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The deposition and accumulation of endemic planktonic diatoms in the sediments of Lake Baikal & an evaluation of their potential role in climate reconstruction during the Holocene

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Final Report to NERC - GEOPASS on Contract GR3/10529

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1. Introduction

Planktonic diatoms play a central role in studies of Lake Baikal. Not only are they dominant primary producers in the lake's food chain, but (i) the exceptionally long, lake sediment records are diatom rich, and (ii) many of the taxa are endemic which makes them of interest for evolution studies. In this study we have collaborated with Swiss and Russian scientists and the wider BICER (Baikal International Centre for Ecological Research) community to develop an understanding of the relationships between diatom production and life-cycle strategies, diatom sedimentation in the water column, and diatom preservation and accumulation in sediment records. Our primary aim has been to explore, using quantitative techniques, the potential and limitations of diatoms as indicators of past environmental change in the sediment record.

1.1 Approach

We have used samples, material and data from this and associated projects described in our proposal. These include samples and data from the regular monitoring of phytoplankton crops, samples and data from the deployment of sediment trap arrays, and core material from many locations throughout the lake. Phytoplankton monitoring has been carried out as part of a collaborative Russian/UK/Austrian INTAS project (INTAS96-1937), with other financial support from the Royal Society (RS) and Russian Academy of Sciences. The sediment traps were installed, maintained and sampled by Swiss collaborators from EAWAG-Zurich using Swiss Research Council funding. The Swiss were also responsible for collecting many of the sediment cores and for some aspects of the analyses of trap and core samples (including on board core stratigraphy, scanning electron microscopy of trap and core material and ^{210}Pb dating of selected cores). Although the NERC funded project has now finished, phytoplankton monitoring continues until the end of 1999, with resources from INTAS and the RS. Sediment trapping is also being maintained by the Swiss until March 2000, but at a different location in the lake (beside the Neutrino Telescope experiment in the South basin).

Despite continuing difficulties with Russian research funding, none of the work originally proposed has been compromised by logistic problems. All sampling and coring that was planned has been successfully carried out. This is testimony essentially to the excellence and commitment of a number of Russian scientists in Irkutsk and the support systems put in place under the auspices of BICER (co-funded in the UK by the Royal Society). Collaboration within the project has also worked extremely well. A series of meetings and workshops have been held to discuss project management, operational strategies and results and taxonomic harmonisation (see Appendix A for Research Reports).

1.2 Principal achievements

The following report addresses the extent to which the specific objectives of the project have been met. The results are striking and provide definitive answers to some of the issues that have long been debated amongst Baikal scientists, including:

- endemic diatom population sizes are controlled by the physical and biotic environment of Baikal, e.g. temperature, ice formation and mixing and grazing, rather than by nutrient availability;
- population successions are controlled by complex interactions with zooplankton;
- diatom sinking rates can be extremely rapid, up to 64 m per day;
- no resuspension or lateral transport of sediment occurs above 100 m water depth from lake bottom;
- little diatom valve dissolution occurs in the water column, except perhaps for *N. acicularis*, and some other finely silicified taxa
- only *c.* 1 % of total diatoms in the water column are finally incorporated in the sediment record;
- diatom dissolution occurs principally at the surface sediment - water interface;
- preservational differences are spp. specific, and preliminary correction factors have been established;
- canonical ordination techniques suggest that several variables linked to climate are significant in explaining variation in the diatom flora;
- diatom-inference models constructed as predictors of climatic variables, show promise;
- snow depth in March and July heat balance have been reconstructed over the last 500 years or so, and applied to the core BAIK38. They tentatively demonstrate changes in climate consistent with a cold period co-inciding with the Little Ice Age, and an ameliorating climate during the last 150 years;
- most of the cores examined are affected to some degree by turbidite formation, although effects appear to be less in shoulder regions of the lake.

2. Specific Objective 1: characterisation of the environmental controls on the abundance of key endemic taxa

Regular monthly sampling of the diatom plankton of the south basin began in 1994 along a transect between Lystvyanka and Tanhoi. Since 1996, sampling has been expanded to include sites in all three basins. Figure 1 shows data for changes in populations for the last five years (1994-1998).

The diatom plankton is dominated by a small number of taxa whose populations vary significantly from year to year, principally in relation to variations in the physical environment (ice formation, water temperature and water column mixing) and biotic interactions, especially from zooplankton grazing. Numbers of nauplii which consume diatoms during late winter will determine the innoculum of diatoms under the ice, which in turn largely determines the size of the final crop the following summer. Nutrient limitation is not an important factor as the nutrient reservoir in the lake is very large, extending in June to a mixed depth of over 100 m. For *A. baicalensis* we now have cell measurements that include sexual reproduction, recruitment and resting stages. In Baikal, these are important because the associated morphological changes in cell wall structure (length and diameter) are independent of nutrients and changes in community assemblage, and are observable in both water and sediments. The changes in valve length (Figure 2) are seasonal, varying with snow cover, depth of mixing and summer stratification. Valve-lengths vary from 5 to 83 μm, making it one the longest relative changes observed in diatoms and which is readily quantifiable as a seasonal response. The observation that taxa are mainly subject to physical controls is confirmed from laboratory culture experiments that show clear differences in the growth rate dependence of taxa on both temperature and light (Fig. 3). *S. acus* and *S. binderanus* have higher growth rates at higher temperatures than *Aulacoseira* or *Cyclotella* spp. Also, *S. acus* grows faster at higher light intensities than *Aulacoseira* or *Cyclotella*. These findings are used to interprate the diatom profile in Section 7 below.

