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Diatom succession trends in recent sediments from Lake Baikal and their relation to atmospheric pollution and to climate change

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Recent environmental change in Lake Baikal has been attributed to anthropogenic influences on the ecosystem, especially through pollution and cultural eutrophication. These hypotheses are tested in this paper principally by diatom analyses in 20 short sediment cores. Most of the cores were collected with a new type of box corer specifically designed for use on Lake Baikal. Most cores contain a good sediment record but turbidites occur in some sediment profiles which may be best recognized using a combination of techniques, such as radiometric dating and percentage dry weight analyses. The most recent sediments, especially those in the southern basin and in the very north of Baikal, contain a record of anthropogenic contamination in the form of lead and spheroidal carbonaceous particles, which confirms that the southern basin of Baikal is most affected by atmospheric sources of pollution. However, there is no sedimentary diatom evidence indicating offshore water quality deterioration in Baikal owing to air pollution or eutrophication. Small increases in diatoms which indicate nutrient enrichment (e.g. *Stephanodiscus minutulus*, *Synedra acus* v. *radians* and *Synedra acus* v. *acus*) may reflect local eutrophication of the shallow waters close to the Selenga Delta and certain coastal sites in the southern basin near to the Baikalsk paper and pulp mill.

By using numerical techniques, Lake Baikal can be split into at least four regions on the basis of its surface sediment flora: the south, middle and north basins, and the shallow waters surrounding the Selenga Delta region. Diatom analyses reveal that the endemic flora of Lake Baikal has been constantly changing over at least the last 2000 years and that these fluctuations are probably responses to natural climatic variability. Recent sediments of Baikal may be affected by taphonomic processes (e.g. dissolution) and turbidite deposition, and these must be taken into account when interpreting the sedimentary diatom record.

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The diatom flora of the lake is currently dominated by several species, such as *Aulacoseira baicalensis*, *A. islandica*, *Cyclotella minuta* and *Stephanodiscus binderanus* v. *baicalensis*. All these species, except for *C. minuta*, have become more common in the lake in approximately the last 130 years, and we hypothesize that these changes may be attributed to a number of different processes linked to an ameliorating climate after the end of the Little Ice Age. The results presented here have important implications for this recently designated World Heritage Site, with regard to future pollution controls and catchment management policies.

Keywords: Lake Baikal; diatoms; atmospheric pollution; climate change; palaeolimnology

1. INTRODUCTION

Large lakes (defined as those with a surface area of over 500 km^2 (Tilzer & Serruya 1990)) contain over 90% of global surface fresh water resources (Herdendorf 1982) and are irregularly spread out across the globe. It is increasingly recognized that growing numbers of these lakes are under threat from anthropogenic stresses, most notably pollution in the form of acid rain and cultural eutrophication (see, for example, Charles & Whitehead 1986). These stresses are important, therefore, in terms of global ecology and economy. Recent scientific attention has focused on the largest lake in the world, in terms of volume of water held, Lake Baikal.

Lake Baikal is situated in the centre of the Asian continent, in southeast Siberia, between 51°28′–55°47′ N and 103°43′–109°58′ E (see figure 1). It exists within a tectonic rift valley that began to form over 30 million years ago (Belova *et al*. 1983) and is by far the oldest lake in the world. Although in area Lake Baikal is only the seventh largest freshwater lake in the world, because of its great depth (in excess of 1600 m) it does in fact contain a larger volume of surface fresh water than any other single body (23 000 km^3) (Kozhov 1963), accounting for some 20% of global resources (Wetzel 1983). By virtue of its age and immense volume, Lake Baikal is undoubtedly one of the most interesting freshwater ecosystems for scientific study in the world today because there are over 2500 extant plant and animal species in Baikal, of which over 75% are believed to be endemic (Galazii 1989). This high level of endemicity stems from immigration, speciation and extinction (Martens 1997). Furthermore, a principal feature that sets Lake Baikal apart from other deep lakes is that its hypolimnion is saturated with oxygen owing to regular, part renewal of the deep waters every year in spring and autumn (Weiss *et al*. 1991; Shimaraev *et al*. 1994), resulting in the upper sediment layers being oxidized (Knyazeva 1954; Leibovich 1983; Martin *et al*. 1993). More importantly, this oxygenation supports an extensive, and almost wholly, endemic fauna, including fish and invertebrates in the deep waters (Fryer 1991).

The Baikal depression is the deepest continental depression on the Earth, on which some 7500 m of sediment have accumulated (see, for example, Hutchinson *et al*. 1992). Past glaciations have had dramatic effects on the Lake Baikal region, i.e. its hydrology, sedimentology, ecosystem and shoreline (Grosswald & Kuhle 1994) but the lake itself has never been glaciated. Lake Baikal, therefore, potentially contains an uninterrupted sediment record comparable to that usually found only in marine environments. Its location in a high latitude, mid-continental interior setting, close to the boundaries of regional weather systems makes it an important site for palaeoclimate research (see, for example, Colman *et al*. 1995) and as such it is a key site in the Pole–Equator–Pole (PEP II) transect in the PAGES programme (Dodson & Lui 1995). Recent studies have used the diatom history of the Baikal ecosystem to reconstruct past climates, either in the form of species identification, see, for example, Bradbury *et al*. (1994), or by using biogenic silica as a proxy for climate change (for examples, see Vykhristuyk 1979; Granina *et al*. 1992, 1993*b*; Karabanov *et al*. 1992; Colman *et al*. 1995) and palaeoproductivity (see, for example, Qui *et al*. 1993). Diatoms are by far the dominant producer of biogenic silica, contributing approximately 98% of all sedimentary silica (Granina *et al*. 1992). A more complete interpretation of this record is hampered, however, because the link between climate and diatom productivity is, as yet, unknown and there is a potential problem of diatoms dissolving out of the sedimentary record (Colman *et al*. 1995).

(a) *Environmental threats to the Baikal ecosystem*

In recent decades, concern regarding environmental threats facing the ecological balance of Lake Baikal has escalated (making it one of the most highly publicized examples of environmental pollution in the Russian republic (Zeigler 1992)), with increasing levels of industrial and population growth, increased agricultural chemical use and logging on the river tributaries. Public awareness of these threats to the Baikal ecosystem during this period was unparalleled, resulting in the designation of several environmental laws and decrees which sought, for example, to control logging and the transport of logs along the coastline and tributaries to protect spawning grounds of endemic omul (*Coregonus autumnalis migratorius* Georgi) (Galazii 1982), to convert the Selenginsk paper and pulp mill to a closed-cycle water system (see next paragraph), to move the cellulose operation at Baikalsk elsewhere (see, for example, Pryde 1991) and to set up a number of protected areas and national parks throughout the Baikal catchment during the 1970s and 1980s (Vorob'yev & Martynov 1989).

Scientific and political interest has focused on the suspected pollution of Baikal, via effluents, consisting mainly of factory waste products and partly treated sewage, as well as atmospheric contamination (see, for example, Flower 1994; Flower *et al*. 1995*a*). Effluents enter Baikal directly in the far north and south of the lake, and from rivers, especially the River Selenga, Baikal's largest tributary (figure 1). Perhaps the most important sources of pollution are the two pulp and cellulose processing factories, one of which is on the southern shore at Baikalsk city and the other, smaller one on the River Selenga at Selenginsk (Stewart 1992). The Baikalsk mill began operating in 1966 and has become the most significant polluter

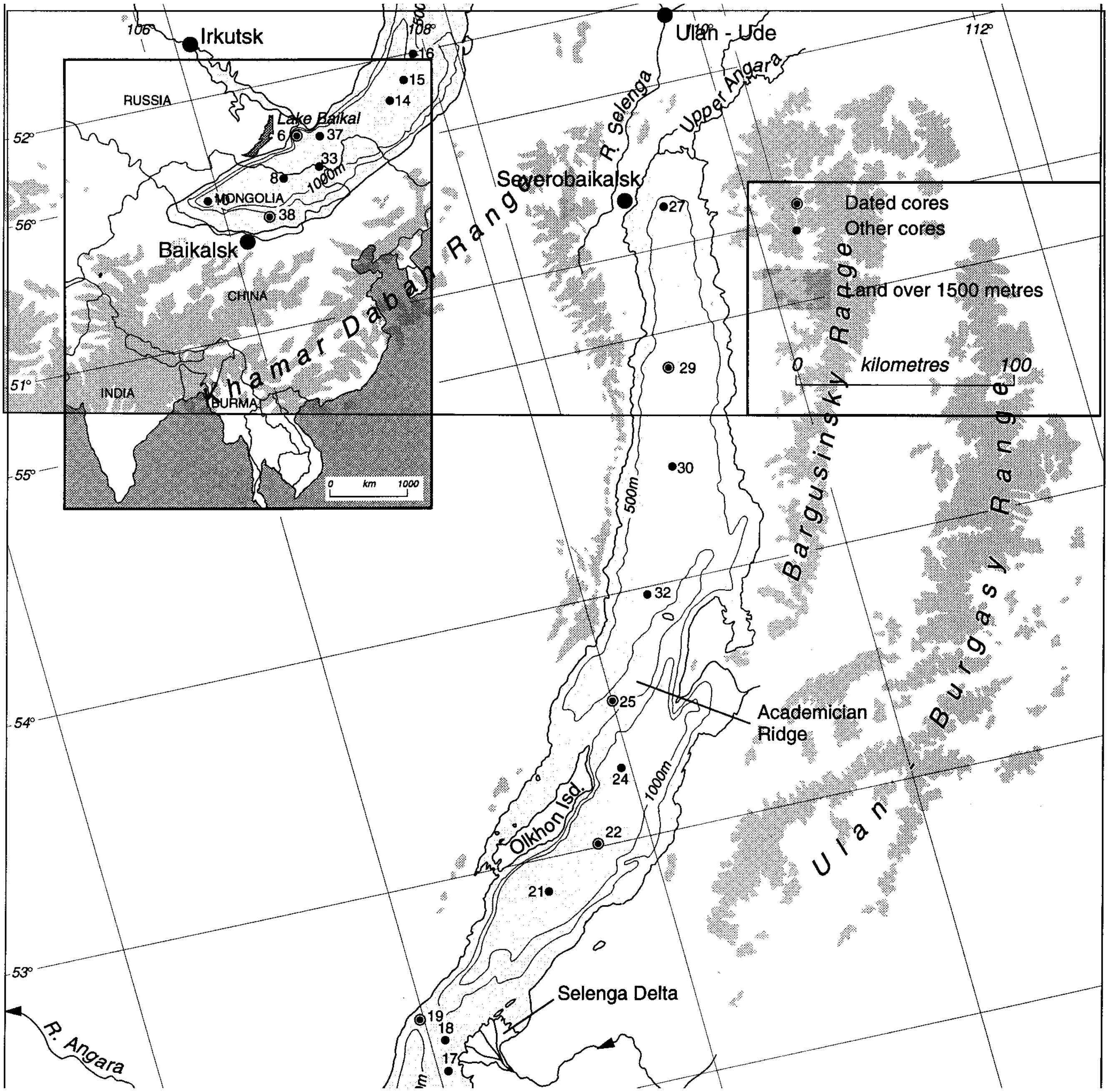


Figure 1. Map of Lake Baikal and its immediate catchment. Surficial cores and major towns are indicated, as are the rivers, Selenga (Baikal's largest tributary) and the Angara (Baikal's only outflow).

of Lake Baikal, having introduced about 1.5 billion cubic metres of industrial waste into the lake including organochlorine compounds (see, for example, Maatela *et al.* 1990). The mill at Selenginsk has recently been converted to a closed-cycle water system (Gurulev 1994) but its impact on the environment before this was substantial. The Baikalsk factory is still considered to be a primary source of pollution. Several studies have demonstrated increasing levels of agro-chemicals, such as DDT, especially towards the southern region of Baikal (Kucklick *et al.* 1994; Iwata *et al.* 1995). These studies show that concentrations of DDTs and also of PCBs were highest in the southern basin and the Selenga region, indicating local sources contributing to both atmospheric and riverine inputs. Galazii (1982) suggests that pollution loading into the Selenga Delta can be detected over an area as large as 1500 km^2. Anthropogenic impacts are also increasing in the north of Baikal, with the construction of the Baikal–Amur Mainline railway and the growth of new industrial cities such as Severobaikalsk.

Kokorin & Politov (1991) suggest that atmospheric deposition across the Baikal basin from factories and fossil fuel combustion is now a rapidly growing problem and it has been suggested that this deposition poses a bigger threat to the ecosystem than point-source water pollution (Galazii 1989; Stewart 1990). Sources of atmospheric pollution include all the industries around the Baikal region as well as the two pulp and cellulose mills. Unlike point-source effluents, whose effects are likely to be more localized, atmospheric pollutants have the potential to be carried long distances. They can, therefore, have deleterious effects on more remote regions around Baikal, affecting not only water quality directly but also indirectly by deposition onto vegetation in the catchment area. More than 90% of water entering Baikal derives from forested areas (Polikarpov *et al.* 1994), which it has been suggested recently are being adversely affected by pollution (see, for example, Van der Sleesen 1994).

Controversy exists as to the effects of these combined forms of pollution on the Lake Baikal ecosystem. Spawning of the endemic omul has decreased, as well as general fish size and weight, and populations now have to be protected (Stewart 1990). The death of thousands of endemic seals from seal distemper in the late 1980s has also been linked to increases in pollution causing seal immunities to be lowered (Grachev *et al.* 1989), for example by organochlorines (Iwata *et al.* 1995). Furthermore, Popovskaya (1991) claims that the diatom assemblage of Baikal is changing, especially with small, cosmopolitan planktonic forms and *Synedra* spp. increasing in frequency as a result of increased nutrient loading, at the expense of the planktonic endemics. In view of these problems, the designation of Lake Baikal in 1990 as a World Heritage Site was postponed until the Baikal basin could be included as a World Heritage Area (UNESCO, unpublished report). It was granted this status in 1996.

Whereas local water quality problems are generally acknowledged, some scientists believe that the pollution of the lake has been grossly over-estimated (see, for example, Grachev 1991). In contrast to an earlier publication (Grachev *et al.* 1989), Grachev (1991) suggests that recent fish stock declines and the incidence of seal distemper may be explained by natural variation and to factors other than water pollution. In a preliminary palaeolimnological study of one core in the southern basin of Baikal, Flower *et al.* (1995*a*) concluded that endemic diatom populations have not been affected by increasing pollution levels. International concern about Baikal has also risen, principally because of the changing political climate in Russia since the late 1980s. These factors facilitated easier access to Baikal by western scientists and journalists, which in turn allowed the formation of the Baikal International Centre for Ecological Research (BICER) in 1990. The Centre, created by founding member countries UK, USA, Belgium, Switzerland and Japan, in conjunction with the Russian Academy of Sciences, and based at the Limnological Institute in Irkutsk, seeks to nurture scientific cooperation between western and Russian scientists. The Royal Society has been fundamental in providing resources for BICER and for coordinating the British scientific effort.

(b) *Project rationale*

The approach used in this study determines environmental change from both biological and chemical records in recently deposited sediments through the high resolution analyses of several cores (see, for example, Battarbee 1991), based especially on the sedimentary diatom record throughout the length of Baikal. Diatoms are important primary producers in Baikal, comprising approximately 57% of the lake's planktonic community (Popovskaya 1977) and are good indicators of water quality. Within this project the whole lake is surveyed and thus it follows that stratigraphical correlation between cores by using diatom analyses is an integral part of the project. Rudimentary core correlation of long sediment cores by using diatom analyses has been tried comparatively recently by Bradbury *et al.* (1994). However, they only analysed six cores at low resolution, some of which had lost their core tops (Colman *et al.* 1993). In this study, we also examine the recent sediments for evidence of atmospheric pollution, by using trace metal and spheroidal carbonaceous particle (SCP) analyses. Temporal and spatial trends in our diatom results are investigated by using multivariate statistics, which are then critically compared with recent studies by Popovskaya (1991), Stoermer *et al.* (1995) and Edlund *et al.* (1995), as any realistic policy for the environmental protection of Baikal from anthropogenic pollution necessitates a comprehensive survey of anthropogenic contaminants and diatom composition change across the whole lake.

Taphonomic factors are usually ignored during palaeolimnological investigations, although their importance is increasingly being recognized in the interpretation of sedimentary assemblages (see, for example, Flower 1993*b*; Cameron 1995; Ryves & Battarbee 1997). Thus, we also assess spatial and temporal heterogeneity of sediment records and the problem of preservation by extending the work reported in Flower *et al.* (1995*a*).

2. MATERIALS AND METHODS

(a) *Coring procedure*

Approximately 40 short sediment cores (*ca.* 80–500 mm) were collected during three field expeditions on Lake

Baikal (i) in September 1992 (Flower *et al.* 1995*a*), (ii) between June and July 1993 aboard the ship 'Titov' (Mackay *et al.* 1993), and (iii) in the Spring of 1994 when the lake was frozen. Cores were collected by using several corer types: the Baikal box corer (Flower *et al.* 1995*b*), a modified Glew corer and a simple gravity corer. The type of corer chosen was dependent on weather conditions, water currents and length of core required. For example, although the box corer was the preferred instrument (see, for example, Flower 1995*b*), it could only be used when weather conditions were calm, or when cores were collected by using the frozen lake surface as a stable platform. The cores were sectioned by using a screw-threaded extruding rig: most being extruded in 2 mm sections (0–5 cm), then in 5 mm sections (5–10 cm) and then every 10 mm. Samples were immediately sealed in Whirlpak bags and stored, when possible, at 4 °C. Cores that were disturbed were discarded. A total of 20 cores were retrieved with visually intact surface sediments and form the basis of this paper (figure 1): location coordinates, depth of water from which they were taken, type of corer used and length of core used for analyses are given in table 1. The material collected was transported back to the UK for analyses. A total of six cores were subsequently further selected for radiometric dating.

(b) *Sediment analyses*

(i) *Lithostratigraphic analyses* (20 *cores*)

Samples were routinely analysed for wet densities (WD) and percentage dry weight (%DW) at 105 °C. Estimates of weight loss at 550 °C were made in all cores (Stevenson *et al.* 1987).

(ii) *Diatom analyses* (20 *cores*)

Unlike many other freshwater sediments, no chemical pretreatments (e.g. with acids such as HCl, or oxidizing agents, such as H_2O_2) are necessary for the preparation of Baikal sediment samples for diatom analyses. Indeed, an initial study by Flower (1993*b*) has suggested that aggressive chemical pretreatments may actually have an adverse effect on the preservation qualities of certain frustule types that are lightly silicified. Consequently, 0.1–0.3 g wet sediment per sample was put into a plastic centrifuge tube, weighed and then simply washed three times in distilled water. To enable diatom concentrations to be calculated, a known weight of divinylbenzene microspheres (approximately 1–2 g, with a mean diameter of 6.4 μm) was then added to the cleaned samples (Battarbee & Kneen 1982). Subsamples of the suspensions were diluted and settled out onto coverslips until dry. The coverslips were fixed onto slides by heating with *Naphrax* on a hotplate at 130 °C. The original suspensions are stored in methanol in labelled airtight glass vials, and currently archived at the Environmental Change Research Centre (ECRC), London.

Table 1. *Locations of cores used in this study from Lake Baikal*

core name	location	basin	depth (m)	corer used length (mm)
BAIK6	51°48′38″ N 104°51′38″ E	south	1425	box 115
BAIK8	51°38′52″ N 104°35′03″ E	south	1433	box 80
BAIK10	51°42′32″ N 103°57′42″ E	south	1348	glew 200
BAIK14	51°47′27″ N 105°27′15″E	south	1502	glew 200
BAIK15	51°55′02″ N 105°40′32″ E	south	1367	gravity 200
BAIK16	52°05′32″ N 105°51′31″ E	south/ Selenga	64	gravity 150
BAIK17	52°11′07″ N 106°05′38″ E	Selenga	34	box 160
BAIK18	52°18′50″ N 106°07′30″ E	Selenga	87	box 190
BAIK19	52°27′00″ N 106°07′32″ E	Buguldieka Saddle	342	box 210
BAIK21	52°43′03″ N 107°00′05″ E	middle	1337	box 120
BAIK22	52°59′17″ N 107°39′58″ E	middle	1624	box 160
BAIK24	53°15′09″ N 108°06′54″ E	middle	1678	box 150
BAIK25	53°33′18″ N 107°58′00″ E	Academician Ridge	307	gravity 300
BAIK27	55°25′35″ N 109°25′56″ E	north	820	gravity 150
BAIK29	54°48′01″ N 109°12′58″ E	north	910	box 160
BAIK30	54°25′12″ N 109°00′11″ E	north	888	gravity 290
BAIK32	53°54′19″ N 108°34′35″ E	north	720	gravity 210
BAIK33	51°42′16″ N 104°59′43″ E	south	1478	gravity 230
BAIK37	51°48′20″ N 104°53′13″ E	south	1390	glew 470
BAIK38	51°34′06″ N 104°31′43″ E	south	690	glew 400

A total of 500 valves in contiguous samples were counted in cores that were selected for radiometric analyses. Diatom counts in the remaining cores were reduced to 300 valves in alternate samples. Valves were counted at ×1000 magnification by using an oil-immersion lens and phase contrast and counts are currently archived on the ECRC database AMPHORA. Routine analyses also included procedures for recording diatom preservation quality. A total of three stages of valve preservation of *Aulacoseira baicalensis* (Meyer) Simonsen and *Cyclotella minuta* (Skv.) Antipova were recorded under the light microscope. A simple index of diatom dissolution (DDI) (Flower & Likhoshway 1993) was used to enable samples to be numerically compared:

$$\mathrm{DDI} = \left(\sum_{i=1}^{n} x_{1i}\right) \Big/ \left(\sum_{i=1}^{n} x_{1i} + \sum_{i=1}^{n} x_{2i}\right),$$

where n is number of taxa, x_{1i} is number of valves i in preservation stage 1 (pristine), x_{2i} is number of valves in preservation stage 2 and above. If all the valves are affected by dissolution then DDI = 0, but DDI = 1 if all the valves are pristine. However, instead of expressing indices for *Aulacoseira* and *Cyclotella* separately, here we combine their scores, and express the index as dissolution per sample (D. B. Ryves, unpublished data). Dissolution stages were not counted for BAIK17 because of the low numbers of *Cyclotella* valves present. Bradbury *et al*. (1994) document problems of diatom analyses by different co-workers, especially taxonomic and counting procedures. These problems were also initially encountered at the beginning of this project, but an exchange programme between the ECRC and the Limnological Institute, enabled the harmonization of counting strategies and taxonomic identifications. Diatom taxa were identified to species level or lower by using a range of both western and Russian floras (for examples, see Genkel 1992; Genkel *et al*. 1992; Gleser *et al*. 1988; Hustedt 1930–1966; Khursevich 1989; Krammer & Lange-Bertalot 1986, 1991; Lange-Bertalot 1993; Patrick & Reimer 1966, 1975; Skabichevskii 1960; Zabelina *et al*. 1951). Diatom diagrams were constructed by using TILIAGRAPH 2.1 and main zones of compositional change were delimited by the technique of stratigraphically constrained incremental sum-of-squares cluster analyses (Grimm 1987) by using the program CONSISS, with no data transformation.

(iii) *Radiometric analyses (six cores)*

A total of six cores were selected for dating purposes on the basis of their diatom lithostratigraphy and location—BAIK6 and BAIK38 from the southern basin, BAIK19 from the Buguldeika Saddle (opposite the Selenga Delta), BAIK22 from the middle basin, BAIK25 from the Academician Ridge and BAIK29 from the northern basin (figure 1). Sediment samples were sent to the Liverpool University Environmental Radiometric Laboratory for dating by ^{210}Pb and ^{137}Cs by non-destructive gamma spectrometry (Appleby *et al*. 1986). Corrections to each count were made for the effect of self absorption of low-energy rays within the same sample (Appleby & Oldfield 1992).

(iv) *SCP analyses (six cores)*

SCP analyses were done to assess the temporal distribution of atmospheric contaminants derived from high-temperature fossil-fuel combustion. Analyses were done by the method detailed in Rose (1994) on the six dated cores. For counting purposes, known fractions of residues were evaporated onto coverslips, mounted using *Naphrax*, and the whole coverslip counted at ×400 magnification.

(v) *Trace metals*

The six dated cores were analysed for trace metals (University of Liverpool, Department of Geography), to assess the palaeolimnological evidence for heavy metal pollution in Lake Baikal. Samples from BAIK6 and BAIK22 underwent total digestion by using a mixture of HF, HNO_3, and $HClO_4$. For the other cores, a part extraction with 10% HCl was used. Analysis grade reagents were used. Quality control was assessed by using repeat analyses of NIST SRM 2704 (Buffalo River Sediment).

(vi) *Biogenic silica*

A total of 13 cores were analysed for biogenic silica by using dried subsamples of sediment. The samples were analysed in Irkutsk by using alkali digestion (Mortlock & Froelich 1989): silica was extracted from 50 mg of dry sediment by 15 ml of 20% Na_2CO_3 solution for 5 h at 85 °C. Extracts were analysed colorimetrically by using a blue silicon–molybdate complex.

(c) ***Numerical analyses***

Multivariate ordination techniques were done by using the program CANOCO (ter Braak 1987), version 3.1 (ter Braak 1990) on diatom data equal to 1% in one or more samples, extracted from the database, AMPHORA.

(i) *Individual core data*

The main gradients of floristic variation in the diatom data in every core were first assessed by using detrended correspondence analysis (DCA) (Hill & Gauch 1980), with detrending by segments, nonlinear rescaling of axes, log transformation of species data and rare species down-weighted. Core data with axis 1 gradients less than 2 standard deviation (s.d.) units were subsequently investigated by using the linear response model, principal components analyses (PCA) (ter Braak & Prentice 1988), on a correlation biplot with log transformation of the species data and further centring of species on a covariance matrix; sample data were not centred or standardized. Species turnover through time was assessed by using the gradient of the first axis derived from DCA analyses (Hill & Gauch 1980). In the six dated cores, the significance of changes in the diatom assemblages was calculated by using redundancy analyses (RDA) using time as a single quantitative constraining variable (Juggins *et al*. 1996). Restricted Monte-Carlo permutation tests (99 permutations, $p = 0.01$) were then used to test the explained variance.

To test if changes in the sedimentary diatom record could be linked with the contamination record, trace metals concentrations were treated as non-predictor environmental variables; the diatoms in each core were ordinated by PCA, regressing the metal concentration data onto the PCA axes rather than treating the metals as predictor variables, thereby preventing the metals from constraining the diatom data. Metals displaying a high level of collinearity (variance inflation factors, 20) were excluded from the analyses because of unstable canonical coefficients (ter Braak 1986). Forward selection was used to predict if any metals were significant in explaining most variation.

