

# Ionic Composition and Driving Factors of Salt Lake Brines in the Burabay Massif, Eastern Kazakhstan

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## ABSTRACT

The salt lakes of the Burabay massif in Eastern Kazakhstan form unique geochemical systems shaped by a sharply continental climate, where evaporation exceeds precipitation. The hydrochemical analyses of 15 lakes showed mineralization ranging from 529 to 9023 mg/L and alkaline pH values between 8.1 and 9.3. The ionic composition is dominated by sodium, bicarbonate, chloride, and sulfate, reflecting a progressive evolution from Ca-HCO<sub>3</sub> waters in young lakes to highly mineralized Na-Cl and Na-CO<sub>3</sub> brines in closed basins. Geochemical modeling using Saturation Indices (SIs) (PHREEQC) indicates supersaturation with calcite, dolomite, and sodium carbonate in most lakes, while gypsum remains undersaturated and halite is near equilibrium in highly saline environments. This evidence points to active carbonate precipitation, evaporation-driven concentration, and the formation of soda-type waters. The analysis regarding Rare Earth Elements (REE) revealed positive correlations between mineralization, alkaline conditions, and REE accumulation in both water and bottom sediments, highlighting Burabay lakes as natural laboratories for studying evaporative concentration, hydrochemical evolution, and geochemical behavior of trace elements in arid continental settings.

**Keywords**-salt lakes; mineralization; ionic composition; geochemistry; Burabay massif; evaporation; saturation; PHREEQC; water typing; alkalinity; natural resource

## I. INTRODUCTION

A comparison between the saline lakes of the Burabay Massif and well-known hypersaline systems worldwide (the Great Salt Lake, Lake Urmia, and the Aral Sea) reveals both common [1-3] and distinctive features. The Total Dissolved Solids (TDS) in the Burabay lakes (0.5–9 g/L) are significantly

lower than in the Great Salt Lake and Lake Urmia (50–300 g/L), yet higher than in freshwater bodies, making them an intermediate stage in brine evolution. Unlike the classical Na-Cl systems typical of global analogs, the Burabay lakes are dominated by Na-HCO<sub>3</sub>, reflecting the influence of carbonate equilibrium and the massif's lithological composition. The relatively high pH values (up to 9.3) indicate the soda character

of the waters and promote the accumulation of REE, distinguishing these lakes from other systems. Thus, the Burabay lakes represent a unique regional analog of global hypersaline environments, where evaporation and carbonate equilibrium govern the formation of a specific hydrochemical regime.

The salt lakes of Eastern Kazakhstan are unique geochemical systems that are formed under sharply continental climate conditions, where evaporation prevails over precipitation and there is limited surface runoff. The most obvious examples of such lakes are concentrated within the Burabay massif, a natural zone that combines mountain forest relief with a series of shallow and brackish water bodies [4].

The chemical composition of the water in these lakes is determined by several factors, including the geological structure of the catchment areas, type of water supply, intensity of evaporation, and chemical processes occurring in the water-rock system. Of particular importance is the thermodynamic equilibrium between the solution and mineral phases, which can be quantitatively assessed using SI calculations [5].

This article analyzes the conditions for the formation of the composition of the waters of salt lakes in Eastern Kazakhstan, using the Burabay massif as an example. It presents data on chemical parameters, geochemical modeling results, and interprets the mineralization mechanisms and migration routes of the chemical components [6].

## II. MATERIALS AND METHODS

### A. Natural and Climatic Conditions of the Region

The Burabay massif is located in the northern part of central Kazakhstan, within the Akmola region, and is a unique natural and geographical complex with alternating granite hills, coniferous forests and numerous lakes. The study area was confined to the southern edge of the Kazakh Uplands, which is part of the inland continental drainless zone [7].

The climate of the region is sharply continental, with pronounced seasonal temperature variations. The average annual temperature is about 2 or 3 °C, ranging from -35 °C in winter to +35 °C in summer. Annual precipitation fluctuates between 300 and 400 mm, most of which falls during the warm period of the year. Evaporation significantly exceeds the amount of precipitation and averages 700–800 mm per year, which determines the general arid direction of the water balance of lake systems. The hydrological network of the region is poorly developed. The lakes are mostly endorheic and are fed by precipitation and, to a small extent, underground runoff. The surface inflow is represented by seasonal streams and temporary creeks that become active in the spring and summer. Due to the predominance of evaporation over runoff, as well as the structural features of the catchment basins, there is a concentration of dissolved substances and a gradual increase in mineralization [8]. Geologically, the Burabay massif is mainly composed of granites from the Kalbin complex and metamorphic rocks from the Takyr series of Upper Proterozoic to Paleozoic age (Figure 1). These lithological complexes are characterized by low mineral solubility, resulting in the generally weak buffering capacity of

natural waters. However, as indicated on the geological map, carbonate- and sulfate-containing formations of the Burabay and Ablakerken suites are locally developed both within the massif and along its periphery. Weathering and leaching of these sedimentary and meta-sedimentary rocks can have a localized impact on the formation of the hydrochemical background of the lakes [9].

