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Biogeochemical cycles in thermokarst lake basins

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ABSTRACT

The article presents the results of comprehensive studies of the thermokarst lake basins in Central Yakutia by the scheme: soil – vegetation - bottom sediments - lake water. As the model areas there were taken the territories of closed alas basins of the Tyungyulyunsky terrace of Central Yakut plain. There were identified two schemes of material migration with a pronounced natural origin, enhanced by the anthropogenic influence. The main transporter of chemical materials within the thermokarst lake basins in Central Yakutia is soil organic material, and the concentrator is the bottom sediments.

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INTRODUCTION

Since the scientific study of the interaction of living organisms with the environment, it was found that the processes of biogenic mass transfer are cyclical in nature [1]. Close attention is paid to the cyclic processes of planetary character, but a regular cycling also occurs at the regional level [2, 3]. And in this sense, the study of materials' biogeochemical cycles under the condition of thermokarst basins development, which were formed due to the ground ice melting, is of particular interest especially at the current stage of intensive anthropogenic impact [4, 5].

One of the peculiar manifestations of permafrost evolution is the thermokarst basins - alases. According to the Pekarskiy E.K. (1959) definition, alas is a Yakut word, which can be translated as meadow space surrounded by a wooded mountain [6]. In the works of Grave N.A. (1944) and Soloviev P.A. (1959, 1962, and 1963) there is provided a definition of "alas" as a thermokarst basin. Thermokarst is a multistage historical and geological process and its corresponding phenomenon, which is expressed in the formation within the multi-year permafrost icy strata of closed and semi-closed basins together with specific alas sediments [7-9].

In general, alases of Central Yakutia represent intrazonal landscapes cryolithozones with specific soils and meadow vegetation, climate and wildlife, are dynamic systems, where occur unique processes of material and energy transformation between the biological and inorganic components of given systems [10].

Methodology:

The working material is represented by the results of comprehensive researches of alas ecosystems in Central Yakutia in compliance with the scheme: soil – vegetation – bottom sediments – lake water. The findings are based on full-scale surveys of the territories with more than 90 thermokarst basins, into which there are included 72 soil profiles and selected about 150 soil samples, bottom sediments, 70 samples of mixed herbaceous vegetation associations constituting ground cover and 30 samples of lake water. As model areas there were taken territories of closed alas basins of the Tyungyulyunsky terrace of various degrees of degradation – the Tebyuren alas and the Uolen alas, which are used as grasslands and rangelands (Fig. 1).

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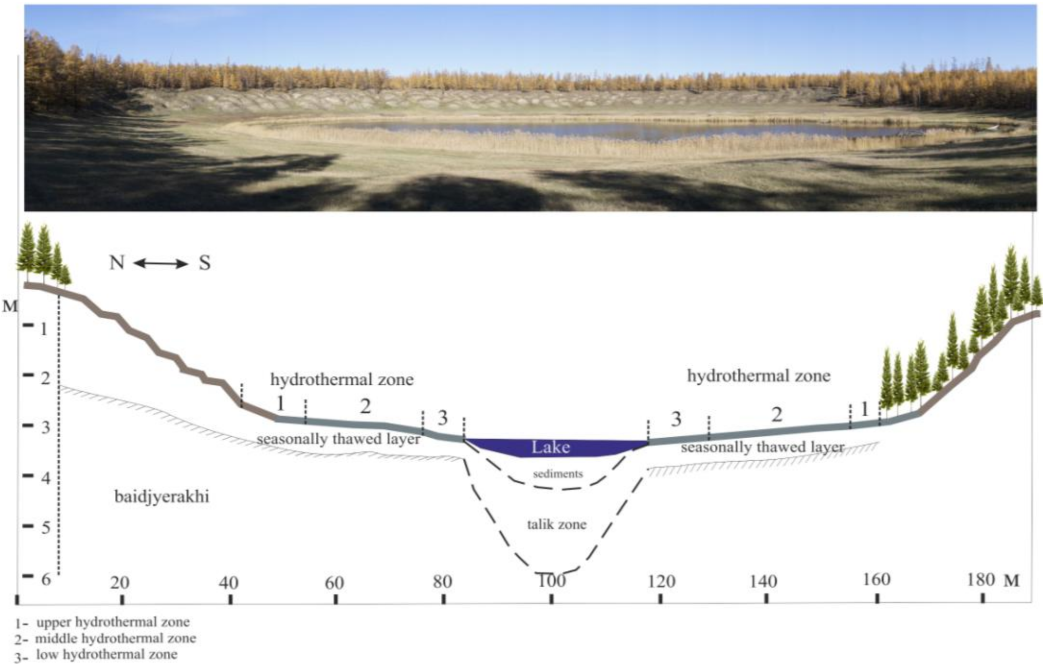

