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Reconstruction of a High-Resolution Late Holocene Arctic Paleoclimate Record from Colville River Delta Sediments

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Reconstruction of a High-Resolution Late Holocene Arctic Paleoclimate Record from Colville River Delta Sediments

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Abstract

This work was partially supported by the Sandia National Laboratories, ‘Laboratory Directed Research and Development’ (LDRD) fellowship program in conjunction with Texas A&M University (TAMU). The research described herein is the work of Kathryn M. Schreiner (‘Katie’) and her advisor, Thomas S. Bianchi and represents a concise description of Katie’s dissertation that was submitted to the TAMU Office of Graduate Studies in May 2013 in partial fulfillment of her doctorate of philosophy degree.

High Arctic permafrost soils contain a massive amount of organic carbon, accounting for twice as much carbon as what is currently stored as carbon dioxide in the atmosphere. However, with current warming trends this sink is in danger of thawing and potentially releasing large amounts of carbon as both carbon dioxide and methane into the atmosphere. It is difficult to make predictions about the future of this sink without knowing how it has reacted to past temperature and climate changes. This project investigated long term, fine scale particulate organic carbon (POC) delivery by the high-Arctic Colville River into Simpson’s Lagoon in the near-shore Beaufort Sea. Modern POC was determined to be a mixture of three sources (riverine soils, coastal erosion, and marine). Downcore POC measurements were performed in a core close to the Colville River output and a core close to intense coastal erosion. Inputs of the three major sources were found to vary throughout the last two millennia, and in the Colville River core covary significantly with Alaskan temperature reconstructions.

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NOMENCLATURE

CE	common era
DOC	dissolved organic carbon
OC	organic carbon
PCA	principal component analysis
POC	particulate organic carbon
TAMU	Texas A&M University

1. INTRODUCTION

Half of the entire global soil carbon pool resides in the top few meters of Arctic permafrost soils. Recent estimates indicate that these Arctic soils could contain as much as 1,850 Pg of organic carbon (OC) [Tarnocai *et al.* 2009] – equivalent to more than double the amount of carbon currently residing in the atmospheric CO₂ pool [IPCC 2007]. Much of this OC, stored in old soils and peats, is thousands of years old and represents an important store of terrestrial OC [Schuur *et al.* 2009]. However, the future of this sink is uncertain as temperatures in the high latitudes are predicted to rise by as much as 7°C by 2100, and many regions of Arctic permafrost have already begun to warm and thaw [IPCC 2007]. It is likely that in addition to direct conversion of soil OC to CO₂ and CH₄, there will be increased river mobilization of dissolved and particulate OC (DOC and POC, respectively) resulting from thawing and erosion of this soil carbon pool.

In addition to breakdown of soil carbon stores, the vegetation of the Alaskan North Slope is currently undergoing a significant change due to warming temperatures. The vegetation of the North Slope is characterized by dwarf shrub and low shrub tundra, with mossy carpets and moist peaty soils [Walker *et al.* 2002], and is composed almost exclusively of C₃ vegetation [Dunton and Schell 1987; Naidu *et al.* 2000]. There is significant evidence that woody shrub encroachment onto mossy tundra, likely due to Arctic warming, has been occurring over the past 50 to 60 years in the Arctic as a whole and especially in northern Alaska and Canada [Sturm *et al.* 2001; Tape *et al.* 2006].

The potential impacts of long-term climate change and atmospheric oscillations on changing terrestrial and algal carbon inputs in the Arctic are likely to be significant. In order to better elucidate the effects of these changes, the specific goals of this study were:

1. Determine historical changes, and make predictions about future changes, in the sources and amounts of POC input to the Colville River delta, nearby Simpson's Lagoon, and the Beaufort Sea
2. Better understand changes in the terrestrial vegetation of the Colville River watershed over the recent Holocene
3. Further constrain the temperature and moisture regime changes on the Alaskan North Slope over the past 2000 years.

