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Recent environmental change in Lake Baikal, eastern Siberia, with special reference to the sedimentary diatom record

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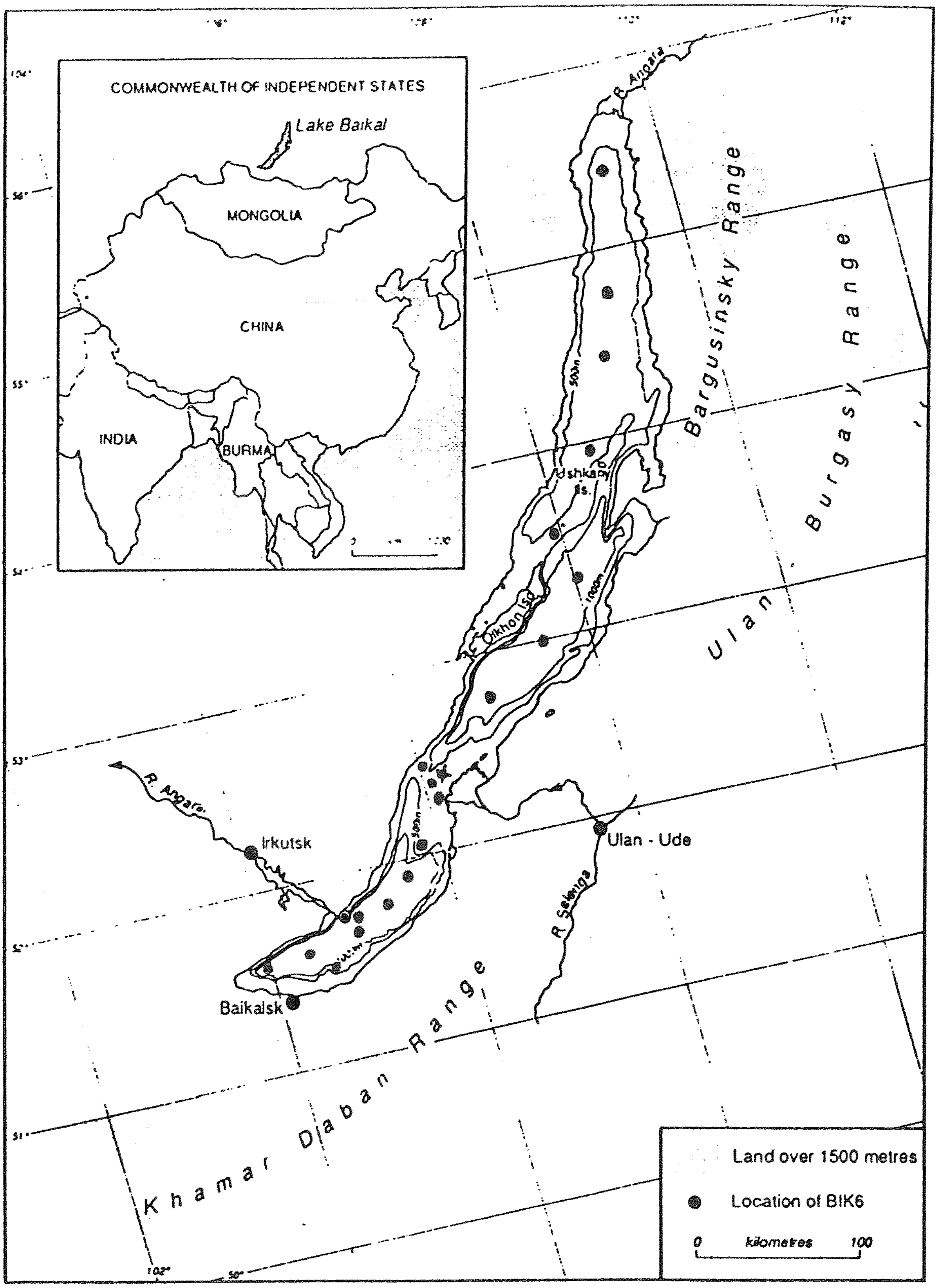
Fig 1 Location of Lake Baikal



1. Introduction

Lake Baikal is a Miocene-age rift lake in south-eastern Siberia (Colman *et al.* 1992) (Fig 1) and is undoubtedly one of the most interesting biological sites for scientific study in the world today (eg Galazy 1982; Fryer 1991). Lake Baikal is internationally famous for its rich, and largely endemic, flora and fauna: over 2,500 animal and plant species have been identified (Galazy 1989) of which over 1000 are believed to be endemic (Kozhov 1963; Stewart 1990a). The biological uniqueness of Lake Baikal stems from both its great age, and the fact that its waters are oxygenated down to its greatest depths (Kozhov 1963; Leibovich 1983; Fryer 1991). Lake Baikal is probably the oldest lake in the world (current estimates age it at between 25 million and 50 million years old) and it is certainly the deepest at over 1600m (Stewart 1990a; Fryer 1991). In terms of area, Lake Baikal is only the 7th largest lake in the world (Stewart 1990a). However, because of its great depth, it contains the largest volume of freshwater, 23,000 km^3 (Kozhov 1963), accounting for one-fifth of the global resources of surface freshwater (Wetzel 1983) and for more than 80 % of that in the Former Soviet Union (Galazy 1989). The only outflow from Lake Baikal is via the Angara river in the southern basin.

Lake Baikal has a catchment area of an estimated 540,000 km^2 (Kozhov 1963), including over 300 rivers that flow into the lake (Galazy 1989). Unsurprisingly, Lake Baikal and its catchment area have been exploited by people, and potential changes to its ecology have resulted from increased levels of pollution from industrial and domestic effluent, from atmospheric contamination and from uncontrolled logging of the catchment area. Although the dangers of these processes have long been recognised and documented (eg Galazy 1982) they have increasingly come to the attention of the World Media since the break up of the Former Soviet Union (eg Stewart 1990a & b).

Effluents, consisting mainly of factory waste products and partially treated sewage, enter Baikal directly in the far north and south of the lake, and from rivers, especially the Selenga, Baikal's largest tributary. Perhaps the most serious sources of pollution are the two pulp and cellulose mills, one of which is on the southern shore of Baikalsk and the other, smaller one on the Selenga river at Selenginsk (Stewart 1990b). The Baikalsk mill began operating in 1966 and has become the most significant polluter of Lake Baikal, having introduced about 1.5 billion cubic metres of industrial waste into the lake eg. organic chlorine compounds (Maatela *et al.* 1990). Pollution loading into the Selenga Delta can be detected over an area as large as 1,500 km^2.

Pollutant contamination of the Lake Baikal basin via atmospheric deposition is a rapidly growing problem (Kokorin & Politov 1991) and may now pose a bigger threat to the ecosystem than point source water pollution (Stewart 1990b), contributing to an estimated 32% of the total loading to the lake (Galazy 1989). Sources of atmospheric pollution include not only the two pulp and cellulose mills, but all the industries around the Baikal region. In 1985 an estimated 1.2 million tonnes of atmospheric pollutants were emitted from industries in the Irkutsk region alone. Other sources of pollution, such as vehicular exhaust gases which will contribute NO_x compounds, and heavy metals are also likely to be significant.

Unlike effluents, whose effects are likely to be more localised, atmospheric pollutants have the potential to be carried long distances, and hence exert deleterious effects on more remote regions around Baikal, affecting not only water quality directly but also indirectlt by deposition onto vegetation in the catchment area.

Uncontrolled logging has lead to two distinct problems. The first was the increased erosion of soils which accompanied the destruction of large expanses of taiga forests (Galazy 1989). This erosion resulted in vast quantities of silt being washed into the rivers, and then into Baikal itself (resulting in the disappearance of hundreds of rivers and small tributaries). The second problem involved millions of logs rotting in the rivers and river mouths, creating anoxic conditions and fish death (Galazy 1982; Leibovich 1983). Since 1988 however, all felling has been banned in a belt along the coast and provision for fire prevention improved, but changes regarding the transportation of the logs has yet to be dealt with (Galazy 1989).

The environmental effects of these combined forms of pollution must have an affect 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 1990b). The death of thousands of endemic seals from seal distemper in the late 1980's (Grachev *et al.* 1989) has also been linked to increases in pollution causing seal immunities to be lowered. However, whilst local water quality problems are generally acknowledged, some scientists believe that the pollution of the lake has been grossly over-estimated (eg Grachev 1991). They suggest that recent fish stock declines and the incidence of seal distemper may be explained by natural variation and to factors other than changes in water quality.

In light of the number of endemic species in Lake Baikal, the site has been proposed as a World Heritage Site by UNESCO. In 1990, however, the visiting UN delegation advised the postponement of such a designation until the environmental problems facing the lake, such as pollution, are solved. It is thus imperative to be able to evaluate sustained changes on Baikal's ecosystem through long-term monitoring, but biological records for Baikal only extend a few decades and are of insufficient length and quality to determine whether sustained changes in Baikal's ecology have taken place. However, changes in species composition and abundances, related to changes in water quality, can be established over a time-scale of decades using palaeoecological techniques (eg Battarbee *et al.* 1990), most notably diatom analyses in dated sediment cores. Diatoms are very important primary producers in Lake Baikal, comprising approximately 47 % of the lake's planktonic community (Granina *et al.* 1992). Approximately 98 % of the silica in Baikal sediments is derived from diatoms, and according to Bezrukova *et al.* (1991), their silica remains are generally well preserved in the sediment. Central to the technique of diatom analyses is accurate identification of diatom taxa in sediment assemblages which is fundamental to detecting floristic changes.

1.1 Objectives of Project

The overall objective of this project is to obtain a suite of surface sediment cores from the three main sub-basins of Lake Baikal to furnish evidence about the nature and extent of recent environmental changes in the lake. This has been done using a variety of sediment coring techniques, but is based principally on the recently developed UCL box corer (Monteith *et al.* 1993). The investigation will centre upon diatom analysis of the sediment cores. Selected cores will be dated radiometrically and analysed for trace metals and magnetic minerals, thereby allowing the reconstructions of both the recent pollution history of the lake and increased terrigenous input from the catchment area (Kling *et al.* 1993).

