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Soils of Lacustrine Depressions of Pulsing Chloride Lakes in Endorheic Areas of Central Asia: Morphology, Physicochemical, and Geochemical Features

V. I. Ubugunova[a], *, L. L. Ubugunov[a], A. D. Zhambalova[a], T. A. Ayushina[a], and V. L. Ubugunov[a]

[a] Institute of General and Experimental Biology, Siberian Branch, Russian Academy of Sciences, Ulan-Ude, 670047 Russia
*e-mail: ubugunova57@mail.ru

Abstract—Data on saline soils of endorheic lacustrine depressions in the areas of ultracontinental climate with 25–30-year-long cycles of lakes level fluctuations are obtained for the first time. Fluctuations correspond to alternating arid and humid climatic phases. Different soils are formed in landscapes adjacent to strongly mineralized chloride lakes of the southeastern Transbaikalia: gley solonchaks (Gleyic Solonchaks (Loamic, Chloride)) in superaqual–subaqual positions; humus-gley saline soils (Calcaric Mollic Gleysols (Arenic, Endosalic, Sodic)) in superaqual positions; and light-humus saline soils (Fluvic Kastanozems (Epiarenic, Amphiloamic, Sodic)) in eluvial-superaqual geochemical positions. Salinity rate of the studied soils varies. The cations are dominated by sodium, and among anions chlorides are most common in solonchaks and in humus-gley topsoils. Soda-chloride and chloride-soda anion composition prevails in other soils. Gley solonchaks are characterized by strongly alkaline pH, high content of carbonates, and predominance of Na^+ among exchangeable cations. Many chemical elements are concentrated in the solonchakous horizon (Sr, S, Li, Mg, and Ca), and a high content of As is a regional feature. The humus-gley saline soil is similar to the light-humus saline soil by physicochemical parameters and to solonchaks by the element composition and texture. Both features are related to periodical functioning of this soil in semihydromorphic or hydromorphic regimes during arid and humid phases, respectively. The high groundwater level contributes to the enrichment of soils with the elements typomorphic for lake water. The paleohydromorphic formation stage has been recorded in lower layers of light-humus saline soil as a high content of easily soluble salts and carbonates. The geochemical specificity of soil-forming rocks is the significant As accumulation and Li, Ba, and Pb elevated concentrations. It has also been revealed that the low Ca/Sr ratio is inherent to their geochemical composition. The cluster analysis of parameters of the studied soils shows that both dynamic and stable soil parameters are reflected in humus-gley soil, therefore, it is recommended for monitoring the dynamics of endorheic lacustrine ecosystems in Central Asia with cyclic climatic phases.

Keywords: highly mineralized chloride lakes, cyclic soil functioning, lakeside soils, salinity

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INTRODUCTION

The study objects of various specialists in the late 20th and in the early 21st centuries were represented by saline and soda lakes of intracontinental arid and semiarid areas of the World, including the Eastern Steppe and Gobi Landscape Regions of Mongolia and the plains of Kazakhstan, Central Asia, and China [27, 37, 39, 40, 47, 49, 51, 55, 57–60]. These lakes are unique natural indicators of natural and anthropogenic changes [6], which cause variations in migration of substances [2, 46, 53].

The trans-boundary endorheic Central Asian basin (in the steppe zone of the East Mongolian Plain within Mongolia, China, and Russia) with numerous lakes (about 5000) is of particular interest. Several hundreds of them are located in the southeastern Transbaikalia [37], being the contact zone between the southern perma-frost boundary and the northern boundary of the vast arid zone. Most lakes are filled with water during humid climatic phases. In aridization periods, the level of lakes significantly falls, their area shrinks, and they often completely dry up. The duration of these cycles is 25–30 years [32, 51].

The evolution of lake ecosystems is related not only to climatic changes, but also to the latest geodynamics [28]. Soils around the lakes are poorly studied in this region. There are only isolated and fragmentary data on saline soils of the coastal zone of soda Khara-Nur lakes [2], Bol'shoi Chindant Lake [29, 30, 42], and Torei lakes [44]. Specific factors of salt accumulation under conditions of mountain-basin relief in the south of Eastern Siberia greatly differ in each particular basin, so it is almost impossible to extrapolate the available fragmentary data over the vast area of the Central Asian Region with inland runoff [45].

We have not found any data on lakeside soils of highly mineralized chloride lakes with unstable level. These soils may be assigned to those of extreme formation conditions [10]. Similarly to soils of sea coasts and river deltas, soils close to lakes are periodically flooded, which causes changes in the water and redox regimes, and alkaline–acid conditions, salinization, humus formation, and geochemical speciation of landscapes [20, 52, 56]. Salinization, very weak humus accumulation, and aeolian removal of salts together with the fine fractions of silicate material predominate in soils of the basins of large coastal salt lakes (Caspian Sea, Aral, etc.) during the regressive phase, and sulfidogenesis, gleyzation, oxidogenesis, and accumulation of organic matter are the main processes during the transgressive phases [9, 20].

The study of soils in the landscapes close to the lakes in the intracontinental Central Asian basin as a key component of ecosystems seems theoretically and practically urgent. The lack of data restricts a comprehensive understanding of steppe ecosystems with numerous endorheic lake basins formed under ultracontinental climate with pronounced permafrost processes. This makes difficult the solution of many problems concerning the nature management of the steppe zone, including monitoring of protected and recreational areas. Therefore, the purpose of this paper is to provide information on morphological, physicochemical properties, and geochemical features of soils of super-aqual–subaqual, superaqual, and eluvial-superaqual geochemical positions in lacustrine depressions with chloride-salt lakes.

OBJECTS AND METHODS

We have studied lakeside soils of chloride Bab'e Lake located in the Onon-Argun province of Central Asia [41] (Fig. 1). The main morphostructures of this area are represented by accumulative and denudation plains and isolated low-mountain massifs [8, 11]. The main features of morphology were formed under the leading effect of pediplanation [31] and are mainly related to the latest subsidence [11, 28].

The research area is located in the contact zone of the Central Asian Mobile Belt and the Siberian Platform [11]. According to morphostructural zoning, it is assigned to the intra-mountain Aginskii basin [8]. The tectonic structure of the Bab'e Lake basin is determined by branches of the Aginskii Fault, separating heterogeneous Sredneononskii, Ononskii, Urtuiskii, and Borzinskii strata of different age [34]. The rocks include sedimentary and volcanogenic-sedimentary formations of the Borzinskii series of the Permian age (siltstones, tuff-siltstones, chlidolites, and limestones), of the Turginskii Early Cretaceous series (trachybasalts, trachyandesites, andesibasalts, and rhyolites), of the Late Riphean Urtui and Early Carbonic Upper Urtui formations, as well as Quaternary deposits of the Nozhii formation (pebbles and boulders with sand and clay lenses) and weathering products of granite rocks of mountain outliers [11].

Climate of the studied area is extremely continental with mean annual temperatures below 0°C, insufficient moisture (the mean annual precipitation is 150–400 mm), and uneven precipitation distribution by seasons. Concentrated discharge of precipitation as heavy rains occurs during the Pacific cyclone in July–August. It causes intensive slope erosion of material transported into numerous endorheic basins of small rivers [2, 24]. Alternation of wet and dry periods, lasting about 30 years, is a typical climatic feature of the area [13, 21, 32, 33]. Arid phase is accompanied by a decrease in soil moisture reserves to the wilting point and lower, by widespread drying and death of tree stands, by xerophytization and a 1.5–2-fold decrease in productivity of meadow-steppe and steppe phytocenoses, and by a drop in the water level in lakes up to their complete disappearance [14]. The water content in lakes of the region is determined by the precipitation cycles [21, 32, 33, 49, 51]. The area of solonchaks increases in the bottoms of dry lakes during the arid phase [14].