This project seeks to address these goals by examining core sediments from the Colville River delta and the inner shelf of the Alaskan Beaufort Sea. Colville River deltaic sediments will provide a unique Arctic paleoclimate record from the recent Holocene not yet previously described. This study marks the first attempt to describe POC delivery from a North American watershed completely contained within the high Arctic, and provides the first integrated view of changes in the terrestrial, riverine, and algal carbon sources from the watershed over the late Holocene.

2. RESEARCH APPROACH

2.1. Study Area

Estuarine systems, like the Colville River delta / Simpson's Lagoon system targeted for this study (see map, Figure 1), integrate marine and terrestrial signals, providing a unique study area. Coastal marine sediments are an excellent recorder of continental climate history, integrating large terrestrial areas (an entire river basin, as opposed to, for example, a small lake basin) and high sedimentation rates, preserving organic material and allowing for finer-scale resolution [Bianchi and Allison 2009]. Measured sedimentation rates in Simpson's Lagoon vary with proximity to the river mouth, but average about 1 to 5 mm yr⁻¹, and sediments are well-laminated with no disturbance from ice grounding or macrofauna [Hanna *et al.* in review].

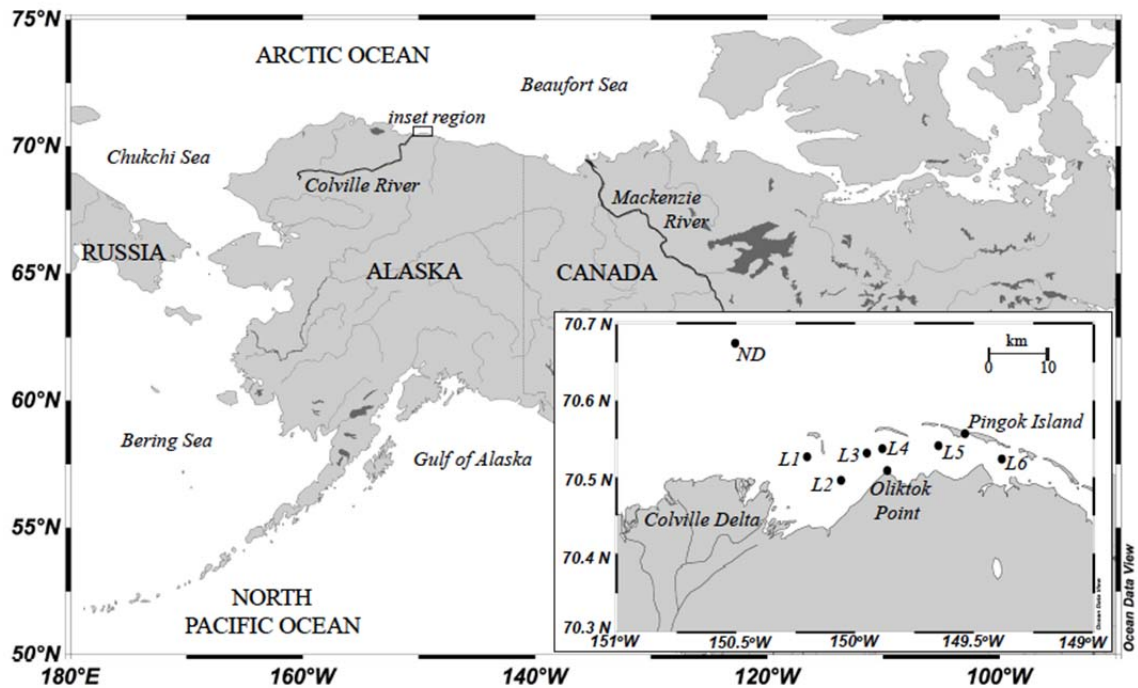


Figure 1. Map of Alaska and northern Canada, showing the Colville and Mackenzie Rivers. Inset shows the study area for this report, including coring stations and end-member collection points.

