
18 Vertical Particle Flux in Lake Baikal

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18.1 INTRODUCTION

Since the invention of the time-series sediment trap twenty years ago, much has been learned about the vertical particle flux in the oceans (this volume, Chapter 7). One of the major results is that the particle flux is accomplished mainly by large flocs (e.g., "marine snow", Honjo, 1980; Shanks and Trent, 1979; Alldredge and Silver, 1988; Urrere and Knauer, 1981), with sinking speeds of about 100 m d⁻¹ (Asper, 1987). Therefore seasonal changes in the particle flux and its chemical composition are transmitted to the sea bed, providing "seasons" to abyssal life.

Little, if nothing, is, however, known about the vertical particle flux in deep fresh water bodies. Not many fresh water bodies exist, which have depths comparable to marine conditions. Only three lakes are deeper than 1000 m: Lake Baikal (1710 m), Lake Tanganyika (1450 m) and the Caspian Sea (1025 m). Of these only Lake Baikal and Tanganyika contain fresh water. In the recent geological past, at least one other, ca. 2000 m deep fresh water body existed: the Black Sea. During Glacial low-sea-level-times it became a fresh water lake with a volume equal to all modern fresh water bodies (53 x 10⁴ km³ versus ca. 51 x 10⁴ km³). The study of the vertical particle flux in fresh water lakes has therefore implications for our understanding of lake sediments in the geological past as well as for the genesis of modern lacustrine sediments.

Several principal differences exist between Lake Baikal and Lake Tanganyika: The latter is stratified, lacking oxygen in bottom waters and it has a temperature of ca. 28°C. Lake Baikal is oxygenated and has a temperature close to 3°C at depth. Lake Baikal therefore offers the only opportunity to investigate a deep oxygenated fresh water body and its biogeochemical fluxes.

In contrast to the long tradition of biological research, which was initiated by the exiled Polish scientist B. J. Dybowski (1835–1930), detailed hydrological and biogeochemical investigations of the deep Lake Baikal have begun only recently. International cooperation with joint expeditions employing modern scientific gear suitable for deep water research, were conducted only after Lake Baikal scientists were allowed to handle their own scientific affairs under "glasnost". A milestone

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was the SCOPE/UNEP conference on Interactions of Biogeochemical Cycles in Aqueous Ecosystems at the Institute of Limnology at Lysvianka/Baikal, in 1988 (Degens et al., 1992). The contacts established during the meeting led to two joint expeditions with the participation of the Institute of Biogeochemistry and Marine Chemistry of the Hamburg University in 1989 and 1990 during which a sediment trap mooring was deployed and recovered from Lake Baikal (Wong et al., 1991).

18.2 LAKE BAIKAL

Lake Baikal (Figure 18.1, Table 18.1) occupies an elongated, NNE-SSW striking trough, caused by tectonic rifting at the border of the Siberian craton and several microplates of south-central Asia (Zonenshain and Savostin, 1981). The trough is divided into three separate basins, each representing a tectonically separate halfgraben structure. The southernmost basin (7828 km²) is 1414 m deep. It is separated from the central basin by the sublacustrine section of the Selenga Delta where the depth decreases to less than 400 m. The central basin (9634 km²) is the deepest. It is interesting to note that its depth has not been finally determined: National Geographic (1981), cites 1620 m; Weiss et al. (1991) and Scholz et al. (1993) quote 1632 m; Wong et al. (1991) give 1637 m; and Edington et al. (1991) suggest 1710 m for the depth of the central basin. The northern basin (13500 km²) is the shallowest with 989 m depth and is separated from the central basin by the Academician Ridge (Figure 18.1a). All basins are asymmetric in structure: the eastern walls have gradients of 6–15° while the western slopes can be as steep as 45° (Figure 18.1b). They represent the faults along which the basin floor is downfaulted. The largest island is Ol'khon, which is 72 km long and 14 km wide and borders the central basin to the west.

Geological development of the basin started in the Eocene/Lower Oligocene. Shallow depressions developed in the area of the southern basin, accumulating up to 1500 m of fine-grained, fossiliferous sediments (Nikolaev et al., 1985). In the Lower Miocene the first deep water lake developed and the rising Khamar-Dapan

Table 18.1 Lake Baikal, morphometric data (Wong et al., 1991).

Lake surface above sealevel	456.6	m
N-S length of lake	636.0	km
Maximal width	79.4	km
Minimal width	25.0	km
Area of lake surface	31500	km ²
Maximal depth	1620–1710	m
Water volume	23000	km ³
Shore line length	1760	km

Range south of the lake delivered coarse sediments to the southern basin (Belova et al., 1983). In the north, fine-grained sediments with peat and lignite formed a sediment suite, 4000 m thick (Logatchev and Zorin, 1987). In the Upper Pliocene

