IMAGE ANALYSIS SEDIMENTS AND PALEOENVIRONMENTS

PROGRAM AND ABSTRACTS

UNIVERSITY OF MASSACHUSETTS AMHERST

NOVEMBER 8 - 10 TH, 2001

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Image analysis, Sediments and Paleoenvironments
University of Massachusetts
Amherst, November 8-10 th, 2001

PROGRAM

Thursday, November 8th, 2001, Campus Center, room 905-909

18:00-20:00 **Ice breaker party and browsing through poster exhibition**

Friday, November 9th, 2001, Campus Center room 904-908

9:00	**<u>Welcome and Introduction</u>**	
	P. Francus	
9:15	**<u>Overview</u>**	
	J. Thurow	RECORDS – WHAT HAVE BEEN USED AND WHAT CAME OUT OF IT
	R. Bradley	THE IMPORTANCE OF HIGH RESOLUTION STUDIES FOR PALEOCLIMATE RECONSTRUCTION
9:45		Brief discussion
10:00	*Coffee Break**	*(make copy of passports and visa)*
	<u>Keynote</u>	
10:25	Dork Sahagian	EXTRACTION OF QUANTITATIVE 3-D INFORMATION FROM DIGITAL IMAGERY
	<u>Session 1: Image analysis of surfaces of sediment cores</u>	
11:10	S. Nederbragt	DIGITAL SEDIMENT COLOR ANALYSIS AS A METHOD TO OBTAIN HIGH RESOLUTION CLIMATE PROXY RECORDS
11:35	J. Ortiz	TOWARDS A NON-LINEAR GRAYSCALE CALIBRATION METHOD
12:00	A. Prokoph	FROM DEPTH TO TIME: THE TRANSFORMATION OF SEDIMENT IMAGE COLOR DATA INTO HIGH-RESOLUTION TIME-SCALES
12:25	*Lunch*	*administrative for foreign attendees*
14:00	**<u>Poster session</u>** <u>+ coffee</u>	
		including a fishing for ideas session
15:00	*Coffee*	
15:45 - 17:45	**<u>Bytes games (Morrill Sciences Center)</u>**	
		Demo of Stereology (Alex Proussevitch)
		Practicing NIH Image on test images
		Acquiring pictures at the SEM,
20:00	***Conference dinner***	
	At Pinnocchio's, Amherst Center. Free public transportation available	

Saturday, November 10th, 2001, Campus Center, room 904-908

9:00	**Session 2: Automated recognition**	
	I. France	A FLEXIBLE IMAGE RECOGNITION SYSTEM APPLIED TO POLLEN COUNTING
	I. Rovner	APPLICATIONS OF IMAGE ANALYSIS IN ENVIRONMENTAL ARCHAEOLOGY
9:50	**Keynote**	
	E. Pirard	IMAGE ANALYSIS IN A STATISTICAL PERPECTIVE: IS IT REALLY ACCURATE ?
10:35	*Coffee Break*	
	Session 3: Image analysis of X-ray radiography and thin-sections	
11:00	P. Francus	IMAGE ANALYSIS OF THIN-SECTIONS TO RECONSTRUCT PALEOENVIRONMENTS
11:25	E. Hunt	THE USE OF IMAGE ANALYSIS TO INVESTIGATE THE CLIMATIC HISTORY OF A LAMINATED TURKISH CRATER LAKE SEQUENCE
11:50	A. Kemp	NEW OPPORTUNITIES FOR RAPID ANALYSIS OF LAMINATED SEDIMENTS USING DIGITAL SCANNING ELECTRON MICROSCOPY
12:15	S. Principato	IMAGE ANALYSIS OF FIVE DIAMICTON UNITS: AN APPROACH TO UNDERSTANDING THE DEPOSITIONAL ENVIRONMENT OF MARINE CORES FROM THE ICELAND SHELF
12:40	*Lunch*	
14:00	**Reports of reporters**	
14:50	**Discussion groups**	
		3 groups: image acquisition, image processing, measurements. elaboration of protocols and recommendations for image analysis
16:00	*Coffee Break*	
16:25 – open end	**Summary - Elaboration of the table of content of the Book. Conclusions**	

INTERPRETING FIRE HISTORY DATA FROM TREELINE LACUSTRINE SEDIMENTS: A CASE STUDY USING IMAGE ANALYSIS

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Fire history data are important to evaluate landscape and vegetation changes through time. Traditionally, palynologists have recorded charcoal fragments on pollen slides, assuming that peaks in charcoal concentration represent fires that occurred in the vicinity of the lake, the rest being background noise resulting from fires that burned outside the watershed. But is this way of accounting for past fire activity really accurate? While it is true that most large fires will be easily detected by this method, some small fires might be missed because they do not produce enough charcoal for their peaks to be detected, even using statistical tests. It thus appears that taking into account the size of the charcoal fragments will allow for better precision. Larger fragments are brought to a lake by inlets and runoff following a local fire, while regional fires are represented by smaller wind-dispersed fragments.

A quick and simple method is presented here, using charcoal fragments from pollen slides and relying on simple image analysis techniques. Charcoal fragments are filmed by a digital camera mounted on a microscope and connected to a computer and can thus be counted and measured. It is then possible to draw, for each sampling level, a histogram of particle size distribution. Assuming that local fires will produce a greater amount of large fragments compared to fires from outside the watershed, one would expect a shift towards the large fragments in the histograms from sampling levels where local fires occurred. The smallest size classes will account for most of the counted fragments, but less so than for regional fires. A Kolmogorov-Smirnov test should detect this difference. This method will lead to the detection of all the fires that affected a particular watershed, regardless of their size.

Two lakes with well-known fire histories were sampled at the treeline in subarctic Québec to test this method of fire detection in lacustrine sediments. There were very few fires in the region since deglaciation ca. 6000 years ago. The fires are thus easier to detect.

X-RAY DENSITOMETRY AND BSEI ANALYSIS OF A 1,200 YEAR LONG VARVED COASTAL SEDIMENTARY RECORD

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A high resolution record of hurricane and tropical storm activity for the Boston area is being developed based on the 1,200 year long annually resolvable (varved) sedimentary record archived in the Lower Mystic Lake. The Mystic Lake is a low elevation (1 m above sea level), meromictic coastal lake that is directly connected to Boston Harbor by the Mystic River. Occasional large hurricane and storm surge events have affected the lake, and such events can be detected by changes in sedimentology (turbidite/detritus layers) and diatom assemblages.

The varves are typically 1-3 mm thick, and composed of organic detritus, diatom blooms, and minerogenic laminae. A floating varve chronology based on microscope analysis of petrographic thin-sections has been developed, and shows very good agreement with the results of radiocarbon analyses. Cross-validatation of the thin-section based varve chronology was originally intended to be done with X-ray densitometry measurements using “DendroScan” (Campbell, 1996), a semi-automated tree ring width and density measurement tool. However, pilot runs showed the varves are too complex for DendroScan to easily interpret and count.

Densitometry measurements of X-ray images will still be performed, and will be used in conjunction with back-scatter electron microscope images (BSEI) following Ojala and Francus (2001). Ojala and Francus (2001) documented a strong correlation between between mean gray levels of X-ray images and grain counts of black and white images processed from BSEI work. We expect to document a similar relationship for the Mystic Lake record. Thus, the X-ray densitometry measurements will serve as a long term index to interpret the sedimentary inputs into the lake, in particular, minerogenic content. Minerogenic content may be related back to several environmental parameters, in particular the strength of wind-driven mixing during the fall which appears to the the main contributor, as well as changes in precipitation/runoff, and land use changes. BSEI analysis (Francus, 1998) will also be used to characterize and quantify the minerogenic grain size and counts of normal laminae versus a series of turbidite/detritus layers which are present in the chronology. These turbidite/detritus event layers may be related to possible overwash events from large hurricanes and storm surges. The rich historical record will serve as an important tool to calibrate these results.

Campbell, I.D., 1996 (online), DendroScan: tree-ring width and density measurement system: INQUA Sub-Commission on Data-Handling Methods Newsletter 14, July 1996, URL: http://www.kv.geo.uu.se/inqua/news14/n14-ic.htm.

Francus P., 1998, An image analysis technique to measure grain-size variation in thin sections of soft clastic sediments, Sedimentary Geology, v. 121, p.289-298.

Ojala, A. and Francus, P., 2001, Comparing X-ray densitometry and BSE –image analysis of thin-section in varved sediments, Boreas (accepted for publication).

AUTOMATED SIZE MEASUREMENTS OF PLANKTIC FORAMINIFERA WITH AN INCIDENT LIGHT MICROSCOPE

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Manual collection of a statistically significant quantity of unbiased and reproducible data on microfossil morphology is time consuming. Therefore, fully automated operating robots are needed that recognise and analyse microfossils. Here, a robot is described that independently measures the size and shape of randomly oriented planktic foraminifera using an incident light microscope (Figure 1). The robot is able to capture about 1000 images of particles larger than 63µm per hour and then extracts prominent morphological features including size. The system has successfully completed about 400 deep-sea sediment analyses. The robot can also be used for automatic analysis of particles other than planktic foraminifera because elementary problems such as contrast and focus on an incident light microscope have been overcome using a low reflectance and levelled glass tray.

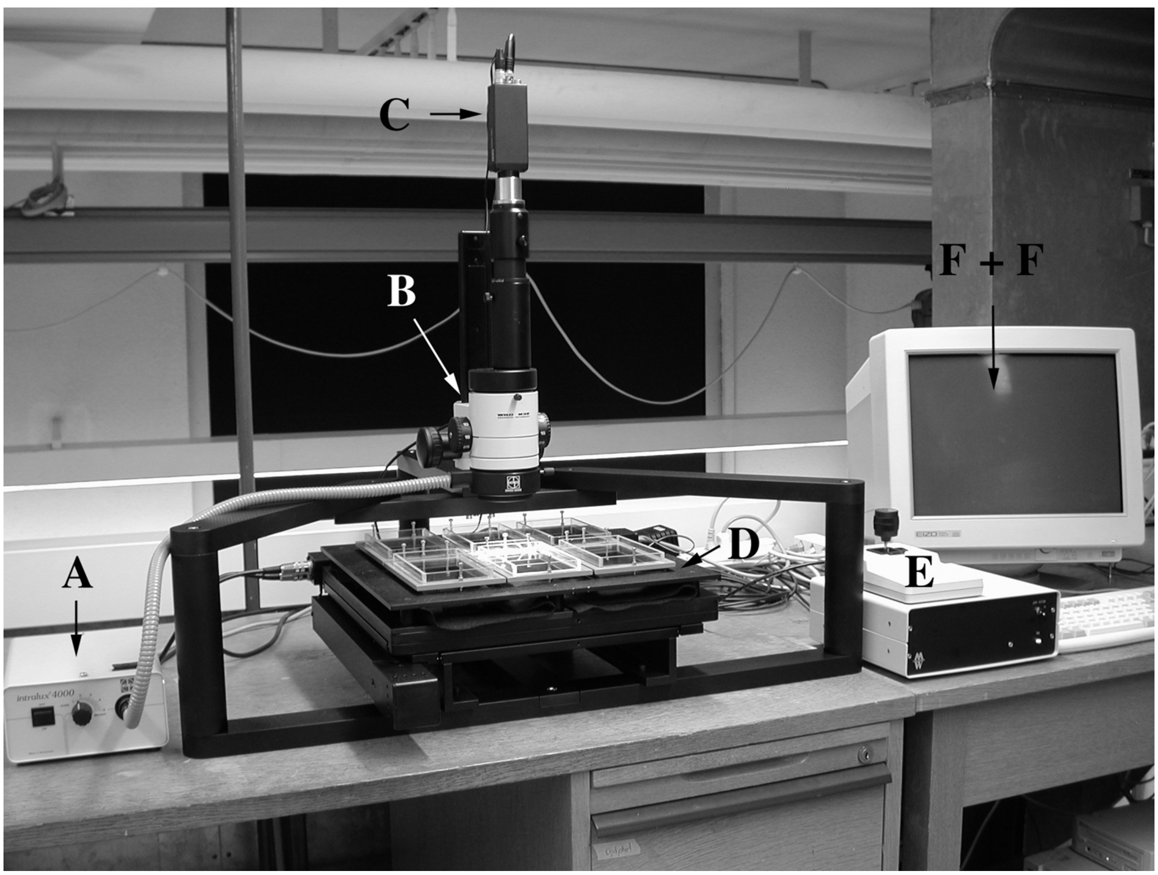

Figure 1: System set-up. A: Ring light; B: Microscope; C: CCD video camera; D: Glass tray with level holder; E: Computer controlled motorised X, Y — stage, F: Computer, G: Video frame grabber. (modified after Bollmann et al., (submitted)).

