

Geochemical Changes in the Caspian Salt Marshes Due to the Sea Level Fluctuations

Nicolay S. Kasimov¹, Alexandre N. Gennadiev¹, Maria S. Kasatenkova¹, Michail Y. Lychagin¹,
Salomon B. Kroonenberg² & Peter Koltermann³

¹ Department of Landscape Geochemistry and Soil Geography, Faculty of Geography, Moscow State University, Moscow, Russia

² Delft University of Technology, Department of Geotechnology, Delft, Netherlands

³ Natural Risk Assessment Lab, Faculty of Geography, Moscow State University, Moscow, Russia

Correspondence: Maria S. Kasatenkova, Department of Landscape Geochemistry and Soil Geography, Faculty of Geography, Moscow State University, Leninskiye Gory, 1, GSP-1, Moscow 119991, Russia. Tel: 7-495-939-4407. E-mail: kasatenkova2010@mail.ru

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Abstract

The Caspian Sea is subject to alternating transgressions and regressions that exert a strong impact on the topography, sediments, vegetation, and soils in coastal zones. The last transgression of the Caspian Sea (1978-1995) caused the development of a marsh-lagoon system along the accumulative seashore of the Central Dagestan. Salt marshes are complex and dynamic systems highly vulnerable to sea level fluctuations; therefore, they may be considered as a regional model of rapid environmental changes. Hazards in coastal zones may critically change the soil geochemistry affecting agricultural potential of large areas. Assessments of risks of the natural hazards in coastal zones are extremely difficult unless the end-to-end understanding of all natural factors. The research in the Caspian region shows the impact of extreme events in the coastal zones. Detailed landscape-geochemical investigations of the Caspian salt marshes were carried out in 1995-1996 (during the final stage of the transgression period) and in 2001-2003 (during the period of the sea level stabilization). These coastal areas are influenced by different landscape-geochemical processes, such as sulfidization, gleyization, ferrugination, humus accumulation, halogenesis, and changes of alkali-acidic conditions. The development of the processes characterizes different stages of the Caspian Sea level fluctuations. This paper presents a discussion on stages and rates of landscape-geochemical processes, formation of geochemical barriers, and trace elements distribution in soils of the salt marshes.

Keywords: coastal zone, lagoon, trace elements, sea-level rise, risk assessment

1. Introduction

Global warming and the rise of the world's ocean level are among the most important present-day environmental problems. Many coastal areas experience inundation and water logging by sea water. At the same time, these dynamic regions are of immense ecological and economic importance. Therefore, studies of environmental consequences of sea level changes are of particular importance. Within the most of the world, the present sea level change proceeds rather slowly and it is almost imperceptible in human lifetime. The Caspian Sea offers a unique opportunity to study the impact of sea level change on the coastal zone during a short-term period, because the Caspian Sea level change is much more rapid than that of the world's ocean (Kroonenberg, Baduykova, Storms, Ignatov, & Kasimov, 2000). The Caspian Sea is well known for large and rapid sea level fluctuations (Figure 1).

The most recent cycle lasted only 65 years (Cazenave, Bonnefond, Dominh, & Schaeffer, 1997; Kaplin & Selivanov, 1995; Klige & Myagkov, 1992; Rychagov, 1993). The sea level fell by over 3 m between 1929 and 1977 and rose again by 2.4 m by 1995, when it started falling again. Today, it is stable at about -27 m, and there is no reliable forecast of its behavior even for the near future. The rate of the sea level rise averaged 150 mm/yr during the 1977-1995 transgression, and had its maximum of 340 mm in 1991. In this way, a one year of the Caspian Sea level rise equals to a century of the eustatic sea level rise in the oceans (Kroonenberg et al., 2000).

Many scientists believe that such short-term sea level fluctuations are related to climatic changes in the Caspian Sea basin (Rodionov, 1994; Kroonenberg, Rusakov, & Svitoch, 1997). Understanding consequences of the Caspian Sea level changes is very important as they threat large areas with inundation, water-logging, and other environmental changes (Kasimov, Gennadiyev, Lychagin, Kroonenberg, & Kucheryaeva, 2000; TED Caspia, 1992).

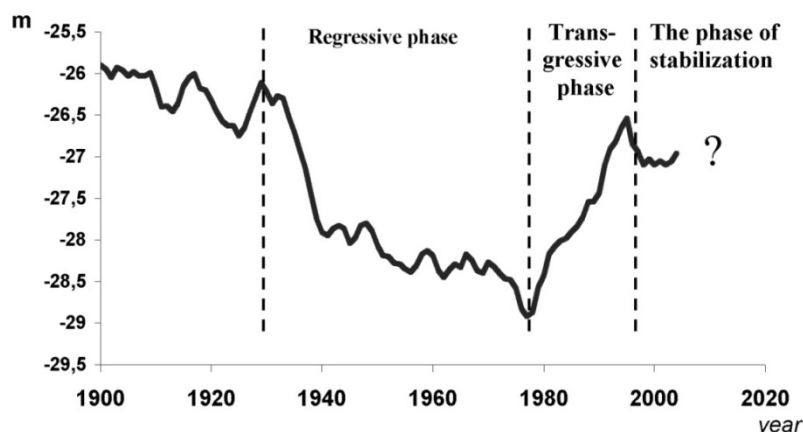


Figure 1. The Caspian Sea level fluctuations in the XX century

Different types of the Caspian littorals show various reactions to the sea level changes. The recent sea level rise generally did not cause qualitative changes at the abrasion shores and was manifested, first, in activation of abrasion processes and increase of their rate. Environmental effects of the sea level rise on the near-shore river mouth areas (Volga, Terek, Sulak, and other) were complicated by seasonal variations in river runoff, creation of artificial levees and channels, and use of river water for irrigation. The most dramatic consequences of the rapid marine transgression were found for accumulative shores. The width of the coastal zone affected by inundation and water-logging varied from hundreds meters to 10-20 km depending on the gradients of the submarine slope.

