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GRAVITATIONAL STABILITY OF THERMAL-CHEMICAL STRATIFICATION IN A RESERVOIR

By

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SYNOPSIS

A water quality measurement was carried out in a eutrophic reservoir where a double-density structure of chemical-thermal stratification was found. Vertical profiles of temperature, dissolved oxygen and electric conductivity were measured with portable field devices. Water samples were collected from four different levels and their water qualities such as metals, nutrients, organic matters and so on were examined in a laboratory. The measurements were carried out every month for the last two years. It is a striking feature of this reservoir that; temperature near the bottom is inversely stratified throughout a year; the bottom water contains extraordinary high concentration of solutions, although there is no local source of salinity; and the water body has never been overturned in the last few years. The field data suggest that dissolved and suspended materials are so highly concentrated near the bottom that the double-density field is always kept overstable there. This is a reason why the reservoir water has not experienced a full-scale overturn even in a cold winter season.

INTRODUCTION

In enclosed water areas such as lakes, reservoirs and sidearm in bays, oxygen is consumed a great deal through resolution of organic compounds. Anaerobic water mass is then produced especially near the bottom. Under such a situation, nutrients and ionic metals tend to come out of bottom sediments and salinity there is highly concentrated. This could bring serious water quality troubles. Nevertheless, the bottom water usually has a chance to be aerated in Autumn and/or Spring by full-depth scale overturn due to natural convection, even in a highly stratified reservoir.

The reservoir under this study, however, showed totally different water quality behaviors from ordinary lakes and reservoirs. They are as follows.

- A very anaerobic and eutrophic water mass was sitting near the bottom throughout a year. This showed high electric conductivity and has never been exchanged in the last few years.
- Near the bottom, an inverse temperature stratification has been constructed and kept very stable, while water was warmer than 4℃.

Such an inverse temperature gradient is sometimes observed in coast-near lakes where sea water intrusion creates a stable heat-salt stratification. Although this type of thermal structure was observed in a few inland lakes and reservoirs as well, little is known about the heat source for producing the warm bottom layer[1),2)].

Because the water near the reservoir bed is highly contaminated with nutrients and metal components, it is much worried that unpredictable water quality problems could occur one day. This could happen, for instance, when the bottom layer would be imposed on extraordinary mixing actions such as strong natural convection, a high discharge of flood inflow and so on.

In order to find out how the double density structure with inverse temperature gradient was constructed, the authors carried out a monthly field measurement of water quality. Seasonal variation of water qualities and density structure are discussed. It is also examined how each water quality components contributes to fluid density and how the double density structure is kept gravitationally stable.

OUTLINE OF FIELD MEASUREMENT

The plane and vertical views of the reservoir are illustrated in Fig.1, where water sampling points are plotted. The reservoir was constructed for flood control and irrigation in 1979. Reservoir water is discharged through a set of selective inlet works mounted on the dam. During the period of our field measurement, only the gate located at EL.195m was used for discharging water. The normal high water level is EL.207m and the corresponding water depth at the measuring station is 32m. The water surface area at EL.207m is 0.134km^2 and the storage capacity is $1.95 \times 10^6 m^3$. The exchange rate defined by $\alpha \equiv$ [storage capacity]/ [annual inflow] is comparatively small among reservoirs in Japan; it was α=1.93 in 1994. The reservoir water tends to be highly stratified especially in summer.