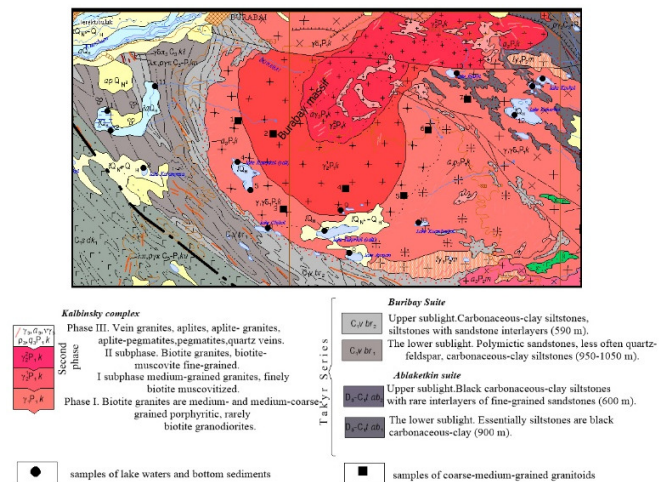


Fig. 1. Burabay rock mass district: (a) relief and location of the analyzed lakes; (b) geologic map (according to V.P. Solyannik). Adapted from [10] under the CC BY 4.0 license.

The diagrams in Figure 1 illustrate the comparative hydrochemical facies of lakes with varying salinities (a spatial cross-section), consistent with a typical evaporative trajectory. These comparisons do not represent temporal reconstruction of brine evolution. Spatial variations in the hydrochemical composition were observed, whereas temporal evolution was not analyzed.

Hydrogeomorphological conditions also contribute to the formation of closed depressions in which lake basins are located. The relatively small depth of the lakes (usually less than 5 m) and their area (from several ha to several tens of km<sup>2</sup>) predetermine high sensitivity to climate change and fluctuations in the water-salt balance.

The combination of climatic, geological, geomorphological, and hydrological factors creates conditions for the active formation of salt lakes and the accumulation of dissolved components in them, which makes this region especially interesting for geochemical research [11].

### B. Water Sampling

Water sampling was conducted in 15 lakes (Figure 2) in the Burabay Massif during summer. Samples were collected at several depths in each lake:

- Surface layer (20 cm below the water table).
- Mid-depth (half the lake's total depth, typically 1–2 m).
- Bottom zone (20–30 cm above the sediment).

For shallow lakes (<2 m), only the surface and bottom horizons were used. This approach enabled accounting for possible aquifer zonation, which, as shown in studies of hypersaline lakes, can control ion distribution and the types of evaporite minerals that form.



Fig. 2. Position of the studied lakes within the Burabay area.

### C. Measurements

pH, electrical conductivity, and TDS were measured on-site using a YSI ProDSS multiparameter meter (or the similar Hach HQ40d), pre-calibrated using standard buffers (pH 4.00, 7.00, and 10.00) and KCl solutions (1413  $\mu\text{S}/\text{cm}$  and 12.88  $\text{mS}/\text{cm}$ ). The water temperature was recorded simultaneously to ensure proper temperature compensation.

### D. Laboratory Methods

The samples were filtered through 0.45  $\mu\text{m}$  membranes. The cationic samples were preserved with  $\text{HNO}_3$  at  $\text{pH} < 2$ . Major cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$ ) were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP OES) (Agilent 5110) and Inductively Coupled Plasma Mass Spectrometry (ICP MS) (Agilent 7900) in the laboratory of the School of Earth Sciences, EKTU named after D. Serikbaev. Major anions ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ) were analyzed using ion chromatography (Dionex ICS 2100). TDS was additionally verified gravimetrically (drying a 100 ml aliquot at 105  $^\circ\text{C}$  to constant weight).

### E. Calibration and Quality Control

Certified reference materials (NIST SRM 1640a, SPEX CertiPrep) were used. Blanks and duplicates (10% of the total) were included. The acceptable ion balance discrepancy did not exceed  $\pm 10\%$ .

### F. Chemical Composition of Salt Lake Water

Hydrochemical studies have shown that the TDS in the waters of the Burabay massif lakes (Figure 3) ranges from 529 to 9023  $\text{mg}/\text{L}$  (Table I) [14], classifying them as brackish and saline, and in some cases, as transitional to hypersaline waters. According to Table I, the ionic composition of the water is characterized by the predominance of  $\text{Na}^+$  and  $\text{K}^+$  cations and  $\text{HCO}_3^-$  and  $\text{SO}_4^{2-}$  anions. This composition reflects water evolution under endorheic conditions and active evaporation, which is typical of saline lake systems [12].

The cationic composition of water is mainly represented by sodium ( $\text{Na}^+$ ), calcium ( $\text{Ca}^{2+}$ ), and magnesium ( $\text{Mg}^{2+}$ ) ions. The concentration of  $\text{Na}^+$  reaches 3207.6  $\text{mg}/\text{l}$ ,  $\text{Mg}^{2+}$  303.8  $\text{mg}/\text{l}$ ,  $\text{Ca}^{2+}$  190.4  $\text{mg}/\text{l}$ . The high  $\text{Na}^+$  content indicates the presence of alkaline leaching processes and ion accumulation due to evaporation.



Fig. 3. Photograph of objects under study using a quadcopter.