Along accumulative shores with intermediate (0.03° - 0.3°) gradients of submarine slopes (Ignatov, Kaplin, Lukyanova, & Solovyova, 1993; Kaplin & Selivanov, 1995), a rapid sea level rise caused a formation of a barrier-lagoon system that moved landward with the sea transgression, with a corresponding rise of the groundwater table, and with simultaneous vigorous development of vegetation in newly-formed hydromorphic and semi-hydromorphic areas. On the contrary, the previous regression led mainly to the passive drainage of the shore zone. The formation of such barrier-lagoon systems is typical for the Caspian shore (Badyukova, Solovoyova, & Spolnikova, 1993; Kravtsova & Lukyanova, 1997) and for the world's oceanic shores (Recent global changes of the natural environment, 2006). The general domination of accumulative coasts on the global scale reflects the eustatic sea level rise in the postglacial period (Leontiev, Lukyanova, Nikiforov, Solovyova, & Holodilin, 1977).

Inundation and water-logging of accumulative shores due to the sea transgression caused formation of salt marshes in some coastal areas. Until recently, nobody considered such a type of landscapes in the Caspian region. Typical salt marshes are flat and poorly drained areas of land that are subject to periodic or occasional flooding by salt water and are usually covered by a thick mat of grassy halophytic (salt tolerant) plants (Bates & Jackson, 1980). They form important nutrient sources for estuarine and offshore fisheries and play an integral role in coastal defense (Allen & Pye, 1992).

Sea level and groundwater level are very unstable in the study area. This is caused by seasonal changes of the Caspian Sea level, wind and wave activity, seasonal rains, etc. That is why the marsh area adjacent to the lagoon is flooded often. Thus, its water regime is quite similar to that of the typical salt marshes that experience tidal effects.

Another important feature of salt-marshes is vegetation zonation. It was described by many authors (Bockelmann, Bakker, Neuhaus, & Lage, 2002; Myalo & Malkhazov, 2000; Rogel, Silla, & Ariza, 2001; Silvestri, Defina, & Marani, 2005) who evaluated environmental factors affecting the distribution of plants. Along the Caspian seashore, the vegetation cover develops under conditions of rapid environmental changes caused by the sea level fluctuations and, therefore, is highly dynamic. Grass vegetation is presented here by halophyte-hydrophytes' successive series that are common for low seashores (Myalo & Malkhazov, 2000). This fact also supports the

notion that these coastal landscapes can be considered as salt marshes.

Coastal soils are also affected by sea level changes. Soil morphology, organic matter content, salt composition, and other soil properties are influenced by salinity and the depth of the groundwater table. In our previous study, we have identified main stages of the regression–transgression cycle of the coastal soil development (Gennadiyev, Kasimov, Golovanov, Lychagin, & Puzanova, 1998). During the last sea level cycle, the geochemical pattern within the coastal zone diversified, especially within the areas of the salt marshes (Kasimov et al., 2000). The regression phase was characterized by a relatively simple pattern, but the transgression phase resulted in a more complex soil-geochemical pattern differentiated into the zones of mobilization and accumulation of chemical elements.

Behavior of trace elements indicates the degree of development and the rate of geochemical processes in coastal soils where the sea level fluctuations caused changes in natural background values of chemical elements. Understanding such naturally occurring changes of the local geochemical background facilitates assessment of human-induced pollution in the coastal zone. Earlier (Kasimov et al., 2000), we have found that during the transgression phase, many heavy metals (Cu, Co, Zn, Ni, Cr, Fe, and Pb) accumulate at the geochemical barriers in the marsh zone.

There are many publications on geochemistry of salt marshes (Shaw, Gieskes, & Jahnke, 1990; Velde, Church, & Bauer, 2003; Zwolsman, Berger, & Van Eck, 1993). A special attention is paid to their pollution (Cundy et al., 2005; Williams, Bubb, & Lester, 1994) and to pollution sources (Cundy, Croudace, Thomson, & Lewis, 1997; Price, Winkle & Gehrels, 2005; Spencer, Cundy, & Croudace, 2003; Valette-Silver, 1993). A great number of studies have been conducted to investigate the impact of sea level rise on behavior of the coastal systems (Allen, 2000; Gornitz, Couch, & Hartig, 2002; Simas, Nunes, & Ferreira, 2001).

In our previous work (Gennadiyev et al., 1998; Kasimov et al., 2000), we studied soil evolution and geochemical changes in the salt marshes along the western Caspian seashore for the regression and transgression phases. The subsequent stabilization of the sea level provided an excellent opportunity to continue the study and finally to report the effects and dynamics of soil-geochemical processes during the full cycle of the sea level changes including the stabilization phase.

2. Material and Methods

2.1 Study Area

Fieldwork was conducted on the semi-arid barrier coast of the Turali area in Dagestan Republic of Russia. The Turali site is located 30 km to the south of Makhachkala, the capital of Dagestan (Figure 2). This area has been intensively studied in 1995-1996 when the sea level was the highest (Gennadiyev et al., 1998; Kasimov et al., 2000) and in 2001-2003 when it stabilized.

