Paleoclimate studies of minerogenic sediments using annually resolved textural parameters

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Received 8 March 2002; revised 10 April 2002; accepted 18 April 2002; published 31 October 2002.

[1] We obtained quantitative multivariate data from each varve of a minerogenic lacustrine sequence from the Canadian High Arctic, using an image analysis technique applied to thin-sections. The information on each varve from the uppermost core section was compared with a 35 yr meteorological dataset. Snowmelt intensity, which is an index reflecting the energy available for sediment transport, correlates well with the median grain-size measured for each varve, as well as with the weight of the 10–20 and 20–60 μm fractions. The proportion of fine silt also correlates with low intensity summer precipitation. This methodology allows us to decipher the climatic control on sedimentary processes and yield a new perspective for constructing models which link climate to sediments that contain few biological remains. This model can then be used to infer paleoclimate with annual resolution from the downcore grain-size analysis. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 9315 Information Related to Geographic Region: Arctic region; 1863 Hydrology: Snow and ice (1827); 1694 Global Change: Instruments and techniques. **Citation:** Francus, P., R. S. Bradley, M. A. Abbott, W. Patridge, and F. Keimig, Paleoclimate studies of minerogenic sediments using annually resolved textural parameters, *Geophys. Res. Lett.*, *29*(20), 1998, doi:10.1029/2002GL015082, 2002.

1. Introduction

[2] High-resolution proxy data (such as tree rings, banded corals, ice cores and varved sediments) can provide annually resolved paleoclimate information for periods of time longer than instrumental records. Paleoclimate records from Polar Regions are of particular interest because the instrumental record is short and the observational network is limited. However, Arctic lakes generally contain extremely low organic matter content which makes the sediments very difficult to date by radiocarbon techniques [*Abbott and Stafford*, 1996]. In addition, the lack of biological productivity limits the use of biological remains to quantify past climate using transfer functions. Nevertheless, laminated, mainly clastic sediments from the Arctic can provide paleoclimatic information if the sediment can be shown to be annually resolved and contains some identifiable climate information. Here, we apply a recently developed image analysis technique to thin-sections of sediments from an Arctic lake to assess their relevance for high-resolution paleoclimatic studies. This innovative technique is particularly relevant for the study of varved sediments because it allows the measurement of microstructural and textural parameters within each varve [*Francus*, 1998]. Here, we investigate the prospects for calibrating these parameters with the instrumental meteorological record.

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0094-8276/02/2002GL015082$05.00

2. Field Area

[3] Sawtooth Lake (SL) (unofficial name) is located 80 km south east of Eureka, Ellesmere Island, Canada (Figure 1). Meteorological records maintained since the early fifties at Eureka indicate that the region is a dry and cold desert. We computed a prospective set of climatic indices (Table 1) from the Eureka data. An on-site automated weather station at SL indicates similar climatic conditions to those at Eureka.

[4] A single main tributary, mainly fed by snowmelt, flows into the lake at its eastern end. There is currently no glacier in the watershed. A 60 m deep sill separates proximal and distal sedimentary basins, which are 100 m and 80 m deep, respectively. The lake is ice-covered for 10–12 months per year. The distal basin is depleted in oxygen and contains annual clastic laminations. A coarse and fine silt layer is deposited during the snow-melting season, and is overlaid by a distinctive clay layer, which results from the deposition of fine material from the water column during ice-covered winter months [*Lamoureux*, 1999a]. The sedimentation in the distal basin is mainly due to settling, because the sill protects the basin from most turbidites [*Patridge*, 1999].