Among the anions, bicarbonates ( $\text{HCO}_3^-$ ), sulfates ( $\text{SO}_4^{2-}$ ), and chlorides ( $\text{Cl}^-$ ) were predominant. Maximum concentrations reach 1256.6  $\text{mg}/\text{L}$  for  $\text{HCO}_3^-$ , 4797.9  $\text{mg}/\text{L}$  for  $\text{SO}_4^{2-}$ , and 455.9  $\text{mg}/\text{L}$  for  $\text{Cl}^-$ . The predominance of sodium over chloride is attributed to the intense weathering of silicates in the granitic and metamorphic rocks of the Burabay massif, followed by evaporative concentration under endorheic conditions. As a result, sodium bicarbonate and sodium sulfate water types are formed, reflecting varying degrees of water-salt saturation and a mixed genesis of the waters. The acidity index (pH) of the lake waters ranged from 8.14 to 9.25, indicating alkaline conditions. Despite the contribution of carbonate dissolution, sodium strongly dominated calcium in the solution. This is attributed to the intensive weathering of sodium-bearing silicate minerals in the granitic–metamorphic rocks of the Burabay massif, combined with the removal of calcium from the solution through carbonate precipitation under alkaline conditions and evaporative concentration in endorheic lakes.

The ratios between the ions indicate different degrees of geochemical evolution of the waters. Lakes with an increased content of  $\text{Na}^+$  and  $\text{HCO}_3^-$  are characterized by higher saturation, while in less saturated water bodies,  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  predominate. This allows for a preliminary classification of the lakes by the chemical brine type (soda, sulfate, chloride), which will be discussed in the next section.

The chemical composition of the waters of the studied lakes is formed under the influence of evaporation, the lithological composition of the catchment exposed outcrops, and the degree of closure of the lake basins, which corresponds to the classical model of the evolution of intracontinental lake systems [13].

This study was based on single-time sampling. The obtained results represent a spatial snapshot of the hydrochemical states of the lakes at the time of sampling and are not intended for analyzing seasonal or long-term dynamics.

TABLE I. IONIC COMPOSITION AND DIMENSIONS OF THE LAKES IN BURABAY MASSIF (IN % EQUIV.) [14]

Lake	pH	Ca <sup>2+</sup> (%)	Mg <sup>2+</sup> (%)	Na <sup>+</sup> +K <sup>+</sup> (%)	Cl <sup>-</sup> (%)	SO <sub>4</sub> <sup>2-</sup> (%)	HCO <sub>3</sub> <sup>-</sup> (%)	TDS (mg/l)	Length (km)	Width (km)	Depth (m)	Area (km <sup>2</sup> )	Mirror area
1	9.08	13	30	57	4	26	63	529	2.28	0.26	5	0.51	0.37
2	8.17	26	24	50	2	18	79	639	2.18	0.41	3	0.69	0.6
3	8.14	30	23	47	3	17	79	733	1.13	0.69	3	0.56	0.36
4	8.93	4	7	89	5	9	84	1896	3.14	1.0	11	2.48	1.83
5	8.93	4	8	88	5	9	79	1420	1.09	0.32	5	0.25	0.26
6	9.09	1	2	97	15	39	41	5059	0.77	0.23	3	0.13	0.12
7	8.14	28	16	56	1	3	94	616	3.54	0.78	9	2.34	1.05
8	9.24	3	14	83	9	34	48	2147	1.52	0.61	5	0.55	0.43
9	9.24	4	12	84	9	34	49	2253	0.76	0.19	4	0.11	0.05
10	9.23	15	51	34	9	35	45	1548	1.16	0.32	7	0.35	0.17
11	8.21	24	18	58	2	4	93	601	2.21	1.13	4	2.28	1.5
12	9.1	1	1	98	15	40	40	5849	2.7	1.35	11	2.75	2.07
13	9.23	2	5	93	8	55	31	2881	1.54	0.49	6	0.43	0.25
14	9.25	2	5	93	8	51	35	3074	0.93	0.36	5	0.37	0.26
15	8.74	5	8	87	4	92	2	9023	1.34	0.50	4	0.56	0.46

### G. Dependence of pH on Water Mineralization (15 Lakes)

The general trend shows that pH remained in the alkaline range (8.1–9.3) with increasing mineralization (Figure 4). There is no strict linear dependence, but at TDS > 2000 mg/l a more stable alkaline reaction of the environment is observed, characteristic of soda and sodium waters.

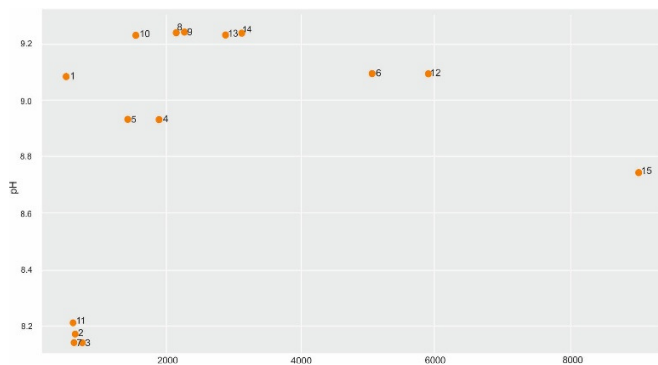


Fig. 4. Dependence of pH on mineralization (TDS, mg/l) in the waters of the lakes of the Burabay massif.

### H. Analysis of Heavy Metals and Rare Earth Elements

ICP-MS was used to assess the REE content in the water–bottom sediment system. Bottom sediment samples were collected from 15 lakes of the Burabay (Figure 2) massif using a soil sampler and dried at 40 °C to constant weight. Water samples were filtered through membrane filters (0.45 μm) and acidified with nitric acid to pH < 2 [14].

The concentrations of heavy metals (Cu, Pb, Zn, Ba, Sr, etc.) were determined in bottom sediments (Table II) in units of g/t (mg/kg). The concentrations of REE in lake waters (Table III) (La, Ce, Nd, Sm, Eu, etc.) are expressed in g/dm<sup>3</sup>. To interpret the results, the total REE content was calculated and used in correlation and comparative analysis [15].

