–1178.

Leslie, L.D., 1989. Alaska Climate Summaries, second ed. University of Alaska, Anchorage, Arctic Environmental Information and Data Center. Alaska Climate Center Technical Note 5.

Loisel, et al., 2014. Northern peatland database and synthesis. Holocene 24, 1028. http://dx.doi.org/10.1177/0959683614538073.

Lutz, H.J., 1930. Observations on the invasion of glacial moraines by trees. Ecology 11, 562–567.

MacDonald, G.M., Beilman, D.W., Kremenetski, K.V., Sheng, Y., Smith, L.C., Velichko, A.A., 2006. Rapid development of the circumarctic peatland complex and atmospheric CH_4 and CO_2 variations. Science 314, 285–288. http://dx.doi.org/10.1126/science.1131722.

Mann, D., Hamilton, T., 1995. Late Pleistocene and Holocene Paleoenvironments of the North Pacific Coast. Quat. Sci. Rev. 14, 449–471.

Malmer, N., Wallen, N., 1986. Inorganic elements above and below ground in dwarf shrubs on a subarctic peat bog. Oikos 46, 200–206.

Nichols, J.E., Peteet, D.M., Moy, C.M., Castenda, I.S., McGeachey, A., 2014. Impacts of climate and vegetation change on carbon accumulation in a south-central Alaskan peatland assessed with novel organic geochemical techniques. Holocene 24 (9), 1146–1155.

Peteet, D., 1986. Modern pollen rain and vegetational history of the Malaspina Glacier district, Alaska. Quat. Res. 25, 100–120.

Peteet, D.M., 1991. Postglacial history of lodgepole pine near Yakutat, Alaska. Can. J. Bot. 69, 786–796.

Peteet, D.M., Mann, D.H., 1994. Late-glacial vegetational, tephra, and climatic history of southwestern Kodiak Island. Alsk. Ecoscience 1 (3), 255–267.

Plafker, G., 1969. Tectonics of the March 27 1964 Alaska Earthquake, p. 174. U.S. Geological Survey 757 Professional Paper 543-I.

Plafker, G., Lajoie, K., Rubin, M., 1993. Determining intervals of great subduction zone earthquakes in southern Alaska by radiocarbon dating in Taylor RE. In:

Long, A., Kra, R.S. (Eds.), Radiocarbon After Four Decades − an Interdisciplinary Perspective. Springer, New York, pp. 436–452.

R Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rigg, G.B., 1914. Notes on the flora of some Alaskan Sphagnum bogs. Plant World 17, 167–182.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2013. 6.1 (WWW Program and Documentation).

Tarr, B.S., Martin, L., 1914. Alaskan Glacier Studies of the National Geographic Society in the Yakutat Bay, Prince William Sound, and Lower Copper River Regions. National Geographic Society.

Tolonen, K., Turunen, J., 1996. Accumulation rates of carbon in mires in Finland and implications for climate change. Holocene 6, 171–178.

Tuthill, S.J., Field, W.O., Clayton, L., 1968. Postearthquake studies at Sherman and Sheridan glaciers. In: the Great Alaska Earthquake of l964 − Hydrology. Natl. Acad. Sci. Publ. 1603, 318–328.

Viereck, L.A., Little, E.L., 1972. Alaska trees and shrubs. In: USDA Forest Service Agriculture Handbook, vol. 410.

Warner, B.G., Chinnappa, C.C., 1986. Taxonomic implications and evolutionary trends in pollen of Canadian Ericales. Can. J. Bot. 64, 3113–3126.

Wetterich, S., Grosse, G., Schirrmeister, L., Andreev, A., Bobrov, A., Kienast, F., Bigelow, N.H., Edwards, M.E., 2012. Late Quaternary environmental and landscape dynamics revealed by a pingo sequence on the northern Seward Peninsula, Alaska. Quat. Sci. Rev. 39, 26–44.

Wiles, G.C., Jacoby, G.C., Davi, N.K., McAllister, R.P., 2002. Late Holocene glacier fluctuations in the Wrangell Mountains, Alaska. Geol. Soc. Am. Bull. 114, 896–908.

Wiles, G.C., D'Arrigo, R.D., Barclay, D., Wilson, R.S., Jarvis, S.K., Vargo, L., Frank, D., 2014. Surface air temperature variability reconstructed with tree rings for the Gulf of Alaska over the last 1200 years. Holocene 24, 198–208.

Winkler, G.R., Plafker, G., 1993. Geologic Map of the Cordova and Middleton Island Quadrangles, Southern Alaska. In: Miscellaneous Investigations Series Map 1984, Scale 1:250,000. US Geological Survey.

Zander, P.D., Kaufman, D.S., Keuhn, S.C., Wallace, K.L., Anderson, R.S., 2013. Early and Late Holocene glacial fluctuations and tephrostratigraphy, Cabin Lake. Alsk. J. Quat. Sci. 28, 761–771.