Heterogenic communities compose the vegetation spatial pattern in the study area. Halophytic communities grow in the center of salt accumulations, and then usually give way to meadows with *Puccinellia* sp., communities of *Carex reptabunda* and *Artemisia* sp., and the "saz" steppes, depending on moisture content and salinity. This is a typical concentric band pattern around lakes. The area of halophytic meadows and pioneer halophytic vegetation with the domination of annual plants - representatives of Chenopodiaceae family increases during the arid phase [15, 43]. The appearance of species of a different biogeochemical specialization as compared to the previous dominants is an indicator of a deep transformation of geosystems [13].

Soil survey was performed for superaqual–subaqual, superaqual, and eluvial-superaqual positions of the lakeside landscape. Three key reference pits and nine supplementary ones were made. The morphological description of the key pits is given below (Fig. 1e).

Pit B-1 (50.29955° N, 116.38027° E). Lakeside depression, 50 m from the shoreline of Bab'e Lake under a Suaeda–Saussurea community. The projective cover is 20%. The plant cover is mosaic with alternation of plant associations and bare spots.

Sg,ca, 0–5 cm, stratified, clayey, moist, with alternating bluish and humus-enriched layers, plant roots. Strong effervescence with HCl. The transition is recorded by color, density, and particle-size composition.

Cg,ox,s,ca, 5–20(22) cm, rusty-ochreous with bluish layers, moist, massive structure, compact sandy loam. There are roots of herbaceous plants. Strong effervescence with HCl. The transition is seen by color and particle-size composition.
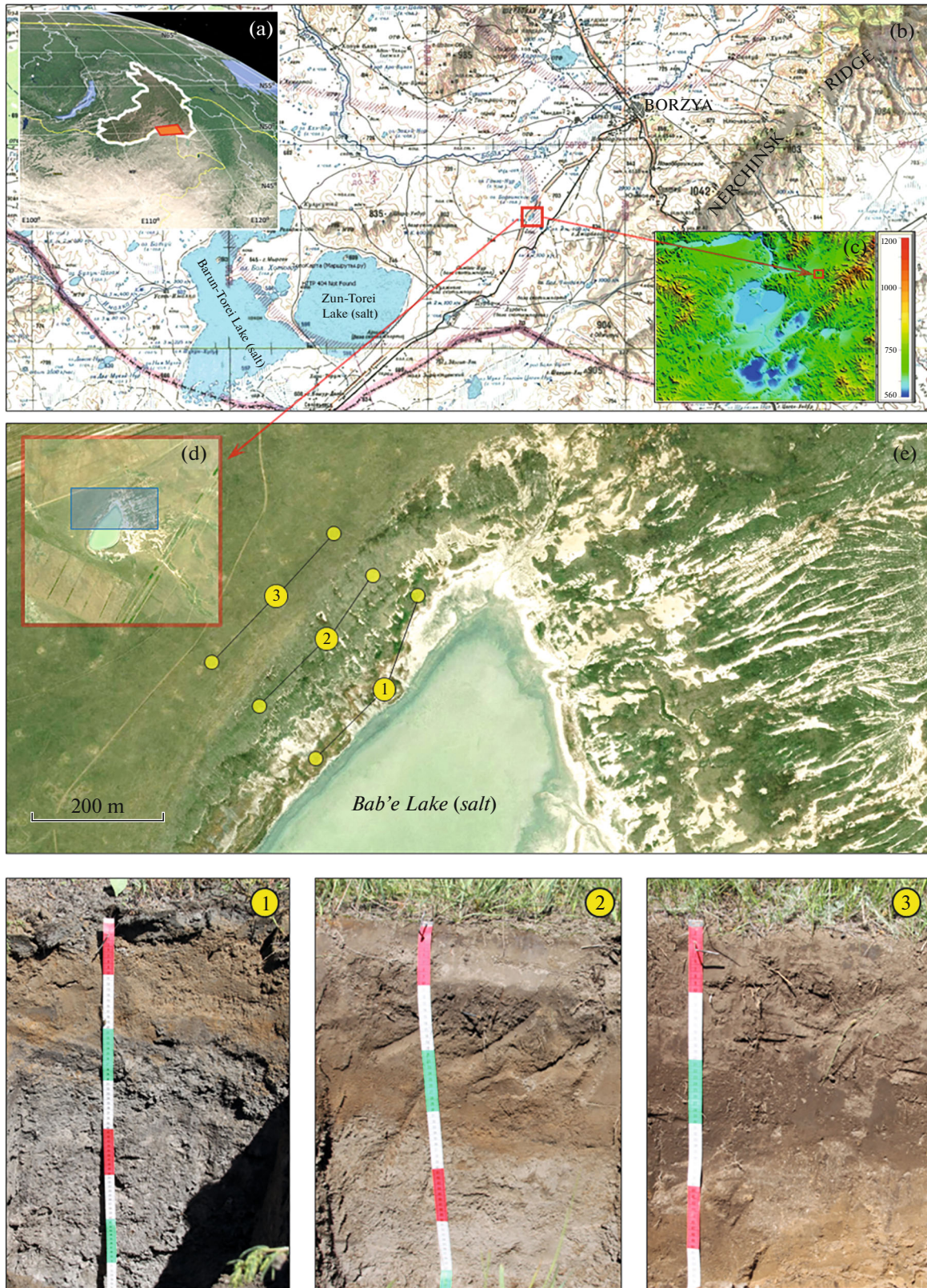
Fig. 1. Geographical (a) and administrative (b) position and orographic scheme (c) of the research area; satellite images of lake-side landscapes of Bab'e Lake (d, e); test plots (e) and profiles of reference soil pits: (a) boundary of Zabaikal'skii krai; (b, c) study area and location of Bab'e Lake; (d) boundary of insert (e); (e) location pits B-1, B-2, B-3 and shallow pits.

CGs, 20(22)−80 cm, whitish-bluish clayey rather compact loam, with more dark clay loamy layers. Groundwater appears at the depth of 80 cm.

The soil was identified as gley solonchak (Gleyic Solonchak (Loamic, Chloride)).

Pit B-2 (50.30025° N, 116.37903° E) was made in the lakeside depression, 153 m from the shoreline of Bab'e Lake under Puccinellia−Artemisia−Hordeum community. The projective cover is 40%. The plant cover is mosaic: plant associations alternate with bare spots. There are small pebbles on the soil surface.

AJca,s, 0−15(18) cm, dark gray with black hue, slightly moist, weak crumb structure, loamy sand, many roots of herbaceous plants; effervescence with HCl. The transition is seen by color, the boundary is slightly wavy.

ACca,s, 15(18)−34(39) cm, yellowish-brown, moist, massive compact sandy loam, single roots of herbaceous plants; effervescence with HCl. The transition is abrupt by color and particle-size composition.

CGca,s, 34(39)−65 cm, uniformly colored layer of wet gleyed sand; effervescence with HCl.