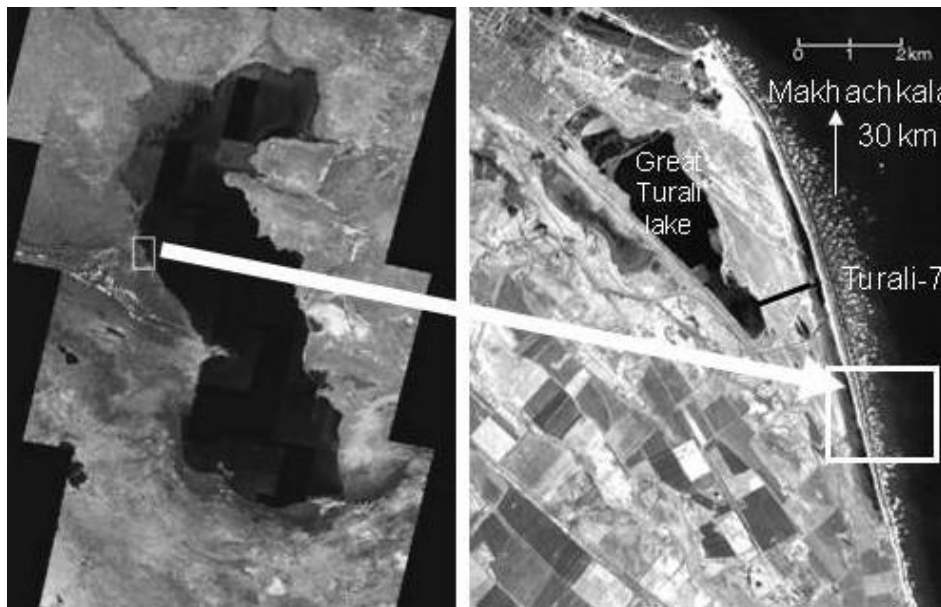


Figure 2. The study area (satellite image of the Dagestan coastal area)

The main part of the coastal plain is formed by a New-Caspian (Holocene) coastal terrace at about -22 m below ocean level (Kronstadt gauge). The terrace ends on its seaward side by a fossil cliff of about 3 m high, and is separated from the sea by a modern terrace which varies in width from 100 to 500 m. A series of low bars of 1929, 1941, and 1956 can be distinguished within its surface (Figure 3). They were formed during different phases of the Caspian Sea retreating in 1929-1978. In 1978-1995, a considerable part of the terrace was inundated. Presently, this part is occupied by a 0.8-1.0 m deep and a few hundreds of meters wide lagoon separated from the sea by a modern barrier beach with a height of 1.0-1.2 m and a width of 10-30 m (Figure 4).

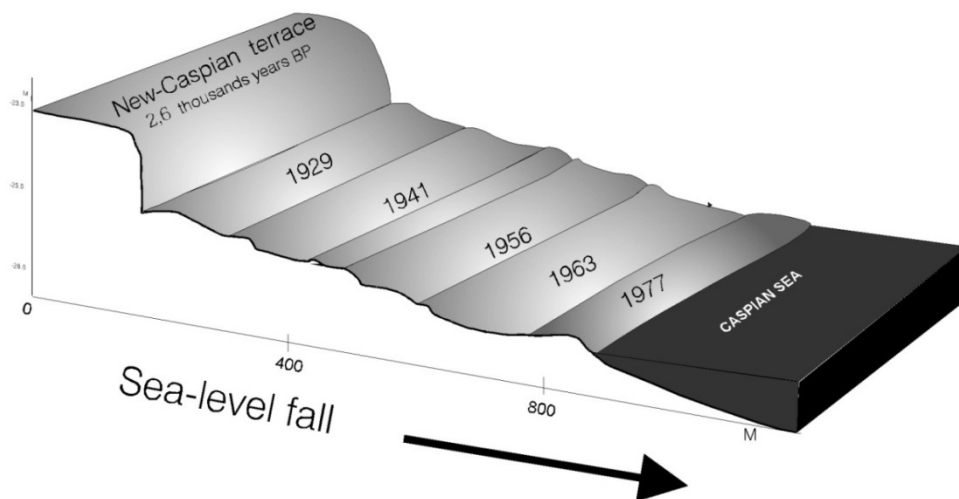


Figure 3. The formation of a series of the sea terraces during the regression cycle (1929-1978) (Badyukova et al., 1993; Kroonenberg et al., 2000)