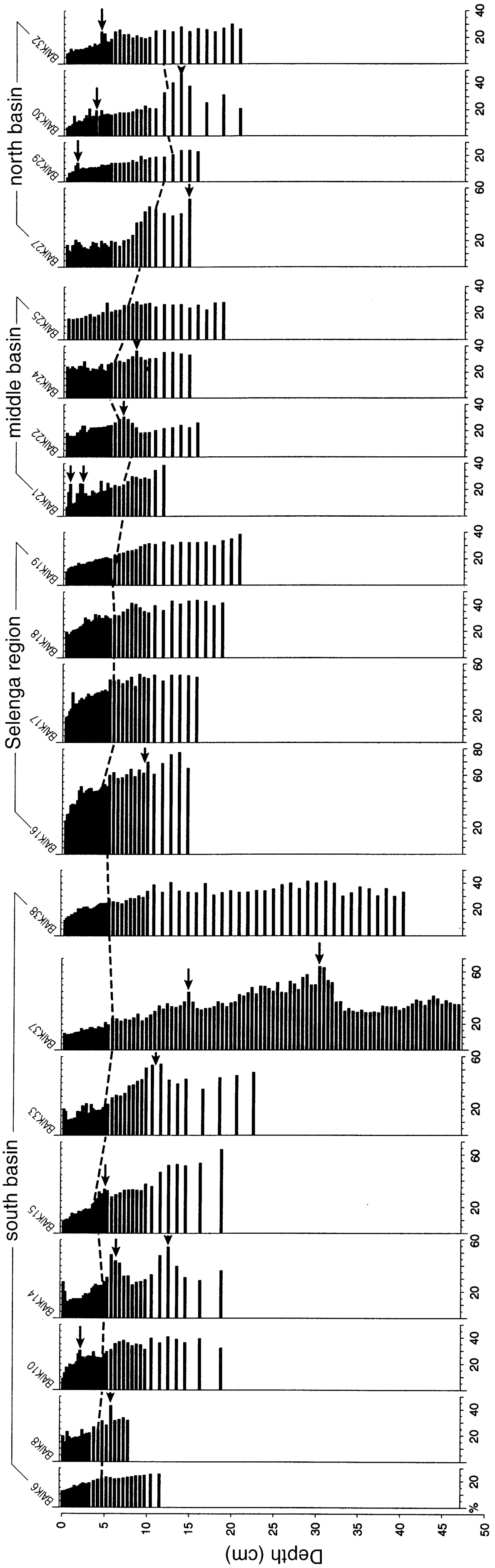
(ii) *Combined data set of 20 cores*

Spatial trends in the recent diatom history across the whole of the lake were assessed by using DCA to assess the main gradient in the diatom flora, followed by PCA on a combined data set of all the cores analysed above (sample number 490) by using diatom data equal to 1% in one or more samples.

3. RESULTS

(a) ***Lithostratigraphic analyses***

The 20 cores collected are of variable length, between 80 mm (BAIK8) and 470 mm (BAIK37) (table 1). All the cores typically display upper, brown, oxic sediments, overlying grey, anoxic sediments, in accordance with Leibovich (1983) for Baikal pelagic sediments. These brown layers are characteristically *ca*. 35–75 mm thick and all the 20 cores used in this study had oxic layers within this range. All the %DW profiles show a similar pattern of gradually increasing values from *ca*. 15% at the surface to *ca*. 40% further down the core profiles (figure 2). Several cores, however, show substantial peaks in %DW,



reaching 60%, and these are marked on figure 2 with an arrow (→). It is argued below that these peaks may represent turbidites: %DW values are especially high in the shallow waters surrounding the Selenga region. The approximate boundary between the oxic and anoxic layers are also marked on the same diagram. Per cent loss-on-ignition (%LOI) at 550 °C gives an approximation of organic carbon content in sediments (see, for example, Stevenson *et al.* 1987) and profiles are shown in figure 3. These values, between 5 and 10%, tend to increase towards the surface of most cores, to between 10 and 15%. Notable reductions in %LOI are apparent where %DW values exceed 60%, e.g. throughout most of BAIK16 and between 26 and 33 cm in BAIK37. Actual measured values of organic content in Baikal sediments are much lower than those measured here using ignition at 550 °C, at *ca.* 1–3% (see, for example, Vykhristyuk 1980; Williams & Jenkins 1993; Flower *et al.* 1995*a*) and so %LOI at 550 °C is not giving a good approximation of organic content. Flower *et al.* (1995*a*) have already determined that 75% of the LOI value is mineral-bound water and only a very weak correlation could be made between %LOI and organic matter.

(b) *Radiometric dating*

All six cores analysed contained good records of ^{210}Pb in the recent sediments, though significant differences between sediment accumulation rates were shown by the fact that ^{210}Pb–^{226}Ra radioactive equilibrium was reached at widely varying depths, ranging from 6–16 cm. Dates were calculated by using both the CRS (constant rate of supply) and CIC (constant initial concentration) ^{210}Pb dating models (Appleby & Oldfield 1978), and composite time–depth plots for each core based on a site by site assessment of the two models are given in figure 4. Mean ^{210}Pb inventories and sediment accumulation rates are summarized in tables 2 and 3, respectively.

(i) *BAIK6*

Beneath a small surficial zone of reduced ^{210}Pb activity, unsupported ^{210}Pb activity in BAIK6 declines exceptionally with depth or the less uniform sediment accumulation rate since *ca.* 1900 of $0.021 \pm 0.002\ \mathrm{g\,cm^{-2}\,yr^{-1}}$ and there is little significant difference between the two dating models. Both indicate a more or less uniform sediment accumulation rate since *ca.* 1900 of $0.021 \pm 0.002\ \mathrm{g\,cm^{-2}\,yr^{-1}}$ ($0.093 \pm 0.009\ \mathrm{cm\,yr^{-1}}$). A small, but significant, change in the slope of the ^{210}Pb profile below *ca.* 9 cm suggests that sediment accumulation rates before 1900 may have been lower than those prevailing during the past 90 years.

(ii) *BAIK19*

Unsupported ^{210}Pb activity again declines more or less exponentially with depth, apart from a small surficial zone of reduced ^{210}Pb activity. Although there appear to have been significant short-term fluctuations in sediment

Figure 2. (*opposite*) Composite stratigraphical diagram showing %DW profiles (%LOI at 550 °C), plotted against depth, for all 20 cores analysed. Cores are grouped by region. The boundary between the oxic–anoxic layers are stratigraphically linked with a dashed line, and suspected turbidite layers are marked with an arrow (see text for details).

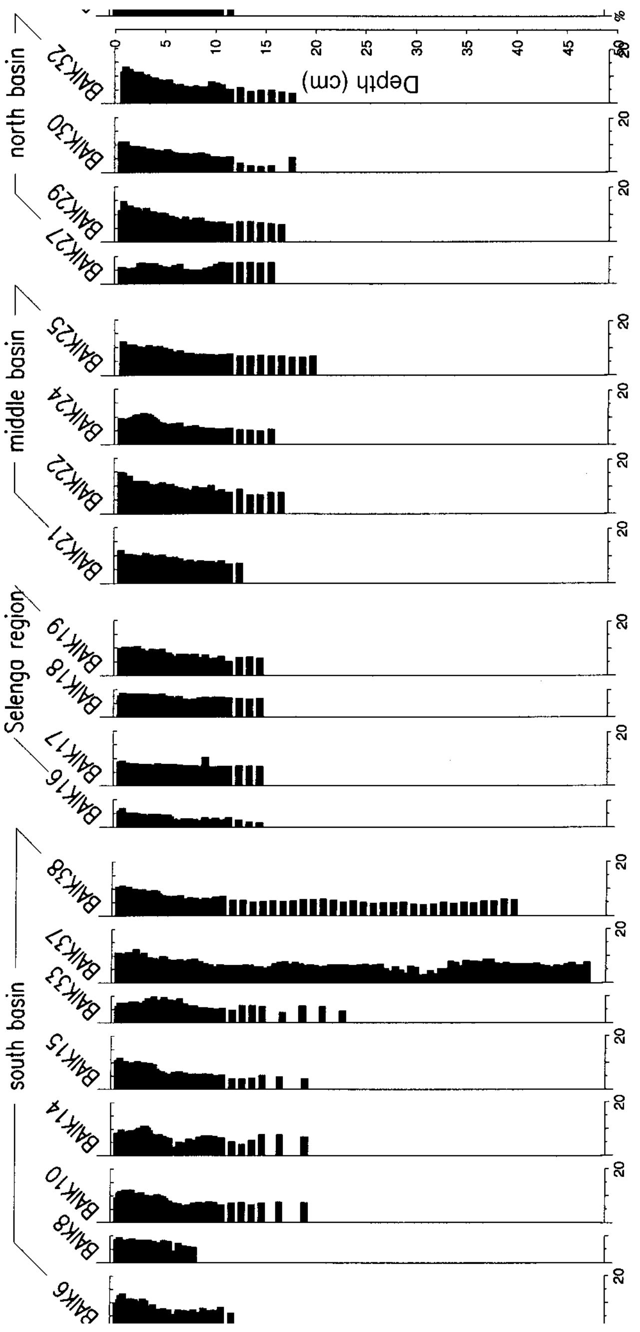


Figure 3. Composite stratigraphical diagram showing %LOI at 550 °C, plotted against depth, for all 20 cores analysed.

accumulation during the past *ca.* 100 years, the two ^{210}Pb dating models give similar estimates for the sediment accumulation rate, with a mean value for this period of 0.071 ± 0.002 g cm^{-2} yr^{-1} (0.076 ± 0.009 cm yr^{-1}).

(iii) *BAIK22*

A zone of irregular ^{210}Pb activity, extending down to 11.5 cm, almost certainly records episodes of rapid sediment accumulation (Mackay *et al.* 1996; Appleby *et al.* 1998). These episodes are particularly evident at core depths of 2.1 cm and 7.25 cm, where there are significant reductions in unsupported ^{210}Pb activity. As a result, this core could not be dated using the CIC model (Appleby & Oldfield 1983).

The mean sediment accumulation rate in recent decades is estimated to be nearly three times that for BAIK6. Below 11.5 cm there does, however, appear to have been a much 'quieter' period (spanning at least 70 years) during which sediment accumulation rates were relatively constant at *ca.* 0.0011 ± 0.002 g cm^{-2} yr^{-1}, significantly lower than BAIK6. As the unsupported ^{210}Pb inventory of BAIK22 is about 50% higher than the average value for all Baikal cores (table 2), it would appear that the conditions of the CRS model are only partly fulfilled at this site and that the higher sediment accumulation rates in recent decades have also given rise to a higher ^{210}Pb flux. By using the methods indicated in Oldfield & Appleby (1984), corrections were made to the raw CRS model dates by assuming that the ^{210}Pb flux during the period of normal sediment accumulation before recent disturbances was typical of the other cores. These calculations date the transitional level at 11.5 cm depth to 1934 and give a mean post-1934 accumulation rate of 0.052 g cm^{-2} yr^{-1}, nearly five times the pre-1934 value.

(iv) *BAIK25*

Sediment accumulation rates at this core site (located on the Academician Ridge) appear to have been relatively slow, with ^{210}Pb equilibrium being achieved at a depth of only 6 cm. The mean post-1900 sediment accumulation rate calculated by using the CRS model (0.0076 ± 0.0014 g cm^{-2} yr^{-1}) is significantly lower than that given by the CIC model (0.00110 ± 0.0013 g cm^{-2} yr^{-1}) (Mackay *et al.* 1996), which suggests that there may have been a small increase in sediment accumulation rates during this period, particularly during the past 40 years.

(v) *BAIK29*

Sediment accumulation rates at this location (centre of the north basin) are a little higher than at BAIK25, with ^{210}Pb equilibrium occurring at a depth of about 10 cm. Sediment accumulation rates calculated using the CRS model show a slight secular increase during the past 130 years, from a nineteenth century value of 0.0088 ± 0.004 g cm^{-2} yr^{-1} to a post-1950s value of 0.011 ± 0.001 g cm^{-2} yr^{-1}.

(vi) *BAIK38*

The CIC and CRS models give similar estimates of the mean sediment accumulation rate for the past 50 years, the average from the both methods being 0.014 ± 0.002 g cm^{-2} yr^{-1} (0.066 ± 0.009 cm yr^{-1}). Both models also suggest lower sediment accumulation rates before *ca.* 1940, with a mean value for the preceding 100 years of 0.0095 ± 0.001 g cm^{-2} yr^{-1} (0.033 ± 0.004 cm yr^{-1}).

(vii) *^{137}Cs results*

Although ^{137}Cs was recorded in all cores down to depths ranging from *ca.* 5 cm in BAIK25 to *ca.* 10 cm in BAIK22, the results were of little chronological value. None of the profiles had a peak that could clearly be identified as recording the 1963 weapons fallout maximum. This would appear to support the inference in Edgington *et al.* (1991) of a 20-year residence time for ^{137}Cs in the water column.

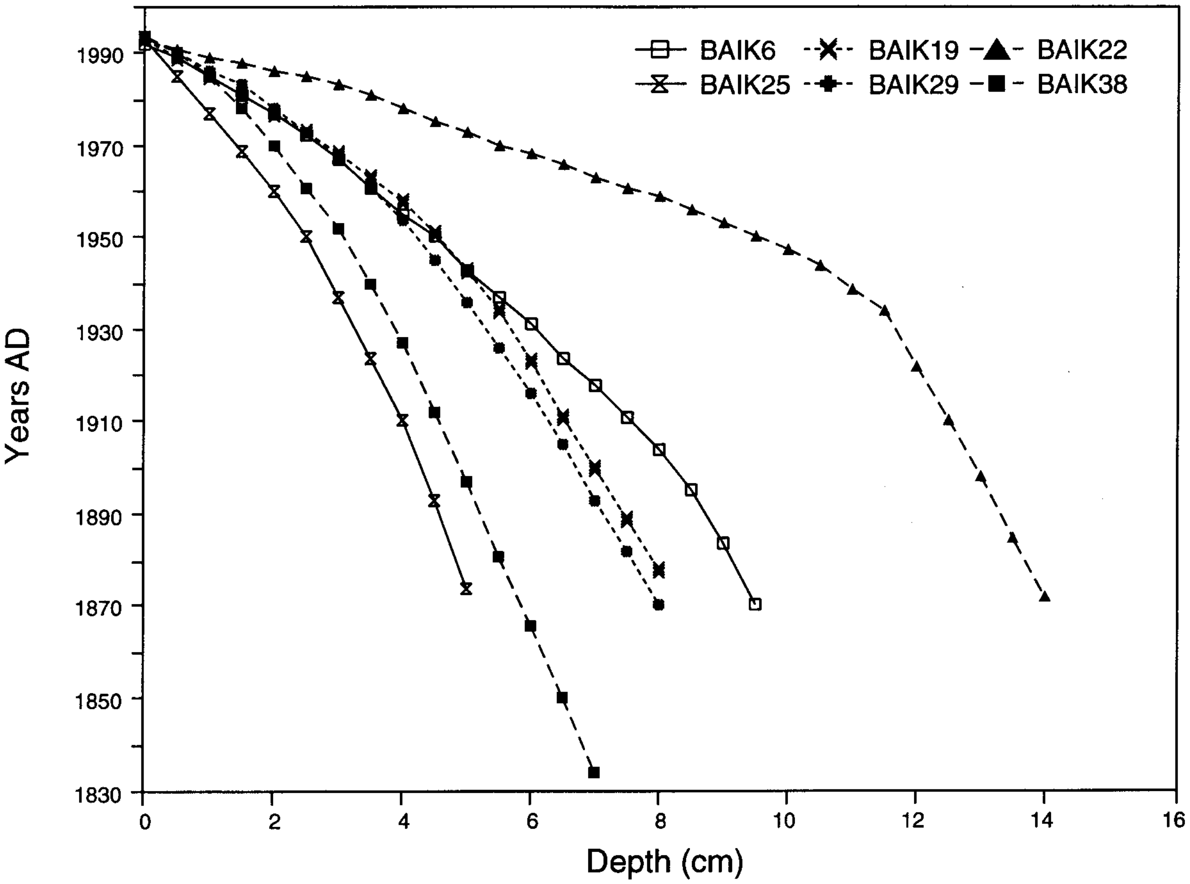


Figure 4. Plot of ^{210}Pb dates from the six dated cores against depth of sediment deposited. Lines connecting dates are based on the assumption of constant accumulation in the period between pairs of dates.

Table 2. *Unsupported ^{210}Pb inventories of Baikal sediment cores*

core	inventory Bq m^{-2} (±)	flux Bq m^{-2} yr^{-1} (±)
BAIK6	4952 (120)	154 (4)
BAIK38	2890 (113)	90 (3)
BAIK19	4328 (145)	135 (4)
BAIK22	5978 (175)	186 (6)
BAIK25	2259 (113)	70 (4)
BAIK29	3431 (132)	107 (4)
mean values	3973	124

Table 3. *Mean sedimentation rates in Lake Baikal*

core		g cm^{-2} yr^{-1}	±
BAIK6		0.021	0.002
BAIK19		0.017	0.002
BAIK22	(post-1934)	0.052	—
	(pre-1934)	0.011	0.002
BAIK25		0.009	0.002
BAIK29		0.009	0.001
BAIK38		0.011	0.001
mean		0.017	(including BAIK22)
		0.014	(excluding BAIK22)

(c) ***Diatom stratigraphies***

(i) *Presentation of* A. baicalensis *and* C. minuta *results*

There are two *Aulacoseira* species that occur in recent sediments of Baikal: *A. baicalensis* and *A. islandica*. Kozhova & Kobanova (1995) have recently renamed *A. islandica* to *A. kozhovi*. Simultaneously with Kozhova & Kobanova (1995), Edlund *et al.* (1996) had also been studying the morphology of *A. islandica* v. *helvetica* and they also concluded that it was a new species, naming it *A. skvortzowii*. We believe, however, that *A. islandica* may exhibit considerable morphological variability when present in either pelagic or littoral zones and so, for the time being, nomenclature in this paper keeps the old name of *A. islandica* v. *helvetica*. Different morphotypes and resting stages of each of these species are present; some investigations have split *A. baicalensis* into its various morphotypes (see, for example, Skvortzow 1937; Edlund *et al.* 1995), whereas others, including this study, have grouped the morphotypes as one species (see, for example, Popovskaya & Skabichevskii 1970). Likhoshway *et al.* (1992) have suggested that it is not possible to characterize *A. baicalensis* by visual inspection of the fine structure of the areolae alone as there is a degree of morphological overlap with the areolae of *A. islandica*. However, Genkal & Popovskaya (1991) have shown that only thin-walled frustules of *A. islandica* predominate in Baikal, and that these valves are quite distinct from *A. baicalensis*. *A. islandica* is present in the form of finely silicified valves and more heavily silicified resting stages. Edlund *et al.* (1995) document in their study that

A. islandica is found almost exclusively in its resting stage but we have not found this in our study, with normal valves making up *ca*. 50% of the total *A. islandica* count (see, for example, Mackay *et al*. 1993). This difference may be because of the chemical methods of diatom preparation used in their study dissolving the finely silicified valves or because they used bright-field microscopy. In our study, we have found that the lightly silicified valves can only be routinely identified and counted under phase-contrast.

A total of three endemic *Cyclotella* species are found in contemporary Baikal and in the surficial sediments: *C. minuta*, *C. ornata* (Skv) Flower, and less frequently *C. baicalensis* (Meyer) Skv (see Flower 1993*a*). Other workers, however, consider *C. ornata* to be a morphotype of *C. minuta* (Loginova & Khursevich 1986; Genkal & Popovskaya 1990). In our study, dissolution of these valves, with 50% being affected, presented a problem with their identification. Many of these valves could only be identified by their undulating central area, which is not sufficient to differentiate between *C. minuta* and *C. ornata* (Flower 1993*a*) and therefore counts are expressed as *C. minuta* only. Amalgamation of these two species does not affect any stratigraphical interpretations here because *C. minuta* is by far the most dominant species.

(ii) *Diatom stratigraphies*

Numerical analyses of the 20 cores analysed have identified four regions within Lake Baikal, each with their own trends in changing diatom populations: the south, middle and north basins, and the shallow waters of the Selenga region (see figure 16). A total of seven composite diatom stratigraphies, representative of each of these regions, are shown in full (figures 5–11). These include the six cores that have been radiometrically dated, together with BAIK17, an undated core from the zone of shallow water near the Selenga Delta. The diagrams consist of the following components: (i) individual diatom profiles with species equal to 2% in one or more samples; (ii) diatom concentrations (valves g^{-1} DW) (except BAIK6); (iii) diatom accumulation rates (valves $\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$) in the sections of cores that are dated radiometrically; (iv) changing sample DDI values; and (v) per cent biogenic silica (except for samples between 5–21 cm in BAIK19, and the whole of BAIK38). ^{210}Pb dates (expressed in years AD) are shown down the right-hand side of each diagram (except BAIK17). The remaining 13 diatom stratigraphical profiles are included in Appendix 1. The stratigraphies of these deepwater cores show that two endemic diatom species, *A. baicalensis* and *C. minuta*, dominate throughout most of Baikal (apart from shallow water areas near to the Selenga Delta). Main trends in the stratigraphies of these deepwater cores are discussed region by region.

South basin

Diatom profiles range from 8 cm (BAIK8; Appendix 1) to 46 cm (BAIK37; Appendix 1). In the longer profiles, one of the most striking aspects of the diatom profiles is the switch in dominance in the top 10 cm of sediment from a *C. minuta* dominated assemblage to one dominated by both *A. baicalensis* and *C. minuta*. This switch also occurs in the shorter cores: i.e. both BAIK6 (figure 5) and BAIK8 exhibit this switch at the very bottom of the profiles. In BAIK6, this shift has been dated to *ca*. 1870 (table 4), and because of its higher sediment accumulation rate (table 5), the switch occurs at the very bottom of the profile at *ca*. 9.75 cm. It is notable that the switch in BAIK38 (figure 10) occurs somewhat earlier than in the other cores (table 4) at *ca*. 1810, but that the corresponding dating errors are also higher.

Concomitant with recent increases in *A. baicalensis* are increases in other taxa, most notably *A. islandica*, *Stephanodiscus binderanus* v. *baicalensis* Popovskaya & Genkal, and *Synedra acus* v. *acus* Ehr, although *S. binderanus* v. *baicalensis* declines in the uppermost layers. Other taxa showing small increases in certain cores include *S. acus* v. *radians* (e.g. BAIK10 (Appendix 1) & BAIK38), *S. hantzschii* f. *hantzschii* (BAIK15 & BAIK37 (both Appendix 1)). In BAIK38 there is a marked increase in *Synedra acus* v. *acus* during the late 1960s and early 1970s.

Several cores exhibit a marked decrease in *C. minuta* during its phase of dominance (e.g. BAIK37: 12–33 cm; BAIK15 (Appendix 1): 11 cm to the bottom). Lowered *Cyclotella* populations are replaced by increases in taxa more commonly associated with the shallow waters in the region close to the Selenga Delta, for example, *Stephanodiscus parvus* (Stoermer & Håkansson) and *Fragilaria pinnata* v. *pinnata* (Ehr.).

Middle basin

In this section we have included the three cores from the middle basin proper (BAIK21 (Appendix 1), BAIK22 (figure 7) and BAIK24 (Appendix 1)) and one taken from the Academician Ridge (BAIK25, figure 8) because the surface sediment analyses of these cores reveal them to be quite similar (see figure 16). However, the following description of diatom changes within the cores treat the deepwater cores, BAIK21, 22 and 24 as distinct from BAIK25, taken from a water depth of *ca*. 300 m.

In the deepwater cores, *Cyclotella* and *Aulacoseira* occur at similar frequencies throughout the cores, although there is evidence of the *Cyclotella–Aulacoseira* switch, especially at the bottom of BAIK21, BAIK22 and BAIK24 at 15.5 cm. Further, unlike the cores described from the southern basin, there are no concomitant increases in species such as *A. islandica* and *S. binderanus*. It is worth emphasizing here that radiometric analysis of BAIK22 has shown it to be disturbed (see previous paragraphs). All three cores do exhibit recent increasing populations of *Synedra* species however, especially *S. acus* v. *acus*, which is dated to begin in the early 1970s, similar to the increase observed in BAIK38.

