A computer-assisted thin-section study of Lake Baikal sediments: A tool for understanding sedimentary processes and deciphering their climatic signal

Article *in* International Journal of Earth Sciences · September 2000

DOI: 10.1007/s005319900064

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Int J Earth Sci (2000) 89 : 260–267

ORIGINAL PAPER

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A computer-assisted thin-section study of Lake Baikal sediments: a tool for understanding sedimentary processes and deciphering their climatic signal

Received: 27 November 1998 / Accepted: 13 September 1999

Abstract A freeze-drying technique for cutting thin-sections of soft sediments without disturbance is used to study several Lake Baikal sedimentary microstructures. Image analysis methodology is applied to selected thin-sections. This new technique provides quantification of the size, shape, orientation and packing of the objects forming the sedimentary structures. Sedimentary processes, which were previously poorly documented, have been identified, and others are better understood. Spheroidal lens-like pure aggregates of the diatom genus *Synedra* are found in hemipelagic sediments, providing a new insight into their traditional paleoecological interpretation. They are possibly related to a transportation mechanism from the littoral zone or to lacustrine snow. Laminae of *Aulacoseira* have also been recorded. Evidence of rapid sedimentation suggests they are due to massive algal blooms. The depositional mechanism that was suggested by other studies for explaining the laminations at the Buguldeika uplift is confirmed: the hemipelagic sedimentation is interrupted by terrigenous pulses due to discharge events. The sedimentation rate appears to be increasing during these pulses. Preliminary results from the Academician Ridge show stronger microbioturbation during cold periods. This observation strengthens the hypothesis of intense water circulation during colder times. Thin-section image analysis provides crucial information for deciphering lacustrine records and their regional and palaeoclimatic significance.

Key words Image analysis · Sedimentary structures · Thin-sections · Lake Baikal · Laminations · Diatoms · Paleoclimate

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Introduction

As one of the world's oldest and largest existing lakes (Khozov 1963), Lake Baikal provides an unusual opportunity for studying a long, continuous record of continental climate change. Therefore, Lake Baikal has been studied intensively by multidisciplinary teams grouping together, for example, seismic studies, geochemistry, physical limnology, sedimentology, pollen and diatoms studies, and palaeomagnetism (Edgington et al. 1991; Weiss et al. 1991; Lake Baikal Paleoclimate Project Members 1992; Colman et al. 1993; Granina et al. 1993; Peck et al. 1994; BDP-93 Baikal Drilling Project Members 1995; Colman et al. 1995; BDP-93 Baikal Drilling Project Members 1997; Flower 1998). To our knowledge, no previous attempts have been made to describe Lake Baikal sediments using thin-sections. This study aims to document as many different sedimentary facies as possible from Lake Baikal to obtain a better understanding of sedimentary processes. This information will assist in deciphering the palaeoclimatic signal recorded in the sediments. We also apply some image analysis techniques to refine observations and obtain quantified measurements on sedimentary facies. The most significant results are presented in this paper.

Materials and methods

Samples were taken from six piston and gravity cores and from 14 different depths within those cores. Sampling was conducted to retrieve as many different sedimentary facies as possible to document Lake Baikal sedimentary processes, focusing on the less understood and poorly documented ones. Particular attention was given to comparing sediments from glacial and interglacial periods. The most significant results are presented here: laminations and spheroidal lens-like aggregates (SLA) from the deep hemipelagic Northern Basin, Academician Ridge and Buguldeika uplift sediments (Fig. 1).

Undisturbed thin-sections were cut from soft-sediment cores using a freeze-drying technique similar to the one described by von Merkt (1971) and Francus (1997). Optical microscope examinations were performed to study the sediment microfabric. Photomicrographs were digitised and stored on a Kodak Photo CD (Kodak, Rochester, N.Y.) system. In addition, backscattered electron (BSE) microscope pictures were acquired digitally for additional image analysis measurements. Digitised pictures were processed on a Power Macintosh computer (Apple Computer, Cupertino, Calif.) using the public-domain NIH Image v. 1.60 program Rasband (1996). Processing of the 256 grey-scale images produced binary images, where white pixels represent the matrix (defined as the finer-grained, clay-rich material enclosing, or filling the interstices between, the larger grains or particles of the sediment) and black pixels represent objects to be measured (e.g. clastic grains, organic debris, diatoms). This methodology is described and discussed in more detail by Francus (1997, 1998).