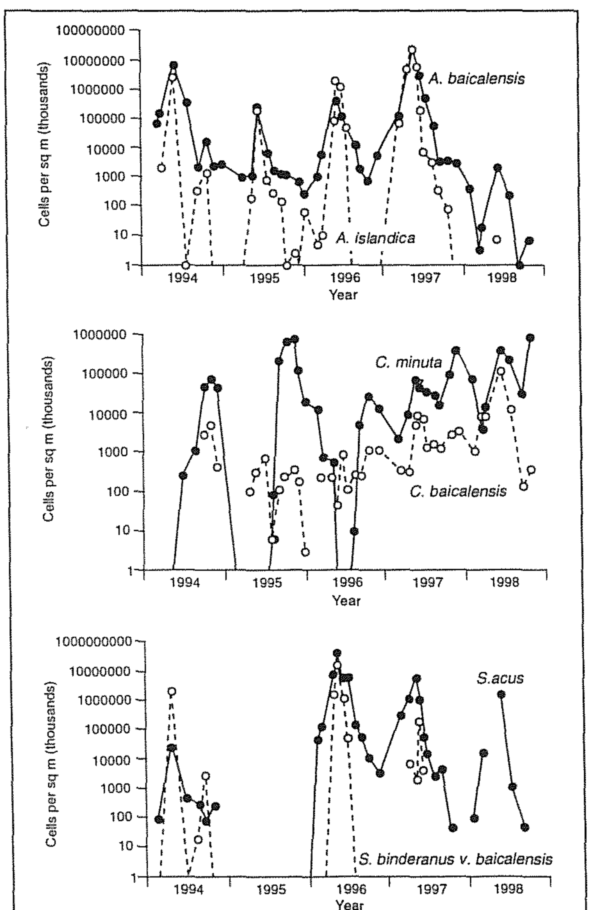

Figure 1: 5 year crop data for 6 species

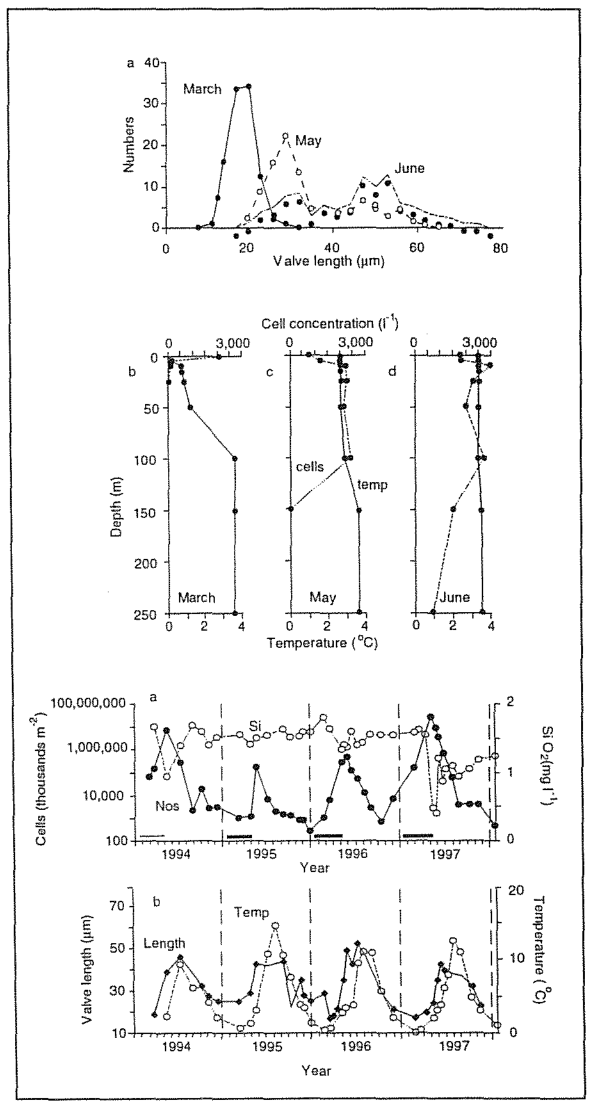

Figure 2: *A. baicalensis* valve length measurements and cell concentrations plotted *vs.* temp. and silica concs.