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AUTOMATED IMAGE ACQUISITION AND MICROFOSSIL CLASSIFICATION USING A SCANNING ELECTRON MICROSCOPE COMBINED WITH A NEURAL NETWORK CLASSIFIER

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The manual collection of a statistically significant amount of unbiased and reproducible data on microfossil abundance with a SEM is very time consuming. We have therefore developed a fully automated image capture and identification system using a SEM (Philips XL30 LaB6), combined with the analySIS imaging software and a convolutional neural network classifier.
The system autonomously scans a predefined area and captures either detailed images of single objects at maximum magnification (e.g. up to approx. 120 single objects per hour for microfossil classification and morphometry) or overview images (e.g. up to 1000 images per hour for offline plankton counts on membrane filter). The former mode was successfully applied to collect several thousand images of coccoliths for training and testing a convolutional neural network classifier. The mean recognition rate using the trained neural network classifier is currently 84% for 13 coccolith species.
The latter mode was successfully applied to collect several hundred thousand overview images from membrane filters. This mode enables nearly optimal utilization of the SEM as overview images can be stored on CD-ROMs and processed manually on a PC.
The next step is to incorporate the neural network classifier into the SEM acquisition program for online classification.

THE IMPORTANCE OF HIGH RESOLUTION STUDIES FOR PALEOCLIMATE RECONSTRUCTION

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The exceptional warmth of the 1990s - the warmest decade since instrumental records began - has sharpened concern over the nature of anthropogenic influences on climate. However, the causes of 20th century climate variability are difficult to resolve, because the period of instrumental records coincides with the time during which the atmosphere has increasingly been contaminated by greenhouse gases. What are the "natural" variations that underlie the observed warming of the 20th century?

These questions require a large-scale perspective on climate that must be based on a variety of paleoclimatic data. Various attempts to reconstruct temperature changes of the last millennium have been based mainly on tree ring data, supplemented by information from ice cores, corals and historical documents. Each of these data sets represents a limited geographical domain. On a global scale, large areas remain under-represented. Furthermore, methodological issues with some proxies raise questions about the veracity of currently available long-term paleoclimatic reconstructions. Varved sediments can contribute to a better understanding of past climate variability, providing that chronologies are verified and quantitative relationships are established between the sedimentary record and climate. In addition to image analysis of the sediments, this requires more field-based process studies.

LAKE SUPERIOR VARVES: ARE THEY RECORDS OF THE RATE OF LAURENTIDE ICE SHEET RETREAT?

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As the Laurentide Ice Sheet withdrew from the region north of the Lake Superior basin, sediment laden meltwater funneled into Lake Superior and deposited up to 1,300 calcareous, gray varves. Overlapping sediment cores from the northern edge of the lake provide a set of varves that are unusually distinct. Digital images and smear slides of these varves detail a high resolution record of sediment supply to the Lake Superior basin during a period of ice sheet retreat between 9500 and 8200 ^{14}C years BP. Basal varves are characterized by summer layers that are carbonate rich, silty clay and winter layers of finer-grained clay. Sandy laminae are common. The varves grade upward into finer-grained couplets devoid of sandy laminae. There is a general decrease in dropstones upsection. Varve thickness measurements on digital images suggest that there were two periods of increased sediment supply to the basin, a 400 year period near the base of the record and a brief 50 year interval near the top of the record. The thickest varves are within the fine-grained varves at the top of the record when the ice sheet was presumably farthest from the basin. Varve thickness is hypothesized to correlate with increases in the relative water supply from the melting ice sheet. If this is the case, the ice sheet north of Lake Superior stopped or slowed dramatically for a 500 year period sometime between 8900 and 8400 ^{14}C years BP. The Nakina moraine located over 100 km north of Lake Superior is the likely expression for this long delay in ice margin retreat. Varve thickness, total inorganic carbon, grain size, and oxygen isotope measurements from other varve records in Lake Superior should help demonstrate how well these records correlate within the basin and clarify the timing of the record.

DETERMINING GRAIN SIZE IN LAMINATED LAKE SEDIMENTS USING IMAGE PROPERTIES

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Quantifying grain size in laminated sediments using image properties of sediment images, rather than sub-sampling and completing particle size analysis has many practical advantages. Grain size measurements obtained from physical subsampling limited by the resolution of the sampling equipment. We have subsampled sediment at half-millimetre intervals, but found that there was a problem in retaining enough sediment (c. 150 mg) for analysis and typically need use one millimetre-thick subsamples. Our goal is to develop a method to use sediment image properties to determine grain size at fine resolution for detailed paleoenvironmental analysis.

In most laminated lake sediments there is a noticeable image property (i.e. mean gray scale, gray scale standard deviation) associated with particular grain sizes. For example, in thin section images, clay from most proglacial lakes is darker than silt and sand sized particles. This is primarily due to reduced light transmittance and to a lesser extent, mineralology. Once the image properties and their relationship to sample grain size have been determined, our premise is that it will be possible to measure grain size from image properties for other sediments taken from the same lake. Therefore, we acknowledge that our approach is likely to be lake-specific, but our results to date do not indicate that the calibration procedure is an onerous task.

We have taken thin section images and corresponding grain size results for three different types of lake sediment and attempted to design an experimental approach/protocol to predict grain size for each of these sediment types. From Summit Lake, British Columbia, we have two sediment unit samples. The first unit is a 223 mm- thick graded unit (or Natural Sedimentary Event (NSE)) found within a sediment core. The NSE was removed from the core and sub-sampled into millimetre-thick sections. Another part of the same NSE was freeze-dried and vacuum embedded using epoxy resin and thin sectioned using standard methods. Digital images were obtained by scanning the finished thin sections at 600 dpi using a flatbed transparency scanner. Using Scion Image software, image mean, mode and standard deviation gray scale measures were sampled to correspond to the physical grain size sub-samples. Our initial results indicate that mean grain size and the image standard deviation are a positively correlated was useful for predicting grain size from the upper NSE sample. The correlation was highest at the top of the NSE (1 – 84 mm of 223 mm), where the largest variation in grain size occurs ($r^2 = 0.55$, n=78, $p<0.001$).

The second sample from Summit Lake was produced in the laboratory using material from sediment cores. Sediments covering approximately the 1– 100 µm grain size range were homogenized in distilled water and placed in a 22 cm-tall, clear settling chamber to produce a synthetic graded bed. The goal was to mimic sub-annual event beds found in the sediment cores but to impose a higher accumulation rate suitable for physical subsampling. The resulting graded unit was subsampled for grain size analysis and embedded for thin sectioning in the same way as the NSE. Two thin sections were made from the same embedded sediment with the purpose of testing the reproducibility of the model. From the image and grain size data of the sedimentary event simulation experiment (SESE) it was determined that the image mean gray scale and the mean grain size were highly correlated when the top two samples were removed ($r^2 = 0.95$ n=6, $p<0.001$) but both parameters were still correlated when these samples were included ($r^2 = 0.37$, n=8, $p<0.1$). The second thin section from the same SESE supported similar findings ($r^2 = 0.96$, n=6, $p<0.001$, $r^2 = 0.63$, n=8, $p<0.01$). The reason for differences in correlation are likely attributed to thin section edge effects, or, because the image sample size (in pixels) was smaller than the rest of the samples in order to correspond to the grain size sample interval. The number of measurements was low because of the thin sedimentary unit produced by this preliminary experiment.

The third test of our experimental approach used two thick varves from Bear Lake, Nunavut. Following the similar methods as described above, the relationship between mean grain size and mean image gray scale for the image produced a good correlation (r^2=0.61, n=13, $p<0.001$).

The SESE and Bear Lake examples provided us with the best results likely due to the quality of the thin sections and the broad range of the grain sizes contained in the samples. We had less success with the NSE due to the small range of changes in grain size over a large proportion of the sample depth.

We believe this method holds promise as a tool for determining grain size in laminated sediments. Our ongoing work will work with thicker SESE from Summit Lake and to deal with issues regarding image properties from different thin sections. Ultimately, a successful method would aid in characterizing sub-annual events in varved sediments as a measure of environmental variabilit

CLIMATE AND FOREST FIRE RELATIONSHIPS INFERRED FROM LAKE SEDIMENTS ALONG A NORTH-SOUTH TRANSECT ON INTERIOR PLATEAU (BRITISH COLUMBIA, CANADA)

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Increases in greenhouse gases are expected to result in warmer and drier conditions in western Canada (Saporta et al., 1998). These changes in climatic conditions may result in an increasing danger of wildfires. In this context, important questions are how will fire intensity, extent, and frequency change under warmer and drier conditions? One of the possible keys to answer these questions is to decipher the relationships between climate and fire characteristics since the last deglaciation.

A comprehensive understanding of the climate/fire dynamics is not possible because of the short duration of the available instrumental records. Paleolimnological techniques can be used to reconstruct past environmental conditions (Stoermer and Smol, 1999) including climate change and fire regimes. First, there is a great potential for quantitative reconstructions of past climatic conditions from diatoms preserved in lake sediments. The ability of diatoms to reconstruct past climatic conditions in this region is already demonstrated by previous studies (Bennett, 1999, Bennett et al., 2001). Additionally, it is possible to track changes in fire regimes from lake sediments using charcoal transported to and preserved in lake sediments (Clark et al., 1997). Lakes are an integral part of the forested landscape and any process occurring in their watersheds may potentially impact the dynamic of aquatic ecosystem, including changes in water chemistry, phytoplankton, zooplankton, and fish (Figure 1). Thus, the biological, chemical, and physical information preserved in lake sediments can be used to reconstruct past climate conditions and fire events.

The climate/forest fire relationships will be assessed along a north-south transect over the Holocene on the Interior Plateau of British Columbia in three different biogeoclimatic zones: 1) Sub-boreal Spruce; 2) Interior Douglas Fir; and 3) Engelmann Spruce/Interior Douglas Fir. From each biogeoclimatic zone, lake sediments will be used to infer past climatic patterns using diatom-based transfer functions (Cumming et al., 1995; Willson et al., 1996) and to reconstruct fire regimes using microcharcoal analysis. Furthermore, the linkages between climate and fire and their spatial and temporal variability will be assessed over the Holocene in the study region. The resulting records will reveal the spatial extent of change in climatic conditions, the patterns in fire regimes under different climatic conditions, the impact of climate and fire in these biogeoclimatic regions, as well as plausible scenarios that can be used to help assess mechanistic models of climate change and fire regimes that are predicted to occur with global warming.

