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 A. W. Mackay

Climate change in Lake Baikal: diatom evidence in an area of continuous sedimentation

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Abstract The presence of inhomogeneous sedimentation is acknowledged as being an important problem in palaeolimnological studies. Sediment records can be disturbed by erosional and redepositional events, which redeposit microfossils within a basin and may then lead to misinterpretations of fossil diatom assemblages. This study uses a combination of sedimentological tools, magnetic susceptibility measurements and high-resolution diatom analysis to show that a sediment core, BAIK80, taken in 345 m water depth from a shoulder region in the North Basin of Lake Baikal, is free of disturbances. Our results confirm that the sediment record is consistent and continuous for the uppermost sediment. Consequently, the fossil diatom data can be used to establish a continuous record of past climate variability over approximately the past 1300 years. Distinct changes occur in downcore abundances of endemic taxa *Aulacoseira baicalensis* and *Cyclotella minuta*, and principal components analysis (PCA) indicates a gradual transformation of taxa over the past 1300 years. These changes are likely to be related to climate, although definite links still have to be established.

Key words Climate change · Diatoms · Turbidites · Palaeolimnology · Lake Baikal

Introduction

Understanding past climates is fundamental to forecasting trends in future climate change. One aim of recent palaeoclimatic research has been to develop a better understanding of climate change on a global scale, and much of this research has been coordinated through the Past Global Changes (PAGES) Program. One focus of the PAGES Program is the PANASH Project (Paleoclimates of the Northern and Southern Hemispheres) which links individual studies through a series of pole–equator–pole (PEP) transects, encouraging scientists to look beyond the local or national scale and consider their work in the wider global context (Dodson and Lui 1995).

One of the key sites on the PEP-II transect, which extends from eastern Asia through Australasia and across the Southern Ocean to Antarctica, is Lake Baikal (Fig. 1). Situated in the tectonically active Baikal rift zone in southeastern Siberia, and formed perhaps 25 million years ago, the lake is the deepest, most voluminous (23,000 km³) and probably the most ancient in the world. Baikal is also unique biologically as much of its diverse flora and fauna are endemic (Kozhov 1963).

In the context of climate change research, Lake Baikal is important for several reasons. Firstly, the lake's high-latitude location makes it sensitive to long-term changes in insolation patterns reflecting changes in orbital forcing, and to short-term changes associated with shifts in the Siberian high- and Asiatic low-pressure monsoon systems (Dodson and Lui 1995). Secondly, the sedimentary record potentially holds a record of the lake's history and the surrounding environmental conditions since the Miocene. Although there is evidence of at least three extensive late Pleistocene glaciations in the North Basin of the Baikal

M. Bangs · R. W. Battarbee · R. J. Flower · A. W. Mackay (✉)
 Environmental Change Research Centre, University College
 London, 26 Bedford Way, London WC1H 0AP, UK
 e-mail: amackay@geog.ucl.ac.uk