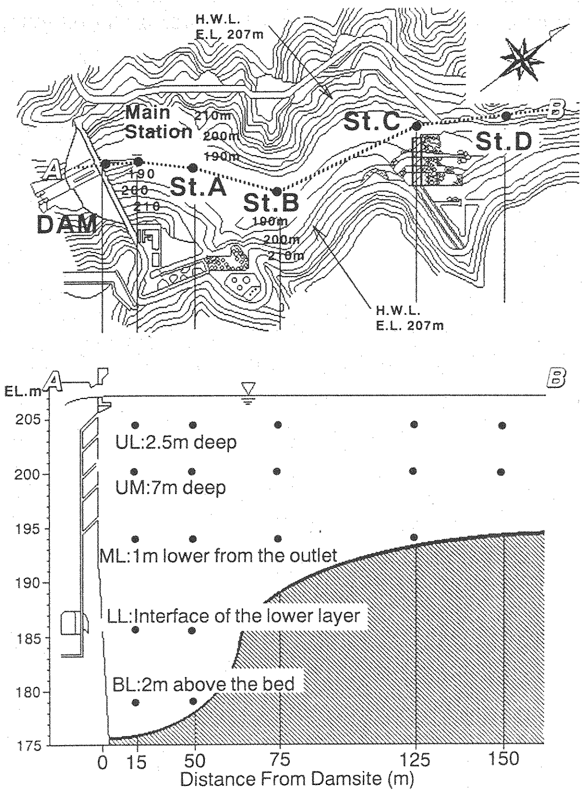

Fig.1 Plane and vertical views of reservoir. Dots are sampling points of waters.

The field measurement was started in 1994. Vertical profiles of water temperature, dissolved oxygen DO and electric conductivity EC were obtained by in-situ probe measurements. Water samples were collected from four different levels shown in Fig.1 and their water qualities were examined in a laboratory. The items examined are total residue TR and total concentration of metal components such as Fe, Mn and Na. Hydrological and meteorological data were automatically measured at a control station of the reservoir. Concentration of nutrients and Chemical and Biological Oxygen Demands were also measured but their results are not discussed here.

SEASONAL VARIATION OF WATER TEMPERATURE AND QUALITIES

Isopleths of water temperature and electric conductivity EC are shown in Figs.2 and 3. The shaded parts denote anaerobic layers where saturation rate of dissolved oxygen is less than 5%.

Seasonal Variation of Water Temperature

During the heating season from May to October in '94 and '95, a well-defined thermal stratification was developing. Meantime we had a very dry weather during August to September in '94, a thermocline around EL.195m was very sharp and then moved downward due to natural convection until November. On the other hand, when we had more precipitation in '95, the thermocline was weaker compared to the year before. From this, one can suppose how the thermal structure depends on vertical mixing actions due to river through-flows.

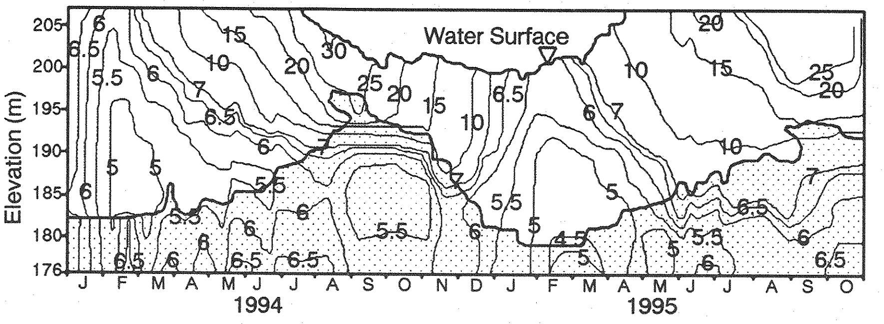

Fig.2 Seasonal variation of temperature. Numeric shows temperature in Celsius. The shaded area denotes anaerobic water whose saturation rate of dissolved oxygen is less than 5%.

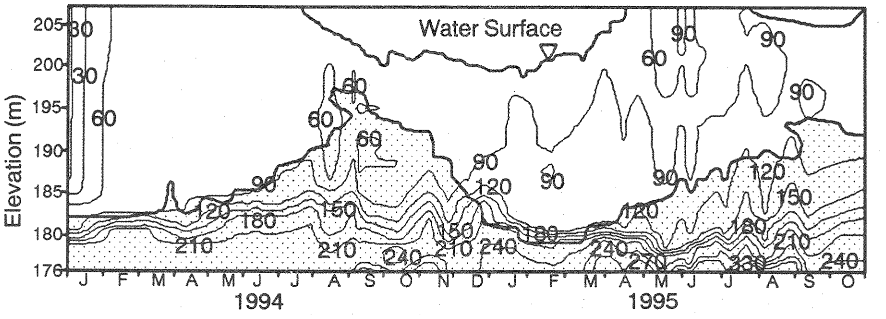

Fig.3 Seasonal variation of electric conductivity EC in μS/cm.