3. Specific Objective 2: transport and alteration of diatom crops through the water column using plankton and sediment trap data

A key objective of our project was to assess how rapidly and faithfully the plankton crops are transferred to the sediments. Data needed to address this issue are derived from the 5 years of crop statistics (1994-1998) and the 2 years of sediment trap data (1996-1997). The sediment trap data include data from upper (522 - 560 m) and lower (1284 - 1384 m) sequencing traps and from upper (522 - 560 m) and lower (1287-1390 m) open traps. The open traps represent integrated 6 monthly samples whilst the sequencing traps opened and closed automatically at two week intervals over the 2 year sampling period. We have worked both with fluxes of total cells and individual species. Unfortunately, however, insufficient material was available from the sequencing traps for estimates of diatom concentration and hence fluxes to be made. For these traps only relative abundance data are available. The degree of diatom dissolution was calculated for each sample using Flower's diatom dissolution index (DDI) (Flower and Likhoshway 1993). The diatom phytoplankton crop data derived from regular sampling were re-calculated to show the number of valves for each species for each of the 5 year sampling periods expected to be sedimented out of the water column (see Table 1).

During the growing period, diatoms are distributed throughout the mixed layer and this extends down to 120 m in early June in the southern and middle basins, but is less in the north. Relatively little loss from sedimentation occurs during the growing period. The situation changes rapidly at the beginning of June, when deep water vertical mixing ceases and summer stratification begins. Settling from the upper layers takes place rapidly at the end of the growth period. All species have been tracked down through the water column with time. The main crops sink rapidly, although some dispersed cells can take from 12 to 18 months to reach the bottom, The various taxa have different sinking strategies, e.g. *A. baicalensis* sedimentation is enhanced by the formation of longer, heavier cells that can clump and form larger particles. The rapidity of sinking can be clearly seen from a comparison of the crop records in the top and bottom sequencing traps (Figure 4).

The species succession in the bottom trap is almost identical to that of the top trap. In some cases the sedimentation is exceptionally rapid. The *A. baicalensis* bloom of 1997, measured as a mass flux, was recorded simultaneously in the upper and lower traps implying settling rates as high as 64 m per day. The similarity between the boffom and top traps, in terms of mass flux and species composition throughout the two year exposure period, indicates that any sediment resuspension or lateral transport that occurs must be confined to water deeper than the depth of the bottom trap i.e. 100 m above the bed of the lake. These data indicate that not only is the flux of diatoms to the sediment rapid, but that little overall dissolution takes place in the water column. This view is supported by the relatively high and similar values for DDIs for the diatoms in the upper and lower sequencing traps (Figure 5). The lowest values of DDI in 1997 coincide with the *S. acus* bloom. *S. acus* is a finely silicified diatom, but the high flux values to the lower traps (data not shown here) suggest that little complete dissolution has taken place in the water column. A possible exception to the rule that water column dissolution is not significant occurs for *N. acicularis*, an extremely delicate species. This taxon occurred in abundance in 1995 (Table 1) but not in 1996 or 1997 when the traps were exposed. Very few cells were present in the traps in 1996 and it is almost completely absent from the lake sediments (Mackay *et al.* 1998). Consequently, it is lost either in the water