Other specific objectives include -

- identifying changes of gradients of diatom species in surface sediments across the southern basin, with a view to identifying the ecological effects of point sources of pollution (eg the Selenga Delta).

- to collect water and modern diatom samples from in and around the lake to learn more about the species diversity and ecology of Baikal diatoms and

- to extend the large computer database of diatoms and water quality held at the ECRC to enable the possibility of quantitative diatom-based historical reconstructions of lake water quality in Baikal to be made.

1.2 Sampling Strategy

This report describes in detail the results of the pilot study prior to the main project. The specific objectives for the pilot study were to test out the new type of sediment box corer which would be capable of retrieving intact surface sediments from the deepest parts of Lake Baikal. Box corers offer many advantages over conventional narrow tube gravity and piston corers. They can collect relatively large quantities of material, and because the surface area of the sediment sampled is also much larger, surface sediment compression effects are minimized (Nevissi *et al.* 1989). Conventional box corers are however usually heavy, partially a result of the cumbersome jaw closing mechanisms. Additionally, these jaws have a large cross-sectional area which restricts penetration of the corer into sediment. The box corer developed specifically for this project breaks away from the traditional jaw closing mechanism and uses a thin stainless steel cutting blade operated by tensator springs to close the sampling box (Monteith *et al.* 1993).

A core was collected (BIK 6) using the UCL designed box corer in September 1992 (Fig 1). The sediment was subsampled and dated radiometrically using ^{210}Pb analyses before being analysed for diatoms, heavy metals, magnetic minerals and carbonaceous particles.

The sampling program was resumed in July 1993 and a total of 29 surface sediment cores were retrieved from the three basins of Lake Baikal using both the UCL box corer and a conventional gravity corer (Appendix 3, Fig 19). These cores were sectioned immediately after collection and sealed in Whirlpak bags. They are currently awaiting analysis at the ECRC, London.

2. Methods

2.1 Coring procedure

A surface sediment core was taken from a deep part of the lake (1420 m) (September 1992) in the southern basin of Baikal (51° 48' 38" N, 104° 51' 38" E) using the UCL designed box-corer (Fig 1). The box corer was attached to a metal cable and lowered using a motorised winch on board the Russian science vessel RV *Verashchagin*. The core (BIK 6), which had an undisturbed surface sediment - water interface, was extruded at 2 mm intervals (for the top 3 cm of the core) and then at 5 mm intervals below and sectioned using a screw-threaded extruding rig. The sections were immediately sealed in Whirlpak bags, labelled and returned to UCL for further investigation.

2.2 Sediment analyses

Sediment samples were subjected to lithostratigraphic analyses according to the methods described in Stevenson *et al.* (1987).

2.3 Radiometric Dating

Sediment samples were analysed for ^{210}Pb, ^{137}Cs and ^{241}Am by non-destructive gamma spectrometry (Appleby *et al.* 1988).

2.4 Geochemical Analyses

0.125 g of dried sediment were digested using 5 ml HF, 1 ml HNO_3 and 0.5 ml $HClO_4$ (all concentrated analytical reagents). The mixture was evaporated to near dryness on a hot plate in 50 ml PTFE beakers. The resulting salts were dissolved in 1 ml HCl and diluted to 15 ml.

Elements were then determined using a Varian AA-1275 with programmable sample changer under the conditions set out in Table 1 (see over).

2.5 Mineral Magnetic Analyses

Samples of dried sediment were gently ground from which an aliquot of ca. 0.2 g was taken for measurement in a Molspin vibrating sample magnetometer (VSM). The VSM measured the magnetisation of the sample through a preset sequence of 21 field strengths ranging from zero to 1000 mT. After each magnetisation the sample was measured at zero field for its isothermal remanence. The VSM is calibrated to a palladium standard (moment at 1000 mT = 31.23 mA m^2) and field strengths are repeatable to ± 0.1 mT at zero field, and to ± 1 mT at high fields (> 100 mT). The precision of the equipment, as shown by the coefficient of variation for repeated measurements of the calibration sample, is ca. 0.1 %. The detection limit is ca. 0.01 mA m^2; the nylon sample holders have a diamagnetic moment of ca. -0.2 mA m^2 at 1000 mT which was insignificant to the moment of the samples.

2.6 Carbonaceous particle analyses

Dried sediment samples were prepared for carbonaceous particle analyses by the method detailed in Rose (1989). For counting purposes, a known fractions of the residue were evaporated onto coverslips, mounted using 'Naphrax' and the whole of each coverslip counted at x 400 using a light microscope.

2.7 Diatom analyses

Wet sediments were prepared for diatom analyses following the procedure set out by Battarbee (1986), omitting the hydrogen peroxide treatment as organic content of the sediment is generally less than 3 % (Edgington *et al.* 1991). Diatom identifications were based on LM and SEM, using published diatom floras eg. Krammer & Lange-Bertalot (1991) and Russian and English literature, eg. Skvortzow (1937); Skvortzow & Meyer (1928); Håkansson & Stoermer (1984).

Routine analyses also included procedures for recording diatom preservation quality. Different stages of valve preservation of 5 diatom species could be recognised under the light microscope: three stages for *Aulacoseira* spp. and four for the *Cyclotella* spp. (Flower & Likhoshway 1993). In each sample analyzed, preservational states for each common diatom taxa were recorded and a simple index of diatom dissolution (DDI) was used to enable samples to be numerically compared.

$$DDI = \frac{\sum_{i=1}^{n} x_{1i}}{\sum_{i=1}^{n} x_{1i} + \sum_{i=1}^{n} x_{2i}}$$

where n = no. of taxa, x_{1i} = no. of valves i in preservation stage 1 (pristine), x_{2i} = no. 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.

Table 1 Operating conditions for trace metal analysis using a Varian AA-1275

Element	Dilution	Method	Oxidant	Additives
Fe	1:30	AAS	air	$LaCl_2$
Mn	1:30	AAS	air	$LaCl_2$
Al	1:30	AAS	N_2O	$LaCl_2$
Mg	1:30	AAS	air	$LaCl_2$
Ca	1:30	AAS	air	$LaCl_2$
Na	1:30	Emission	air	KCl
K	1:30	Emission	air	$LaCl_2$
Cd	none	AAS	air	none
Co	none	AAS	air	none
Cu	none	AAS	air	none
Ni	none	AAS	air	none
Pb	none	AAS	air	none
Zn	none	AAS	air	none

3. Results

3.1 Lithostratigraphy

Wet density and percentage dry weight profiles (Fig 2) show a general decline from the bottom of the core up to the top, indicating a gradual increasing water content in the upper layers of sediment. There are however some reversals in this trend, the most notable one occurring between 1934 - 1946 ^{210}Pb years AD (corresponding to 6 cm and 5 cm). Two further short-lived increases in % dry weight occur between 1969 and 1974 ^{210}Pb years AD (2.4 - 2.8 cm) and in 1983 ^{210}Pb years AD (1.5 cm). Sediments from Lake Baikal are primarily siliceous with substantial quantities of iron and manganese oxides in the upper most layers (Leibovich 1983) (Table 2).

3.2 Radiometric Dating

The ^{210}Pb results are given in Table 3 and the ^{137}Cs and ^{241}Am results in Table 4. Dates were calculated using both the CRS and CIC ^{210}Pb dating models (Appleby & Oldfield 1978). The results are shown in Fig 3 and there is little significant difference between the two sets of dates. Both models indicate a more or less constant sediment accumulation rate over the past 150 years of 0.019 ± 0.002 g cm^{-2} yr^{-1} (0.079 ± 0.010 cm yr^{-1}). Accumulation rates since 1900 do appear to be slightly higher than in the 19th century. The results are summarised in Table 5.

Maximum values of the fallout radionuclide ^{137}Cs occur in the top 2 cm of the core, though there is no discernable peak in the activity. The graph of ^{241}Am activity versus depth, also a product of fallout from the atmospheric testing of nuclear weapons does have a distinct peak at the 1.7 cm level, though standard errors in the determination of this radionuclide are quite high. Taken together, the two sets of results suggest that the 1963 fallout maximum is recorded at a depth of just above 2 cm. Since this level of the core has been dated by ^{210}Pb to ca. 1980, it would appear that there is a time lag of ca. 15 years for transport of fallout radionuclides through the lake waters to the sediments, as suggested by Edgington *et al.* (1991).

3.3 Geochemical Analyses

The results of geochemical analyses are shown plotted against depth in Fig. 4 and averaged values for the top 1 cm and bottom 2 cm are shown in Table 6 where they are compared with average shale (Krauskopf 1982).

The composition of the deeper sediment is very similar to average shale; the alkalis and alkaline metal totals are somewhat lower than average however, with the overall total lower. The surface sediment on the other hand, differs strongly in its Mn and to a lesser extent its Fe content, which are both relatively enriched.

Mn and Fe enrichment occurs only in the top 4 cm of the core (Fig 4). The two increase simultaneously, but Fe peaks at 2 cm, and falls to the surface, while Mn peaks at 1 cm and remains high. All of these trace elements show some enrichment in the upper part of the core. They do, however, vary in degree of enrichment and pattern. Co, and to some extent Ni, behave like Mn, by having similar increasing concentration profiles. In the top 4 cm of the core 96 % of the Co variance, and 90 % of the Ni variance, can be explained by Mn concentration. Cu and Pb are very slightly enriched in the upper part of the core, but in both cases the enrichment starts at a slightly greater depth than the Mn and remains constant to the surface instead of rising as Mn does. Zn does not show a general enrichment in the upper part of the core, but instead shows a sharp increase in the top 1 cm of the core. There is come indication that Cu behaves in a similar way.