Table IV summarizes the comparative hydrochemical characteristics of the Burabay lakes and major hypersaline systems worldwide. In contrast to the classical Na–Cl brines of the Great Salt Lake, Lake Urmia, and the Aral Sea, the Burabay waters are characterized by significantly lower

mineralization and a dominance of the Na–HCO<sub>3</sub> type. The higher pH values and the prevalence of carbonate equilibrium processes indicate soda-type evolution rather than chloride concentration. These differences highlight the transitional geochemical status of the Burabay lakes and explain their enhanced potential for rare earth element accumulation under alkaline evaporative conditions.

Table I presents the detailed ionic composition, pH, TDS, and morphometric parameters of the studied lakes. The data demonstrate a geochemical differentiation between low-mineralized Ca–HCO<sub>3</sub> waters and highly mineralized Na-dominated brines. With increasing TDS, the proportion of Na<sup>+</sup>+K<sup>+</sup> systematically increases, while Ca<sup>2+</sup> and Mg<sup>2+</sup> decrease, reflecting progressive carbonate precipitation and evaporative concentration. Highly mineralized lakes (Nos. 6, 12, 13–15) show Na<sup>+</sup>+K<sup>+</sup> contents exceeding 90% of total cations and elevated chloride and sulfate fractions, indicating advanced stages of hydrochemical evolution. These results provide the quantitative basis for the Piper classification and confirm the transition from young carbonate waters to mature soda–chloride brines. Figure 5 shows a general tendency toward higher total REE content with increasing mineralization. However, the relationship is characterized by noticeable scatter and cannot be considered strictly linear. Particularly high values of total REE were observed in lakes with mineralization above 2000 mg/l.

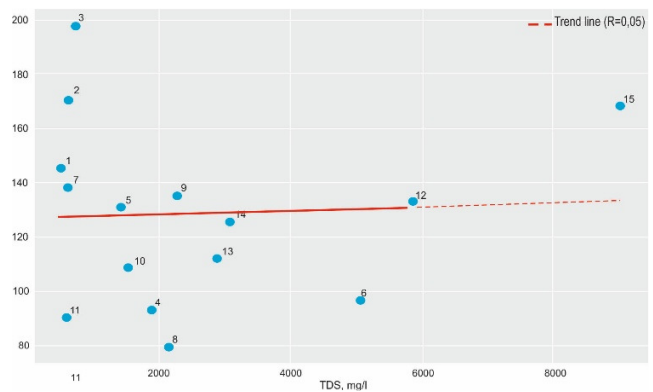


Fig. 5. Relationship between mineralization (TDS) and total REE content.

TABLE II. CONCENTRATION OF HEAVY METALS IN BOTTOM SEDIMENTS

Sample	Cu	Pb	Zn	Ba	Sr
D-1	1015.0	97.36	287.8	182.9	203.9
D-2	374.7	68.34	153.7	201.5	76.46
D-3	533.1	97.12	155.1	178.8	186.1
D-4	387.6	93.52	118.5	217.8	95.11
D-5	413.6	68.79	153.5	198.4	90.42

TABLE III. TOTAL REE CONTENT IN EACH LAKE WATER

Lake	1	2	3	4	5	6	7	8
Total REE (g/dm <sup>3</sup> )	145.23	170.92	197.92	92.52	130.78	96.96	137.99	79.16
Lake	9	10	11	12	13	14	15	
Total REE (g/dm <sup>3</sup> )	135.38	107.86	89.99	132.62	111.66	125.28	168.40	

TABLE IV. COMPARISON BETWEEN THE SALT LAKES OF THE BURABAY MASSIF WITH WORLD'S SALT LAKES

Lake / region	Mineralization (TDS)	Main ions	pH range	Key processes
Great Salt Lake (USA)	50–270 g/L	Na <sup>+</sup> , Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup>	7.5–8.5	Evaporation, precipitation of halogenates
Lake Urmia (Iran)	150–300 g/L	Na <sup>+</sup> , Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup>	7.8–8.6	Evaporation, anthropogenic influence
Aral Sea (central Asia)	10–100 g/L (until dry)	Na <sup>+</sup> , Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup>	7.5–8.2	Anthropogenic reduction of runoff
Burabay Massif (Kazakhstan)	0.5–9 g/L (529–9023 mg/L)	Na <sup>+</sup> , HCO <sub>3</sub> <sup>-</sup> , Cl <sup>-</sup> , SO <sub>4</sub> <sup>2-</sup>	8.1–9.3	Evaporation, carbonate equilibrium, REE accumulation

III. RESULTS AND DISCUSSION

Classification of studied lake waters was carried out on the basis of ionic composition using the Piper diagram, which allows classifying waters by predominant cations and anions, as well as identifying their hydrochemical type [15, 16]. The general trend showed that the pH remained in the alkaline range (8.1–9.3) with increasing mineralization (Figure 6). There is no strict linear dependence, but at TDS>2000 mg/l, a more stable alkaline reaction of the environment is observed, characteristic of soda and sodium waters.

The Piper diagram (Figure 6) (in the projection of Na<sup>+</sup> and K<sup>+</sup> versus Cl<sup>-</sup>) reflects the types of water. The colors correspond to mineralization (the brighter the color, the higher the TDS). Most samples are shifted to the field of sodium chloride or sodium sulfate waters, which confirms the presence of evaporative concentration processes and alkaline evolution of the composition.