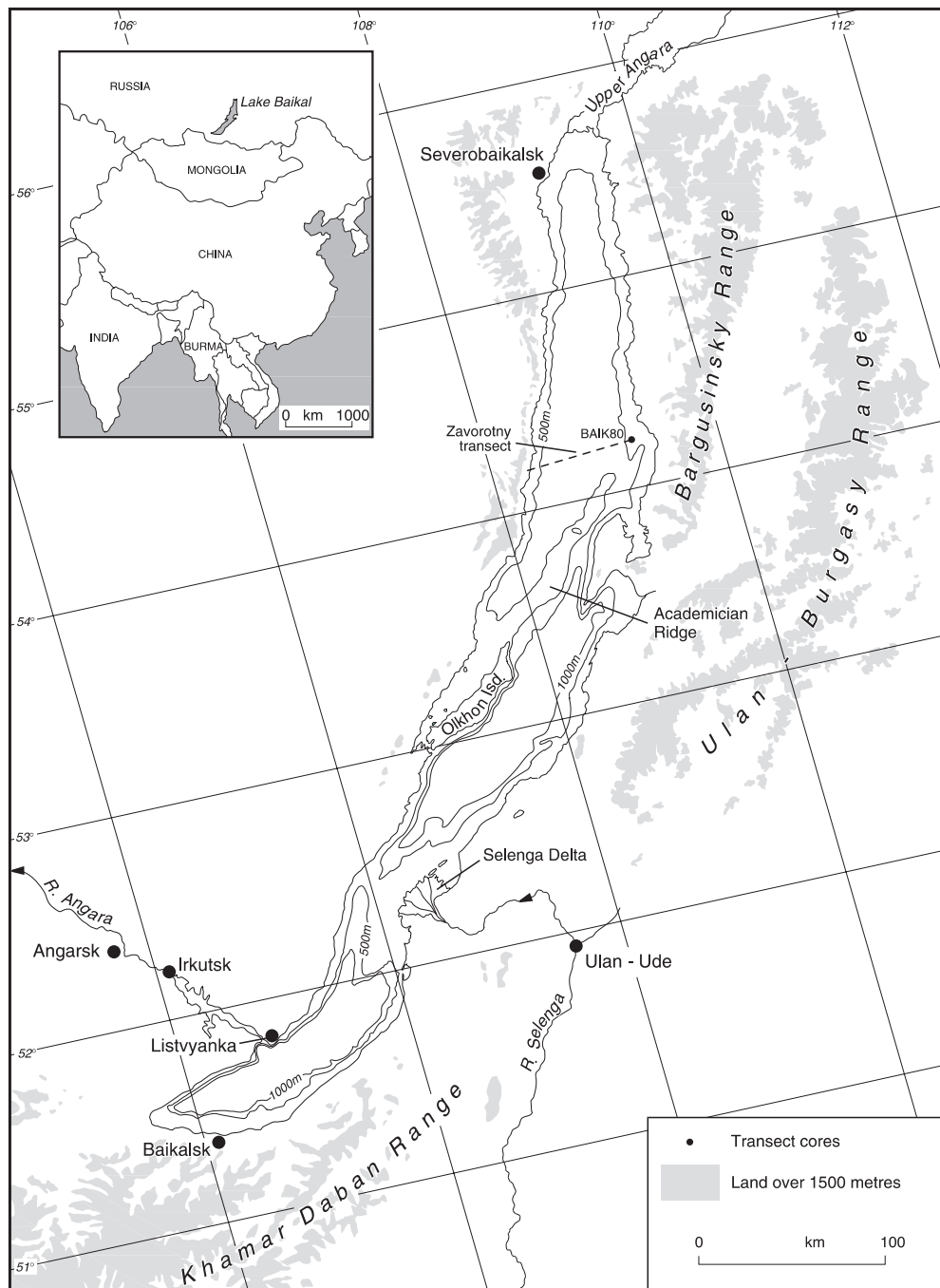
D. Jewson
 Freshwater Laboratory, University of Ulster, Traad Point,
 Ballyronan, Magherafelt, Co. Derry, BT45 6LR, UK

J. A. Lees
 Department of Geography, Centre for Quaternary Sciences,
 Coventry University, Priory Street, Coventry, CV5 1FB, UK

M. Sturm
 Environmental Physics/Sedimentology, Swiss Federal Institute
 for Environmental Science and Technology,
 Überlandstrasse 133, CH-8600, Dübendorf, Switzerland

E. G. Vologina
 Limnological Institute, SB-RAS, P.O. Box 4199, Irkutsk 664033,
 Russia

Fig. 1 Map of Lake Baikal and its immediate catchment. Zavorotny transect cores are marked, as are the major towns, and the rivers Selenga (Baikal's largest tributary) and Angara (Baikal's only out-flow)



Rift (Grosswald and Kuhle 1994; Back and Strecker 1998), the lake sediments themselves are thought to be largely uninterrupted by glaciation periods (Kashiwaya et al. 1997). Finally, numerous biostratigraphical studies on both Pleistocene and Holocene timescales (BDP Members 1997; Bradbury et al. 1994; Colman et al. 1995; Edlund et al. 1995; Flower et al. 1995; Mackay et al. 1998; Qui et al. 1993) have interpreted temporal changes in diatom assemblages as being a response to changes in prevailing climatic conditions. Such results reinforce the idea that Lake Baikal's sediment record of endemic planktonic diatoms can

potentially be used as a powerful proxy method of reconstructing climate change.

A critical interpretation of Lake Baikal's sedimentary diatom record is, however, hampered by numerous problems. Firstly, there are numerous difficulties surrounding the taxonomy of Baikal's endemic diatoms, and despite considerable research into the lake's flora, there are still taxonomic issues to be resolved (e.g. Ryves and Flower 1998). Secondly, there is the potential problem of dissolution in the more lightly silicified diatom frustules. Thirdly, clear independent evidence indicating climate control of planktonic dia-

tom abundances in Baikal is lacking. Finally, as in every sedimentary basin, there are problems associated with sedimentation processes within the lake. Taxonomic issues are being addressed through a series of workshops (e.g. Ryves and Flower 1998), and Mackay et al. (1998) have suggested that although dissolution of certain species occurs largely in the water column, it is not a serious problem once diatoms are incorporated in the sediment. In addition, preliminary research as part of an ongoing study at the University of Ulster shows that the population ecology and life-cycle strategies of Baikal planktonic diatoms appear to exhibit a relationship with climatic factors. However, of the many sedimentary processes operating within the Lake, numerous authors (Mackay et al. 1998; Lees et al. 1998a, 1998b) have found that, particularly in high-resolution analyses, turbidites pose considerable problems for an accurate interpretation of the sediment record.