Dating of BAIK25 reveals that not only is this core undisturbed, but that it also has the lowest accumulation rate of all the cores used in this study (table 3). Like the intact cores collected from the southern basin, the uppermost sediments display decreasing numbers of *C. minuta* as populations of *Aulacoseira* species increase, especially *A. baicalensis*, during the latter half of the nineteenth century. However, because this core has a slower accumulation rate than the other cores collected, it also exhibits stratigraphical changes not seen in any of the other cores. It is immediately apparent, that, at this site at least, *C. minuta* has not always been the dominant species in relatively recent years. BAIK25 shows that the diatom population in Baikal has been extremely dynamic over the last 1000 years or so: previous to *C. minuta*, *S.* cf. *parvus* was the dominant species for a

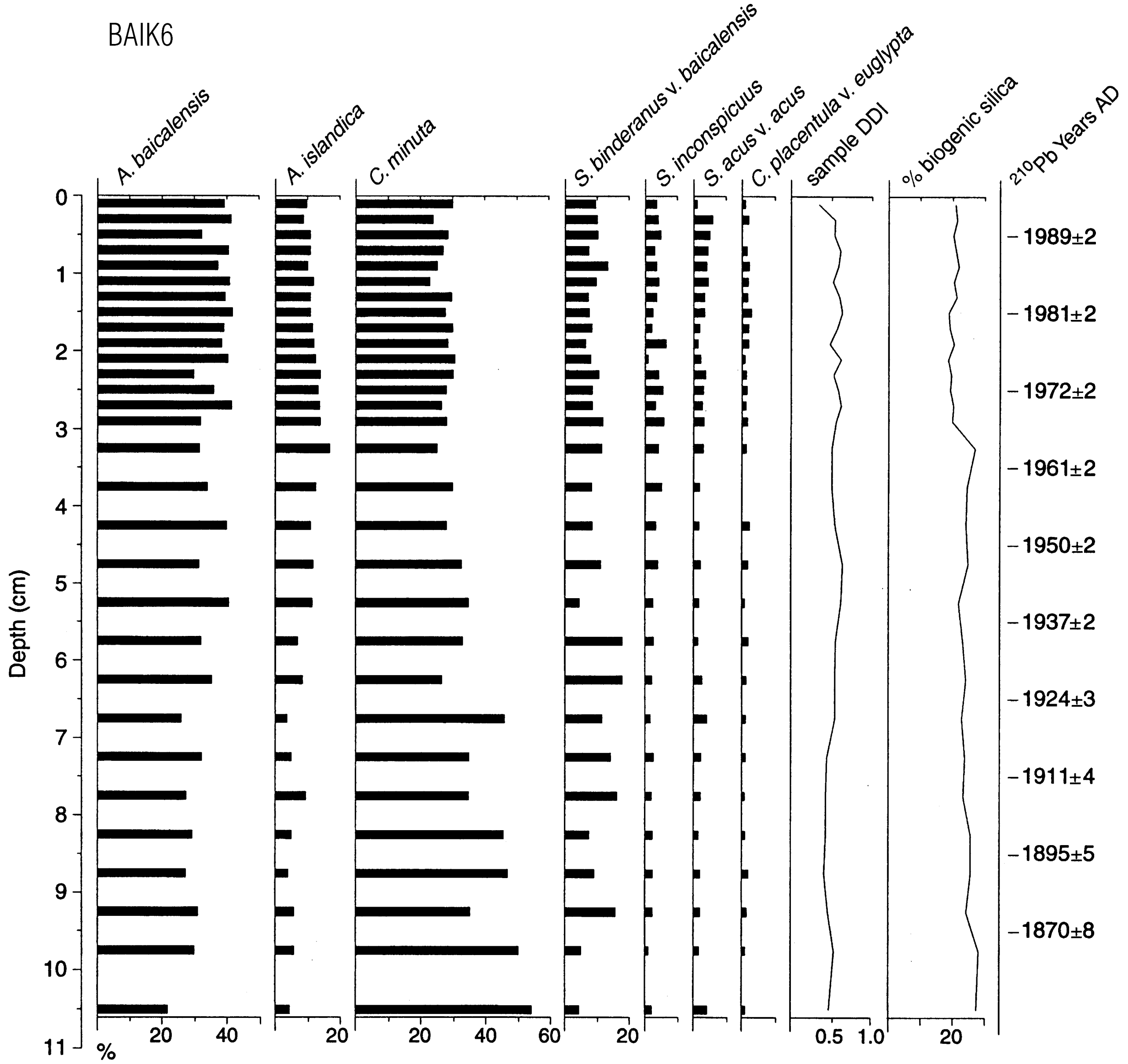


Figure 5. Composite diatom diagram for BAIK6, taken from near the mouth of the River Angara in the south basin. Diatom species $\geqslant 1\%$ are plotted against depth of sediment. Sample DDIs (see text for details) and per cent biogenic silica are also plotted against depth. ^{210}Pb dates are plotted down the right-hand side of the diagram.

short period of time, which itself had superseded *S. acus* v. *acus* as the dominant taxa. The taxonomy of *S.* cf. *parvus* in this core is currently under further investigation by the principal author.

North basin

The diatom stratigraphies of the four cores taken from the north basin are all very similar (i.e. BAIK29 (figure 9) and BAIK27, 30 and 32 (Appendix 1): *A. baicalensis* has been the dominant species up until the mid-nineteenth century (table 4). Before then, in common with cores taken from the south basin and the Academician Ridge, *C. minuta* used to predominate. However, unlike cores taken from the south basin, when this switch occurs, there are only small increases in *A. islandica*, *S. binderanus* v. *baicalensis* and *S. acus* v. *acus*.

The longer cores, such as BAIK30 exhibit increases in certain taxa that occurred before *C. minuta* was the dominant species, e.g. *S. acus* v. *acus*. These are similar to increases exhibited in BAIK25, and some long cores taken from the south basin, such as BAIK38. One core however, BAIK27 is somewhat different from the other three: over the last 140 years, *A. baicalensis* was by far the dominant species and accounted for almost 80% of total taxa counted. Consequently, *C. minuta* has only been present recently in small numbers at this site. Further, benthic taxa, such as *F. pinnata* v. *pinnata* were also common before *A. baicalensis* started to predominate.

Shallow waters around the Selenga region

The four cores taken from the shallow waters surrounding the Selenga Delta, including the dated core BAIK19 from Buguldieka Saddle (figure 6) are all somewhat different from each other, although they do exhibit some similar trends. BAIK17 (figure 11) has consistently low levels of *A. baicalensis* and *C. minuta*. Other species characteristic of shallower waters, such as *A. islandica*,

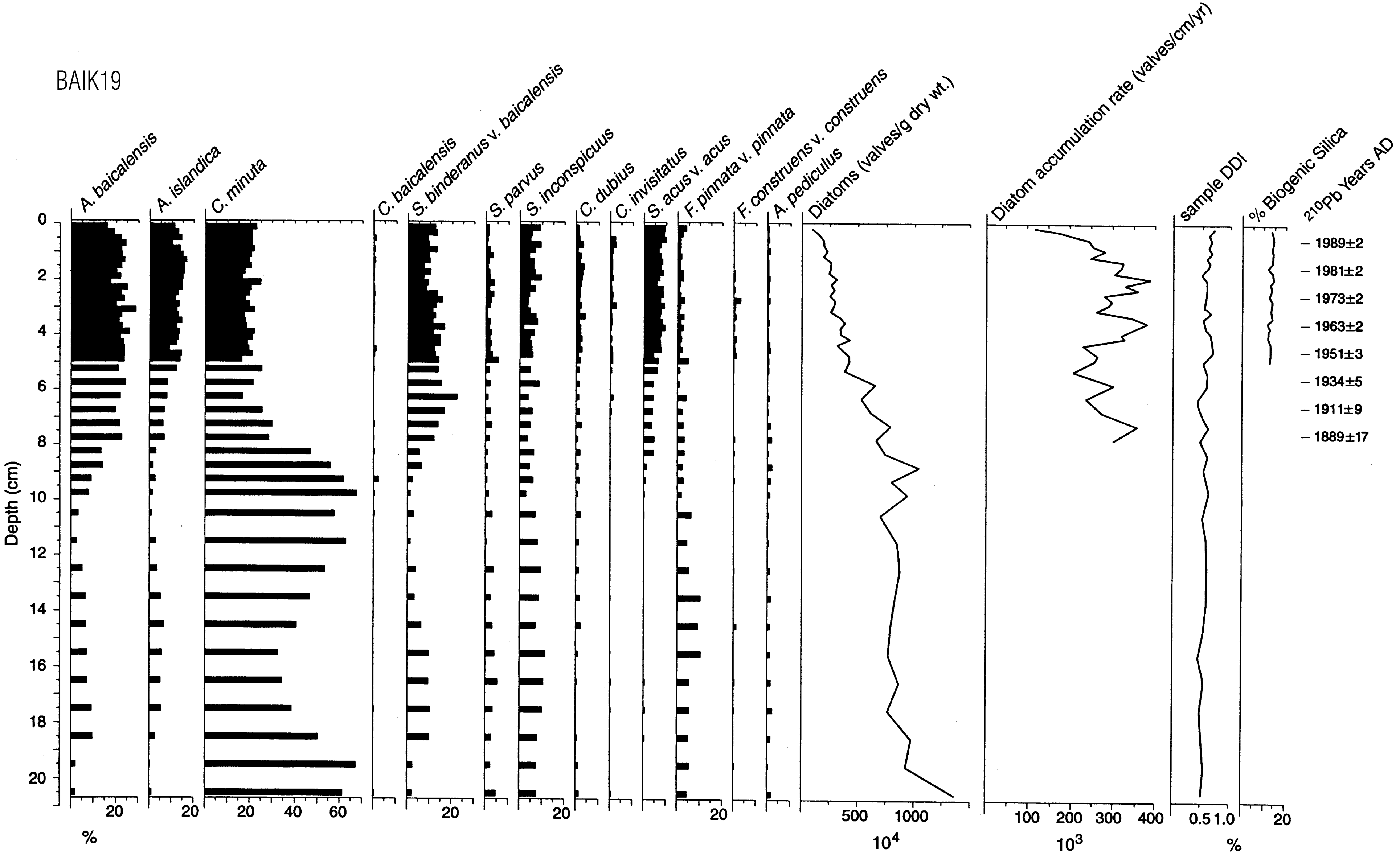


Figure 6. Composite diatom diagram for BAIK19, taken from the Buguldieka Saddle, opposite the shallow waters near the Selenga Delta. Diatom species ⩾1% are plotted against depth of sediment. Diatom concentrations (valves g^{-1} DW), diatom accumulation rates (valves cm^{-1} yr^{-1}), sample DDIs (see text for details) and per cent biogenic silica are also plotted against depth. ^{210}Pb dates are plotted down the right-hand side of the diagram.

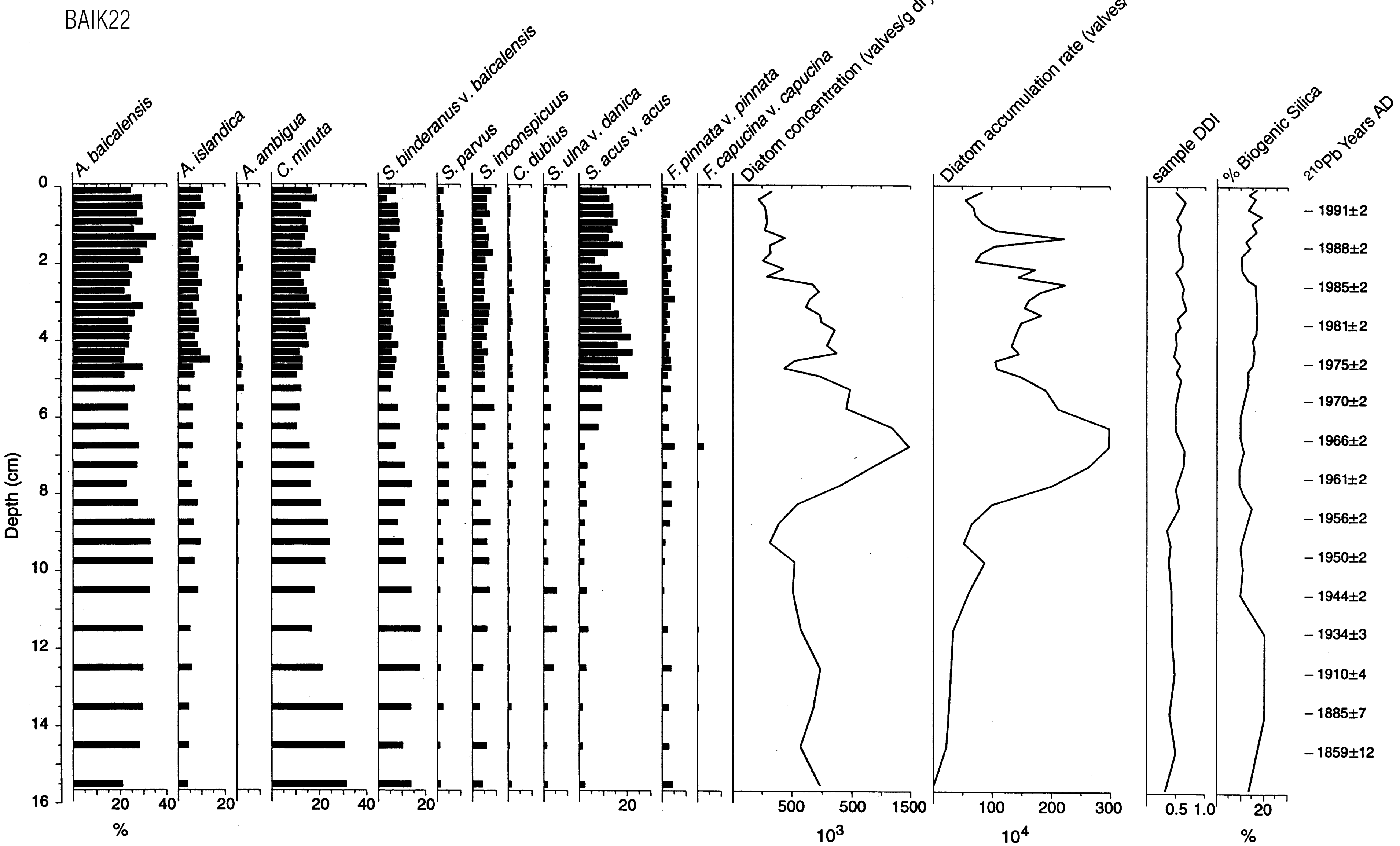


Figure 7. Composite diatom diagram for BAIK22, taken from the middle basin. Diatom species ⩾1% are plotted against depth of sediment. Diatom concentrations (valves g^{-1} DW), diatom accumulation rates (valves cm^{-1} yr^{-1}), sample DDIs (see text for details) and per cent biogenic silica are also plotted against depth. ^{210}Pb dates are plotted down the right-hand side of the diagram.

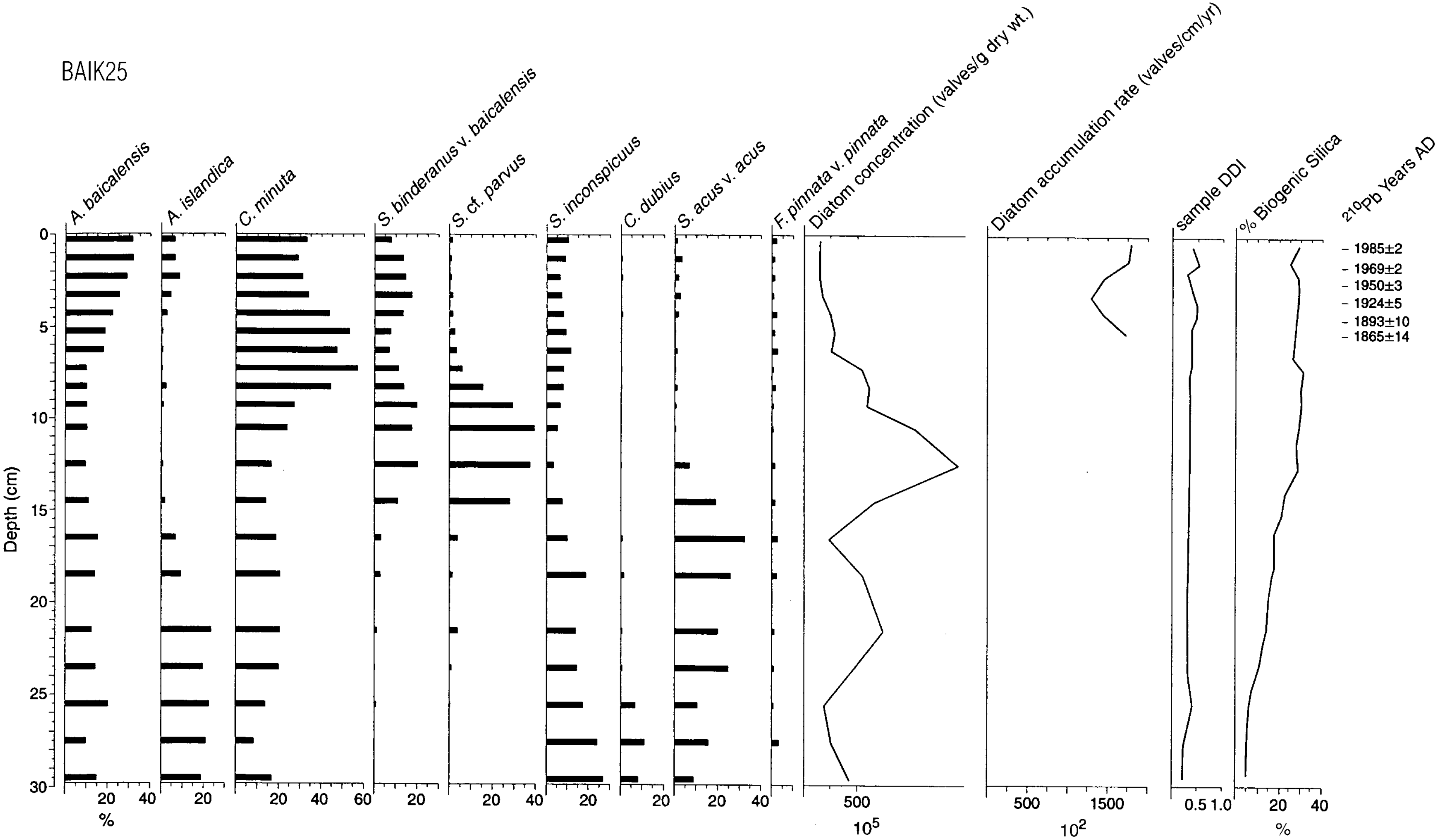


Figure 8. Composite diatom diagram for BAIK25, taken from the Academician Ridge, between the middle and north basins. Diatom species ⩾1% are plotted against depth of sediment. Diatom concentrations (valves g^{-1} DW), diatom accumulation rates (valves cm^{-1} yr^{-1}), sample DDIs (see text for details) and per cent biogenic silica are also plotted against depth. ^{210}Pb dates are plotted down the right-hand side of the diagram.

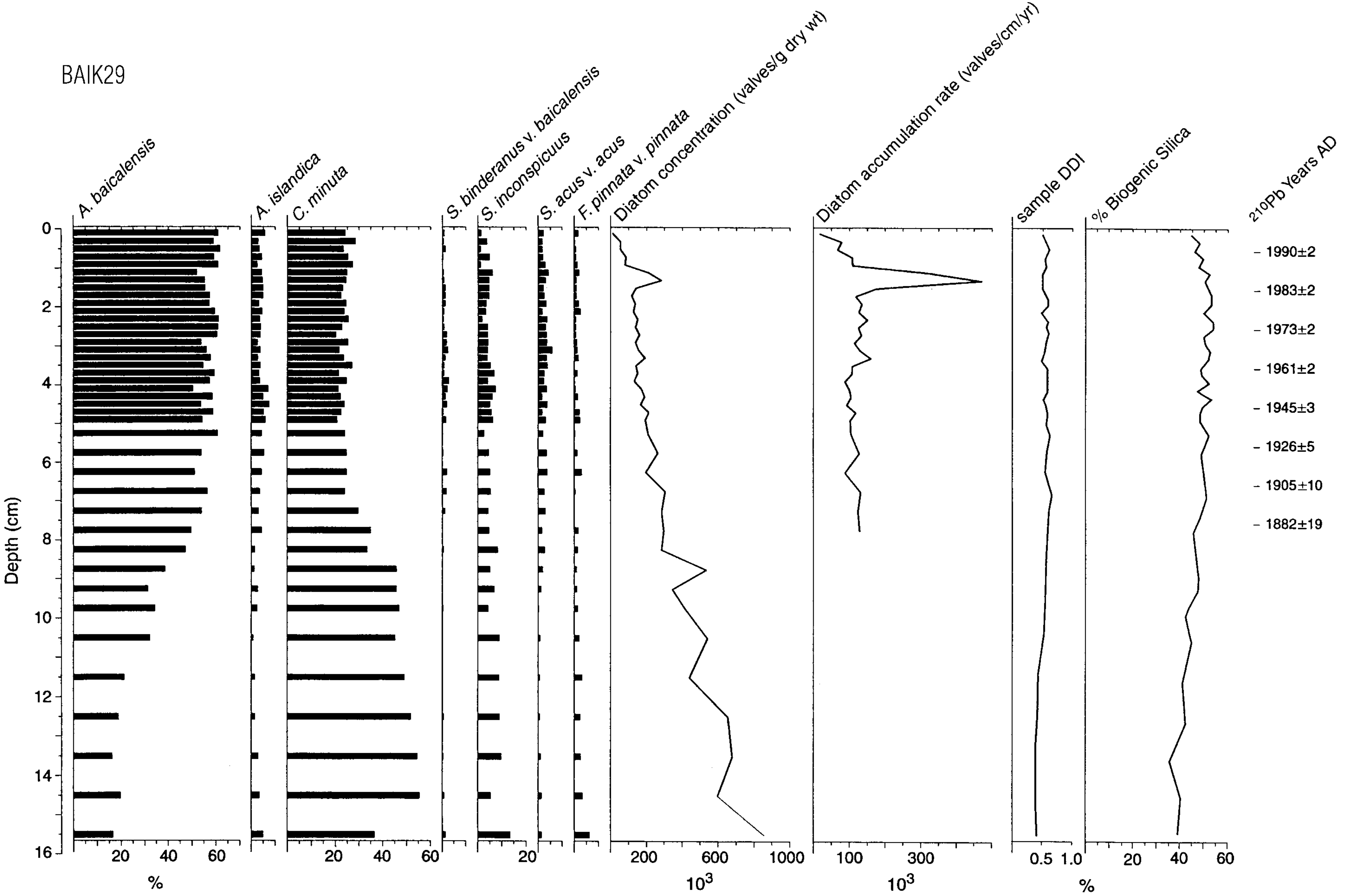


Figure 9. Composite diatom diagram for BAIK29, taken from the north basin. Diatom species ⩾1% are plotted against depth of sediment. Diatom concentrations (valves g^{-1} DW), diatom accumulation rates (valves cm^{-1} yr^{-1}), sample DDIs (see text for details) and per cent biogenic silica are also plotted against depth. ^{210}Pb dates are plotted down the right-hand side of the diagram.

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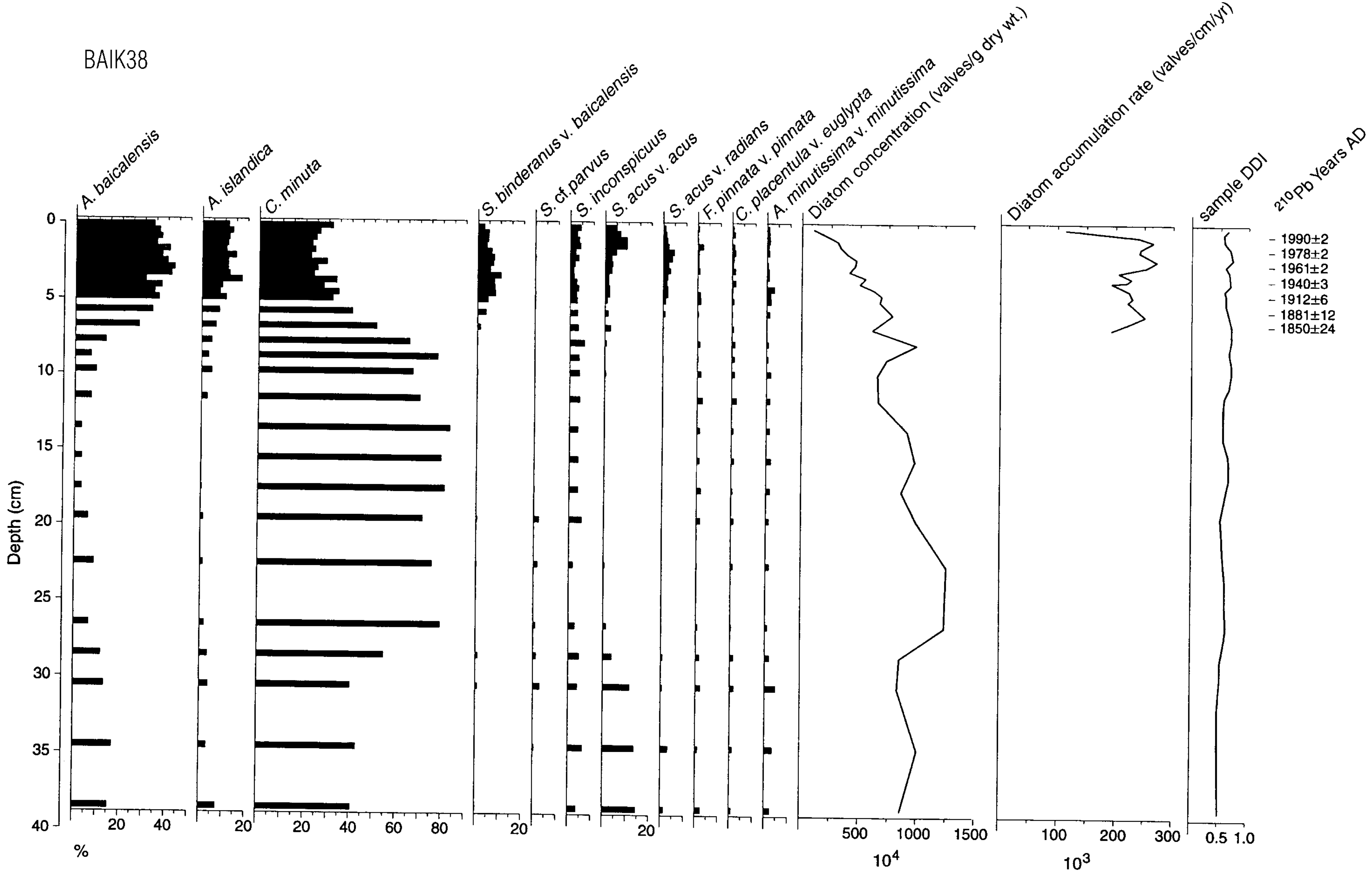

Figure 10. Composite diatom diagram for BAIK38, taken from a shoulder in the south basin, near to the Baikalsk paper and pulp mill. Diatom species ⩾1% are plotted against depth of sediment. Diatom concentrations (valves g^{-1} DW), diatom accumulation rates (valves cm^{-1} yr^{-1}) and sample DDIs (see text for details) are also plotted against depth. ^{210}Pb dates are plotted down the right-hand side of the diagram.