The soil was identified as humus-gley saline (Calcaric Mollic Gleysol (Arenic, Endosalic, Sodic)).

Pit B-3 (50.30074° N, 116.37787° E) was made 400 m from the shoreline of Bab'e Lake under feathergrass steppe. The projective cover is 60%.

AJca, 0−33(39) cm, dark chestnut, weakly moist, rather compact, weak crumb structure, loamy sand with abundant roots of herbaceous plants; very slight effervescence with HCl. The transition is seen by color, density, and carbonate neoformations. The boundary is slightly wavy.

ACca,dc,s, 33(39)−44(47) cm, light gray with whitish mottles of carbonates, weakly moist, sandy loam. Humus streaks are visible throughout the horizon. There are many roots of herbaceous plants; effervescence with HCl. The transition is visible by color, density, and moisture. The boundary is slightly wavy.

Csa,s, 44(47)−60 cm, light brown with yellowish hue, loose loam, effervescence with HCl.

The soil is identified as light-humus saline (Fluvic Kastanozem (Epiarenic, Amphiloamic, Sodic)).

Morphological, physicochemical, and geochemical methods were used [7, 36]. The soils were classified according to [23, 35, 50]. Geographical coordinates were recorded for all objects, using a GPS receiver. The activity of Na^+, Ca^{2+}, and Cl^- ions and pH were measured in soil pastes with the moisture content of 30 wt % by ELIS ion-selective electrodes on an Ekotest-120 recording ionomer in two−three replications. Organic carbon (C_{org}) was measured by the method of wet combustion according to Tyurin [7]; exchangeable cations—by the method by Pfeffer modified by Molodtsov and Ignatova [36]; the chemical composition of salts, salinity rate, and hypothetical salts according to [3]; and the particle-size composition by Kachinskii method. The following calculated parameters were additionally used:

− D_{mean}—the mean grain size calculated as a weighted mean [12].

− F—a dynamic factor, representing the ratio of physical sand to physical clay. The parameter characterizes sedimentation conditions. At $F > 1$, the input of fragmentary material from near and moderately distant sources by dragging and saltation (to about 10 km) prevails, which most likely takes place in a very dynamic environment with strong winds. At $F < 1$, the material input is smaller: these are mainly aerosols from distant sources, and post-sedimentation in situ transformations, of deposits, mainly pedogenic [18];

− K is the dispersion index, reflecting the type of clay components formed as a result of transformation, transfer, and localization of fine matter in various deposits. It is calculated by the formula $K = (\ln F_5 - \ln F_1)/1.609$, where F_5 is the content of particles (%) with a diameter of <5 μm; and F_1 is the content of particles (%) with a diameter of <1 μm [4].

A comprehensive analysis of the geochemical status was performed for 26 elements, which are most typical for saline soils. The total content of elements was determined at the accredited testing laboratory of the Republic Analytical Center by the atomic emission method with inductively coupled plasma (ICP) on a Spectroarcos spectrometer. A mixture of hydrofluoric (HF), chloric ($HClO_4$), and nitric (HNO_3) acids was used for the decomposition of soil samples (*GOST PND F* 16.1:2.3:3.11-98). Concentration coefficients and scattering coefficients were calculated relative to the lithosphere according to [19] to reveal the distribution pattern of elements in saline soils.

RESULTS AND DISCUSSION

Lakes in aridic areas of southeastern Transbaikalia are characterized by strong dynamism [6]. Water mineralization (*M*) in Bab'e Lake fluctuates from 1.5 to 85 g/L, depending on the humid or arid phases, respectively [5] (Fig. 2). The ratio between anions significantly changes; therefore, the chemical composition of waters according to this indicator was chloride-soda during the humid phase (2009) and chloride (2013) or sulfate-chloride (2022) at the arid phase. Precipitation of particular minerals depends on the chemical composition, salinity, pH, and temperature of lake waters and organic productivity of the lake [53]. When water is saturated with carbonates, magnesium calcites (Ca, Mg)CO_3 and Ca-excess dolomites CaMg$[CO_3]_2$ are formed [40]. Gypsum stage of mineral formation in the waters is absent. In addition to carbonate minerals, there are magnetite, lepidocrocite, goethite, kaolinite, and montmorillonite in bottom sediments [5, 6, 49]. The terrigenous component is represented by albite, orthoclase, microcline, quartz, and calcite [5].
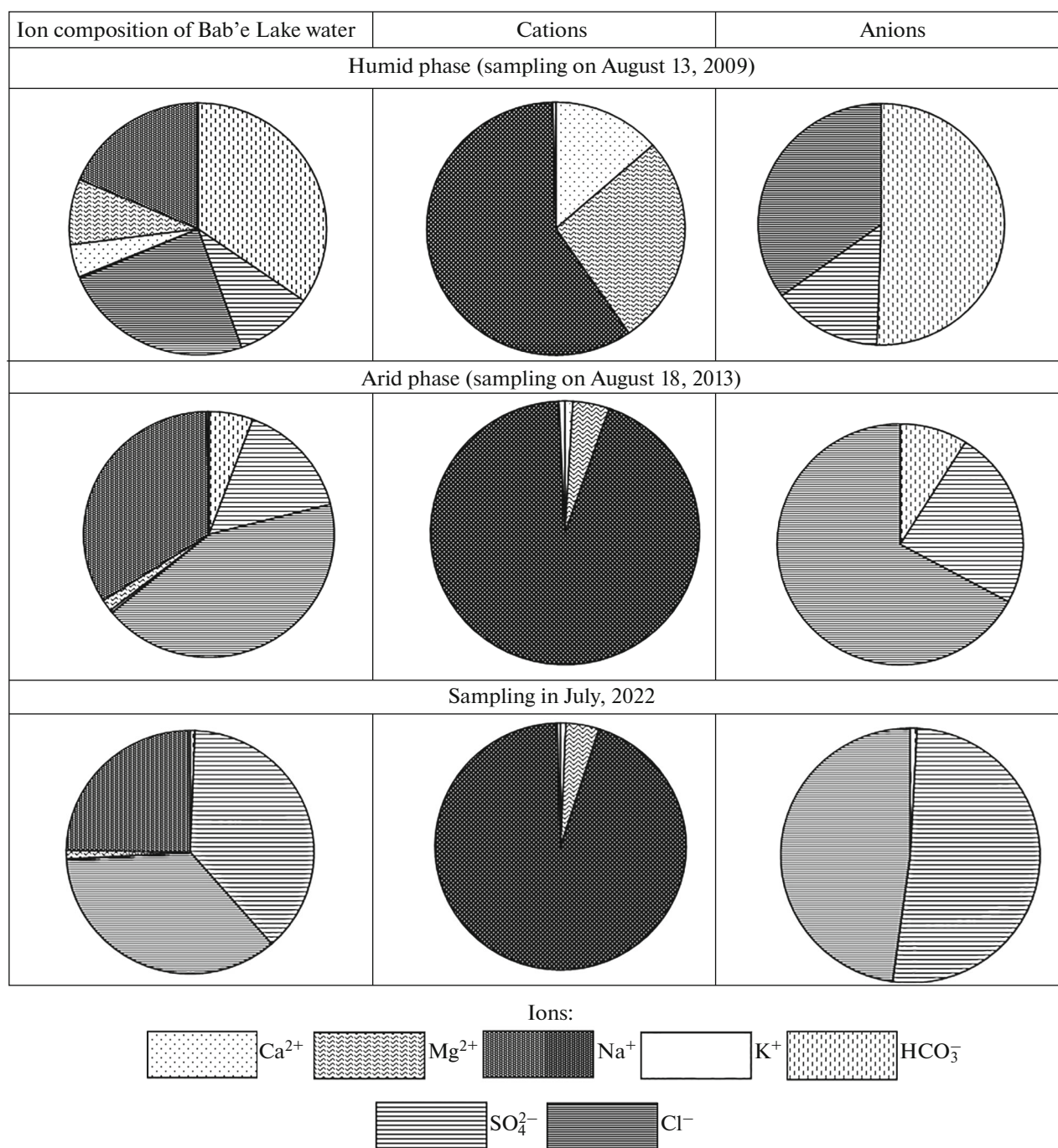
Ion composition of Bab'e Lake water	Cations	Anions
Humid phase (sampling on August 13, 2009)		