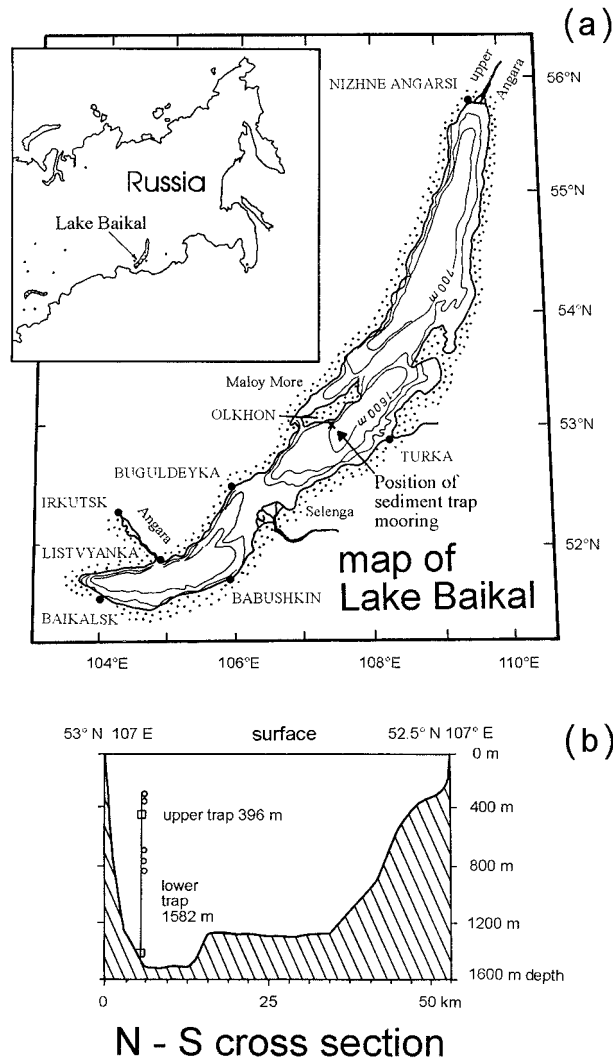


Figure 18.1 (a) Map of Lake Baikal and the position of the sediment trap mooring in the central basin east of the Island of Ol'khon and (b) N-S cross-section across the central basin slightly east of sediment trap position. Note that the sediment trap mooring is projected into the profile and that the lower trap was moored in reality at a lower position than suggested in the graph.

the modern development of the lake basin started, which led to higher relief gradients and to the development of the present deep water basins. Increased erosion led to the deposition of lacustrine conglomerates and gravel with an overall average sedimentation rate of 0.3 mm y^{-1} . Even though this rate is a factor of magnitude larger than during the first phase of basin development (0.03 mm y^{-1} ; Artyushkov et al., 1990), downfaulting proceeded faster than the accumulation of sediments resulting in the formation of the deep basins of Lake Baikal.

Lake Baikal is fed by ca. 300 rivers, very diverse in size, discharge and physiography of their catchment areas. Total input to the lake amounts to $60 \text{ km}^3 \text{ y}^{-1}$. Most rivers are low in mineralization (between 25 and 250 mg total dissolved solids (TDS) per liter), and have a $\text{HCO}_3\text{-SiO}_2\text{-Ca}$ or $\text{HCO}_3\text{-Ca-SiO}_2$ character (Votintsev, 1985). The Selenga is the largest tributary to the lake, accounting for 50% of its input and having a TDS of $100\text{--}200 \text{ mg l}^{-1}$. It drains the mountainous steppe landscapes of Northern Mongolia and the forest-steppe and taiga areas of Western Transbaikalia. The Upper Angara (15% of discharge tributary to the lake and $50\text{--}100 \text{ mg TDS l}^{-1}$) and the Barguzin rivers (9% of water input, $139 \text{ mg TDS l}^{-1}$) are next in size.

The composition of Lake Baikal with regard to major ions is - within the error margins of such mass balance calculations - apparently well explained by the added average input from tributaries and direct precipitation (total $9 \text{ km}^3 \text{ y}^{-1}$) (Table 18.2). This data set suggests the conservative behavior of all major elements in their passage through Lake Baikal. We will later see that this cannot be entirely true for Ca and HCO_3 .

The waters of Lake Baikal are oligotrophic (Table 18.3). In surface waters the highest concentrations of NO_3 and PO_4 are reached in winter (ca. 6 and $0.32\text{--}0.48 \text{ }\mu\text{mol l}^{-1}$, respectively) and lowest in summer ($2.1\text{--}3.6$ and $0.06\text{--}0.16 \text{ }\mu\text{mol l}^{-1}$, respectively). For silica, two maxima occur, one in winter and one in summer. Water column sampling showed that nutrient concentrations increased significantly downward with oxygen decreasing at the same time (Table 18.3).

Exact concentrations of nutrients depend largely on methods employed. Therefore detailed measurements of depth profiles conducted by Liebezeit (1992) and Weiss et al. (1991) report somewhat different concentrations for nitrate,

Table 18.2 Lake Baikal and tributaries, major ion composition in mg l^{-1} (after Votintsev, 1985).

	HCO_3	SO_4	Cl	Ca	Mg	Na+K	TDS
Baikal tributaries	79.3	6.7	0.7	20.0	4.3	5.1	116.1
Precipitation	5.8	0.9	0.3	1.0	0.1	0.1	9.1
Average input	66.2	5.6	0.7	16.7	3.6	4.2	97.0
Lake Baikal	66.6	5.2	0.6	15.2	3.1	3.8	96.4
Lake Baikal*			0.44	16.1	3.06	3.6+0.94	

* for comparison, Falkner et al., 1991

Table 18.3 Differences in oxygen and nutrient concentrations observed in Lake Baikal between the surface and ca. 1500 m depth.

Parameter	Surface water	Deep water
pH	7.3 – 8.7	7.0 – 7.1
C _{org} mg l ⁻¹	1.5 – 1.6	up to 1.0
Si μmol l ⁻¹	38	up to 90
NO ₃ μmol l ⁻¹	2.9 – 4.3	5.7 – 6.4
PO ₄ μmol l ⁻¹	0.2 – 0.3	0.38 – 0.48
O ₂ saturation %	ca. 100	75 – 80

phosphate, and silica compared to the values in Table 18.4. Weiss et al. showed that NO₃ increased to 9 μmol l⁻¹, PO₄ to 0.6 μmol l⁻¹ and SiO₂ to 70 μmol l⁻¹ at 1500 m depth in the central basin. Below, values decrease somewhat. Liebezeit (1992) also found increases in reactive PO₄ to 0.6 μmol l⁻¹ at 1500 m but for SiO₂ only increases of up to 50 μmol l⁻¹. Liebezeit (1992) also published ammonia values which varied between 0.3 and 0.7 μmol l⁻¹ without a distinct depth-dependent trend.

Oxygen decreases with depth, caused by the remineralization of the sinking organic matter. Weiss et al. found a decrease down to 300 μmol l⁻¹ and Liebezeit down to 325 μmol l⁻¹ at 1500 m. The maximum occurs near the surface with about 390 μmol l⁻¹. In Table 18.3 the differences in oxygen and nutrients are listed in order to estimate later the amount of sinking particulate carbon consumed and to compare it with the carbon fluxes intercepted with the sediment trap.