The Colville River has the largest drainage basin in the Arctic that is confined to the zone of continuous permafrost (53,000 km² and 29% of the Alaskan North Slope) [Walker and Hudson 2003]. Because the river drains the glaciated Brooks Range, it has a relatively high sediment load for an Arctic River (362 g m⁻³ [Arnborg *et al.* 1967]). Tributaries to the river originate in the Brooks Range, flow over the Arctic foothills, and through the Arctic coastal plain into the Beaufort Sea. The river thus integrates a terrestrial signal from a wide range of Arctic permafrost ecosystems. The Colville displays a strong seasonal variability in flow and sediment delivery to the shelf. The hydrologic year lasts for 4 months, with stream-flow beginning after ice breakup in early May in the upper reaches of the basin and slightly later in the lower reaches [Walker and

Hudson 2003]. Approximately 62% of the Colville's annual sediment load (5.3 Tg yr^{-1} [*Arnborg et al. 1967*]) is transported in 13 days during spring flooding [*Walker and Hudson 2003*]. Core samples analyzed in this study were collected in August 2010 aboard the R/V *Annika Marie*. Six cores (labeled in Fig. 1 as L1 to L6) were collected via vibracoring using a Rossfelder P-3 electro-percussive vibracorer and 10 cm diameter liner-less aluminum core barrels. The cores range in length from 1.5 m to almost 3 m, but only surface samples (0-2 cm) and whole cores L2 and L6 were analyzed for this study. Additionally, one surface "grab" sample (ND) was collected directly north of the Colville River delta using a short core barrel and the vibracore head as a weight. Soil samples were collected from Pingok Island, one of the barrier islands on the northern side of Simpson's Lagoon. A peat sample was collected from eroding mainland shoreline close to Oliktok point.

2.2 Experiment and Method

Before organic analyses were performed (described below), core age models were developed using methods described in Hanna et al. [*in review*]. Core L2 (located near the outflow of the Colville) spanned approximately 1800 years, while core L6 (located on the eastern end of the study area in Simpson's Lagoon) spanned approximately 600 years.

Detailed chemical methods for bulk OC and biomarker analysis are described in Schreiner et al. [*2013*]. Briefly, core samples were analyzed for bulk organic parameters including %OC, %N (these were combined to calculate C:N ratios), $\delta^{13}\text{C}$, and select samples were analyzed for radiocarbon and neodymium isotopes (which are used to determine provenance of the mineral portion of sediment). Core samples were also analyzed for a suite of biomarkers including lignin-phenols, non-lignin-phenols, and algal pigments. Select samples were analyzed for radiocarbon content of long-chain fatty acids. All of these analyses were performed to better elucidate sources of OC to the Lagoon throughout the time period of the cores. Lignin-phenols are indicative of fresh organic matter inputs, non-lignin-phenols are indicative of soil and peat inputs, and algal pigments are indicative of marine and riverine phytoplankton inputs. Bulk parameters are also used for source identification. Radiocarbon dating of long-chain fatty acids was used to differentiate between fresh vegetative OC and old soil-sourced OC.

3. RESULTS

3.1. Surface POC

The results of this study are described in detail in Schreiner et al. [2013] and described only briefly here. It was found that Simpson's Lagoon receives mineral sediments from two distinct provinces: the Colville River watershed and the Mackenzie River watershed to the east. The Mackenzie, which is a much larger river, distributes sediments over most of the Beaufort Sea coast, which are diluted by Colville River sediments close to the Colville delta.

POC in the Lagoon originated from three distinct sources: river POC (which could be from either the Colville or the Mackenzie), coastal erosional POC, and primary production POC (i.e. from marine or riverine phytoplankton). An estimate of the contribution of each is shown in Figure 2 (details of the mixing model, including end members chosen, justifications, and model equations, can be found in Schreiner et al. [2013]). Riverine input is the most important at stations close to the Colville outflow, and riverine input becomes less important as one moves eastward across the Lagoon, with the exception of station L5. Station L6 at the eastern end of the Lagoon receives a significant amount of its input from coastal erosional sources. The riverine POC input at stations L5 and L6 is likely sourced from the Mackenzie River to the east, as shown by neodymium and biomarker data [Schreiner et al. 2013].