An interesting feature is that the temperature field was inversely stratified in a few meters thickness above the reservoir bottom. The bottom layer was always kept warmer than the layer above. This "inversion layer" was very stable even in mid-winter, which means that some extra solutions were concentrated near the bottom to stabilize the density field. The temperature data also suggest that the system was stratified all the seasons or the water body has never been overturned.

Anaerobic Water Mass Behaviors

The anaerobic layer thickened during heating season from May to August and then shrank from October to February. In August and September the layer was capped by the thermocline and did not grow any more. In this stage, the surface layer was well aerated by gas exchange across the air-water interface and mass exchange with the inflow water, while the lower layer was confined without being exchanged. The top interface of the anaerobic layer moved between EL.183m and EL.195m. The anaerobic water has never disappeared even in winter season, which suggests again no overturn occurring in this reservoir.

Seasonal Variation of Electric Conductivity: EC

In all the seasons, the layer below EL.180-185m showed high electric conductivity, which means that solution was highly concentrated there. The EC interface showed different behaviors from the DO interface and the inversion layer.

Seasonal Variation of Metals: Fe, Mn, Na

Field data of temperature and EC suggest that some chemicals were concentrated near the bottom to compensate density deficit due to the inverse temperature gradient.

In an anaerobic layer, ionic metal components such as Fe^{2+}, Fe^{3+}, Mn^{2+} tend to come out of sediments and fluid density there could be increased. An ion chromatography examination was conducted in order to find out a relationship between metal components behaviors and the density structure.

Seasonal variations of total iron T-Fe, total manganese T-Mn and total sodium T-Na are drawn in Figs.4 to 9. In the figure, the notation "UL" means the upper layer of 2.5m deep from the water surface, "ML" the middle layer at EL. 194m, "LL" the lower layer of 2m above the bottom and "IN" and "OUT" the inflow and outflow waters, respectively. Results from bottom sediments are also listed in Table-1.

(a) Iron: Fe (Figs.4, 5)

Concentration in the inflow water was between 0.01-0.04mg/l, while that from the outflow water showed higher values. Regarding reservoir waters, the lower layer contained more T-Fe than the upper and the middle layers. Table-1 documents that high concentration between 34,000-39,000mg/kg was detected from the bottom sediments. From these, one can guess that iron was supplied from the bottom under chemical and biological reactions, because sediments were extensively reduced in such an anaerobic environment. Part of the highly contaminated bottom water could be entrained from the bottom layer into the outlet, which brought high concentration of T-Fe in downstream.

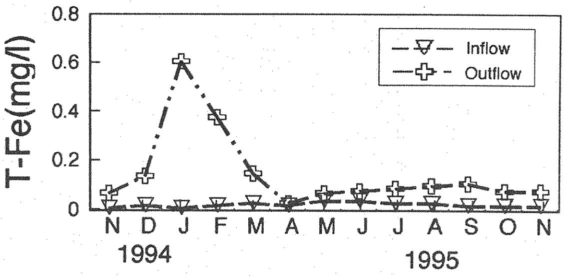

Fig.4 Seasonal variation of total iron T-Fe (mg/l) in inflow and outflow river waters.

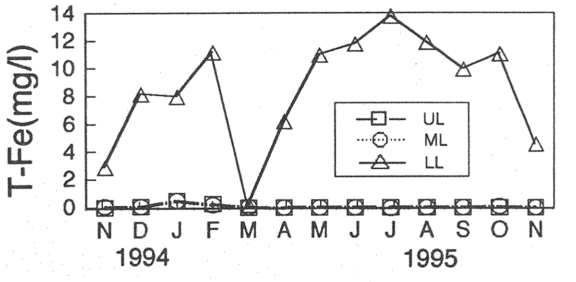

Fig.5 Seasonal variation of total iron T-Fe (mg/l) in impounded reservoir waters.

Table-1 Concentration of T-Fe, T-Mn and T-Na in bottom sediment (mg/kg).

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Date	11/17	12/15	1/12	3/15	4/13	5/17	6/15	7/14
T-Fe	36,000	35,000	39,000	34,000	34,000	39,000	33,000	36,000
T-Mn	870	780	910	780	780	880	860	850
T-Na	10,000	10,000	11,000	9,800	8,500	12,000	14,000	15,000

(b) Manganese: Mn (Figs.6, 7)

High concentration of total manganese, 0.01-0.55mg/l, was observed in the outflow water; the inflow water had less concentration around 0.01mg/l. Just like the iron's case, the lower layer was more highly concentrated with Mn than the upper and middle layers.