Fig. 2. Chemical composition of Bab'e Lake water during humid and arid phases; composition of anions and cations, % of the total. Data for 2009 and 2013 are given according to [6]; data for 2022 were obtained by the authors.

The first model plot is located in the most dynamic section of the lacustrine depression. Solonchaks are formed in the coastal part during the arid period with shallow water and drying out of lakes, and they are flooded during the wet climatic cycle, when lakes are filled. According to [9] and in our opinion, this is a cyclic superaqual–subaqual position.

The morphological profile of solonchaks is strongly differentiated. Shallow groundwater (80 cm)

exerts a great effect on the redox regime of soils. The heavy-loamy solonchakous horizon is most likely formed under the impact of the saline lake waters discharged to the surface under the periodic influence of lake uprush (quick rise of lacustrine water). According to the system of genetic horizons (Sg,ca–Cg,ox,s,ca–CGca,s), this soil is assigned to gley solonchaks (Gleyic Solonchak (Loamic, Chloride, Calcaric)) [23, 35, 50].
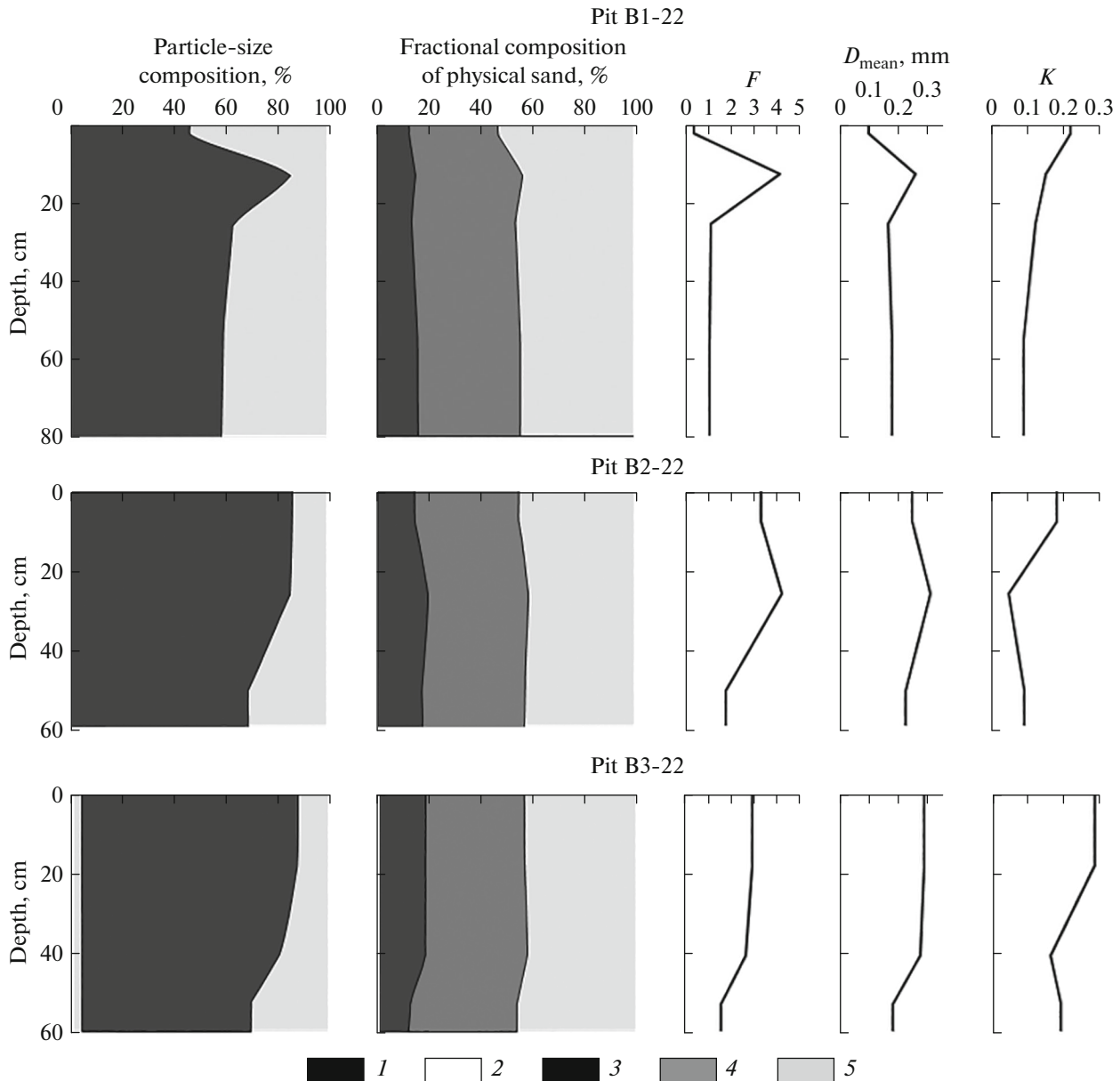
Fig. 3. Profile distribution of particle-size composition, fractions of medium (MS) and fine (FS) sand and coarse silt (CS), dynamic factor (F), mean grain size (D_{mean}), and dispersion index of sediments (K) in pits B-1, B-2, and B-3: (*1*) physical sand, (*2*) physical clay, (*3*) medium sand, (*4*) fine sand, and (*5*) coarse silt.

In terms of the particle-size composition, the sedimentation layer of gley solonchaks consists of heavy loamy (0−5 cm), sandy loamy (5−20(22) cm), and medium loamy (30−80 cm) layers. According to the weighted mean (D_{mean}), particles of fine and medium sand and clay fraction predominate (Fig. 3). The analysis of the dynamic factor (F), characterizing the sedimentation conditions, shows various stages of sedimentation in the soil pit. The upper 5-cm- and from 30- to 80-cm-thick layers correspond to lacustrine sedimentation conditions ($F \leq 1$) with a fine-colloidal clay component (K). The sandy loamy layer ($F \geq 3$)

with coarser particles (D, K) reflects the increasing role of aeolian processes during climate aridization and reduction of lake areas [4, 12, 18].

The solonchak is characterized by alkaline and strongly alkaline pH (Table 1). The C_{org} content in the Sg,ca horizon is sufficiently high. The higher vegetation on this plot is represented only by monodominant halophyte communities with low projective cover, so the main source of organic matter is most likely represented by cyanobacterial mats [1].