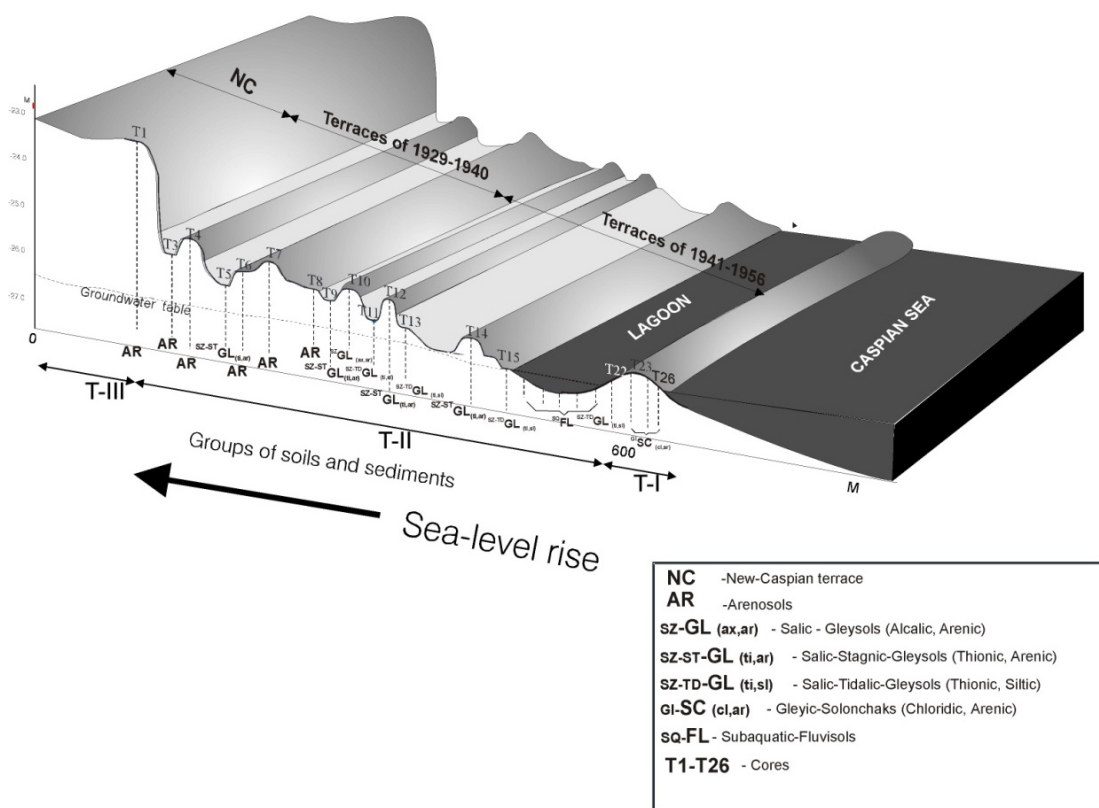


Figure 4. The distribution of soils and sediments in the profile T

2.2 Sampling Procedures

The fieldwork was carried out at a cross-section (150×400 m) stretched from the New-Caspian terrace towards the sea. The landscape-geochemical, geomorphologic, soil, and geobotanical investigations were conducted at four parallel transects (T, 2D, 2N, 2M) located across the coastal plain. The main transect is T. The study of soil pits along the main transect T was carried out both in 1995-1996 and 2001-2003. Transects 2D, 2N, and 2M were studied only in 1995-1996. During fieldwork, about 500 soil samples, 100 samples of bottom sediments, and 100 samples of natural water were collected.

A number of physical and chemical parameters of water and soils were defined immediately at the sampling points: pH, Eh, total dissolved salts (TDS), and the sodium content. The measurements were done with the portable devices (HANNA Instruments, Italy). For the lagoon sediments and soil horizons located below the groundwater table, the measurements were done directly under their natural moisture. For determination of physical-chemical parameters in dry soil horizons, distilled water was added to each soil sample at 1:1 ratio; the mixture was stirred by a plastic stick and measurements were made in the suspension obtained.

The cation content in the water samples, as well as the content of bulk and mobile forms of chemical elements in the soils, were analyzed by the atomic-absorption method using the spectrophotometer Hitachi 180 (Japan). The content of Na, K, Ca, and Mg was determined without background correction, since the content of Fe, Mn, Ni, Cr, Co, Zn, Pb, Cd, and Mo was defined with correction based on the Zeeman effect. In order to define the bulk values of heavy metals in soils and sediments, the samples were digested with a mixture of concentrated acids (HNO₃ and HF). For analysis of mobile forms of elements, 1N (2N) HCl was used as the extraction agent. This extraction shows a general amount of water-soluble, exchangeable, and amorphous forms of elements (Solovyov, 1989).

3. Results

Morphometric studies of the topography of the coastal zone showed that, during the period from 1978 to 1995, the area of the modern terrace decreased by more than 200 m. The rise in the sea level by a centimeter led to the expansion of the lagoon by 4 m and the retreat of the coastline by 2-3 m (Badyukova et al., 1993). This reduction was the result of the movement of the bar-lagoon system. Finally the lowest part of the terrace formed in 1957-1977 was inundated by the sea. The adjacent part of the terrace was occupied by the coastal bar and the lagoon. Higher levels of the present terrace formed in 1929-1941 were subject to water-logging.

The coastal soils have close evolutionary links. They have undergone differently directed evolutionary stages. In their dependence on particular site conditions, the soils and sediments of the coastal zone can be subdivided into three evolutionary groups with respect to their response to the advances and retreats of the sea (Gennadiev et al., 1998).

The first group includes recent beach deposits (T-I). They occupy the most seaward position. The strand plain along the shoreline has a width 20-30 m. It is not covered by vegetation and consists of fine-grained sandy deposits of a yellow-gray color, with carbonates, and with darker interlayer of sand and shell detritus. It is a very dynamic zone and the processes of soil formation are periodically interrupted. The beach deposits represent the youngest evolutionary group of the site.

The oldest evolutionary group includes the soils of the New-Caspian terrace (T-III) that are not affected by modern water table fluctuations. The Arenosols of the New-Caspian terrace virtually have not changed since the 1930s. However, before that they had undergone all the previous stages of the soil cover development of the regression and transgression phases. The presence of buried ferruginous horizons is considered a specific soil feature that attests to the previous hydromorphic stage of soil development within the New-Caspian terrace (Gennadiev et al., 1998). The morphology of these soils is very close to the other soils of the site. The soils of the New-Caspian terrace are considered as the most developed stage of soil evolution in comparative analysis aimed at understanding the results of superimposed geochemical processes and at evaluating their duration.

The New-Caspian terrace is generally characterized by a deep groundwater table (> 3 m), low TDS values (20-40 mg/l), oxic environment (Eh>150 mV), and relatively high alkalinity (pH 8.3 to 8.5) in soils. Humus accumulation takes place here under the sparse grass-herbal semi-desert vegetation, so humus content is relatively low - 0.3-0.5 %. The Arenosols of the terrace show predominantly low content of chemical elements (Table 1).

