A GEOPASS-NERC PROJECT ON DIATOM DEPOSITION AND SEDIMENT ACCUMULATION IN LAKE BAIKAL, SIBERIA

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Introduction

Siberian Lake Baikal is arguably the world's most interesting freshwater lake. Its main features of great age and depth and a high incidence of endemism are well known (e.g. Koshov 1963). The lake has attracted much international attention during the 1990s and joint British research on Baikal was summarized previously in *Freshwater Forum* (Flower 1994). However, there is now increasing interest in the palaeoenvironmental records stored in the ca. 7 km of sediments that lie beneath modern Lake Baikal (BDP-93 1997). These deposits offer major opportunities for reconstructing environmental change over a variety of time-scales ranging from decades (Flower et al. 1995; Mackay et al. 1998) to millennia (Grachev et al. 1997; Williams et al. 1997). Sediment records of climate change over the past 5 million years are the focus of an international deep-drilling programme, the Baikal Drilling Project (BDP; see BPD-93 1997). The lake is also a key site in the Pole-Equator-Pole (PEP II) programme that aims to produce a coherent quantitative record of global palaeoclimates during the Quaternary Period (PAGES 1995).

Reconstructing palaeoclimates for the Holocene/Pleistocene periods is a primary goal of much Quaternary research in Lake Baikal (e.g. Peck et al. 1994; Colman et al. 1995, 1996). Sedimentary planktonic diatoms are important palaeoclimate indicators (Bradbury & Dieterich-Rurup 1993) and in Baikal sediment they are abundant, generally well preserved, and exhibit marked abundance changes during glacial and inter-glacial periods (Grachev et al. 1997; Julius et al. 1997). These Baikal microfossils potentially offer a powerful proxy method of reconstructing climate change. However, before confident quantitative palaeolimnological reconstructions can be undertaken, we need a better understanding of the factors that control the abundance of modern planktonic diatoms and those that influence the composition of sedimentary diatom assemblages.

Interrelated studies aimed at clarifying these factors began in 1995 and involve British, Swiss and Russian scientists. These studies partly include an Anglo-Russian project, supported by The Royal Society, involving regular water quality and phytoplankton sampling, begun in 1994. This is now linked with GEOPASS (Geochemistry, Particle Formation and Sediment Sources), a research programme formulated initially by scientists at the Swiss Federal Institute for Environmental Science and Technology (EAWAG). In 1995, independent funding from the British Natural Environmental Research Council (NERC) enabled the diatom component of these studies to be expanded. The resulting GEOPASS-NERC project is coordinated through international meetings held under the auspices of BICER (Baikal International Centre for Ecological Research; see Flower 1994).

The GEOPASS-NERC Baikal project

This new project is multidisciplinary, with physical and chemical paleolimnological aspects mainly the responsibility of Swiss and Russian scientists, and the biological limnology and paleolimnology components mainly undertaken by the British and Russian groups. The overall project aim is to improve palaeoclimate reconstructions using sedimentary diatoms by promoting better understanding of diatom ecology and sediment-forming processes. The initial work plan is divided into four main parts, outlined below, al1 of which are fundamental to achieving this goal.

(1) To understand diatom phytoplankton ecology more fully. Identifying the key factors that control periodicity and abundances of the modern endemic Baikalian diatom phytoplankton is necessary so that changes in the species composition of sedimentary assemblages can be interpreted more accurately.

(2) *To assess taphonomic changes associated with the transformation of phytoplankton diatom communities into sediment assemblages.* Recognising compositional changes in diatom species abundances during the formation, sinking and incorporation of sedimenting material is required so that effects of differential diatom preservation and other taphonomic processes can be separated from ecological changes. (Taphonomy is the study of how living communities are transformed into assemblages of dead organisms and, importantly for diatoms, taphonomic processes can cause changes in the composition of species assemblages.)

(3) *To demonstrate sediment core integrity and representativity.* Irregularities in sediment deposition can compromise core integrity and representativity. They can decouple links between diatom species abundances and palaeoclimate change. It is therefore important to select cores that have good microfossil preservation and have uniform sediment accumulation, free from turbidites (underwater mud-flow deposits) and other disturbances.