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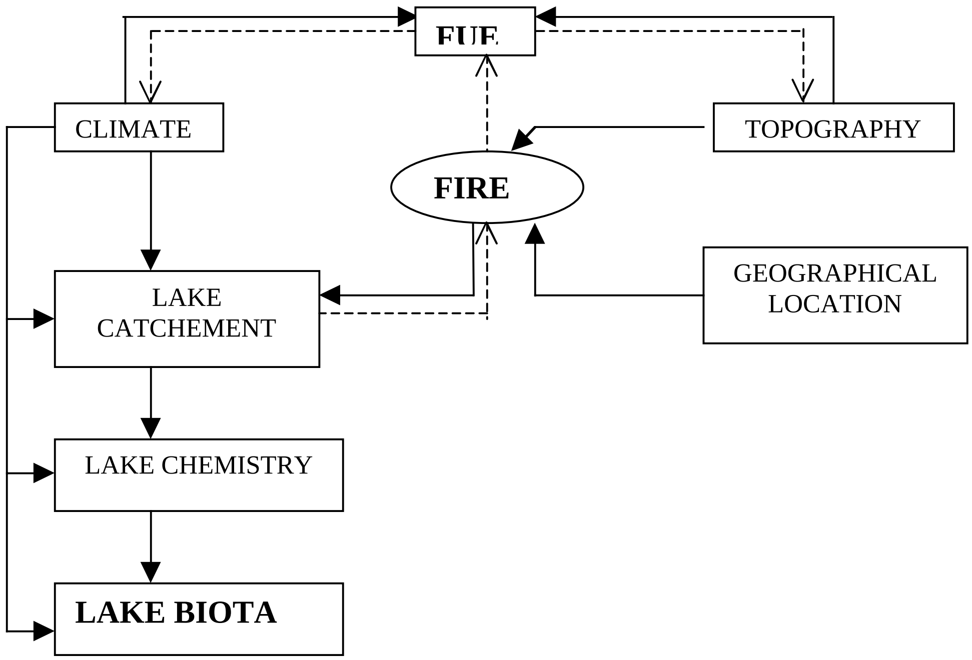

Figure 1. Climate, fire, and vegetation relationships and potential impact on lacustrine ecosystems.

A FLEXIBLE IMAGE RECOGNITION SYSTEM APPLIED TO POLLEN COUNTING

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Palynological analysis is required in many applications, but the pollen counting task is highly skilled and time consuming [1]. Developing an automated system would enable a faster of larger samples, and would provide a higher quality analysis [2].

The field of pollen recognition provides special challenges for image processing; the large number of pollen types means that any recognition technique either has to be small scale -- to concentrate on a small number of pollen types -- or to be flexible -- so that different types can be added as required.

We describe a flexible image classifying neural network [3] which we have applied to the task of pollen classification [4]. The results we have obtained show promise on a sample data set. Based upon the experiences gained we suggest a number of criteria which a pollen recognition system should have.

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X-RAY DENSITOMETRY VS IMAGE ANALYSIS OF THIN-SECTIONS: A COMPARED STUDY OF VARVED SEDIMENTS OF LAKE NAUTAJÄRVI, FINLAND

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A 10 cm long section of lake Nautajärvi, Finland, has been analyzed using both X-ray densitometry images retrieved from hardened sediment slabs and image analysis of backscattered electron microscope images (BSEI) of thin-sections. Lake Nautajärvi's varves are alternating of silicoclastic material deposited in spring and organic matter settling in summer, autumn and winter. In X-ray images, varved sediments appear as a succession of black and white stripes, white ones being the spring detrital layers. Due to the sharp onset of minerogenic spring layer, a semiautomatic tree-ring width and density measurement system DendroScan was applied to X-ray radiographs.

In BSEI, the amount and size of accumulated spring detrital grains was of our intrest. Micrographs are processed to produce black and white images, where white pixels represent the clay-rich sedimentary matrix and black pixels represent particles in the matrix: silt- or sand-sized, terrigenous or authigenic particles like diatoms. Measurements of the size, shape, orientation and packing of the particles forming the varves were obtained.

The results obtained at an annual resolution are compared and discussed. For each varve, mean gray level values in BSEI correlate well with the mean gray-level value of X-ray images. Grain-size obtained on BSEI do not correlate with any parameters computed from X-ray radiography. Strengths and weakness of both techniques are discussed and recommendations are provided.

IMAGE ANALYSIS OF THIN-SECTIONS TO RECONSTRUCT PALEOENVIRONMENTS

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A freeze-drying technique is used to obtain thin-sections from soft-sediments without disturbance. Optical and backscattered electron microscope photographs are digitized from thin-sections. Processing of the 256 grey-scale pictures produces binary (black and white) images, where white pixels represent the clay-rich sedimentary matrix and black pixels represent objects in the matrix: silt- or sand-sized, terrigenous or authigenic particles, diatoms or organic debris. Measurements of the objects allow calculation of the value of several simple indices. These indices are defined to estimate quantitatively the grain-size, shape, orientation, and packing of the objects that constitute the sedimentary microstructures. The methodology advantageously replaces most of the time-consuming and laborious counting and measurements carried out in classical microsedimentological studies. It can be easily modified according to the needs of the user.

Two indices are defined to quantify grain-size from siliciclastic sediments: D_0 = equivalent disk diameter; and *P%* = phase percentages. The technique is applied to South Sawtooth Lake, Ellesmere Island (79˚ 20’ N, 83˚ 51’ W), an oligotrophic lake located at the southwestern part of Fosheim Peninsula. The distal basin contains annual clastic laminations: coarse and fine silt sediment during the snow-melting season, followed by the settling of clays during the ice covered winter season. We produced multivariate and quantified data for each varve for the upper section of the sequence. The data obtained on each varve of the uppermost section of the cores have been compared with meteorological and climatological data, e.g. temperature, snow melt, wind, and stream discharge. For the last 33 years, snowmelt intensity correlates well with the median grain-size measured for each annual lamination. We are now producing a measurement of the spring melt intensity for the laminae downcore. This information would have been inaccessible using classical grain-size techniques.

Traditional ichnofabric descriptive (semi quantitative) schemes rely upon subjective estimates of the degree to which original sedimentary fabrics have been disrupted. This paper presents an objective method of quantifying bioturbation in hemipelagic sediments based on a thin-section image-analysis technique. An index, *H*, is defined to quantify the horizontal orientation of the larger grain size fraction of the sediment. *H* is low for bioturbated fabric and high for laminated sediments. In hemipelagic suspension deposits, *H* can be used to quantify bioturbation, assuming that no other sedimentary processes have disrupted the original depositional fabric. The quantitative bioturbation scheme described here is consistent with existing semi quantitative bioturbation schemes; in addition, it is objective and provides higher-resolution descriptions of biological processes that disrupted the sediment after deposition. Applying this quantitative scheme should refine future paleoecological reconstruction derived from lacustrine and marine successions.

A DETAILED COMPARISON OF HIGH-RESOLUTION INVASIVE SAMPLING VS. DIGITAL NON-INVASIVE CORE IMAGING TECHNIQUES: RECORDS OF STADIAL/INTER-STADIAL EVENTS FROM ARABIAN SEA (ODP) SITE 723

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We have analyzed sedimentary nitrogen isotope ratio, %N and chlorin abundance from non-laminated, high accumulation rate Oman Margin marine cores to demonstrate millennial-scale variability in Arabian Sea denitrification and productivity during the last glacial period with very similar pattern in detail to the Dansgaard/Oeschger (D/O) events recorded in Greenland ice cores (Altabet *et al*., *Nature* submitted).

Denitrification occurs under suboxic conditions when bacteria utilize NO_3^- as an electron acceptor, converting it to N_2 gas. This typically occurs in organic-rich continental margin sediments and Intermediate Waters within Oxygen Minimum Zones (OMZ) and causes strong fractionation of nitrogen isotopes, leaving the remaining NO_3^- enriched in ^{15}N. A paleoceanographic record for denitrification intensity is created when ^{15}N-enriched NO_3^- is transported to surface waters and consumed by phytoplankton. After downward transport of resultant organic matter (OM) and excellent sedimentary preservation, we have shown that bulk sedimentary $\delta^{15}N$ provides a record of OMZ (monsoon) intensity with unprecedented detail. Abundance measurements of %N and total chlorins, the early-stage diagenetic sedimentary pheopigment products of chlorophyll *a*, are employed as proxies for OM export.

Assuming synchronicity of low- and high-latitude records, warm phases of the Greenland D/O events correspond to periods of enhanced water column denitrification (as intense as found at present) and high productivity as a likely effect of stronger summer monsoonal upwelling. Conversely, stadials coincide with intervals of little or no denitrification and minima in primary export production.

To further investigate sub-millennial scale monsoon climate variability, we have utilized a range of non-invasive sediment analytical techniques combined with mm-scale sampling of U-Channel sub-cores provided by ODP for the interval 30-46 Ka. Datasets have been generated employing dispersed spectral reflectance (DSR; *FieldSpec*®, Analytical Spectral Devices, Inc.), digital photographs (RGB stacks), ODP Initial Results (onboard) grayscale images, as well as conventional magnetic susceptibility. Image processing software has been employed to quickly and easily extract color intensity profiles from digital photographs (*Scion Image*, Scion Corporation). Solutions for inherent problems with core-surface analysis, such as the resolution of surface roughness, expansion gaps, drying cracks and shadow effects, have been explored using wavelength-normalization, cross-core averaging and automated spike removal techniques.

This investigation of variability at ultra-high temporal resolution has three purposes: (i) to discover which method is most practicable and precise for correlating parallel ODP Holes 723A and 723B (since no composite splice was produced during initial drilling); (ii) to identify which method most closely resembles either productivity proxy or denitrification records; and (iii) to facilitate exploration of maximum achievable resolution given the absence of laminae in otherwise an-/sub-oxic sediments.

All three core-imaging techniques revealed broadly similar patterns within the studied interval. Significantly, each technique clearly detected all stadial/inter-stadial events. However, correlation seems equally strong with both indices of organic matter content and nitrogen isotopes. Comparison of down-core DSR wavelength profiles with records from high-resolution invasive sampling revealed maximum similarity (by root mean square) between these records at λ=510nm and λ=665nm. Significantly, these wavelengths correspond closely with absorbance maxima for carotenoid and chlorin pigments (Satellite I region) respectively. Discrepancies in the recorded rapidity (10^0-10^2 yrs) and exact timing of transitions between stadial and inter-stadial events suggests that organic matter content is not the primary factor determining sediment color. Furthermore, discrepancies revealed between core-surface measurements and invasive sampling results may indicate significant variations in sediment moisture content, lithic fabric and mineralogy (*e.g.* grain size, hematite abundance), likely related to monsoon wind intensity and/or glacially-induced source area aridity.

THE USE OF IMAGE ANALYSIS TO INVESTIGATE THE CLIMATIC HISTORY OF A LAMINATED TURKISH CRATER LAKE SEQUENCE

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A high-resolution study of laminated sediments from Eskı Acigöl, a crater lake in Central Turkey, has employed image analysis techniques to help further our understanding of environmental variability over the last interglacial-glacial transition.

The core sequence comprises an upper unit of non-laminated banded silts and peats of mid-late Holocene age. The lower 12 metres are composed of late Pleistocene to mid Holocene laminated silts. The laminae comprise authigenic carbonate (mainly aragonite), amorphous silica (diatom frustules) and organic matter, and evidence shows that the sediments were formed in a deep, meromictic lake.
The objectives of this project were to:

- Establish the composition and formation of the sediment and to determine whether the laminations were annual
- Construct a varve chronology
- Assess variations in laminae thickness
- Compare the findings with collaborative research using other proxy data

The laminated part of the core was prepared for image analysis by resin embedding and thin sectioning. The whole sequence was then examined using the analySIS® 3.0 software package. 0.8-cm segments of each 6.5-cm thin section were captured on screen in full colour at x 0.75 magnification. After classification into a series of sediment types, individual laminae were counted and automatically measured. The data were stored directly into an Excel spreadsheet for numerical analysis and a digital image of each segment was preserved as an archive with counts and measurements attached.

The results obtained to date show that image analysis can highlight rapid changes in sediment thickness and composition. These changes can be linked directly to sediment type through SEM microprobe analysis. The ability of the analySIS® package to track annual changes appears to be excellent.
Some of the units of the Eskı Acigöl core were impossible to count by eye but have provided some of the best images on the analySIS® software. Comparisons of visual counts on the core with the high-magnification digital count on thin-sections, show almost a third more laminations being identified by the image analysis. A further advantage of the analySIS® package is its ability to obtain high-resolution data for sections of cores that are unsuitable for visual or scanner inspection. The data are to be compared with Digital Colour Sediment Analysis counts on the same core in order to assess the benefits of each system. The information that the analySIS® software has provided, combined with multi-proxy data from the core, will provide a high-resolution picture of environmental variability through the interglacial-glacial transition.