3. Methods

[5] Short gravity cores, vibracores and freeze cores were retrieved from the distal basin. Clear visual matches between the cores from different locations within the basin confirmed the quality and the representativity of the sequence [*Petterson et al.*, 1993]. Three cores from both basins were dated with ^{210}Pb and ^{137}Cs. Thin-sections were prepared using a freeze drying technique [*Lotter and Lemcke*, 1999]. Large-scale photographic prints of the thin-sections were used to locate lamina boundaries with 0.05 mm precision and to map images acquired thereafter at the microscope. Images of single laminae were taken from thin-sections using both petrographic and scanning electron microscopes (SEM). If necessary, we masked the previous or following year's sediment, as well as other sedimentary features not related to early spring run-off, i.e. eolian sands and rain events [*Lamoureux*, 1999a]. In order to compare the results between the two sets of images, photographs were taken at the same

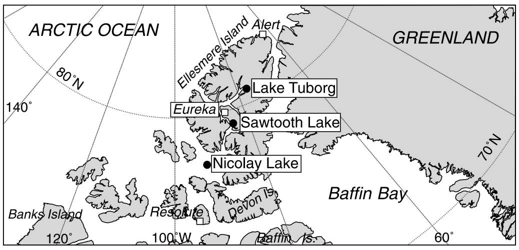

Figure 1. Location map. White squares are weather stations. Black circles are the sites mentioned in the text. Sawtooth lake is located at 79°20′N, 83°51′W, 280 m a.s.l., Nunavut, Canada.

magnification (× 100). We used a digital camera to acquire photographs from a petrographic microscope at a resolution of 0.86 pixels/μm. Backscattered Electron Images (BSEI) were acquired at the SEM (operated at 20 kV and 20 mm working distance) using a 4 pi™ system at a resolution of 1 pixel/μm. Images covering a surface area ~1300 × 1000 μm were processed using *NIH Image* v1.61 (developed at the U.S. National Institute of Health and available at http://rsb.info.nih.gov/nih-image/). In this process, the original 255 gray level value images were transformed into black and white images, where black pixels represent detrital grains to be measured [*Ojala and Francus*, 2002]. *Image* was then used to measure the surface area of every grain, typically ~1000 grains per photo. On these images, we determined the grain size using the apparent disk diameter [*Francus*, 1998], which is the diameter of a sphere having the same surface area as the particle [*Last*, 2001]. The smallest grains are not directly measured with this technique, i.e. <4 μm with the current setting. Nineteen parameters of the grain-size distribution were computed (Table 1). We obtained annually resolved textural parameters for the last 400 yrs including the period overlapping the instrumental record at Eureka.

4. Results

4.1. Chronology

[6] Establishing an accurate chronology was complicated by a lake-wide 2 cm thick slightly erosive turbidite at 2 cm depth. However, by comprehensive examination of the sediment at the SEM and knowing the location of the ^{137}Cs peak we have established a reliable chronology. We

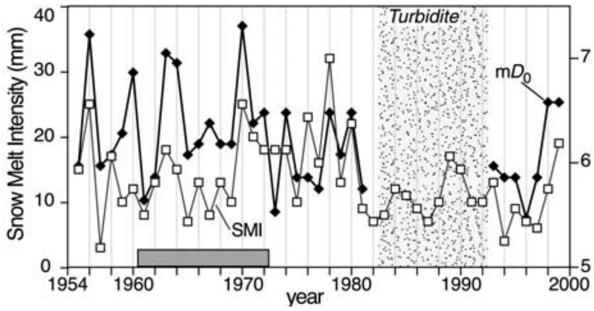

Figure 2. Calibration of the grain-size signal with the Eureka instrumental data set, and location of the 5 mm thick interval (±2.5 mm for sampling accuracy) containing the ^{137}Cs peak, i.e. 0.20 Bq/gr. ±0.006 (gray box). SMI (open squares) and mD_0 (black diamonds) from core #99-10-7 (r = 0.53 with p = 0.001).

obtained from the same location an intact water sediment interface with both a freeze corer and short gravity corer in two successive years. Sediment cores from 2000 contained one additional lamination compared to the cores retrieved in 1999. This confirms that the laminations are annual. We counted 7 varves from the top of the sequence to the turbidite. Below the turbidite is a well-defined ^{137}Cs peak that identifies 1963 (Figure 2). This peak occurs at the exact same stratigraphic position in the three cores. We believe that the peak is located at its real stratigraphic position and that migration down-core is very unlikely, because the sediment is laminated, very poor in diatoms and organic matter, rich in clays, and because the ^{137}Cs peak has been shown to be reliable in minerogenic clay-rich Arctic sediments [*Lamoureux*, 1999b]. We estimate that ~9 yrs of sediments were eroded by the turbidite, by counting varves upward from the interval of the ^{137}Cs peak to the lower boundary of that event. The varve count below 1963 is consistent with the chronology inferred from the ^{210}Pb curve. However, some microbioturbation occurs below 1963, suggesting that the correlation with instrumental data before 1963 may not be as accurate as in the uppermost section.