On the right (Figure 7), in the cation triangle, water with a high content of sodium and potassium (Na<sup>+</sup>+K<sup>+</sup>) predominates, especially in lakes with high mineralization (Figure 6). This is typical of alkaline and soda lakes formed under conditions of intense evaporation [17]. On the left, in the anion triangle, a

significant part of the water is characterized by the dominance of chlorides and sulfates, especially in lakes with TDS>2000 mg/l. This indicates the accumulation of easily soluble salts in the closed basins. In the diamond-shaped projection, most of the water is distributed in the right and upper parts of the field, which indicates chloride-sulfate-sodium waters. This hydrochemical signature (specifically sodium chloride, sodium sulfate, or mixed sodium chloride-sulfate types) is typical for closed lake systems in arid and semi-arid climatic conditions [18]. Less mineralized waters, found in some lakes with TDS<1000 mg/l, demonstrate a more pronounced presence of hydrocarbonates and calcium/magnesium, which indicates a sulfate-hydrocarbonate calcium-magnesium type and the initial stages of chemical evolution.

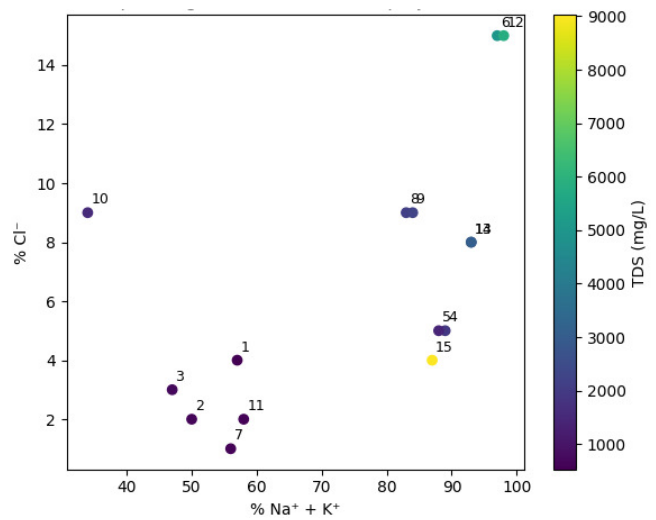


Fig. 6. Diagram of the distribution of water samples from the Burabay massif lakes based on the relative content of Na<sup>+</sup> + K<sup>+</sup> and Cl<sup>-</sup> (equivalent %).

The Piper diagram (Figure 6) made it possible to visually track the geochemical evolution of waters from low-mineralized (Ca–HCO<sub>3</sub> type) to highly mineralized alkaline waters of soda and chloride nature. Also, the Piper diagram for several atypical lakes (No. 3, 4, 5, 6, 8) shows a shift of points toward the marginal regions of the cation and anion triangles. This position is due to the predominance of individual ions (Na<sup>+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>) in highly mineralized waters. These features reflect the natural characteristics of saline waters in closed lake systems, which form in arid climates and are accompanied by a pronounced ion imbalance.

Analysis revealed that these waters are characterized by a high proportion of Na<sup>+</sup> and K<sup>+</sup> ions, reaching up to 95% of the total cations (lake 6), with a simultaneous deficiency of calcium and magnesium, the content of which in some cases does not exceed 5%. Hydrocarbonates and sulfates predominate among the anions. Such ratios are characteristic of highly mineralized alkaline soda and soda-chloride lakes in the late stages of geochemical evolution and experience significant evaporative concentration. These features are most clearly evident in lakes 5 and 6.