NEW OPPORTUNITIES FOR RAPID ANALYSIS OF LAMINATED SEDIMENTS USING DIGITAL SCANNING ELECTRON MICROSCOPY

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Research on laminated sediments over the last decade has demonstrated that back scattered electron imagery (BSEI) of resin-embedded sediment sections is the most powerful method of resolving the fine scale structure of sediment fabrics. BSEI will dependably resolve the finest scale lamination and is a pre-requisite to reliably resolving the varve and the internal seasonal/ sub-seasonal laminae for example in the sediments of Saanich Inlet where up to 19 laminae per varve occur. Until now BSEI has generally been carried out using pre-digital or hybrid Scanning Electron Microscopes (SEM). However the production of a new generation of fully digital SEMs (begun by Canbridge Instruments (now LEO) in the mid 1990s) presents new opportunities for streamlining and increasing through-put in BSEI studies. The recent acquisition at Southampton of a LEO 1450VP SEM will greatly enhance our ability to process laminated sediment records. These new generation SEM systems essentially comprise an electron optical column attached by fibre optic cable to a PC. Most have Windows-driven operating systems with user-friendly interfaces. A key step in the quantification of lamina parameters is the production of a low magnification photomosaic at the appropriate scale to resolve and quantify measureable lamina features. Hitherto this has been done using physically pasted mosaics of photo-micrographs - a time consuming (operator-intensive) and expensive (£2.10 per 4”x 5” Polaroid) method. The new digital SEM affords the potential to fully automate and digitise this process. LEO Electron Microscopy (Ltd.) have agreed to provide us access to their Application Program Development (API) Kit. This Application Programmers Interface (API) is a software kit that permits access to SEM functions via the LEO server which enables the development of specialised applications designed to meet specific user requirements. LEO software research and development group have agreed collaborate with us in the design and implementation of specialised, stand-alone applets (routines) for rapid low magnification survey and imaging of large sample areas**.** This should increase sample throughput and analysis at least by a factor of 5.

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DIGITAL SEDIMENT COLOR ANALYSIS AS A METHOD TO OBTAIN HIGH RESOLUTION CLIMATE PROXY RECORDS

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Digital images of sediment surfaces allow the possibility to analyse millimeter scale variations in sediment composition, which are too small to handle with conventional geochemical techniques. Since the color of a sediment reflects its chemical composition, color records provide a proxy for changes in sediment composition. The resolution that can be obtained with a typical digital camera is typically around 100 measurements per centimeter of sediment. With the computing power of modern personal computers, it is relatively easy to collect and process large data sets. Digital sediment color analysis is therefore ideally suited to collect long and continuous high resolution records from sediments that are laminated at a millimeter-scale. The method has been applied successfully to various laminated marine and lacustrine sections, allowing analysis of high-frequency climate variability (Schaaf and Thurow, 1994; Merrill and Beck, 1995; Schaaf and Thurow, 1995; Schaaf and Thurow, 1998; Nederbragt et al., 2000; Nederbragt and Thurow, 2001a; Nederbragt and Thurow, 2001b).
However, various corrections need to be made to the raw color values registered in the digital image, to allow extraction of the calibrated color values that describe stratigraphic variation. Here we illustrate the procedures needed to generate a calibrated color record from a set of digital images, using examples from Holocene varved marine sequences cored by the Ocean Drilling Program in the Santa Barbara Basin (California), Saanich Inlet (British Columbia), Palmer Deep (Antarctica) and Cariaco Trench (off Venezuela).

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LINE-SCAN DIGITAL IMAGE ANALYSIS OF X-RAY RADIOGRAPHS IN DETERMINING ACCUMULATION RATES OF SEASONAL COMPONENTS OF CLASTIC-ORGANIC VARVES IN LAKE NAUTAJÄRVI, CENTRAL FINLAND

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The key issues for the use of this method described in the following paragraphs have been to provide a routine method of digital documentation of the varve records with a high temporal resolution. This includes two major goals. First, an easy storage of the varve chronology that facilitates the cross-validation of replicated varve counts and a “varve-by-varve” re-evaluation of the constructed chronology. Second, quantitative analyses of the varve components (seasonal laminae) can be investigated more objectively, rapidly and with very fine-scale resolution.

X-ray radiography (e.g. Mehl & Merkt, 1992; Algeo *et al*., 1994) and digital image analyses (e.g. Ojala & Francus, *in press*; Tiljander *et al*., *in press*) were applied on the Nautajärvi sequence to obtain grey-scale (256 shades of grey) images of 10 cm long sediment slabs (0.2 cm thick) cut from embedded sediment blocks. Sediment embedding was achieved using a modification of the *water-acetone-epoxy-exchange* method (Lamoureux, 1994; Tiljander *et al.*, *in press*) for the purpose of continuous subsampling of the entire sediment profiles (with an overlap of 2 to 3 cm). Images were then processed with a semi-automatic tree-ring width and density measurement system, DendroScan (Varem–Sanders & Campbell, 1996), that translates grey-scale values along an analytically drawn path into a linear X-ray density signal (i.e. line-scan image analyses system), identifying varve boundaries as a major inflection point between the minimum and maximum density (Figure 1). Based on the density data (1000 dpi, i.e. 24 data points per one 0.6 mm thick varve), we then calculated several variables that are comparable with the internal structure of each varve.

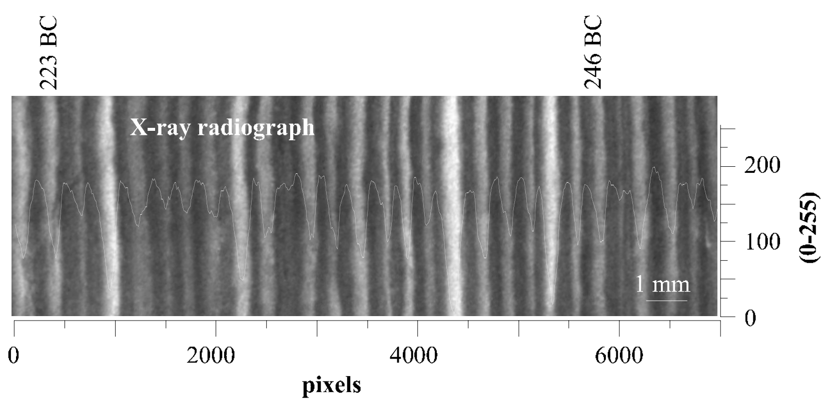

Figure 1. Digital line-scan image analysis of X-ray radiograph of the Lake Nautajärvi varves.

This method is especially convenient in the study of lake sequences (e.g. Lake Nautajärvi, central Finland) where a section clastic-organic varves is formed by a depositional cycle of minerogenic material consequent to spring floods, particulate organic material from in-lake production (summer-autumn) and a thin, fine-grade and dark-coloured organic layer in winter (e.g. Ojala, 2001; Ojala & Saarinen, *in press*). In the Lake Nautajärvi section, the annual average relative X-ray density mainly reflects fluctuations in the annual influx and accumulation of detrital minerogenic matter. It provides a potential proxy-environmental indicator of palaeohydrology, which is linked to the supply of fine-grained minerogenic matter in the catchment and the susceptibility of the catchment to erosion. Calculated DS -value, on the other hand, describes an annual accumulation of organic matter and is related to length and strength of the growing season via autochthonous primary production.

Some of the characteristic features reflected in the Lake Nautajärvi physical varve data were described. There is, for instance, a very low content of sediment minerogenic matter occurring in Nautajärvi record between *c.*

AD 1000 and AD 1200. It indicates a less intensive period of catchment erosion, probably due to attenuated spring floods suggesting that this period, known as the Medieval Climate Anomaly (MCA), was characterised by milder winters free of snow accumulation in continental Fennoscandia. Prior to that, between *c.* 900 BC and AD 100, an increased rate of influx of minenorogenic matter indicates more intensive catchment erosion probably due to a higher spring melt-water discharge. It was possibly caused by colder and longer (severe) winters that resulted in increased net accumulation of snow.

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TOWARD A NON-LINEAR GRAYSCALE CALIBRATION METHOD

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Modern paleoclimate studies require access to high resolution proxies to adequately sample climate processes on sub-orbital time scales. While a number of approaches have been employed, grayscale analysis of existing core photographs remains attractive because it provides a means of potentially extracting high resolution information from the large existing data set of DSDP and ODP core photos. The quality of the extractable information depends on a number of intrinsic and extrinsic factors: core quality, lighting properties, photographic processing, digital capture, and post-capture image processing. Whether an image is "born digital" or converted from an analog source also influences the extractable information. Taken as a whole, these factors can be viewed as the component of the digital lifecycle of the image. Ideally, calibration of the core photos from a single DSDP or ODP hole requires correction for both intra- and inter-photographic grayscale variations. The traditional calibration approach employed in grayscale analysis is the constant background subtraction method. In this method, the grayscale value of each pixel in the digitized core photo is normalized to correct for intra-photo lighting variations (e.g. hotspots or shadows) by the subtraction of an adjacent background white value. The assumption behind this constant correction method is that all shades of gray respond linearly to variations in lighting. In practice however, this assumption is generally not valid due to changes in the slope of the illumination to photographic density curve. Mid-tones are much more sensitive to variations in lighting than bright highlights or dark shadows. We present an alternative, non-linear calibration methods, which employs the grayscale calibration card photographed with each core. This methods results in greater correction factors for midtone grayscale values. The accuracy of the non-linear method is tested by regression against measured sediment carbonate concentration. Errors determined by residual analysis indicate an RMSE of 9.67%, which is comparable to carbonate prediction errors based on diffuse spectral reflectance of similar sediments from Leg 162.

AN ANALYSIS OF VARVED SEDIMENTS FROM MURRAY LAKE, ELLESMERE ISLAND, NUNAVUT, CANADA.

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The concerns involving recent and future climate change have placed considerable emphasis on developing climate records that encompass all regions of the world. In addition to modern climate records, there has been an emphasis on the recovery of high-resolution paleoclimatic records from regions that are highly sensitive to climatic change in order to gain an understanding of long term climate trends (Overpeck et al. 1997; Lamoureaux and Bradley, 1996). High Arctic lakes that contain annually laminated (varved) sediments have been shown to provide high resolution paleoclimate records on spatial and temporal scales that are important in studying climate variability (Hardy et al., 1996: Lamoureux and Bradley, 1996; Gajewski et al., 1997, Hughen et al., 2000; Lamoureux et al., 2001). For the purposes of this study, varves from short sediment cores taken from Murray Lake and are analyzed to develop records of late Holocene paleoclimate variability.

Murray Lake is located on the eastern coast of Ellesmere Island at 81°20'N, 69°30'W. The lake is approximately 6 km^2 and 46 m deep and lies 106 m above Archer Fjord. Runoff into the lake is dominated by nival melt from the west, spill over from the Upper Murray Lake to the north and a combination of nival and glacial melt from the Simmons and Murray Ice Caps to the east. Two short cores were retrieved from the northern basin in June of 2000 in 45 m of water. Analyses of the cores revealed a sequence of sediments that was undisturbed, finely laminated and clastic. The analysis of thin sections revealed 1200 sub-millimeter laminae-couplets that are believed to be varves. In addition to revealing a continuous sequence of varves with no apparent interruptions or disturbances, the cores also produced organic macrofossils at two separate intervals that could contstrain the chronology. During the field season of 2001 two long (5 meter) vibracores were retrieved from the deep basin. The sediment sequence reveals a sedimentation in the upper 2.2 m similar to that of the short cores retrieved and analyzed in 2000. Below 2.2 meters, the sedimentation abruptly changes but appears to retain the laminae couplets until 4.5 m depth where there are intermittent pulses of sand.

This project intends to use the Murray Lake long and short cores to develop an accurate, continuous chronology for the laminated sediments using varve counts from thin sections, radiocarbon dates, and paleomagnetic data. In addition, the project will reconstruct the sedimentary history of the lake within the timeframe of the laminated sediments using laboratory and imaging techniques that measure magnetic susceptibility, bulk density, loss on ignition, grain size, sediment structure and varve thickness. Finally, with the use of the chronology and the measurements taken with imaging techniques, specifically varve thickness and grain size characteristics, the Murray Lake varves from the last 1000 years will be compared to instrumental climate data and other regional climate proxies in order to reconstruct local climatic changes for the late Holocene.