The content of CO_2 of carbonates in soils is high (2.3−9.4%); it is maximal in the Sg,ca horizon and

Table 1. Physicochemical properties of lakeside soils of Bab'e Lake

Horizon, depth, cm	pH	CO_2 of carbonates	C_{org}	Exchangeable bases, cmol(c)/kg of soil	Ca^{2+}	Mg^{2+}	Na^+	K^+
		%			% of the sum			
Pit B-1. Gley solonchak								
Sg,ca, 0−5	8.4	8.3	2.81	27.5	7	25	68	0
Cg,ox,ca,s, 5−20(22)	8.8	2.3	0.28	13.3	18	30	46	6
CGs,ca, 20(22)−30	8.5	7.8	0.37	17.3	16	25	57	1
2CGs,ca, 30−80	8.2	9.4	0.26	12.8	22	31	44	3
Pit B-2. Humus-gley saline soil								
AJca,s, 0−15(18)	8.6	1.9	0.71	9.8	33	53	11	3
ACca,s,15(18)−34(39)	9.7	1.6	0.17	11.1	22	22	53	3
CGca,s, 34(39)−65	9.6	6.0	0.24	12.4	19	26	53	2
Pit B-3. Light-humus saline soil								
AJca, 0−33(39)	7.5	0.5	0.74	8.6	51	37	8	4
ACca,dc,s, 33(39)−44(47)	9.4	0.6	0.53	19.1	19	21	59	1
Cca,s, 44(47)−60	9.2	1.3	0.39	20.7	17	15	66	1

lacustrine sediments and is related to the evaporative concentration and hydrogenic accumulation, respectively. Maximal values of cation exchange capacity (CEC) (27.5 cmol(c)/kg of soil) are typical for the solonchakous horizon and significantly decrease with depth. Exchangeable cations are dominated by sodium and magnesium throughout the soil profile.

The Sg,ca and Cd,ox,s,ca horizons of solonchaks are very strongly saline, and the gley layer (CGs,ca) is strongly saline (Table 2).

Mineralized waters are sources of salts, and the salinization mechanism is related to the temperature gradient of the cryoaridic climate and to the effect of the permafrost [22, 26, 45]. The distribution of salts along the profile is accumulative, and the chemical composition of salts is sodium-chloride. Anions are significantly dominated by Cl^-. Its concentration is maximal in the solonchakous horizon and decreases in deeper layers, but remains high (6.02−8.64 cmol(c)/kg). The CO_3^{2-} and $HCO_3^-{}_{tot}$ content in the gley solonchak is low, and their vertical distribution is uniform. The amount of sulfate ions varies from 1.25 to 4.13 cmol(c)/kg of soil and is maximal in the Sg,ca horizon. In the composition of anions, the portion of SO_4^{2-} varies from 9 to 21%. The type of chemical composition in solonchaks is sodium by cations, and Na^+ predominates among them (91−94% of total cations).

The calculation of hypothetical salts shows [3] that the neoformations in solonchaks are mainly represented by halite (NaCl). Its content in the Sg,ca horizon is 75.9 cmol(c)/kg, which is 2.2 if dry residue is 2.7.

The second model plot is located at superaqual positions of the lakeside depression. The previous series of dry years with shallow waters and drying of lakes favored a decrease in the groundwater level, which were absent in the soil profile during the survey,

so the redox conditions were rather stable. The soil profile has the following system of genetic horizons: AJca,s−ACca,s−CGca,s and according to [23, 35, 50] corresponds to humus-gley saline soil (Calcaric Mollic Gleysol (Arenic, Endosalic, Sodic)).

The studied soils are characterized by heterogeneous particle-size composition: there are loamy sandy (0−34(39) cm) and loamy (34(39)−65 cm) layers. The dynamic coefficient presumes aeolian sedimentation in the upper layers ($F > 3$) and lacustrine one in the lower layers ($F < 1$). There are also differences in the dispersion of the clay component (K): colloidal-clay in the light-humus horizon and thin colloidal in lacustrine sediments (Fig. 3).

Humus-gley saline soil is characterized by strongly alkaline pH, which is maximal in the lower horizons (9.7−9.6). The content of carbonates varies from 1.6 (in the ACca,s horizon) to 6.0% (in the CGca,s horizon). The soils are low-humus, so the upper horizon can be hardly qualified for the dark-humus one. At this stage of research, the designation AJ is used. The absorption capacity of the studied soils is low. Exchangeable cations in the upper part of the profile are dominated by Mg^{2+} (more than 50%) and Ca^{2+} (33%). The sodium portion sharply increases (to 53% of total cations) in the ACca,s and CGca,s horizons.

The studied soil (pit B-2) is weakly saline in the upper 15(18)-cm-thick layer, and there is an increase in the content of easily soluble salts to medium salinity in deeper layers. The distribution of easily soluble salts in the profile corresponds to the eluvial-illuvial type. The chemical composition of salts is soda-chloride by anions in the AJca,s horizon and chloride-soda in the ACca,s and CGca horizons. With respect to cations, the salinity is evenly sodium. The content of Cl^- in the studied soil is ten times lower as compared to solonchaks. Its portion of the sum of anions varies from 60%

Table 2. Water extract from soils of the lakeside depression of Bab'e Lake

Parameter	Soil type, depth, cm									
	gley solonchak				humus-gley soil			light-humus soil		
	0–5	5–20	20–30	30–80	0–15	15–34	34–65	0–33	33–44	44–60
Easily soluble salts, %	2.680	0.761	0.604	0.471	0.103	0.315	0.226	0.059	0.281	0.435
Toxic salts, %	2.624	0.725	0.567	0.439	0.078	0.267	0.202	0.039	0.232	0.387
Composition of anions, cmol(c)/kg										
CO_3^{2-}	0.32	0.36	0.36	0.16	0.16	1.36	0.64	0.01	1.20	1.60
HCO_3^-	1.00	0.76	0.72	0.60	0.24	1.52	41.76	0.24	1.52	1.76
Total alkalinity	1.16	0.94	0.90	0.68	0.68	0.72	0.84	0.24	2.12	2.56
SO_4^{2-}	4.13	2.63	1.46	1.25	0.06	0.25	0.25	0.05	0.59	1.22
$SO_{4\,tox}^{2-}$	4.13	2.63	1.46	1.25	0.06	0.25	0.25	0.04	0.59	1.22
Cl^-	39.72	8.64	7.90	6.02	0.68	0.72	0.84	0.64	0.92	1.44
Composition of cations, cmol(c)/kg										
Ca^{2+}	0.70	0.45	0.45	0.40	0.30	0.60	0.30	0.25	0.60	0.60
Mg^{2+}	2.10	0.30	0.20	0.25	0.15	0.50	0.35	0.10	0.15	0.20
Na^+	35.48	11.3	8.26	6.41	1.08	3.07	3.19	0.57	3.26	6.74
K^+	0.23	0.03	0.02	0.02	0.05	0.10	0.09	0.01	0.05	0.02
% of total anions										
CO_3^{2-}	1	3	3	2	14	35	1	1	28	26
HCO_3^-	2	6	7	7	21	39	96	26	36	29
SO_4^{2-}	9	21	14	16	5	7	1	5	14	20
Cl^-	88	70	76	75	60	19	2	68	22	25
% of total cations										
Ca^{2+}	2	4	5	6	20	14	8	27	15	8
Mg^{2+}	6	2	2	4	9	12	9	11	4	3
Na^+	91	94	92	90	68	72	81	61	80	89
K^+	1	0.2	0.2	0.2	3	2	2	1	1	0.3

in the AJca,s horizon to 19 and 2% in the ACca,s and CGca,s horizons, respectively. The HCO_3^- content is maximal in the lower part of the profile. Cations are dominated by Na^+ in all horizons (68–81% of the total of cations). The content of Ca^{2+} and Mg^{2+} pronouncedly increases in the AJca,s and ACca,s horizons. The rise in these cations proportion also affects the composition of hypothetical salts. Their composition is characterized by an increase in carbonate formations (56% of the total salts mainly due to Na_2CO_3 and $NaHCO_3$) and by a sharp decrease in chloride (to 10%) and sulfatic (4–6%).