Fig. 1: The scheme of landscape profile of thermokarst basin of the "Tebyuren alas" in Central Yakutia.

Analytical works were carried out in the laboratory of physical and chemical methods of analysis Scientific and Research Institute of Applied Ecology of the North "North-Eastern Federal University" SRIAEN NEFU (accreditation ROSS RU.001.517741) generally accepted in soil science and agricultural chemistry methods. Determination of mobile forms of ten microelements was made by the atomic absorption method with extraction of 1H HNO3 on a multichannel spectrometer MGA-915 "LUMEX".

To interpret the results, there were used the following factors [11]:

- mechanical migration coefficient (K_1);
- biological absorption coefficient (A_x). At A_x>1 elements accumulate in plants, and at A_x<1 they are only captured;
- water migration coefficient ($K_в$). The higher $K_в$ is, the stronger an element is leached from the rocks, and the more intense its water migration is;
- bottom-soil coefficient (D_x). At D_x>1 there is an accumulation of elements in bottom sediments.

Main part:

The specificity of biogeochemical processes occurring in alas ecosystems, is determined by the features of soil formation in alas [12]. The beginning of thermokarst is characterized by the manifestation of primary lakes on the plain surface [6]. Lakes are the heat accumulators, which leads to ice complex thawing underneath. The role of these lakes is not only in shaping the contours of the future alas basin, but also in partial changing the composition of the clay loam mantle due to their thermokarst redeposition.

According to the researches made by Katasonov E.M. and Ivanov M.S. [7], as a result of redeposition, there is formed a combination of highly different in mechanical composition lithogenic sediments (sand, sandy loam, loam, etc.) and organic lacustrine formations (silt, peat, sapropel), which, being formed in closed basins, are alas deposits representing the soil-forming substrate.

Given the primary role in the implementation of the main soil ecosystem process - the interaction of biotic and mineral components, the processes of material migration were the leading factor in the study of dynamics and transformation of environmental components within thermokarst basins and soils were the defining object of the study.

Alas type of soil is determined by the existence of two stages: hydromorphic and xeromorphic. In the range of these stages, as well as within their mutual transfer, the alas functioning contributes to the passage of soils through the independent development phases: the lake soil, marsh soil, meadow soil, and steppe like soil [8], which corresponds to the formation of distinctive zones in alas – the lower (lake or marsh phase), medium (meadow phase), and upper (steppe like phase). Moreover, the development phase of the lake, or the lower zone, due to its large geochemical differences, is divided into two semi-phases, the first of which corresponds to an affluent regime of lakes, and the second corresponds to the drying up one.

In parallel there occurs the formation of interalas space soils that, being influenced by the drier conditions, are developing at higher, if compared to alas basins, relief elements under a canopy of larch-lingonberry grassy taiga under the condition of suprapermafrost non-clearing water regime (Fig. 2). There are still areas of treeless space, occupying the upper part of the alas basin slope, where the soils of soil genesis are formed, but due to the geomorphological conditions with the transformed top organic and mineral part of the soil profile.

Accordingly, these soils are characterized by the accumulation of carbonates in the accumulative-carbonate horizon, development of the solodization processes, and some degree of alkalinity. Quite often, even in the upper zone of alas, there occur the permafrost fawn transitional soils that carry signs of both alas, and forest soils.