Bathymetric characteristics, sediment inflows and interflows and redeposition processes can all fundamentally affect the nature of the sediment record, and this is particularly so for Lake Baikal. Here, long, steep, unstable underwater slopes, strong, deep-water currents and silty river inflows combine with basin variables, such as geology and aspect, to influence sediment supply and disturb conformable deep-water sediment accumulation (Nelson et al. 1995). More recently, high-resolution particle and sediment studies, using sediment trap moorings and short gravity cores from different areas of Lake Baikal, have shown that sedimentation in the lake is dominated by three main processes: (a) deposition of diatoms; (b) influx of detrital material from rivers; and (c) redeposition of sediments by turbidity currents (Sturm et al. 1997). These studies have highlighted major temporal and spatial differences between the sediments and sedimentation processes in different parts of Lake Baikal (Sturm et al. 1998).

This paper is part of a wider, collaborative project between UK, Swiss and Russian scientists, which started in 1995 under the auspices of BICER (Baikal International Centre for Ecological Research) and has been financed by EAWAG-GEOPASS 85/051 and NERC-GEOPASS GR3/10529 (Flower et al. 1998). These projects are focussed on ways in which the integrity of Lake Baikal sediment cores used for analyses can be established. Many of the sedimentation problems described above occur extensively throughout the Lake's deep basins. While exhibiting relatively high sediment accumulation rates (in comparison with the ridges and slopes), such deep basin zones are prone to inputs from turbidity currents. Areas of Lake Baikal which are free of turbidites and other sediment discontinuities are of particular interest for palaeostudies, and this paper is based on the analysis of one core (BAIK80) taken at the eastern slope, opposite Zavorotny sub-basin in 345 m water depth (54°16.36' N; 109°17.59' E; see Fig. 1). It is assumed that sed-

iments of this relatively shallow region (<500 m) are not influenced by turbidity currents and yet, unlike some of the ridges in the lake, accumulation rates are rapid enough to allow for high-resolution diatom analysis.

Materials and methods

A gravity core (BAIK80), 83 cm long with a diameter of 6.3 cm was collected in July 1996 in 345 m water depth from the eastern coast of Lake Baikal's North Basin (Fig. 1), using a light-weight (ca. 60 kg) Swiss EAWAG gravity corer. Bartington Instruments MS2 Magnetic Susceptibility System, in conjunction with a MS2C Whole-core sensor, was used to measure non-mass specific (volume) magnetic susceptibility (κ , κ) immediately after core recovery. Volume magnetic susceptibility is a measure of magnetisation over field, both of which have the same units, making κ dimensionless but values are expressed in 10^{-5} . The whole-core sensor has a resolution of 1.5–2 cm giving a moving average effect (Lees 1998b). The information derived from this technique is very similar to information derived from measuring κ -values on specific sub-samples (e.g. see Lees 1998a) and is preferred in this study because of the rapidity in which analyses could be carried out.

The core was then cut longitudinally, photographed and sampled for smear slides, which were used for a detailed lithological description (Fig. 2). One half of

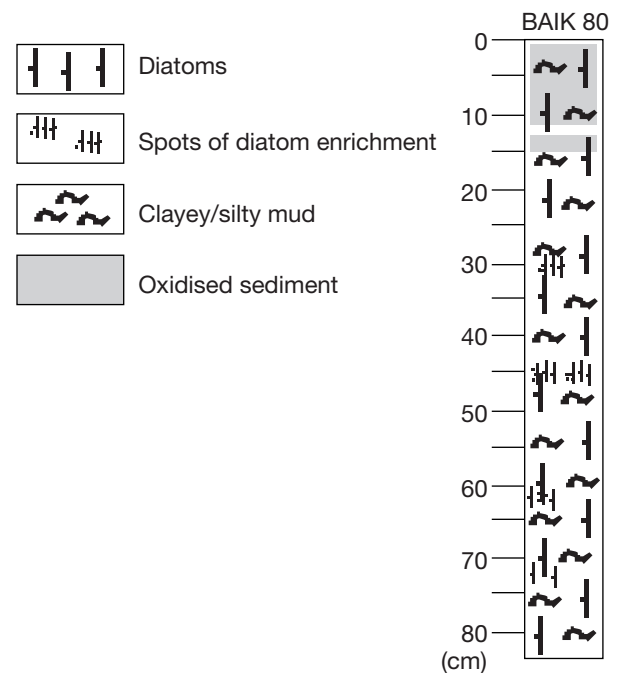


Fig. 2 BAIK80 core lithology. Note that diatoms are present throughout the length of the core, there are no sandy layers and the uppermost sediments are oxygenated down to approximately 10 cm