3.4 Mineral Magnetic Analyses

As yet only a preliminary report is available and only the figures referred to in the discussion are described here.

The data were analysed in two ways. First, the complete magnetisation and remanence sequences for each sample were graphed both as mass specific and normalised data sets. Second, conventional magnetic parameters were calculated from the data sets and graphed for each sample in depth sequences. The following parameters were calculated from a specially designed spreadsheet, but not all are described in this report; low-field susceptibility, high-field susceptibility, low-field susceptibility - high-field susceptibility, high field remanence, low field remanence, (saturation) remanence at 1000 mT (Mrs), (saturation) magnetisation at 1000 mT (Ms) and finally the ratio of saturation remanence to saturation magnetisation (Mrs/Ms).

Remanence and magnetisation curves.
Figure 5 shows mass specific remanent magnetisation curves for all 28 samples measured. All the curves, except 2, rise from the origin and reach maximum values in field strengths of 100 - 300 mT. The curves all show fairly steady values in successively higher fields up to 1000 mT. The main difference between the samples is the magnitude of the maximum remanent magnetisation, ranging from ca. 300 to ca. 800 mA m^2 kg^{-1}. The values of the two samples which do not start at the origin are erroneous and should be ignored.

Magnetic parameters
A combination of magnetisation and remanence data provides a large number of magnetic parameters. Here, three parameters have been chosen which identify specific mineral groups. The difference between low and high field susceptibilities is a measure of the ferrimagnetic minerals, such as magnetite, a dominant constituent of fly ash particles (Oldfield & Richardson 1990). Fig 6 shows this parameter rising from minimum values at the base of the core to reach peak values at 7.0 - 7.5 cm and 3.5 - 4.0 cm.

Fig 7 shows high field susceptibility which is a measure of paramagnetic minerals, which may define many rock-forming and clay minerals. The values indicate that about 25 % of the overall susceptibility is caused by the presence of non-ferrimagnetic minerals. The plot with depth is similar in trend to Fig 7, but with a clear peak in the uppermost 2 cm, and high values at lower depths are less pronounced.

In Fig 8, the canted antiferrimagnetic component, normally haematite or goethite, is recorded by the parameter IRM 1000 mT - IRM 100 mT. It shows the clearest trend of all the parameters with values quadrupling from the base of the core to reach peak values at 1.0 - 2.5 cm. A secondary peak is apparent at ca. 10 cm.

3.5 Carbonaceous Particle Analysis

The concentration of carbonaceous particles in BIK 6 sediments show an approximate 5 - fold increase between ^{210}Pb years 1974 and 1989 (Fig 9). Taking into account the possibility of long residence times of particles in the lake, the actual date of this increase may be put back to the early 1960s. Concentration and flux values of carbonaceous particles in from BIK 6 are similar to those found for remote Scottish lochs (eg. Rose 1989; Rose & Battarbee 1991).

3.6 Diatom Analyses

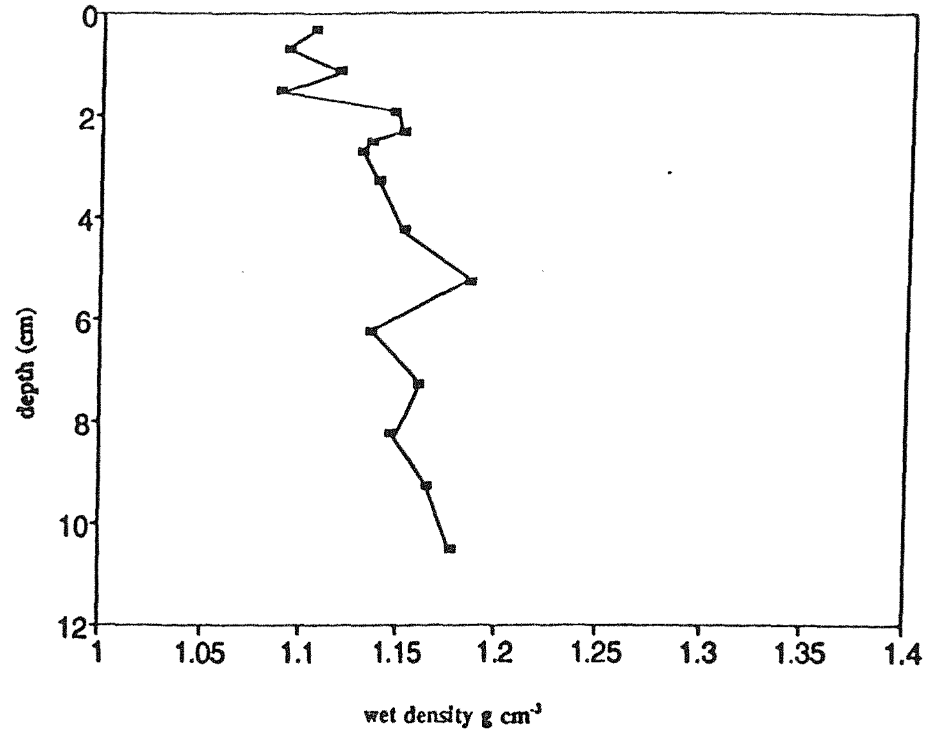
There is little variation in the diatom flora down the length of the core: planktonic taxa are by far the dominant taxa accounting for around 95 % of all the species identified throughout the profile (Fig 10). Overall, there appears to be a minor shift in species composition between the two genera, *Cyclotella* and *Aulacoseira* species. Between 1989 AD and 1992 AD, however, there is a notable shift between *Aulacoseira islandica* type cells to *Aulacoseira baicalensis* type cells. These two cell types are morphotypes of the same species, *Aulacoseira baicalensis* (Popovskaya & Skabitschevsky 1970; Likhoshway *et al.* 1992).

Other features of note in the diatom profile include a rise in *Stephanodiscus* cf. *parvus* from the late 19th century until the 1930s, when numbers decline to around 10 % total diatoms up to the present day. A sustained presence of *Cyclostephanos dubius* exists after 1957 AD. There is also a small increase in the percentage of *Synedra acus* from approximately 3 % in 1963 AD to 6 % at the present day.

Dissolution indices have been calculated for the two most common genera, *Cyclotella* spp. and *Aulacoseira* spp. (Figs 11 and 12). Overall, dissolution patterns for the two genera are very similar, with better preservation coinciding with higher % dry weights. It can be seen from the indices that the majority of valves of both species are affected to some degree by dissolution, with the DDI values for *Cyclotella* spp. decreasing to lower levels than for *Aulacoseira* spp. in the top 3 cms of sediment. The low DDI values for *Cyclotella* spp. at ca. 3 cm coincides with the change from oxidised sediment to reduced, anoxic sediment (Table 6). Overall, DDI values for n = 4 indicate that diatom valves are slightly better preserved in the upper sediment layers than those deeper down.

A comprehensive list of diatom taxa encountered in this core is given in Appendix 2.

Fig 2 Wet density measurements (g cm^{-3}) and dry weight values vs depth (cm)



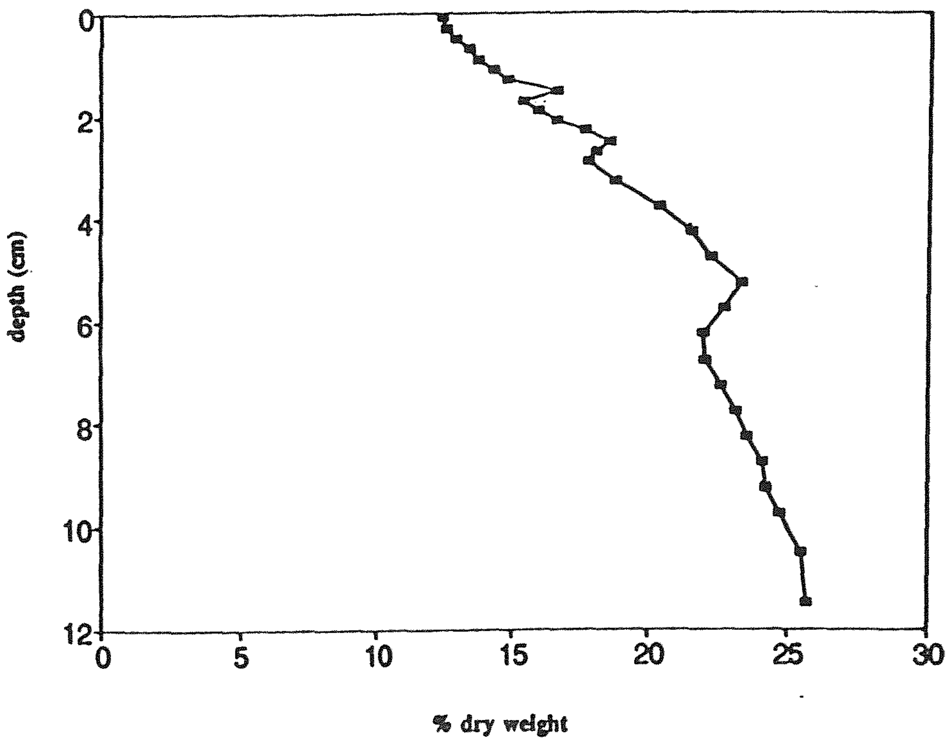


Table 2 Lithostratigraphy of core BIK 6

Depth (mm) Description

BIK 6	Description
0 - 13	10YR 2/1 very dark brown Lso3 Lf1
14 - 16	2.5YR 4/8 red / brown Lf4
17 - 30	10YR 2/1 very dark brown Lso3 Lf1
31 - 100	2.5Y 6/0 grey Lso4
101 - 130	2.5Y 6/0 grey + 2.5Y 2/0 black Lso4