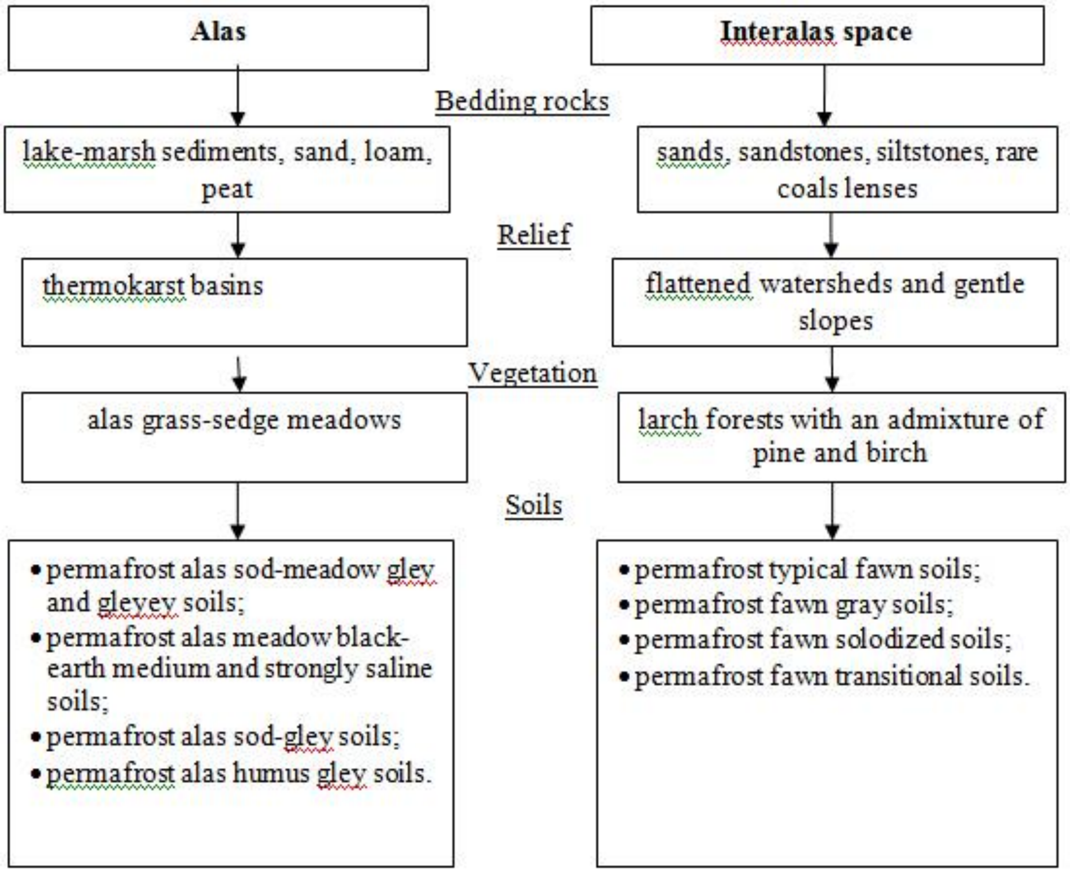

Fig. 2: Scheme of soil formation conditions within the closed thermokarst basins in Central Yakutia.

A presupposition exists [10] that there is a gradual subsidence of permafrost fawn soils as a result of melting of ground ice of small power and multi-iced potting soils, followed by daylight surface flooding in a relatively short period of time. Consequently, at the present stage of development of thermokarst basins, the fawn soils of interalas space serve as the foundation of soil formation of both interalas spaces and alas themselves. Thus, within the study area, there were formed different subtypes of permafrost fawn soils occupying interalas space and permafrost alas meadow black-earth soils, permafrost alas sod-meadow gley and gleyey soils, and permafrost alas humus and sod-gley soils occupying lacustrine alas territories. According to their physico-chemical characteristics the soils as a whole meet their natural state. Except in the alas areas used as hay and pasture lands. The main reasons of environmental state degradation of alas ecosystem soils are the strong flooding, leading to the active development of gley processes worsening anaerobic soil properties.

Exactly the cyclicity of the alas soil formation defines the geochemistry specificity of habitat conditions of living organisms of this type of landscape [12]. Heterogeneity of the chemical composition of permafrost soils of thermokarst basins in Central Yakutia at the macro level in conjunction with geochemical specificity of the parent rocks determines differences in microelement composition of different types and subtypes dominating within the alas ecosystems. The uniform for the considered soils formed within alas basins, is the distribution tendency of manganese, cobalt and copper – the elements consistently accumulating in soil stratum and inherited from parent rocks of terraced complexes (Fig. 3).