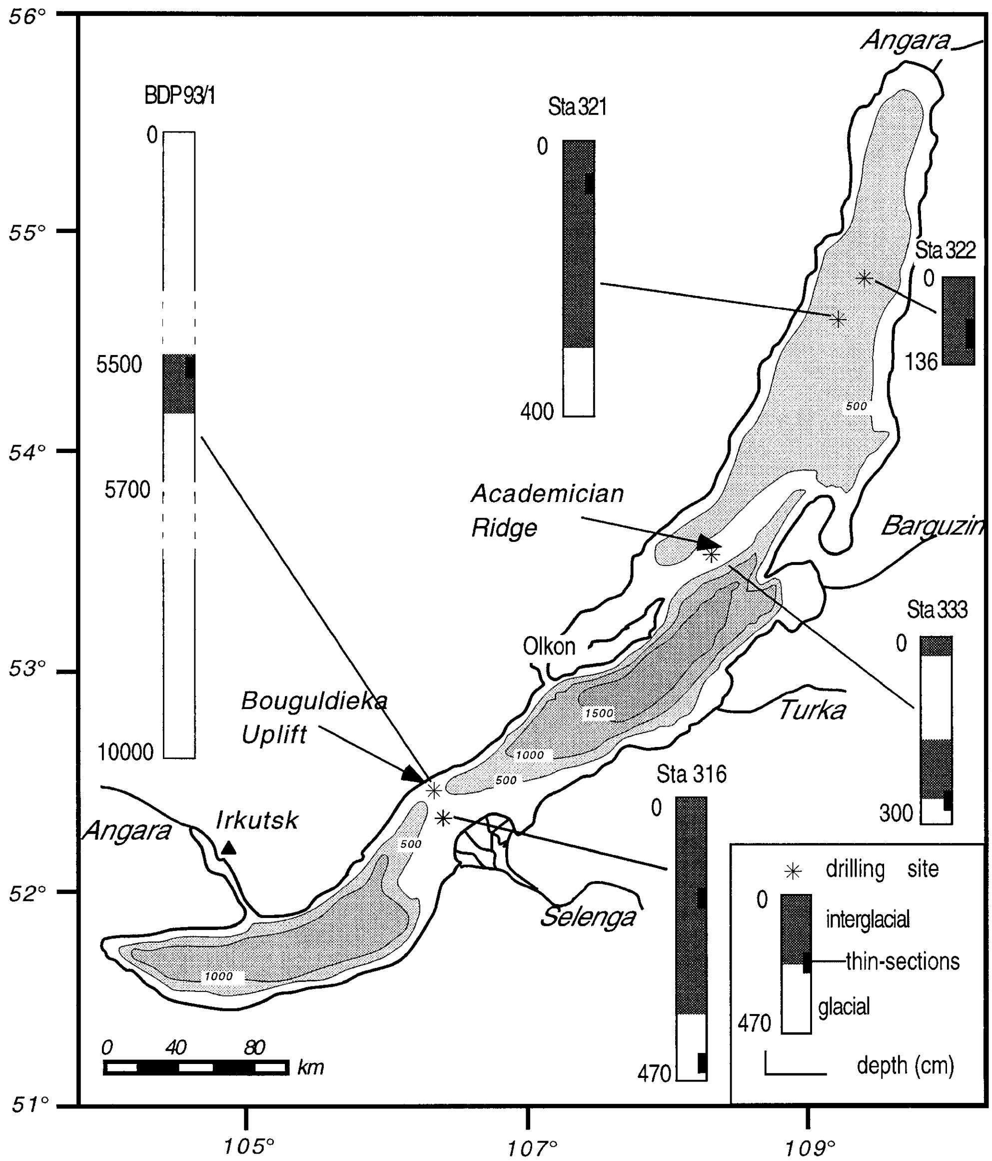


Fig. 1 Sediment core location map

Table 1 Definition of indices

Sedimentary features	Defined index	Comments
Size	$D_0 = 2\sqrt{\frac{A}{\pi}}$	Apparent diameter D_0 is estimated measuring area (A)
Packing	$P\% = \frac{(\#black\ pixels)}{(\#image\ pixels)} \times 100$	P % is a phase percentage. It gives the amount of coarse objects compared with clay matrix
	$H_i = \left(\frac{L}{l} - 1\right)((2\cos(2\alpha))\|\cos(2\alpha))\left(\frac{D_0 - \mathrm{M}D_0}{\mathrm{s}D_0}\right)$	H_i is a horizontality index: it is strong (high) for big, elongated horizontal objects, and weak (low) for small spherical and vertical objects. $\mathrm{M}D_0$ and $\mathrm{s}D_0$ are D_0's median and standard deviation, respectively
Shape	$R_i = \frac{4A}{\pi L^2}$	R_i=1 for circle and is near 0 for lines
Orientation	$\tan\Theta = \frac{\sum_i^n p_i sin\alpha_i}{\sum_i^n p_i cos\alpha_i}$ where $p_i = \left(\frac{L}{l} - 1\right)L$	Resultant vector Θ could be calculated and orientation diagrams could be created as well. p_i is a weighting factor to strengthen big, elongated objects within an image

On each object of interest in the sedimentary matrix, the following parameters are measured: gravity centre (g); area (A); long (L) and short (l) axes of the object; and orientation (α) of the long axis with respect to the horizontal. Those measurements are used to process indices that quantify sedimentary structures (Table 1). From those indices, it is possible to compute mean, median or standard deviation, as well as other statistical parameters which describe the population of the indices values. In this paper we use the median of D_0 ($\mathrm{M}D_0$) as a measure of the apparent grain size. $\mathrm{m}R_i$ is the mean R_i. $\mathrm{m}R_i$ is close to one when sediment is made mostly of spherical objects, and is close to zero when composed of elongated objects. H is the mean of H_i calculated on grains which have D_0 greater than $\mathrm{M}D_0$. H values less than one have been reported for randomly oriented microstructures and H greater than 5 for horizontal packing of grains in the microstructure. Significance and limitations of indices are discussed elsewhere (Francus 1998; P. Francus, submitted; http://www.geo.umass.edu/climate/francus/).