Table 3 Lake Baikal BIK 6: ^{210}Pb data

Depth	Dry Mass	^{210}Pb Concentration			
		Total		Unsupported	
(cm)	g cm^{-2}	pCi g^{-1}	+/-	pCi g^{-1}	+/-
0.10	0.014	16.07	0.46	14.38	0.47
1.10	0.162	16.79	0.61	15.03	0.62
1.70	0.264	16.98	0.74	15.10	0.76
2.30	0.377	13.83	0.56	12.32	0.57
3.25	0.575	11.01	0.30	9.73	0.31
4.25	0.808	7.51	0.33	6.33	0.34
4.75	0.935	6.04	0.23	4.77	0.24
6.25	1.333	4.41	0.21	3.10	0.22
7.25	1.588	3.30	0.23	2.03	0.24
8.25	1.854	2.69	0.18	1.40	0.19
9.25	2.132	2.53	0.32	1.46	0.33
9.75	2.275	2.16	0.19	0.81	0.20
11.5	2.798	1.40	0.14	0.27	0.15

Unsupported ^{210}Pb inventory: 13.8 +/- 0.40 pCi cm^{-2}

Unsupported ^{210}Pb flux: 0.43 +/- 0.01 pCi cm^{-2} yr^{-1}

Table 4 Lake Baikal BIK 6: ^{137}Cs and ^{241}Am Data

Depth	^{137}Cs conc		^{241}Am conc	
(cm)	pCi g^{-1}	+/-	pCi g^{-1}	+/-
0.10	4.92	0.13	0.03	0.02
1.10	4.96	0.14	0.08	0.04
1.70	4.55	0.21	0.11	0.03
2.30	4.22	0.13	0.06	0.03
3.25	3.00	0.07	0.02	0.01
4.25	1.52	0.08	0.05	0.02
4.75	1.15	0.05	0.00	0.00
6.25	0.32	0.03	0.00	0.00
7.25	0.15	0.04	0.00	0.00
8.25	0.00	0.00	0.00	0.00
9.25	0.00	0.00	0.00	0.00
9.80	0.00	0.00	0.00	0.00
11.5	0.00	0.00	0.00	0.00

Inventories 3.56 +/- 0.08 pCi cm^{-2} 0.05 +/- 0.01 pCi cm^{-2}

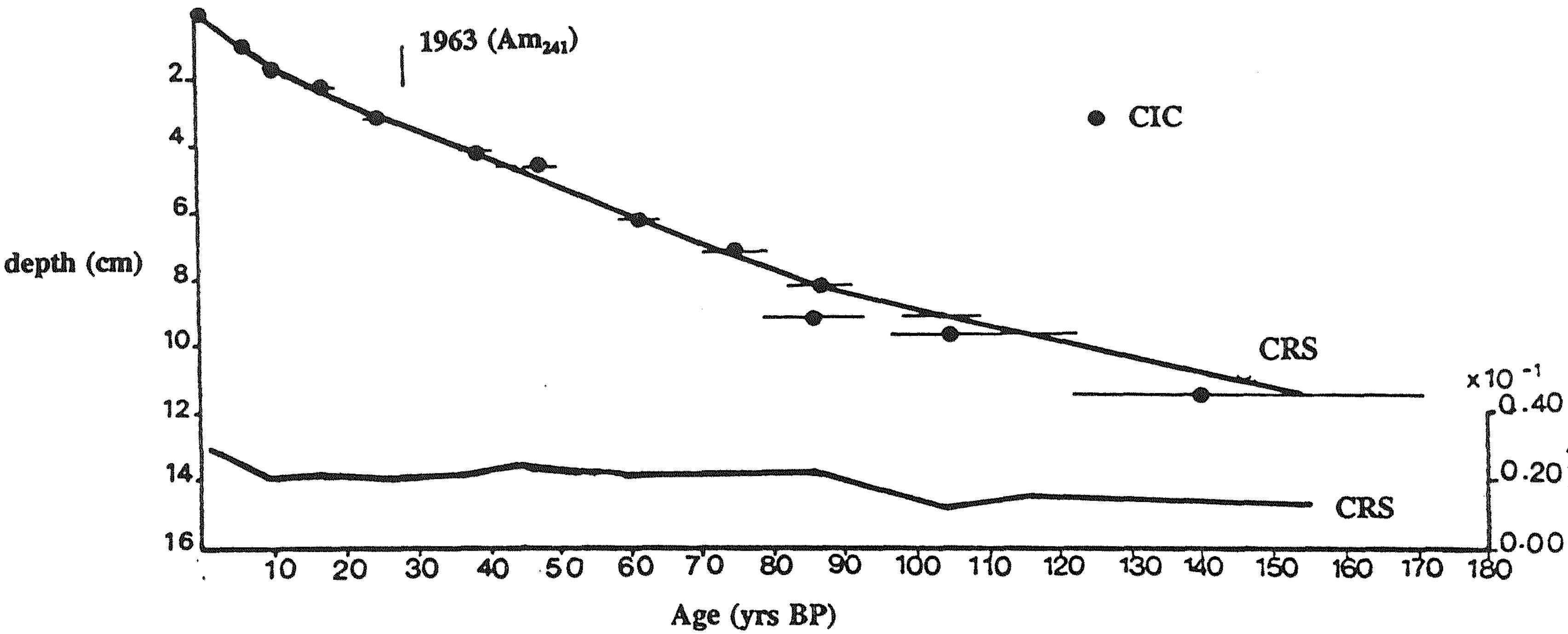


Fig 3

BIK 6 ^{210}Pb Chronology

Table 5 Lake Baikal BIK 6: ^{210}Pb chronology

Depth	Dry Mass	Chronology			Sediment Accumulation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	+/-	g cm^{-2} yr^{-1}	cm yr^{-1}	+/-
0.00	0.000	1992	0				
0.50	0.073	1989	3	1	0.0271	0.180	4.2
1.00	0.147	1986	6	1	0.0242	0.156	4.6
1.50	0.230	1983	9	1	0.0214	0.126	5.2
2.00	0.320	1979	13	2	0.0207	0.109	5.2
2.50	0.418	1974	18	3	0.0207	0.101	4.9
3.00	0.523	1969	23	3	0.0200	0.093	4.7
3.50	0.643	1963	29	3	0.0200	0.088	5.1
4.00	0.750	1957	35	3	0.0207	0.088	6.2
4.50	0.872	1952	40	3	0.0222	0.089	6.5
5.00	1.002	1946	46	3	0.0229	0.087	6.8
5.50	1.134	1940	52	3	0.0219	0.084	7.8
6.00	1.267	1934	58	3	0.0210	0.080	8.8
6.50	1.397	1928	64	4	0.0207	0.079	10.4
7.00	1.524	1921	71	4	0.0211	0.081	12.5
7.50	1.654	1915	77	5	0.0212	0.081	14.3
8.00	1.788	1909	83	5	0.0210	0.078	15.9
8.50	1.924	1901	91	6	0.0185	0.068	18.9
9.00	2.063	1892	100	7	0.0160	0.045	
9.50	2.204	1883	109	8	0.0160	0.045	
10.0	2.350	1874	118	10	0.0160	0.045	
10.5	2.499	1865	127	13	0.0160	0.045	
11.0	2.649	1856	136	16	0.0160	0.045	
11.5	2.798	1846	146	18	0.0160	0.045	

Fig 4 Trace metal profiles plotted against depth for BIK 6

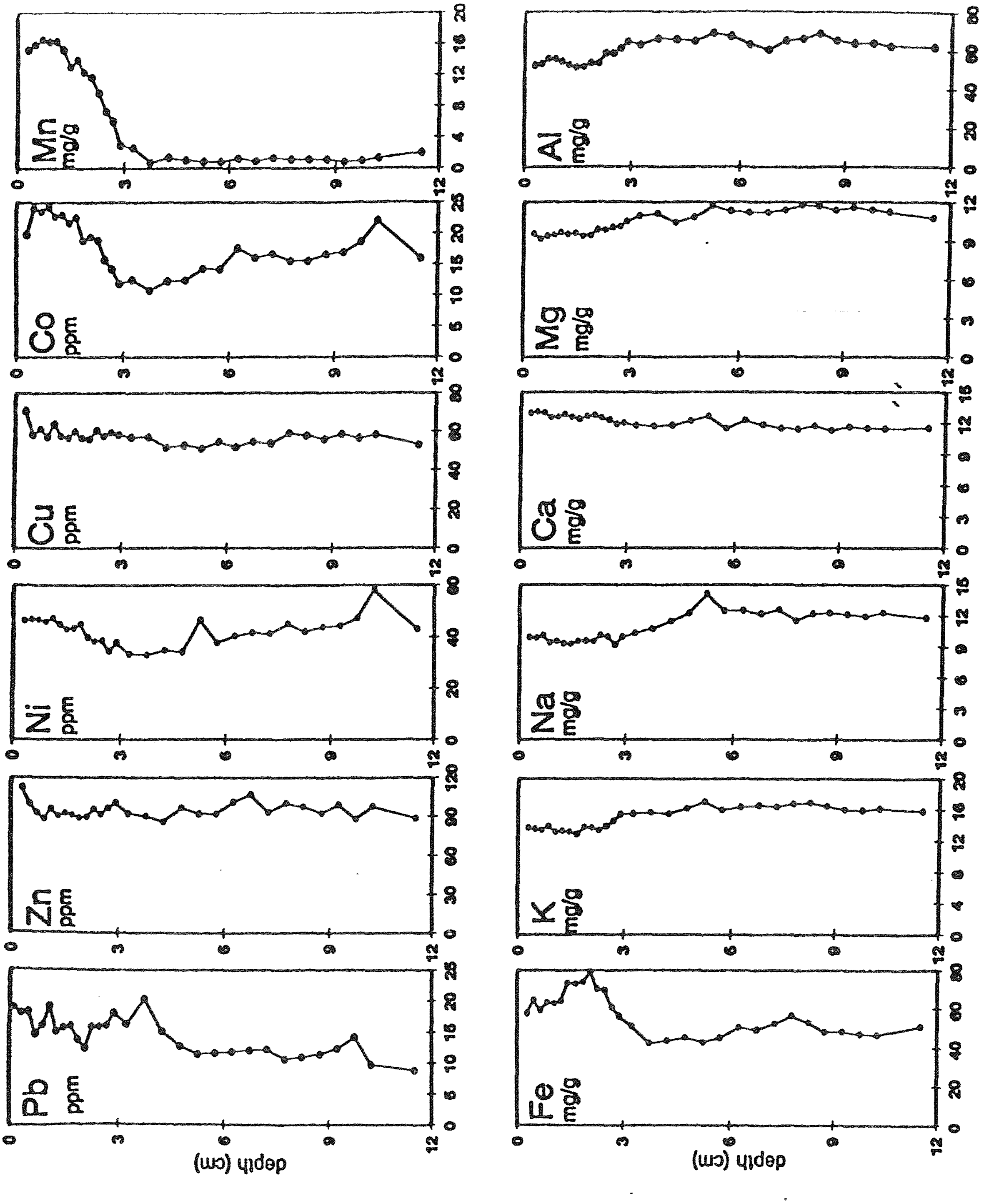


Table 6 Averaged values for trace metals for top 1 cm and bottom 2 cm compared with average shale (Krauskopf 1982)