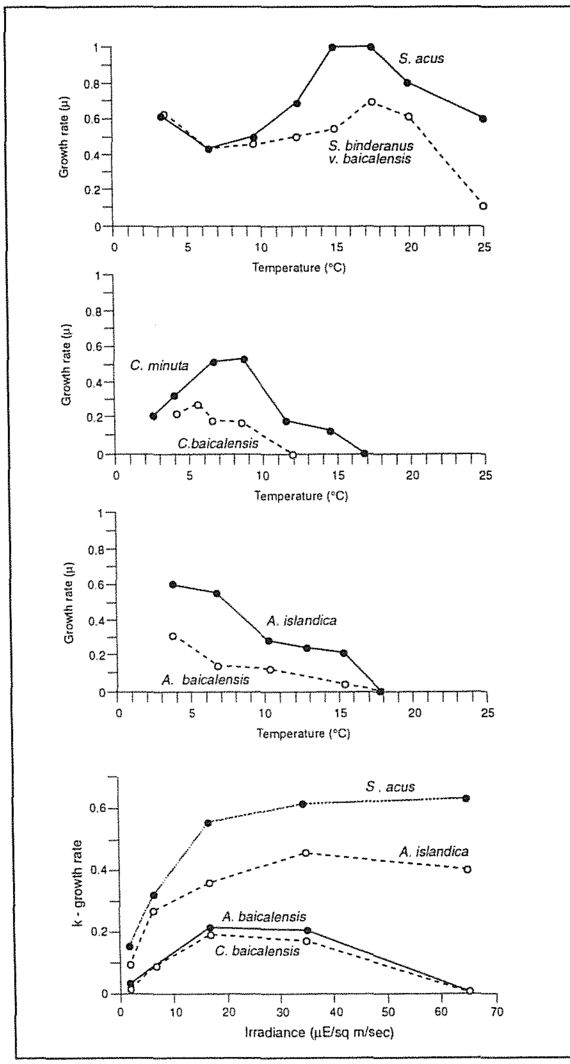

Figure 3: Diatom growth rates vs. temperature and light

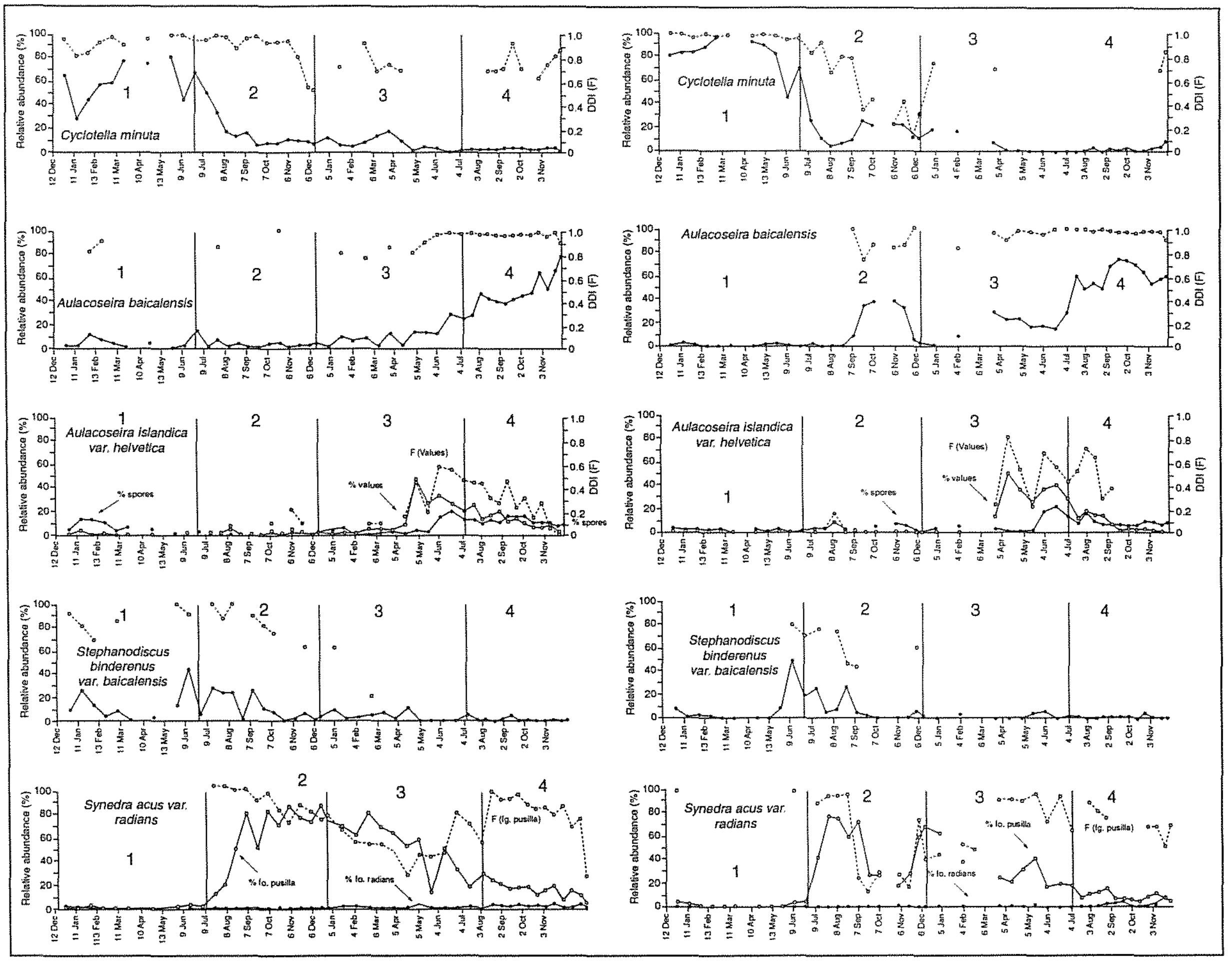

Figure 4: Relative abundances of selected species in sequencing traps 1 and 3

column and/or in the surface sediments. Further work is required to establish where the dissolution occurs.

4. Specific Objectives 3 and 5: comparison between diatom fluxes to the sediment and the surface sediment diatom record

Another central objective is to assess how faithfully the composition of diatom assemblages in the sediment reflect the overall composition of live diatom populations in the lake. We have attempted to quantify this relationship by comparing diatom fluxes in the water column ("expected" in the sediment) with diatom accumulation rates in recent sediments ("observed" in the sediments). We have then used these data to calculate the expected and observed percentages of each taxon in the sediment and to derive a series of correction factors that allow the "real" percentages to be reconstructed. There are a number of potential error sources in making meaningful comparisons of water column and sediment records. These are mainly concerned with problems of spatial and temporal variability and with matching equivalent time periods. In this case we are matching the average of 5 years plankton data from 1994-1998 (Table 1) with the diatom accumulation rates of the top sample (0 - 2 mm) of a core taken in 1993 from a location several kms distant from the site of phyto-plankton sampling. Nevertheless, we will soon have similar diatom accumulation rate data for a number of cores taken in 1997 when ^{210}Pb dating in Switzerland has been completed.