The third model polygon is located on a gentle slope of the eluvial-superaqual (lakeside-zonal) section of the paleohydromorphic position of the lake depression. The soil profile (B-3) is described by the following formula: AJca–ACca,dc,s–Cca,s and indicates the type of light-humus saline soil (Fluvic Kastanozem (Epiarenic, Amphiloamic, Sodic)) [23, 35, 50].

The AJca horizon is characterized by a slightly alkaline reaction (pH 7.5), which sharply increases to strongly alkaline (9.2–9.4) in deeper layers. The content of carbonates is low. The soils are low-humus, and the distribution of organic matter along the profile is gradually decreasing. The cation exchange capacity varies from 8.6 to 20.7 cmol(c)/kg. This parameter is minimal in the upper light-humus horizon, and the ratio of exchangeable cations in it is typical for zonal soils. The absorption capacity increases two times with depth (in the ACca,s and Cca,s horizons) mainly due to a rise in the portion of exchangeable sodium to 59–66%.

Table 3. The content of elements in the lakeside soils of Bab'e Lake

Element	Soil type, depth, cm									
	gley solonchak				humus-gley soil			light-humus soil		
	0—5	5—20	20—30	30—80	0—15	15—34	34—65	0—33	33—44	44—60
%										
Al	5.06	5.67	5.47	5.31	5.47	5.47	5.48	5.78	6.01	6.17
Fe	1.97	1.32	1.39	1.27	2.25	1.36	1.44	1.92	2.07	2.34
Ca	5.06	1.98	2.02	6.97	7.16	1.52	3.00	0.71	0.77	1.36
Mg	3.55	0.71	0.83	1.67	0.97	0.82	2.12	0.27	0.46	0.68
K	1.83	2.61	2.48	2.36	2.12	2.53	2.33	2.44	2.43	2.38
Na	1.99	2.17	1.81	1.73	1.55	1.81	1.66	1.69	1.78	1.96
Ti	0.22	0.16	0.19	0.15	0.20	0.14	0.16	0.22	0.21	0.24
mg/kg										
Li	55.2	29.5	27.8	34.6	27.7	31.9	39.1	24.6	27.1	28.7
Cu	19.2	10.6	9.8	12.3	16.3	9.4	13.6	11.1	12.5	13.3
Sr	1465	520	454	873	662	438	866	287	270	280
Ba	454	608	604	545	580	586	542	581	573	569
Be	1.8	2.2	2.1	1.8	1.8	2.2	2.1	2.3	2.4	2.4
Zn	52.8	19.6	23.1	25.8	37.1	20.0	26.4	26.5	33.1	38.7
Sc	7.4	4.5	4.9	5.0	6.7	4.6	5.5	5.8	6.5	7.4
V	13.5	7.8	9.9	9.3	13.3	7.7	9.3	11.2	11.8	13.3
La	17.7	13.2	17.8	15.7	19.2	15.5	15.0	19.6	21.0	22.2
Ce	40.6	26.2	30.9	29.3	38.8	27.8	30.9	27.7	40.8	41.4
Pb	24.8	22.6	23.8	17.9	22.5	18.0	17.1	24.7	20.7	23.9
P	588	190	268	284	587	173	160	289	224	208
V	54.8	24.5	26.5	23.0	42.5	28.6	28.8	41.5	46.8	51.9
As	22.3	13.2	10.5	9.6	9.5	14.5	14.4	13.6	16.3	17.1
S	2250	584	319	807	904	212	212	278	437	890
Cr	34.5	19.7	20.5	21.1	24.3	19.6	21.2	26.6	30.7	35.6
Mn	477.3	234.3	321.3	320.4	673.1	228.5	281.5	376.9	301.9	339.8
Co	9.6	5.2	5.9	4.9	8.5	5.5	6.4	7.8	7.7	9.0
Ni	21.9	9.5	10.0	9.4	15.6	8.7	13.5	12.8	17.7	22.2

Soil salinity varies. The upper humus horizon is not saline, whereas the salt content increases five and seven times in the ACca,s and Cca,s horizons, respectively, as compared to the AJca horizon and corresponds to medium (ACca,s) and strong (Cca,s) salinity category. The distribution of easily soluble salts along the soil profile is of the accumulative type. The profile distribution of CO_3^{2-} and CO_3^{2-} + HCO_3^- is uneven: their content is minimal in the light-humus horizon and is maximal in the lacustrine sediments. This high concentration of bicarbonate ions results in soda salinization. The content of chlorides is low (0.64—1.44 cmol(c)/kg) and increases with depth in saline horizons (Table 3). The content of sulfate ions in the light-humus saline soil is low and gradually increases with depth. Sodium predominates among cations. Its participation in the cation composition is different: 61% of CEC in the nonsaline horizon and 80—89% in saline horizons. The chemical composition of salts in the studied soils is soda-chloride and chloride-soda by anions and sodium by cations. Non-toxic cal-

cium carbonate and halite compose the hypothetical salts in the AJca horizon of light-humus saline soil. The content of salts is the highest in the ACca,s horizon: they are dominated by $NaHCO_3$, $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$, whereas $Na_2CO_3 \cdot 10H_2O$, $NaHCO_3$, $Ca(HCO_3)_2$, and $Mg(HCO_3)_2$ also participate. Accumulation of halite NaCl and thenardite Na_2SO_4 is revealed in the Cca,s horizon.

The elemental composition of genetic horizons and of the soil-forming lacustrine and lacustrine-aeolian deposits was studied to assess the geochemical specialization of lakeside soils. Strong variability was revealed for S, P, alkaline-earth elements (Mg, Ca, and Sr), and elements of iron group (Cr, Mn, Co, and Ni) ($V > 50\%$). A rather wide range is typical for Li, Zn, Y, La, Pb, and V ($V = 33$–50%). The variation range is the smallest for As and Fe ($V = 20$–33%), as well as for Na, K, Ba, Be, and Al ($V = 10$–20%).