Results

Synedra spheroidal lens-like aggregate

Synedra valves, probably *S. acus*, are found in cores from the centre of the Northern Basin at several depths in the sediment. Occurrences are also reported at Buguldeika uplift and at Academician Ridge. In thin-sections *Synedra* occur as small spheroidal concentration zones approximately 100 µm in diameter, looking like a lens (Fig. 2). Sometimes they also appear as truncated 200-µm-thick and up to 800-µm-long laminae.

Bradbury et al. (1994) mention that *Synedra* live in coastal and shallow environments. Edlund et al. (1995) interpret *Synedra* occurrence as resulting from an increase of eutrophic conditions within the lake, whereas Bradbury et al. (1994) point out that they may reflect a warm spring season, and a quick ice melting, coupled with increased precipitation. A massive *Synedra* bloom has also been reported in the hemipelagic zone (Popovskaya 1991).

Because of their deposition as SLAs, *Synedra* occurrences should be interpreted taking into account the factor of preservation. Indeed, *Synedra* is a long and fragile diatom species. In most oligotrophic lakes, only a small fraction of total primary biological SiO_2 in surface water is preserved in the sediment. Selective dissolution of diatoms clearly affects preserved diatom assemblages (Brodie and Kemp 1994; Colman et al. 1995). *Synedra* has a large area/volume ratio and is therefore more subject to dissolution (Sancetta 1989). It is possible that the preserved specimens are those which conglomerate: massive algal blooms and some kind of lacustrine snow have been observed during dives of the submersible "Pisces" Monin (1979) and investigations using sediment traps and photo cameras (Pilskaln et al. 1990). The absence or low concentration of *Synedra* valves in surficial sediments (Popovskaya 1971) and the presence of *Synedra* SLAs could be explained by fast sinking of lacustrine snow aggregates without dissolution. Since *Synedra* are more frequently observed growing in the littoral zone, SLAs could also reflect a stronger transportation mechanism from the littoral to the hemipelagic area. Transportation should occur as overflow, or a similar