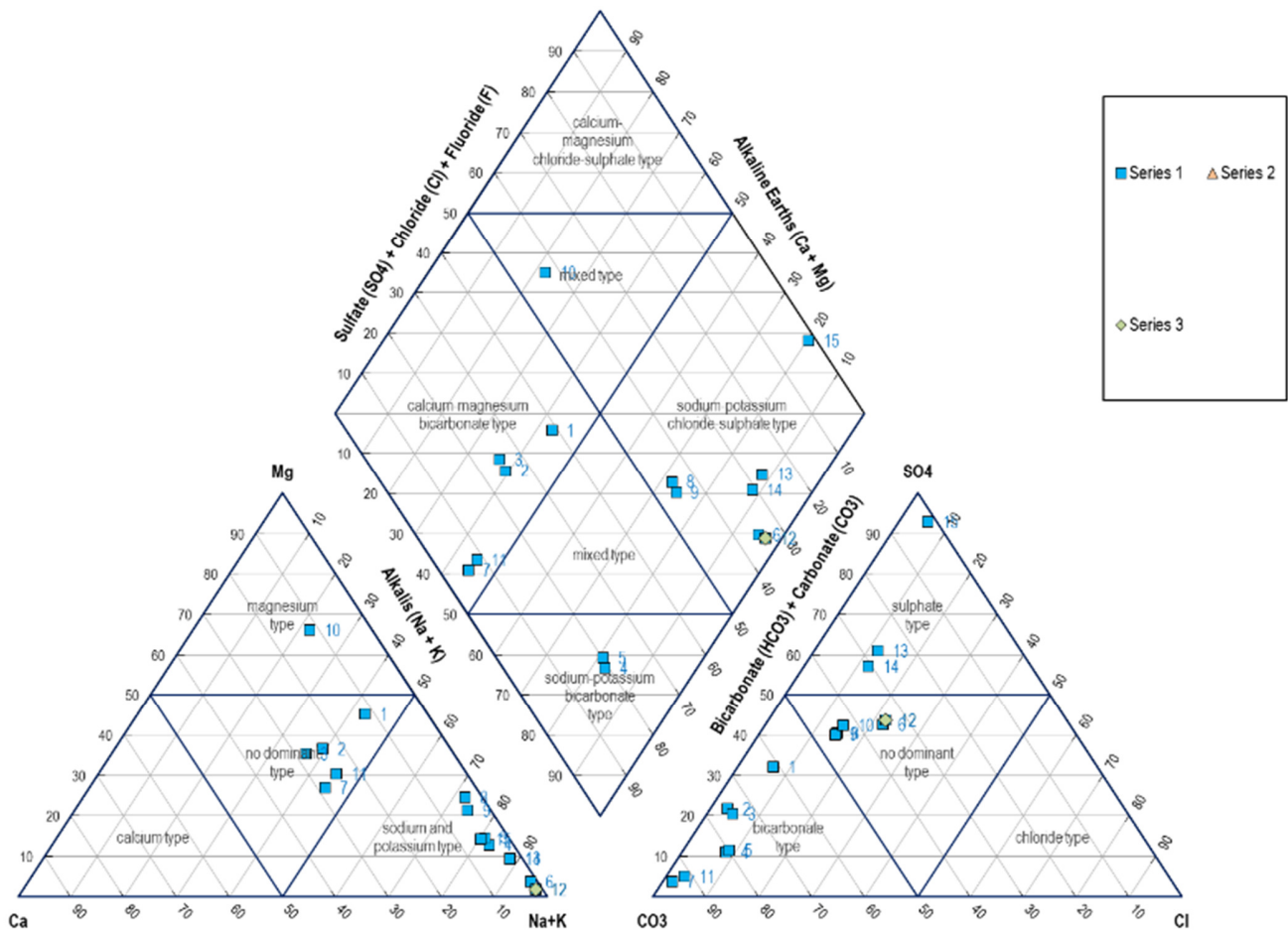


Fig. 7. Typification of waters by ionic composition (on the right - cations, on the left - anions).

A. Water Saturation Indices for the Main Minerals

To assess the geochemical equilibrium and potential mineral formation processes in the waters of the lakes of the Burabay massif, SIs were calculated for the following mineral phases (Table V): calcite ( $\text{CaCO}_3$ ), dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), halite ( $\text{NaCl}$ ), and sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) [19].

TABLE V. SIS FOR MINERALS PHASES

Lake	Calcite	Dolomite	Gypsum	Halite	Sodium carbonate
1	9.09	18.88	4.91	-1.11	1.23
2	9.59	19.5	5.15	-1.2	0.47
3	9.66	19.55	5.2	-1.2	0.36
4	9.69	19.9	4.91	0.2	3.05
5	9.6	19.82	4.87	0.18	2.99
6	9.81	20.29	5.99	1.8	4.74
7	9.74	19.6	4.42	-1.37	0.69
8	9.68	20.35	5.74	0.77	3.67
9	9.76	20.42	5.8	0.82	3.79
10	9.72	20.32	5.81	-0.19	1.71
11	9.64	19.49	4.43	-1.28	0.68
12	9.79	20.25	5.99	1.94	5.02
13	9.55	19.82	5.99	1.02	3.94
14	9.62	20.0	5.99	1.05	4.1
15	9.74	20.02	7.56	1.72	3.77

Positive SI values indicate supersaturation of the solution for a given mineral, whereas negative values indicate undersaturation [20]. Positive SI values for calcite and dolomite reflect the possibility of their precipitation, but the formation of dolomite as a primary mineral from brine is not expected. Negative SI values for gypsum are associated with a  $\text{Ca}^{2+}$  deficiency due to carbonate precipitation.

B. Calcite and Dolomite

Almost all the studied lakes were characterized by positive SI values for calcite, indicating the supersaturation of water with this mineral phase. This is consistent with the high pH (more than 8.5) and the predominance of  $\text{HCO}_3^-$  in the anion composition, which creates favorable conditions for calcite precipitation. Positive SI values for dolomite indicate the thermodynamic possibility of precipitation. However, the direct formation of dolomite as a primary mineral from brine is unlikely. Rather, it is a potential tendency toward precipitation or secondary processes associated with water-rock interactions. (e.g. in lakes 5, 6, 12) [19, 21].

C. Gypsum

The SI values for gypsum were mainly negative, indicating undersaturation with  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . The main cause is a deficiency of  $\text{Ca}^{2+}$  in the solution, caused by its removal during

the precipitation of carbonate phases (calcite, dolomite) under alkaline pH and sodium alkalinity conditions. At such ion ratios, the  $\text{Ca}^{2+}$  concentration is insufficient to achieve equilibrium with gypsum, even in the presence of sulfate. Exceptions are observed in most mineralized lakes (6, 12), where the SI for gypsum approaches zero, reflecting a higher ionic strength and increased activity of  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$ .

#### D. Halite

SIs for halite ( $\text{NaCl}$ ) vary from negative to positive, which may be due to different levels of evaporation and the influence of tectonic/ground fluids. Lakes with  $\text{SI} > 0$  (e.g. 6, 12) may be in equilibrium or even supersaturated with halogenite, especially at very high mineralization ( $M > 5000$  mg/L).