Metal	BIK 6: 0 - 1.0 cm	BIK 6: 10 - 12 cm	Average shale
mg g^{-1}			
Al	54.3	64.4	92
Fe	61.2	49.2	47
Mn	16.1	1.2	0.85
Mg	9.5	11.3	14
Ca	13.0	11.5	25
K	13.7	16.2	25
Na	9.9	12.1	9
ppm			
Co	23	18	20
Cd	< 0.2	< 0.2	0.3
Cu	65	57	50
Ni	47	46	80
Pb	17	11	20
Zn	108	94	90

Fig 5 Mass specific remanent magnetisation curves for all samples measured

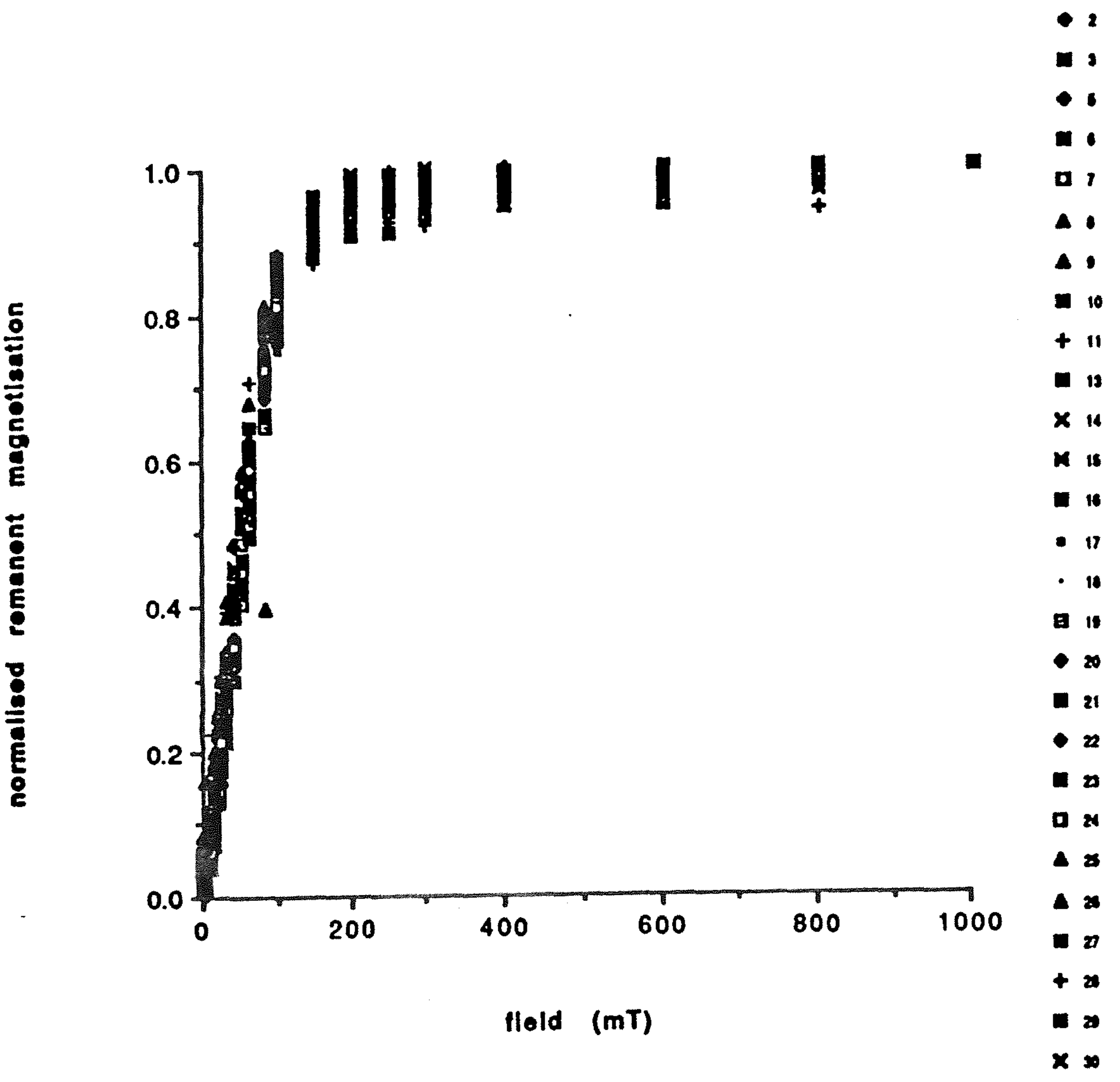


Fig 10 BIK 6 Summary diatom diagram (showing spp. found at values greater than 2 %)

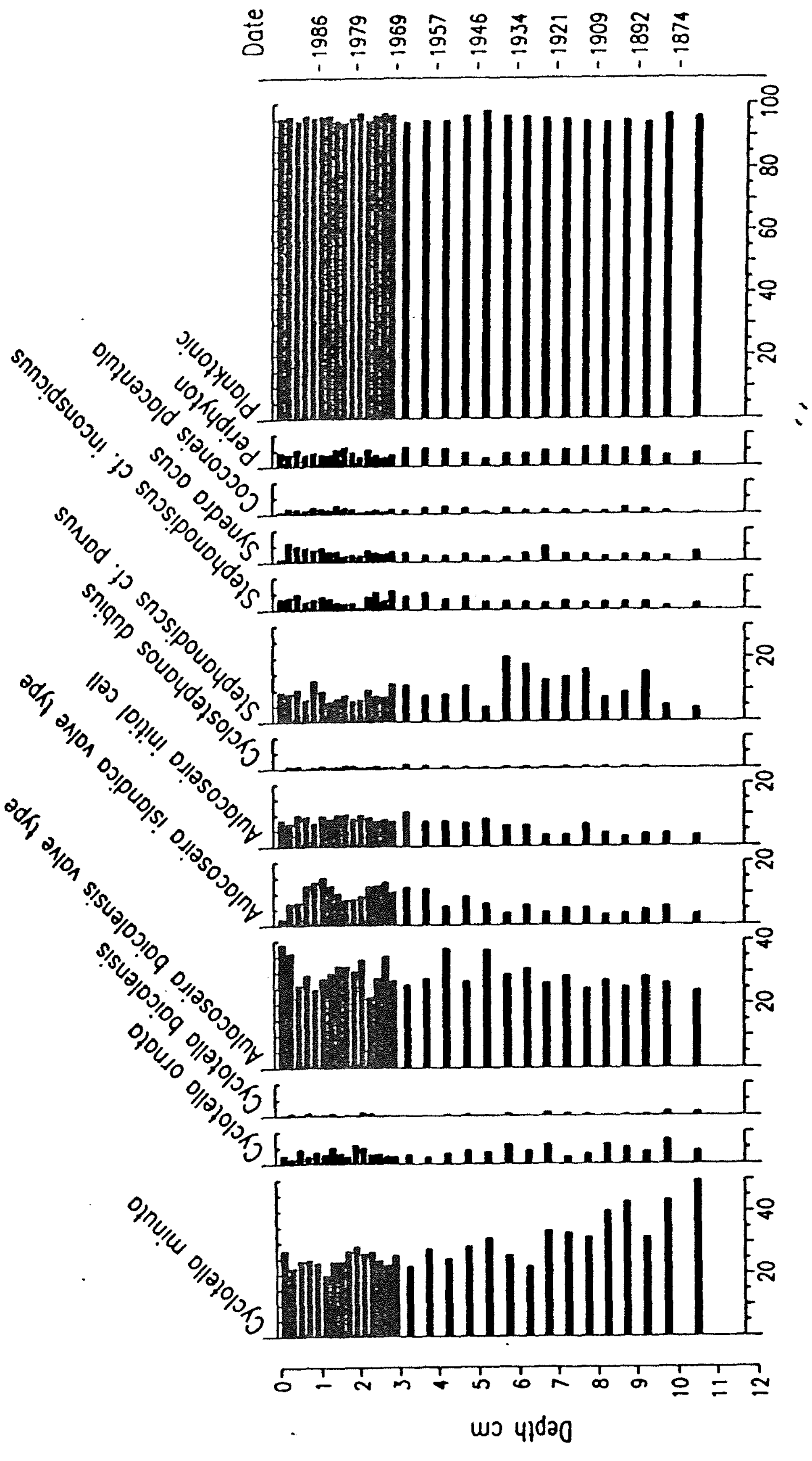


Fig 11 Diagram showing diatom dissolution indices (DDI) for *Cyclotella* spp. type valves (solid line) and for *Aulacoseira* spp. type valves (broken line).