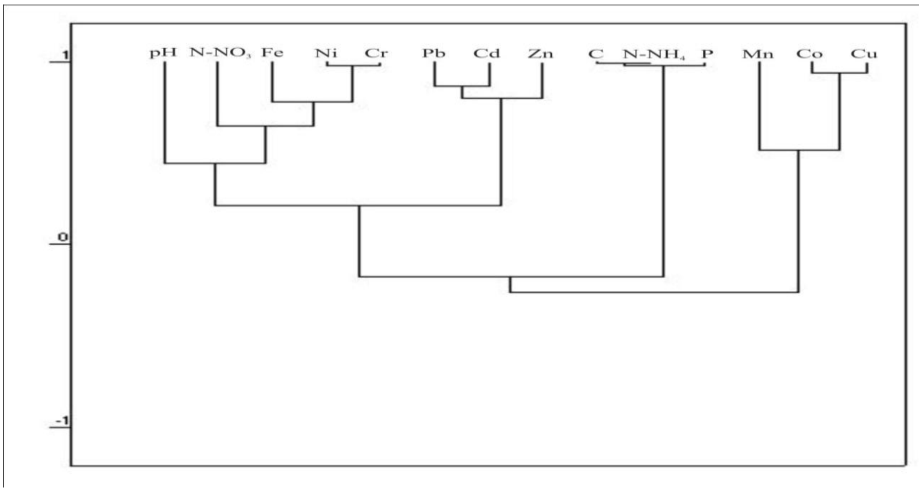

Fig. 3: Dendrogram of the microelement mobile forms content dependence on the pH variation and macroelements content in frozen soils of thermokarst basins in Central Yakutia.

Apart there are distinguished groups of microelements, which controlling factor of redistribution is represented by a soil organic substance, like Cd, Zn, and Pb. Accumulation of litho-siderophile elements Ni, Cr is largely dependent on the variations and forms of Fe2+ and Fe3+ existence. Redistribution of organic carbon content and related to it ammonia nitrogen and labile phosphorus occurs in the soil profile as a result of cryoturbation, and in connection with mechanical migration along the slope of the basin. Intensity of mechanical redistribution along the thermokarst basin slope is illustrated by the mechanical migration coefficients (Table 1).

Table 1: Mechanical migration coefficients along the thermokarst basin slope .

Coefficient	Agrochemical parameters					Microelements							
	Organic carbon content	N-NH$_4$	N-NO$_3$	P	Fe	Pb	Ni	Mn	Cd	Co	Cr	Zn	Cu
K_1	0.3	0.5	3.7	0.6	0.8	1.0	0.9	1.0	1.0	0.9	1.0	0.9	1.0
K_2	1.1	0.9	10	0.9	0.8	0.1	0.1	0.1	0.3	0.1	0.3	2.6	0.5
K_3	0.9	1.0	1.5	1.2	1.1	1.0	1.2	0.5	0.8	0.7	1.2	0.5	0.8
K_4	3.1	2.2	7.1	0.9	1.9	0.8	1.2	1.3	1.0	0.9	1.1	1.1	0.5
K_5	3.7	4.1	0.12	12.4	0.9	1.3	1.2	0.7	2.5	0.7	4.6	16.7	0.5

Note: K_1= slope/forest soil
K_2=upper zone/slope
K_3=middle zone/upper zone
K_4= lower zone/middle zone
K_5=bottom/lower zone

As it can be seen from the calculation of the mechanical migration coefficients, the main accumulation of organic materials occurs in the lower zone of alas and in bottom sediments. Bottom sediments of the studied lakes are of dark gray color, are characterized by sandy and loamy composition, with a large admixture of vegetable residue, alkaline medium (pH 7.6-8.9) with a characteristic odor of hydrogen sulfide. In microelement composition, the most consistent and intense accumulation as a result of mechanical migration takes place exactly in bottom sediments, where there are deposited Ni, Pb, Cd, Cr, and Zn. When calculating the bottom-soil coefficient using an average content of microelements in soils in the example of the Tebyuren alas territory, there was built the next cumulative row:

D_x- $Ni_{1.1} < Cd_{1.2} < Fe_{1.3} < Cr_{1.3} < Pb_{1.3} < Zn_{3.5} < Cu_{7.3}$.