4.2. Calibration With the Instrumental Record and the 400 Years Record

[7] Sediment measurements are reproducible among the cores: the median apparent disk diameter, mD_0, of two cores separated by 200 m, correlates well for 35 yrs (r = 0.76).

Table 1. Most Significant Climate and Sediment Parameters Used in This Paper

Climate parameters from Eureka
SMI (snow melt intensity) = maximum snow depth decrease for a period of 10 days (cm)[a]; Snow Depth: maximum snow depth (cm)
Rain M–S = total rain from May to Sept (mm)
pcp M–S = precipitation from May to September (mm) (rain and snow, snow being expressed in equivalent rain (mm))
T° MJJ = mean temperature (°C) for May, June and July; MDD MJJ = Melting Degree Days for May, June and July (°C)
Sediment parameters from image analysis
n = Number of grains in the field of view
D_0 = Apparent grain diameter; mD_0 = median apparent grain diameter [*Francus*, 1998]
% 4–10, % 10–20, % 20–60 and % >60 = Weight % of D_0 fractions between 4–10, 10–20, 20–60 and >60 μm respectively, 100% being all fractions. Weight is calculated using the formula: $((4/3) \times \pi \times ((D_0/2)^3)) \times 2.65$. Grains are therefore considered as spherical quartz grains.
Wght 4–10, Wght 10–20, Wght 20–60, Wght >60 = Absolute weight of the 4 different fractions: 4–10, 10–20, 20–60, and >60 μm (μg).
$R_i = A/L^2$. A = surface area measured by counting enclosed pixels; L = long axis of the best fitting ellipse. R_i is a shape index = 1 for spheres.

Initially, a set of climate (27) and sedimentary (19) parameters has been computed for comparison. The most significant are displayed here.
[a]We acknowledge that one point measurement of snow depth may be not representative of the snowpack. However, correlation between SMI from the multi-point snow survey and mD_0 is r = 0.44 at p = 0.076 (low significance due to only 17 yrs of overlap).

Table 2. Extract of the Matrix of Correlation Coefficients (Pearson-Pairwise) of the Variables Defined in Table 1 With Measurements of BSEI of Core #99-10-7

	SMI	Rain M–S	pcp M–S	MDD MJJ	T° MJJ	Snow Depth
MDD MJJ	−0.09	−0.20	−0.20	1.00		
T° MJJ	−0.28	−0.07	−0.03	**0.82**	1.00	
SnowDepth	0.21	0.24	0.24	−0.27	−0.21	1.00
mD_0	**0.53**	−0.31	**−0.56**	0.11	−0.04	0.07
% 4–10	−0.19	**0.35**	**0.44**	0.01	0.00	−0.07
% 10–20	0.06	0.22	0.19	0.07	−0.05	−0.10
% 20–60	0.11	−0.32	**−0.45**	−0.06	−0.03	0.06
%>60	0.02	−0.13	−0.04	0.01	0.07	0.07
Wght 4–10	0.24	0.08	−0.03	0.23	0.12	0.02
Wght 10–20	**0.53**	0.04	−0.16	0.22	0.07	0.03
Wght 20–60	**0.50**	−0.09	−0.28	0.28	0.21	0.02
Wght >60	0.06	−0.06	−0.03	0.18	0.17	0.06
Vrv Thickn	0.10	−0.30	−0.15	0.27	0.16	0.06

Correlations in Boldface are significant at p = 0.05. Coefficients discussed in the text are underlined. Vrv Thickn = varve thickness.