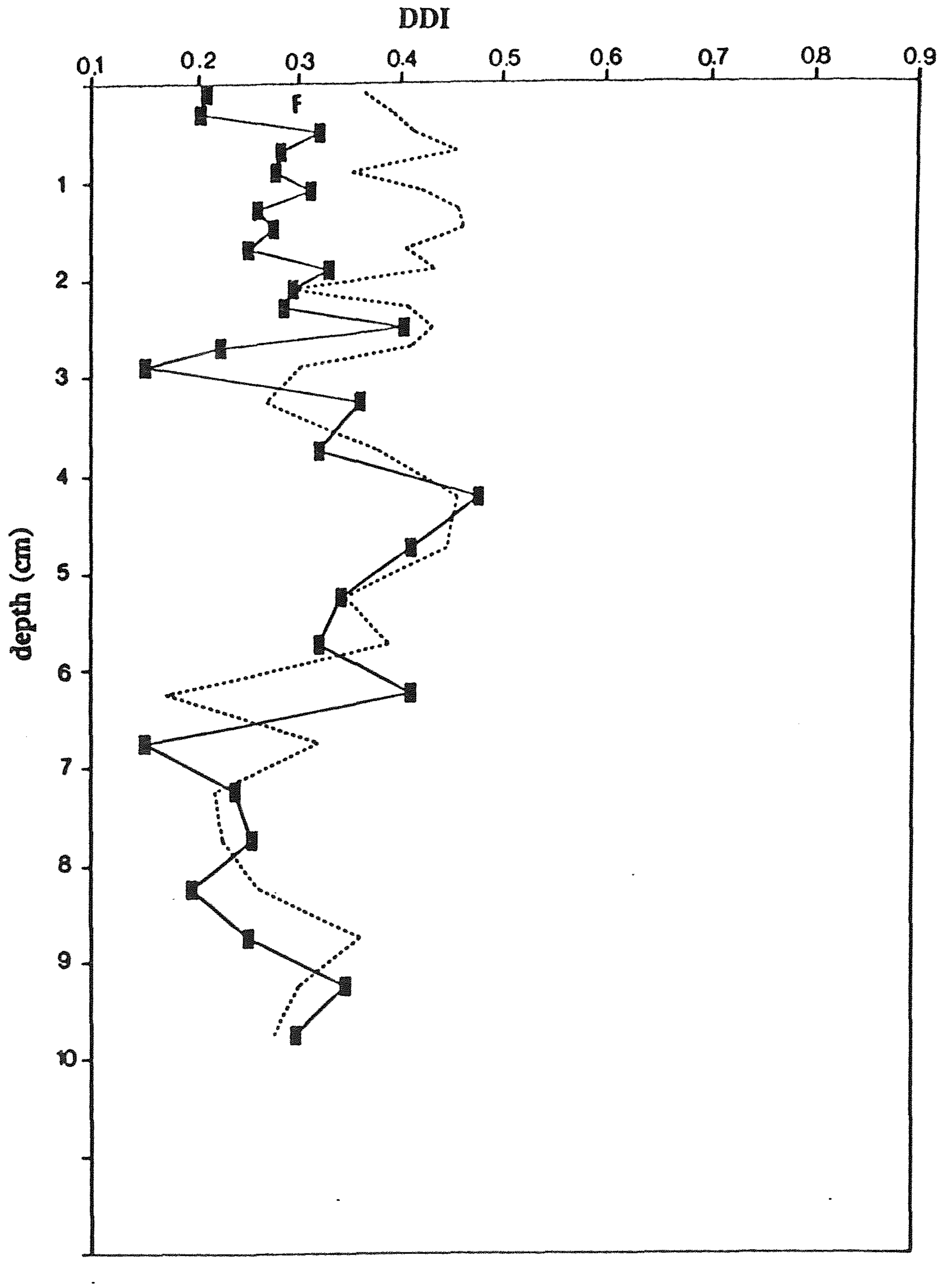
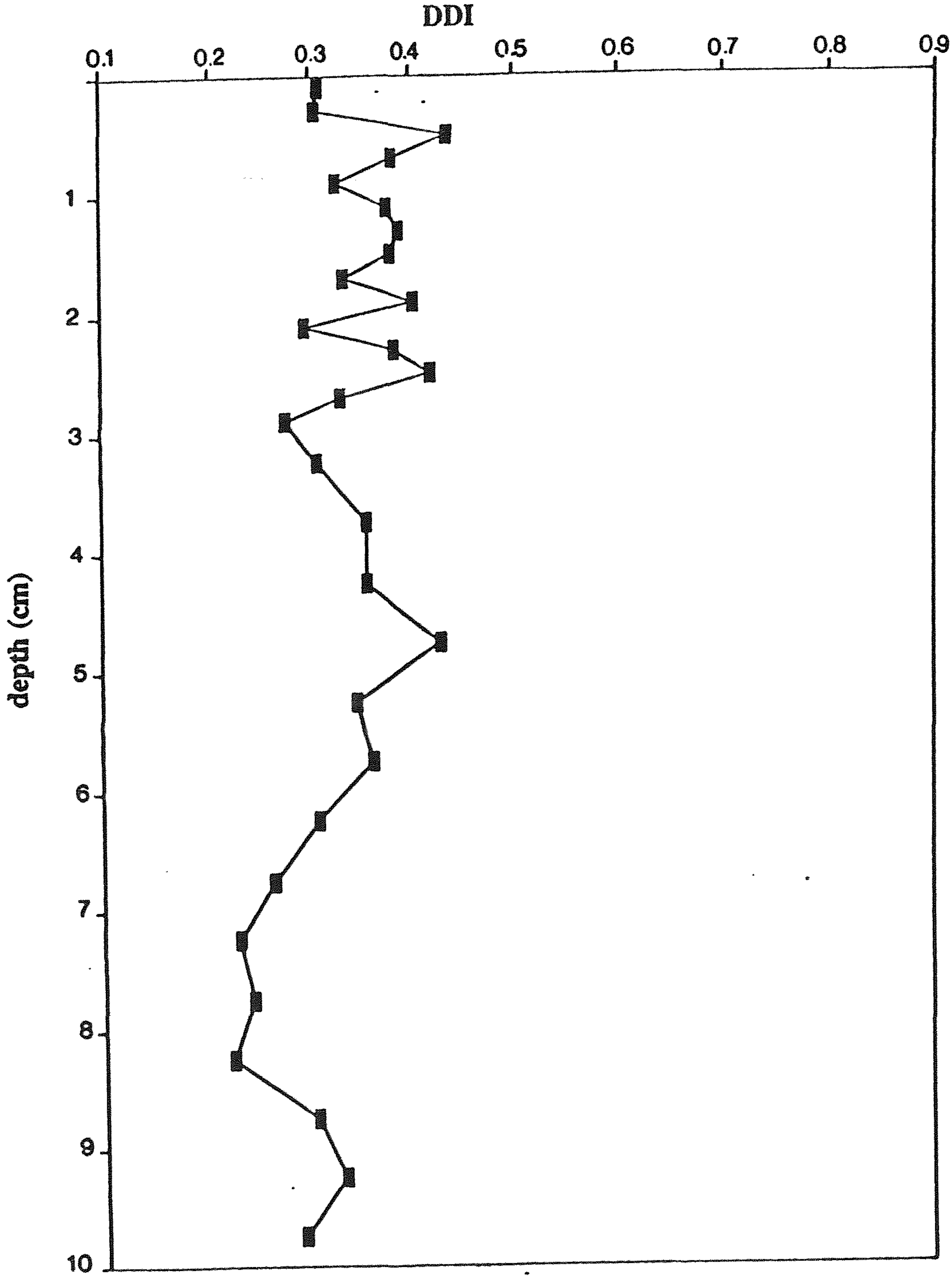


Fig 12 Diagram shown dissolution indices (DDI) for all valve types combined (n = 4)



4 Discussion

4.1 Lithology and Accumulation Rates

The Fe and Mn oxides give the upper oxidised sediments their characteristic brown colour. The bottom of the oxidised layer is usually represented by an Fe - Mn microzone in which the two elements are separated in accordance with their normal redox potential: under the very dark Mn layer is an orange iron crust (Leibovich 1983). These process are discussed in detail below. One of the major factors that sets Lake Baikal apart from other deep lakes is that the hypolimnion of Baikal is saturated with O_2, resulting in the upper sediment layers being oxidised (Leibovich 1983; Fryer 1991; Martin *et al.* 1993). As in ocean basins, the depth of this oxidised layer and redox potential increases from the edge of the lake to the centre (Leibovich 1983). Martin *et al.* (1993) recognise a distinct oxic layer and a deeper oxidised layer of sediment, which are strongly correlated. High Eh values in this oxic layer is associated with the presence of manganese oxides (Leibovich-Granina 1985 & 1987).

The dry weight sediment accumulation rate is fairly constant, suggesting that there has been little disturbance of sediment accumulation processes. The slight post 1900 increase in accumulation rate may be a factor of increasing lake productivity (due to effluent pollution), to an increased input of terragenous matter from the catchment because of logging and soil erosion, eg. as also suggested by the small increases in magnetic mineral concentrations, or simply a function of some ^{210}Pb mixing in the uppermost sediments (Edgington pers. comm). Granina *et al.* (1993) report an increase in biogenic silica (SiO_2) in the uppermost sediments of cores taken from the southern basin. They have attributed this increase to a natural eutrophication of the lake, although the apparent increase in biogenic silica could be a factor of incomplete silica dissolution (Schelske *et al.* 1983; Granina *et al.* 1993).

The reversal in trends of wet density and % dry weights described above may be significant for core correlation if they show up in other cores from the same area. The increase in % dry weight at 5 cm depth is likely to reflect a change in sediment grain size. If this is the case, then the change will probably show up in other cores, which may allow this increase to be used as a stratigraphical marker.