Salinization processes favor concentration of elements, in the Sg,ca horizon of gley solonchaks, in particular, which is explained by a combination of
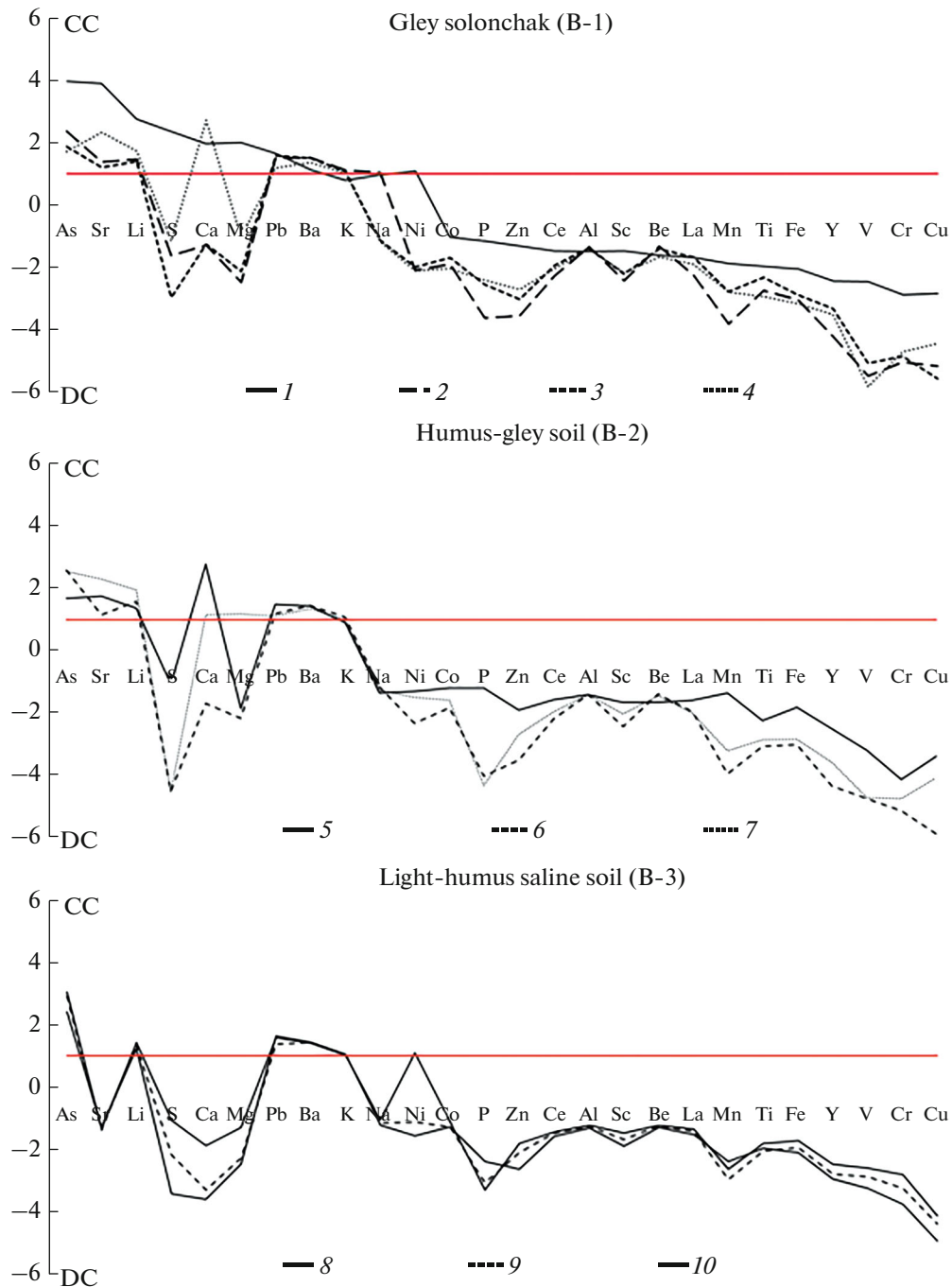
Fig. 4. Geochemical spectra of chemical elements of lakeside soils of Bab'e Lake with respect to the clarke of the lithosphere: CC—concentration clarkes; DC—dispersion clarkes; horizons: (*1*) Sg,ca, (*2*) Cg,ox,ca,s, (*3*) CGs,ca, (*4*) 2CGs,ca; (*5*) AJca,s, (*6*) ACca,s, (*7*) CGca,s; (*8*) AJca, (9) ACca,dc,s, and (*10*) Cca,s.

evaporative, oxidative, and sorption barriers. The geochemical specialization of this horizon is determined by the accumulation of the following elements: $As_{4.0}Sr_{3.9}Li_{2.8}S_{2.4}Mg_{2.0}Ca_{2.0}Pb_{1.7}$. The lacustrine sediments of this soil profile accumulate $Ca_{2.7}Sr_{2.3}As_{1.7}Li_{1.7}Ba_{1.4}$ (Fig. 4). The medium contrast of radial differentiation in solonchaks is typical for S, As, Mg, Sr, and Li. The content of elements higher

than the clarke in light-humus soil is only revealed for $As_{2.4-3.1}Pb_{1.4-1.6}Ba_{1.1-1.5}Li_{1.2-1.4}$, and the low content (CC < 0.2−0.3) is typical for Ca, Mg (in the AJca and ACca,s horizons) and for Cu, P, V, and Cr (in the entire soil profile).

The processes of carbon accumulation are reflected in the behavior of alkaline- earth elements, primarily of Ca, Mg, and Sr, and to a smaller extent of Ba. The cal-
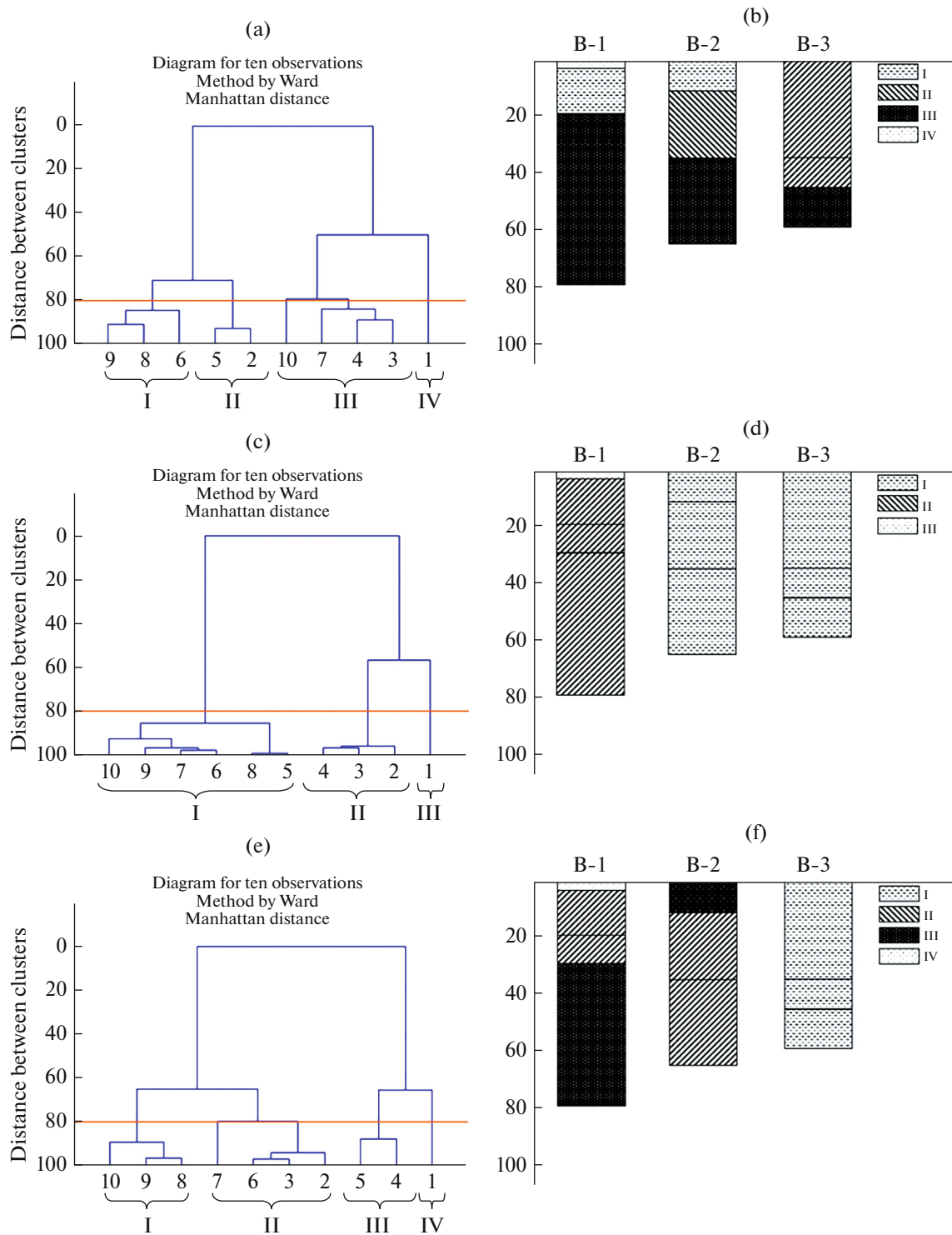
Fig. 5. Dendrogram of similarity and ranking of soils according to the particle-size distribution (a, b), physicochemical properties (c, d), and bulk elemental composition (e, f). Pit B-1: (*1*) Sg,ca (0−5 cm); (*2*) Cg,ox,ca,s (5−20/22 cm); (*3*) CGs,ca (20/22−30 cm); (*4*) 2CGs,ca (30−80 cm); (*5*) AJs (0−15/18 cm); (*6*) ACca,s (15/18−34/39 cm); (*7*) CGca,s (34/39−65 cm); (*8*) AJca (0−33/39 cm); (*9*) ACca,dc,s (33/39−44/47 cm); and (*10*) Cca,s (44/47−60 cm).