The fact that oxygen does decrease significantly with depth but is not exhausted suggests that the deeper water column is not mixed completely annually, rather, complete mixing seems to take several years.

This question was addressed by the study of Weiss et al. (1992) who sampled the water column of Lake Baikal for CFC-12. Results showed that the mixing time

Table 18.4 Annual average composition of surface and deep waters of Lake Baikal (after Votintsev, 1985).

Parameter	Votintsev	Liebezeit	Weiss et al.
Oxygen μmol l ⁻¹	-	- 65	- 90
NO ₃ μmol l ⁻¹	ca. + 3	-	ca. + 3
PO ₄ μmol l ⁻¹	ca. + 0.2	+ 0.5	+ 0.3
SiO ₂ μmol l ⁻¹	ca. + 50	ca + 20	ca. + 45
N/P	15	-	10
O/P	-	130	300

increased from ca. 1 year in the well mixed surface layer (down to 250 m) to 16 years in the layer between 1200 and 1400 m. Below that depth, mixing time decreased to 9–8 years.

The mechanism which governs deep water mixing in Lake Baikal is - because of its enormous depth - singular among fresh water lakes. In temperate, shallow fresh water lakes mixing occurs normally twice annually, once in early winter and once in spring, when the surface water temperature reaches 4°C, the temperature of highest density ($T_{\rho_{\max}}$) of fresh water. Then the surface layer becomes more dense than the bottom waters and convection starts, mixing the entire lake and filling the deeper basin with water at $T_{\rho_{\max}}$. In this respect fresh water lakes differ from oceans, where bottom waters (even though much colder than 4°C) do not attain the temperature of highest density, which is - because of the higher salt content of seawater - at several degrees below 0°C.

The problem of mixing deep fresh water lakes arises from the fact that $T_{\rho_{\max}}$ decreases with increasing pressure with ca. $-0.021 \text{ }^{\circ}\text{C bar}^{-1}$ (Eklund, 1965; Chen and Millero, 1986). Therefore, water cooled to 4°C at the surface, cannot convect down because it is less dense at depth than the colder water already filling the hypolimnion. Weiss et al. (1991) suggest that mixing of deep fresh water lakes is occurring only if deep wind mixing of surface waters colder than 4°C (and colder than the already existing bottom waters) occurs (see scheme in Figure 18.2). Only then is the lower part of the mixed surface layer dense enough to start deep convection. Such a convection would be initiated locally and episodically, therefore limiting deep convection to certain periods of the year when both fast cooling occurs and strong winds mix the surface layer deeply. This mechanism explains why the bottom temperatures of deep fresh water lakes are significantly lower than 4°C. In fact, the potential temperature of Lake Baikal decreases to almost 3.1°C at the bottom of the central basin. Certainly deep mixing in Lake Baikal cannot occur during times of ice cover. Temperature profiles recorded by Weiss et al. (1991) show that temperature follows the $T_{\rho_{\max}}$ line down to about 250 m; i.e., down to that depth mixing occurs when the surface layer has temperatures lower than 4°C but higher than bottom temperatures. Below 250 m mixing is only episodically, apparently restricted to times of strong external forcing and when temperatures in the surface layer are cooled to below 3.5°C. Newly forming bottom waters originate therefore at a depth of at least 200 m and not necessarily at the air-water interface. Water mixed down may therefore not be fully equilibrated with atmospheric gases.

Deep convection in lakes is an essential process needed to replenish nutrients to the surface waters. Considering that the volume of Lake Baikal is 23000 km³ and that the annual water input is 60 km³ (neglecting the balance between precipitation and evaporation), then water has an average residence time of close to 400 years in Lake Baikal. Considering the decadal time scale of vertical mixing, it is

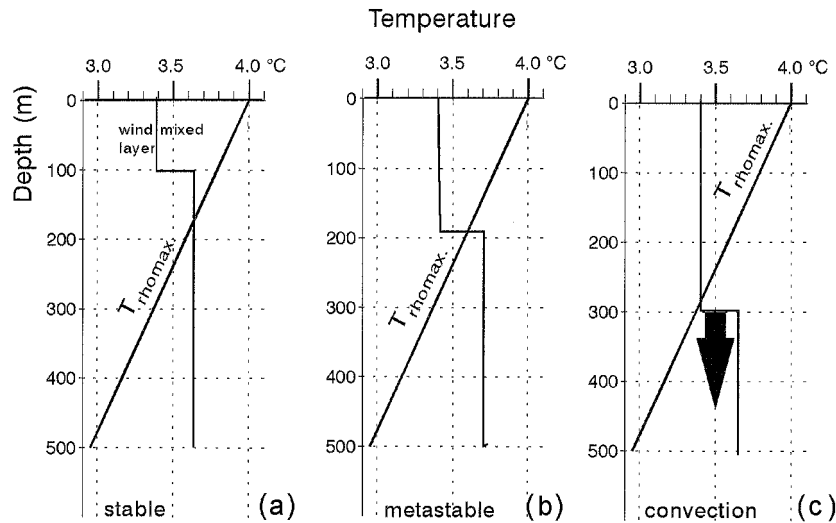


Figure 18.2 Relationship between vertical temperature structure and $T_{\rho_{\max}}$ ($T_{\rho_{\max}}$, temperature of highest density). Mixing in deep fresh water lakes can only proceed when wind mixing of surface water - cooled to below 4°C - to a depth where $T_{\rho_{\max}}$ is surpassed occurs. (a) stable stratification with less dense, colder water topping warmer bottom water; (b) metastable situation where the interface of the cold wind-mixed layer intersects the $T_{\rho_{\max}}$ curve; (c) unstable situation where the lower part of the colder wind-mixed surface layer is depressed below the $T_{\rho_{\max}}$ curve, starting convection towards the depth. Exchange of water originates at a depth of several hundred meters and not necessary at the air-water interface. Therefore water mixed down may not be fully equilibrated with atmospheric gases (after Weiss et al., 1991).

apparent that water and therefore also nutrients are recycled several times between bottom and surface waters before leaving the lake.