#### E. Sodium Carbonate

Several lakes (5, 6, 8, and 12) showed a high degree of saturation with soda, including positive SI values. This is typical for highly alkaline soda waters, in which  $\text{Na}^+$  and  $\text{CO}_3^{2-}$  predominate at  $\text{pH} > 9$ . Such a composition is representative of lakes with intense evaporation and a lack of drainage. The possibility of precipitation of trona and natronite may be realistic with further increase in concentrations.

The presented SI values serve as indicators of mineral stability and the direction of geochemical processes. Positive SI values indicate the potential for precipitation of minerals from supersaturated waters, whereas negative values indicate their dissolution or failure to achieve equilibrium.

#### F. Factors Controlling the Chemical Composition of the Waters of the Lakes of the Burabay Massif

The chemical composition of the waters of the lakes of the Burabay massif is formed under the influence of a complex of natural processes reflecting the geological structure of the region, climatic conditions, hydrological regime, and degree of evaporation. The established ionic ratios, high pH values, as well as changes in mineralization indicate the participation of both lithological and climatic factors [4].

The basic factor determining the initial composition of the ion background is the lithology of the catchment areas. Granitoids and quartz rocks containing plagioclase, potassium feldspar, biotite, and secondary carbonate formations predominate within the massif. Their leaching causes the entry of  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{HCO}_3^-$ , and  $\text{Ca}^{2+}$  ions into the reservoirs. In lakes with high mineralization (5, 6, 12),  $\text{Na}^+$  and  $\text{HCO}_3^-$  predominate, indicating the destruction of sodium silicates (albite) and possibly the formation of soda minerals. The influence of carbonate rocks is expressed by the supersaturation of calcite and dolomite, especially at high pH. Evaporation is the key mechanism for salt concentration, specifically in endorheic lakes. This is confirmed by:

- High mineralization (up to 9000 mg/l).
- Increasing proportion of  $\text{Na}^+ + \text{K}^+$  as mineralization increases.
- Increasing SI for soda and halite in the most saline lakes.

The diagram of the pH dependence on total mineralization demonstrates a positive correlation, characteristic of evaporative systems [19].

#### G. Ionic Ratios and Correlations

The results of the correlation analysis (Figure 8) demonstrate that:

- A strong relationship between  $\text{Na}^+$  and  $\text{Cl}^-$  ( $r > 0.9$ ) may indicate the influence of halogen-containing waters or saline deposits.
- A positive relationship between mineralization and SI for sodium carbonate reflects the progressive alkaline evolution of the water.
- Weak or negative correlation between  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  with mineralization, indicating their participation in sedimentation.

#### H. Anthropogenic and Local Impacts

For most lakes of the Burabay massif, signs of anthropogenic influence are minimal. However, in some cases, such as lake 15 (Figure 8), a sharp increase in  $\text{Cl}^-$  and  $\text{K}^+$  was observed, which may be associated with agricultural or domestic runoff. This requires additional confirmation using isotopic or microcomponent indicators.

Figure 8 shows the relationship between sodium and chloride concentrations in meq/l. A pronounced linear positive correlation was observed, especially in lakes with high mineralization (5, 6, 12, 13, 14). This suggests a joint origin of these ions due to the leaching of halogen-containing rocks, evaporative thickening, or the influx of deep fluids enriched in  $\text{Na}^+$  and  $\text{Cl}^-$ . Lakes with deviations from the general trend (e.g., 1, 2, and 7) have lower mineralization and may be weakly affected by these processes. It follows that the system is close to equilibrium with halogenite in a number of lakes, and  $\text{Na}^+$  and  $\text{Cl}^-$  play a key role in the formation of the ion background.

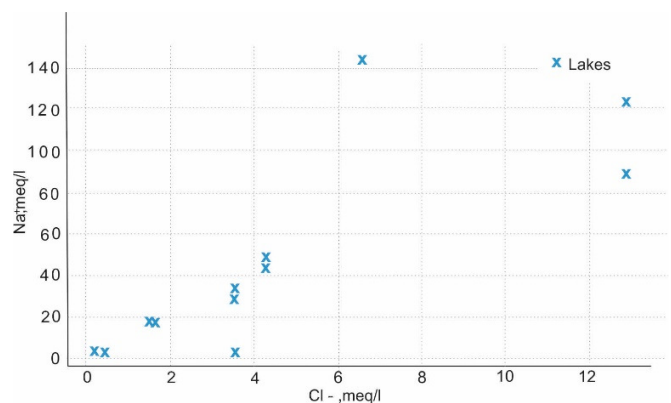


Fig. 8. Correlation between  $\text{Na}^+$  and  $\text{Cl}^-$  ions.

#### I. Geochemical Evolution of Lake Waters

The geochemical evolution of lake waters of the Burabay massif reflects the patterns of transition from waters of/in the initial stages of formation with the participation of carbonate equilibrium to highly mineralized alkaline and chloride brines,

which are in the late stages of hydrochemical development [22].

#### J. Evolution Stages

The term "geochemical evolution" in the present study is employed in a comparative-typological and conceptual-genetic context. The stages examined reflect variations in ionic composition, mineralization, and pH among different lakes situated at distinct levels of hydrochemical maturity, rather than the temporal dynamics of the water composition within a single reservoir. The long-term seasonal monitoring, necessary for analyzing the actual temporal evolution of brines, was not carried out within the scope of this research [23].