Note that T-Mn in the middle layer was small but showed a certain amount, which was contrary to that T-Fe was negligibly small there. Because oxygenation-reduction potential of manganese is smaller than that of iron,

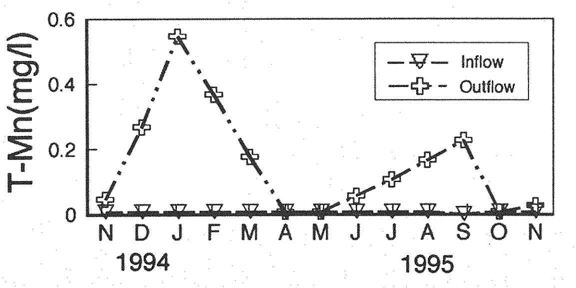

Fig.6 Seasonal variation of total manganese T-Mn (mg/l) in inflow and outflow river waters.

manganese must be less oxygenated than iron. In other words, iron is more possibly oxygenated in the aerobic middle layer. As a result, oxidants like $Fe(OH)_3$ tend to settle down and iron concentration there decreases. On the other hand, less oxidants are produced from manganese and most of manganese is kept dissolved as ionic components. This might be a reason why concentration of manganese was kept higher than iron in the middle layer.

(c) Sodium: Na (Figs.8, 9)

Both of the inflow and outflow showed the same order in concentration. No clear stratification of sodium was found in the reservoir. In general, sodium concentration is a good indicator or tracer of hot spring water, because hot spring usually contains high concentration of sodium[2]. The homogeneous profile of sodium suggests that there was no hot spring water supply from the bottom, in other words, a warm water near the bottom was not supplied from a hot spring.

DENSITY STRUCTURE OF RESERVOIR

It is considered that dissolved metal components contribute to the increase of fluid density and they stabilize density structure near the bottom. This is a possible reason why the water body has not been overturned for years despite temperature was inversely stratified. In order to verify this a fluid density analysis is performed as follows.

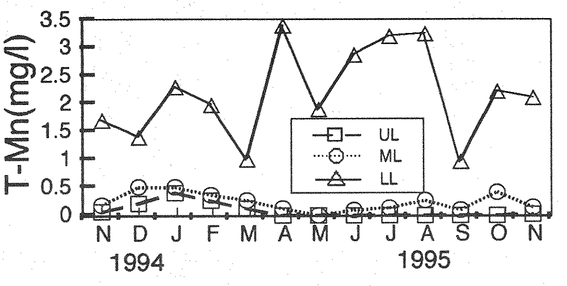

Fig.7 Seasonal variation of total manganese T-Mn (mg/l) in impounded reservoir waters.

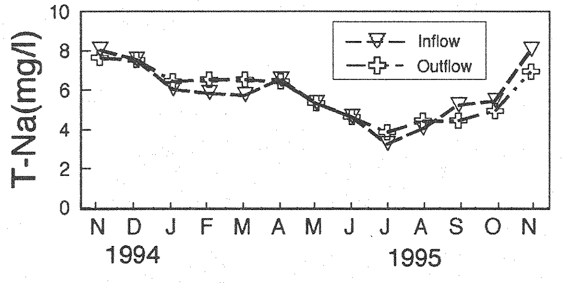

Fig.8 Seasonal variation of total sodium T-Na (mg/l) in inflow and outflow river waters.

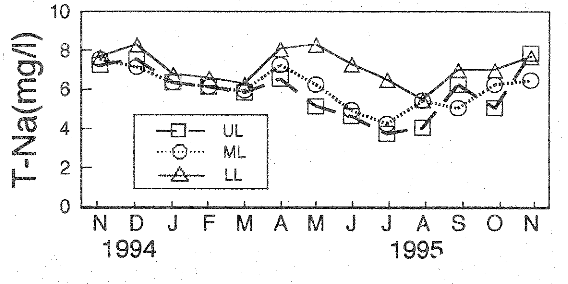

Fig.9 Seasonal variation of total sodium T-Na (mg/l) in impounded reservoir waters.