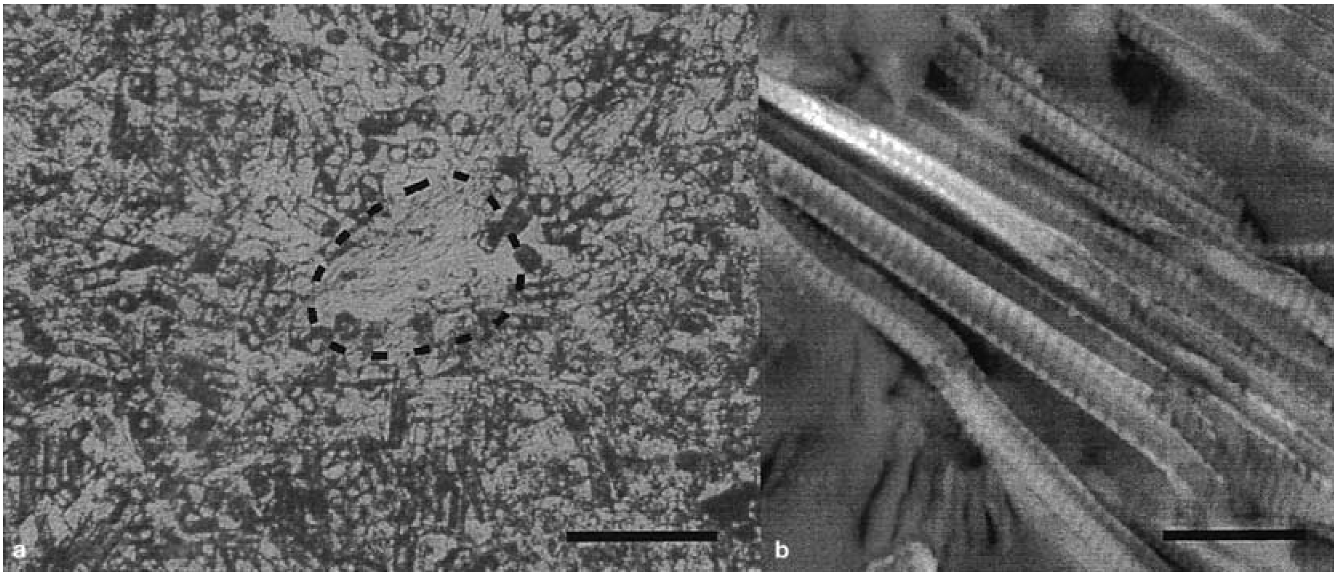


Fig. 2a,b *Synedra* SLA, Lake Baikal, Station 322, 83 cm depth. **a** petrographic microscopic view. SLA is delimited by the *dashed line* and is essentially surrounded by *Aulacoseira*. Scale bar is 100 μm. **b** Backscattered electron microscope view of the same SLA. Scale bar is 10 μm

mechanism, because SLAs are found in the centre of the lake basin, and on isolated bathymetric high as well. But this interpretation does not explain entirely how *Synedra* are forming aggregates. Spheroidal lens-like aggregates could also be interpreted as fecal pellets, but this interpretation is less accurate when *Synedra* occur as short laminae. Finally, since *Synedra* occur in sediment cores as SLA, their presence is not equally distributed along the core; therefore, the probability of sampling a SLA must be considered.

In brief, thin-section observation reveals a particular deposition pattern for *Synedra* and strengthens the opinion of Bradbury et al. (1994) that we must know about the transportation and deposition of diatoms before they can be used to decipher stratigraphic records.

Aulacoseira laminae

Numerous laminae rich in *Aulacoseira*, most probably *A. baicalensis*, are found in several depths in the Northern Basin, during both glacial and interglacial periods, but never continuously (Fig. 3). Those macroscopically grey laminae are 600 μm to 2 mm thick. They are included in a greenish clayey sedimentary matrix. In some place those two facies alternate regularly forming 2-mm-thick doublets. The BSE image measurements (Table 2) point out a 15 % mean diatom content within *Aulacoseira* laminae, whereas in the surrounding greenish sediment diatom content is 9 %. Silt content is similar inside and outside laminae: 6 %. Index H values are stronger in the laminae (Table 2).