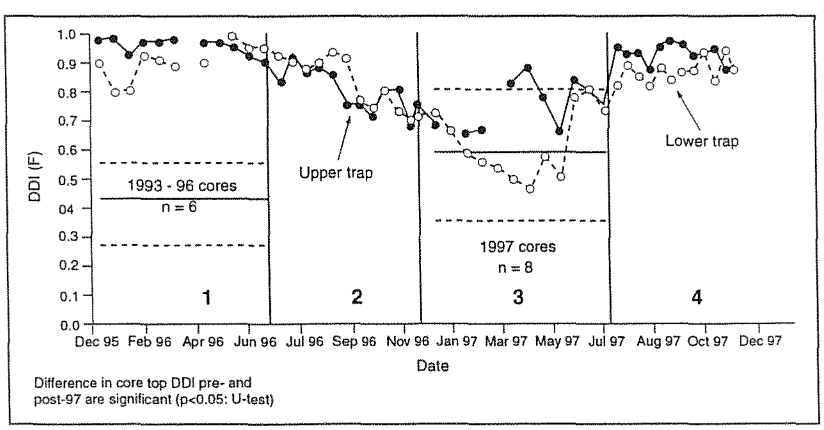

Figure 5: Top and bottom trap DDI comparisons

Table 1 provides an example of the comparison for only one core (BAIK 38) and strikingly illustrates the difference between the expected and observed fluxes, both for total diatom and for each species. Allowing for the problems described above, and assuming that the mean flux to the sediment was not significantly different in the 5 year period or so before 1993, the comparison shows that only *c.*1% of diatoms produced in the water column are preserved in the sediment. Furthermore, preservation is differential between species. Again, assuming that the species composition in the water column in the year before 1993 was similar to that of the 1994-1998 period, the data indicate that *C. minuta* is the most resilient diatom with about 9% of its crop preserved, whereas *S. acus* and *N. acicularis* are least resilient. *N. acicularis* suffers a complete loss and only 0.1% of *Synedra* valves are preserved. This is an important finding for palaeoclimate studies as these less robust taxa are the ones that are more indicative of warmer conditions (see Fig 3).

One conclusion from these data is that the most important site of diatom dissolution is in the surface sediments. This can be illustrated also by the use of dissolution indices that show the sharpest decrease in preservation quality occurs between the lower trap and the surface sediment, rather than in the water column or in the deeper sediment. Once the diatoms become part of the deeper sediment record little further deterioration takes place, suggesting that correction factors based on the difference between the water column and the surface sediment should be applicable for older sediment assemblages. These data show that it will be essential to use correction factors to allow for differential dissolution before species-based climate transfer functions can be satisfactorily developed. The kinds of correction factors needed are illustrated by the case of BAIK38 in Table 1. However, before we establish and publish final correction factors for wider use, we need to re-check all our data and calculations and take into account all available core and water column data as described below.

5. Specific Objective 6: the development of palaeoclimate reconstruction methods using internal transfer functions

Most standard diatom transfer functions use training sets that comprise modern assemblages from many lakes representing environmental gradients of interest. For Baikal this is impossible as the key species are endemic. On the other hand, the lake is exceptionally large, consists of three main basins and a number of other regions and spans a substantial climate gradient from north to south. Our intention is to use this gradient within the lake to explore a range of different internal transfer function options. In the proposal we outlined 4 calibrations methods to be performed. We have here, however, combined several of these using regression (e.g. canonical correspondence analysis (CCA)) and calibration (i.e. weighted averaging partial least squares WA-PLS). *A. baicalensis* valve lengths provide a useful metric for environmental conditions (see above), and these have been included as a variable in the explanatory data-set. The relationship between diatom productivity and accumulation rates along a N-S axis has not been explored, because of the extent of dissolution between the water column and the sediments.

The calibration data-set comprises 93 surface sediment samples collected from across the length of

	C. min	A. baic	A. island	S. bind	S. acus	N. acic	Total
1998	230236	31572	6345	0	465593	36178	826021
1997	200600	5277069	8060791	53167	2955977	2053	16621949
1996	840000	121314	514791	3631803	15283388	15190	20411422
1995	523653	56926	51447	1724701	19618	17304358	19683940
1994	133249	1389636	605966	377367	4834	50968	2565829
Average	385548	1375303	1847868	1157408	3745882	3481749	12021832
BAIK38 (1993)	35562	38038	12942	3264	5514	0	112540
Diff factor	10.84	36.16	142.78	354.60	679.34	∞	106.82
Preservation Factor	**0.092**	**0.027**	**0.007**	**0.003**	**0.001**	**0**	**0.009**
Observ %	31.6	33.8	11.5	2.9	4.9	0.0	
Expect %	3.21	11.44	15.37	9.63	31.16	28.96	

Table 1: Diatom fluxes for selected species and total diatoms between 1994-1998, and for BAIK38, a core taken from a shoulder region in south basin in 1993 (valves per sq. cm). Percentages do not add to 100, as minor taxa are excluded from the table