3.2. Downcore POC

As described above, only two cores were analyzed down their entire length: core L2, close to the Colville output and shown to have significant riverine input and core L6, on the eastern end of the Lagoon and shown to have significant coastal erosional peat input. Sedimentation rates in L2 were lower than in L6 throughout both cores, with L2 averaging a sedimentation rate of 0.1 cm yr⁻¹ and L6 averaging a sedimentation rate of 0.2 cm yr⁻¹ [Hanna et al. in review].

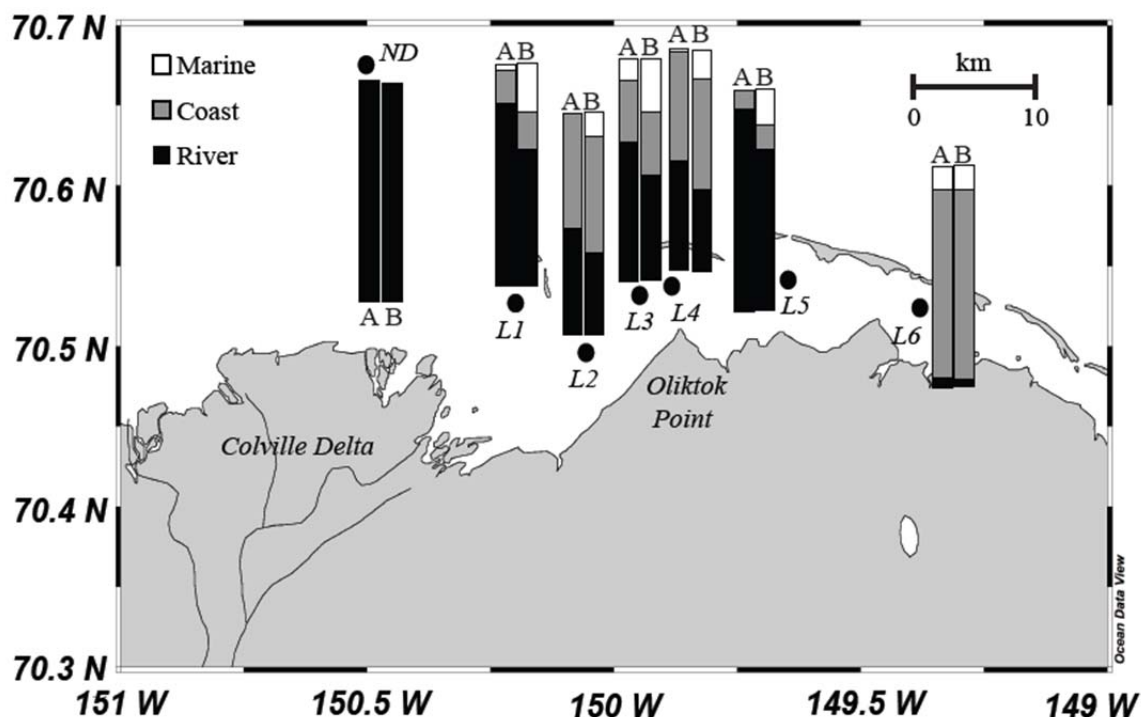


Figure 2. POC inputs from marine, coastal, and riverine sources (described in text) to each coring location. "A" and "B" represent two iteration of a mixing model described in Schreiner et al. [2013].

Quantitative analysis of the inputs of different types of OC to L2 and L6 was performed with principle components analysis (PCA) in the manner of Yunker et al. [1995]. Results are shown in Figure 3. Principle component variables were plotted along with sample points on the same x-y space, with the variable loading axes on the top (x) and right (y) and the sample loading axes on the bottom (x) and left (y). Only variables that were analyzed for every sample (lignin-phenol biomarkers and bulk parameters) were included in the PCA (see Schreiner et al. [2013] for a complete description of variables and methods of biomarker extraction) were included in the PCA. Samples from L6 (labeled SL6 in figure) were plotted in a blue-green color scheme (with blue as surface samples and green as depth) and samples from L2 (labeled SL4 in figure) were plotted in a red-yellow color scheme (with red as surface and yellow as depth).