4.2 Geochemical Analyses

The similarity of most elements to average shale indicates that there is no special enrichment process occurring, suggesting that atmospheric contamination from local industries and automobile use are not sufficient to be clearly recorded against background levels. This contrasts strongly with surface sediments in Western European lakes, where deposition of metals from industrial sources causes substantial enrichment (eg. Jones *et al.* 1990; Renberg *et al.* 1990).

The enrichment of the surface sediment in Mn and Fe is typical of slowly deposited terrigenous sediment, where there is sufficient organic matter (a few percent) to promote sub-surface anoxic diagenesis (Calvert & Price 1970). Oxygen diffusing into the sediment keeps an upper layer of sediment oxidizing (Martin *et al.* 1993). Beneath this layer, conditions are sufficiently reducing for Mn to come into solution, and the steep gradient in dissolved Mn thus generated leads to an upwards migration of the Mn. Depletion of Mn at depth leads, under steady-state conditions, to a sharp subsurface peak in Mn. Fe behaves similarly, but comes into solution only after all the Mn oxide has gone into solution. Depletion and re-precipitation of Fe thus occurs deeper that Mn, leading to a peak deeper in the profile. Dissolution of Fe and Mn oxides releases trace elements which were adsorbed or co-precipitated. Commonly these reprecipitate with the Mn or Fe, such that sub-surface enrichments of trace elements occur. This separation of Fe and Mn can be seen in Table 2 and Figure 5, and is evidence that redox recycling is an important process in Baikal surface sediments. That Mn remains fairly constant over the top 1 cm instead of declining towards the surface indicates either that the position of the redox front has been migrating downwards, or that there is active bioturbation (Gratton *et al.* 1990) which will cause an extension of the diffusive boundary layer more deeply into the sediment (Jφrgensen & Revsbech 1985). Evidence of bioturbation in isolated cores from the Selenga Delta has also been demonstrated by Martin *et al.* (1993).

Leibovich (1984) reports that Cu, Ni, Co, Pb and Zn are slightly enriched in the manganese layers, particularly Co, with an enrichment ration of 1.3. The results presented here suggest greater enrichment of Co, but little if any of Cu and Zn. The composition is similar to that found in Loch Fyne (Calvert & Price 1970) and is typical of near shore (as opposed to pelagic) oceanic manganese enrichments.

Only the Zn distribution cannot be explained by recycling. The small, but sharp, increase is in the top 1 cm, above the zone of recycling. Given the clearly oxidising character of the upper part of the sediment, the surface Zn enrichment cannot be explained by subsurface dissolution. The increase in concentration dates to approximately 1986 AD (Fig 4). However, both Edgington *et al.* (1991) and this study suggest settling rates of radionuclides of approximately 15 years. If this holds true, then the actual date of increasing Zn concentrations would be put back to 1971 AD - only five years after the Baikalsk pulp and paper mill started operating.

4.3 Mineral Magnetic Analyses

Magnetic measurements of lake sediments can provide information about processes which have been operating in the lake's drainage basin eg. erosion of catchment soils resulting from forest clearance and farming (Thompson 1973; Thompson *et al.* 1980).

Only preliminary data are available at this stage, but results so far suggest that there is a trend towards higher magnetic concentrations for BIK 6 in the more recent sediments. Thus it could be argued that in the last 20 - 30 years there has been a higher flux of allochthonous minerals from the catchment to the sediments, presumably as a result of increased erosion from the catchment as logging was carried out.

From the results obtained so far, there is no clear evidence for either a magnetic pollution record or reduction diagenesis / dissolution of magnetic minerals, but neither can be ruled out at this stage. Reduction diagenesis can reduce magnetite (Fe_3O_4) to pyrite (FeS_2) in anoxic sediments (Karlin & Levin 1983). However, Kling *et al.* (1993) also have found no evidence to suggest that this occurs in another, longer core taken from the southern basin.

4.4 Carbonaceous Particle Analysis

Carbonaceous particles are produced by fossil fuel combustion and can be found in considerable quantiites in recent lake sediments in areas of high acid deposition (eg. Griffin & Goldberg 1981; Renberg & Wik 1984; Wik *et al.* 1986; Rose & Battarbee 1991). A close correlation has been shown by Battarbee *et al.* (1989) between the onset of atmospheric contamination, as indicated by carbonaceous particles, and the acidification of lakes as indicated by diatom analysis.

As mentioned above, flux levels of carbonaceous particles found in BIK 6 sediments are appreciable, being similar to those found in remote Scottish lakes. Thus it has been demonstrated, with less ambiguity than for the geochemical and magnetic mineral analyses, that Baikal sediments contain a record of anthropogenic contamination over the last 3 to 4 decades. This is further supported by the carbonaceous analyses done on a remote Highland lake, Lake Kholodny, in the Khamar Daban Range to the south of Lake Baikal (Flower *et al.* 1993). Here, the flux values are less than 10 % of those found in BIK 6. This demonstrates that traces of atmopspheric contamination can be detected in very remote areas (see also Rosen *et al.* 1981) and that the contamination of Baikal is substantially higher than the more remote regions in the catchment area. However, other considerations must be borne in mind at this stage, such as the possibility of a sediment focusing effect in this area, and the actual proximity of the core site to Irkutsk.

4.5 Diatom Stratigraphy

There are no major changes in diatom species abundances in BIK 6 over the last 100 years associated with water quality deterioration or culturally induced eutrophication, as exemplified by the historical responses of small *Stephanodiscus* and *Cyclostephanos* spp. (Haworth 1972; Fritz 1989; Anderson 1990; Bennion 1993) elsewhere. However, throughout the latter half of this century there has been a small increase in more cosmopolitan species, such as *Synedra acus* and the consistent presence of *Cyclostephanos dubius*. Kozhova (1987) has also demonstrated abundance increases in *S. acus* and *Nitzschia acicularis* in the southern part of the lake. However, *Nitzschia* spp. are amongst some of the first species type to be affected by dissolution (Ryves pers. comm.), which may account for the lack of potential increase in valve numbers in the lake sediments.

Major changes in diatom flora resulting from effluent or industrial pollution are more likely to occur in cores taken from sites nearer to pollution sources, such as the Selenga Delta region. Martin *et al.* (1993) have demonstrated that eutrophication of the Selenga Delta waters is complicated by current systems, with regions of the Delta not affected by eutrophication processes. Preliminary diatom analyses of a surface sediment core taken in

March this year, from near the Selenga Delta, do exhibit a small increase in *Stephanodiscus* spp..

The two *Aulacoseira* type valves belong to the same species, *Aulacoseira baicalensis*, but as yet there is little information about whether these two valve types are characteristic if different ecological conditions. Popovskaya & Skabitschevsky (1970) suggest that the age of the valve may be more important in determining the valve type that settles into the sediment. Work addressing this problem using cultures of *Aulacoseira baicalensis* has begun at the Limnological Institute in Irkutsk.

The taxonomy of the two most abundant *Stephanodiscus* spp. has not yet been finalised to species level: SEM work is about to begin to determine the identity of *S.* cf *parvus* & *S. binderanus*, and a paper is already in preparation (Håkansson & Flower unpub) regarding the taxonomy of the recently described *S. inconspicuus* (Makarova & Pomazkina 1992).

4.6 Dissolution Indices

Dissolution indices for *Cyclotella* species and *Aulacoseira* species follow the same pattern, except during the last 20 years where the proportion of dissolved *Cyclotella* valves increases. A possible explanation for this may that the marginal area of *Cyclotella* spp. is not as heavily silicified as the valve mantle of *Aulacoseira* spp. and hence more prone to dissolution in the upper oxidised sediments. High index values, indicative of good preservation, are coincident with high percentage dry weights. This may be because the higher diatom concentrations will result in higher silica concentrations in the sediment pore waters and thus will slow the dissolution of silica from the diatom frustules into the surrounding micro-region.

Lewin (1961) reports that the availability of polyvalent cations may also affect diatom dissolution - these cations provide a protective coating, slowing down the rate of silica dissolution. The upper sediments of BIK 6 exhibit high concentrations of Mn and Fe cations and although no clear relationship appears to exist between DDI's for BIK 6 and Mn and Fe concentrations, one may become apparent as more cores are analysed. It should be noted however, that where the sediment ceases to be oxic, and becomes reduced, there is a temporary increase in the proportion of dissolved valves. Analyses of further cores ought to demonstrate whether this is significant, and whether it is related to changes in Mn concentrations.

Until now, there have been no known studies of the dissolution and preservation of diatoms in Baikal sediments. But these results are likely to be extremely important when taken in conjunction with other parameters such as biogenic silica concentrations and rates of diatom accumulation in the sediments. All three parameters, which are intrinsically linked together, ought to provide clearer information regarding differences in lake productivity from different areas of Lake Baikal.

4.7 Conclusions

The results for core BIK 6 so far indicate that the surface sediments from southern Baikal contain a small, but determinable, record of anthropogenic activities. Many of the processes investigated, such as atomic weapons testing, have occurred only over the last thirty years or so and can only just be detected in the very tops of the sediment. This, together with the fact that Baikal sediments have a slow accumulation rate and that the contamination record has only been in existence over the last few decades, makes the technique of fine resolution analysis intrinsic to data interpretation. Although few floristic changes could be determined in BIK 6, sites closer to pollution sources, such as the Selenga Delta (which also has higher sediment accumulation rates (Edgington *et al.* 1991)) are more likely to provide a more definite record of change due to effects on water quality by anthropogenic activities.

5. Summary

1. A deep - water surface sediment core was successfully retrieved from Lake Baikal using the UCL designed box corer.

2. The recent and undisturbed nature of the core is confirmed by radiometric dating methods -principally ^{210}Pb and ^{241}Am. Sediment accumulation rates are low (ca. 2 mg cm^{-2} yr^{-1}) and are fairly constant. Accumulation rates increase slightly towards the top of the core. A time lag of approximately 15 years has been suggested for the transport of fallout radionuclides through Baikal waters to the sediments. Inventories for these radionuclides are small in comparison to those found in British lakes.