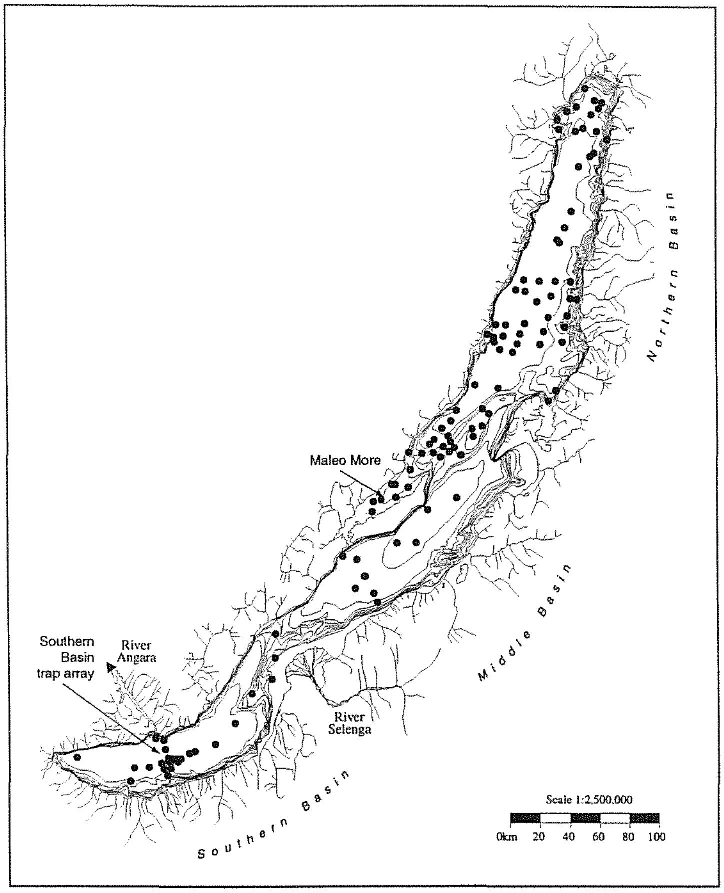

Figure 6: Location of surface sediment site used in training sets

Lake Baikal between 1992 and 1997 (Fig 6). Explanatory data used in regression analyses were collated from a number of sources and are summarised in Table 1 (Mackay 1999; Appendix A). The data have been grouped into 5 broad categories: geography, limnology, meteorology, chemistry and biology for future 'variance partitioning' analyses. Geographical data concerning specific core locations were obtained on-board ship during sampling expeditions using GPS. Systematic water chemistry measurements in Baikal have been carried out for approximately the last four decades, although much of the data is not in the public domain. The most comprehensive source of available data (1961 - 1992) exists in the volume *Baikal Atlas* (1993), and at this time represents best available data for sites across the whole lake. Other recent sources of data used include those of Shimaraev *et al.* (1994) and Bonderenko *et al.* (1996). In all, a total of 27 environmental variables were used in data analyses.

Unimodal methods were selected after detrended correspondence analysis of the response data-set revealed a first axis gradient of 3.057 SD units. Prior to all subsequent analyses, data were screened to determine outliers and to exclude environmental variables that exhibited high collineanty. Initially, the direct gradient technique of CCA was performed on the full data-set. However, here we present results for a reduced set of environmental variables chosen using *forward selection*, a form of step-wise regression analysis. Selected variables were tested using unrestricted Monte Carlo permutation tests and were chosen if significant when $p < 0.01$, taking account of Bonferroni corrections. This procedure reduced the environmental data-set from 27 to 7 significant variables, explaining variation in the diatom data: snow thickness on lake (20%); heat balance (15%); depth of water (8%); suspended matter (8%); solar radiation (7%); suspended organic carbon (6%); temperature of the water surface (5%): see Table 1 in Mackay (1999) for full variable listings. The results of CCA using only these 7 variables are presented as a biplot (Fig 7). Samples from different regions of Baikal are given different symbols. In the biplot, a number of relationships are apparent, which confirm other findings from this project:

(i) based solely on diatom composition from surface sediments, different regions within Baikal are floristically distinct; and
(ii) several spp. appear to have close relationships with some of the selected explanatory variables, including *S. acus* with solar radiation, *A. islandica* with increasing heat balance and *A. baicalensis* with snow cover (see Fig, 3).

Separate CCAs were then performed using each of the climatic variables (snow, solar, tempws and heat) as the sole canonical parameter to explain variance in the diatom data. Eigenvalue ratios between axes 1 and 2 are 0.116, 0.112, 0.200 and 0.193 for each of the variables respectively. These are lower than what one would normally require to develop a predictive model using WA-PLS, and although analyses have been done, results are not presented here. Instead, we have used the two variables that came out top in forward selection analyses above (snow and heat) to develop predictive models. Optimal numbers of components for each model were based on prediction errors. Applications for the WA-PLS models to an existing core are shown below in Section 7, Figure 8.

(i) heat $r^2 = 0.398$, RMSEP = 0.109 kcal cm^{-2};
(ii) snow $r^2 = 0.473$, RMSEP = 0.476 cm).