cium content in studied soils varies from 0.71 to 7.16% (ten times). Its content is minimal (0.71−1.36%) in the light-humus soil and is maximal in the AJca horizon of humus-gley soil (7.16%) and in the Sg,ca horizon of solonchaks (5.06%). The content and distribution pattern of Mg is similar to that of Ca. The carbonate enrichment coefficient (CaO + MgO/Al$_2$O$_3$), reflecting the calcite and dolomite accumulation [54], is low

in the light-humus soil (0.1−0.3) and increases 4−10 times as compared to the zonal soil in the upper horizon (1.4) and lacustrine sediments (1.2) of gley solonchak and in the humus horizon of humus-gley soil (1.1). A rise in calcium content in bottom sediments is caused by its input to lakes with underground and surface runoff and by mineralization of dissolved and accumulated substances in bottom sediments [1, 40, 49].

The development of endemic Kashin−Bek disease is detected in southeastern Transbaikalia, North Korea, and in many areas of China [17]. More than 20 hypotheses of its origin have been proposed, but the biogeochemical Ca−Sr hypothesis by Koval'skii is the most accepted. According to it, the disease is developed in case of Ca deficit and excess of Sr [25]. The increased Sr content in soils, waters, and plants [16, 17, 25] and low Ca content is an environmental risk factor for humans. The Ca/Sr ratio in soils of endemic areas averages 36 ± 11 [16]. In solonchaks and humus-gley soils, this ratio varies from 35 to 108 and corresponds to background (not polluted) soils. In light-humus soils, the Ca/Sr ratio varies from 25 to 29 and is characterized as unfavorable, corresponding to soils of endemic areas [16].

The geochemical features of the studied soils include the increased As content; CC varies from 1.7−4.0. Arsenic accumulation is probably related to location of the study area not far (24 km) from the Sherlovogorsk arsenic biogeochemical province with elevated and extremely high As values (CC = 1183) [38, 48].

The obtained materials were processed by the cluster analysis according to various parameters to determine the effect of lake waters on soils. The soil layers were grouped into four clusters according to their particle-size composition (Fig. 5). Threshold distances distinguish loamy sandy and sandy loamy (clusters 1 and 2), medium and heavy loamy (3), and clay (4) layers. Three clusters were obtained for solonchaks: clay, sandy loamy, and medium and heavy loamy layers. Humus-gley and light-humus soils were characterized by similar alternation of layers: loamy sandy in the upper part and medium loamy ones in the lower part.

Physicochemical properties (pH; CO_2 of carbonates; the content of easily soluble and toxic salts and of water-soluble anions and cations; exchangeable Ca^{2+}, Mg^{2+}, Na^+, and K^+; exchangeable activities aNa^+ and aCl^-; and C_{org} content) were ranked into three clusters (Fig. 5c). The first cluster included all horizons of the light-humus and humus-gley soil. The Sg,ca horizon in solonchaks occupied an individual cluster. The gley horizon and lacustrine sediments were combined into one cluster (Fig. 5d).

According to chemical elements, the studied soils were ranked into four clusters (Fig. 5e). All horizons in the light-humus saline soil were combined into one cluster. Gley solonchaks were characterized by the most contrasting profile differentiation. Different geochemical specialization was detected in the solonchakous and gley horizons and lacustrine sediments. The elemental composition was similar in solonchaks and humus-gley soils (Figs. 5e, 5f). This testified to the effect of mineralized lake waters on soils formed in superaqual-subaqual (gley solonchaks) and superaqual positions (humus-gley soils). The alternation of flooding and regression of the coastline contributed the uniformity of the elemental composition.

CONCLUSIONS

The performed studies show that soils in lakeside landscapes of the steppe zone in the southeastern Transbaikalia are formed on the background of cyclic changes in the level of lakes. Soil morphological properties and data on the material composition testify to manifestation of modern salinization and hydrogenic carbon accumulation.

Aeolian component plays an important role in the formation of lake soils along with the very important hydrogeological factor. High variability of the particle-size composition, pH, salinity, activity of ions, and of the composition of exchangeable cations has been revealed in the studied soils. Differences in the chemical composition of salts are less pronounced.

The concentration of elements is the highest in the solonchakous horizon, in which evaporative, oxidative, and sorption geochemical barriers are combined. Its geochemical specialization is determined by the accumulation of As, Sr, Li, S, Mg, Ca, and Pb. In lacustrine sediments, As, Mg, Ca, Li, Sr, and Ba are accumulated. The content of As and Pb in the light-humus soil is higher than the clarke, CC within 1.2−1.5 is detected for Ba and Li, and the Ca/Sr ratio is similar to endemic soils of the areas, where the Kashin-Bek disease is developed.

Regional geochemical features of the studied soils are related to high As content in the soil-forming rocks.

Indicator properties of the humus-gley soil are the most informative. The soil is close to the light-humus soil by physicochemical parameters and to solonchak by the elemental composition. This soil type may be used as the main one during monitoring of ecosystem dynamics.

We hope that our study of lakeside soils in inland regions of Eurasia will provide additional material for the development of ideas about the diversity of processes in saline long-term frozen soils. Further research will be related to the study of the diversity, genesis, properties, geochemical specialization, and classification of lakeside soils of soda and sulfate salinization types.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

CONSENT TO PARTICIPATE

Informed consent was obtained from all individual participants included in the study.

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