ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 408, No. 4, pp. 645–648. © Pleiades Publishing, Inc., 2006.
Original Russian Text © M.N. Shimaraev, R.Yu. Gnatovskii, V.V. Blinov, A.A. Zhdanov, 2006, published in Doklady Akademii Nauk, 2006, Vol. 408, No. 3, pp. 404–407.

GEOGRAPHY

Relationship between Salinity and the ^3H–^3He Age in Deep Water of Lake Baikal

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Presented by Academician M.A. Grachev July 25, 2005

Received August 11, 2005

DOI: 10.1134/S1028334X06040301

The application of chemical tracers (freon and helium/tritium ratio) in the 1990s made it possible to date Baikal water at different depths by the timing of its contact with the atmosphere [1, 2]. The age increases with depth from 0.5–4 yr in the upper 300–400 m to 10–18 yr at 200–500 m above the bottom. The age is variable in different years in the near-bottom zone. The cause of water aging with depth is the relaxation of processes responsible for its interaction with water of upper layers. Free temperature convection [3] and currents [4] foster active water mixing down to the depth of 300–400 m. In deeper layers where free convection is missing and currents are weakened, the activity of water exchange with upper layers decreases. Approaching the bottom, the activity increases again under the influence of deep (forced) temperature convection [1, 3], near-slope circulation at the thermobaric field front [5], and the current field [4]. Consideration of datings made it possible to calculate the time of deepwater renewal (8–10 yr), the rate of vertical water exchange, and the value of "new" production [1, 2].

Information on water age may provide new insights into processes in Lake Baikal for comparison with the high-precision characteristics of water. We analyzed the distribution of "ion mineralization," i.e., the total content of basic components of the ion composition (S_c), and the ^{3}H–^{3}He age of water for the deepest regions of the southern, central, and northern basins of Lake Baikal based on data of the Russian–Swiss Expedition in May–June, 1995 [2, 6]. The S_c content was calculated on the basis of water conductivity adjusted to temperature and pressure based on relations in [6, 7]. A high resolution of conductivity sensors in SBE-type probes (0.01 μS/cm [6]) makes it possible to calculate the S_c value with an uncertainty of <0.1 mg/kg. For age determination, the helium and tritium contents were measured in water samples taken simultaneously with conductivity sounding [2].

Water in Lake Baikal is relatively uniform in its S_c content (95–96 mg/kg) [8], although the content varies in feeding rivers from 80 mg/kg in tributaries of the northern basin to 124–125 mg/kg in tributaries of the southern and central basins [9]. Such discrepancies should affect the S_c distribution in the lake water. However, the accuracy of present-day analytical methods of hydrochemistry (up to 5–10% for components of the ionic composition) is insufficient for studying this parameter. Precision measurements of conductivity by SBE probes in the 1990s [2, 6, 7, 10] revealed slight but reliable spatial S_c variations. Its average value in the watermass of the northern basin is constantly 0.8–1 mg/kg lower than in the southern and central basins, where the difference does not exceed 0.1–0.2 mg/kg.

Variations in the vertical distribution of S_c values are also reliable, but the distribution turned out to be different. In the upper (down to 200–400 m) and near-bottom (the lowest 100–200 m) zones of the basins, the S_c distribution is unstable because of the influence of several factors (changes in water salinity in tributaries, evaporation and ice growth in winter [7], and dynamic processes). Therefore, we discuss the basic, deep part of the watermass (Fig. 1). In the main deepwater body of the southern (400–1100 m) and central (400–1400 m) basins, the S_c value decreases with depth by 0.4–0.5 mg/kg (the maximal uncertainty does not exceed 0.2 mg/kg). By contrast, in the deep zone of the northern basin (200–800 m layer), the S_c value increases with depth by 0.4–0.6 mg/kg due to a constant sinking of more saline water to its bottom zone from the central basin in the course of water exchange [6, 10].