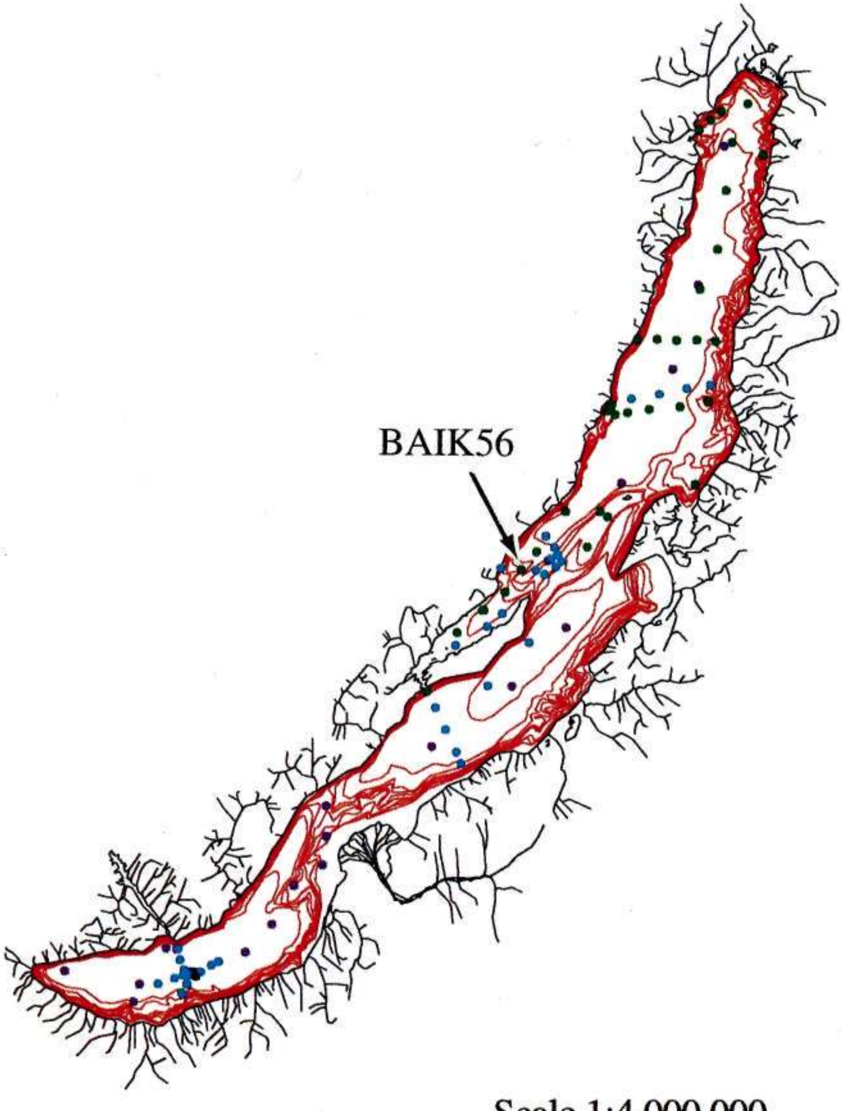
BAIK56
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FIG. 1. *(On opposite page).* Lake Baikal, showing locations of short cores collected in 1993-1997. Red points indicate cores collected as part of a Leverhulme Project in 1993 (see Mackay et al. 1998). Green and blue points indicate cores collected during GEOPASS-NERC cruises in 1996 and 1997, respectively. The black point in the southern basin marks the GEOPASS sediment trap mooring station (see Sturm et al. 1997) and the main diatom phytoplankton sampling location (see the text). Cores are coded BAIK and the location of BAIK56 (see the text) is indicated.

(4) *To calibrate modern diatom assemblages against contemporary climate records.* Once the influence of climate on living diatom populations is known more fully (see (1) above), surface sediment diatom assemblages from different parts of the lake can be calibrated to climate-related variables. This should enable an "internal" transfer function to be generated so that quantitative palaeoclimate reconstructions for the Holocene period and beyond can be undertaken.

Phytoplankton ecology

Although the general succession patterns of Baikal diatom phytoplankters are known (Kozhov 1963), the causes of interannual variability in composition and abundance are not. The joint Anglo-Russian programme, begun in 1994, is an attempt to quantify the major environmental factors involved, and so support aims of the GEOPASS-NERC project.