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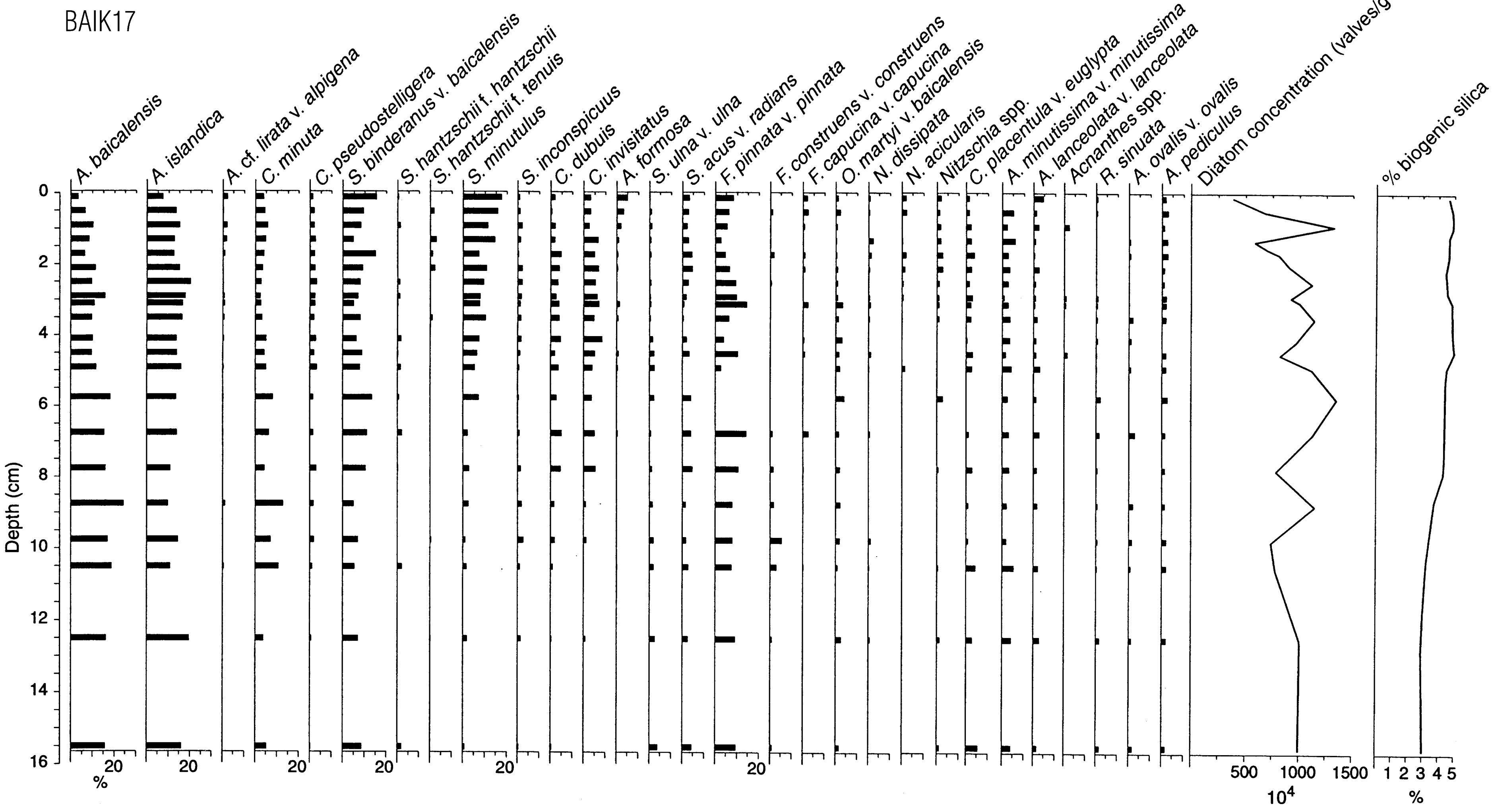


Figure 11. Composite diatom diagram for BAIK17, taken from the shallow waters near the Selenga Delta. Diatom species ⩾1% are plotted against depth of sediment. Diatom concentrations of (valves g^{-1} DW) and per cent biogenic silica are also plotted against depth.

S. binderanus v. *baicalensis* and *F. pinnata* are common throughout the core. Species more characteristic of eutrophic waters, such as *Stephanodiscus minutulus* (Ktz.) Cl. & Möll. and *Cyclostephanos invisitatus* (Hohn & Hellermann) Theriot, also increase in numbers towards the top of the core. There are more benthic taxa in this core than in any of the deepwater cores. The stratigraphy of BAIK18 (Appendix 1) exhibits a decrease in *C. minuta* at the bottom of the core, with concomitant increases in *A. baicalensis*, but especially *S. binderanus* v. *baicalensis* and *A. islandica*, a somewhat different biological response than shown in the cores taken from the south and north basins. There are somewhat fewer benthic taxa in BAIK18 than in BAIK17. BAIK19 (figure 6) is similar to cores taken from both the south and north basins in terms of recent *A. baicalensis* dominance, preceded by a period dominated by *C. minuta*. As *A. baicalensis* becomes more dominant during the mid-to-late nineteenth century, there are also concomitant increases in other species, such as *A. islandica*, *S. binderanus* v. *baicalensis* and *S. acus* v. *acus*. The *C. minuta* profile shown in BAIK19 is very similar to BAIK37, exhibiting a bimodal response. The profile taken from BAIK16 (Appendix 1) is unusual in that no diatoms are to be found below 7 cm. This is coincident with high %DW values, which may represent a turbidite in wash (see § 4).

Distributions of certain taxa in the surface sediments suggest that they are most abundant in cores from the Selenga region and lowest in cores taken from the northern basin (see, for example, figure 12). Other taxa commonly found in the Selenga region today include *F. pinnata* and *Cyclostephanos dubius* (Fricke) Round (see figure 13).

Timing of the switch between A. baicalensis *and* C. minuta

In many of the dated cores, this switch in species occurs immediately below the limit for ^{210}Pb dating; ^{210}Pb dates have therefore been extrapolated back to cover the depths at which these changes in dominance occur (table 4). For BAIK6, BAIK19, BAIK25 and BAIK29 these changes occur between *ca.* AD 1860 and AD 1885. Taking into account the errors associated with these measurements, it is probable that that the switch from *C. minuta* dominance to *A. baicalensis* dominance occurred simultaneously across the lake during the mid-to late nineteenth century. Using this assumption, a combined diagram of PCA axis 1 scores has been plotted for all the cores analysed in this study (figure 14). Switches in *Cyclotella* dominance to *Aulacoseira* dominance in all the cores (apart from BAIK17) are reflected in these axis 1 scores, and have been stratigraphically linked.

(ii) *Diatom concentrations in the dated cores*

Diatom concentrations (figures 6–11) show considerable variation and ranges, both within and between cores, e.g. from *ca.* 1.24×10^5 valves in the most recent sediments in BAIK29 to over 2.8×10^7 valves in BAIK25. In general, however, concentrations throughout Baikal have tended to decrease recently, especially as *A. baicalensis* increases in dominance. Diatom accumulation rates, which take account of sediment accumulation rates, may provide a more complete picture of the changing diatom populations because, despite recent decreases in concentrations in most of the cores analysed, diatom accumulation rates have remained reasonably constant until the most recently deposited sediments, where, in almost every core, accumulation rates decline. Diatom accumulation rates in the Selenga region (*ca.* 250 000 valves cm^{-2} yr^{-1}) and the southern basin (*ca.* 200 000 valves cm^{-2} yr^{-1}) are approximately twice those in the northern basin (*ca.* 100 000 valves cm^{-2} yr^{-1}) and the Academician Ridge (150 000 valves cm^{-2} yr^{-1}). However, rates in the sediment in BAIK22 exhibit a somewhat different pattern: low down in the core, they are similar to those found in the southern basin but reach almost 3×10^6 valves cm^{-2} yr^{-1}, greater than a factor of ten more, during the period of inferred disruption to the sediment column (as inferred from the dating analyses detailed here). There is a notable peak in concentration of diatoms in BAIK25 between 8 and 16 cm depth, coinciding with a high numbers of *S.* cf. *parvus*.

Table 4. *Dates extrapolated back from* ^{210}*Pb analyses to record the decline of* C. minuta *dominance*

site	extrapolated ^{210}Pb date (AD years)
BAIK6	1870
BAIK19	1878
BAIK22	1833
BAIK25	1884
BAIK29	1860
BAIK38	1810

(iii) *Dissolution indices*

In each of the composite profiles, sample dissolution indices have remained more or less constant for each of the cores through time at *ca.* 0.5, demonstrating that approximately 50% of diatom valves are affected to some extent by dissolution.

(iv) *Biogenic silica*

Biogenic silica values are generally between 10 and 25%, with little change down core profiles, except in BAIK25, where silica values have gradually increased from less than 5% at the base of the core, to values of *ca.* 30% at the top (figures 5–11). Biogenic silica values are generally higher in the northern basin, e.g. BAIK29, of between 40 and 50%, whereas they are very low for cores in the shallow waters close to the Selenga region, e.g. BAIK17, between 3 and 5%.

(iv) *Numerical analyses*

Trends in the diatom assemblages in the dated cores are also assessed from redundancy analyses by using time as a single constraining variable. Further estimates of species turnover for all the sites have been derived from the gradient of the first axis during DCA (table 5). Time itself is significant in explaining changes in the diatom assemblages in cores BAIK6, BAIK19 and BAIK22. However, time was not significant in explaining changes from BAIK25, BAIK29 and BAIK38. This may in part be attributable to the low accumulation rates, at least for BAIK25 and BAIK38 (Anderson 1990; Allott *et al.* 1992). Turnover for all the sites is low, with no core exhibiting complete assemblage replacement: a gradient of 4 s.d. units or more would suggest that samples at opposite ends of rescaled axes will have few species in common (Hill & Gauch 1980). Longer cores, such as BAIK25 and BAIK38, show that there have been several dynamic changes in the diatom flora throughout the recent history of Lake Baikal, and this is reflected in the longer DCA axis 1 gradients (table 5) (Allott *et al.* 1992).

DCA analyses of the combined data set gave an axis 1 gradient of 1.748, and so the data were subjected to PCA (figure 15). The biplot shows that BAIK17 is a clear outlier from all the other cores. However, because there are so many samples in the biplot, further runs of PCA, omitting samples from BAIK17 do not clearly show the spatial distribution of the cores.

Separation of different cores was tried using ordination analyses on surface sediments only. Principal components analyses of all 20 sites also splits of BAIK17 (figure 16*a*). Cores from the north-basin group together (BAIK27, BAIK29, BAIK30 and BAIK32), as do those from the shallow waters close to the Selenga Delta and middle basin (except for BAIK24 & BAIK25). A further PCA, omitting samples from BAIK17 further separates cores from the shallow waters close to the Selenga Delta (BAIK16 and BAIK18) from the other sites (figure 16*b*) and allows closer grouping of other cores according to which basin they came from.

(d) *Trace metal analyses*

The results of the chemical analyses of selected metals (Pb, Cu and Zn) are shown in the form of age–depth profiles (figure 17). Concentrations in p.p.m. tend to increase for all three metals towards the upper sediment layers of each core. The profiles clearly distinguish the stratigraphic patterns of Cu and Zn from Pb. Pb profiles show similar increases in concentration between cores, whereas the Zn and Cu profiles, although similar to each other, exhibit considerable between core variation in shape. Profiles of Mn and Fe are also shown (figure 18), reflecting metal cycling within the oxidized surface sediments as described in Leibovich (1983) and Flower *et al.* (1995*a*). Mn and Fe enrichment occurs down to 30 cm in BAIK25.

PCA biplots of each core, showing diatom species and regressed metal concentrations, are shown in figure 19. Alternate samples and species with small vectors have been hidden from each plot to aid clarity and interpretation of main trends in the results. The direction of each arrow, or vector, shows the direction of most abundant change (ter Braak 1995). It follows, therefore, that diatom species such as *A. baicalensis* are associated with samples towards the top of each core, whereas species such as *C. minuta* are more closely associated with samples lower down. In most of the cores, trace metals are generally associated with sediment samples in upper layers of the six cores: notable exceptions include Mn, Cu, Zn and Fe in BAIK25, Fe and Cu in BAIK29 and Zn, Cu and Fe in BAIK38. The angle between vectors gives a measure of the degree of correlation between metals, e.g. metals separated by a perpendicular angle show little correlation, whereas those at 180° exhibit negative correlation (ter Braak 1995). There is no obvious pattern between the metals in figure 19, i.e. none of the metals exhibit collinearity, apart from metals that appear to be more correlated to each in other in BAIK6 and BAIK19.

Table 5. *Results from redundancy analyses of the dated portions of cores using time as a single constraining variable, mean sediment accumulation rates from table 3 and estimates of species turnover*

(*n* is the number of samples used in the redundancy analyses, *p* is probability using 99 permutations.)

site	*n*	*p*	mean sedimentation rate mm yr^{-1}	turnover (s.d. units)
BAIK6	30	0.01	0.79	0.703
BAIK19	31	0.01	0.66	0.998
BAIK22	40	0.01	1.76	0.820
BAIK25	6	0.16	0.38	1.495
BAIK29	31	0.27	0.75	0.964
BAIK38	15	0.04	0.52	1.368
BAIK17	n.a.	n.a.	n.a.	0.984

Forward selection of the metals reveals that Pb significantly explains most of the variation in the metals in three of the cores: BAIK6, BAIK19 and BAIK22; this is also evident from the biplots, which shows Pb as having the longest vector in each of these cores.

(e) *SCP analyses*

Spheroidal carbonaceous particle (SCP) flux profiles for the six dated cores are shown in figure 20. These profiles exhibit three notable features: (i) SCPs are present in some of the cores as far back as the mid-nineteenth century; (ii) accumulation rates increase over the last couple of decades; and (iii) SCPs are detected throughout the length of the lake. In half of the profiles, SCPs are first detected in the early to mid-1900s, except for cores in the middle of the lake, where detection is much later, and in BAIK38, where particles are detected as far back as the mid-nineteenth century. Concentrations in all cores are initially low and tend to increase after *ca.* 1960. This is not the case for BAIK22 and BAIK29, where increases in SCPs occur post-1980. One other feature to note in these profiles is that there is an apparent accumulation rate decrease in half of the cores, within the last five years: BAIK19, BAIK22 and BAIK38. Highest surface accumulation rate values are found in BAIK6 (67 cm^{-2} yr^{-1}; table 6) and tend to decrease away from Irkutsk, and industrial regions in general, towards the north of the lake. The lowest accumulation rate is for BAIK25 (5.7 cm^{-2} yr^{-1}) but accumulation rates for BAIK22 to the south of BAIK25 and BAIK19 to the north are similar at 16 cm^{-2} yr^{-1} and 14 cm^{-2} yr^{-1}, respectively.

4. DISCUSSION

(a) *Collection of intact sediment cores*

This project has focused on the sedimentary record of recent changes in the surface sediment deposited in the past 100–150 years. As such, a fundamental requirement is the need to collect cores with undisturbed sediment–water interfaces. It is difficult to collect such cores, routinely, from depths of 1000–1600 m. Numerous other studies have experienced the shortfalls of using standard gravity and piston corers (see, for example, Colman *et al.*

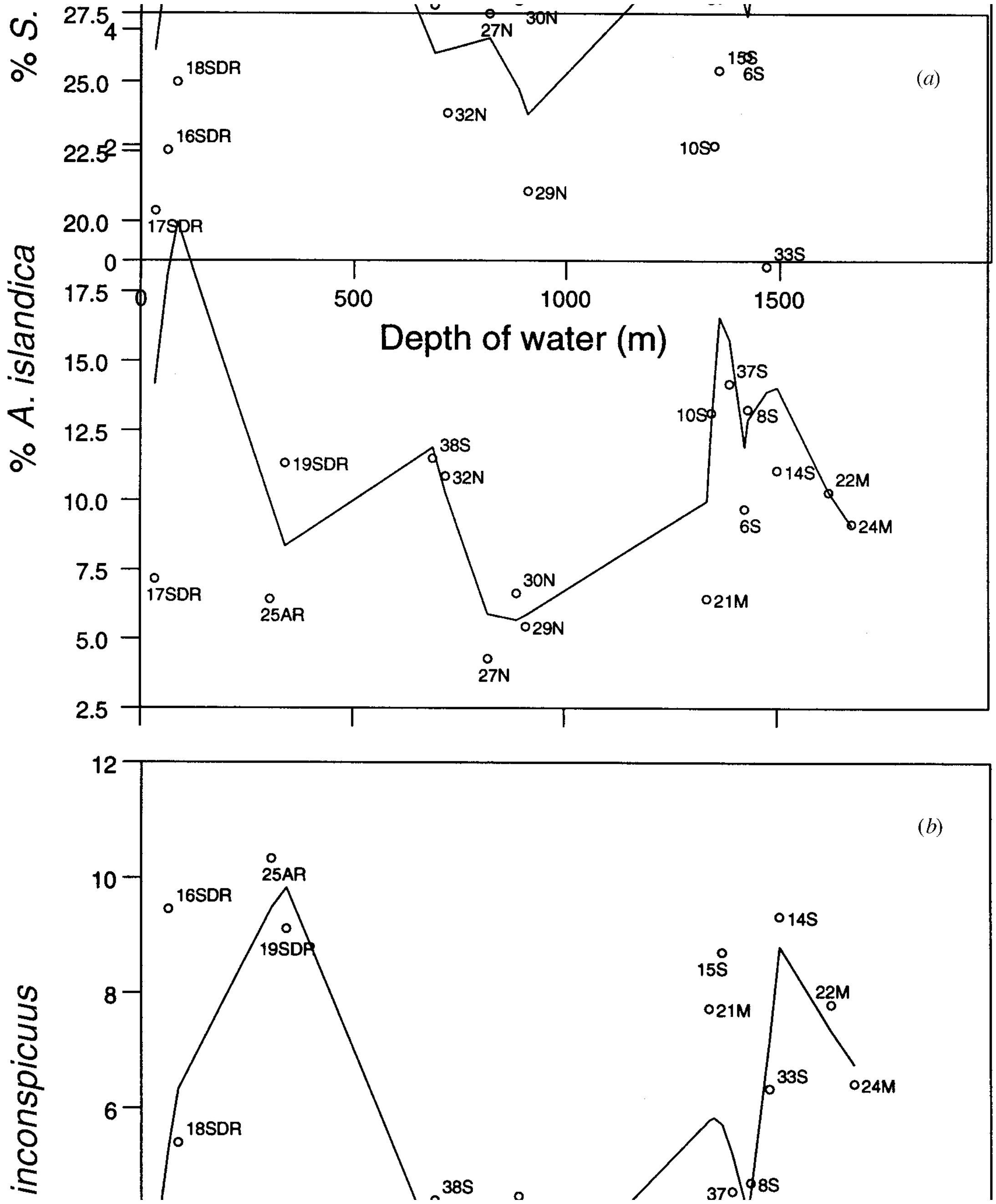


Figure 12. Composite diagram showing LOWESS curves drawn through selected centric taxa, plotted against water depth (see text for details). Core details are summarized as follows, e.g. 6 becomes 6S, where S is south basin; 22 becomes 22M where M is middle basin; 29 becomes 29N, where N is north basin; 25 becomes 25AR where AR is Academician Ridge and 17 becomes 17SDR where SDR is Selenga Delta region etc.

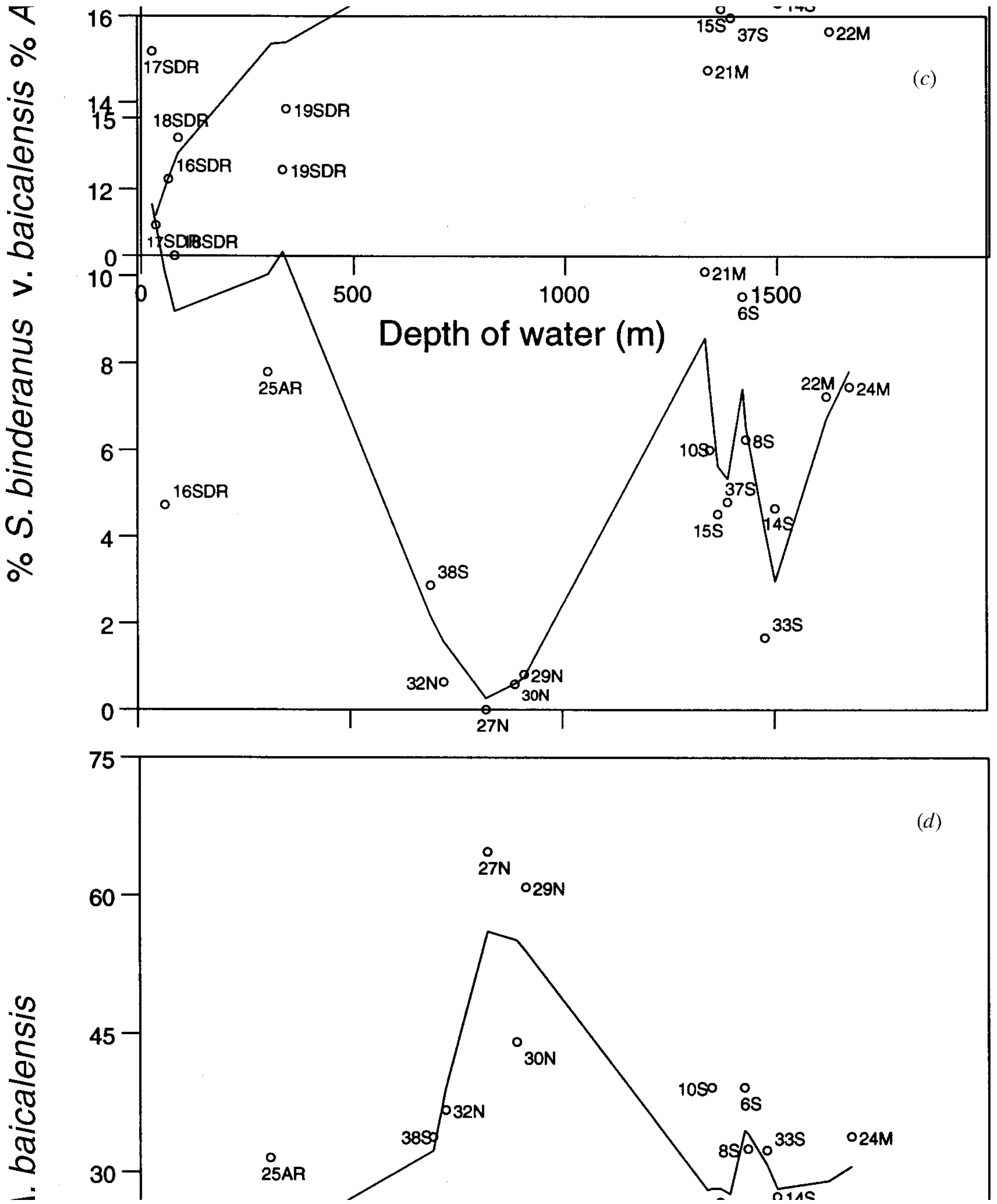


Figure 12. (*Cont.*)

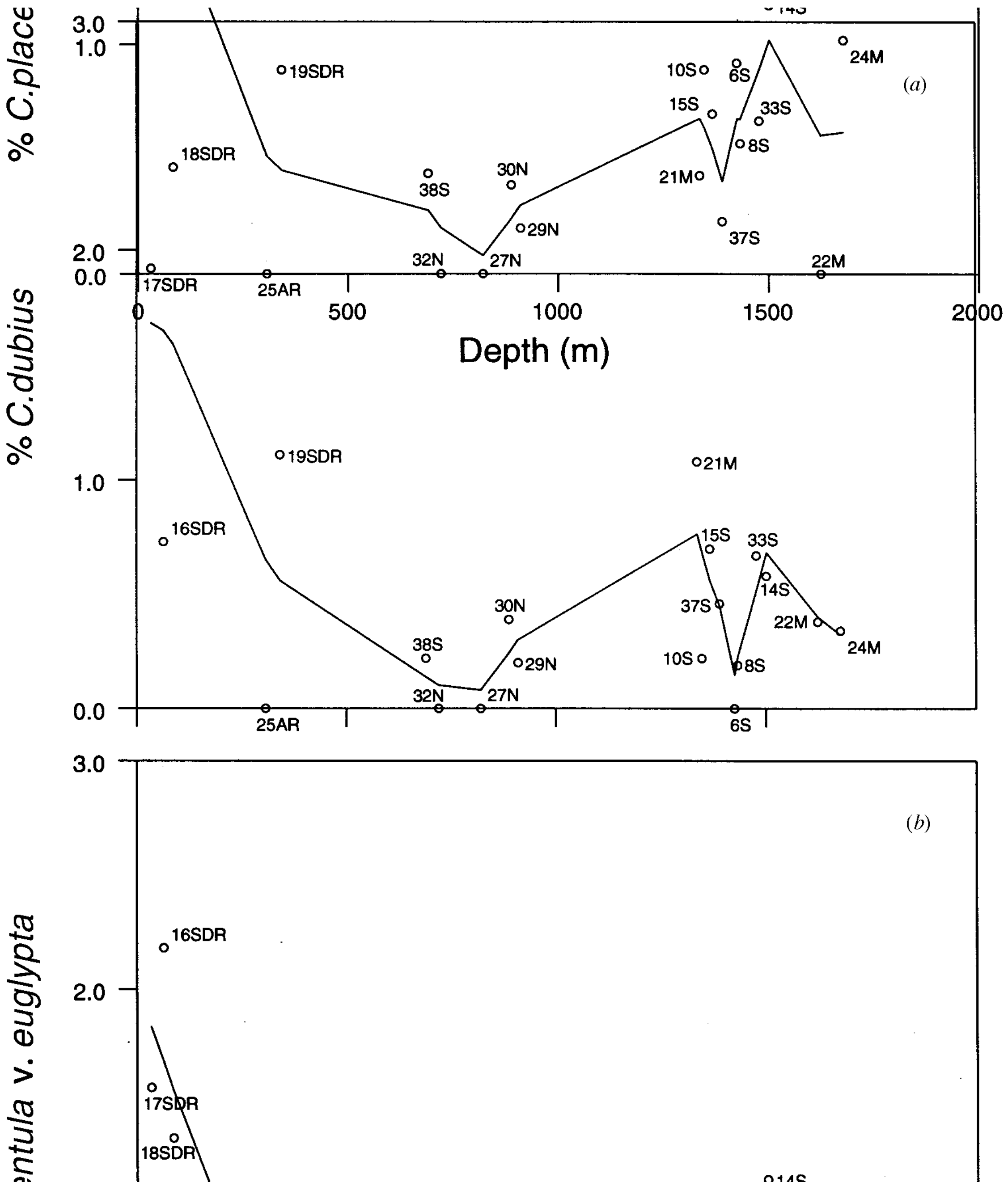


Figure 13. Composite diagram showing LOWESS curves drawn through selected taxa, plotted against water depth (see text for details). Core details are summarized as follows, e.g. 6 becomes 6S, where S is south basin; 22 becomes 22M where M is middle basin; 29 becomes 29N, where N is north basin; 25 becomes 25AR where AR is Academician Ridge and 17 becomes 17SDR where SDR is Selenga Delta region etc.