Results show that the first PCA mode (PC1, x-axes) accounted for 52% of the variance in the data, while the second mode (PC2, y-axes) accounted for 15% of the variance, for a total of 67% of the data variance accounted for in the first two modes. PC1 appeared to split the data between degraded components, as evidenced by negative values that were dominated by $[Ad:Al]_v$, PON, and 3,5-Bd; and fresh components, evidenced by positive values that were dominated by the V, S, and C lignin-phenols. The split shown by PC2 was less clear, but most indicators of terrestrial carbon plotted on the positive side (lignin-phenols, $[Ad:Al]_v$ ratio), while bulk parameters that can indicate either terrestrial or marine input (for example, C:N ratio) plotted on the negative side. Deeper samples from L6 were for the most part located in the area of the plot corresponding to fresh organic matter, much of which was from a marine source, possibly due to a high sedimentation rate from coastal erosional inputs. In both cores, moving from deeper samples to shallower samples (or older parts of the core to younger parts) showed a higher degree of OC

degradation. This was almost certainly due to higher deliveries of degraded OC from the Alaskan tundra to these coastal sediments in recent times. Arctic permafrost is slowly warming [Osterkamp and Romanovsky 1999; Schuur et al. 2008], causing an increase in the delivery of old carbon both by Arctic rivers [Guo et al. 2007] and coastal peat erosion [Vonk et al. 2012].