3. There is some evidence of heavy metal enrichment of the sediment caused by atmospheric contamination. These increases are small, however, and complicated by redox processes involving Mn and Fe oxides.

4. There is a trend of increasing magnetic concentrations in recently deposited sediments which may indicate an increasing terrigenous input from the catchment area, caused by soil erosion. Diagenetic effects cannot, however, be ruled out at this stage.

5. Carbonaceous particle concentrations and fluxes increase substantially in the uppermost sediments, providing perhaps the most conclusive evidence that a determinable record of anthropogenic activity, from fossil fuel combustion, is held in Lake Baikal sediments. Flux levels are comparable to those determined for some Scottish lochs.

6. The diatom profile is dominated by two planktonic taxa, *Cyclotella minuta* and *Aulacoseira baicalensis* and there is little overall change in species abundances that may be caused by changes in water quality. There are notable increases, however, in more cosmopolitan species, such as *Synedra acus* and species characteristic of more eutrophic waters, such as *Cyclostephanos dubius*. Other minor changes include the decline of *C. minuta* abundances from the late 19th century until the mid 1930's as *Stephanodiscus* cf. *parvus* exhibits an increase. There is also a notable increase in coarsely punctate valves of *A. baicalensis* at the very top of the core. The reasons for such changes are as yet unresolved.

7. Results so far indicate that the upper sediments from southern Lake Baikal contain a record of a small, but detectable, contamination from anthropogenic activities. There are also small floristic changes in the diatom record, but whether these are linked to the contamination record is as yet unclear.

8. More cores from different locations need to be examined: the 29 cores collected during the summer of 1993 will be screened and some selected for detailed analyses in 1994.

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APPENDIX 1

BIK 6 Diatom Species List

Achnanthaceae, Bacillariaceae, Epithemiaceae, Fragilariaceae, Naviculaceae, Surirellaceae

Acnanthes cf. **amoena** Hust.
Acnanthes cf. **biasolettiana** Grun.
Acnanthes calcar Cleve
Acnanthes clevii Grun.
Acnanthes conspicua Mayer
Acnanthes daui Foged
Acnanthes denticula (Kutz.) Grun.
Acnanthes exigua Grun.
Acnanthes grana Hohn et Hellerman
Acnanthes grischuna Wuthrich
Acnanthes hauckiana Grun.
Acnanthes holstii Cleve
Acnanthes cf. **hungarica** (Grun.) Grun.
Acnanthes lanceolata (Bréb.) Grun.
Acnanthes laterostrata Hust.
Acnanthes linearis (W. Sm.) Grun.
Acnanthes lutheri Grun.
Acnanthes minutissima Kutz.
Acnanthes minutissima var. **jackii** (Raben.) Lange-Bertlot
Acnanthes oblongella Oestrup
Acnanthes ploenensis Hust.
Acnanthes salvadoriana Hust.
Acnanthes subexigua Hust.
Acnanthes unident.
Amphora inariensis Krammer
Amphora ovalis (Kutz.) Kutz.
Amphora ovalis var **pediculus** (Kutz.) Cleve
Amphora pediculus (Kutz.) Grun.
Amphora proteus Greg.
Amphora rotunda Skv.
Amphora sibirica Skv. et Meyer
Cocconeis placentula Ehr.
Cymatopleura solea (Bréb) W. Sm.
Cymbella lacustris (Ag.) Cleve
Cymbella minuta Hilse
Cymbella parva W. Sm.
Cymbella prostrata (Berk.) Cleve
Cymbella silesiaca Bleisch
Cymbella tumida (Bréb.) Van Heurck
Cymbella tumidula Grun.
Cymbella turgida Greg.
Diatoma vulgaris Bory
Didymosphenia geminata (Lyngbye) M. Schmidt
Diploneis domblittensis (Grun.) Cleve
Diploneis elliptica (Kutz.) Cleve
Diploneis parma Cleve
Diploneis turgida Skv.
Epithemia turgida (Ehr.) Kutz.
Fragilaria arcus (Ehr.) Cleve

Fragiliaria brevistriata Grun.
Fragilaria capucina Desmaz.
Fragilaria construens var. **venter** (Ehr.) Grun.
Fragilaria elliptica Schumann
Fragilaria lapponica Grun.
Fragilaria parasitica (W. Sm.) Grun.
Fragilaria pinnata Ehr.
Fragilaria pseudoconstruens Marciniak
Gomphonema innata Skv.
Gomphonema insigne Greg.
Gomphonema gracile Ehr.
Gomphonema minuta (Ostrup) Cleve-Euler
Gomphonema olivaceum (Hornemann) Bréb.
Gomphonema quadripunctatum sensu Patrick et Reimer
Gomphonema rhombicum Fricke
Gomphonema ventricosum (Greg.)
Gomphonema unident.
Gyrosigma attenuatum (Kutz.) Raben.
Meridion circulare (Greville) Ag.
Navicula anglica Ralfs
Navicula atomus (Kutz.) Grun.
Navicula cf. **bacillum** Ehr.
Navicula bottnica Grun.
Navicula capitata Ehr.
Navicula exilis Kutz.
Navicula expecta Van Landingham
Navicula goeppertiana (Bleisch) H. L. Smith
Navicula hasta Pantosceck
Navicula lanceolata (Ag.) Ehr.
Navicula lucinensis Hust.
Navicula miniscula Grun.
Navicula mutica Kutz.
Navicula perminuta Grun.
Navicula cf. **protracta** (Grun.) Cleve
Navicula reinhardtii Grun.
Navicula schoenfeldii Hust.
Navicula slesvicensis Grun.
Navicula subplacentula Hust.
Navicula vulpina Kutz.
Navicula unident.
Nitzschia alpina Hust.
Nitzschia angustata Grun.
Nitzschia fonticola Grun.
Nitzschia minuta Bleisch
Nitzschia subacicularis Hust.
Nitzschia spp. A
Nitzschia spp. F
Pinnularia obscura Krasske
Pinnularia cf. **viridis** (Nitzsch) Ehr.
Pinnularia spp. F
Reimeria sinuata (Greg.) Kociolek et Stoermer
Rhoicosphenia abbreviata (Ag.) Lange-Bertalot
Rhoicosphenia curvata (Kutz.) Grun.
Synedra acus Ehr.
Synedra ulna (Nitzsch) Ehr.
Tabellaria ventricosa Kutz.

Centrales

Aulacoseira baicalensis (Meyer) Sim.
Aulacoseira islandica ssp. **helvetica** (O. Mull.) Sim.
Cyclostephanos dubius (Fricke) Round
Cyclotella baicalensis Skv.
Cyclotella minuta (Skv.) Antipova
Cyclotella ornata (Skv.) Flower
Stephanodiscus cf. **parvus** Stoerm. et Hakan.
Stephanodiscus cf. **inconspicuus** Makarova et Pomazkina
Stephanodiscus cf. **skabitschevsky** Popovskaya

APPENDIX 2

Core Locations for ECRC study: Recent Environmental Change in Lake Baikal

NAME	DATE	LOCATION	BASIN
BIK 6	23-9-92	51° 48' 38" N 104° 51' 38" E	South
BIK 8	4-7-93	51° 38' 52" N 104° 35' 03" E	"
BIK 9	4-7-93	51° 43' 47" N 104° 21' 51" E	"
BIK 10	5-7-93	51° 42' 32" N 103° 57' 42" E	"
BIK 11	6-7-93	51° 47' 16" N 104° 47' 36" E	"
BIK 12	7-7-93	51° 41' 29" N 105° 00' 14" E	"
BIK 13	7-7-93	51° 41' 29" N 105° 00' 14" E	"
BIK 14	8-7-93	51° 47' 27" N 105° 27' 15" E	"
BIK 15	8-7-93	51° 55' 02" N 105° 40' 32" E	"
BIK 16	9-7-93	52° 05' 32" N 105° 51' 31" E	"
BIK 17	9-7-93	52° 11' 07" N 106° 47' 38" E	Selenga
BIK 17a	9-7-93	52° 06' 40" N 106° 07' 08" E	"
BIK 17e	10-7-93	52° 23' 25" N 106° 20' 26" E	"
BIK 17f	10-7-93	52° 27' 15" N 106° 26' 31" E	"
BIK 18	9-7-93	52° 18' 50" N 106° 07' 30" E	"
BIK 19	10-7-93	52° 27' 00" N 106° 07' 32" E	Buguldeika
BIK 20	11-7-93	52° 43' 29" N 106° 46' 12" E	Middle
BIK 21	11-7-93	52° 43' 03" N 107° 00' 05" E	"
BIK 22	12-7-93	52° 59' 17" N 107° 39' 58" E	"
BIK 23	13-7-93	53° 09' 42" N 107° 47' 31" E	"
BIK 24	14-7-93	53° 15' 09" N 108° 06' 54" E	"
BIK 25	15-7-93	55° 33' 18" N 107° 58' 00" E	"

BIK 26	16-7-93	54° 55' 36" N 109° 26' 08" E	North
BIK 27	17-7-93	55° 25' 35" N 109° 25' 56" E	"
BIK 28	18-7-93	55° 25' 35" N 109° 25' 56" E	"
BIK 29	18-7-93	54° 48' 01" N 109° 12' 58" E	"
BIK 30	19-7-93	54° 25' 12" N 109° 00' 11" E	"
BIK 31	20-7-93	54° 09' 56" N 109° 00' 05" E	"
BIK 32	20-7-93	53° 54' 19" N 108° 34' 35" E	"
BIK 33	10-8-93	51° 42' 16" N 104° 59' 43" E	South

Fig 19 Map showing locations of BIK cores taken during the summer of 1993.