Table 1. Concentration of elements in slightly affected soils and sediments of the site, mg/kg (n=5)

Concentration	Fe	Mn	Ni	Co	Cr	Cu	Zn	Pb	Cd	Sr	Mo
Bulk	10000	155	5.3	2.6	2.2	2.9	18.8	5.7	0.07	405	6.7
Mobile	1382	87.7	0.3	0.5	0.65	1.1	4.6	2.6	<0.01	225	---

The bulk Fe value varies from 0.9 to 1.2 % being about 1% on average, which is the same as in the sandstone (0.98 %) (Turekian & Wederpohl, 1961) and about 5 times less than the average content (clark) (Vinogradov, 1962) of this element in the Earth's crust (4.65 %). The concentration of mobile Fe in these sediments is the lowest (500-600 mg/kg), but they include ferruginous layers that are the former oxidized sulfide horizons with mobile iron content of 2000-3500 mg/kg. The bulk content of Fe in sediments of the present-day beach is very low – about 0.19 % with mobile Fe accounting for 0.17 %.

The average content of Mn, Zn, Pb, Cd, and Co is 3 to 5 times lower than that in the Earth's crust (clark) (Vinogradov, 1962), while Cu, Cr, and Ni contents are 15 to 25 times lower. In comparison with sandstone averages (Turekian & Wedepohl, 1961), the content of Ni is 2.5 times, Co – 8.6 times, and Mo – 33.5 times higher; the content of Zn and Pb is the same, and content of Cr is 17 times lower. Low geochemical background of the chemical elements is due to the light texture of marine sediments composed of pure sand and shell detritus. Only Mo shows increased background value, which corresponds to the boron-molybdenum geochemical specialization of the Caspian region. The average value of Sr is close to the clark, because this element is highly migratory and accumulates in soils under chloride-sulfate halogenesis.

The middle evolutionary group (T-II) includes different soils of the marsh-lagoon zone that were transformed variably by superimposed processes during the last transgression and the subsequent stabilization of the sea.

3.1 The Transgression Phase

The rise of the Caspian Sea level, started in 1978, has led to flooding and waterlogging of the coastal zone, which determined significant changes of the geochemical conditions and chemical composition of the modern soils and sediments.

The *Arenosols*(1) formed at the surface of 1929-1940 of the present terrace (cores T3, T4, T7) (Figure 4) are characterized by predominantly oxic alkaline environment in topsoil, and reduced alkaline conditions in the lower horizons (Table 2).

Table 2. Changes of geochemical properties in soils and sediments of salt marshes upon the fluctuation of the Caspian Sea level

Soils	Phase	Eh, mV	pH	TdS,mg/l
1	<i>transgression</i> (23) <i>Note 1</i>	+150...+200	8.2-8.6	20-100
	<i>stabilization</i> (30) <i>Note 2</i>	+150...+200	8.1-8.6	20-100
2	<i>transgression</i> (32)	-159...+150	8.4-9.2	100-1000
	<i>stabilization</i> (59)	-80...+120	8.3-8.7	200-5800
3	<i>transgression</i> (22)	-150...+100	8.1-8.5	500-2500
	<i>stabilization</i> (30)	-130...+150	6.1-7.4	1200-7100
4	<i>transgression</i> (14)	-50...-380	7.5-8.3	2000-6000
	<i>stabilization</i> (19)	-150...-300	6.1-7.3	3000-6000

Soils: 1- Arenosols, 2- Salic-Gleysols (Alcalic, Arenic) and Salic-Stagnic-Gleysols (Thionic, Arenic), 3- Salic-Tidalic-Gleysols (Thionic, Siltic), 4- Subaquatic Fluvisols.

They are confined to the most elevated positions within hydromorphic landscapes. The average content of trace elements in these soils is the same as in the New-Caspian sediments (Table 3). Thus, the chemical composition of these soils has not changed during the transgression.

Table 3. The concentrations of chemical elements in soils and sediments of salt marshes (Turali site), mg/kg

Soils	Phase	Forms	Fe	Mn	Ni	Co	Cu	Zn	Pb	Cr
1	<i>transgression (23)</i>	bulk	9500	152	4	1,7	2,5	15	5,8	2,5
		mobile	1500	101	0.4	0.4	0.8	4.1	2.4	0.05
	<i>stabilization (30)</i>	bulk	8700	144	3.7	1.5	2.4	13.5	6.3	2.3
		mobile	1850	121	0.6	0.5	0.7	2.9	1.8	0.05
2	<i>transgression (32)</i>	bulk	9300	163	3.8	2.0	2.0	14.8	4.1	2.8
		mobile	1200	109	0.5	0.6	1.0	5.6	2.6	0.14
	<i>stabilization (59)</i>	bulk	8900	189	4.3	1.7	2.2	15.2	4.5	2.5
		mobile	1500	118	0.9	0.8	0.7	4.1	2.4	0.09
3	<i>transgression (22)</i>	bulk	6500	227	3.9	2.2	1.9	15.6	4	3.7
		mobile	4200	131	0.7	0.9	1.2	7.3	3.2	0.15
	<i>stabilization (30)</i>	bulk	7600	248	6.2	2.4	2.5	17.1	5.7	4.4
		mobile	3100	161	1.4	1.5	1.8	9.2	2.7	0.12
4	<i>transgression (14)</i>	bulk	5950	136	3.2	2.2	3.0	13	3.5	8.8
		mobile	5400	102	2.6	1.2	2.9	12.1	3.2	0.9
	<i>stabilization (19)</i>	bulk	5200	176	6.5	2.6	3.3	14.2	4.5	6.6
		mobile	4400	110	1.6	1.6	2.7	13.0	3.0	0.11

The *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)* (2) developed in more hydromorphic positions with rather close groundwater table (40-70 cm). They show higher salinity (TDS values up to 1000 mg/l), alternating redox regime, and higher alkalinity. The bulk content of the trace elements is up to 3 times higher than in the New-Caspian sediments. The Fe and trace elements accumulate in topsoil while the concentrations in the lower horizons fall down. The maximum content of the trace elements in topsoil is usually 2-3 times higher than in subsoil.