the core was sampled in 2-cm intervals for percent dry weight at 105 °C and were then prepared for diatom analysis, using the Environmental Change Research Centre (ECRC) protocol for Lake Baikal slide preparation (Mackay et al. 1998). To enable the calculation of diatom concentrations, a known weight of divinylbenzene microspheres (ca. 1–2 g, with a mean diameter of 6.4 µm) was added to cleaned diatom samples during preparation (Battarbee and Kneen 1982). The other half of the core was sampled continuously in 0.5-cm intervals (0–10 cm) and 1-cm intervals (10–83 cm), respectively. Samples of 0–10 cm were used for γ -spectroscopy measurements with a CANBERRA borehole detector (\varnothing 10 mm). Samples of the entire core were then used for determination of C_{org} and N_{total} using a HEREAUS CNS Autoanalyser. In addition, the top 8 cm of the core was analysed for ^{210}Pb to establish the sediment accumulation rate and to estimate the age of sediments lower down the core.

The diatom profile diagram was produced using TILIAGRAPH 2.1 and the main zones of change in the diatom assemblages were identified by stratigraphically constrained, incremental sum-of-squares, cluster analysis using CONISS (Grimm 1987). Multivariate ordination techniques were carried out using CANOCO (ter Braak 1987), version 3.1 (ter Braak 1990). To establish whether species responses were linear or unimodal, floristic variation in the diatom data was assessed using detrended correspondence analysis (DCA; ter Braak 1987). The axis-1 gradient was less than 2 standard deviation units, indicating a linear response. The main gradients of floristic change within BAIK80 were then assessed using principal components analysis (PCA) on a correlation biplot, with log transformation of species data and down-weighting of rare taxa. Sample classification was carried out using TWINSPLAN (Hill 1979), a programme which uses correspondence analysis to group core subsamples according to species assemblage.

Results

The lithological profile of BAIK80 (Fig. 2) shows a homogeneous succession of grey-olive (USGS colour chart 5Y4/2) pelitic diatom ooze with *Aulacoseira* and *Cyclotella* as the dominant taxa. Small light spots within the homogeneous, grey mud are dominated by abundant *Synedra* spp. Occasionally a few grains of detrital mica and quartz and isolated spicules of sponges have also been observed. Between 0–9 cm and between 12.5–15 cm, the sediment is oxidised to a dark-brown colour (USGS colour chart 10YR2/2). In sediments deeper than 15 cm, black spots and stripes of hydrotroilite appear within the homogeneous sequence of the core, indicating anoxic pore-water conditions. Core sediment does not show any visual evidence for any inhomogeneities, such as turbidites, sand layers or erosional hiatus.

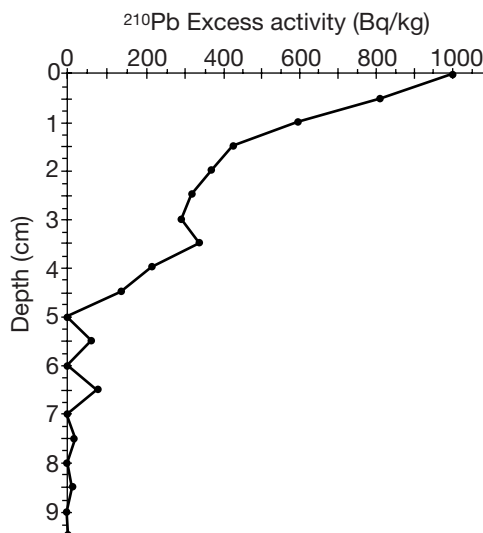


Fig. 3 Plot showing excess ^{210}Pb activity ($Bq\ kg^{-1}$) for BAIK80, against depth of sediment (centimetres)