The presence of laminae in oxygenated basins is unusual, because bioturbation normally occurs. Nevertheless, comprehensive microscope examination (Francus 1997) reveals microbioturbation traces as described by Brodie and Kemp (1995). Laminations have also been reported in oxic environments elsewhere (Khuel et al. 1988). Doublets found here could not be annual because in the deep Northern Basin mean sedimentation rates are 1.1–0.2 mm/year (Edgington et al. 1991; Colman et al. 1993; Qiu et al. 1993; Appleby et al. 1998). Laminae are probably not due to variations in the clastic supply, because silt P % and mean grain shape mR_i (Table 2) are similar inside and outside the laminae. Laminae correspond to massive algal blooms described by Khozov (1963), Bradbury et al. (1994) and Edlund et al. (1995) that occur irregularly every 3–4 years but rarely in successive

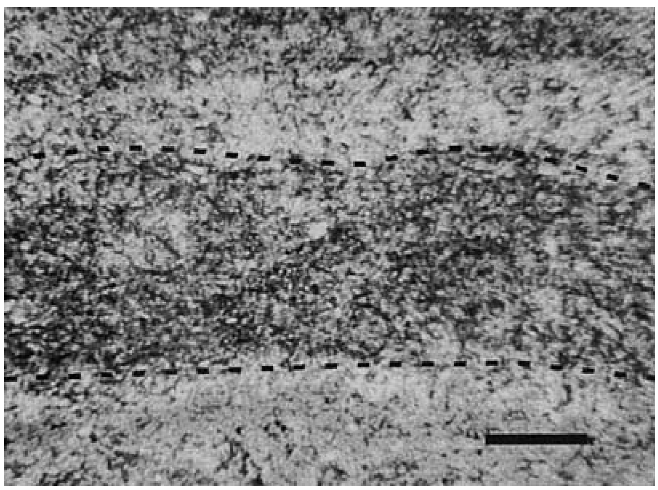


Fig. 3 *Aulacoseira* lamina, Lake Baikal, Station 321, 69.3 cm depth. Petrographic microscopic view. Dark laminae are made mostly of *Aulacoseira*; clear part is the sediment background. Scale bar is 500 μm

Table 2 Image analysis measurements taken from eight different backscattered electron microscope pictures of the area illustrated in Fig. 3. *N* is the number of measured objects. Student's *t*-test indicates that samples 2–5 are statistically different (95 % confidence interval) by mean *H* indices from samples 6–9

Sample no.		*N*	Diatoms	Silts	Diatoms and silts		
			P %	*P* %	MD_0	*H*	mR_i
2	*Aulacoseira* laminae	328	13.01	6	3.01	1.23	0.52
3		241	12.03	7.2	3.78	0.94	0.53
4		301	13.08	6.2	3.43	0.57	0.56
5		326	16.58	7.4	3.69	0.37	0.54
6	Background sediment	291	9.42	6.25	2.88	0.01	0.54
7		311	9.80	7.30	3.07	−0.08	0.56
8		254	9.73	5.82	3.05	0.05	0.53
9		240	8.83	5.20	3.02	−0.02	0.55

years. Sturm (1998) recorded those algal blooms in sediment traps, with extraordinarily high sinking velocities (>100 m/day), which resulted in a centimetre-thick layer of non-compacted algal mud. This quick sedimentation explains the discrepancy between *H* measured outside and inside *Aulacoseira* laminae. Laminae are protected against microbioturbation, because they settle rapidly and, therefore, show high *H* index values. On the other hand, the clayey sedimentary background between two *Aulacoseira* blooms is exposed to microbioturbation during a much longer time period, at least 3–4 years. Therefore, it is no longer appropriate to speak in terms of annual mean sedimentation rate because of the huge temporal variation in sedimentation. This is probably why so many different sedimentation rates have been measured previously. A slight variation in the occurrence of diatom blooms could change the mean sedimentation rate drastically.