This conclusion is of course very general, because the individual river input exchange times differ due to their varying distances from the Angara River, the "output" of Lake Baikal. Selenga water, for example, has a good chance of leaving the lake within a year because of its proximity to the Angara and of the general pattern of surface circulation (Figure 18.3). In the lake N-S transport occurs along the western shore and S-N transport along the eastern shore. Five major gyres turning anticlockwise accomplish water transport across the lake basin. Water entering with the Upper Angara should therefore take a much longer time to reach the Baikal outlet than that of the Selenga and has a better chance of being incorporated into the deep bottom waters than Selenga water.

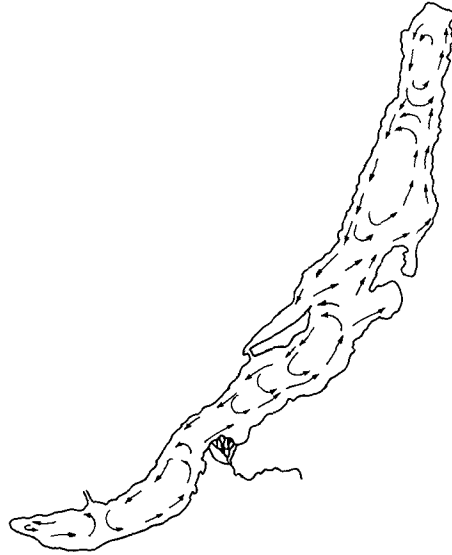


Figure 18.3 Surface currents of Lake Baikal (after Kozhov, 1963).

18.3 MATERIALS AND METHODS

18.3.1 SEDIMENT TRAP MOORING

The double sediment trap mooring was deployed in the central basin of Lake Baikal at 53°00.0 N, 107°35.5 E at a water depth of 1610 m (Table 18.5); i.e., close to the deepest point of the lake. The upper trap was at a depth of 396 m (i.e., already deeper than most fresh water lakes world-wide), and the lower trap at a depth of 1582 m; i.e., 28 m above the lake bottom. The two traps were programmed to sample at the same time. The sampling cups were filled with a NaCl solution of 200 mS cm⁻¹ conductivity and preserved with saturated HgCl₂ solution.

The trap was programmed to close on September 1, 1990 but the mooring had to be recovered on August 4, 1990 because of a change in expedition timing. Therefore cup 13 was open upon recovery and cannot be evaluated. The rotation dates are given in Table 18.6.

18.3.2 ANALYTICAL METHODS

After recovery of the traps, the pH and the conductivity of the cupwaters were measured. The cups of the upper trap had a strong putrefactive smell and the very low conductivities of cupwaters showed that almost all of the preservative had

Table 18.5 Sediment trap mooring, technical data.

Position	53°00.0 N / 107°35.5 E	
Water depth	1610 m	
Length of mooring	ca. 1230 m	
Buoyancy spheres	20	
Release	acoustic Benthos release 895	
Anchor	1000 kg	
Deployed	09/07/89	
Recovered	08/04/90	
Trap designation	Lake Baikal LB-T	Lake Baikal LB-B
Trap depth	396 m	1,582 m
Trap opening	0.509 m ²	0.509 m ²
Trap type	Honjo Mark VI	Honjo Mark VI
Number of cups	13	13
Collection time	09/10/89–08/04/90	09/10/89–08/04/90
Sampling intervals	13: 28 or 27 days	13: 28 or 27 days
Preservation	NaCl - HgCl ₂	NaCl - HgCl ₂
Problems	cup 13 open	cup 13 open

Table 18.6 Rotation dates of LB-T and LB-B (cups closed at midnight).

Cup No.	Opened	Closed	Days	Interval
1	09/10/1989	10/07/1989	28	September/October
2	10/08/1989	11/03/1989	27	October/November
3	11/04/1989	12/01/1989	28	November/December
4	12/02/1989	12/29/1989	28	December
5	12/30/1989	01/26/1990	28	December/January
6	01/27/1990	02/22/1990	27	January/February
7	02/23/1990	03/21/1990	27	February/March
8	03/22/1990	04/17/1990	27	March/April
9	04/18/1990	05/14/1990	27	April/May
10	05/15/1990	06/10/1990	27	May/June
11	06/11/1990	07/07/1990	27	June/July
12	07/08/1990	08/03/1990	27	July/August
13	08/04/1990	-	-	

disappeared from the cups. The cups were then sealed and taken to the laboratory at Hamburg. There cupwaters were decanted and the still wet samples were sieved through a 1 mm sieve. The fraction of > 1 mm contained only macroorganisms and was therefore not included in the chemical flux determinations. Due to the

presence of decaying organics, it was impossible to filter the samples with the < 1 mm fraction through the nucleopore filters. Therefore the samples were desalted with bidistilled water and freeze-dried in small portions. Most of the particulate sample was ground in an agate mortar but a small aliquot was kept for SEM investigation.

On the dissolved fraction the following investigations were conducted:

- pH and conductivity, aboard the research vessel (using battery powered hand-held instruments, pH 91 meter, LF 91 meter, both by WTW);
- dissolved silica (photometry at 880 nm, Koroleff, 1983a);
- dissolved reactive phosphate (photometry at 880 nm, Koroleff, 1983b);
- dissolved nitrite (photometry at 545 nm, Grasshoff, 1983);
- dissolved ammonia (photometry at 630 nm, Koroleff, 1983c).