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LATE QUATERNARY CLIMATE RECORDS USING LAMINATED LAKE SEDIMENTS OF AN AUCKLAND MAAR CRATER, PUKAKI CRATER, AUCKLAND, NEW ZEALAND.

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The object of this project is to investigate the history of Quarternary climate change in the Auckland region, New Zealand using laminated lake sediments. In early February 2001 two volcanic craters (Pukaki and Onepoto Maars) in Auckland were cored to extract a continuous record (to a maximum depth of 85.65m) of these laminated lake sediments. A co-ordinated study using optical mineralogy, image analysis and spectral analysis will be used to determine whether the laminated lake sediments represent an annual climate record and to reconstruct climatically driven changes in the sedimentation. The coring of the craters recovered three distinct sediment types in both cores. At Pukaki the upper section (0 – 48.28m) of the core consisted of massive estuarine mud's with shell rich silts. The mid section (48.28 – 73.10m) is a sequence of laminated lake sediments punctuated by approximately 70 tephra layers while the lowest unit (73.10 – 85.65m) consists of well sorted basaltic silts and sands with shell fragments (provisionally identified as ejecta).

The laminated sediments in each (Pukaki and Onepoto) core vary in colour contrast and thickness. The laminae range from sub mm to mm in thickness in the Pukaki core and are sub mm in thickness in the Onepoto core. Each laminum is laterally continuous and is made up of two distinct layers. These are a dark brown to black layer, composed of mainly mineralogic and amorphous organic material, and a light off-white layer which mainly contains diatoms. The light layer is assumed to be a spring/summer layer and the dark an autumn/winter layer (Brauer et al 1999, Brauer et al 1999, Zolitschka, B. 1991). We have not yet confirmed annual layering. Provisional results from core images and thin-sections have shown 552 laminae in a 38cm length section from Pukaki core between two tephras giving a mean laminum thickness of 0.7mm. Age ranges from the tephras are being determined. Other sections in the core have also been counted and show similar thickness results ranging from <1–2mm for laminated couplets from the scanned images. Detailed optical microscopy of overlapping thin-sections is being conducted in conjunction with image analysis as a control to determine if all of the laminae present are identified.

A key advantage of the New Zealand maar project is the presence of many well known dated tephras throughout both cores. Approximately 80 tephras were recorded in the Pukaki core and over 100 tephras in the Onepoto core. Critically these include well dated rhyolitic tephras. The origin of these tephras is due to the presence of an active volcanic centre approximately 190km south of the Auckland region, the Taupo Volcanic Zone (TVZ). There are also some andesitic tephras from Mt Taranaki a distal source (~300km south west). The rhyolitic tephras are presently the main dating control within both cores as they allow an accurate tephrostratigraphy to be established. This allows the core to be divided up into selected segments that are bound by known ages, and will answer the question 'do the laminae represent an annual climate record'.

The core was electronically scanned using a DMT Core Scan Color unit, allowing high resolution color images to be obtained from the surface of the core. Software packages used in this project allowed the images to evaluated, objects and features to be measured and the image properties to be quantified through the use of color contrast or grey-scale. Once the laminae measurements are complete, the data will then be used for spectral analysis. Spectral analysis will be concentrated in selected sections of the core with full recovery using datable tephras as boundaries. The main portion of the data to be used in the spectral analyses of the core is still to come from DMT.

Spectral analysis of this data will provide the basic patterns of paleoclimate information from which we should be able to determine questions such as how long, and in what manner, phenomena such as the El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have affected New Zealand during the Late Quaternary.

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IMAGE ANALYSIS IN A STATISTICAL PERSPECTIVE : IS IT REALLY ACCURATE ?

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Accuracy and precision are rarely discussed in image analysis papers. Results are very often stated without evoking the number of processed images or without referring to any standard deviation of the results. This is a rather surprising situation when considering that everybody in the field has experienced the subjectivity of putting a threshold onto a gray level image.
Starting from a few disappointing situations, this paper tries to identify the various error sources in the image analysis protocol. The formalism adopted throughout the paper is inspired from Pierre Gy’s famous sampling theory for particulate materials, recognizing thereby that image analysis is a multifold sampling problem.
The quantitative analysis of a lab sample starts with the preparation of an adequate section for imaging. This is the classical stereological problem of reducing the 3-D space to a representative series of 2-D sections. Furthermore, collection of images have to be taken to adequately represent the sections. This is a second sampling step involving geostatistical considerations (how many images ?, where should we implant those images?, at which magnification should one work?). Finally, and not least, pixels have to be sampled to build a representative digital image of the scene (how many pixels?, at which resolution should one work?, what kind of grid could we use?).
It is important to recognize that pixels, images and sections are all steps in a sampling protocol. The corollary of this is that specialists in image analysis have to control the whole chain of imaging and not only the last step of pixel based measurements.
The first series of errors discussed in this paper are “image preparation errors”. These involve potential errors coming from the sample preparation, the optical devices, the sensor performances and the analog to digital conversion protocol. Improved phase ratio estimations in multispectral ore microscopy are given as an example.

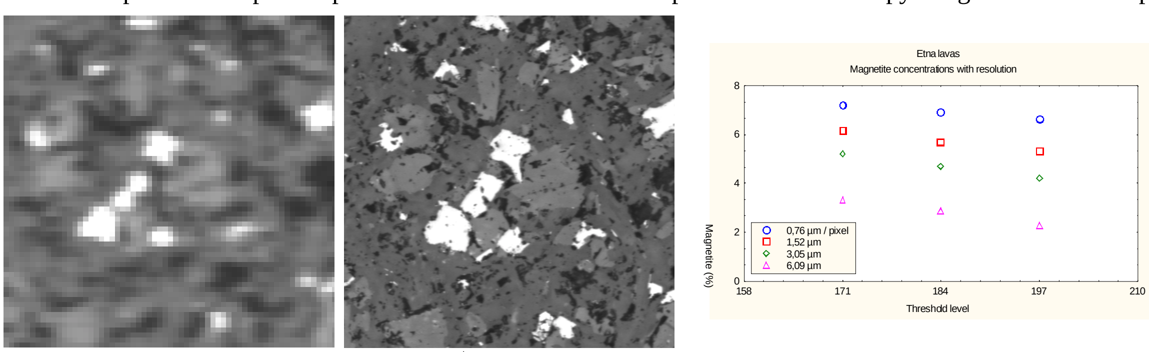

Fig.1. Estimation of magnetite content in M^t Etna lavas at various resolutions and for various thresholds.

A second series of errors are the ones grouped under the term “image integration errors”. These refer in practice to the influence of resolution and grid rotation on image analysis results and on the other hand to the influence of magnification. To illustrate this, the question of estimating magnetite content in the M^t Etna lavas is raised. The dispersion of measures with respect to resolution and grid rotation is further investigated on more than seventy different digital representations of the same object. This allows to point out reasonable limits of validity for comparing results gained at various scales or comparing data on various sizes of particles.

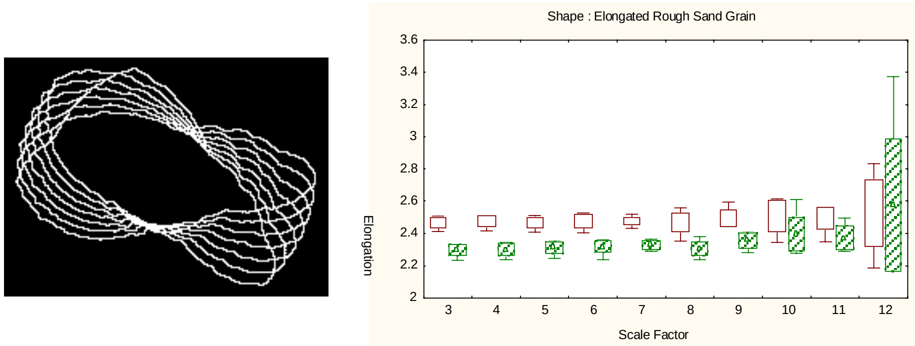

Fig.2 Various digital representation of the same sand grain and scattering of the elongation measures using either Feret diameters or inertia tensors. The horizontal axis refers to the pixel grid resolution going from 12000 pixels / grain to 23 pixels / grain in a geometrical progression.

Finally, a last class of errors is linked to the quality of the digital estimates of the euclidean geometric properties. “Analytical errors” are the ones generated by the algorithm used for computing length, perimeters, diameters or shape factors. Not all measurement algorithms are equally sensitive or equally robust and the image analysis community should progress towards a selection of the most adequate tools for estimating visual properties from digital images.

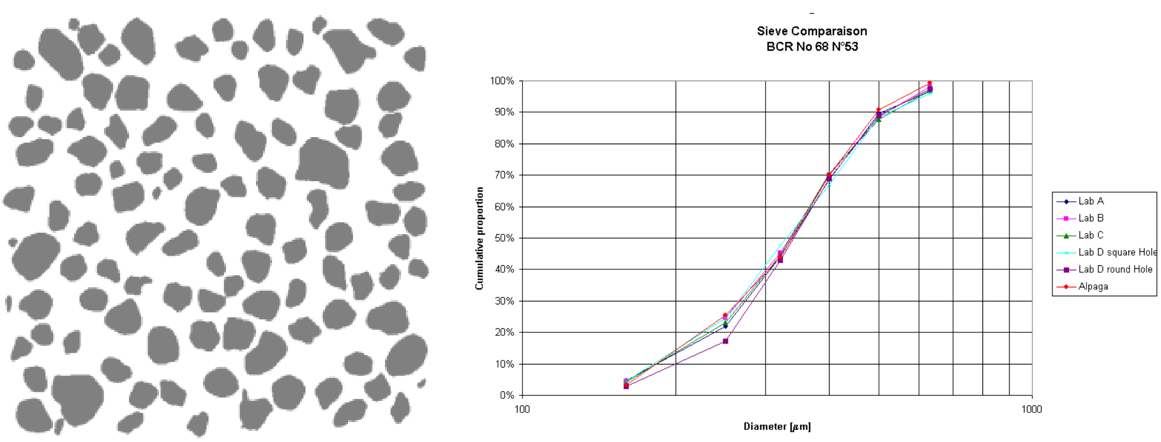

Fig. 3. Size distribution of a European sand (Bureau for Certified Reference Material n°68) as measured by sieving (labs A to D) and by image analysis (Alpaga instrument).

This raises the point of necessary validation. More studies in the future should state their results in statistical terms and assess the quality of the analysis through potential correlation with other physical properties. More cross correlation studies between laboratories should be organized in order to normalize the image analysis protocols and make the technology reach maturity.

A few examples do exist today where image analysis has been capable of entering industrial standards. This proves at least that, when controlling all aspects of imaging, from the sample to the pixel, measures of unrivalled quality can be gained.

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IMAGE ANALYSIS OF FIVE DIAMICTON UNITS: AN APPROACH TO UNDERSTANDING THE DEPOSITIONAL ENVIRONMENT OF MARINE CORES FROM THE ICELAND SHELF

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On the Iceland shelf, as in other previously glaciated regions, diamicton units are present and identifying the origin of these units is difficult (Vorren, et al., 1983; Domack and Lawson, 1985; Licht *et al.*, 1999). They could be glacial till, glacial marine sediment, reworked glacial marine sediment, or some other combination of glacial and glacial marine processes. It is important to determine the depositional environment of diamicton units in order to understand depositional processes, but it is also necessary to reconstruct the extent of past ice sheets. This study focuses on the description and analysis of diamicton units recovered in marine cores collected in 1997 and 1999 from the southwestern and northern Iceland Shelf (Helgadottir, 1997). These cores contain diamicton units that vary in length from 2 meters to over 10 meters, but these represent only minimum thicknesses of the diamicton units. At least 7 properties, including sedimentologic parameters, x-radiograph analyses and fabric analyses, of the diamicton units are measured to facilitate the interpretation of these units. In general, the diamicton units are the lowermost stratigraphic unit in the cores and are characterized by an increase in mass magnetic susceptibility and a decrease in carbon and water content. In at least one core, foraminifera are a low, but constant proportion of the matrix in the diamicton unit (Helgadottir and Andrews, 1999). Sedimentological analyses of the diamicton units alone do not provide a clear understanding of the depositional environment of these units.