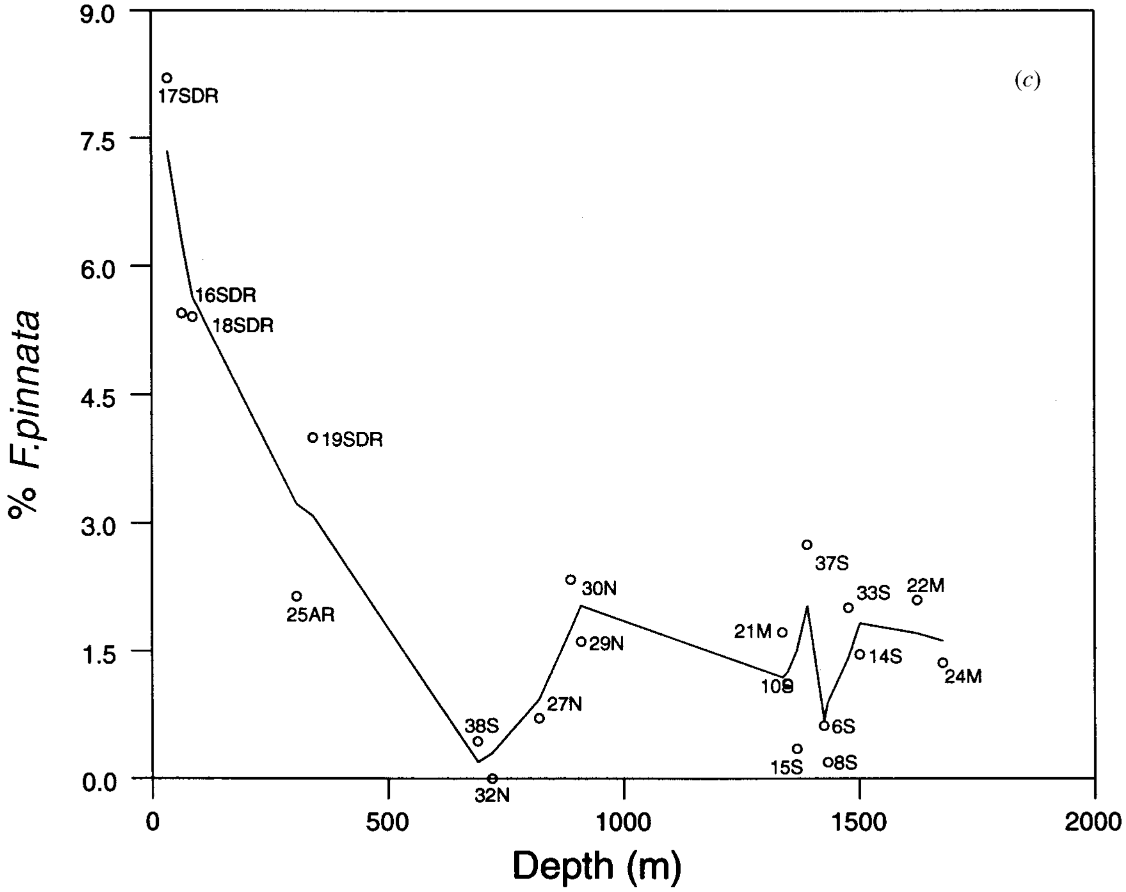


Figure 13. (*Cont.*)

1993; Bradbury *et al.* 1994). Conventional box corers previously used on Lake Baikal often lose the upper surface sediment through leakage (E. Karabanov, personal communication). A new type of box corer was developed especially for use on deepwater lakes (specifically Lake Baikal) that would collect cores with intact surface sediment–water interfaces (Flower *et al.* 1995*b*). The integrity of these cores, as far as collecting an intact stratigaphical profile is concerned, has been confirmed by ^{137}Cs and ^{210}Pb analyses and matching lithostratigraphic profiles (Flower *et al.* 1995*b*; Mackay *et al.* 1996; Appleby *et al.* 1998). However, all the cores collected exhibited brown oxic layers within the ranges found for the box core profiles and therefore we are confident that the stratigraphical changes are representative of real changes that have occurred within the lake and its catchment, and are not affected by procedural artefacts.

(b) *Sediment accumulation anomalies, especially turbidites*

This study, and that of Edgington *et al.* (1991), confirms the regionality of sediment accumulation patterns within Baikal. Shallow waters close to the Selenga Delta (e.g. BAIK19; figure 6) have higher sediment accumulation rates than those of the deep bottom (e.g. BAIK29; figure 9), whereas cores taken from ridges or slopes have lower accumulation rates (e.g. BAIK25; figure 4). These sites also exhibit a low ^{210}Pb inventory (table 2), which may reflect sediment erosion from these environments. However, one core, BAIK22, has a particularly unusual sedimentary profile with several non-monotonic features, extending down to 11.5 cm. This very rapid sedimentation zone is most probably due to turbidity currents.

Turbidites are main suppliers of sediment to lake basins (see, for example, Span *et al.* 1992) and their occurrences in Baikal are well-known (Knyazeva 1954; Goldryev & Vykhristyuk 1968; Goldryev 1977; Karabanov & Fialkov 1987; Nelson *et al.* 1995). In large lakes, such as Baikal, two forms of turbidite are common: (i) those that are fluvial in origin, perhaps arising from increased river input (see, for example, Lambert & Giovanoli 1988); and (ii) those that are caused by the slumping of unconsolidated sediments from river deltas (Gilbert 1975), or slopes, and by earthquakes (Giovanoli 1990). Turbidites disturb the normal stratification of the sediments and this must be considered when reconstructing the palaeogeographical conditions of the lake. For example, while moving along the bottom of the lake, suspension flows erode the upper sedimentary layer, which then becomes included into the flow.

Some of the cores collected in this study have probably been affected by turbidites to a greater or lesser degree and it is important to emphasize that those profiles cease to be a record of ecosystem change within the lake and its catchment. Therefore, it is important to be able to identify affected profiles to gain a better understanding of sediment accumulation processes and to gain a more accurate environmental reconstruction history of the lake.

Depending on the causal agent, turbidites have different features (mainly thickness and composition)

Table 6. *Surface sediment SCP flux measurements* ($g\,cm^{-2}\,yr^{-1}$)

site	SCP flux ($g\,cm^{-2}\,yr^{-1}$)
BAIK6	67
BAIK19	30.4
BAIK22	16
BAIK25	5.7
BAIK29	14
BAIK38	47.1

(Karabanov & Fialkov 1987). In Baikal, turbidite layers vary from a few centimetres to several tens of centimetres thick and usually consist of two elements: very fine sand or coarse alevrite towards the bottom and peltite mud in the upper part of the turbidite (Goldyrev 1977; Karabanov & Fialkov 1987). Karabanov & Fialkov (1987) call these layers turbidite rhythms, and they have detected up to 8–10 rhythms in the upper 1 m of surface sediment. Typically, turbidites are usually characterized by lowered concentrations of diatoms and biogenic silica (see, for example, Karabanov *et al*. 1992; Granina *et al*. 1992, 1993*a*), however, the turbidites found in BAIK22 are diatom rich, and are therefore unlikely to have come from the clastic rich sediments of the Selenga Delta. It is more probable that these turbidites have been derived from sediment slumping on the steeply shelving sides of the basin. Furthermore, they also contribute to the ^{210}Pb in these zones, and so are likely to have been derived from recently deposited sediments. These turbidites could account for the unusual increases in diatom concentration and diatom accumulation rate profiles in figure 7, which are mirrored by increases in %DW (figure 2). Extending these inferences, the sharp increase in diatom accumulation rate and %DW at 1.3 cm in BAIK29 may be due also to a small turbidite, of which there is other confirmatory evidence in the form of lesser non-monotonic features in the ^{210}Pb record (Appleby *et al*. 1998).

Radiometric dating can thus reveal where turbidites may be present, but dating is expensive and it is thus impractical to do radiometric analyses on every core. However, as we saw above, %DW profiles may also give an indication of where turbidites may be present, especially where values are in excess of 50%: e.g. the two peaks in BAIK14 and peaks in BAIK30 may represent disturbances (figure 2). A more complex example involves the bimodal distribution of *C. minuta* in BAIK19, which is very similar to that found for BAIK37 (see Appendix 1): a temporary decrease in *Cyclotella* is accompanied by increases in shallow-water taxa such as *F. pinnata*, *S. binderanus* v. *baicalensis* and *S. parvus*. Unfortunately, these changes in species composition are below the dated portion of the core but the %DW profile for BAIK37 (figure 2) would suggest an input of non-local sediment at this time. However, this is not accompanied by an increase in diatom concentration. A reasonable explanation may be that this period represents an input of clastic rich sediment (see, for example, Gilbert 1975) from the Selenga Delta, carrying with it diatoms more commonly found there, for example, benthic taxa such as *F. pinnata* (see figure 13). The bimodal *Cyclotella* profile found at BAIK19 is unlikely, therefore, to be a response to changes in water quality but more a reflection of complex sedimentary processes within the lake.

Another core with an unusual diatom profile, BAIK16 (Appendix 1), was taken from a region between the shallow waters of the Selenga region and the south basin. It has only a very short diatom profile, with no diatoms present below 6.5 cm and probably represents sediment slumping from the Selenga Delta region (see, for example, Gilbert 1975; Giovanoli 1990). Other studies (for examples, see Loginova & Khursevich 1990; Bradbury *et al*.1994) also document zones in Baikal sediments with very few diatoms and conclude that these zones are biostratigraphically important, representing periods of different prevailing environmental conditions. However, the possibility that these zones may reflect the presence of turbidites appears not be taken into consideration. A critical examination of stratigraphical profiles of other studies, e.g. by Chernyaeva (1970), may also reveal the presence of turbidites, but once again they are not considered. Inferences based solely on the presence and absence of diatoms, with no discussion of turbidites, may result in erroneous conclusions regarding historic ecosystem and climatic changes in the Baikal region. A summary of types of turbidites found in this study is given in table 7, but fortunately the integrity of most of the cores collected in this study appear to be intact and we can identify those which may have been affected by secondary processes.

Turbidites may also be recognized by mineral magnetic analyses of sedimentary profiles. However, although these analyses are not covered in this paper, they do form the basis of a series of papers currently in press (Dearing *et al*. 1998; Lees *et al*. 1998*a*,*b*), and of a recent UK Natural Environment Research Council award (GR3–10529) to the ECRC.

(c) *Recent diatom trends in Lake Baikal*

(i) *Temporal trends in the diatom data*

It is immediately apparent that the pelagic diatom stratigraphy of Lake Baikal is dynamic and that many taxa which are important components of the contemporary flora were present in the lake in much smaller abundances from as little as 200 years ago (e.g. *A. baicalensis*, *A. islandica*, *S. binderanus* v. *baicalensis* and *S. acus* v. *acus*). Therefore, the discussion of the diatom history in Baikal will principally focus on the nature of these historical changes, their timing and whether they are represented across the whole lake. We will then go onto discuss some of the longer-term changes exhibited by the diatom record in many of the cores, and finally we assess to what extent external factors, such as pollution and climate change, have had on the floristic history of the lake.

However, before any attempts at environmental reconstruction are made, it is necessary to consider what effects taphonomic processes, especially dissolution, may have on the sedimentary record. Sample dissolution values of *A. baicalensis* and *C. minuta* remain stable down each core at *ca*. 0.5, which would suggest that preferential dissolution of these two species within the sedimentary column is not a contributing factor to selective species loss. Species loss owing to dissolution processes may,

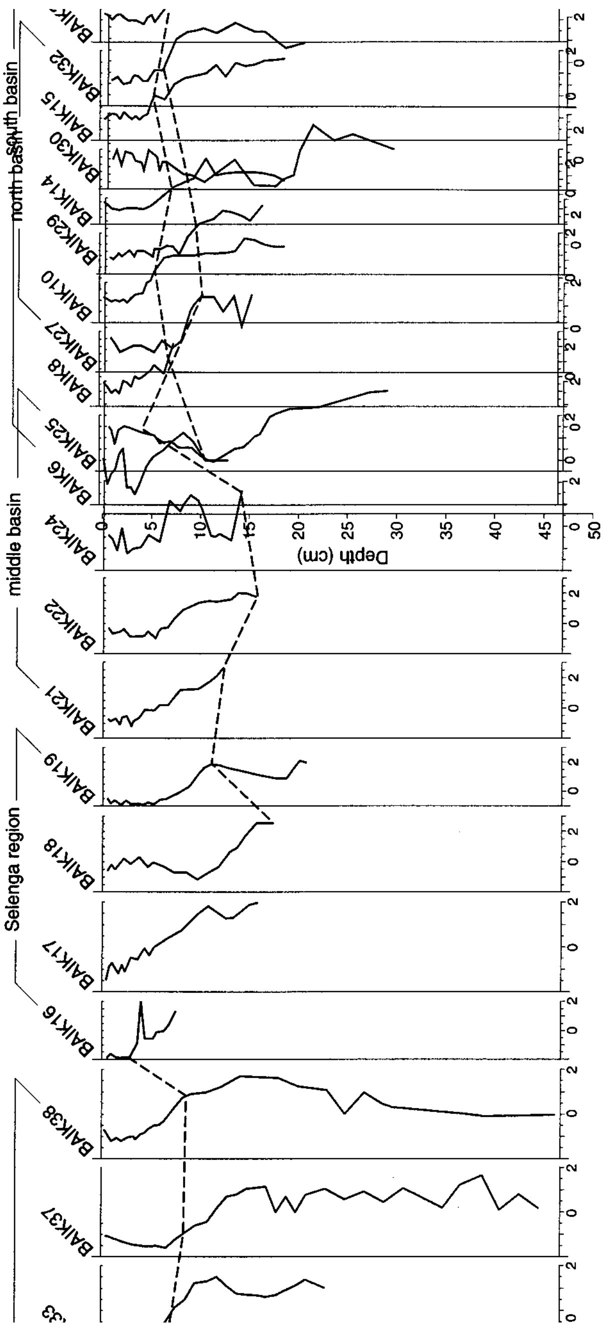


Table 7. *Table summarizing turbidite types found in Lake Baikal surface sediments*

turbidite example	increased DAR	%DW peak (depth cm)	diatom concentration	possible origin of turbidite
BAIK22	yes	1.2–1.4 5.75–6.75	high	diatom rich sediments
BAIK29	yes	0.6–0.8	high	diatom rich sediments
BAIK19	—[a]	none	low	sediments from Selenga shallows
BAIK37	—[a]	14.5–16.5	low	sediments from Selenga shallows
BAIK14	—[a]	5.5–7.5	low	not determined
BAIK16	—[a]	2.5–end	zero	clastic sediments from Selenga region

[a] Below dated portion of core, or core not dated.

however, be a significant factor in the water column or at the surface-sediment–water interface. In most other lakes, water depth would probably preclude diatom dissolution in the water column but with Lake Baikal this may not be the case. Popovskaya (1991) documents increased development of *Nitzschia acicularis* Hustedt, especially around the shallow waters near to the Selenga Delta; N. Bonderenko and D. Jewson (personal communication) have also found recent increases of *N. acicularis* in all basins. *N. acicularis,* however, is very poorly represented in the sedimentary record. It may be that the finely silicified valves of this species are dissolved (either in the water column or at the surface-sediment–water interface) as suggested by P. R. Sweets (unpublished data). These results thus demonstrate that dissolution of diatoms is a significant factor in the interpretation of stratigraphical profiles, as approximately 50% of the valves are undergoing some form of dissolution, and certain taxa are undoubtedly underrepresented. The relative proportions of *Aulacoseira* and *Cyclotella* valves appears not to be affected however, and so we can have confidence in our following inferences.

Most of the dated cores record principal changes in the diatom flora between AD 1860 and AD 1875. These changes occur somewhat earlier in BAIK38, but the errors are larger, and in BAIK22, the core which shows several monotonic features. Therefore, it is likely that these diatom changes occurred simultaneously throughout the length of the lake and are a response to some external signal affecting the whole of the Baikal basin. Most of the other cores in this study exhibit these changes too, except those with inferred disturbed stratigraphies (e.g. BAIK21, Appendix 1), or those from the Baikal shallow zone near the Selenga Delta (e.g. BAIK17) (table 4). These changes are characterized by recent decreases in PCA axis 1 sample scores throughout the lake (figure 14). It has been suggested that these changes may be caused by pollution

Figure 14. (*opposite*) PCA axis 1 scores plotted against depth of sediment for all 20 cores analyses. The switch in dominance from *Cyclotella* to *Aulacoseira* dominance in the last 150 years or so is shown by the dashed line.

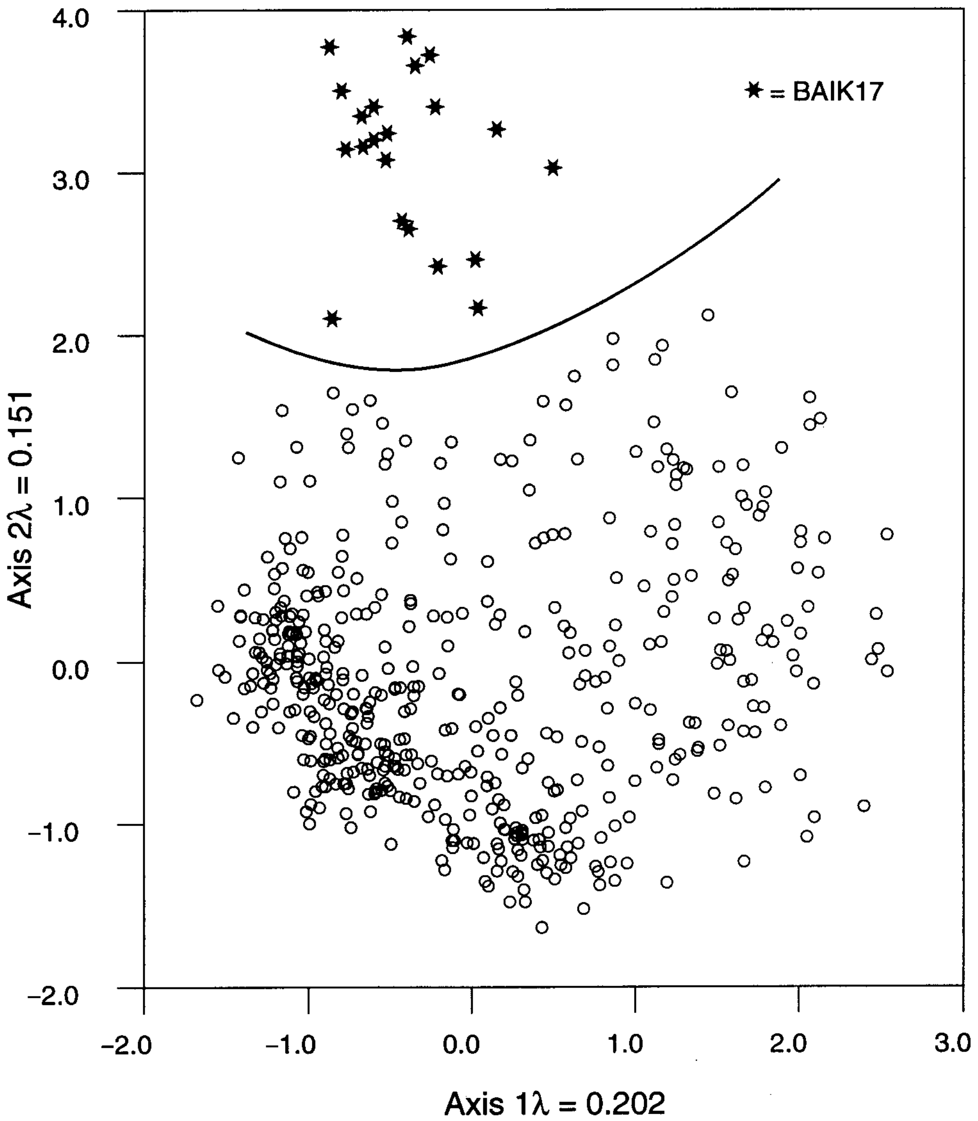


Figure 15. Correlation biplot showing PCA of 490 samples analysed in this study. Note that BAIK17 separates out from the rest of the sites analysed.

(Edlund *et al.* 1995), or climate change, i.e. natural variation (Edlund *et al.* 1995; Flower *et al.* 1995*a*). The merits of each of these hypotheses are discussed here.

(ii) *Temporal trends as evidence of recent climate change*

The recent changes in species composition which occur throughout the length of Baikal in the middle of the nineteenth century, do so before any significant industrialization of the Baikal catchment. It seems likely, therefore, that these changes are a response to a stimulus that could affect the whole lake, such as a change in the prevailing continental climate. Diatom species in Baikal are adapted to the unique physical processes in the lake and different communities develop according to the season, for example, *Aulacoseira* sp. grow under the ice and during ice breakup in late spring (Skabichevskii 1960). Snow and ice cover of the lake are critical in determining the reproductive strategy of *A. baicalensis*, with increased snow cover reducing cell growth, and if snow depth exceeds 10 cm, then growth actually ceases (D. Jewson, personal communication). *C. minuta* on the other hand dominates the phytoplankton during autumn months, reaching maximum development in September–October (see, for example, Antipova 1974; Popovskaya 1991). Back *et al.* (1991) conclude that photosynthetic efficiency of *C. minuta* is highest during periods of low saturating light levels (*ca.* 62–97μE m^{-2} s^{-1}).

The mid-eighteenth century marks the end of the Little Ice Age in Siberia, followed by global warming during the mid-nineteenth century (Pulyaevskii 1994), which coincides with the documented changes in diatom flora reported here and in Edlund *et al.* (1995). It may be that during the Little Ice Age, a combination of persistent snow cover on the lake while it was frozen and a prolonged cooler climate was unfavourable for *A. baicalensis* growth, allowing other species such as the autumnal *C. minuta* to predominate. When the climate ameliorated after the end of the Little Ice Age, conditions would have become more favourable for *Aulacoseira* growth. Shifts in species composition such as these may reflect a biological response to changes in the water level of Baikal which is believed to be dependent on changing solar cycle activities.

An ameliorating climate is also probably responsible for the increases in other pelagic species such as *A. islandica* and *S. binderanus* v. *baicalensis*. The latter species especially predominates in Baikal ‘contact’ zones, or thermal bars, which are zones where deep water comes into contact with waters from the tributaries (Likhoshway *et al.* 1996); this is also known as an ‘edge’ effect (Odum 1975). The end of the Little Ice Age and concomitant melting of the snow

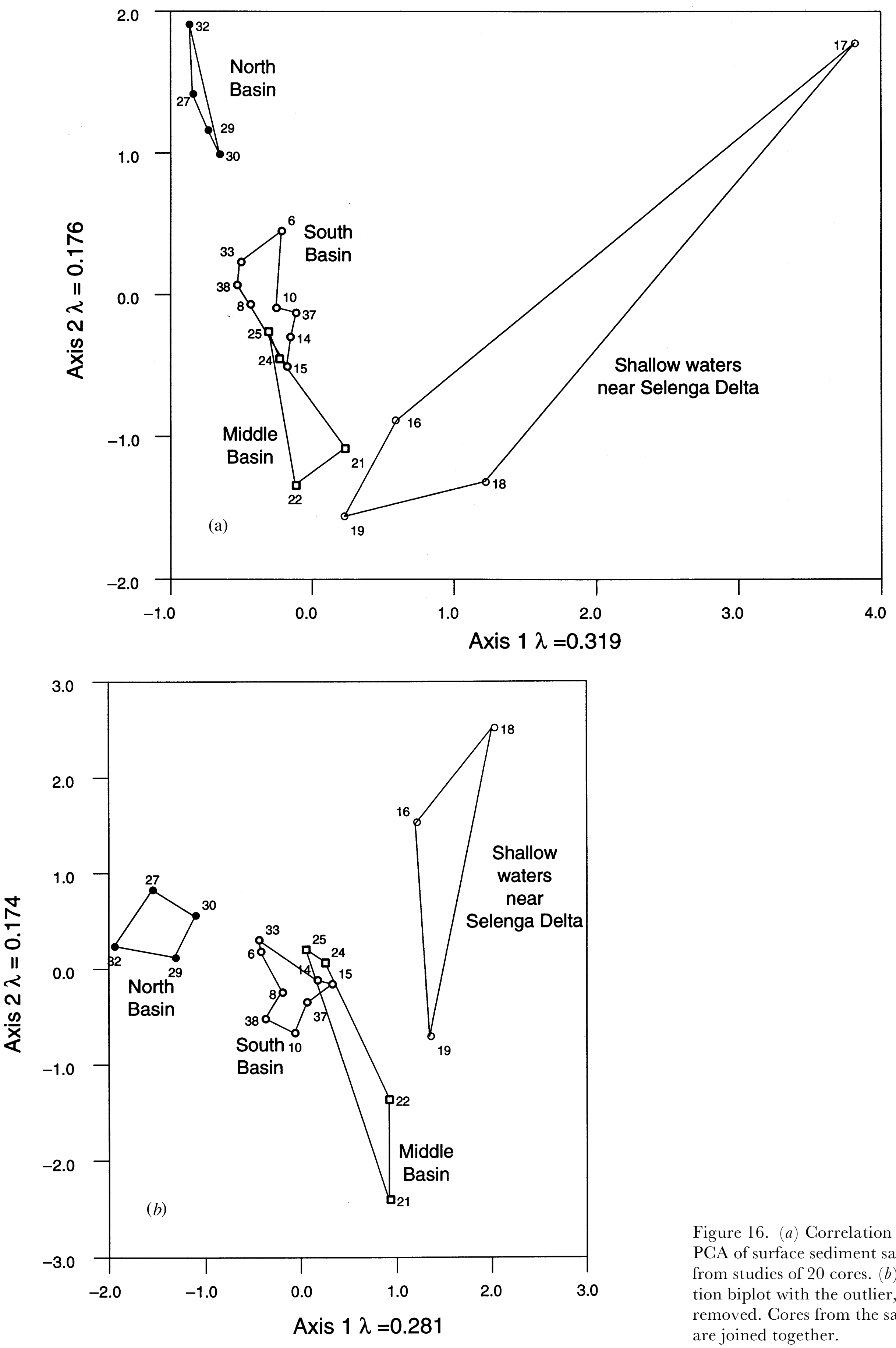


Figure 16. (*a*) Correlation biplots of PCA of surface sediment samples from studies of 20 cores. (*b*) Correlation biplot with the outlier, BAIK17, removed. Cores from the same basin are joined together.

caps would also have led to an increase in water run-off from the catchment into Baikal and as the River Selenga is Baikal's largest tributary, it is likely that most of this run-off entered via the Selenga. Waters from the Selenga flow mostly into the middle basin (60%) but also into the southern basin (40%) (Shimaraev *et al*. 1994). An increase in Selenga waters would also mean an increase in Selenga diatoms being transported to other regions of the lake in the form of spring pulses (Popovskaya 1991). The appearance of species such as *S. acus* v. *acus* in cores taken from the northern basin will, however, have their sources in the tributaries of northern rivers such as the Upper Angara and the Kichera.