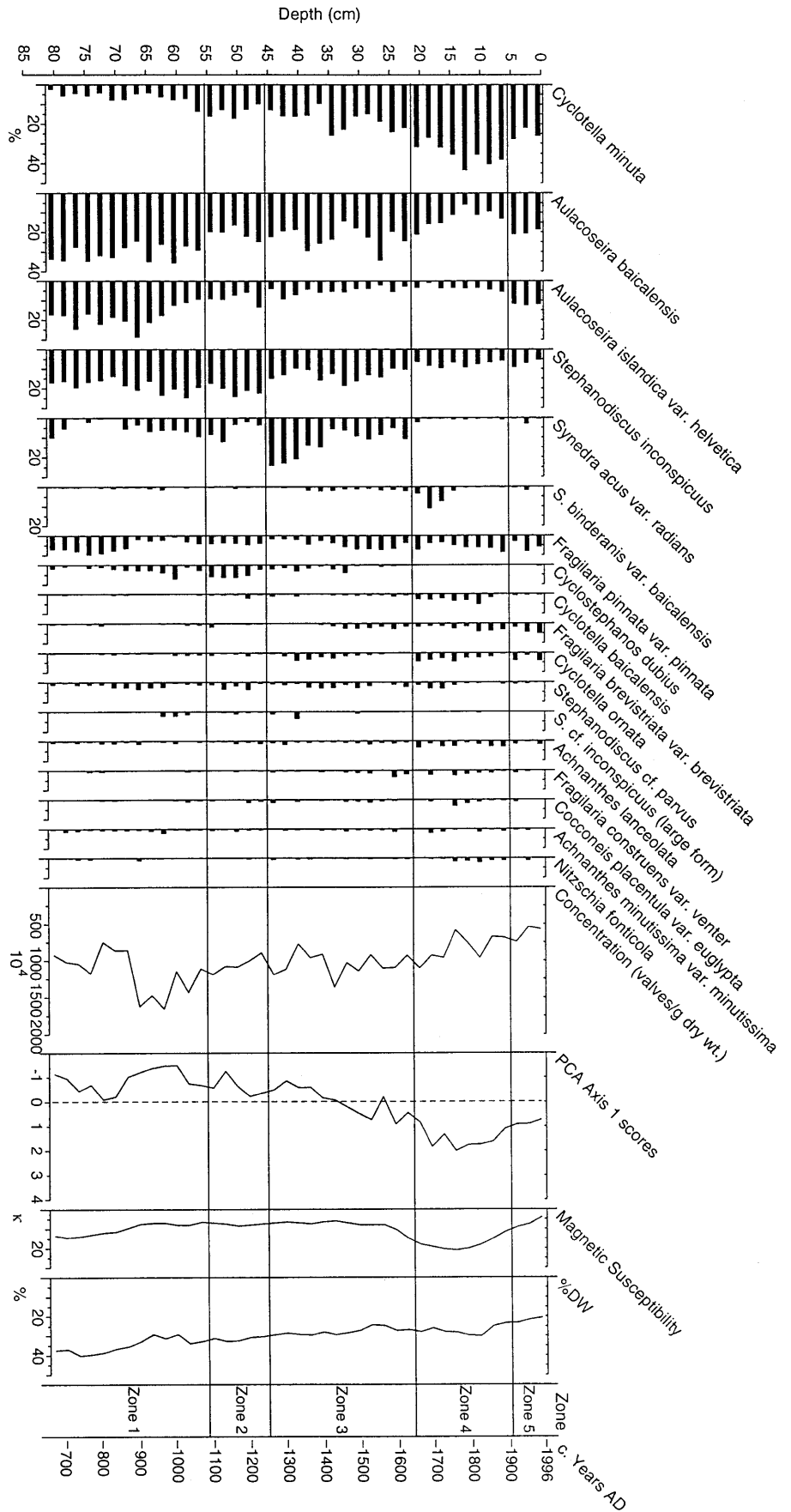
The dry-weight profile of the core (see Fig. 4) shows a gradual increase from ca. 20% at the top to ca. 40% at the base of the core, consistent with compaction with depth. Magnetic susceptibility κ -values of the core are relatively low (<22) and without distinct peaks within the core. These values can be compared with those found for other cores in the North Basin with turbidites, e.g. BAIK106, which have κ -values up to 230 (Lees 1998b). Results of $^{210}Pb_{excess}$ measurements show a rapid, but gradual decrease of activity from approximately 1000 $Bq\ kg^{-1}$ at the top of the core, to background activities at approximately 10 cm core depth (Fig. 3), resulting in an average sedimentation rate of $0.61\ mm\ a^{-1}$.