The particulate fraction was analyzed for the following parameters:

- total weight;
- total carbon and nitrogen (using Carlo Erba NA 1500 Nitrogen Analyzer);
- organic carbon (same as total carbon, carbonate removed by 2 N H₃PO₄; to obtain total organic matter, C_{org} values were multiplied by the factor 1.8 in accordance with Ittekkot et al. (1991), and Müller et al. (1986));
- carbonate (as difference between C_{tot} and C_{org});
- biogenic opal (after Mortlock and Froelich (1989); samples were decarbonated and organic carbon was removed with 2% H₂O₂, opal was dissolved by boiling for 5 h in 5% Na₂CO₃ solution and the resulting solution was then photometrically determined as in the cupwaters; according to Mortlock and Froelich (1989) biogenic opal is assumed to have a water content of 10%, opal (SiO₂ x 0.4 H₂O) weight was therefore determined from Si concentrations by multiplying with a factor of 2.4);
- total phosphorus (after Williams et al. (1976); samples were incinerated at 550°C and dissolved in 1 N HCl, and the solution was then photometrically determined as in the cupwaters);
- lithogenic fraction (because of the low sample amounts available, the lithogenic fraction could only be determined by difference between the biogenic components and total weight; because all analytical mistakes add in this determination and because of the factors used to calculate total organic carbon and silica the sum may not represent the conditions of the material in the samples accurately, since the values for lithogenic fraction are relatively inaccurate; evidence for this is the resulting negative values in the upper trap which is very low in lithogenics);
- SEM and EDAX (aliquots of the unground samples were glued to aluminum studs and sputtered with gold and then investigated by scanning electron microscopy and energy dispersive analysis with X-rays).

The results of all determinations are listed in the appendix. Results are more fully discussed by Schaumburg (1994).

18.4 DISCUSSION OF RESULTS

18.4.1 DISSOLVED FRACTION AND REMINERALIZATION

When the cups were taken off the rotor after recovery of the traps, a strong smell was noticed, putrefactive in the cups of the upper trap and fishy in the cups of the lower trap. The measurement of the conductivity (Tables 18.A1 and 18.A2 of the appendix) showed that in fact most of the salt solution had been lost from the cups. Ambient lake water has a conductivity of 130 to 137 $\mu\text{S cm}^{-1}$ while the salt solution had originally a conductivity of 200 mS cm^{-1} . We can therefore calculate that between 94.7% and 99.9% and between 98.9% and 100% of the original solution had been lost from the cups in the upper and lower traps, respectively. This loss was more thorough and regular in the lower trap than in the upper trap where losses in winter were smaller than during the warm season. Remains of small fish (upper trap) and crustaceans (lower trap) recovered in the > 1 mm fraction shows that apparently these swimmers entered the cups and displaced most of the original solution. A few of these intruders were caught in the cups when the rotor moved on to the next position and were killed. The problem of swimmers entering cups is common with sediment trap research (Gardner et al., 1983; this volume, Chapters 5 and 7) but so far we never encountered such a massive cupwater loss in any of the traps deployed in oceanic environments. It remains unclear if the swimmers could carry any of the collected particulate material out of the cup or even out of the trap cone. The strong chemical gradient across the cup opening should have in fact prevented fresh water biota from entering highly concentrated salt solutions. Nevertheless a loss of particulates may have occurred and all values should be considered to represent minimum flux values.

Due to the overall low concentrations of carbonates in the sinking material and in the water of Lake Baikal, the pH is not well buffered against changes when additional CO_2 is generated by bacterial remineralization. pH measurements in the cupwaters therefore tell something about the lability of the trapped material, even more so since the preservative apparently had been diluted in the cups to the point to become ineffective. In the upper trap, pH values of between 5.85 and 7.3 (which is representative of ambient lake water at the depth of the upper trap) were measured and a linear trend was evident, illustrating the progress of remineralization with passing time. In the lower trap values were higher (between 6.9 and 8.0), suggesting that the organic material caught above the floor of Lake Baikal is more inert and is not rapidly degraded by microorganisms.

The analysis of dissolved nutrients recovered small amounts of silica and nitrite and large amounts of reactive phosphate and of ammonia (Tables 18.A1 and 18.A2, appendix).

The concentration of silica in the cup waters was, on average, three times higher in the bottom than in the top trap. However, the recovered amounts (up to $2.5 \mu\text{mol l}^{-1}$ at most) were much lower than in the ambient water (see Table 18.3). Because the cup solution was exchanged almost completely with ambient lake water, much higher silica concentrations should have been present. Consequently, opal was precipitated in the cups due to their acidic condition. The lower concentrations in the top trap were therefore in accordance with the lower pH values encountered in the cups of the top trap in comparison to the cups of the bottom trap. The conclusion that opal was precipitated in cupwaters is also substantiated by the missing time trend in the data. Precipitation would occur fast and would not show a similar time dependency as for example observed in bacterial remineralization.

In contrast to silica, the phosphorus concentration of the cupwaters (in the upper trap $50\text{--}150 \mu\text{mol l}^{-1}$ and in the lower trap 1.2 to $10 \mu\text{mol l}^{-1}$) exceeded by far those in the ambient lake water. Phosphorus must have been released from the collected organic matter. The upper trap has much higher values than the lower trap, again (as in case of pH) a clear indication that the upper trap intercepted much more labile matter than the lower trap. When one compares the P amounts remineralized with the total intercepted P (particulate plus dissolved), one finds remineralization proportions of between 1.2% and 17% (upper trap) and between $\ll 1\%$ and 6% (lower trap). Concentrations and remineralization rates are plotted in Figure 18.4 (for values see Tables 18.A3 and 18.A4 in the appendix). Apparently in both traps lowest remineralization values occurred in winter. In the top trap the most labile material apparently arrived in November, May and July, while in the lower trap the May peak arrived one cup later and the July peak seemed to be mirrored by a peak in cup 1. It is also interesting to note that no trend with time was apparent. This suggests that remineralization of phosphorus is fast, degrading the available, easily remineralizable phosphorus-bearing compounds and then stopping. The overall remineralization ratio (calculated from the total flux; i.e., weighted for time and concentrations) amounted to 3.9% and 1.0% suggesting that phosphorus in the lower trap is present mostly as inorganic forms (Table 18.7). The total measured phosphorus fluxes during the observation period amounted to $420 \text{ mg } (13.5 \text{ mmol}) \text{ m}^{-2}$ in the upper trap and $118 \text{ mg } (3.8 \text{ mmol}) \text{ m}^{-2}$ in the lower trap; i.e., it intercepted 3.56 times less P than the upper trap. It has to be noted that some remineralized phosphorus may be locked in dissolved organic compounds. Therefore remineralization ratios and total fluxes may be underestimated.