Cores spanning longer periods, such as BAIK38 (figure 10) and BAIK25 (figure 8) demonstrate that while *A. baicalensis* has not always been the dominant diatom taxa in Baikal, neither has *C. minuta*. This is especially apparent in BAIK25, which documents several changes in species dominance, probably over at least the last two millennia. In BAIK25, before *C. minuta* dominance, other centric species characteristic of more eutrophic conditions are co-dominants: *S. binderanus* v. *baicalensis* and *S.* cf. *parvus*. While these two species are dominant, there is also an approximate threefold increase in diatom concentration, which may reflect a period of higher productivity (Haworth 1972; Battarbee 1978; Whitmore 1991). These changes in diatom species almost certainly occurred before man could have had such a significant impact on the lake, and until they are adequately dated it is not possible to confirm what may have caused them. One likely possibility however, is that these changes are a response to climate change, which would reinforce the conclusions by Bradbury *et al*. (1994) who also detail significant changes in the Baikal flora over the Holocene. Increasing levels of *S. acus* v. *acus* in BAIK25 would, according to Bradbury *et al*. (1994), record periods of warmer climate. Assuming constant accumulation rates from the base of the ^{210}Pb profiles downwards, this phase of *S. acus* occurs during a weak warming of the Baikal region. This period coincides with the Little Climatic Optimum, *ca*. 1100 years ago. Whatever the cause, these changes almost certainly reflect a period of increasing natural eutrophication of Lake Baikal over the past 1000 years, a process which is confirmed by increasing biogenic silica values (this study; Granina *et al*. 1993*b*). The dominance of *S*. cf. *parvus* in BAIK25 (figure 8) in excess of 40%, has important implications for interpreting more recent increases this century. It is not sufficient to attribute these changes to cultural eutrophication without gaining a wider perspective on the historical patterns of Baikal diatoms. Furthermore, we cannot say at present whether these changes are localized to BAIK25 or whether they would have occurred in more cores if we had longer profiles, but it is clearly evident that high resolution analyses of cores is important if we are to identify environmental signals from Baikal's sediments.

We have shown, therefore, that the sediment record of endemic planktonic diatoms can potentially be used as a powerful proxy method of reconstructing recent changes in climate, which is extremely important given that, first, Baikal is a key site in the PAGES program (Dodson & Lui 1995) and, second, work is under way to obtain cores spanning the Quaternary period and longer from the Academician Ridge (Baikal Drilling Project Members 1994). Furthermore, current research on the population ecology and life cycle strategies of the dominant taxa has demonstrated a clear relation between their relative abundance and the variable temperature, snow–ice-cover and mixing characteristics of the lake (D. Jewson, unpublished data). However, as we have shown here, reconstruction of the climate signal is potentially complicated by the presence of turbidite deposits and our current lack of understanding of taphanomic processes within the lake. These problems were unfortunately not addressed in the low-resolution Holocene study by Bradbury *et al*. (1994)

Table 8. *Average water depth, air temperature and ice cover and length over three basins in Lake Baikal*

basin	average water depth (m) (Kolokoltseva 1968, in Shimaraev *et al*. 1994)	average air temperature (°C)	length of ice cover (weeks) (Shimaraev *et al*. 1994)	average ice thickness (cm)
north	576	−3.2	22	75
middle	854	−1.9	20	80
south	843	−1.3	18	95

(iii) *Spatial variation in the diatom data*

Numerical techniques on both whole core and surface sediment data reveal that cores from the north basin are distinct from the rest of the lake. By using the locally weighted regression techniques of drawing LOWESS curves, which are based on 'generalized additive models' (Trexler & Travis 1993), through surface data demonstrates that not only are species such as *A. baicalensis* restricted to the open water in Baikal but that this species is also more prevalent in the sediments of the northern basin (figure 12). As biological material falls through the water column, the picoplankton component (which is present in higher concentrations in the north basin than anywhere else in the lake (Popovskaya 1987)) dissolves out, resulting in a greater percentage of *A. baicalensis* accumulating in the sediment. Biogenic silica values in the north basin are higher too, (although phytoplankton productivity in northern Baikal is the lowest among Baikal basins) because of less dilution of sediments with terrigenous material as compared with the middle and, particularly, southern basins (Tab. 1 in Granina *et al*. 1993*b*). The predominance of *Cyclotella* species further helps to discriminate between cores that are mainly from the middle part of Baikal or from the south basin (with the exception of BAIK24, Appendix 1). PCA analysis of surface sediment assemblages also groups cores from the northern basin, but does not distinguish very well between south-basin cores from middle-basin cores. The north basin differs from the southern and middle basins primarily because of its lower average depth and its location: ice cover is always thicker and lasts longer here than in the rest of the lake (table 8).

Numerical techniques also demonstrate that diatom assemblages taken from the shallow waters close to the Selenga region have historically been different from other

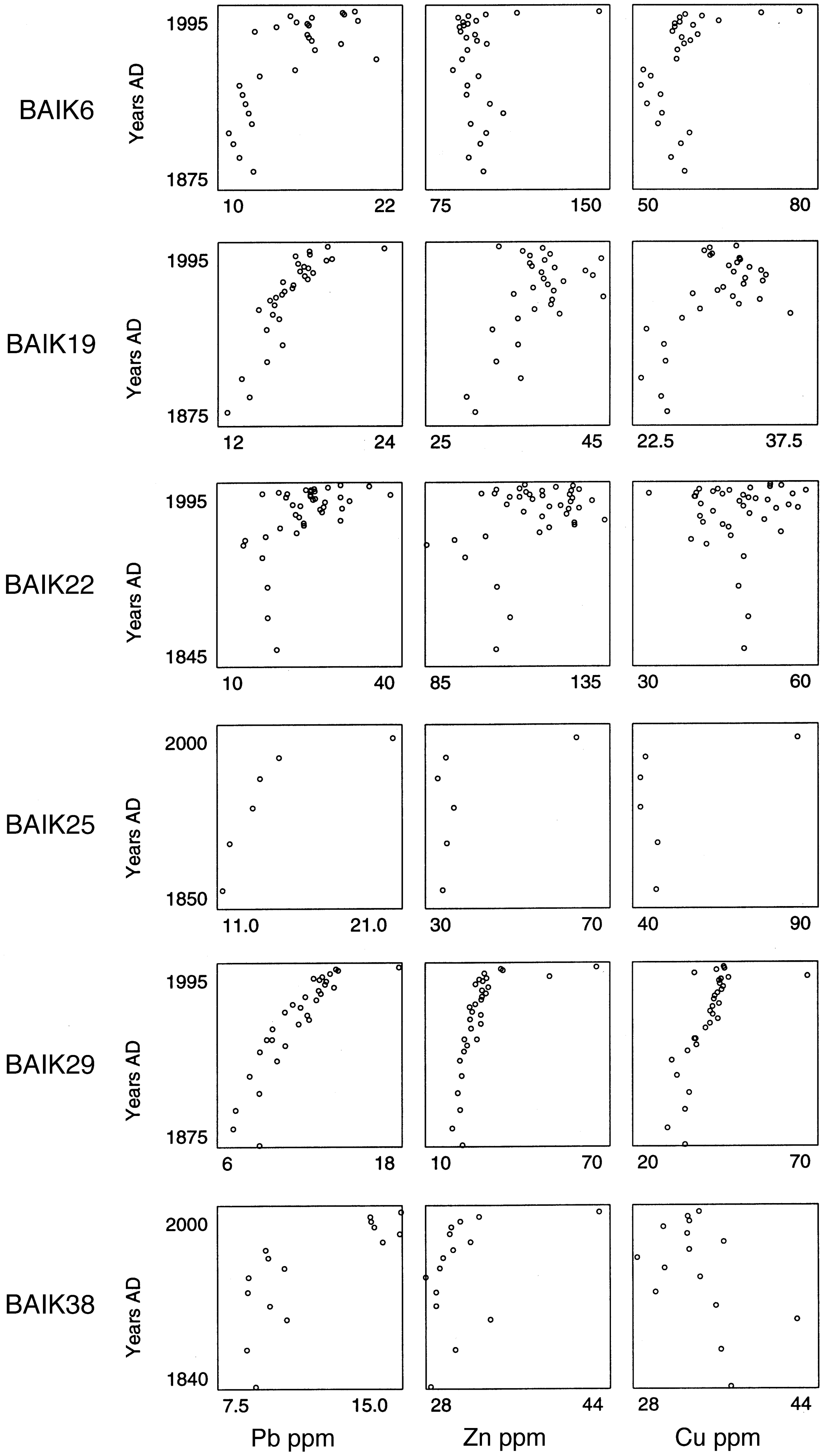


Figure 17. Concentrations (p.p.m.) of Pb, Zn and Cu plotted against AD years for the six dated cores analysed. Note different scales of *x*-axes.

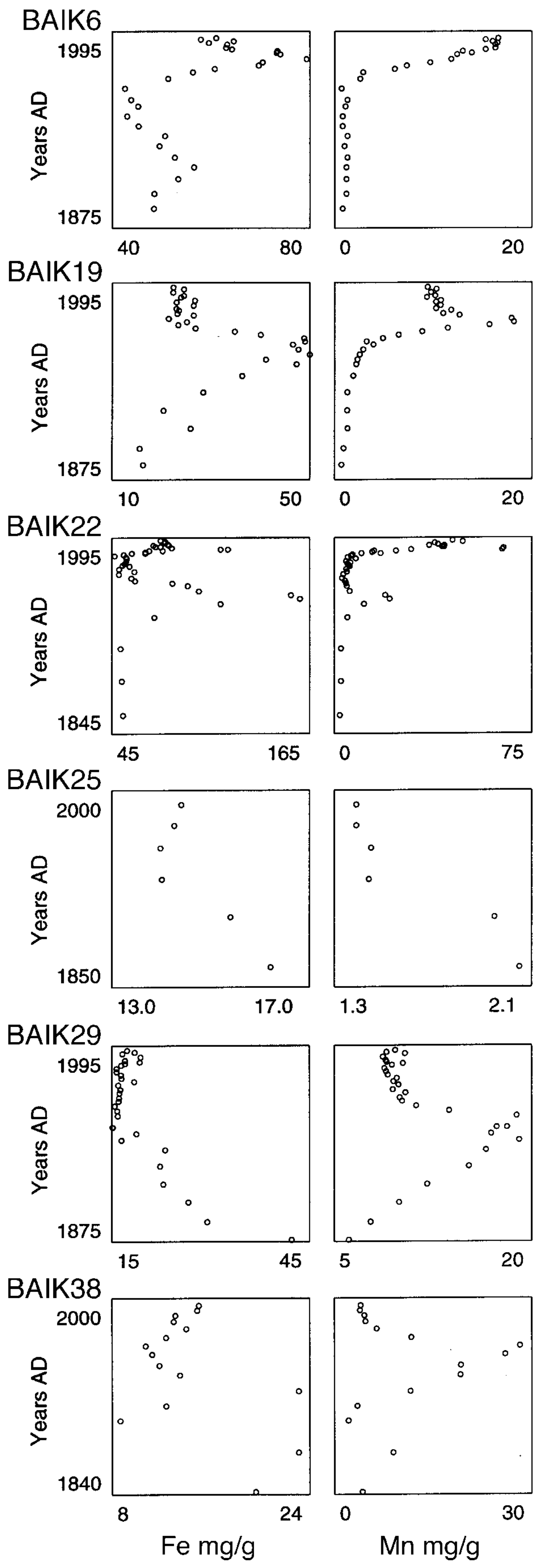


Figure 18. Concentrations (mg g^{-1}) of Fe and Mn plotted against AD years for the six dated cores analysed. Note different scales of *x*-axes.

regions in Baikal. Analyses of only the surface sediment samples show that this shallow water region is still unique within Baikal, especially on the basis of the presence of *A. islandica*. To show this more clearly, we have again investigated trends in individual taxa by using LOWESS curves (figures 12 and 13; Trexler & Travis 1993). For example, LOWESS curves drawn through plots of species percentages versus depth of water in surface sediment samples indicate that certain species, such as *A. islandica*, *S. binderanus* v. *baicalensis*, *C. dubius*, *Cocconeis placentula* v. *euglypta* Ehr. and *F. pinnata* are found predominately in the shallow waters close to the Selenga region, where the water is more eutrophic and contains more riverine forms of diatoms. All these species are recorded in lower numbers in cores from the north basin, which is furthest from the influence of Selenga waters, so these species are instead under the influence of northern tributaries, such as the Upper Angara (figure 1). These analyses may have implications for the interpretation of results from deep-drilling projects (Lake Baikal Palaeoclimate Project Members 1992), with regard to the diatom components. Studies such as Edlund *et al.* (1995) and Stoermer *et al.* (1995) are based on cores taken primarily from waters close to the Selenga Delta and the north basin. However, their conclusions continually refer to the Selenga Delta as 'southern Baikal', which, as demonstrated by our analyses, is not strictly correct: cores taken from the Selenga region may actually, if anything, be more akin to the middle basin.

(d) *Anthropogenic contamination of recent sediments*

Edlund *et al.* (1995) concluded that, in the Selenga region at least, the historical changes in diatom species described here are a result of increased anthropogenic disturbances, in the form of industrialization and urbanization of the catchment. They suggest that their results confirm those of Popovskaya (1991). It is, therefore, important to address whether the recently deposited sediments actually contain evidence of anthropogenic contamination and whether this evidence may be linked to ecological effects, namely changes in the diatom assemblages.

(i) *Atmospheric contamination*

Evidence for an enhanced supply of metals Pb, Cu and Zn and the diagenesis of Mn and Fe provide the focus for discussion of the geochemistry of recently deposited sediments in Baikal. Mn and Fe hydroxides form an oxidized microzone in well ventilated deep waters, similar to that for ocean sediments (Leibovich 1983). The shallow subsurface peaks of Fe and Mn, observed in all parts of the lake, may be attributed to active redox-related diagenetic recycling (Dearing *et al.* 1998). In general, Fe concentrations peak below Mn, which is also apparent in the PCA biplots, owing to differences in their redox potentials (Leibovich 1983). Concentration increases lower down in some cores, e.g. in BAIK25 (figure 8), may reflect relics of oxidized ferromanganese formations, which arise from slower sediment accumulation rates, especially in north basin and Academician Ridge (Granina 1991; Granina *et al.* 1993*a*). Ferromanganese recycling also causes co-enrichment of the upper oxidized layers of other metals, such as Pb, Cu, Co, Ni and Zn. These correlations are weak but the fact itself is important because micro-element enrichments in oxidized layers are more usually characteristic of marine and oceanic environments rather than lacustrine sediments (Leibovich 1983). Diagentic recycling is much more intensive in the central and northern basins and the Academician Ridge, rather than in the southern basin (Leibovich 1983; Granina 1991; Granina *et al.* 1993*a*). Flower *et al.* (1995*a*) have shown that in southern Baikal, metals such as Co, Ni and Cu are influenced by Fe and Mn enrichments in the surface layers but that there was little, if any, correlation between these enrichments and Pb, Cu and Zn.

The Pb concentration profiles show up-core increases for all the cores. The fact that near-surface concentration increases are universal, and that surface concentrations are significantly greater than subsurface values, is compatible with a pollution impact at all sites. However, similar up-core increases are also seen for ^{226}Ra which does not have a significant anthropogenic source. It is thus likely that most of the near-surface Pb enrichment is related to enhanced catchment supply, probably related to catchment disturbance (Boyle *et al.* 1998). If a correction is made for the changing catchment contribution to Pb, a strong up-core increase remains for BAIK6, BAIK19 and BAIK38. Thus, detectable trace metal pollution is found in the southern basin and the region near the Selenga Delta but is not seen elsewhere in the lake.

Cu and Zn show up-core concentration increases in some cores, most notably in the northern basin. However, much greater between core variability is seen than for Pb and several cores show subsurface concentrations as high as those seen at the surface. Cu and Zn also show strong surface enrichments which are probably not related to metal supply but are instead caused by diagenetic effects at the sediment–water interface (Boyle *et al.* 1998). If allowance is made for possible changing catchment contributions to Cu and Zn, then all the up-core increases can be accounted for. Thus, while it is clearly not possible to preclude Cu and Zn pollution, it is not possible to convincingly demonstrate it.

Unambiguous evidence for atmospheric contamination is provided by the SCP record in each core. The SCP record in BAIK6 and BAIK29 starts in the 1930s and 1940s. This is in agreement with the SCP record of a remote mountain lake, near to Lake Baikal (Flower *et al.* 1994), suggesting that this period is the most likely date for the start of the SCP record in Baikal. The late start date at BAIK22 and BAIK25 may be owing to the very low numbers of particles encountered in these two cores exposing the detection limit of the SCP technique. These two records may represent the start of the rapid increase of particle fluxes exhibited in the other cores i.e. when depositions rise above the SCP detection limit. The rapid increase in BAIK29 is later than those in the southern basin, perhaps because of later industrial development in the town of Severobaikalsk. In 1988 an estimated 18 000 tonnes of suspended particulate matter were emitted from the town (Mote 1992). There are two cores (BAIK19 and BAIK38) that exhibit SCP presence from as far back as the mid-nineteenth century. This date does not precede the start of the SCP record in Europe (1850s and 1860s) and may possibly reflect long-distance transport of pollutants. However, the distances involved and the absence of particles in the other cores makes this an unlikely explanation. It may be that there were some local sources close to these regions: coal mining around the Irkutsk region has risen from 40 tonnes in 1900 to a peak of 25 900 tonnes in 1980 but has since fallen in more recent years down to 15 000 tonnes in 1995 (M. A. Grachev, personal communication). The decrease in SCP accumulation rates shown in BAIK19 and BAIK38 may further be reflecting recent decreases in coal use. However, more definite conclusions necessitate taking more cores from the same region. There are no apparent links between increasing Pb and SCP concentrations.

Accumulation rates of carbonaceous particles in the southern basin confirm that this region is experiencing higher levels of pollution than the rest of the lake. The accumulation rate values found in BAIK29 are only approximately one-quarter of those found in BAIK6. Overall, however, accumulation rates are low in comparison to mountain lakes in Europe and the UK (Wathne *et al.* 1995). It may even be that the low concentrations found at BAIK25 represent hemispherical background levels, similar to those found in polar regions (Rose 1995). These findings are similar to other pollution-monitoring studies. A recent study of aerosol composition across Baikal (Khodzher *et al.* 1994) indicated that aerosols in the north and middle basin are predominately terrigenous in origin, for example, ammonium sulphate and calcium sulphate, and may be referred to as background continental aerosols. However, aerosols in the southern basin contain prevalent amounts of sodium chloride, sodium hydrocarbonate and sodium sulphate, which are probably enhanced from industrial centres such as Irkutsk and Angarsk as well as by the paper and pulp mills.

These results demonstrate that there is a determinable record of anthropogenic contamination throughout the whole of Lake Baikal. The levels of contamination, which are low but significant, are greatest in the southern basin where there is most industrial activity (Flower *et al.* 1995*a*; Rose *et al.* 1998). It is now necessary, therefore, to examine whether there is any evidence in the diatom record that is suggestive of changing water quality conditions caused by this pollution.

(ii) *Diatom evidence of contamination*

Popovskaya (1991), Stoermer *et al.* (1995) and Edlund *et al.* (1995), all record changes in diatom species composition over the last few decades, which they link to changes in water quality, either through eutrophication and/or pollution of the lake. For example, Popovskaya notes increasing numbers of small centrics and *Nitzschia* species, whereas Edlund and co-workers infer that the switch from *C. minuta* to *A. baicalensis*, which they found concomitant with increases in *S. binderanus* in the shallow waters near to the Selenga Delta, is indicative of deteriorating water quality. We have demonstrated here that the stratigraphical record holds a significant, albeit small, record of contamination but in all our profiles analysed, even within the shallow waters close to the Selenga region, i.e. BAIK19 (figure 6), the changes described by Edlund *et al.* (1995) all occur before industrialization. It is, therefore, important to consider whether there is any other evidence for eutrophication, such as that described by Popovskaya, in our profiles.

Recent increases in *S. acus* v. *acus* and *S. acus* v. *radians* start simultaneously with *A. islandica* and are likely to be

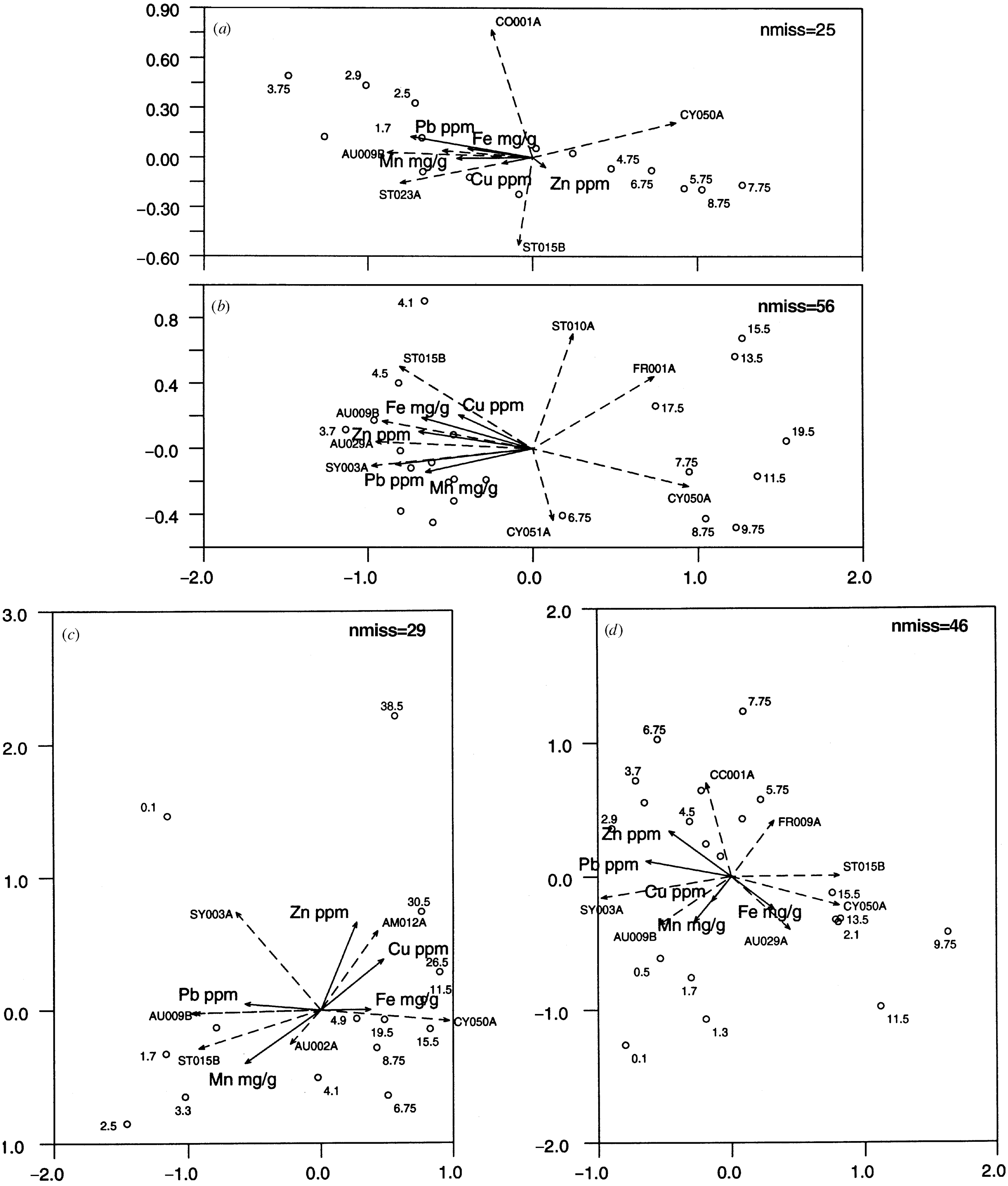


Figure 19. Composite diagram showing correlation biplots of PCA analyses of each of the dated cores, showing diatom species and regressed metal concentrations. (*a*) BAIK6: axis 1, $\lambda=0.274$; axis 2, $\lambda=0.171$; (*b*) BAIK19: axis 1, $\lambda=0.493$; axis 2, $\lambda=0.070$; (*c*) BAIK38: axis 1, $\lambda=0.616$; axis 2, $\lambda=0.153$; (*d*) BAIK22: axis 1, $\lambda=0.325$; axis 2, $\lambda=0.119$; (*e*) BAIK25: axis 1, $\lambda=0.635$; axis 2, $\lambda=0.187$; (*f*) BAIK29: axis 1, $\lambda=0.404$; axis 2, $\lambda=0.318$.