Thus, it appears that as a result of the material mechanical migration along the slope of thermokarst basins, and also due to cyclical changes in the water table, in alas lakes the bottom sediments are the main concentrators, where there are formed specific sulfide and gley geochemical barriers, which determines the level and range of microelement coprecipitation.

Further, the migration of elements depends on the prevailing redox conditions in the system of bottom sediments – lake waters. Usually, the investigated thermokarst lakes of alas basins under the classification of Alekin O.A. [13] possess a hydrocarbon composition with a predominance of magnesium and sodium cations (Fig. 4) and are characterized by increased and high mineralization, with hard and extremely hard water with weak alkaline and alkaline medium.

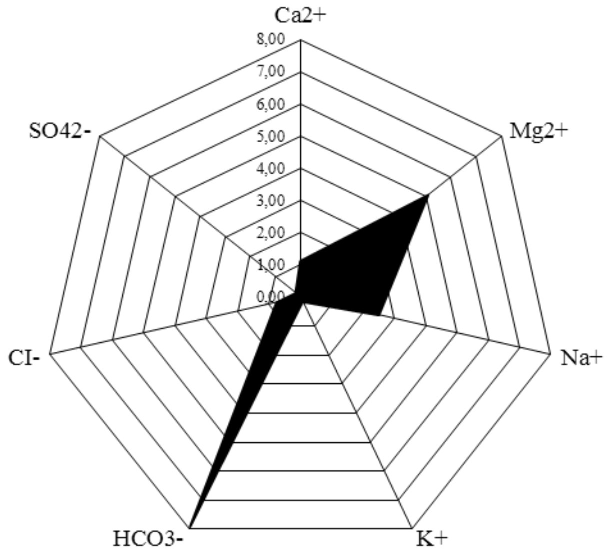

Fig. 4: The averaged ionic composition of surface waters of alas lakes in Central Yakutia.

In microelement composition of the studied lake waters there are revealed high contents of Fe, Mn, and Cu [14]. Typically, Mn and Cu provide geochemical association with Fe 2+ at acidic and weakly acidic pH [15]. Sediments of the studied alas lakes, as mentioned above, are characterized by slightly alkaline and alkaline pH. Therefore, it is naturally to assume that it is manganese and copper that are the most migration capable in the system of bottom sediments – lake waters.

The next very important component of closed alas ecosystems in the general biogeochemical cycling is vegetation, which microelement composition is determined by the chemical composition and physico-chemical properties of soils, which in turn is reflected in the floristic composition and ecological status of vegetation cenosis (Fig. 5).

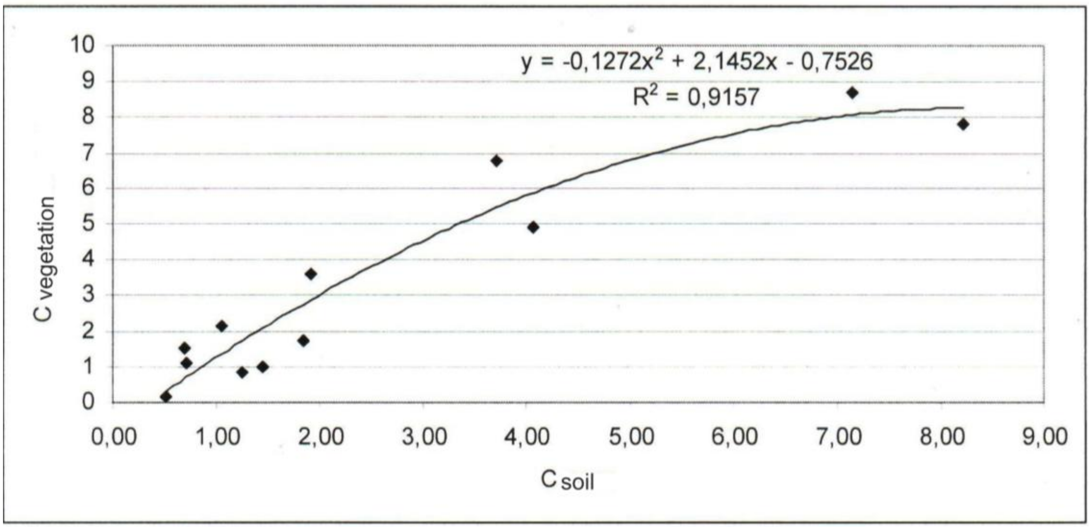

Fig. 5: Dependence of microelements content in soils and plants in thermokarst basins of Central Yakutia