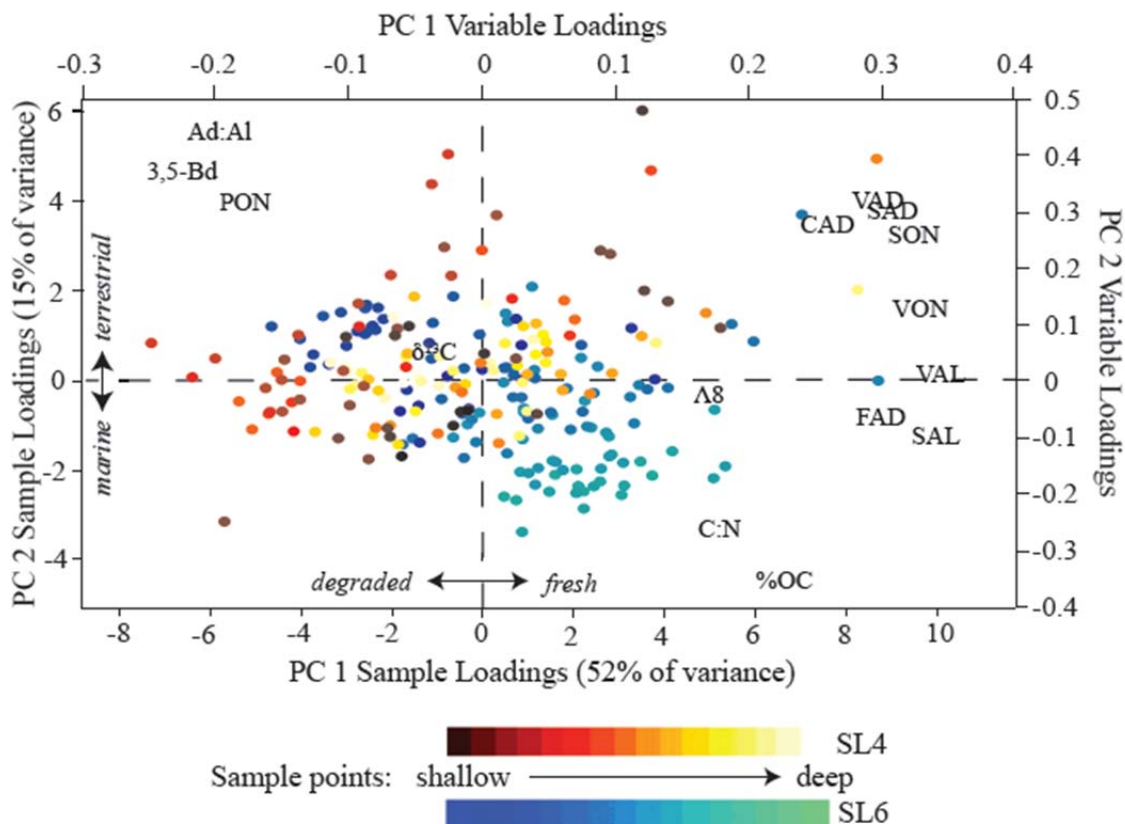


Figure 3. Summary of Principle Component Analysis results. PC variable loadings are shown on top x-axis and right y-axis, while PC sample loadings are shown on bottom x-axis and left y-axis. Variables are plotted with their abbreviation (explanations can be found in Schreiner et al. [2013], and samples are plotted with colored dots. Color corresponds to core and depth. SL4 refers to core L2 and SL6 refers to core L6.

A comparison of downcore biomarker concentrations (lignin-phenols, shown in units of Δ_8 , and long-chain fatty acids) for core L2, along with a temperature reconstruction from Holocene lake sediment cellulose concentrations from a lake in Alaskan Brooks Range close to the Colville headwaters [Anderson et al. 2001] is shown in Figure 4. Profiles A and B clearly co-vary in the top half of the core (approximately 1000 CE to present). Deviations in the $\delta^{18}\text{O}$ toward more positive values indicate warmer temperatures, while deviations toward more negative values indicate cooler temperatures. Increases in the proportion of tPOC likely originate from one of the following two sources: (1) thawing permafrost, allowing both increased erosion of peats and soils from the watershed which are then deposited in the delta, and direct input of peats and soils from shoreline retreat; or (2) increasing shrub abundance in the watershed, which results in increased fresh plant POC delivered by the river to deltaic sediments. Fresh plant material should have a relatively low Ad:Al ratio [Hedges et al. 1988; Opsahl and Benner 1995; Bianchi et al. 1999]. For the time period shown, Ad:Al is negatively correlated with Δ_8 ($R^2 = 0.29$, $P < 0.001$)

and depositional age of fatty acids is negatively correlated with Λ_8 ($R^2 = 0.65$, $p < 0.01$), indicating the more highly degraded POC is also older (likely derived from soil or peat), while the less degraded POC is younger (likely derived from fresh vegetation). Warmer periods therefore correspond to greater contributions of fresh, young POC, likely derived from shrub expansion similar to that which is currently occurring across the North Slope [Sturm *et al.* 2001; Pearson *et al.* 2013]. With the exception of the past century, there appears to be little evidence of thawing and eroding permafrost due to warmer temperatures during the last 2000 years, as warmer temperatures consistently correspond with higher Λ_8 values, lower Ad:Al values, and where data is available, younger fatty acid depositional ages. The signature of terrestrial POC is older and more degraded during cooler times, which is reflective of deeper stored POC when active shrub growth is highly reduced, which then becomes diluted by fresh, young, shrub-derived POC during warmer times.