The cupwaters contained high concentrations of ammonia and nitrite, much higher than their occurrence in ambient waters (Figures 18.5a, b). In all cups more ammonia than nitrite was found, but the ratio of nitrite to ammonia and the overall nitrite concentration was significantly higher in the lower trap ($0.1\text{--}14 \mu\text{mol l}^{-1}$) than in the top trap ($0.04\text{--}0.9 \mu\text{mol l}^{-1}$), indicating that the cupwaters of the lower trap were less reducing than in the top trap. In fact, ammonia concentrations in the upper trap reached values of between 0.5 and 11 mmol l^{-1} , while in

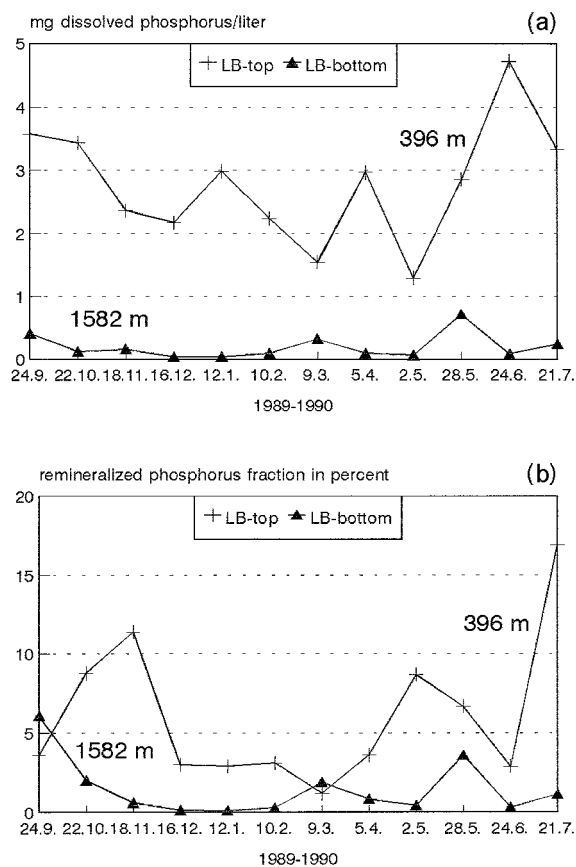


Figure 18.4 (a) Comparison of the concentrations of dissolved phosphorus in the cupwaters of both traps and (b) of the fraction of phosphorus remineralized from the total flux.

the lower trap concentrations range only between 3 and 800 $\mu\text{mol l}^{-1}$. Because of the high ammonia concentration, nitrate, which was not measured, could not occur in significant concentrations. Even nitrite hardly plays a significant role in the nitrogen budget. In Tables 18.A3 and 18.A4, appendix, the dissolved fraction is added to the particulate nitrogen (Figure 18.6a) and the remineralization fraction was calculated (Figure 18.6b). It ranged between 8 and 85% in the upper trap and between < 1 and 7% in the lower trap. Remineralization was one order of magnitude higher in the top trap than in the bottom trap (averages 43.3 and 3.8%, respectively) (Table 18.7). Nevertheless, it is astonishing how well the relative changes of the remineralization ratio matched between the two traps (Figure

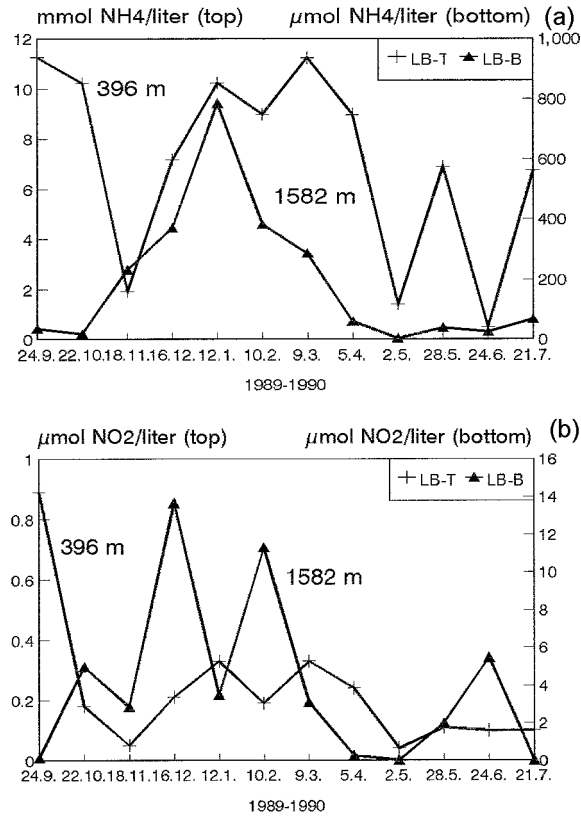


Figure 18.5 (a) Concentrations of ammonia and (b) nitrite in the upper (LB-T) and lower (LB-B) Lake Baikal traps.

18.6b; $r=0.56$, $p=95\%$), indicating that material of higher lability reached both traps during winter and of lower lability during summer. The differences between total P and N fluxes between the top and bottom traps was similar (factors 3.6 and 3.2, respectively). Therefore remineralization was - averaged over the water column - similar for N and P compounds, slightly more than one third of the material passing the upper trap was intercepted by the lower trap.