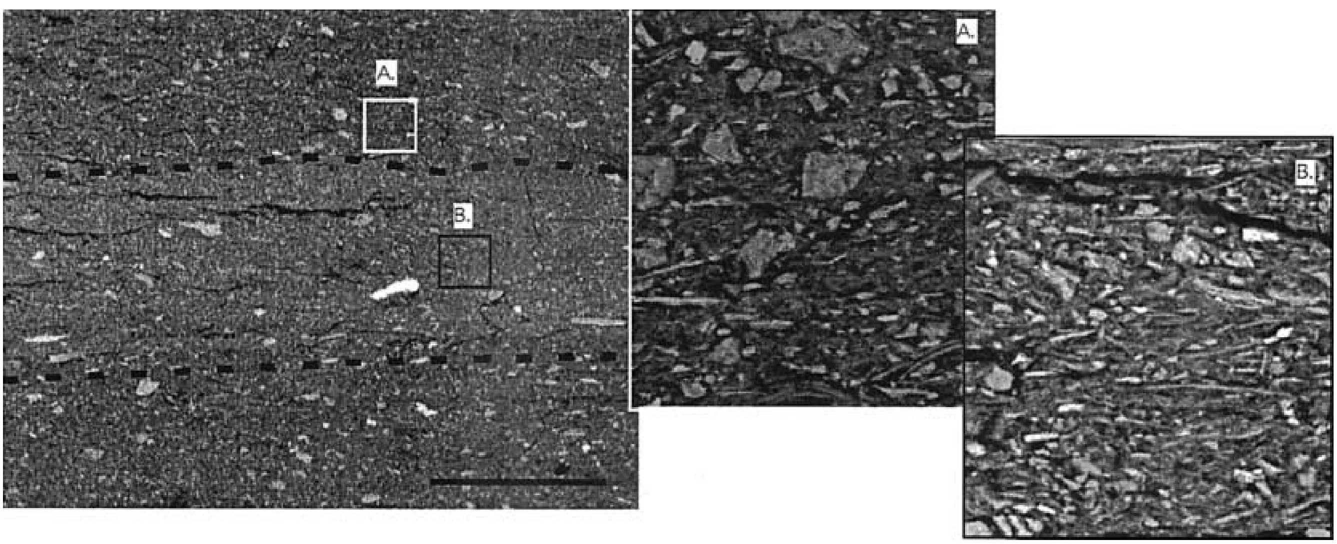
Laminations at Buguldeika uplift

At station BDP93/1 and station 316 PC1, diffuse 500-μm-thick laminations interrupt the hemipelagic sediment (Fig. 4). Observation and measurements (Table 3) characterise the sediment as follows: because laminae are lighter in BSE images, they have a heavier mean atomic weight; laminae are more elongated (mR_i weaker); laminae elements show stronger *H* index values, pointing to a horizontal disposition; *P* % indices are stronger in laminae, pointing to a richer content in detrital elements; and grain size are similar in both members (D_0 constant). A similar pattern is found in both glacial and interglacial sediments and in the ~300-ka-old sediment at 5512 cm depth in the BDP93/1 core, as well (Kuzmin et al., this volume).

Table 3 Image analysis measurements. Mean values from ten different backscattered electron microscope pictures in similar area as illustrated in Fig. 4. *A* mean values for the sedimentary background; *B* mean values for discharge pulses laminae

Indices	Matrix (A)	Laminae (B)
H	3.26	6.62
mR_i	0.46	0.41
MD_0	1.20	1.30
sD_0	1.47	1.01
P %	18.4	24.0

Fig. 4 Buguldeika uplift lamination, BDP93/1, 5512 cm depth. Backscattered electron microscope image of the lamination. The terrigenous pulse member is lighter and delimited by *dashed lines*. Scale bar is 500 μm. *A* and *B* are enlarged views of delimited squares in left general view. Measurements in *A* and *B* and similar zones are displayed in Table 3