X-radiograph image analyses of five of the diamicton units supplement the grain size data. X-radiographs were examined on a light table, and visible clasts (>2mm) were traced onto mylar. Clasts were manually traced in order to have more control in identifying actual clasts versus non-geologic and other discolorations on the x-rays. These tracings of the clasts were scanned and filled in Adobe Photoshop. The resulting images were exported as binary files and analyzed using the public domain NIH Image Analysis program (U.S. National Institute of Health). At least six properties of the clasts were automatically calculated using this program, including length of the major axes, tilt of the major axes, pebble perimeter, pebble area, shape, and pebble counts. The mean length of the major axes of these 5 diamicton units varies from 6.63mm up to 9.65mm, and the standard deviation varies from 3.07 to 6.4. The tilt measurements provide the apparent dip of the clasts, and the standard deviation of these measurements is quite large. Mean tilt values range from 35.77 degrees from horizontal to 47.8 degrees, and the standard deviation varies from approximately 25 degrees to 56 degrees. All five diamicton units have a shape factor (Francus and Karabanov, 2000) between 0.64 and 0.69, which shows that the majority of the clasts are sub-rounded.

The image analyses should be used in conjunction with the sedimentology data in order to understand the depositional environment of diamicton units in marine cores from the Iceland shelf. Anisotropy of magnetic susceptibility measurements and thin section micro-fabric analyses is also in progress and should supplement these data. Despite all of these analyses, it is still difficult to differentiate the origins of these diamicton units. It is most probable that they are the products of complex glacial and glacial marine processes.

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FROM DEPTH TO TIME: THE TRANSFORMATION OF SEDIMENT IMAGE COLOR DATA INTO HIGH-RESOLUTION TIME-SCALES

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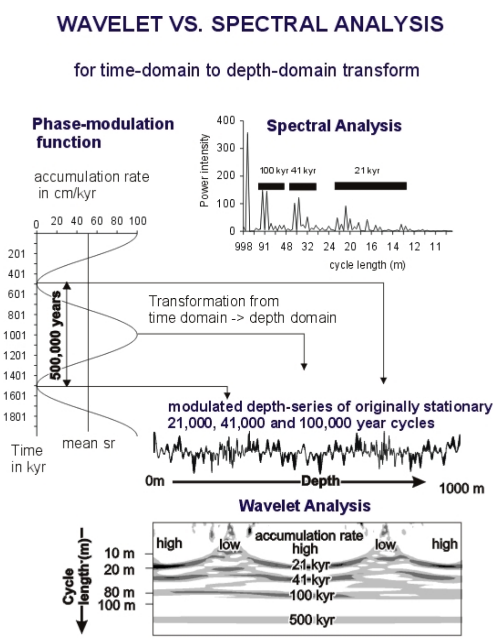
Paleoceonographic models utilize relationships between different geological, climatic and oceanographic processes, i.e. changes over time. However, data from sediment columns including sediment color data from photo-or X-ray images of laminated sediments are measured in depth scale determined by the resolution (pixel size) of the images. Currently, most time scales for the Holocene are constructed by interpolation between radiometric age data (e.g. C-14). Commonly, the sediment thickness *S* and (radiometric) ages *T* are measured and *sr* is of interest. Than, then

sedimentation rate *sr* is defined as $$sr = S/T, \tag{1}$$

or by linear regression from multiple discrete sample intervals *n*: For laminated sediments without a large set of C-14 ages, ages are determined from sediment thickness *s* for a number *n* of annual layers Δt=1yr.

Here we introduce a new methodology of semi-automatic high-resolution transformation of image color data of annual laminated sediments into time-related signals. In detail, we use utilize a wavelet transform with Morlet wavelet as its analysing mother wavelet (Rioul and Vetterli, 1991) that extracts the wavelengths = sediment accumulation rate according to their depth (s). Figure 1 (see in http://www.geocities.com/speedstat) demonstrates the power of the analysis techniques on a sedimentation model.



In this model periodic climatic forcing (here in Milankovitch scale) is overlaid by a sedimentation rate fluctuation of much lower frequency. The resulting signal (e.g., color from image) from sedimentation appears chaotic. The power spectrum from Fourier transform cannot resolve the underlying processes (sedimentation rate change and Milankovitch cycles).

Here, we focus on the inverse problematic: from depth to time domain. For laminated sediments, we have no measured ages but sediment thickness *s* for a number *n* of annual layers Δt=1yr. The sedimentation rate for each layer *i* is

$$sr_i = \Delta s_i / \Delta t_i \;. \tag{2}$$

Thus, in time domain it would become would be: $\Delta t_i = \Delta s_i / sr_i$,

and for a time scale $$T_j = \sum_{i=1}^{j} \Delta t_i = \frac{\sum_{i=1}^{j} \Delta s_i}{\sum_{i=1}^{j} sr_i}, \tag{3}$$

with i =1,2,….n, and j=1 to T. Unfortunately, automatic image analyses provide data (e.g., color coded pixel) in depth and not in time domain and $\Delta s = k$ is constant and not Δt. The following methodology has been used for this transform.

Wavelet analysis with program CWTPC.F –which is a greatly improved version of the program CWTA.F in public domain (Prokoph and Barthelmes, 1996)- on the possible annual sediment cycle bandwidth range (e.g., 0.1 –0.8cm) gives annual cycle thickness = sedimentation rate sr_k as function of depth s_k as major cycle length in third column of file CWTDT.DAT. $\Delta s = k$ is set by the user of CWTPC.F by selecting the number of locations *m* to be calculated $k = S/m$.

(1) Calculating the time scale by $T_l = \sum_{k=1}^{l} \Delta t_k = \frac{\sum_{k=1}^{l} \Delta s_k}{\sum_{k=1}^{l} sr_k}$ (4)

with $k = \Delta s = 1,2,\ldots.n$, and l=1 to S.

(2) Then, the non-equidistant time scale as a function $\Delta s = k$ is transformed into equidistant ***annual*** time intervals $\Delta t = i$ by calculating $T_j = \sum_{i=1}^{j} \Delta T_l$ (5)

Then, all signals *x* from this image (or set of images) including sedimentation rate, grey values, or chemical analysis taken from the core can be transformed from x_k to x_i..

The methodology has been applied to the analysis of X-ray image from laminated sediment cores from Effingham Inlet at Vancouver Island, B.C., Canada (. By classical C-14 interpolation techniques a mean sedimentation rate of 0.295cm/year and periodicities of ~1300 years, 300 years, 200 years and ~80 years in the grey-value signals have been determined. However, the high-resolution analysis shows that sedimentation rates fluctuates strongly (0.1 – 0.4cm/year) and often independently from the grey-value signals (Fig. 2), and exhibits major periodicities of ~ 500years versus ~40, 80, 140, 200, and 300 years, respectively.

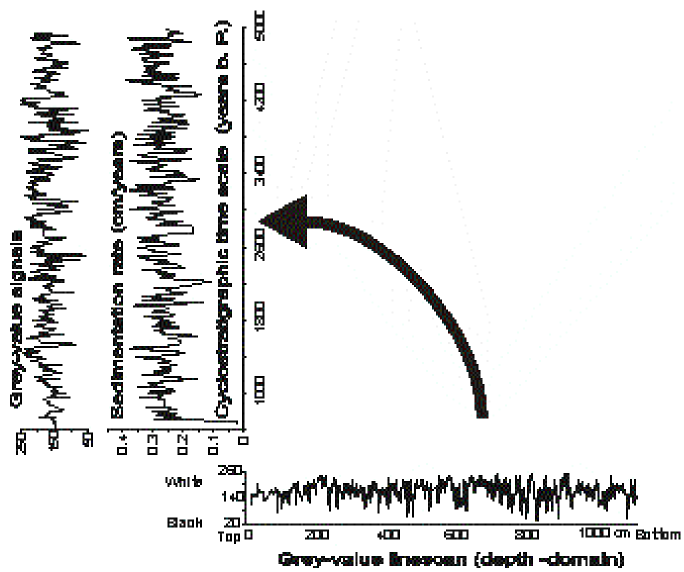


Figure 2: Horizontal axis: grey value time-series in depth domain (x(s)) from x-ray images of core Effingham Inlet. Vertical axis: greyv alue signals x(t) and sedimentation rate sr(t) in time scale (from ~600 -~5000 years BP). Note the obvious independence of grey-values as proxy for sediment chemistry, texture and biotic content and sedimentation rate as proxy fro amount of sediment supply (e.g. wet/dry periods, fluctuating productivity)

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APPLICATIONS OF IMAGE ANALYSIS IN ENVIRONMENTAL ARCHAEOLOGY

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Environmental Archaeology is the interdisciplinary study of the relationship of paleoanthropology and paleoecology, i.e. human adaptation to and exploitation of natural environments through time. This relationship is dynamic and reciprocal, inasmuch as human activity is a factor that modifies the natural environment through time. Virtually any and all methods that address issues of paleoecology are relevant to environmental archaeology research.
Although a great many studies in archaeology generally and in environmental archaeology are grounded in morphological systematics and morphometric analysis, studies employing the robust power of image analysis have been exceedingly rare. Support for image analysis applications is virtually non-existent even to the point of inexplicable antipathy. Nevertheless, some 15 years of experimental applications of image processing and morphometric analysis using the Prism Expert Vision program has provided substantial analytical insights into assemblages of archaeological and ecological artifacts that substantially surpass conventional analysis in quantity, quality, efficiency and cost effectiveness (Rovner, 1995).

A brief demonstration of the Prism Image Analysis System (Russ, 1992), comprised of PrismView and PrismCalc, will be provided using selected case studies in environmental archaeology. specifically related to earth science and paleoecology. PrismView provides image acquisition, processing and enhancement of both gray and binary images, manual or automatic threshholding, Boolean processing of multiple images, etc. PrismView morphometry provides a menu of some 40 measurement of both feature specific and global (mosaic) parameters. Examples presented will emphasize feature specific parameters of size, shape, texture and fractals on populations of discrete objects. Tomographic parameters of skeletonized images ; e.g., counting and measurement of loops, nodes, endpoints, are also available, but not utilized in these studies. PrismCalc provide statistical description, analysis, testing and graphic display capabilities available anytime tao assess data during or after generation of data.

Typical image fields of 10 to 50 or more individual objects have been successfully measured in a single image pass. Relatively large and comprehensive data sets can be generated from statistically large sample populations quickly, efficiently and cost-effectively.

Three specific examples form previous studies in environmental archaeology will be presented:1. tracing the source of sand used in architectural construction materials (Sickles-Taves, et al., 19); 2. classification and taxonomic identification of microfossils, specifically plant opal phytoliths (Russ and Rovner, 1989), Rovner and Russ, 1992a), and 3. classification and taxonomic identification of macrofossils, specifically seeds. There is, however, nothing limiting the application of Prism image analysis and morphometry to these specific categories of material. Rather, they represent procedures that are as easily applied to a wide range of microscopic- and macroscopic-sized object assemblages (Russ and Rovner, 1992b).

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DARWIN, EXPERT VISION IMAGE ANALYSIS AND THE DEATH OF TYPOLOGY: A MORPHOMETRIC PARADIGM FOR SYSTEMATIC CLASSIFICATION

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Conventional typology currently dominates investigations which employ systematic morphological classification. Typology involves reduction of morphological variation in a population to a representative standard form or "type," a.k.a. ideal form, mean, wild type, morphotype, central tendency, etc. However, reduction of variation in a Darwinian universe to a single arbitrary form should *sui generis* provide sufficient intuitive basis for treating this concept with great suspicion, if not outright rejection (Russ and Rovner, 1992a, Rovner, 1995, 2000). While the arbitrary and subjective nature of creating morphotypes is well known, persistent use of typology nevertheless continues unabated, probably derived from the absence of an effective alternative. Such an alternative is now available and accessible through the use of interactive, computer assisted stereology, i.e., image processing, morphometric analysis and pattern recognition.