Let us analyze the relation between S_c and water age in the southern and central basins (Fig. 2). The relation is negative in the deep zone and well described by the linear dependence with high values of correlation coefficients. In accord with the S_c gradient sign in terms of τ, the substance flow is directed from upper young

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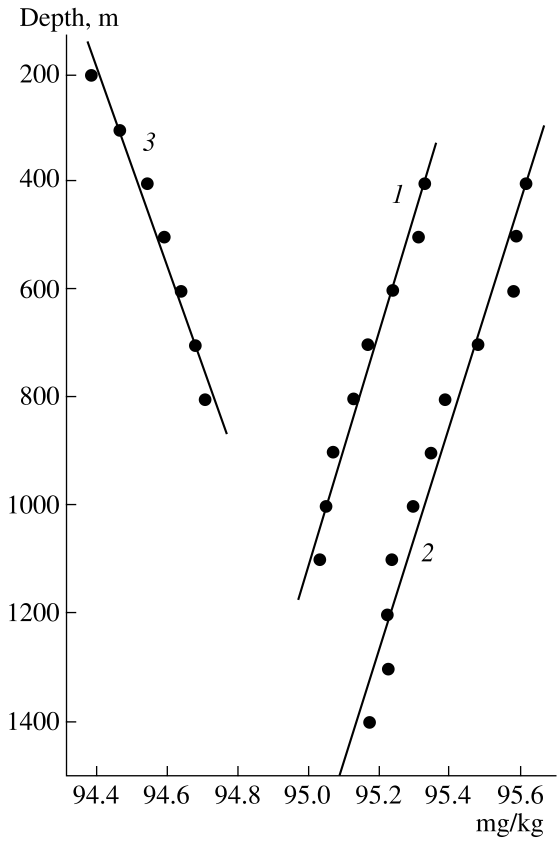

Fig. 1. Vertical distribution of the S_c content in the deepwater zone of the (*1*) southern, (*2*) central, and (*3*) northern basins of Lake Baikal in May–June, 1995.

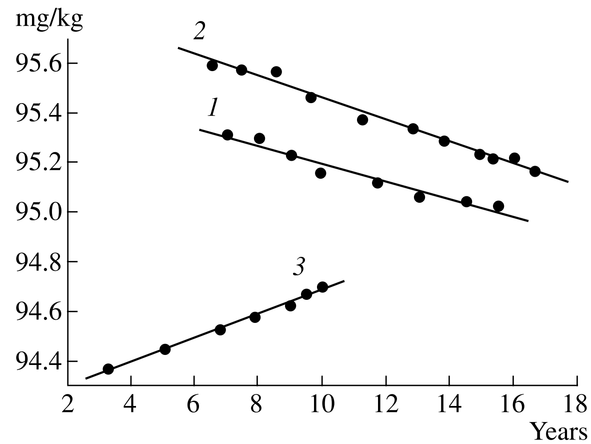

Fig. 2. The S_c content vs. water age in the deepwater zone of the (*1*) southern, (*2*) central, and (*3*) northern basins in May–June, 1995.

water to lower old water. Let us suppose that components of the ionic composition are constant and the flow direction is determined by a steady increase in the substance flow to the lake. According to this scenario, if the process is stationary, the vertical S_c profile should retain in time, and the flow should correspond to the rate of S_c versus water age ($\Delta S_c/\Delta\tau$) variation. In the southern basin, this relationship is described by the equation $S_c = -0.036\tau + 95.55$ ($R^2 = 0.95$, $\sigma = \pm 0.03$)mg/kg. The regression coefficient at τ ($\Delta S_c/\Delta\tau$) is constant within the zone. The uncertainty of its determination at the S_c calculation error ($\pm 3\sigma$) makes up ~30%. In the central basin, the equation is as follows: $S_c = -0.044\tau + 95.90$ ($R^2 = 0.985$, $\sigma = \pm 0.02$) mg/kg. Having integrated $\Delta S_c/\Delta\tau$ by the volume of the deep zone and having divided the resultant value by the total water volume, we find that the weighted average value is equal to 0.019 ± 0.06 for the southern basin and 0.022 ± 0.03 mg/kg/yr for the central basin.