The *Salic-Tidalic Gleysols (Thionic, Siltic)* (3) are widespread in the marsh zone (T11, T12, T13, T15) which occupies a large part of the 1941-1956 surface within the present terrace. They are characterized by a rather high salt content, predominantly reducing environment, and lower pH values. The marsh soils form within micro-depressions adjacent to the lagoon. The depth of groundwater varies from 0 to 40 cm. The main feature of these soils is the horizon enriched with hydrotroilite (G_{FeS}). The bulk Fe content in the marsh zone falls to 6500 mg/kg, but the content of its migratory forms generally increases to 3200-5200 mg/kg. The maximum values of Fe in the marsh topsoil do not exceed 8075 mg/kg. The bulk amount of trace elements in these soils is similar to the other soils of the present terrace, but the content of the mobile forms increases; compared with the New-Caspian sediments, the coefficient of accumulation (Note 3) is as follows: $Ni_{2.3} Co_{2.0} Zn_{1.6} Mn_{1.5} Pb_{1.2}$.

The *Subaquatic Fluvisols* (4) show the highest salt content, mostly reducing environment and slightly alkali reaction. The mean bulk amount of Fe in such soils is rather low, however, the content of mobile Fe reaches its maximum. The bulk values of Mn, Ni, Zn, and Pb are lower in the lagoon sediments than in the soils, but higher for Cu, Cr, and Cd. The concentrations of the mobile forms of the trace elements increase dramatically in the lagoon sediments. The sulfide horizons are enriched with $Ni_{9.3} Zn_{3.5} Mn_{3.2} Co_{1.8} Cu_{1.7} Pb_{1.5}$.

3.2 The Phase of the Sea Level Stabilization

After the stabilization of the sea level, the movement of the bar-lagoon system has stopped and the lagoon has shoaled. The depth of the groundwater table has decreased in the marsh zone. That led to the transformation of the geochemical parameters and the trace elements content in the soils of the salt marshes.

The geochemical properties of the *Arenosols* (1) have practically not changed (Table 4).

Table 4. The coefficient of changes (Note 4) of chemical elements' contents in soils and sediments of salt marshes (Note 5)

Soils	Coefficient of changes	Fe	Mn	Ni	Co	Cu	Zn	Pb	Cr
1	bulk	0.9	0.95	0.93	0.88	0.96	0.9	1.1	0.92
	mobile	1.23	1.2	1.5	1.25	0.88	0.7	0.75	1.0
2	bulk	0.96	1.16	1.13	0.85	1.1	1.03	1.1	0.89
	mobile	1.25	1.08	1.8	1.33	0.7	0.73	0.92	0.64
3	bulk	1.17	1.1	1.6	1.09	1.32	1.1	1.4	1.19
	mobile	0.74	1.23	2.0	1.67	1.5	1.26	0.84	0.8
4	bulk	0.87	1.29	2.03	1.18	1.1	1.09	1.29	0.75
	mobile	0.81	1.08	0.62	1.33	0.93	1.07	0.94	0.12

The line of changes for the bulk values of elements during the stabilization phase is: Pb 1.1>Cu 0.96 >Mn 0.95 >Ni 0.93 >Cr 0.92 >Fe, Zn 0.9 >Co 0.88. The line of changes for the mobile forms looks different: Ni 1.5 >Co 1.25 >Fe 1.23 >Mn 1.2 >Cr 1.0 >Cu 0.88 >Pb 0.75 >Zn 0.7. The concentrations of bulk Pb and the mobile forms of Ni, Co, Fe, and Mn have increased slightly at the stabilization phase. Nevertheless, these distinctions are not essential because the measurement accuracy for the bulk and mobile values is 10 % and 5%, respectively.

During the period of the sea level stabilization, the salinity of the *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)* (2) increased: in a depression within the 1930s surface (T5, T6), the TDS value rose up to 5800 mg/l; in other cases it varied from 200 to 850 mg/l. These soils are still characterized by alternating oxidizing-reducing regime and pH of about 8.5. At the stabilization phase, the bulk value of Fe slightly decreased, since the content of the mobile forms increased. The concentrations of the trace elements changed as well. For the bulk values of the chemical elements, the line of changes is: Mn 1.16 >Ni 1.13 >Cu, Pb 1.1>Zn 1.03 >Fe 0.96 >Cr 0.89 >Co 0.85; for the mobile forms: Ni 1.8 >Co 1.33 >Fe 1.25 >Mn 1.08 >Pb 0.92 >Zn 0.73 >Cu 0.7 >Cr 0.64.

The geochemical properties of the *Salic-Tidalic Gleysols (Thionic, Siltic)* (3) have changed more than in the other kinds of soils. The salinity of the upper horizons has increased. The high salt content was also found in the lower horizons – 1.2-3.5 g/l. This kind of soils is characterized by the predominantly reducing environments. The pH values decreased during the stabilization phase. The bulk Fe content increased, but the content of mobile Fe decreased. The maximum of Fe in the upper horizons reached 15000 mg/kg. The concentrations of trace elements increased also, especially in the upper horizons of the salt marsh soils. The coefficients of changes for the bulk contents of elements in *Salic-Tidalic Gleysols* are: Ni 1.6 >Pb 1.40 >Cu 1.32 >Cr 1.19 >Fe 1.17 >Mn, Zn 1.1 >Co 1.09. So, the concentrations of the bulk forms of the elements increase at the stabilization phase. The line for the mobile forms is: Ni 2 >Co 1.67 >Cu 1.5 >Zn 1.26 >Mn 1.23 >Pb 0.84 >Cr 0.8 >Fe 0.74.