Regular water-column sampling in the south basin of the lake (near the GEOPASS sediment-trap mooring site, Fig. 1) has been carried out at monthly intervals since 1994. Measurements of ice conditions, temperature, nutrients (N, P, Si), phytoplankton biomass and species composition are being made regularly at fourteen depths over the entire water column of 1420 m.

Phytoplankton populations show considerable annual and interannual variability and *Aulacoseira baicalensis* is often the most common diatom (Fig. 2), with peaks in abundance every three or four years (see also Kozhov 1963; Kozhova 1987). The last three such years were 1990, 1994 and 1997 (D. H. J. unpublished). In the intervening years more cosmopolitan species, such as *Nitzschia acicularis* (in 1995) and *Synedra acus* (in 1996), have dominated in the spring, and another endemic diatom, *Cyclotella minuta,* was dominant during the autumn, in the south basin (Fig. 2). Research has focused on the relationship between physical mixing processes and the growth and survival of both endemic and non-endemic species. The main factors already identified in controlling crop size are (i) the ice-cover period and the extent of light-limiting snow cover, (ii) nutrient concentrations, (iii) turbulence, (iv) temperature and (v) grazing (by rotifers and copepods). The timing of the impact of these factors, singularly or in combination, is crucial in determining the seasonal abundance and composition of endemic phytoplankton diatom crops. The environmental signals resulting from the interplay of these factors

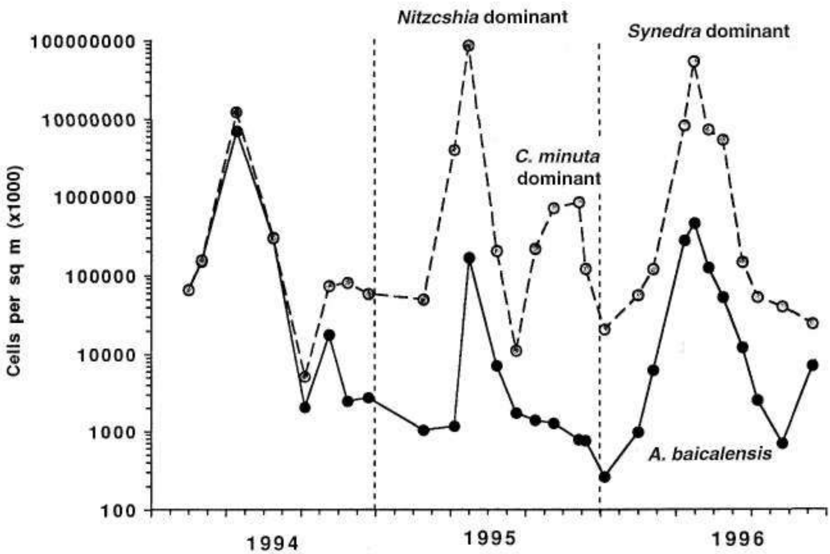


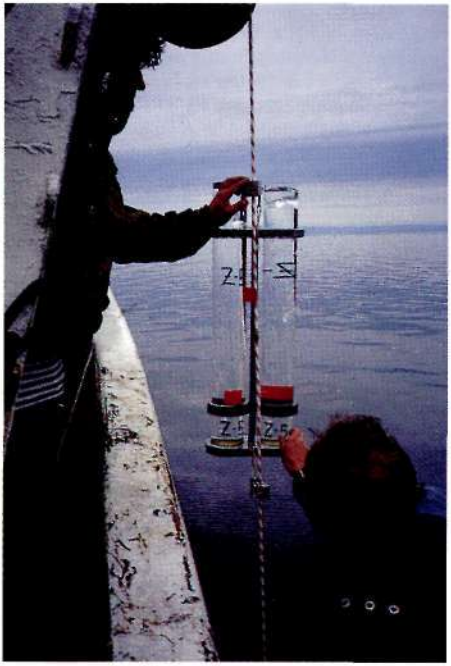
FIG. 2. Seasonal changes in *Aulacoseira baicalensis* (solid line) and total diatom cell numbers (dashed line) integrated for the upper 250 m of the water column of Lake Baikal at the GEOPASS mooring site (south basin, Fig. 1). Periods of dominance by *Nitzschia acicularis, Synedra acus* and *Cyclotella minuta* are indicated.