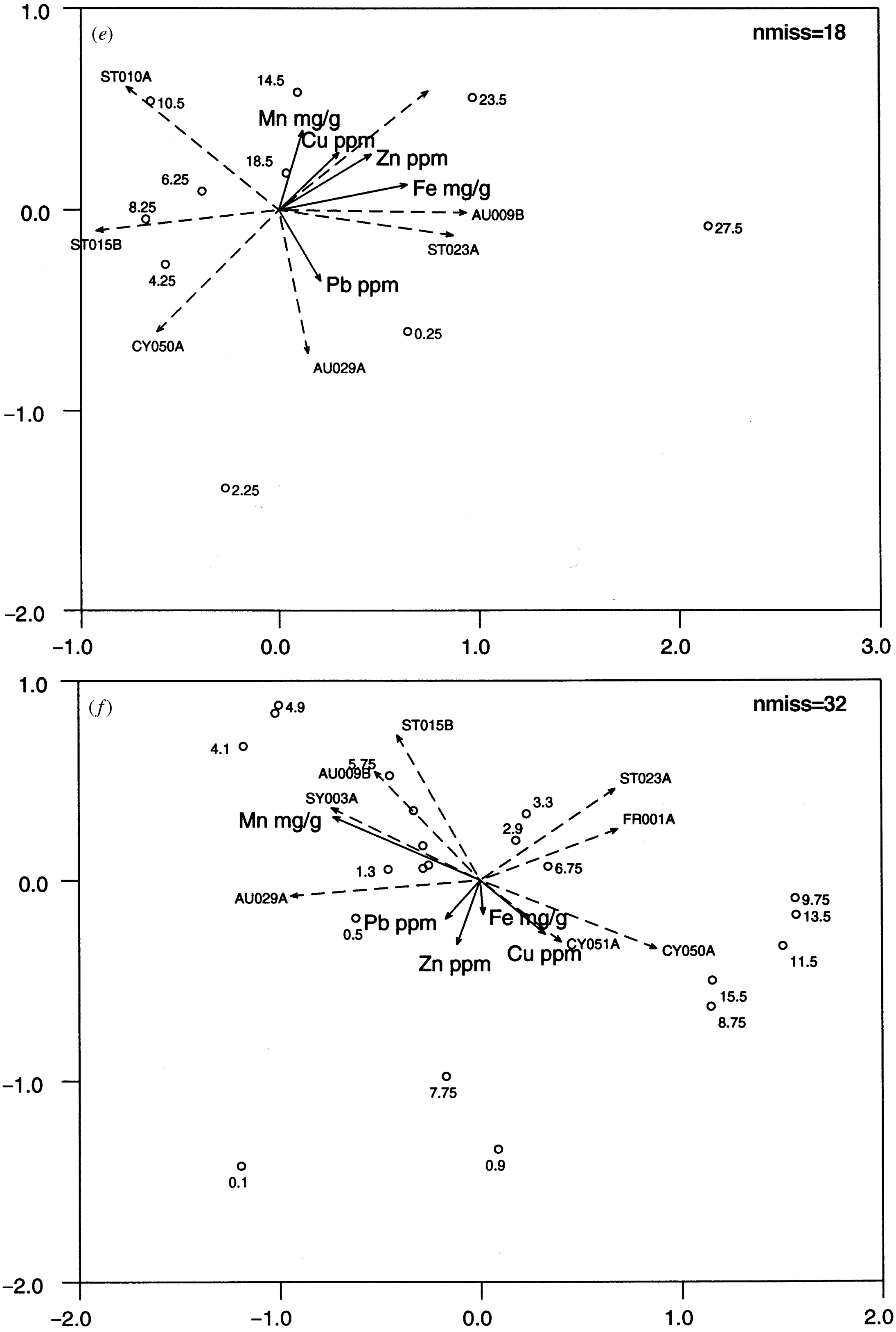


Figure 19. (*Cont.*)

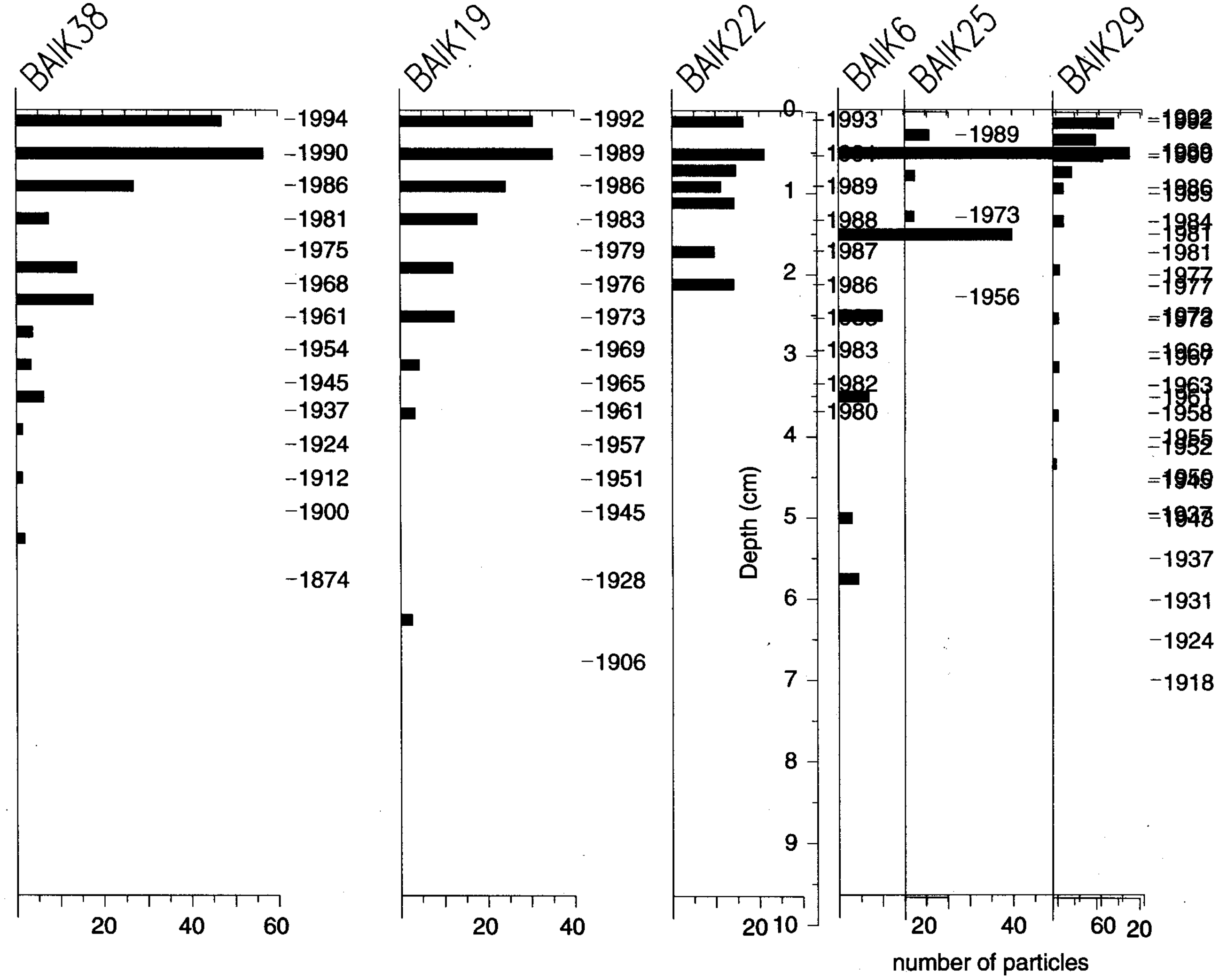


Figure 20. Stratigraphical profiles of SCP numbers plotted against time in AD Years for each of the six radiometrically dated cores.

part of a biological response to climate warming in the Baikal region during the second part of the nineteenth century. The most distinct increases occur within the last 40 years, e.g. BAIK38, and confirm the findings of Antipova (1974) and Popovskaya (1991). These authors attribute the recent increases to disturbances in the Baikal ecosystem by cultural eutrophication, especially within the middle and southern basins. Recent decreases in *Synedra* are likely to reflect changes in the phytoplankton communities of the River Selenga: Yasnitskii (1923) and Meyer (1930) both document *S. acus* as being the dominant species earlier this century. However, later studies document the importance of *N. acicularis, S. hantzschii* and *S. minutulus* in the Selenga river (see, for example, Popovskaya 1960, 1973; A. E. Kuzmina, unpublished data). These qualitative changes are also accompanied by phytoplankton biomass changes and the input of phytoplankton from Selenga waters, which rose from 5500 tonnes in 1958 (Popovskaya & Votintsev 1964) to 27 000 tonnes in 1971 (Popovskaya & Kuzmina 1988). This in part resulted in the biomass increasing in shallow waters close to the Selenga region from 0.1–1.5 $\mathrm{g\,m^{-3}}$ in the 1950s and 1960s, to 2–9 $\mathrm{g\,m^{-3}}$ in the 1980s (Popovskaya 1991). Popovskaya attributes these changes to the eutrophication of not only the River Selenga, but also to the shallow waters close to the Selenga region. Evidence of these changes are found in BAIK17 (figure 11), with decreasing *A. baicalensis* values towards the top of the core, and increasing numbers of more eutrophic species, such as *S. minutulus* and *A. formosa*. Recent increases in *N. acicularis* in BAIK17 and BAIK18 (Appendix 1) are evident too. Turnover of species (table 5), as evidence of rate of species change, is extremely low for all the dated cores (time appears to be the only significant factor in explaining any change), as are any changes in biogenic silica values. We must, therefore, infer from our results that the sediments of the deepwater basins do not contain any significant stratigraphical record indicative of changing water quality conditions associated with a period of recent cultural eutrophication or increased pollution loading of the lake. However, we do present evidence for localized changes in water quality associated with cultural eutrophication, especially in the shallower waters close to the Selenga region. Furthermore, Granina *et al.* (1992) attributed recent increases in biogenic silica to increased diatom productivity due to the climate over the last 300 years. Our data, however, do not support these findings. It may be that biogenic silica dissolution processes in surface sediments are more important than previously supposed and, therefore, need to be taken into account.

5. CONCLUSIONS

Lake Baikal is one of the world's unique ecosystems, in terms of its biology, physics and history. Global environmental concern is, therefore, justified on the basis of uncontrolled pollution and disruption of the catchment area. This study has shown that a record of atmospheric contamination, especially in the form of SCPs, does exist in the sedimentary record throughout the length of the lake. Contamination is greatest in the south basin, where industry and coal mining is common, and least in the middle basin and Academician Ridge. There is also a record of contamination in the far north of the lake, which may reflect the building of the Baikal–Amur Mainline railway and the growth of the new town Severobaikalsk. High resolution analyses also reveal, however, that levels of contamination may actually be decreasing over the last decade or so.

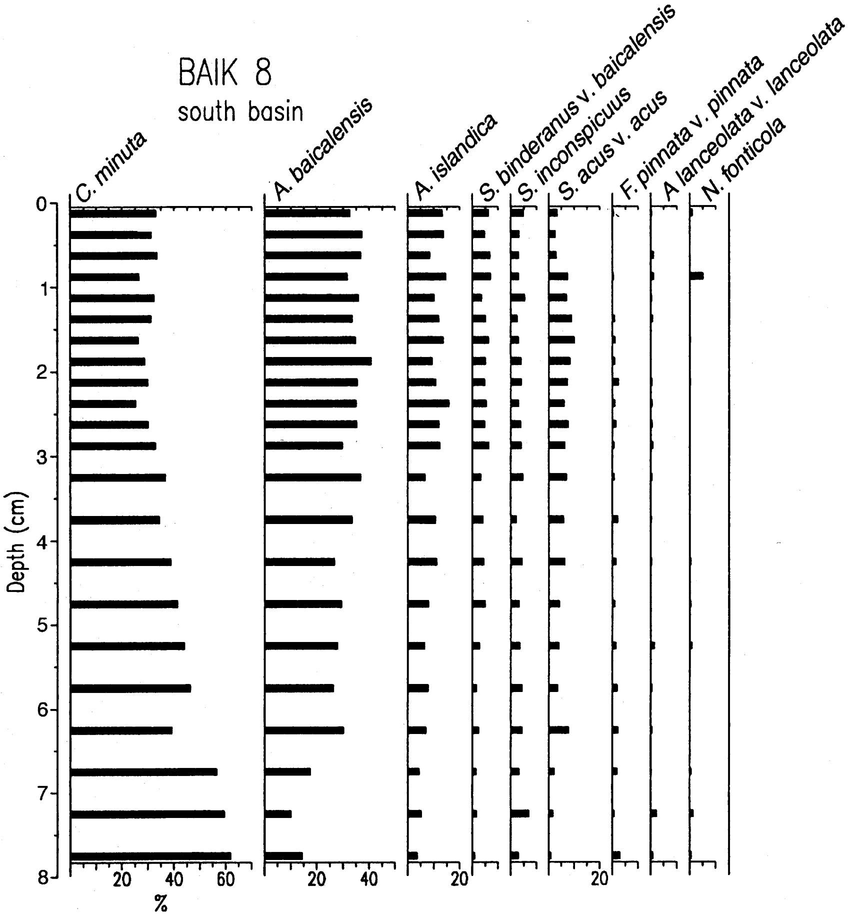
In the deepwater cores, we can provide no evidence from the sedimentary record that the endemic diatom flora of Baikal is being affected by pollution. However, in the shallower waters, especially those near to the Selenga Delta, and to a certain extent those close to the Baikalsk paper and pulp mill, we do provide evidence of localized changes in water quality, with the sedimentary record exhibiting recent increases in diatom species that are usually associated with more eutrophic waters. These data confirm diatom-monitoring data over the last 30 years or so. Changes in species composition have been inferred before for waters close to the Baikalsk paper and pulp mill but, as far as the authors are aware, have never been consclusively shown until now.

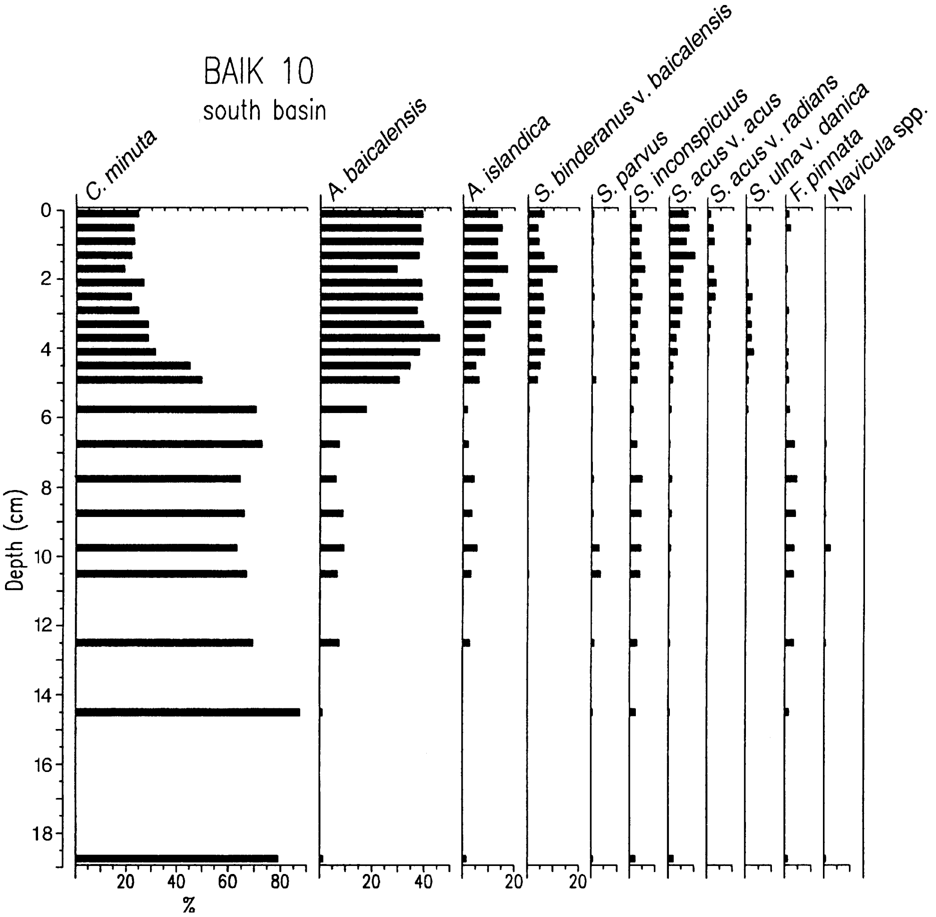
Overall, the sedimentary record of planktonic diatoms in Baikal is dynamic and high-resolution analyses in conjunction with radiometric dating reveal these changes to be associated with changes in prevailing climatic conditions and not due to pollution, as concluded by other authors. In this paper we document clearly the diatom response to both the recent Climatic Optimum of *ca.* 1000 years ago, and the ending of the Little Ice Age *ca.* 140 years ago. The diatom record is potentially complicated by both taphonomic (e.g. dissolution) and sedimentological (e.g. turbidites) processes, both of which must be taken into account when interpreting the sedimentary record, especially for a lake as deep and complex as Lake Baikal. Studies which ignore these processes are suspected to have erroneous conlcusions.

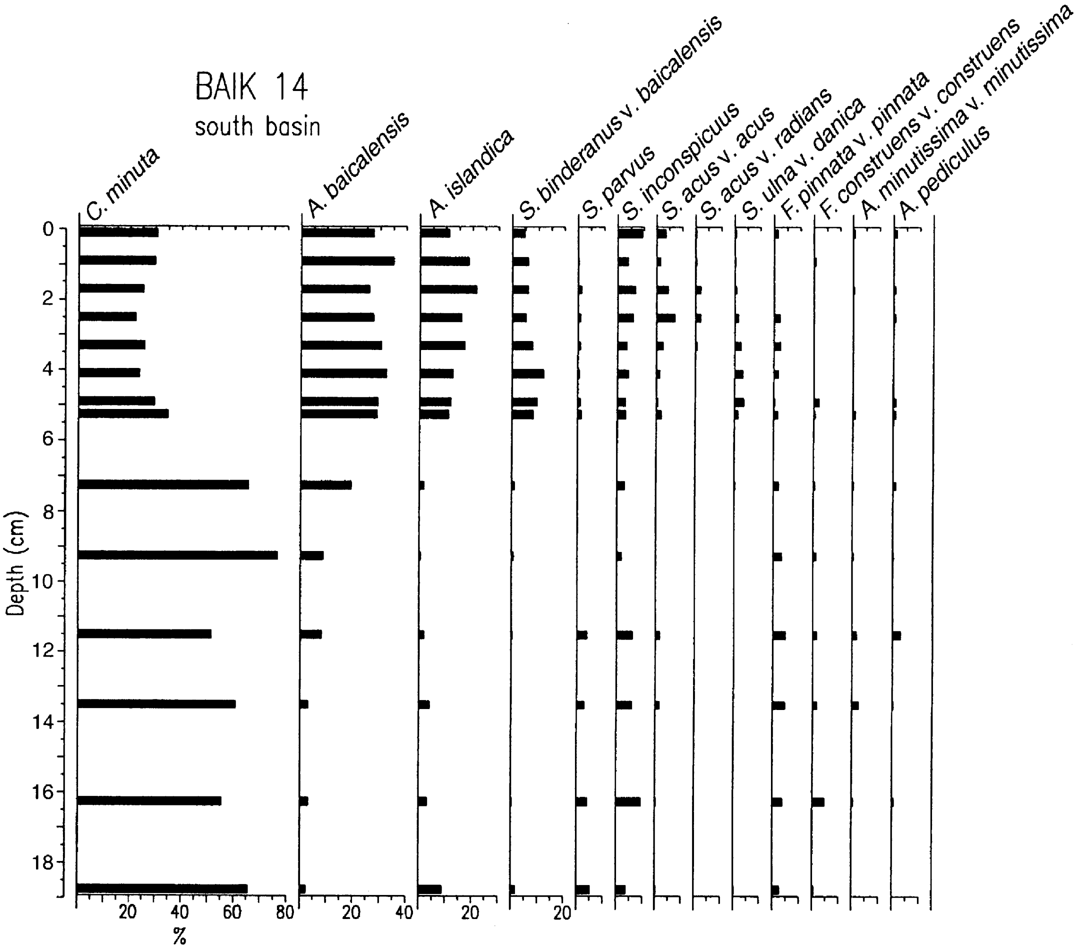
The challenge now is to make quantitative reconstructions of past climatic conditions, for example, a record of past mean temperatures and changing ice-cover conditions. This will necessitate a detailed understanding of the processes linking contemporary diatom life cycles with physical and sedimentary processes in relation to modern climatic conditions. Only then can we hope to reconstruct high-resolution climate variablility during the Holocene and the last glacial–interglacial cycle with confidence. This is now one of the objectives of a new interdisciplinary project between the authors of this paper and University of Ulster, funded by the Natural Environment Research Council (UK) with assistance from the Royal Society.

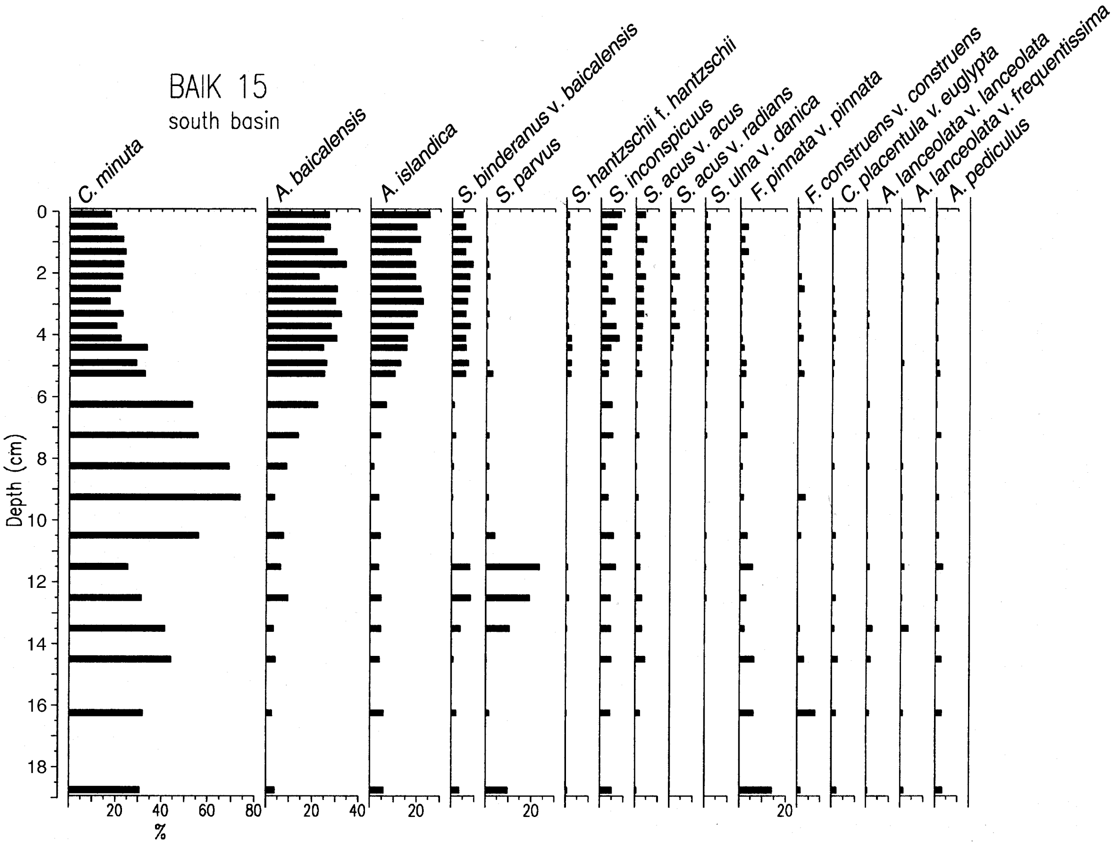
There are many people we would like to thank, both within the UK and in Russia. First, this project would not have been possible without funding from both the Royal Society under the BICER agreement and the Leverhulme Trust (Project Reference F.134 AZ). For help with field work, we thank Don Monteith, Jim Chambers, Dave Jewson, Joan Lees, Yelena Likhoshway, Professor Grachev, Alex Grachev, Eugene Berezikov, Nick Granin, the engineering firm LINA in Angarsk, and the crew of both the Titov and the Vereschagin. We also thank Olga Levina for doing the biogenic silica anlayses and John Birks for advice on statistical techniques. Artwork was done by the Cartographic Unit within the Geography Department, UCL. This is a BICER publication.

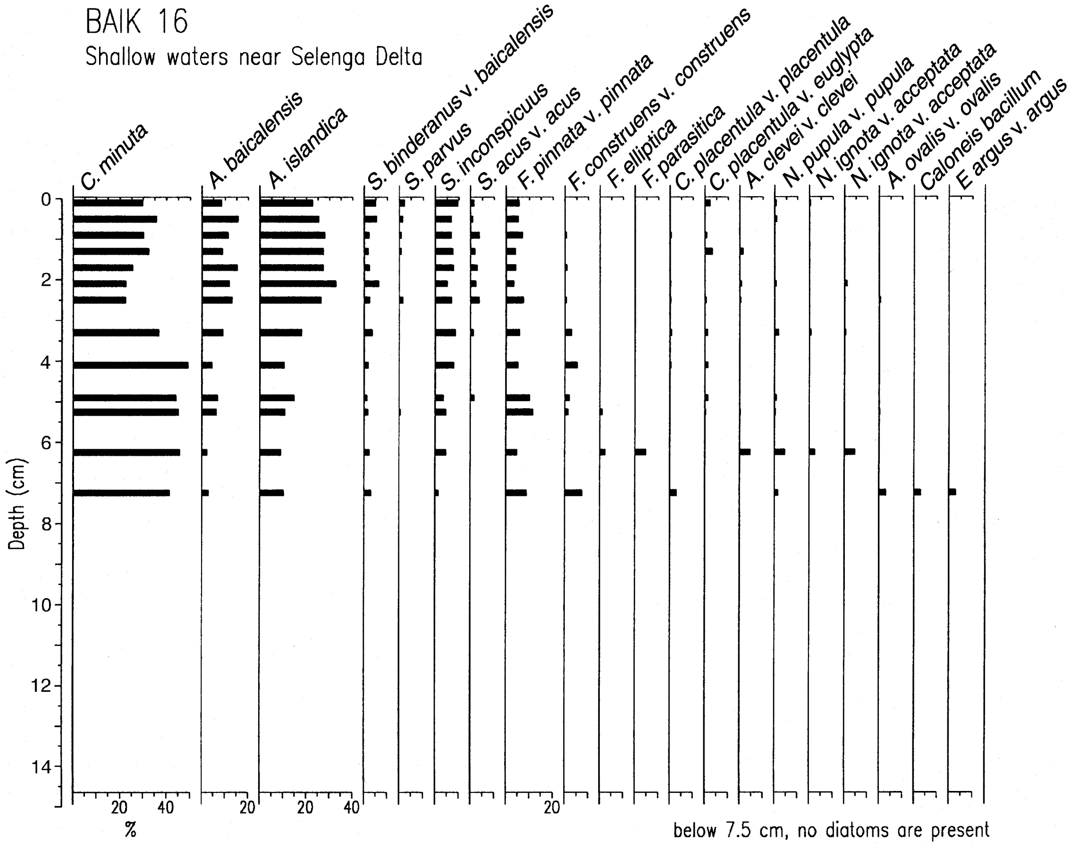
APPENDIX 1.