Analysis data processing of the elemental composition of the ground herbs and mobile forms of microelements of alas soils by the factor analysis method (ULS-modification) showed that the overall variability of microelements in plants is determined by four factors. To simplify the structure of the identified factors there was performed their promax (oblique) transformation [16]. The structure of extracted factors is shown in Table 2. Signe change before the coefficient within the same column indicates the opposite tendency of the element behavior. Thus, in F1 with an increased content of lead, nickel, cadmium, and chromium, there are reduced the concentrations of cobalt and copper, and in F2 with the increased content of iron, the concentration of manganese and lead is decreased. Thus, there works the mechanism of selective accumulation in vascular plants or antagonism between the shown elements.

Table 2: The coefficients of the factor loadings of elements in promax factors.

Elements	F1	F2	F3
Pb	**0.82**	-0.46	-0.35
Ni	**0.87**	0.45	0.21
Cd	**0.87**	-0.48	0.09
Cr	**0.80**	0.58	0.15
Co	**-0.85**	-0.53	0.07
Cu	**-0.92**	-0.32	-0.24
Fe	0.28	**0.70**	0.65
Mn	-0.23	**-0.83**	0.52
Zn	0.55	**-0.82**	0.20
contribution to the total variance, %	68.90	20.60	10.40

Note: elements in bold significantly determine the factor structure

As it can be seen from the Table 2, the variability of chemical element in the terrestrial part of herbs of more than 80% is determined by two factors with a clear geochemical structure, among which the leading role in the absolute values of the coefficients is played by copper and manganese.

According to Perelman A.I. (1975) "the permafrost sections are not the area of geochemical rest ", while it is the area of specific cryogenic processes development, which at low temperatures with pH decreasing on the background of intense leaching of carbonates that promote certain redox conditions and ion exchange, determining the development of materials migration [11]. The intensity of accumulation of microelements in components of alas ecosystems is presented in Table 3. The most high migration ability within thermokarst basins of Central Yakutia is characterized by copper, zinc and manganese.

Table 3: The intensity of microelements accumulation in the ecosystem of thermokarst basins in Central Yakutia.

Ecosystem components		Coefficients, microelement rows of accumulation
Soils	Forest	A_x - Mn<Cu<Pb<Ni<Cd<Cr<Zn
	Slope	A_x- Mn <Pb<Ni<Cu
	Upper zone	A_x - Zn
	Middle zone	A_x - Zn<Cr<Cu
	Lower zone	A_x - Cu<Zn
Bottom sediments		D_x - Ni< Cd<Fe<Cr<Pb<Zn<Cu
Lake water		K_x- Fe<Cu<Mn
Vegetation		A_x - Cd<Mn< Cr<Cu< Zn

Conclusion:

The identified migration tendencies of chemical elements within the thermokarst basins have expressed a natural origin, which determines the relationship with lithology and cryogenic conditions of alas formation and enhanced anthropogenic influence – using of alas grasslands as haylands, violation of soil-vegetation cover due to uncontrolled grazing of domestic animals, violation of coastal water area mode, etc.

In overall there are two main schemes of material migration:

- Soils of inter-alas space → alas soils →bottom sediments → lake waters;
- Soils of inter-alas space → alas soils →vegetation

In the first scheme the decisive role is played by the mechanical material migration along the thermokarst basins slope, where the main conveyor is soil organic material, as well as a concentrator is the sediments. This scheme in alas basin of closed type has a recurring character and fits into the overall scheme of alas sedimentation.

The second scheme is subject to the action of the three migration processes: mechanical migration, inter-soil migration caused by the motions of soil solutions and cryogenic stirring and biogenic migration. This circuit has a one-way traffic because elements absorbed by plants, in this case by the herbal ground cover, are largely withdrawn from the biogeochemical cycle, due to the use of alas as grasslands and rangelands.

Gratitude:

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