When comparing the total phosphorus with the total nitrogen fluxes, an interesting pattern emerged (Table 18.7): In the remineralized fraction nitrogen was clearly present in higher proportions than normally present in organic matter (represented by the so called Redfield C/N/P ratio of 106/16/1). This was true for both traps, but especially for the top trap. The fraction was also much larger than

the N/P ratio of the water column (see Table 18.3) which was close to Redfield ratio. In the particulate fraction and overall, however, the ratios were clearly

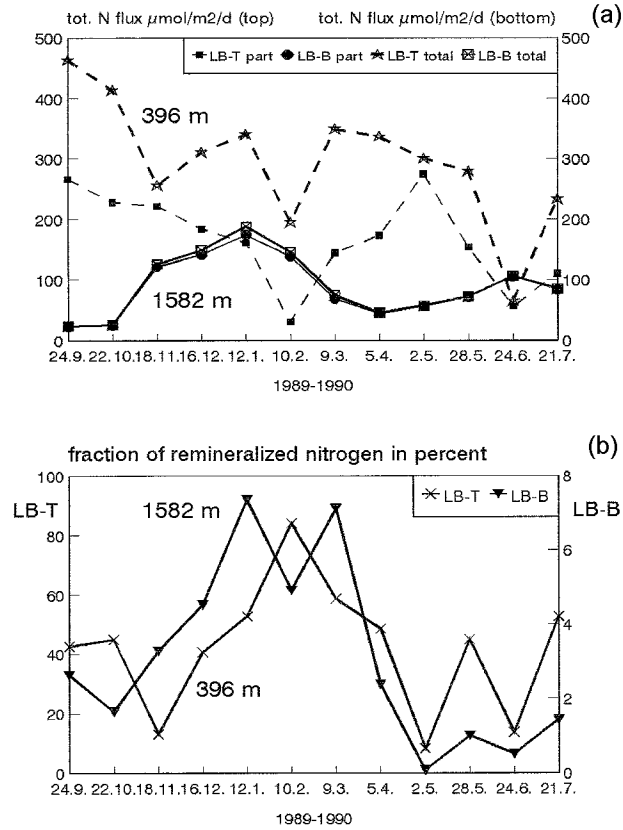


Figure 18.6 (a) Comparison of total nitrogen fluxes in $\text{mg m}^{-2} \text{d}^{-1}$ (residual particulate phase and dissolved remineralized phase) for both traps (dashed lines = LB-T, solid lines = LB-B), and (b) the fraction of remineralized nitrogen in the upper and lower Lake Baikal trap.

phosphorus dominated (compared to Redfield). Apparently two different sorts of material were involved in contributing to the intercepted material, one with a mineral phosphate component (such as fish bones or sedimentary apatite) and one with a component containing easily remineralizable nitrogen (such as proteins).

18.4.2 PARTICULATE FRACTION

The total vertical flux (preserved in particulate form in the cups) showed strong seasonal changes and a large difference between the top and the bottom trap (Figure 18.7; Tables 18.A5 and 18.A6 in the appendix). Both traps showed distinct flux maxima in winter and summer. In winter fluxes peaked at $55.7 \text{ mg m}^{-2} \text{ d}^{-1}$ (in

Table 18.7 Phosphorus and nitrogen fluxes (per m^2) for the time period 09/10/89–04/08/90 (328 days, cups 1–12), and various elemental ratios.

Traps	LB-T, 396 m		LB-B, 1582 m	
	mmol m^{-2}	mg m^{-2}	mmol m^{-2}	mg m^{-2}
Dissolved inorganic P	0.53	16.4	0.037	1.16
Total particulate P	13.00	403.2	3.765	116.70
Sum of P fluxes	13.53	419.6	3.802	117.86
Remineralization ratio %	3.9		1.0	
Ratio of flux top/bottom	3.56			
Total dissolved N (NH_4+NO_2)	42.0	588	1.15	16.1
Total particulate N	55.0	770	28.94	405.2
Sum of nitrogen fluxes	97.0	1358	30.09	421.3
Remineralization ratio %	43.3		3.8	
Ratio of flux top/bottom	3.22			
N/P ratio dissolved	79/1		31/1	
N/P ratio particulate	4.2/1		7.7/1	
N(sum)/P(sum) ratio	7.2/1		7.9/1	

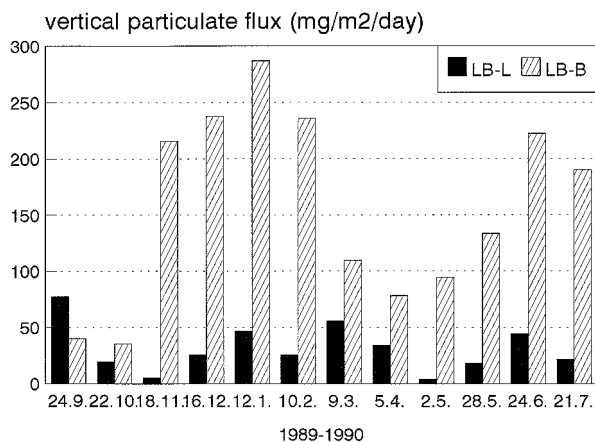


Figure 18.7 Comparison of total fluxes of the intercepted particulate matter in the upper (LB-T) and lower (LB-B) Lake Baikal traps.

February) and at $77.5 \text{ mg m}^{-2} \text{ d}^{-1}$ (in September). In the lower trap the maxima occurred in January ($287 \text{ mg m}^{-2} \text{ d}^{-1}$) and in June ($222 \text{ mg m}^{-2} \text{ d}^{-1}$). During times of low vertical particle flux, the upper trap received 19 times, and the lower trap 8 times, less material than during peak flux. In total the upper trap received 5 times less matter than the lower trap. These results indicate that much of the vertical particle flux was generated along the slopes of the lake at greater depth and that this material should be less labile than the matter generated in the photic zone.