BSEI and petrographic microscope measurements taken on the same core also compare well (r = 0.78). The shape of the grains is mainly rounded, R_i being 0.56 (Table 1). Snow Melt Intensity (SMI), defined as the maximum snow depth decrease for a period of 10 days (Table 1), correlates with mD_0 for 35 yrs of record (r = 0.51 [p = 0.002] for core #99-10-5 using petrographic microscope and 0.53 for core #99-10-7 using BSEI [p = 0.001]) (Figure 2). In core #99-10-7 using BSEI, SMI also correlates positively with the absolute weight of the 10–20 μm and 20–60 μm fractions (r = 0.53 [p = 0.001] and r = 0.50 [p = 0.002] respectively). Varve thickness measured on thin-sections weakly correlates with mean summer temperature (r = 0.16) or melting degree-days (MDD) (r = 0.27) (Table 2).

[8] We measured grain-size for each sedimentary layer for the last 400 years using the image analysis technique. The record shows a clear coarsening trend during the 20th century that is visible in both mD_0 and the relative percentage of the different grain-size fractions (Figure 3). The varve thickness does not show an increase during the 20th century.

5. Discussion

[9] Image analysis provides robust measurements because results can be reproduced from core to core and because petrographic microscope measurements compare well with those derived from BSEI. The strength of the imaging technique is that very fine laminae, down to 300 μm, can be accurately measured. Individual laminations are accessible for grain-size measurements without the risk of contamination from neighboring laminae, as is the case in sampling varves using traditional techniques [*Lotter et al.*, 1997]. It also allows climate data to be directly related to sedimentary processes inferred from textural parameters, which is not the case when lamination thickness is measured. Another advantage of the method is that measurements are not influenced by core compression with increasing depth. Processing the images is not time-consuming (e.g. ~2 min/image). However, image acquisition is time-consuming because the quality of the photographs is critical in order to obtain reliable results [*Ojala and Francus*, 2002]. We acknowledge that, like all grain size analysis techniques, our method involves a systematic error in grain-size measurements by assuming that grains are spheres [*Last*, 2001], but the error is small, because clastic grains have a relatively rounded shape (R_i > 0.5) (Table 1).

[10] In SL sediments, mD_0 and absolute weight of the 10–20 and 20–60 μm fractions correlate well with SMI. This relationship reflects the amount of energy available to mobilize sediment and transport material from the watershed to the lake basin. As the rate of snowmelt increases, more silt grains reach the distal basin. The >60 μm fraction from the main stream is probably deposited in the proximal basin because of the filtering effect of the sill separating the two basins. During exceptional summer rain events coarse

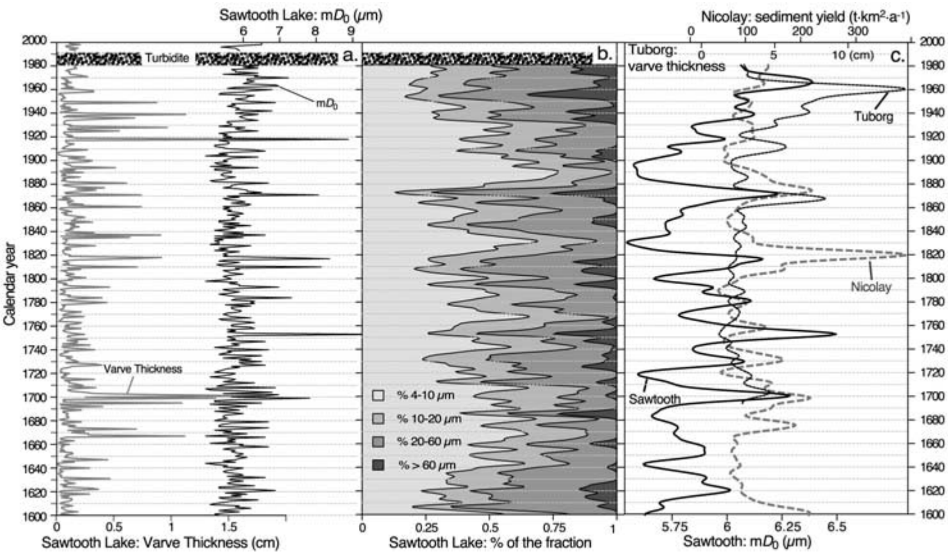

Figure 3. (a) Varve thickness (median = 1 mm; mode = 0.4 mm) measured on thin-sections, and annual mD_0 (μm) measured on BSEI. (b) Relative weight of the different grain-size fractions inferred from image analysis (Table 1) (10-year smoothing applied for readability). (c) Comparison of mD_0 at Sawtooth with sediment yield (t. km^2 .a^{-1}) at Nicolay Lake [*Lamoureux*, 2000] and with varve thickness (cm) (stack) at Lake Tuborg [*Smith*, 1997] (20-year smoothing applied).

sediments may be carried into the lake from slopes closer to the coring site. SMI seems to be proportional to the depth of snowpack but not to summer temperature (Table 2), and is therefore more an expression of the rate of change from cold to warm days.