Those observations and measurements lead to the conclusion that laminae are richer in micas (elongated grains containing heavy elements, such as iron) and terrigenous elements. Laminae are less exposed to bioturbation pointing to a higher sedimentation rate. Particle size is constant in both members (MD_0 constant), arguing in favour of a sorting by overflows or interflows in both members. A turbiditic input would lead to an increase of MD_0 in the lamina, whereas gravity reworking would probably lead to an increase of the grain-size standard deviation sD_0 in the lamina (see Table 3). Those observations lead to the conclusion that laminae in Buguldeika uplift sediments represent terrigenous pulses due to discharge events transported by overflows. This sedimentary pattern has been present for at least 300 ka. If Selenga River is the most important source of sediment for the upper 50 m, terrigenous pulses from the Buguldeika river are also possible (BDP-93 Baikal Drilling Project Members 1997; Kuzmin et al., this issue).

Academician Ridge

Academician Ridge is a large topographic high of tectonic origin and separates the Northern from the Central Basin. At the coring site, station 333–PC1, the lake is only 390 m deep. Bottom water is permanently rich in O_2. The sediment core recovers a period from isotopic stage 5b to stage 1. Diatom-rich zones are correlated to interglacial periods, and clayey ones to colder periods (Fig. 5). In thin-sections different kinds of disturbances are visible. Some are due to growth of diagenetic concretions; others are erosion features, probably produced by bottom currents. Those disturbances are present in both interglacial and glacial periods. Ten observations and measurements are performed between 272- and 255-cm depths within the cores, across the stage 5b to stage 5a transition. Image analysis measurements are taken avoiding the visible disturbances. Indices *H* show significant variations: *H* is weak during glacial periods pointing to a weak horizontality of elements within the sediment. On the contrary, *H* is stronger during interglacial periods. Both *H* indices and biogenic silica content (Fig. 5) show increasing values across this boundary. Because measurements have been taken in areas having no visible disturbance due to currents or diagenetic processes, or any other source of perturbation, *H* variations could be interpreted as bioturbation trends (P. Francus, submitted). The sedimentary fabric difference between cold and interglacial sediments could be explained by differential perturbation by microbenthos. Microbioturbation is strong during glacial periods and weak during interglacial periods.

Bradbury et al. (1994) suggest a deeper epilimnion during glacial periods due to stronger winds during turnover periods. They argue that oxygen-enriched waters could slightly favour the weak microbenthic activity and therefore bioturbation. Another source for variation in the dissolved oxygen content is provided by Kipfer and Peeters (1998). According these authors, the "Selenga feeds the Central Basin with water having a larger salinity than the lake, whereas the Upper Angara provides the Northern Basin with fresh water. As a consequence, at any given depth Central Basin water is slightly more saline and hence denser than Northern Basin waters. At Academician Ridge, transport of surface water from the Central Basin to the North Basin across the sill causes dense Central Basin water to flow along the density gradient propagating down into deep water region of the Northern Basin". It can be assumed that salinity-induced currents also bring additional nutrients to Academician Ridge. Since oxygen is not a strong limiting factor for life, it is more likely that an increase of nutrient input is the strongest factor favouring microbenthic activity. It is reasonable to assume that currents could be controlled by climatic factors since currents are triggered by Selenga discharge. Further work is required to check this hypothesis.

The sedimentation pattern at Academician Ridge is still a debated issue (Flower 1998). The sedimentation rate is slow but variable (0.051–0.34 mm/year), and some authors reported crusts interpreted as interrup-