This conclusion is substantiated by comparing the general composition of the two traps (Figures 18.8a, b) which are fundamentally different. When discussing composition, one has to keep in mind that organic matter is calculated by multiplying the difference between the total carbon measurement and the inorganic carbon measurement with a factor of 1.8. Not all the organic matter may be represented by this factor. Therefore, in samples with large C_{org} concentrations, the lithogenic fraction, which is also calculated by difference, may have negative values (see Table 18.A5 in the appendix). These negative values are omitted in Figure 18.7a and are not used in calculating fluxes in Table 18.8. Lithogenic

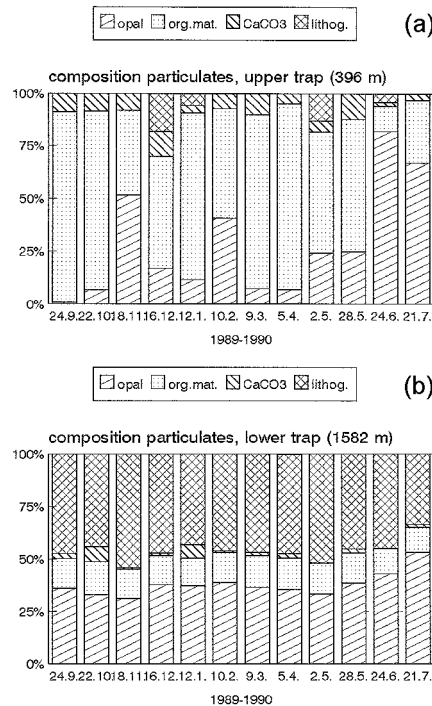


Figure 18.8 Relative composition of the intercepted particulate matter in the (a) upper and (b) lower Lake Baikal traps.

Table 18.8 Totals (calculated for actual trap area) and fluxes (calculated per m² and day) of total particulate matter intercepted and of principal components for the time period 09/10/89–08/04/90 (328 days, cups 1–12).

Traps (0.509 m ²)	LB-T, 396 m	LB-B, 1582 m
Total intercepted weight	5.256 g	26.26 g
Average flux	31.48 mg m ⁻² d ⁻¹	157.30 mg m ⁻² d ⁻¹
Ratio of flux bottom/top	5.0	
Total intercepted opal	1.33 g	10.15 g
Average opal flux	7.96 mg m ⁻² d ⁻¹	60.82 mg m ⁻² d ⁻¹
Ratio of flux bottom/top	7.6	
Total interc. organic matter	3.90 g	3.57 g
Average organic matter flux	23.35 mg m ⁻² d ⁻¹	21.40 mg m ⁻² d ⁻¹
Ratio of flux bottom/top	0.9	
Total intercepted CaCO ₃	0.41 g	0.54 g
Average CaCO ₃ flux	2.47 mg m ⁻² d ⁻¹	3.24 mg m ⁻² d ⁻¹
Ratio of flux bottom/top	1.3	
Total interc. lithogenics	0.135 g	12.00 g
Average lithogenics flux	0.8 mg m ⁻² d ⁻¹	71.86 mg m ⁻² d ⁻¹
Ratio of flux bottom/top	90	

fluxes can therefore be higher than calculated (or lower where present) depending on the factor by which C_{org} concentration is converted to total organic matter.

From Figure 18.8 it is noted that the composition of the material intercepted by the lower trap was rather stable, while that of the upper trap varies with seasons substantially. The upper trap contained hardly any lithogenic material. Its material was dominated by organic matter (maxima in autumn and spring) and by opal (maxima in November, February and June/July). Lithogenics were noticeable only in December and May. In the lower trap lithogenics dominated the composition followed by opal, organic matter and CaCO₃ in very stable proportions throughout the year (except for CaCO₃ which had a distinct maximum in January). Thus we must conclude that the material of the lower trap had a different source with a very stable composition. Resuspension of slope sediments seems to be the most likely process to account for this observation.

When we compared total intercepted particulate fluxes in the two traps (Table 18.8) it becomes clear that not only lithogenics but also opal must derive from this resuspension source. In fact, if one compares their flux data in Table 18.6A (appendix), it is clear that they co-vary significantly. In contrast, the average fluxes of organic matter and CaCO₃ were comparable in size in the top and bottom trap. However, their seasonal patterns (Figure 18.9) were not identical in the two traps.

In the case of organic matter, the winter maximum in the top trap was present in the lower trap in similar magnitude. This seems to indicate that during winter much of the organic matter from the surface reaches the bottom and is instrumental in extracting the resuspended lithogenics and opal. This conclusion is also corroborated by the marked ammonia and nitrite (Figure 18.5) and nitrogen remineralization maxima (Figure 18.6b) in the winter cups of the lower trap. In summer, however, the organic matter flux in the bottom trap exceeded that of the upper trap, and must therefore be associated with resuspended matter.

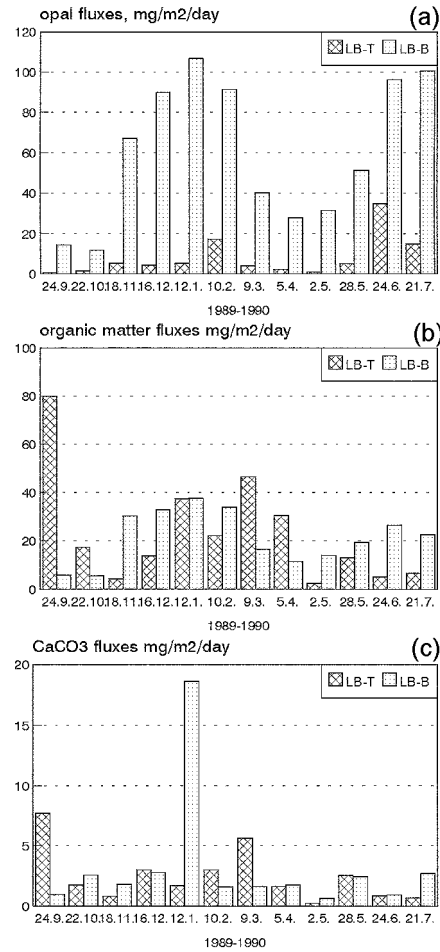


Figure 18.9 Comparison of the fluxes of (a) opal, (b) organic matter, and (c) CaCO₃ between the upper trap (LB-T) and lower trap (LB-B) in Lake Baikal.