The salinity of the reduced *Subaquatic Fluvisols* (4) has not changed; pH has decreased. The bulk content of Ni, Mn, Pb, Co, Cu, and Zn has increased compared to the transgression phase: Ni 2.03 >Mn 1.29 >Pb 1.29 >Co 1.18 >Cu 1.1 >Zn 1.09 >Fe 0.87 >Cr 0.75. The concentrations of the mobile forms of Pb, Cu, Fe, Ni, and Cr have become lower: Co 1.33 >Mn 1.08 >Zn 1.07 >Pb 0.94 >Cu 0.93 >Fe 0.81 >Ni 0.62 >Cr 0.12.

Thus, only the content of Mn has increased in all soils. The bulk values of Pb, Ni, Zn have increased during the stabilization phase in the *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)* (2), the *Salic-Tidalic Gleysols (Thionic, Siltic)* (3), and the *Subaquatic Fluvisols* (4). The concentrations of Fe and Cr have decreased in all soils, except for the *Salic-Tidalic Gleysols (Thionic, Siltic)* (3).

The concentrations of the mobile forms have become higher for Co and lower for Cr and Pb, in all soils during the stabilization phase. The concentrations of Ni and Fe have increased in the *Arenosols* (1), the *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)* (2) and decreased in the *Subaquatic Fluvisols* (4). The concentrations of Zn and Cu change in the opposite order – decreased in the *Arenosols* (1), the *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)* (2) and increased in the *Subaquatic Fluvisols* (4).

4. Discussion

The geochemical conditions in the salt marshes depend on the trend of the sea level fluctuations. The regression stages are associated with weak variability of the geochemical environment in the coastal soils and sediments. They are mainly characterized by alkaline oxidizing conditions. Geochemical diversity of the coastal zone landscapes is much higher during the transgression phase. The conditions vary from neutral to highly alkaline and from oxidizing to highly reducing. After the sea level stabilized, geochemical diversity changed – the salinity of the *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)* and the *Salic-Tidalic Gleysols (Thionic, Siltic)* in marsh zone increased; the conditions in the *Salic-Tidalic Gleysols* became subacidic. Such changes of the geochemical parameters caused redistribution of the chemical elements.

The metal concentrations in the salt marsh sediments depend on a number of factors. These factors include parent material composition, particle size, organic loading, and sediment type, which are intrinsically linked to marsh morphology, estuarine circulation, frequency of flooding, type and extent of vegetation cover, suspended solid loads of incoming waters, and physical and chemical conditions in estuarine waters and marsh itself (Williams et al., 1994). Textural and geochemical characteristics influence the ability of marsh sediments to accumulate heavy metals. Early diagenesis has an important control on chemical element distribution in coastal zone (Zwolsman et al., 1993).

In our study, we use the concept of landscape-geochemical processes (Glazovskaya, 1988) and geochemical barriers (Perelman, 1975) for the explanation of the trace elements distribution in the soils and sediments of the Caspian salt marshes. Landscape-geochemical processes are the set of biogeochemical and physical-chemical processes that cause transport and accumulation of chemical elements. The development of different landscape-geochemical processes in soils leads to the formation of geochemical barriers. The geochemical barriers are places in soils or in the earth crust where a sharp decline in the rate of migration of chemical elements occurs over a short distance, so that they become concentrated (Perelman, 1975).

The development of biogenic and hydromorphic landscape-geochemical processes characterizes different phases of the Caspian sea level fluctuations. The main landscape-geochemical process of regression phase is the accumulation and leaching of soluble salts (halogenesis).

The Caspian Sea level rise caused the development of hydromorphic landscape-geochemical processes in the soils influenced by the sea water. The geochemical transformation of the coastal soils is related to a complex combination of landscape-geochemical processes, such as sulfidogenesis, gleyzation, iron accumulation (ferrugination), accumulation of humus and peat, halogenesis, and changes in redox conditions (Kasimov et al., 2000). These processes are accompanied by concentration of many trace elements, which is especially distinct against the low background content of these elements (except for Mo and Sr) in the sandy beach sediments.

4.1 Redox Changes

The transgression of the Caspian Sea caused flooding and waterlogging of the coastal zone which determined the development of anaerobic environment in the soils and sediments due to restricted atmospheric oxygen diffusion. Organic matter in the hydromorphic soils underwent biogenic decomposition in conditions of brackish groundwater, so sulfate reduction became the dominant reducing process. Black and dark-grey sulfide horizons were often found in the marsh soils of the coastal zone.

The process of sulfidization has characteristic features in different parts of the coastal marsh area. During the transgression stage, the process was the mostly pronounced in the bottom sediments of the newly-formed lagoon. The *Salic-Tidalic Gleysols (Thionic, Siltic)* in the area adjacent to lagoon underwent regular drying because of small-scale sea level oscillations during the transgression. The exposure of reduced sediment layers to oxygen decomposed metal sulfides to oxidized sulfate forms releasing associated counter ions and sulfuric acid to interstitial waters. This resulted in the pH values decrease from 7.0-7.6 to 6.1-7.3 and the Eh values increase from -120-0 to -90+30 mV during the 1995–2003 period.

Sulfidization is among the leading factors governing the distribution of a number of trace elements. Compared to the beach deposits, the sulfide horizons accumulate associations of elements, primarily Fe, which dictates the behavior of minor elements. On the hydrogen sulfide geochemical barrier, the accumulation of Co_{10-12} , Zn_4 , $\text{Cu}_{2-2.5}$, $\text{Ni}_{2-2.5}$, $\text{Cr}_{2-2.5}$, $\text{Pb}_{1.5-2}$ takes place in the marsh soils (Figure 5) and the bottom sediments of the lagoon compared to the soils of the beach ridges.