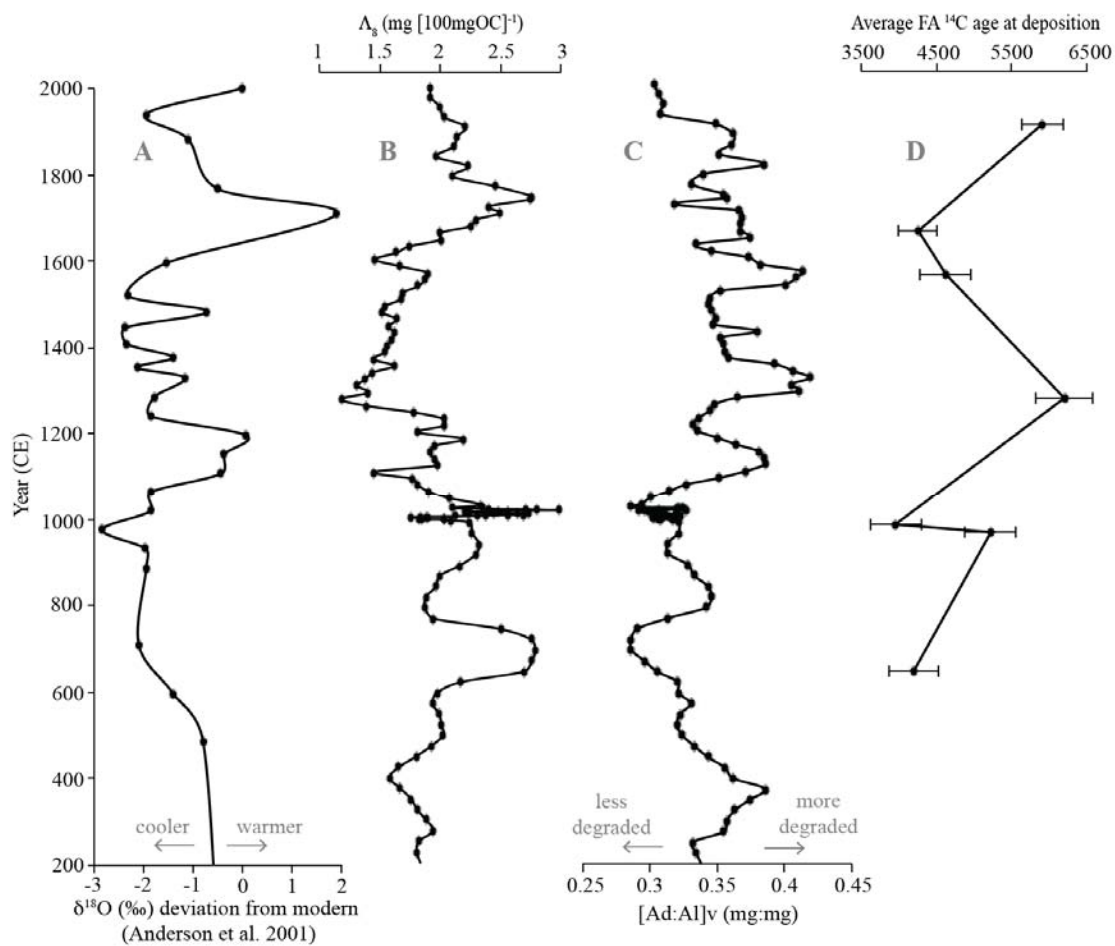


Figure 4. Down-core profiles from Colville River delta core, Beaufort Sea, Alaska. Ages on y-axis are shown in years in the Common Era (CE), with the year 2000 CE at the top. Profiles shown are oxygen isotopic content of cellulose from lakebed sediments ($\delta^{18}\text{O}$, ‰, a proxy for temperature, profile A) [Anderson *et al.* 2001], lignin-phenol abundance (Λ_8 , mg per 100mgOC, profile B), vanillic acid to vanillin ratio ($[\text{Ad:Al}]_v$, mg:mg, a proxy for degradation state of tPOC, profile C), and ^{14}C age at deposition of plant wax fatty acids (FAs, reported as age before present, profile D).

4. CONCLUSIONS

Despite the limited areal extent of Simpson's Lagoon, surface sediments in the system contained a mixture of POC and sediments sourced from a variety of areas, including the Colville River, the Mackenzie River, coastal peat erosion, and marine primary production. As might be expected, input from the Colville River was most important at the western end of the Lagoon, whereas coastal erosional and Mackenzie River input was most important at the eastern end of the Lagoon. For all areas of the Lagoon, terrestrial POC inputs were more important than marine POC inputs.

In addition to surface sediments, downcore sediments from two cores, one near the Colville outflow and one at the eastern end of the Lagoon, were analyzed for POC input. Higher deliveries of more degraded and older POC are found in the surface of each core when compared to downcore samples, indicating that there is currently more input of soil- and peat-sourced POC than there has been before in the Holocene. Additionally, input of fresh vegetative biomarkers correlates well with temperature changes over the North Slope for the past few hundred years, indicating that woody shrub encroachment has occurred in the past in this ecosystem. Temperature-biomarker comparisons further indicate that the current permafrost thaw and erosional input of soil and peat POC is unprecedented in the North Slope over the past 2000 years.

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