are not only recorded by abundance differences in phytoplankton species but also in the morphological changes of cells, including those associated with the life cycle and production of resting spores (particularly by the endemic *Aulacoseira* species, *A. baicalensis).*

Composition and taphonomy of sedimenting material

In December 1995, EAWAG scientists constructed a mooring in the south basin of Lake Baikal (Fig. 1) so that an array of sediment traps, current meters and temperature loggers could be deployed at several depths for a period of two years (Sturm et al. 1997). The trap array, deployed within a 1420 m water column, comprises two trap-types (Fig. 3): permanently open tube traps and automatic sequencing traps that open for set periods of up to 16 days. The open tube traps are sampled every six months.

FIG. 3. *(On opposite page).* Sediment traps deployed in Lake Baikal for consecutive 6-monthly periods during 1995-97 as part of the GEOPASS-NERC project. *Above:* a paired open tube trap assembly being retrieved in July 1996. *Below:* a carousel of sample bottles from an automatic sequencing trap, lifted on the same occasion. Each sample bottle is automatically exposed for 16 days; one bottle has trapped a sculpin fish.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Z-5


2-2

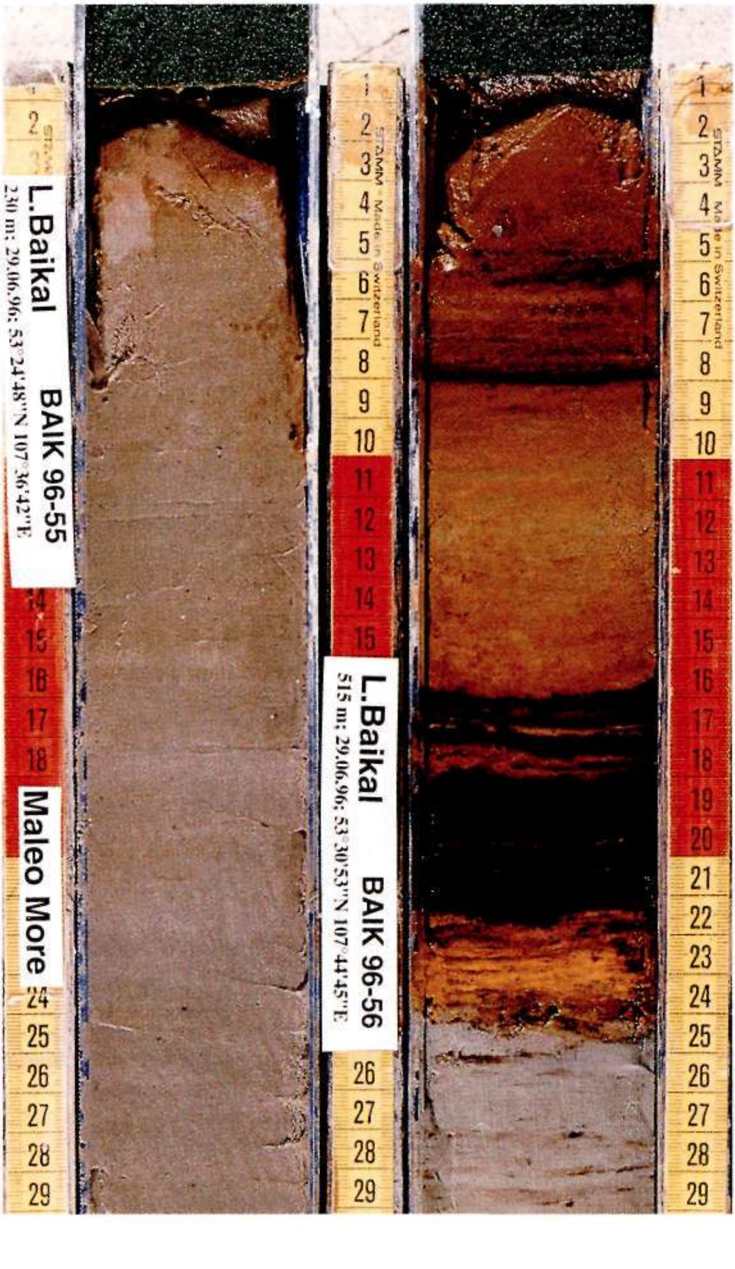
FIG. 4. *(On opposite page).* Photograph (taken by Mike Sturm) of the upper section of two short sediment cores collected from Lake Baikal in 1996. *Left:* BAIK55 collected from a water depth of 230 m. *Right:* BAIK56 collected nearby but from a water depth of 515 m, showing fine and coarse laminations. The green material at the top of the cores is packing used to stabilise the upper sediment during longitudinal sectioning. See Fig. 1 for the location of BAIK56 and Fig. 5 for results of diatom analysis.