[11] Considering that a single year offset in a portion of the chronology, i.e. especially below 1963, would substantially alter the quality of the relationship, the correlation value obtained for the calibration is quite good and based on a physically meaningful model. A more comprehensive set of climate indices may still improve the correlations found here. However, other studies in the Arctic have found similar correlation values with varve thickness and early summer temperature [*Hardy et al.*, 1996; *Hughen et al.*, 2000]. Total varve thickness at SL is weakly related to mean summer temperature or MDD. Two reasons can explain this poor link. First, the potential snowmelt is limited by the small amount of snow that accumulates every winter in this polar desert; once the snow has melted, runoff and sediment flux rapidly diminish. Second, intense rainfall events during snow/ice-free summer months can produce brief periods of high sediment loads [*Hardy*, 1996], and therefore thicker than normal laminations. A similar summer rainfall event might have triggered the turbidite found at 2 cm depth.

[12] Median grain size of the last 400 years shows strong decadal-scale variability, and a clear coarsening in the 20th century (until the 1960s, which was the most recent temperature peak in this region). Periods of high mD_0 are also indicated in the 1870s, 1810s, 1750s and ~1700 (Figure 3). Varve thickness variations in SL sediments show little trend over time. A comparison with mD_0 suggests that overall varve thickness around 1700, in the 1810s and to some extent in the 1870s was also above average. A possible interpretation is that, in addition to a warm early season melt period that provided the necessary energy to move relatively coarse sediment reflected in the higher mD_0, a deeper winter snowpack during those periods contributed to more prolonged runoff and associated sediment flux over the subsequent summer months. On the other hand, some sections contain thick varves and are fine grained (e.g. the 1670s, Figure 3). We interpret these periods as being characterized by frequent but low intensity summer precipitation (mainly drizzle) bringing a larger proportion of fine silts into the lake. This is consistent with the positive correlation between the amount of precipitation from May to Sept and the relative abundance of the fine silt fraction (% 4–10 μm) (Table 2) recorded during the calibration period.

[13] There are strong visual similarities between the record of mD_0 in SL and other records in the Arctic (Figure 3). We note that the varve thickness record from Lake Tuborg reflects a different hydrological system wherein sediment flux to the lake is driven by the melting of outlet glaciers from the Agassiz Ice Cap [*Smith*, 1997], which provides runoff throughout the melt season, long after snow has melted. We also note that sediment yield at Nicolay Lake is influenced by precipitation [*Lamoureux*, 2000]. Despite this differences, co-variations in sediment deposition at Nicolay lake (300 km southwest of SL) and Lake Tuborg (250 km to the northeast) strengthens confidence in the SL varve chronology and its climatic significance. They indicate that a regional climate pattern exists through time in the High Arctic.

[14] In conclusion, image analysis of varved sediments from SL has demonstrated that textural variations reflect early season climatic conditions in the High Arctic. The technique opens new horizons in establishing transfer functions for minerogenic sediments that are poor in organic material. Laminated sequences studied in the past should be revisited to provide more detailed results than previously achieved by simply measuring the varve thickness. The sediments of SL provide an annual record of snowmelt intensity and other climate variables. Our study also indicates the need for direct calibration of sedimentary data with on-site meteorological data, linked to hydrological monitoring.

[15] **Acknowledgments.** This material is based upon work supported by the US-NSF under Grant # 9708071. P. Francus is supported by the University of Massachusetts. We thank Polar Continental Shelf Project, First Air, the members of the 1998–2000 field parties, and S. Lamoureux for Nicolay Lake data. This is PARCS contribution 178.

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