Unlike the southern and central basins, the northern basin shows positive correlation of water age and S_c with depth. The substance flows from old deep layers to young upper layers. The S_c versus age relationship is as follows: $S_c = 0.0485\tau + 94.204$ ($R^2 = 0.996$, $\sigma = \pm 0.01$) mg/kg at the regression coefficient accuracy of ±10%. The average $\Delta S_c/\Delta\tau$ value for the whole basin value is equal to 0.0334 ± 0.003 mg/kg/yr. The annual increase in the S_c content (~260 kt) is mainly provided by water exchange with the central basin.

Data on $\Delta S_c/\Delta\tau$ allow us to determine the vertical flows of the sum of basic ions (Q) by the following equation: $Q_n = -(V_n\Delta S_c/\Delta\tau)S_n^{-1}$, where V_n is the water volume of the deep zone below the isobath n and S_n is the area of the lake section at this isobath. A similar approach was applied for estimation of the rate of oxygen consumption in the Baikal deep zone based on the dependence of its content [1] or deficit [2] on the age. According to the results obtained (Fig. 3a), the flow from the upper layers (Q_n) across horizon 400 m in the southern and central basins makes up 23–27 g/m^2/yr. In the northern basin, the flow of the material arriving from the lower layers to the horizon 200 m is ~23 g/m^2/yr and should generally correspond to its inflow from the central basin.

The substance transfer in the lake is realized by exchange processes. The exchange characteristics are determined by flow data based on the solution of the inverse problem. The reliability of the values obtained is assessed by their comparison with results of other calculation methods and input data.

Based on the annual increment (Π) in the S_c content in the northern basin water (260 kt) and the difference of S_c contents in the northern and central basins δS_c (0.8 mg/kg), we can find the value of water exchange between the basins W from the equation $\Pi = W \cdot \delta S_c$. It is equal to 325 km^3 /yr, which is only 35% higher than the water exchange value established in [10] from the equation of the salt balance in the northern basin (240 ± 50 km^3/yr). The increment can be accounted for errors of Π and δS_c determinations. In addition to water