The diatom assemblage observed in BAIK80 (Fig. 4) is dominated by a number of endemic species. *Aulacoseira baicalensis* (Meyer) Simonsen, *Cyclotella minuta* (Skv.) Antipova and *Stephanodiscus inconspicuus* Makarova and Pomazkina are present throughout the core, along with some less abundant non-endemic species such as *Aulacoseira islandica* v. *helvetica* (O. Mull.) Simonsen (= *A. skvortzowii*), *Synedra acus* v. *radians* (Kutz.) Hustedt. and *Fragilaria pinnata* v. *pinnata* Ehrenb. The assemblage is dominated by planktonic species, although total benthic taxa constitute between ca. 11 and 27% of the entire assemblage throughout BAIK80.

The most striking feature of the diatom profile is the gradual change in species dominance from *A. baicalensis* at the bottom of the core to *C. minuta* towards the surface. The top 5 cm of the core shows increases in *A. baicalensis* and a slight recession in the abundance of *C. minuta*. Other notable significant features include:

1. A decrease in numbers of *S. inconspicuus* towards the top of the core which beginning at approximately 45 cm

Fig. 4 Diatom stratigraphy of BAIK80 showing frequency abundance profiles of species present at $\geq 2\%$ in one or more samples, total diatom concentrations profile, percent biogenic silica, PCA axis 1 scores vs depth, whole-core magnetic susceptibility and percent dry weight. The main zones of floristic change as defined by sum-of-squares cluster analysis are also included. The *Years AD* column is based on dates extrapolated from an accumulation rate of 0.61 mm a^{-1} in the uppermost sediments (see Fig. 3)



2. A peak in levels of *S. acus* v. *radians* in zone 3
3. A small peak in *S. binderanus* v. *baicalensis* Popovskaya and Genkal in zone 4
4. A recession in the abundance of *A. islandica* v. *helvetica* throughout zones 2–4, with peaks levels in zone 1 and 5

Diatom concentrations (Fig. 4) are variable throughout BAIK80, ranging from 0.55×10^7 valves g^{-1} dry weight in most recent sediments, to 1.68×10^7 valves g^{-1} dry weight towards the bottom of the core. Similar decreases in total diatom concentrations were observed by Mackay et al. (1998).

Axis 1 sample scores, extracted from the PCA of BAIK80 species data, are plotted against depth of sediment in Fig. 4. Axis 1 accounts for ca. 26% of the variation in species composition throughout the core, and as Fig. 4 illustrates, this is largely influenced by the ratio between *C. minuta* and *A. baicalensis*. Figure 5 is a PCA biplot of core sub-samples and includes sample classifications derived by TWINSPAN. Five groups are identified which, with the exception of group D, represent changes in species assemblage downcore. The classification is similar to zones identified by CONISS. The most recent sediments are isolated in both sets of analyses, and the most striking feature of the correlation biplot is the gradual change in assemblage with time. Group A represents sample assemblages strongly associated with taxa such as *C. minuta* and *F. brevistriata* v. *brev-*

istriata (similar to stratigraphical zone 4). Groups B and C contain levels in BAIK80 exhibiting co-dominance of *A. baicalensis* and *C. minuta* and an abundance of *S. acus* v. *radians* (as does stratigraphical zone 3). Groups D and E represent the lower levels of the core (CONISS zones 1 and 2) where assemblages are largely dominated by *Aulacoseira* species and *S. inconspicuus*.

Discussion

Assessment for sediment disturbances

Percentage dry-weight values provide an initial indication of lithostratigraphic characteristics. In cores affected by turbidites, Mackay et al. (1998) observed substantial peaks in percent dry weight of up to 60%, whereas in undisturbed cores, values ranged between 15% (surface sediments) and 40%. However, percent dry weight evidence alone is insufficient to establish lithological integrity of BAIK80, as sedimentary disturbances have been found in sediment cores where there are no substantial changes in percent dry weight (e.g. BAIK22; Mackay et al. 1998). Despite small increases in κ -values in the upper 20 cm of the core, whole-core magnetic susceptibility measurements remain relatively low throughout the profile, with a maximum κ -value of 22. Whole-core magnetic susceptibility in other Zavorotny transect cores (Lees et al. 1998b) have much higher values (maximum κ -value of 230), revealing an increase of detrital material caused by the influx of turbidity currents to the deep basin areas (ca. 900 m). Therefore, it is thought that the relatively low κ -values in BAIK80 are characteristic for diatom muds with very little detrital material.