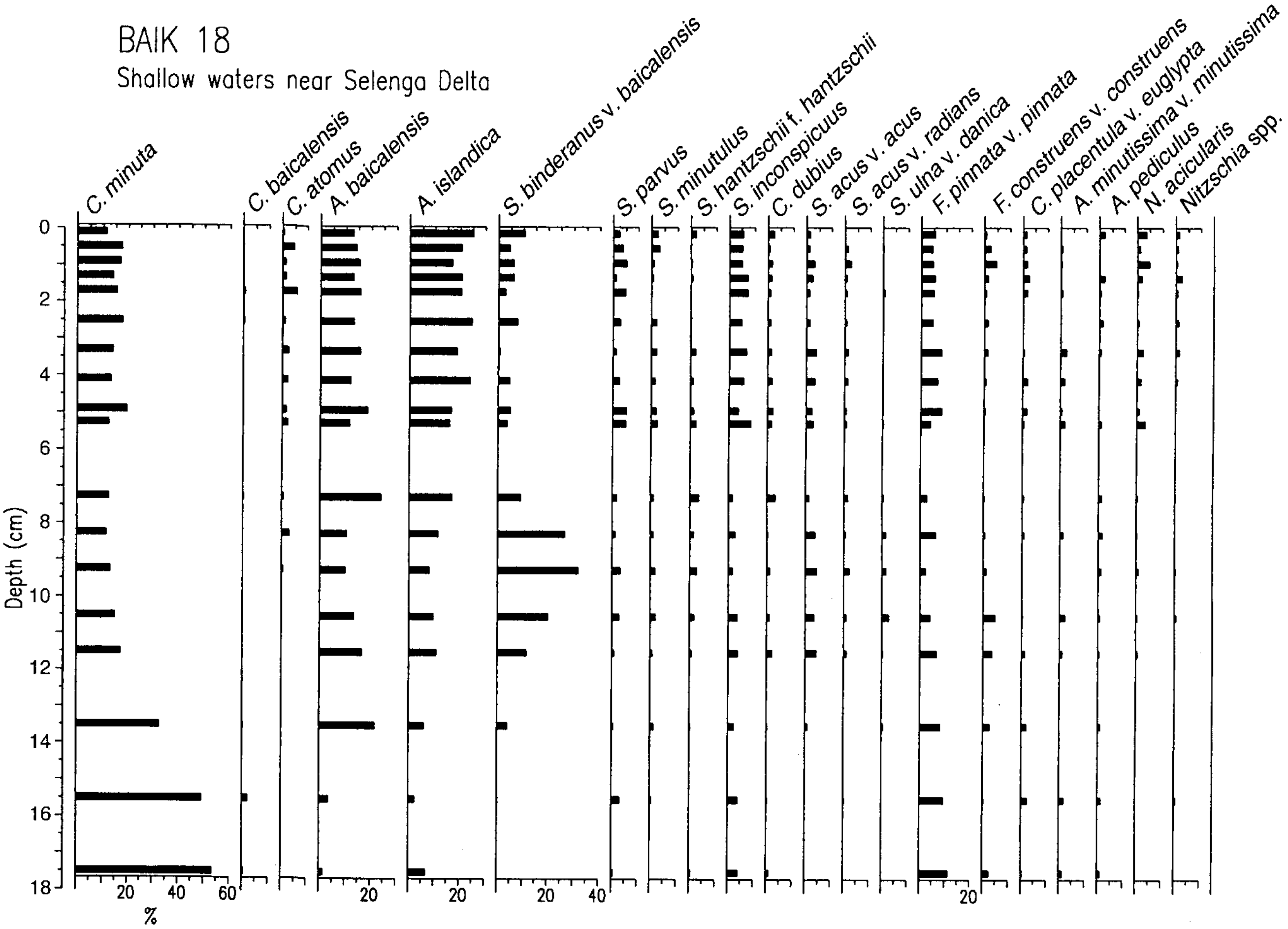

BAIK 8
south basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. inconspicuus
S. acus v. acus
F. pinnata v. pinnata
A lanceolata v. lanceolata
N. fonticola
Depth (cm)
0
1
2
3
4
5
6
7
8
20
40
60
%
20
40
20
20

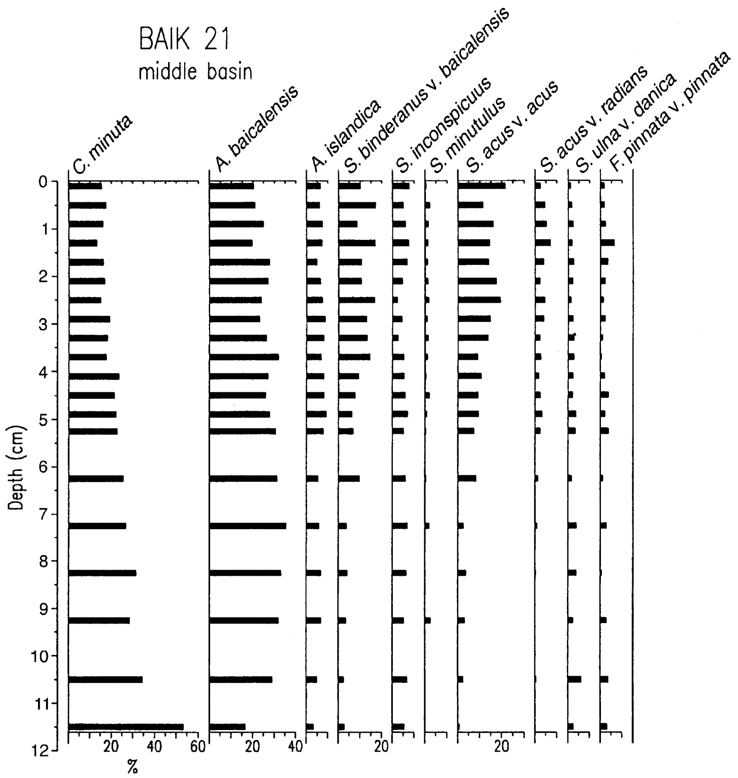

BAIK 10
south basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. inconspicuus
S. acus v. acus
S. acus v. radians
S. ulna v. danica
F. pinnata
Navicula spp.
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
40
60
80
%
20
40
20
20

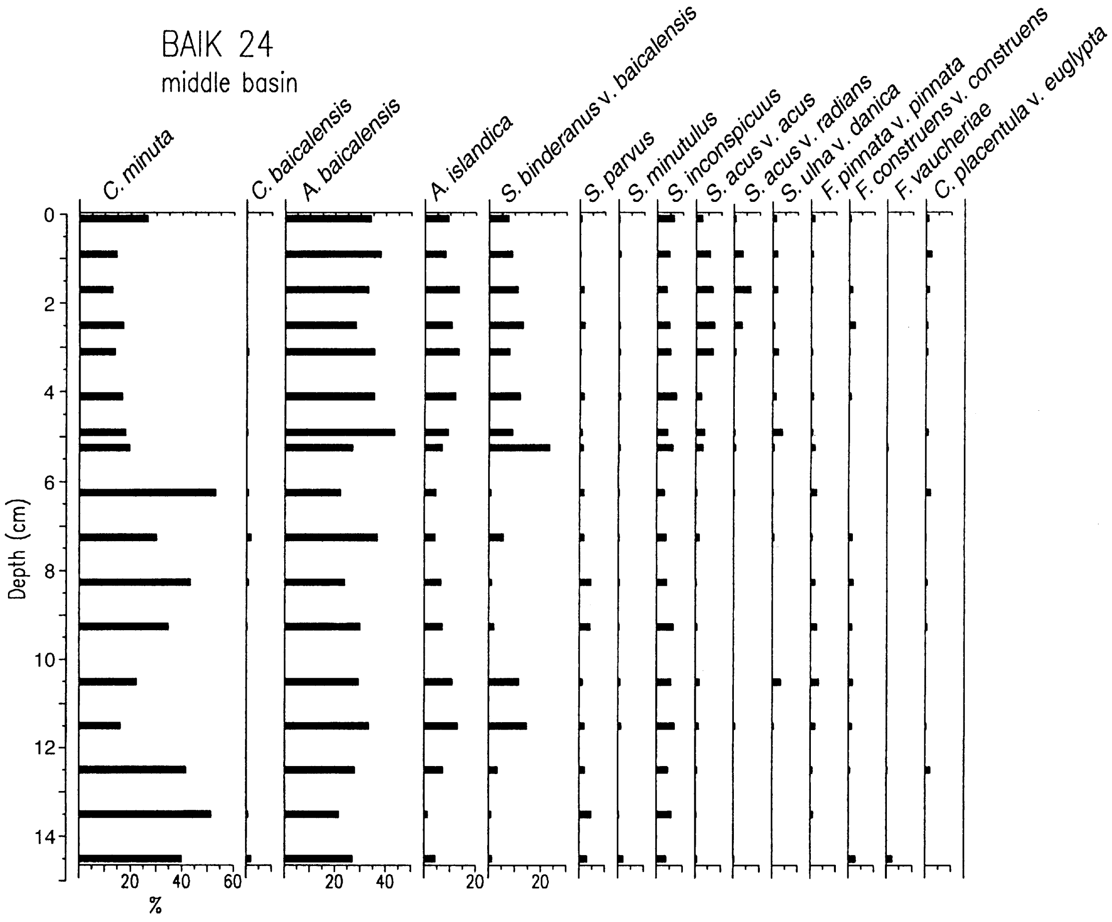

BAIK 14
south basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. inconspicuus
S. acus v. acus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
F. construens v. construens
A. minutissima v. minutissima
A. pediculus
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
40
60
80
20
40
20
20
%

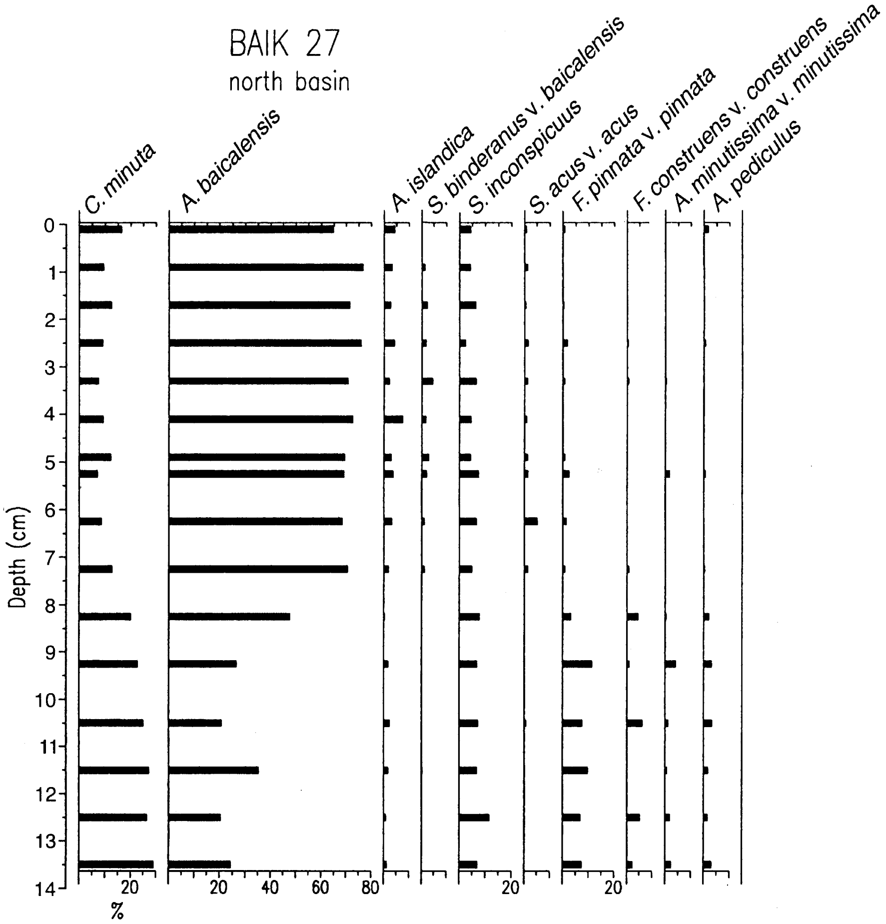

BAIK 15
south basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. hantzschii f. hantzschii
S. inconspicuus
S. acus v. acus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
F. construens v. construens
C. placentula v. euglypta
A. lanceolata v. lanceolata
A. lanceolata v. frequentissima
A. pediculus
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
40
60
80
20
40
20
20
20
%

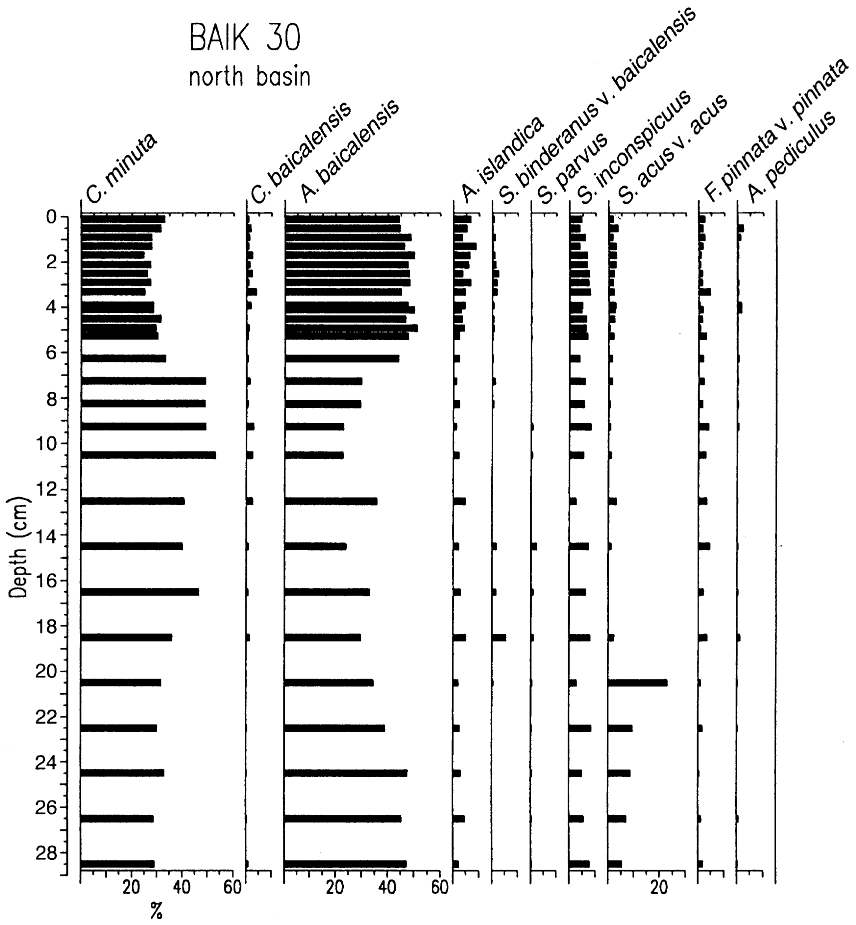

BAIK 16
Shallow waters near Selenga Delta
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. inconspicuus
S. acus v. acus
F. pinnata v. pinnata
F. construens v. construens
F. elliptica
F. parasitica
C. placentula v. placentula
C. placentula v. euglypta
A. clevei v. clevei
N. pupula v. pupula
N. ignota v. acceptata
N. ignota v. acceptata
A. ovalis v. ovalis
Caloneis bacillum
E argus v. argus
Depth (cm)
0
2
4
6
8
10
12
14
20
40
20
20
40
20
%
below 7.5 cm, no diatoms are present

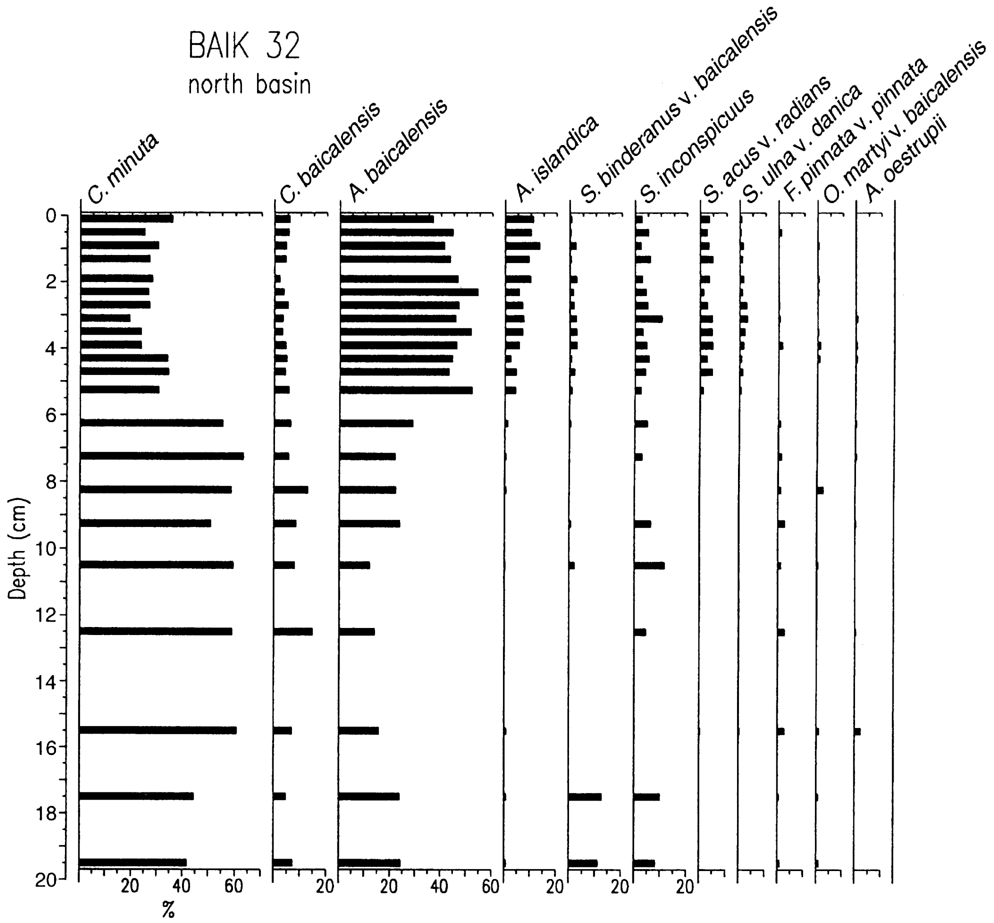

BAIK 18
Shallow waters near Selenga Delta
C. minuta
C. baicalensis
C. atomus
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. minutulus
S. hantzschii f. hantzschii
S. inconspicuus
C. dubius
S. acus v. acus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
F. construens v. construens
C. placentula v. euglypta
A. minutissima v. minutissima
A. pediculus
N. acicularis
Nitzschia spp.
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
40
60
20
20
20
40
20
%

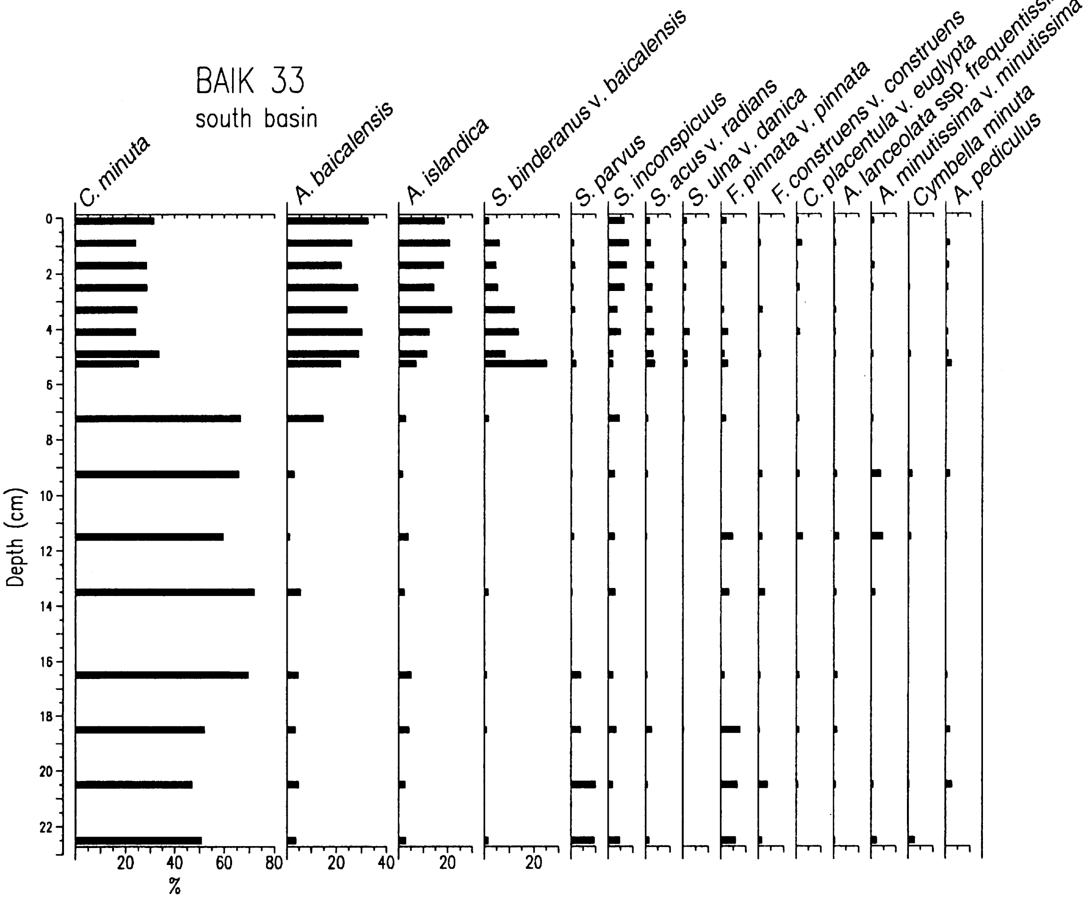

BAIK 21
middle basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. inconspicuus
S. minutulus
S. acus v. acus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
Depth (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
20
40
60
20
40
20
20
%

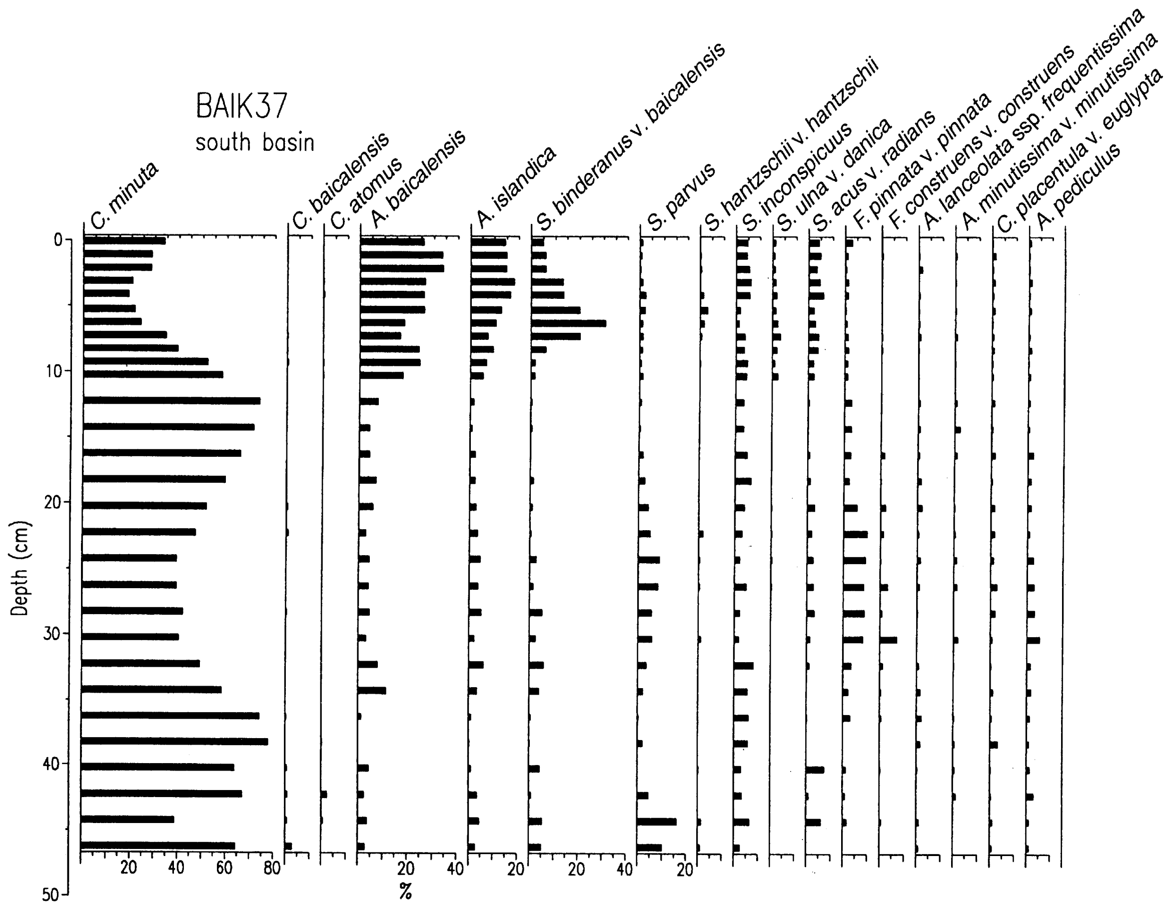

BAIK 24
middle basin
C. minuta
C. baicalensis
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. minutulus
S. inconspicuus
S. acus v. acus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
F. construens v. construens
F. vaucheriae
C. placentula v. euglypta
Depth (cm)
0
2
4
6
8
10
12
14
20
40
60
20
40
20
20
%


BAIK 27
north basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. inconspicuus
S. acus v. acus
F. pinnata v. pinnata
F. construens v. construens
A. minutissima v. minutissima
A. pediculus
Depth (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
20
%
20
40
60
80
20
20


BAIK 30
north basin
C. minuta
C. baicalensis
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. inconspicuus
S. acus v. acus
F. pinnata v. pinnata
A. pediculus
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
20
40
60
%
20
40
60
20


BAIK 32
north basin
C. minuta
C. baicalensis
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. inconspicuus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
O. martyi v. baicalensis
A. oestrupii
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
20
40
60
20
20
40
60
20
20
20
%


BAIK 33
south basin
C. minuta
A. baicalensis
A. islandica
S. binderanus v. baicalensis
S. parvus
S. inconspicuus
S. acus v. radians
S. ulna v. danica
F. pinnata v. pinnata
F. construens v. construens
C. placentula v. euglypta
A. lanceolata ssp. frequentissima
A. minutissima v. minutissima
Cymbella minuta
A. pediculus
Depth (cm)
0
2
4
6
8
10
12
14
16
18
20
22
20
40
60
80
20
40
20
20
%



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