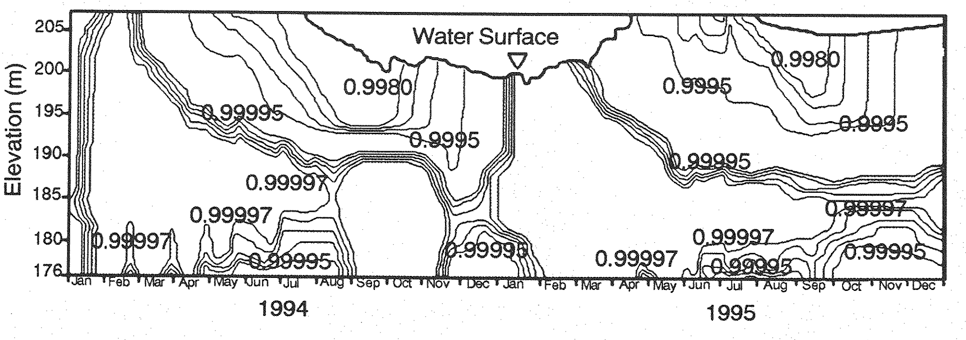

Fig.10 Density isopleth computed from temperature field data by using an equation of state for pure water.

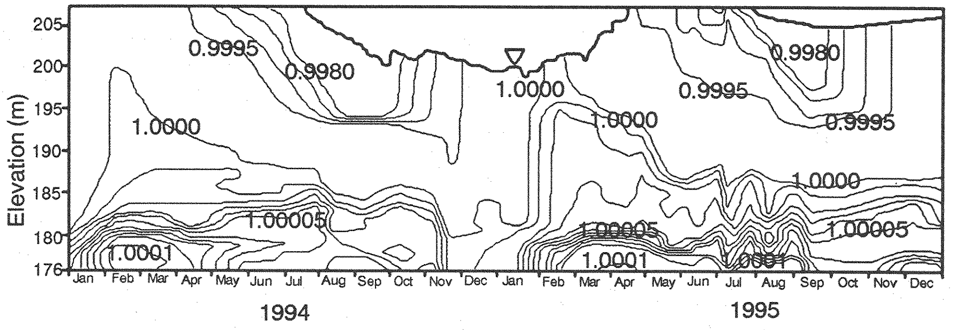

Fig.11 Density isopleth computed by an equation of state for sea water.

Assuming the reservoir being composed of pure water, density profile is computed from the equation of state as shown in Fig.10. The inversion layer is evaluated to be gravitationally unstable in this case. The density defect corresponding to the "unstable layer" is about 100-200mg/l. As discussed above, a certain amount of materials need to be contained here in order to compensate the density defect. Measurements of total residue, TR, show weight anomaly in this layer to be about 150-200mg/l. This is enough amount to stabilize the temperature inversion layer.

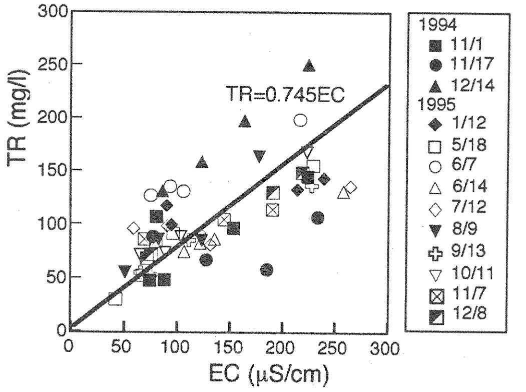

Fig.12 Functional relationship between total residue TR and electric conductivity EC.

In order to discuss the density structure, the fluid density has to be computed as a function not only of temperature but also of chemicals concentration. As the first approximation, we employ an equation of state for sea water assuming that the water quality constitution of the reservoir is equivalent to sea water. The equation is[3)]

$$\rho(S,\ t,\ p) = \rho(S,\ t,\ 0)\ /\ \{1 - p/K(S,\ t,\ p)\} \tag{1}$$

where, ρ: density (kg/m^3), t: temperature (℃), p: pressure (bar) (0 for 1 atm), S: salinity (total weight (g) of solid matters contained in 1kg of water), $K(S, t, p)$: volumetric elasticity.