Correlation values are low for both variables, although RMSEP are low as well. Numerical analyses provide encouragement: variables that appear to be important in significantly affecting diatom distribution are similar to those identified in Section 2 above. Furthermore, now we have identified which variables are important we can make significant improvements in the quality of the data. These include climate indicators, such as surface water temperature and snow cover for all sites across the lake and these can be obtained for recent years from remote sensing.

6. Specific Objective 4: Turbidite recognition, screening and locations for future Holocene coring

Another project aim was to determine regions of sediment accumulation where turbidites are absent, or at least recognisable, and that could be used as future coring locations for studies of Holocene climate variability. We have developed a screening methodology using visual inspection, on board -litho- and magneto-stratigraphy, coupled where necessary with laboratory diatom analysis to identify cores with disturbed sequences (Mackay 1998; Appendix A).

We have used this methodology to screen almost 50 cores taken along transects in both the north and south basins. Visual identification of the cores suggested that most contained turbidites, especially those in tectonic areas, e.g. Zavorotny - sub-basin. Whole-core magnetic susceptibility traces were used on 47 cores to identify turbidite 'fingerprints' which were then correlated between cores along transects (Lees *et al.* 1998; Appendix B). Surface scanning magnetic susceptibility was then used on a subset of 15 cores to identify finer resolution peaks and measure items such as drop-stones and iron / manganese layers. Application of this technique is the first of its kind com-pleted in the field (Lees 1996: Appendix A)

Diatom analysis was then carried out on a further sub-set of cores to examine the different ways in which the diatom record is distorted by turbidites (see Fig. 1 in Mackay 1999; Appendix A). In some of the cores, e.g. BAIK 43, diatoms disappear from the sedimentary record altogether at 35 cm depth, a point in the core at which magnetic susceptibility analyses reveal a large turbidite deposit (Lees *et al.* 1998). Second, in cores such as BAIK 56, there are complex changes in species composition (Flower *et al.* 1998; Appendix B)