For the past three years, development of a systematic classification of reference seed populations, used for the identification of archaeological and fossil seeds, has explored use of morphometry and pattern recognition as an alternative to typological classification. Relatively low level 2-dimensional morphometry has already achieved substantial success, providing accurate species level identification of single taxon populations. Higher levels of morphometric analysis using 3-dimensional parameters promises greater levels of taxonomic accuracy of single seeds and mixed taxon populations.

Meanwhile, stereological classification and comparisons of replicate seed populations clearly demonstrate pervasive inherent fallacies in typology and typological constructs. Natural variation within seed populations is not normally distributed, i.e. not Gaussian. Quantitative description and distribution plots of morphological variation for virtually every size and shape parameter applied to replicate seed populations shows that mean and modal values are inconsistent from one population to the next. In fact, statistically, they are "never" the same.

The simple conclusion derived from this states that a type construct can "never" be truly representative of the taxonomic population it is used to represent. A morphotype, no matter how defined, is "never" precise or accurate. Thus, when used analytically to define a population, a morphotype is fundamentally a systematic error.. Virtually all analyses based on morphotypes are therefore suspect. Rather, morphological analysis of populations of objects must be based on population variation constructed from measured parameters of the actual objects if results are to be precise and accurate. The nature of variation itself must be used to characterize a taxon. This may be accomplished through the use of image morphometry followed by multivariate discriminant functions, "fuzzy logic" and pattern recognition

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EXTRACTION OF QUANTITATIVE 3-D INFORMATION FROM DIGITAL IMAGERY

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A variety of techniques have been employed to generate imagery from digital and other information. However, in general, imagery provides visualization, but no quantitative information regarding the characteristics of displayed objects. To address this problem, we have developed techniques for determining 3-D characteristics of embedded objects from 2-D and 3-D imagery of rocks and other media. From 2-D imagery, it is possible to determine size distributions only. From 3-D imagery, we can also determine shapes, coordination numbers, and other characteristics of the embedded population. Aside from crude physical methods, there are two basic ways to obtain imagery from which quantitative information can be extracted. The first involves stereology applied to 2-D images, and the other involves X-ray tomography.

It is possible to use **stereology** to obtain 3-D size distributions from 2-D images (Fig. 1). We have developed a general formulation for stereological analysis of particle distributions which is applicable to any particle size or size distribution (not limited to log-normal, unimodal, etc.). We have applied numerical techniques to define intersection probability distributions for any shapes (previously only known for spheres), and quantified the errors involved in using spherical coefficients for various non-spherical particles. This stereological technique is based on knowing the probability distribution of random cross sections through various particles so that "small circle" cross sections can be subtracted from an observed population to provide the 3D size distribution of particles. The results indicate that the most important parameter controlling calculated size distribution is particle aspect ratio. For a distribution of particles with a specific aspect ratio or range of aspect ratios, variations of particle form (spherical vs. cubic; rectangular vs. elliptical) do not alter the results, so the technique can be applied to a range of particle shapes. Applications can be made in a petrology, volcanology, and other fields, only a few of which can also be treated using expensive X-ray techniques.

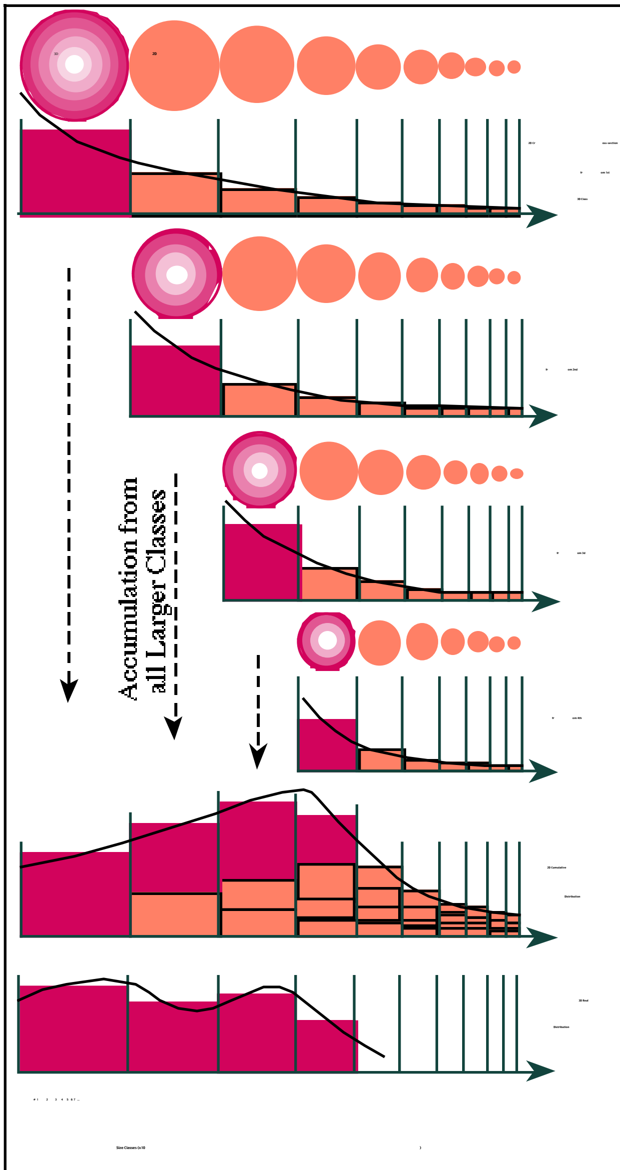

Figure 1

Conceptual illustration of stereology for a cross-section population derived from four spherical particle sizes. Each of the curves plotted on Figure 3 represents a monodispersal system of spheres whose diameter is indicated by the largest circle in each row. Random cuts of the top left sphere produce a distribution of cross-sections as seen to the right. Their sizes are indicated by the width, and frequency as indicated by height of each bar in the accompanying bar graph. For spheres, the largest of these ten size (cross-sectional area) classes is the most frequently cut. A smaller 3D particle also produces a cross-sectional size distribution as indicated on the second row and bar graph. Smaller particles yet are shown below. It is simple to see that each particle produces a predictable set of cross-sections. However, when more than one particle size class is present, the superposition of populations makes it necessary to extract true particle sizes by iteration. There are four distinct particle sizes shown in figure 3 (dark bars). Observable information comes in the form of a 2D cumulative distribution of cross-sections a shown in the lower part of Figure 3. In this bar graph, the monodispersal systems above are superposed, to make a polydispersal system as would be found in natural observations. In order to determine the actual sizes of the 3D particles from this information, one must first subtract from the observed cumulative distribution the light "tail" of the top graph (1st 3D class). This effectively removes all but the largest cuts of the largest particles. The next one subtracts the "tail" of the next smaller 3D particle (2nd class), and so forth until there are no observed cross-sections remaining. Then, after application of Eq. 1, the result is the dark bars in the lowest bar graph of Figure 3, representing the 3D size distribution of particles in the sample. Note that the bar graphs are only schematic, and that the units of the bottom graph are number per volume, but those of the one above are number per area.

Computed X-Ray Tomography provides 3-D imagery and it is possible to directly generate impressive pictures, but further numerical analysis is necessary in order to obtain quantitative 3-D information of embedded objects. 3D voxelized images can be manipulated if their component parts can be identified, cataloged, and measured. However, embedded objects are often clumped together due to actual partial coalescence, or thin films separating objects that are thinner than imagery resolution. It is thus necessary to separate aggregate objects into their individual components if relevant statistics are needed for grain size, pore size, bubble size, and other variations of the "raisin bread" problem. While this seems intuitively simple, the means for doing this numerically for complex structures that result from digital observation techniques are more complex. Toward this end, we have developed schemes that peel away sequential layers of voxels from complex structures until narrow waists that connect individual objects disappear, and each component object can be identified. These peeling schemes provide the most uniform possible cumulative thickness of removed layers regardless of the orientation of the voxel grid pattern.

In selecting a peeling scheme, the challenge is to maintain a constant "skin" thickness regardless of object shape of voxel orientation. Otherwise, complex objects could be split inappropriately, resulting in erroneous component statistics. Peeling schemes can be categorized by the number of steps involved in each peeling iteration. Each step removes voxels according to three possible criteria for defining the exterior of a voxel: exposed faces, edges, or corners. Each of these ultimately causes an initial sphere, for example, to evolve into a cube, dodecahedron, or octahedron, respectively. Combinations of steps can be used to create more complex polyhedra (tetrahexadra, trisoctahedra, trapezohedra, and hexoctahedra) (Fig. 2). The resulting polyhedron that most closely resembles a starting sphere depends on the appropriate definition of "sphericity." Using a metric based on the standard deviation of the polyhedral surface from that of a concentric sphere of equal volume, the optimal scheme is peeling by faces 7 times, by edges 3 times, and by corners 4 times. This leads to a hexoctahedron with Miller indices (14 7 4) and a standard deviation of 0.025. Using a metric based on minimizing surface area, the optimal scheme is peeling by faces 9 times, by edges 6 times, and by corners 5 times, leading to a hexoctahedron with Miller indices (20 11 5). In the past, only 1-step peeling had been used (by faces or corners). If computational or conceptual constraints limit peeling to 1-step, the criterion of edges should be used, as the dodecahedron that results deviates from a sphere by only half the amount of either the cube or octahedron resulting from 1-step peeling of faces or corners, respectively. We also determined the best criteria for 2-step and 3-step peeling.

The peeling schemes we identify can be used to separate objects from complex structures for application to a number of geological and other problems. Information that emerges from the analysis includes object volumes, which can be used for determining grain- or bubble-size distributions in volcanologic, petrologic, and sedimentary, and biological applications, among others.

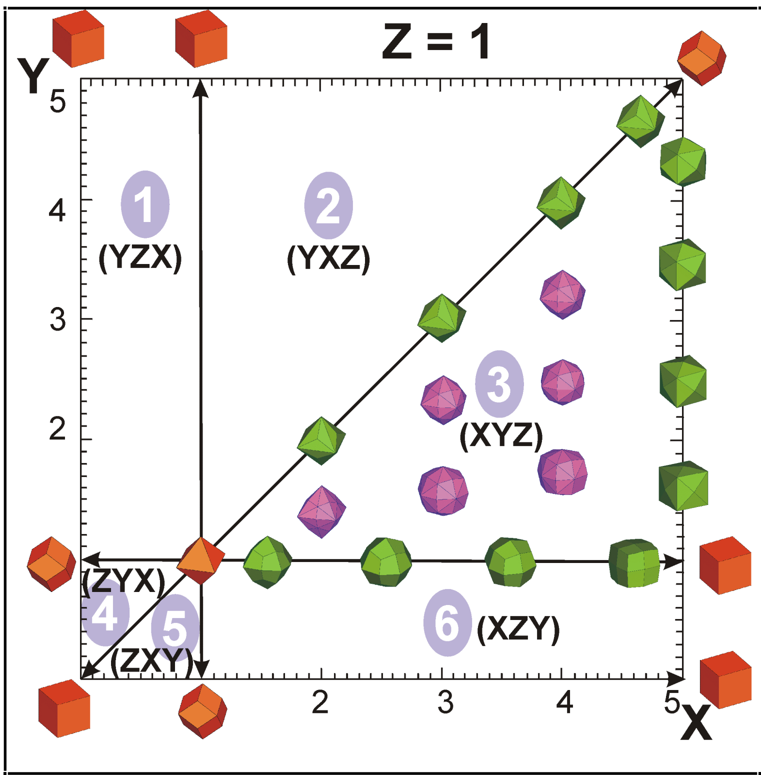

Figure 2.