From the point of view of palaeoecology, the main role of the trap array is to provide material for diatom analysis and to provide short-term and long-term data on particle deposition rates. Analysis is being undertaken to describe the proportions of diatom species collected by the traps at selected depths throughout the water column. Results will be compared with diatom abundances in the plankton (involving an integration of cell numbers over an annual cycle) and in surface sediment (Ryves et al. 1998). At the same time, diatoms in sedimenting material are being assessed for their preservational states. Forms that are weakly silicified, such as *Nitzschia acicularis*, are dissolved largely within the water column and are therefore essentially lost from the sediment record. However, the main species of endemic *Cyclotelld* and *Aulacoseira* are much less affected by dissolution (Ryves et al. 1998).

Diatoms are the main component of sinking material in Lake Baikal and, together with information about qualitative changes, the diatoms collected by sediment traps will provide species-specific data on sinking rates in the water column and on deposition rates at the deep-water sediment surface. However, one potential source of error in using such estimates is resuspended sediment. This is a frequent problem for sediment-trapping studies in shallow lakes (e.g. Flower 1989), and previous trapping in Lake Baikal has indicated that deep-water traps collect much more material than those higher in the water column (Kempe & Schaumburg 1995). This difference in Lake Baikal has been interpreted as evidence for sediment redeposition (Grachev et al. 1996). However, the source and composition of this "redeposited" sediment is unclear and results from the GEOPASS traps will be used to verify these earlier observations.

Recent sediment accumulation processes, core integrity and representativity

Identifying regions of Lake Baikal for obtaining cores best suited for palaeoecological analysis depends on a variety of factors. Cores should be conformable and, if interest focuses on change over geological periods, those with slow accumulation rates will provide the greatest time-span per unit depth of sediment collected. This is clearly advantageous for deep-coring projects and the shallow ridge separating the middle and north basins (Fig. 1) is one region that provides such conditions (cf. Colman et al. 1996). Where


L.Baikal
BAIK 96-55
230 m; 29.06.96; 53°24'48"N 107°36'42"E
Maleo More
L.Baikal
BAIK 96-56
515 m; 29.06.96; 53°30'53"N 107°44'45"E
STAMM · Made in Switzerland