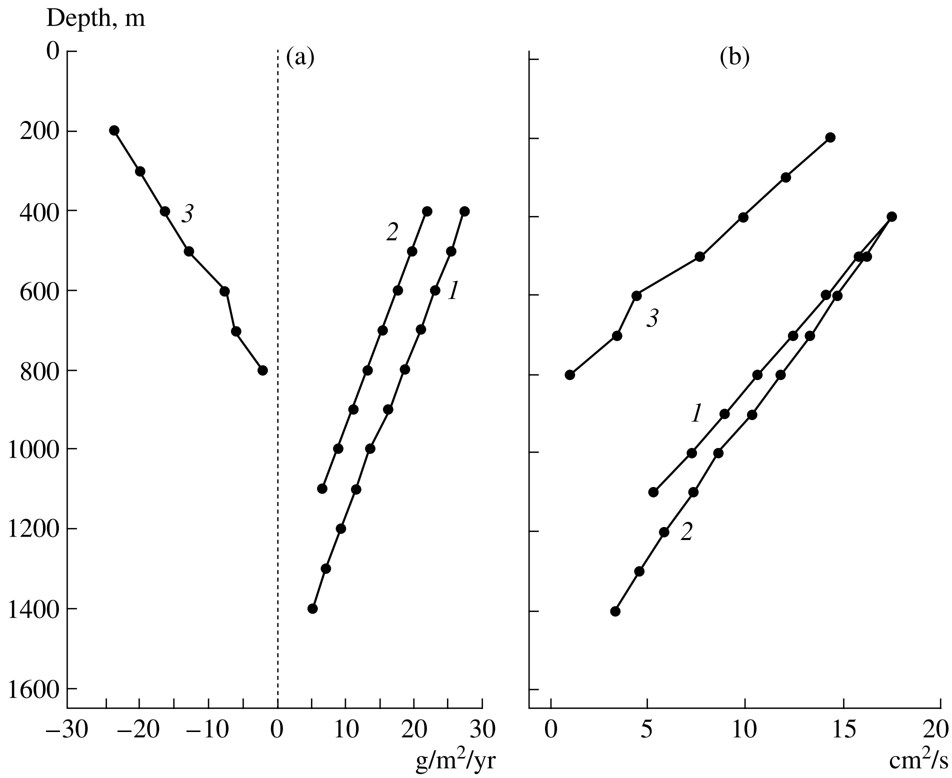

Fig. 3. (a) S_c vertical flows and (b) vertical water exchange coefficients in the deepwater zone of the (*1*) southern, (*2*) central, and (*3*) northern basins of Lake Baikal in May–June, 1995.

exchange, other processes also could affect the Π value. Based on data on flows of basic ions (Q) and gradients $\Delta S_c/\Delta z$, we can determine the vertical exchange coefficients (K_z) from the equation $Q = -K_z(\Delta S_c/\Delta z)$, which characterizes the average (for a long time interval) intensity of water exchange (Fig. 3b). They are comparable to the results of K_z calculations based on annual mean vertical flows of heat and substance (dissolved silicon) [3, 11]. It is hardly possible to use data on K_z for individual years [12] because of variations of water exchange conditions in the deep zones [2]. The comparison has revealed general trends in the distribution of K_z values (decrease with depth and decrease in the northern basin of the lake) determined by different methods. The discrepancy between them at different depths is insignificant (2–4 cm^2/s). Similarity of the results indicates the validity of interpretation datings for determining S_c flows in the watermass of the basins and the reality of flow values.

Let us dwell on causes for S_c flows in the Baikal watermass. They are rather clear for the northern basin. However, the situation is more complicated for the southern and central basins. A downward direction of the S_c flow implies the presence of constant positive (at the upper boundary) or negative (at the lower boundary) sources. Since there is no information for the source, let us hypothetically recognize the first scenario as the basic one. It is possible if the inflow of ion components from outside slowly increases. Such a trend was assumed in [13], but it requires confirmation by special studies with application of precision methods [14]. Judging from the obtained Q values, the additional inflow of ion components to deep zones of the southern and central basins are ~120 and 200 kt/yr, respectively. In order to estimate this parameter for the northern basin, let us assume that the increment of the S_c content in this basin (260 kt/yr) is related to water exchange and inflow from outside. The first constituent is determined by the water exchange value from [10] (240 km^3/yr) and the S_c difference for waters of the central and northern basins (0.8 mg/kg) equal to ~190 kt/yr. Then, the second constituent is equal to the difference between 260 and 190 kt, i.e., 70 kt/yr. The total S_c increment in the Baikal deep water will make up ~390 kt at the growth of concentration by 0.027 mg/kg/yr. If the maximal error in S_c discrepancy at the upper and lower boundaries of the deep zone is ~40%, the S_c concentration may vary from 0.01 to 0.038 mg/kg/yr, while the total content may vary from 230 to 540 kt/yr. Relative to the whole water volume of the lake, the growth of the S_c concentration varies from 0.005 to 0.02 mg/kg/yr (average ~0.015).

The results indicate a slow growth in the S_c content of Lake Baikal. However, in terms of quantity, these values are approximate because of assumptions admitted in the work and limited initial data (for instance, data on one station in the basin are taken as proxy for its whole watermass). Nevertheless, they seem to be more real than the available (see review in [15]) estimates of accumulation of dissolved salts in Lake Baikal (800–1900 kt/yr). The latter values were obtained from calculations of the dissolved salt budget by traditional methods of the hydrochemical analysis, the accuracy of which in the determination of the ionic components is one order of magnitude lower than the values based on conductivity data.

ACKNOWLEDGMENTS

We are grateful to N.G. Granin, I.B. Mizandrontsev, and E.L. Gol'dberg for useful discussions and comments on this work.

This work was supported by the Russian Foundation for Basic Research (project nos. 04-05-64839 and 04-05-64397), the Siberian Division of the Russian Academy of Sciences, and the Integration Program (project no. 131).

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