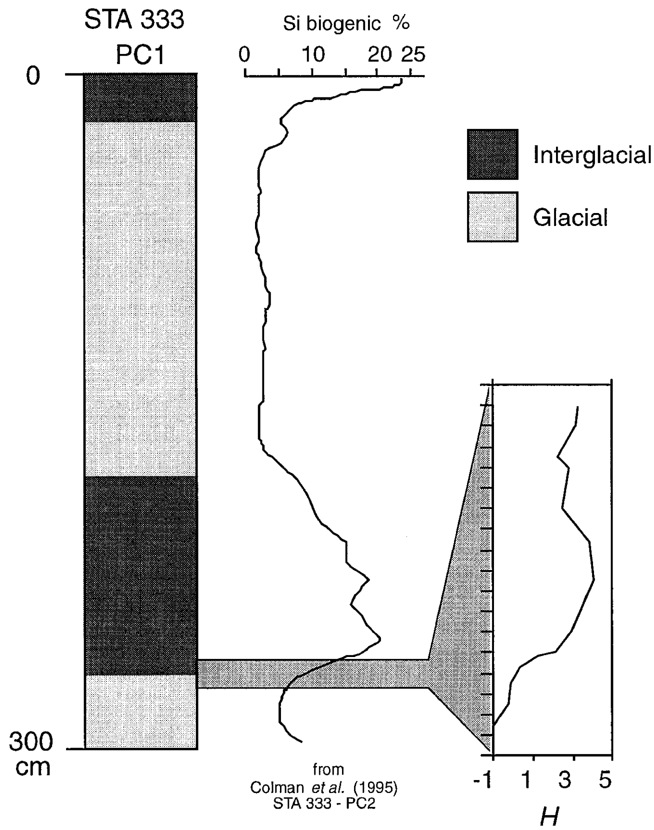


Fig. 5 *H* indices curve at Academician Ridge at the stage 5b–5a transition. Biogenic content data are from the parallel STA 333-PC2 sediment core

tions in the sedimentation (Granina et al. 1993). On the other hand, Colman et al. (1995) conclude that there is no clear evidence of changes in sedimentation rate between interglacial and glacial periods. Our few thin-section observations and measurements do not provide the solution to this issue, but bring a contribution to the understanding of the sedimentary pattern. Measurements also need to be repeated on other cores from the same area to determine if the model described here is widespread at Academician Ridge.

Discussion

High-resolution and continuous palaeoclimatic studies have an essential need for undisturbed sediment sequences. Towards that goal, new tools, such as surface scanning magnetic susceptibility Lees et al. (1998), have recently been developed for identification of sedimentation patterns. Thin-section image analysis is also able to provide a wide range of observations necessary for palaeolimnological reconstructions. Among other examples, retrieved information could validate or invalidate palaeoclimatic interpretation given to diatoms spectra. One can also check the quality of the retrieved sediment cores and verify its relevance for palaeoclimatic reconstructions. Sedimentary patterns could be clearly characterised and quantified. We suggest other potential uses of thin-section image analysis for Lake Baikal: identification of sedimentary events, such as turbidites, ash layers and erosional features, and quantification of the terrigenous input vs diatoms input.

For palaeoclimate reconstruction in general, thin-section image analysis is most valuable when used together with other proxies, improving their interpretations. The technique also potentially offers the opportunity to obtain quantified sedimentary data to be compared with present-day meteorological, hydrological and limnological data. This allows an understanding of how the climatic signal is recorded in the sediments, and the building of a sedimentary transfer function.

Conclusion

Image analysis, applied on both optical and BSE pictures, provides quantified measurements on sedimentary microstructures. Sediment packing, grain-size and shape could be measured at the laminae scale, allowing refined observations and interpretations. *Synedra* have been found in sediment as SLA in hemipelagic zones. They are possibly related to a transportation mechanism from the littoral zone or to lacustrine snow. Massive *Aulacoseira* blooms occurring irregularly every 3–4 years form laminae which settle very quickly. Laminae at Buguldeika uplift are terrigenous pulses due to discharge events, transported by overflows. In Academician Ridge, preliminary results show that bioturbation is stronger during cold times. This observation strengthens the hypothesis of a greater water circulation during colder times, and suggests the possibility of a stronger nutrient input.

Thin-section observations allow a better understanding of sedimentary processes of Lake Baikal. Thin-section image analysis provides crucial information to decipher lacustrine records and their regional and palaeoclimatic significance.

Acknowledgements This work was made possible by Dr. Grachev, Dr. Kuzmin and Dr. Klerkx. It was supported by a PhD valorisation grant from the Université Catholique de Louvain, the OSTC (Belgian Impulse Program on Global Change), and by BICER (Baikal International Centre for Ecological Research). The cores were collected during joint cruises of the Russian Academy of Sciences, University of South Carolina and U.S. Geological Survey. F. Keimig and L. Anderson improved the English text. The authors are grateful to C. Beck and R. Flower for their constructive review.

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