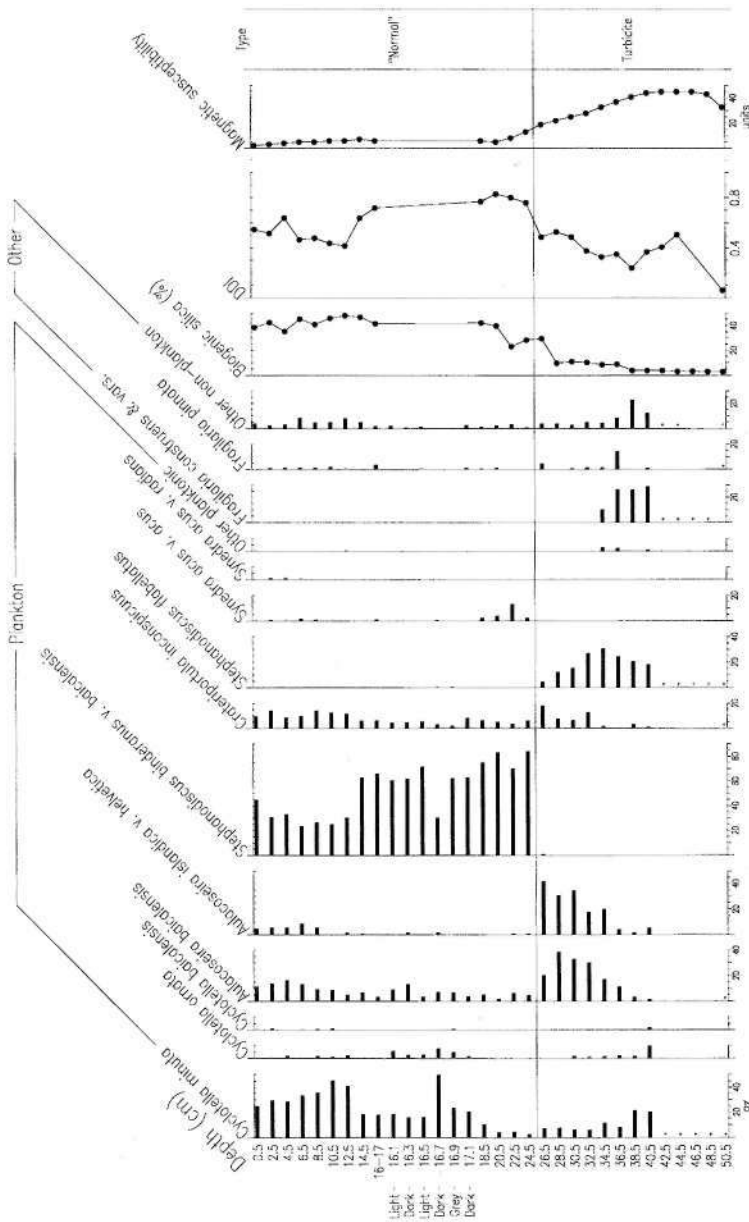

Type
"Normal"
Turbidite
Magnetic susceptibility
units
DDI
Biogenic silica (%)
Other non-plankton
Fragilaria pinnata
Fragilaria construens & vars.
Other planktonic
Synedra acus v. radians
Synedra acus v. acus
Stephanodiscus flabellatus
Cratenportulia inconspicuus
Stephanodiscus binderanus v. baicalensis
Aulacoseira islandica v. helvetica
Aulacoseira baicalensis
Cyclotella baicalensis
Cyclotella ornata
Cyclotella minuta
Depth (cm)
Plankton
Other
%
Light
Dark
Light
Dark
Grey
Dark

FIG. 5. *(On opposite page).* Summary diatom frequency diagram for a core (BAIK56) collected from the south-west part of the north basin (see Fig. 1). Biogenic silica concentration (%), diatom preservation state (DD1, proportion of valves showing dissolution features) and magnetic susceptibilities for this core are also shown. Note (i) change of scale for the 16-17 cm depth section, marked by colour banding, and (ii) the clear stratigraphic discontinuity at around 25 cm depth between normally deposited sediment and a lower turbidite deposit (see the text).

interest lies in environmental signals over a more recent time-scale, sites of high sediment accumulation rates that favour reconstructions at higher resolution are needed.

Several studies have demonstrated considerable variations in diatom frequencies in Holocene sediments from different regions of the lake (e.g. Fedorova 1973; Bradbury et al. 1994; Edlung et al. 1995; Mackay et al. 1998). The latter showed that recent sediment cores from the deep-water basin plains were often affected by underwater mud-flow deposits (turbidites). Such redeposited material is a major feature in cores of Pleistocene sediments (Nelson et al. 1995). Recognition of turbidite features is particularly important for high resolution, recent palaeoecological interpretation, where effects on stratigraphic changes can be subtle (Mackay et al. 1998).

In GEOPASS-NERC, sediment prospecting is designed to detect regions most likely to provide the best available sediment records for Holocene studies. Coring by EAWAG began in 1996 and core transects have been carried out in all three basins (Fig. 1). Results already demonstrate that most turbidite. sequences can be recognized visually (colour and particle size changes) in fresh longitudinal core sections (Fig. 4). Turbidite features can be spatially extensive, and magnetic logging (Lees et al. 1998) has demonstrated that Holocene turbidites can be correlated across GEOPASS-NERC core transects in the north basin.