Based on the analysis of ionic composition, saturation indices, Piper diagrams, mineralization, and pH values, the following types of lakes can be conditionally distinguished according to the degree of geochemical maturity:

1. Initial stage (young lakes). Lakes with Ca-HCO<sub>3</sub> or Mg-HCO<sub>3</sub> types, pH<8.5, and mineralization up to 700 mg/l (for example, 1, 2, 11). These waters are in equilibrium with carbonates but are not saturated with gypsum or halite. Such lakes are characterized by active water exchange and possible participation of underground recharge.
2. Middle stage (alkaline bicarbonate waters). Lakes of the Na-HCO<sub>3</sub> type with mineralization of 1000–3000 mg/l and pH of 8.8–9.3 (4, 5, 8, 9). The waters are supersaturated with calcite, dolomite, and sometimes with soda. Ca<sup>2+</sup> and Mg<sup>2+</sup> are actively removed due to the precipitation of carbonates, and sodium alkalinity dominates.
3. Late stage (concentrated brines). Lakes of the Na-Cl or Na-CO<sub>3</sub> type, with mineralization above 4000 mg/l and pH up to 9.5 (6, 12, 13, 14, 15). These waters are dominated by sodium, have a high content of Cl<sup>-</sup> and CO<sub>3</sub><sup>2-</sup>, and are supersaturated with soda and halite. These are the final stages in the evolution of endorheic lakes under conditions of evaporative balance and a lack of drainage.

The main factors that control the geochemical transformation of water composition are evaporation (the main mechanism for increasing mineralization), ion exchange and precipitation of carbonates (leads to the removal of Ca<sup>2+</sup> and Mg<sup>2+</sup>), lithological control (determines the initial ionic composition), and the hydrological regime (determines the closure and efficiency of runoff).

The interpretations were based on a single set of samples and represent a spatial snapshot. Conclusions about seasonal and interannual evolution require long-term monitoring with repeated sampling across different seasons.

#### IV. CONCLUSIONS

The conducted geochemical analysis of the waters of 15 lakes located within the Burabay massif enabled identifying patterns in the formation of their ionic composition, mineralization, and geochemical evolution. The main factors controlling the chemical composition are the lithological

structure of the catchments, evaporation intensity, hydrological isolation, and carbonate equilibrium.

The bulk of the waters are sodium hydrocarbonate and alkaline types, with a high pH value (up to 9.3) and signs of supersaturation for calcite, dolomite, and soda. Some reservoirs show signs of transition to a chloride or sulfate type with increased mineralization (more than 5000 mg/l), which reflects the final stages of evaporative geochemical evolution. Saturation Indices (SIs) for the main mineral phases confirm active processes of mineral formation of Na<sup>+</sup>, HCO<sub>3</sub><sup>-</sup>, and Cl<sup>-</sup> ions, and Piper diagrams and correlation dependencies indicate stable genetic types of ionic waters. Classification by ionic composition and spatial distribution allows using these data for monitoring, assessing the degree of natural and man-made impact, as well as for predicting changes in water quality in a changing climate.

The ionic composition of the waters of the Burabay massif lakes varies from Ca-HCO<sub>3</sub> to Na-Cl and Na-HCO<sub>3</sub> types, which reflects differences in the geochemical maturity, mineralization and degree of isolation of the reservoirs [24].

The pH values ranged from 8.1 to 9.3, indicating the alkaline nature of the water due to active carbonate and evaporative processes.

In lakes with medium and high mineralization (from 1500 to 9000 mg/l), Na<sup>+</sup> and HCO<sub>3</sub><sup>-</sup> predominate, which is typical for evaporative lakes in arid climates with limited drainage.

Calculating the SIs showed that most waters are supersaturated with calcite and dolomite, undersaturated or close to equilibrium with gypsum, and supersaturated with sodium carbonate in alkaline lakes with pH>9, which indicates active processes of mineral formation and carbonate precipitation.

Typification by ionic composition and SIs made it possible to determine the geochemical maturity of waters, from the young carbonate type to the final stage of soda and chloride brines.

The three-part Piper diagram shows a clear shift from the Ca-HCO<sub>3</sub>/Mg-HCO<sub>3</sub> types towards Na-Cl and Na-CO<sub>3</sub>, corresponding to the typical evaporative trajectory of evolution in arid zones. This confirms that the system is in the stage of natural chemical development without significant anthropogenic interference [10, 25].

Evaporation and leaching of rocks are the main geochemical factors determining the development of the chemical composition of lake waters, whereas anthropogenic impact is weak and requires clarification.

According to the analysis of bottom sediments (Table II), the maximum copper content (1015 and 915 g/t, respectively) was recorded in samples D-1 and D-12, as well as increased concentrations of zinc and barium. This indicates the presence of areas with intense leaching or accumulation of heavy metals in the sedimentary phase [24].

In the lake waters (Table III), the total Rare Earth Elements (REE) content varied from 79.2 to 197.9 g/dm<sup>3</sup>. The highest

values were found in lakes 3, 2 and 15, which may be due to high pH and mineralization values, which contribute to the preservation of dissolved REE forms. Simultaneously, low values (for example, in lakes 8 and 11) may reflect the influence of dilution or fresh surface recharge.

Comparative analysis showed a positive correlation between mineralization and total REE, especially under alkaline conditions (pH > 9), which confirms the hypothesis of evaporation-concentration accumulation of REE in closed systems. Bottom sediments serve as a potential source of trace elements back into the water column when oxidation-reduction conditions change. Therefore, the inclusion of microelement analysis allows for a more profound interpretation of the processes of leaching, migration, and accumulation of elements in the water-sediment system, and expands the understanding of the geochemical evolution of the region's salt lakes.

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