Conceptual diagram of the classes of polyhedra that result from all possible peeling criteria. The two axes indicate two of the (XYZ) Miller indices, the third index taken as 1. Since indices could be listed in any order and all multiplied by any factor without affecting the shape of the corresponding polyhedron, the six sectors of the diagram separated by thick solid lines each contain the same information. To demonstrate this, consider a point in sector 5 at (0.8, 0.4, 1). Multiplication by 2.5 and rearrangement yields (2.5, 2, 1), which is the corresponding point in sector 3. According to our convention (see text) we will only discuss sector 3, as the others are the same. Single-step peeling results in one of the end members (Cube, Octahedron, Dodecahedron), depending on peeling criterion (red). Two-step peeling results in the shapes along bold lines between end members and include trapezohedra between octahedron and cube, trisoctahedra between octahedron and dodecahedron, and tetrahexadra between cube and dodecahedron(green). Three-step peeling results in hexoctahedra in triangular fields between bold lines (purple). The 26 apices of the hexoctahedron derive from the 26 possible peeling directions for a cubic voxel with 6 faces, 12 edges and 8 corners (=26).

GRAIN-SIZE ANALYSIS OF QUARTZ GRAINS IN ANCIENT LOESSITE AS A PALEOWIND INDICATOR: EXAMPLES FROM THE UPPER PALEOZOIC MAROON FORMATION OF WESTERN PANGEA

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The history of late Paleozoic climate is of great fundamental and applied interest. Late Paleozoic Pangea was characterized by expansive polar glaciation similar in magnitude to that of the Quaternary; further the extreme pole-to-pole paleogeographic configuration of Pangea is hypothesized to have greatly perturbed Earth's climate system. Pangea's size and cross-latitudinal orientation have led many to suggest extreme monsoonal climatic conditions for the Pangean interval (e.g. Robinson, 1973; Parrish, 1982). The initiation and temporal evolution of Pangea's megamonsoon during the Late Paleozoic was likely modulated by higher frequency glacial-interglacial climate changes. Understanding how the climate system responded to such extreme conditions in the Late Paleozoic aids our understanding of the processes of large-scale climate change during the Quaternary.

There is a growing recognition of the prevalence of eolian silt (loess) in the late Paleozoic record of western equatorial Pangea (e.g. Murphy 1987; Fischer and Sarnthein, 1988; Johnson, 1989; Soreghan, 1992; Carroll et al. 1998; Kocurek and Kirkland 1998; Evans and Reed, 2000; Stanesco et al., 2000 Kessler, et al., 2001). The widespread nature of the loessite together with evidence for multiple and distal source regions (Soreghan et al., 2000) suggests that atmospheric dust loads were particularly high during this interval. Pangea's continentality and strong monsoonal circulation system apparently induced widespread aridity even within equatorial zones (Parrish, 1993; Kessler et al., 2001) thereby fostering dusty conditions and promoting the formation of desert loess in low latitudes of northern Pangea. Analysis of glacial-interglacial sequences from both the shallow marine and terrestrial realm of western equatorial Pangea (western U.S.), however, establishes that atmospheric dust loads fluctuated substantially between glacial and interglacial climate phases. For example, in the thick (700 m) Maroon Formation loessite of central Colorado, the loessite units are punctuated by a series of paleosols. Sedimentologic (Johnson, 1989) and combined sedimentologic-rock magnetic (Soreghan et al., 1997) data indicate that paleosols reflect wetter interglacial times characterized by drastically reduced silt influx relative to the intervals recorded by the loessite.

Our work on quartz grain size of the Maroon Formation loessite of Colorado is an attempt to compare grain-size data to magnetic susceptibility and geochemical data in order to interpret wind intensities and consequently dust flux on two varying scales. Firstly, we are interested in the variation in quartz grain size within individual loessite-paleosol (glacial-interglacial) couplets. Secondly, we are interested in long-term temporal variation in grain size of the loessite to determine whether we can document the initiation and/or evolution of the megamonsoon through the time recorded by the entire Maroon loessite section. Unpublished detrital zircon data from the loessite indicate that this section may have accumulated in less than four million years, indicating that the cycles expressed in the Maroon Formation are of short duration, and that the section as a whole may be a very high-resolution record of paleowinds.

For our initial study we have selected three consecutive loessite-paloesol couplets at the base, middle and top of the Maroon Formation for a total of nine couplets. Within each couplet anywhere from 5-9 samples were collected. For each sample a small chip was trimmed, polished and mounted for backscatter electron probe analysis. From each polished chip 8-10 backscatter images were collected with a field of view of about 500 µm. The digital images were then imported into Adobe© Photoshop for image processing. The images were duplicated and each layer was processed through a filtering routine that included: a median filter, edge-finding filter and haralick filter. The layers were combined and then thresholded and a smoothing filter was applied. Because the backscatter image shows grains of varying atomic densities with different gray-tone levels, the thresholding allowed us to isolate quartz grains. Dolomite, which has a similar density to quartz, was difficult to isolate from quartz using the routine described above. However, the surface texture of dolomite was such that it could usually be identified and subsequently removed (erased) by hand after the filtering routine. During this final phase grain-grain contacts of quartz grains were also manually separated and spurious pixels were eliminated. The image was then transferred to NIH's Image v. 1.62 for "grain-size" analysis. Because the mineralogy of the smallest (<~8 µm) grains was difficult to identify, we eliminated any grain with an apparent area of less than 20 pixels. NIH Image is able to measure apparent area, perimeter length and minimum and maximum axis of a best-fit ellipse. With 8-10 images per sample we were able to measure at least 800 quartz grains. These measurements do not yield true grain-size as the images reflect a two-dimensional plane of a three-dimensional grain. To further complicate the analysis the silt grains are not simple spheres or even simple ellipses. Therefore, we are presently only using the median sizes of the different size categories (area, maximum length) in relative terms to define trends among the profiles.

We are in the preliminary stages of data analysis, as all the profiles have not been completed. However, the relative change in apparent area and maximum axis of the grains through the profiles indicate an initial coarsening from the base of a loessite upward, followed by a fining toward the paleosol horizon. The paleosol horizons show a significant decrease in apparent area relative to the loessite, suggesting that wind intensities were lower during paleosol formation (inferred to be during interglacial intervals). The grain-size data (inversely) track the magnetic susceptibility data extremely well in that the quartz grain size decreases as the magnetic susceptibility increases within a profile. In one profile, where no obvious sedimentologic evidence for a paleosol was observed, the magnetic susceptibility increases and the quartz grain size decreases. On the long-term temporal scale, the apparent area of quartz grains appear to decrease upward in the section, such that the average loessite grain-size from profiles at the base of the section are coarser than the average loessite grain-size from profiles from the top of the section.

With the completion of this work we hope to continue with a more comprehensive analysis of the grain-size variation in these and other loessites. We believe the grain-size data, coupled with provenance rock-magnetic and geochemical data will allow us to develop a comprehensive dataset that can provide temporal records of both long-term and short-term variations in wind intensity, wind directions and wind seasonality over a large region of western Pangea during the late Paleozoic.

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RECORDS – WHAT HAVE BEEN USED AND WHAT CAME OUT OF IT

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With the advent of powerful scanning devices non-destructive, digital techniques for obtaining long and high-resolution time series from sediments and sedimentary rocks to understand climate variability and climate change can be applied to a variety of marine, lacustrine and continental records. Processing of such data is commonly done using image analysis, hence it can be defined as the technique that provides quantified information from digitized images. The typical sequence of operations includes image acquisition, image processing, measurements, and data processing. Analysis of images is still not widely used in sedimentology and in paleoclimatology. Yet, with the increase of personal computer power, it is now possible to perform image analysis at low cost rendering this an approach which should be encouraged. Recent advances in imaging techniques have demonstrated the ability to provide valuable data for high-resolution paleoclimate reconstruction (e.g. Francus & Saarinen 1999; Petterson et al., 1999). Some examples will be presented here.

Processing images of the surfaces of sediment cores has been the most popular up to now. It allows semi-automated counting and measuring of laminations in marine (e.g. Schaaf & Thurow, 1994, 1997), and lacustrine (Hughen et al., 2000; Lotter & Lemcke, 1999) environments. Long data series from sediment cores can be quickly obtained for time-series analysis (Schaaf & Thurow, 1995, 1997; von Rad et al., 1999). Computer analysis of the color of the sediment has been successfully linked to sediment properties or composition (e.g. Petterson et al., 1999, Nederbragt & Thurow, 2000a) and paleoceanography (Nederbragt & Thurow, 2000b).

Further advances have been made in processing images of X-ray radiographs of impregnated chips. Counting and measuring varves is now performed routinely (Ojala & Saarnisto, 1999), and minerogenic content can be quantified. Backscatter electron imagery (BSEI) of resin impregnated sediment as pioneered by the Southampton group gives the necessary resolution to analyse lamina-scale compositional variation in unbioturbated pelagic and hemipelagic sediments. BSEI and image analysis has e.g. successfully resolved up to 5 intra-annual laminae, which correspond to seasonal fluxes monitored in sediment traps, in both the Gulf of California and the Santa Barbara Basin (Bull & Kemp, 1995; Pike & Kemp, 1996). Time series analysis of variation in intra-annual diatom species composition has successfully been used to quantify decadal-scale ocean variability (Pike and Kemp, 1997).

Image analysis of thin-sections provides high-resolution grain-size data (Francus, 1998), allowing the retrieval in varved sequences of quantified information for each year of sedimentation. Francus et al. (2000) link the annual grain-size to the intensity of snowmelt in an Arctic lake. Sediment fabric can also be quantified, e.g., the extent of bioturbation (Francus, in press; Francus, accepted; Lavoie et al., 1999). Clarck and Hussey (1996) have quantified the charcoal influx and Anselmetti et al., (1998) the carbonate content. Automated recognition of biologic features such as pollen (France et al., 2000) are now under development using neuronal systems approaches. Work is in progress to extend these methods to other paleontological features.

Image analysis of sediment composition and properties is a highly effective, and comparably easy approach and low-cost alternative to more conventional methods used to obtain paleoclimatic and paleoceanographic data from sedimentary records.

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IMAGE ANALYSIS AND COMPARATIVE HOLOCENE VARVE SEDIMENTOLOGY, MID-CONTINENT, USA

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A large network of small, deep glacial lakes make the mid-continent United States an excellent location for regional, high-resolution paleoclimatic study. Further, exceptionally small and deep lakes are often annually laminated (varved), enabling strict chronologic control. Previous work in Elk Lake and Deep Lake, Minnesota, suggests that varve lithology and thickness may be a sensitive indicator of climatic change. This study aims to place this prior site-specific research in a regional context, with new lakes representing areas of differing vegetation and climate. During 1999 and 2001 field campaigns, 13 lakes were cored in Michigan and Minnesota in search of laminated sequences. Most sequences are laminated, and 5 contain excellent, continuous laminae. These new laminated sites form the foundation of a new, regional study of Holocene paleoclimate, with emphasis on the time windows 9-7 Ka and 5-3 Ka, aimed at testing hypotheses regarding the regional nature of Holocene climatic events at 8.2 Ka and around 4 Ka.

Preliminary sediment analysis demonstrates the variable composition of Holocene laminated sediments, even in lakes only 1 km apart. Authigenic mineral content varies from "marl" lakes that contain up to 80% calcite by weight, to lakes containing discontinuous siderite, to lakes with little or no authigenic mineral content. The presence or absence of each sediment component is clearly governed by a complex, poorly understood series of variables, including vegetation, topography, basin morphometry, substrate composition, ground water, and lake trophic state. It is desirable to understand the processes governing the lake-to-lake variability of sediment components to provide a sound framework for climate studies based on this network of vastly differing systems. Further, varve thickness has great potential as a paleoenvironmental proxy, provided that an intimate understanding of the processes governing varve formation from lake to lake is in hand.

Image analysis of macro- and micro-photographs will be important sources of data for this study. Varve counting and thickness measurement will be undertaken using standard image analysis techniques. Further, documenting fine-scale changes in sediment components in thin section using image analysis techniques will place geochemical data in a sedimentologic context and aid in understanding temporal variability in varve composition.

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