Sediment core integrity

Lithostratigraphy and magnetic susceptibility data indicate that turbidites and other inhomogeneities are absent. In addition, radiometric analyses also provide evidence that at least the upper 10 cm of BAIK80 are undisturbed. If an inhomogeneity was present, it is likely that there would also be concomitant changes in (a) total diatom concentration, and (b) species assemblage composition, e.g. changing proportions of benthic taxa. In reality, changes in species assemblage are gradual, with the exception of the peaks in *S. acus* v. *radians* and *S. binderanus* v. *baicalensis*, and both features have been observed in other areas of the lake with undisturbed sedimentation. Zone 4, which corresponds to the elevated κ -values, only shows small increases in the less common endemic *Cyclotella baicalensis* (Meyer) Skv. species, which coincides with the peak in *C. minuta*.

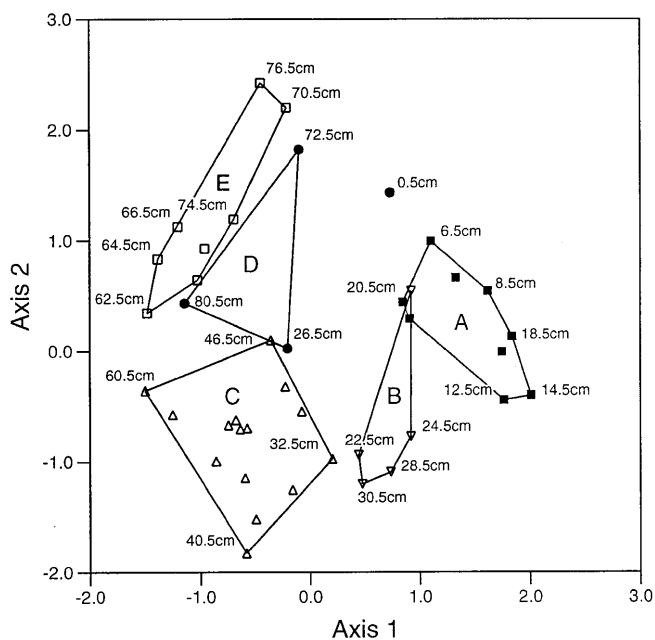


Fig. 5 Principal components analysis correlation biplot of BAIK80 samples analysed for diatoms. Samples are grouped according to TWINSPAN classification, given different symbols and joined together. The classification reveals five sample assemblages with numerically similar compositions, plus the surface sediment sample. These groups are similar to the zones defined by CONISS

The diatom record

As demonstrated above, the sediment record for BAIK80 is undisturbed by inhomogeneities, and we are thus able to consider variations in the diatom assemblage in the context of palaeo-environmental change. Comparisons between this study and those of Edlund et al. (1995) and Mackay et al. (1998) reveals similar trends in *C. minuta* and *A. baicalensis*. Using the technique of cluster analysis, both this study (zone 5) and Edlund et al. (core 324), identify a peak in *A. baicalensis* in the uppermost sediments, the base of which has been dated (in both studies) at ca. 1900 AD. Zone 4 in BAIK80 is characterised by peak levels of *C. minuta*, and a similar zone is also identified in Edlund et al. (core 324). Cluster analysis of both cores also dates these zones between the mid-seventeenth century and the beginning of the twentieth century. Numerous short cores also from the North Basin analysed by Mackay et al. (1998; e.g. BAIK25 and BAIK29) also exhibited a switch between *A. baicalensis* and *C. minuta* at approximately this time.

Another feature of the BAIK80 diatom profile is the peak in *Synedra acus* in zone 3. This coincides with an increase in the abundance of *S. acus* v. *acus* (= *S. acus* v. *radians*; Ryves and Flower 1998) in a short core from the Academician Ridge, between the Central and North Basins (BAIK25; Mackay et al. 1998). In addition, increases in the planktonic species *Aulacoseira islandica* v. *helvetica* evident in surface sediments (zone 5) occur in other cores (e.g. BAIK19 and BAIK38; Mackay et al. 1998). At some sites, these increases are accompanied by increases in another planktonic species, e.g. *S. binderanus* v. *baicalensis*. This latter diatom species peaks in BAIK80 (zone 4) with abundances reaching ca. 10%, similar to those observed in BAIK25.

Diatoms and climate change

Analysis of diatoms from BAIK80 confirms the results of other biostratigraphical studies (Cheremisinova 1973; Rychov et al. 1989; Bradbury et al. 1994; Edlund et al. 1995; Mackay et al. 1998) which have found that Baikal's past diatom flora was diverse and continually changing through time. Historical variations in the diatom flora could potentially be linked to numerous environmental factors such as anthropogenic pollution (factory waste products and atmospheric contaminants), tectonic activity and climate. The recent study by Mackay et al. (1998), however, has already demonstrated that across the main body of the lake, there are no temporal changes in the diatom record that can be attributed to pollution.