Fig.11 shows that a density isopleth computed from Eq.(1) still has unstable layers near the bottom and it is concluded that the equation underestimates the reservoir water density. It is found from the water quality examination that the reservoir has a totally different constitution of water quality from sea, while the sea water mainly consists of NaCl.

Therefore, we have to find another equation in order to correlate fluid density to temperature and chemicals concentration.

Although many kinds of components contribute to the density stratification, it is difficult to identify all functional relationships between fluid density and concentration of every water quality component. Here, chemicals concentration and thus the total weight of chemicals is assumed to be linearly dependent on electric conductivity. A relationship between EC and total residue, TR, is then plotted from the field data as shown in Fig.12. Besides data scattering a regression curve is found to be

$$TR=0.745EC \tag{2}$$

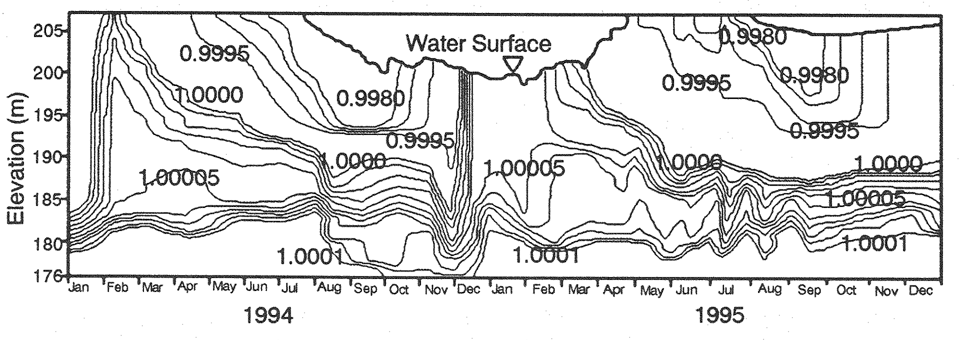

Fig.13 Density isopleth computed from field data of temperature and electric conductivity by using Eq.(2) and an equation of state for pure water.

Adding density anomaly computed from Eq.(2) to water density from temperature data, a density structure is obtained as shown in Fig.13. The figure documents that the water body is gravitationally stable in every layers as well as in all the seasons; the system is so stable that the thermal-chemical stratification has been kept in long without any overturn.

CONCLUDING REMARKS

Main conclusions from the present field work are summarized as follows.

(1) A temperature inversion layer was observed near the bottom for years long; temperature below the inversion layer was kept higher than the layer above.

(2) High electric conductivity was detected below the inversion layer. Water below the thermocline was very anaerobic.

(3) The total iron T-Fe and the total manganese T-Mn were strongly stratified; they were highly concentrated near the bottom.

(4) The sodium concentration T-Na was very homogeneous in the depth direction. It was found that no hot spring groundwater come out of the reservoir bed or the warm water near the bottom was not supplied by the hot spring.

(5) Dissolved materials were so highly concentrated near the bottom that the unstable density gradient of the temperature inversion was gravitationally balanced with density anomaly due to the chemicals concentration.

(6) Assuming TR to be a linear function of electric conductivity, seasonal variation of density profiles are computed from the observed temperature and electric conductivity. The density stratification in the reservoir is found to be very stable in all the seasons, although there was a temperature inversion layer near the reservoir bed. Because of the highly concentrated water mass near the bottom, the water body was kept so stable that it has never been overturned for years long.

The anaerobic water near the bottom must be responsible in bringing high concentration of metals and nutrients there. Therefore, reaeration of the bottom layer could be one of the useful countermeasures for preventing future water quality troubles.

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APPENDIX-NOTATION

DO = saturation rate of dissolved oxygen (%);
EC = electric conductivity in (μS/cm);
K = volumetric elasticity;
p = pressure in bar;
S = salinity of water;
t: = temperature in Celsius;
T-Fe = concentration of total iron in (mg/l);
T-Mn = concentration of total manganese in (mg/l);
T-Na = concentration of total sodium in (mg/l);
TR = concentration of total residue in (mg/l);
α = exchange rate of reservoir water being defined as [annual discharge]/[reservoir storage capacity];
ρ = density of water in (kg/m^3).

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