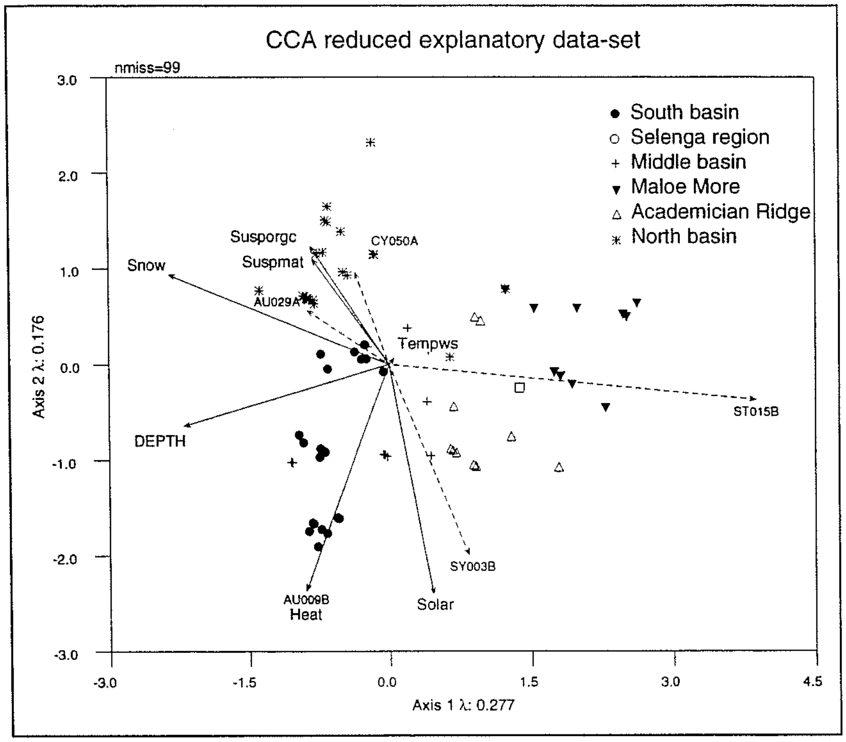

Figure 7: CCA biplot of reduced environmental data-set

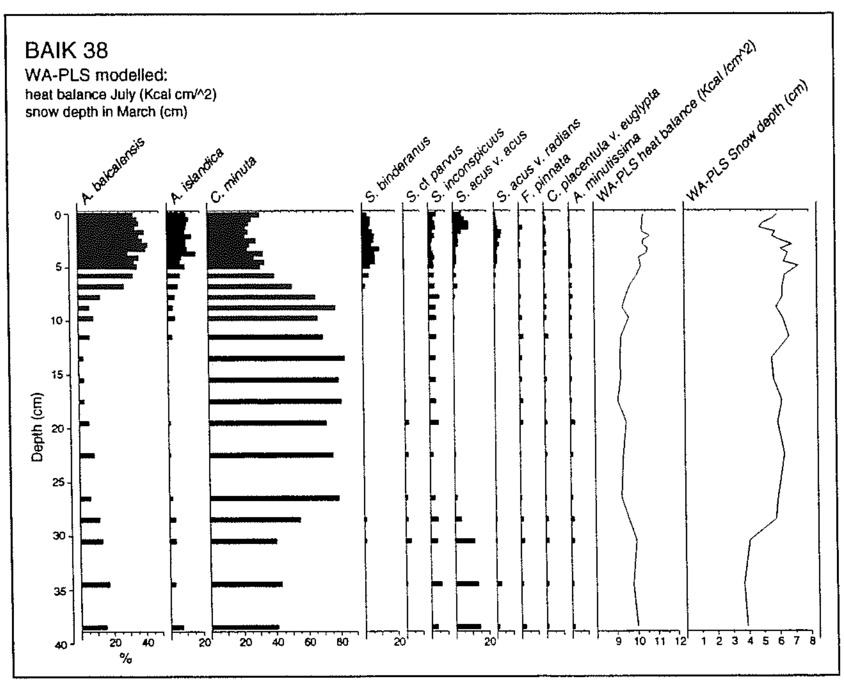

Figure 8: Summary diatom profile of BAIK38, with WA-PLS reconstructed July heat balance and March snow depth

which are a product of older sediments being redeposited. Third, there are cores, e.g. BAIK 78, where magnetic susceptibility measurements indicate the presence of turbidites, but there is little apparent impact on diatom concentration and the relative composition of the flora. The relationships between diatoms and turbidites are therefore complex, and screening for turbidites requires at least two or more of these sedimentological techniques.

Our data confirm the widespread distribution of turbidites in all basins. However some regions are relatively undisturbed, most notably some of the shoulder regions suggested in the original proposal. We have studied one core in detail from the eastern shoulder of the northern basin using all screening techniques (Bangs *et al.* in press; Appendix B). The data indicate that the core is undisturbed and also has a relatively rapid sediment accumulation rate, suitable for future Holocene climate change studies. Promising shoulder areas occur throughout the lake and future work should assess which are most appropriate for detailed stratigraphic studies.

7. Specific Objective 7: application of transfer function to existing core material

Arguably, there are four fundamental requirements that need to be satisfied to generate reliable palaeoclimatic information from Lake Baikal diatom records:

(i) a knowledge of diatom ecology and preferences;
(ii) an understanding of differential preservation problems;
(iii) robust transfer function; and
(iv) undisturbed core material.

Whilst we have still some way to go, the results from this study have illustrated that these requirements can be met and we have the data to attempt a provisional climate reconstruction for one of our earlier cores, BAIK38. BAIK38 was chosen for reconstruction rather than BAIK8O, as it too was taken from a shoulder location, However, changes in the diatom profile of BAIK38 as yet uncorrected for dissolution effects, are much more marked, and, given the relatively low correlations derived above, we believe that if any changes were evident (e.g. in snow depth and July heat balances) over the last couple of hundred years, they are more likely to be picked up in BAIK38 than BAIK8O. Fig. 8 shows a summary diatom profile for BAIK38 with corresponding WA-PLS reconstructed snow depth and heat balance. The top 7 cms of sediment have been dated by ^{210}Pb analyses, and cover the last 150 years (Mackay *et al.* 1998). Reconstructed heat balance measurements indicate that when species more characteristic of warmer waters predominate, as defined in Specific Objective 1 above, values are higher, e.g. in the top and bottom levels of the core. Alternatively, changes in heat balances may affect the distribution of *A. islandica,* which is in turn controlled by thermal bars (Likhoshway *et al.* 1995). Increasing heat balances over the last 150 years, also confirm increasing air temperatures over the same period (Livingstone *in press*). Tentatively, snow depth was least when *S. acus* was abundant at the base of core, which ties in with a period of warmer climate. Snow thickness increases when diatoms indicative of colder conditions predominate (*C. minuta*), and heat balances decrease.

8. Key unresolved issues and future work

1. Continued research into the ecology of the endemic and non endemic species is needed to understand fully the causes for the large inter-annual variability in species succession and crop sizes. This needs to be supplemented by more spatial work with sequential sediment traps and continuous recording equipment deployed in the three main basins along the north-south climate gradient.

2. The present project has highlighted that major losses of diatoms occur at the mud-water interface. A more focused study of this zone is needed to understand the processes responsible for the losses, including silica dissolution and re-cycling and the influence of benthic grazing and bioturbation. An understanding of the transformations that occur in this zone is vital for interpreting the Holocene and longer sedimentary records that are of such interest in Baikal.

3. Work on a provisional internal transfer function between diatoms and environmental variables in the lake show much promise. The current training set needs improvements in the quality of environmental data used in the analyses including more detailed regional snow cover, surface water temperature, and water chemistry. These can be achieved by remote sensing and by undertaking a major water-chemistry sampling programme across the lake. Providing a good model exists, the model will then be applied to longer Holocene cores.

4. The methods developed here, and the growing understanding of the formation of the diatom record in the lake need to be applied to appropriate sediment core sequences. Regions where undisturbed, rapidly accumulating sediments can be found in the lake have been identified and there are now good prospects for

generating high resolution quantitative climate change reconstruction during the Holocene period. Applications of these methods to earlier sediments is also possible, but caution will be needed for time periods where such sediments contain extinct taxa.

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