Two major studies have analysed Lake Baikal diatoms in the context of recent climate change (Edlund et al. 1995; Mackay et al. 1998), and are based on high-resolution diatom analysis of short cores covering

similar time periods, and are therefore comparable with the results of this study. Long-term floristic variations in Lake Baikal have been related to climate largely due to the timescale over which variations in the abundance of dominant species occurs. The fact that changes in the diatom assemblage have been observed simultaneously across the lake, indicating a response to an external variable affecting the whole of this aquatic ecosystem, also suggests that climate is a major influential factor.

Although the ecology of Lake Baikal diatoms is still incompletely understood, current knowledge indicates that diatoms are well adapted to the unique physical environment in the lake, and respond sensitively to annual and inter-annual variations in weather patterns. For example, *Aulacoseira* species grow under ice-cover before, and during, the spring melt (Skabichevskii 1960). The reproductive strategy of *A. baicalensis* in particular is sensitive to levels of snow on the ice, where increases in snow and ice thickness lead to reductions in cell growth (e.g. Mackay et al. 1998). Conversely, *C. minuta* has its main growth period during the autumn months of September and October (Popovskaya 1991). Consequently, the relative abundance of these two endemic species is potentially a very useful indicator of climatic variability. Although less is known about the ecology of other diatom species in Lake Baikal, it is possible that variations in their abundance are also climate related. For example, Bradbury et al. (1994) suggest that *Synedra acus* becomes more dominant in the phytoplankton during warm periods, and Mackay et al. (1998) interpreted high levels of *S. binderanus* v. *baicalensis* as a response to increased natural eutrophication which could also be linked to climate. Current studies being carried out at the University of Ulster on the ecology of *S. binderanus* v. *baicalensis* indicate that this spring-blooming species has higher growth rates than some of the other endemic diatoms when temperatures are higher.

Based on our knowledge of diatom ecology in Lake Baikal, it is possible to make speculative interpretations of how the diatom assemblage may respond to climate change. Past studies of the Baikal sediment record (Edlund et al. 1995; Mackay et al. 1998) have suggested a link between the increase in *A. baicalensis* and decrease in *C. minuta* in the upper sediments (zone 5) and climate amelioration at the end of the Little Ice Age in the mid-eighteenth century, across the whole lake. The timing of this assemblage change in BAIK80 supports this hypothesis. The large peak in *S. acus* v. *radians* could indicate a warm period between the mid-thirteenth and mid-seventeenth centuries, before the onset of the Little Ice Age. If this is the case, the peak of *S. binderanus* v. *baicalensis* (zone 4) would have occurred during the transition between relatively warm and cold climates.

The lack of secure dating prior to the ^{210}Pb timescale makes it difficult to interpret zones 1, 2, and 3 of

BAIK80. However, if the ^{210}Pb sediment accumulation rate is extrapolated, then the core spans approximately 1300 years, over which time *A. baicalensis* and *C. minuta* have been present in the lake at varying abundances. If the relationship between these two endemic species is a response to climate, the gradual shift in phytoplankton assemblage between *A. baicalensis* to *C. minuta* may represent a cooling trend in climate throughout this period until the end of the Little Ice Age, before the mid-nineteenth century warming.

General floristic change, which is well illustrated by PCA of species data (Fig. 5), also supports this climate change hypothesis. Core subsamples, which are close together on the biplot, are similar in species composition, indicating that species assemblages in the core top and bottom are different from mid-core sediments. If the driving force behind this variation were climate, results of PCA would suggest that over the past ca. 1.3 ka, climate in the Baikal catchment has shown a gradual shift, and there has been a return to conditions closer to those which prevailed at the time the lower-most sediments of this core were deposited.

Conclusion

Using a combination of sedimentological analyses, i.e. visual evidence and lithostratigraphy, magnetic susceptibility measurements and high-resolution diatom analyses, we demonstrate that BAIK80 has been formed by continuous sedimentation, and is thus free from any inhomogeneities. It follows, therefore, that changes in the diatom assemblages recorded in the core are indicative of responses to changes in inferred, prevailing environmental conditions; the most likely candidate being climate change. Specific climate-diatom interactions, however, are still not properly understood. Interpretations of changes in the diatom record described here can as yet therefore only be speculative (although current research includes an investigation into the responses of the more common endemic taxa to specific climatic variables, such as temperature).

Increasingly, climate change research is becoming focused on Holocene climate variability. Because of the absence of sediment inhomogeneities at the site where the core was taken, together with the excellent diatom record contained with BAIK80, we conclude that this site could be a valuable location to obtain reliable, continuous, high-resolution palaeoclimate records for the Holocene period and beyond.

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