So far, several GEOPASS-NERC cores have been analysed fully for diatoms. Core B AIK56 is of interest because of brown/grey micro-laminations around 16-17 cm depth and the presence of a remarkable 15 cm thick oxidized surface layer (Fig. 4); the 45 cm long core is from 515 m water depth in the south-west part of the north basin (Fig. 1). The core, analysed at every 2 cm and sequentially in the laminated section, shows no link between diatom abundances and sediment banding or oxidization state (Fig. 5). Biogenic silica and magnetic susceptibility measurements do show a major stratigraphic discontinuity at 25 cm. Diatom preservation and *Stephanodlscus binderanus* abundance fall abruptly below 25 cm, and *S. flabellatus* (common in the Late Glacial; Bradbury et al. 1994), together with shallow-water taxa (e.g. *Fragilaria construens* and varieties), peak at around 35 cm. These features are similar to those already found in a surficial turbidite from the south basin (Flower 1998).

It is already clear that all three of Baikal's basins are affected by Holocene turbidites (Nelson et al. 1995; Sturm et al. 1997). Consequently, GEOPASS-NERC prospect coring is focusing on local regions (underwater platforms and slope shoulders) less likely to be affected by turbidites.

Calibrating diatom assemblages in terms of climate change

This is the final part of the GEOPASS-NERC work plan. Diatom phytoplankton abundances, diatom assemblages in trap material and in ca. 100 surface-sediment samples, with associated environmental attributes, will be analysed numerically. The trap and sediment data will be entered into the Environmental Change Research Centre's database AMPHORA for archiving and statistical analyses. Multivariate techniques will be used to (i) assess the similarities between traps, surface sediment and deeper sediment; (ii) explore the relationships between phytoplankton abundances, surface-sediment assemblages and environmental variables; (iii) develop, if necessary, numerical correction factors for problems of differential diatom dissolution; (iv) explore potential climate reconstruction methodologies by building on transfer-function techniques developed elsewhere (Birks et al. 1990).

It is, however, already clear from ongoing analysis and from Mackay et al. (1998) that *Aulacoseira baicalensis* is relatively more common in north basin sediments, and that *Stephanodlscus* species are largely confined to the southern and middle basin zones. It is not yet possible to attribute frequency differences to environmental factors but it is anticipated that the GEOPASS-NERC dataset will make this possible. Diatom-climate links will be explored in a number of calibrations and potentially combined by (i) a weighted averaging approach using temperature-derived responses from cultures of the main endemic species, (ii) an empirical calibration of species-abundance ratios against temperature or temperature surrogates and ice-cover attributes along a north-south gradient of surface sediment assemblages, (iii) determining the ratio of vegetative cells to resting stages of *Aulacoseira* taxa in surface sediments, and (iv) examining the relationships between diatom productivity and diatom accumulation rates (with and without dissolution weighting) along this axis.

Synopsis

The preliminary results from the interrelated studies of phytoplankton, sediment traps and sediment cores used in GEOPASS-NERC, demonstrate the complexity of links between the living and fossil systems. Furthermore, the nature of recent sedimentation in Lake Baikal is spatially variable and incompletely known. This poses a major challenge to palaeolimnological interpretation. Turbidite deposits and differential preservation of microfossils, combined with inadequate knowledge of the modern ecology of endemic diatoms, all conspire to obfuscate the sedimentary record of environmental change.

Nevertheless, considerable progress on the ecology and life-cycles of *Aulacoseira* taxa has been made, and work on the endemic *Cyclotella* species is in progress. Any major taphonomic effects on sinking diatoms and their incorporation into sediment should be revealed by the 24 months of sediment-trap data collected during GEOPASS-NERC. The major field-trapping programme and survey of surficial sediments are now complete, and examination of the material should allow sediment-forming and accumulation processes to be quantified and further turbidite-free zones to be identified. This will be important for future high-resolution Holocene coring and will help to assess the representativity of records from different parts of the lake. Hopefully, by the end of GEOPASS-NERC in late 1999, data combined from the four sub-projects should make quantitative reconstructions of climate change from Lake Baikal sediment cores possible.

Acknowledgements

Many people have contributed to the joint palaeolimnological studies of the uppermost sediments in Lake Baikal, but much of the research described above would not have been possible without the BICER agreement, the support of The Royal Society (UK) for lake sampling and the co-operation of Dr M. Grachev and Dr N. Granin and his team at the Limnological Institute, Irkutsk. The main GEOPASS-NERC coring programme was carried out with the assistance of the crew of the RV Vereshchagin. The work was financed principally by using grants from the Natural Environmental Research Council (UK), grant number GR3/10529, and EAWAG (Switzerland), research grant number 85051.

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