The trace metal maxima are observed in the sulfide horizons (below 5 cm), which is caused by precipitation of metal sulfides (Williams et al., 1994). A number of trace metals including Cu, Pb, Zn, Ni, and Co commonly co-precipitate with sulfides below the redoxcline and, therefore, show enrichment at some depth. During the

Caspian Sea level stabilization period, the concentrations of these trace elements are also high in the sulfide horizons. However, in the *Salic-Tidalic Gleysols (Thionic, Siltic)*, the capacity of the sulfide horizons decreased at the depth below 10-15 cm.

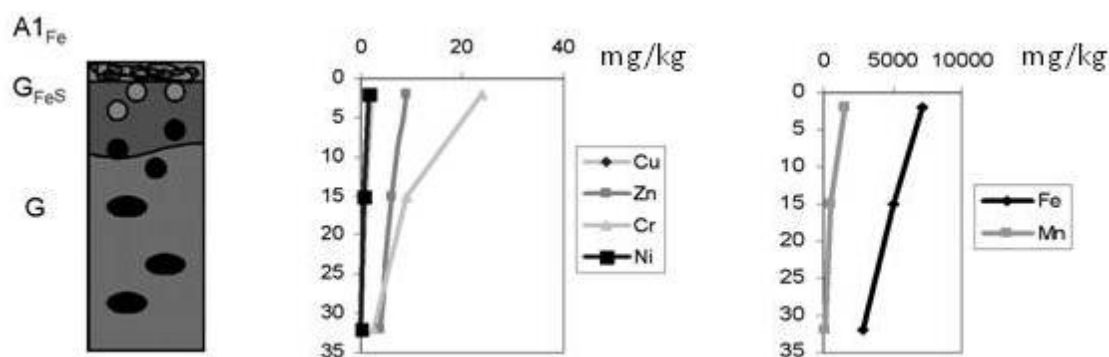


Figure 5. The distribution of the mobile forms of chemical elements in the Salic-Tidalic Gleysols (Thionic, Siltic) (sulfide geochemical barrier)

A1_{Fe}- humus ferruginous horizon; G_{FeS} – sulfide horizon (sulfide geochemical barrier); G – reduced gley horizon

Gleyzation includes the reducing processes in the absence of hydrogen sulfide which form sediments and soils of bluish-grey, green, blue, and ochric-bluish colors. Gleyzation is usually accompanied by the intensive migration of Fe due to its transfer from a less mobile form of Fe³⁺ to a more mobile Fe²⁺. In such environment, Eh decreases from +200 to –100 mV. In marsh soils, the gleyic horizons lay under the sulfide horizons at 10-15 cm below the surface. In the upper 0-10 cm, there is enough organic matter for the sulfides formation. The pH values of the gleyic horizons were higher (7.8-8.6) during the transgression phase than after the sea level stabilization (7.3-7.5) because of acidification of the *Salic-Tidalic Gleysols (Thionic, Siltic)*. In the *Salic-Stagnic Gleysols (Thionic, Arenic)*, the gleyic horizons lie over the sulfide horizons and they are less subject to the influence of sulfate waters. In the transgression period, they appeared 20-30 cm below the surface. The sea level stabilization stopped the fluctuations of the groundwater table and, today, the gleyic horizons lie 40-50 cm below the surface. The process of gleyzation has a much smaller effect on the behavior of the trace elements than the associated processes of sulfidization and ferrugination. Therefore, it is rather difficult to describe the specific features of the trace elements behavior due to gleyzation.

4.2 Ferrugination

The lowest bulk Fe content was found in the sediments of the present beach. About 90% of the total Fe was presented by the mobile forms (Figure 6).

This is the result of a light texture and a high degree of washing of the sediments, while its high migration is due to the gleyzation process. As the distance from the beach grows, the total Fe content shows a sharp increase; the highest values are typical for the soils of the New-Caspian terrace. The concentration of the mobile Fe reaches its maximum in the lagoon bottom sediments because, in the anaerobic conditions, Fe exists in mobile form. With a growing distance from the lagoon, the share of the mobile forms of Fe decreases; within the New-Caspian terrace, they account for about 10% of the total.

During the transgression period, the content of Fe in the *Salic-Tidalic Gleysols (Thionic, Siltic)* near the lagoon showed minor profile differences because of the high groundwater table and reducing conditions. With increasing distance from the lagoon and lowering of the groundwater table, Fe was re-distributed: it accumulated in the upper horizons while the concentrations in the lower horizons fell down. The process was accompanied by a sharp decrease of the mobile Fe in the upper horizons due to its transfer from the mobile to the crystallized forms. Crystallization of Fe under arid conditions and lesser influence of groundwater go on rather rapidly; the process is of a reversible nature (Zonn, 1982).

The diagenetic enhancement of Fe and Mn in the surface sediments of lakes (Farmer & Lovell, 1984), estuaries (Valette-Silver, 1993; Zwolsman et al., 1993) and marine basins (Shaw et al., 1990) is well studied. With burial, microbial decomposition of organic material takes place resulting in the bacterial utilization of O₂ and other electron acceptors such as NO₃⁻, MnO₂, Fe(OH)₃ and SO₄²⁻ (Buckley, Smith, & Winters, 1995). The reduction

of Fe^{3+} and Mn^{4+} forms results in mobilization of these metals and diffusion to oxic surface sediments where they are re-precipitated either as oxides or, occasionally, as carbonates (Farmer & Lovell, 1984).

After the sea level stabilization, the Fe content in the soils of the marsh zone has changed. The total amount of Fe is relatively higher in the upper horizons compared to the lower ones. The content of the mobile forms has decreased. This is the result of a lesser influence of groundwater and the drainage of the marsh zone. Thus, in the *Salic-Tidalic Gleysols* (*Thionic, Siltic*) under the alternating oxidizing-reducing conditions, Fe sulfides transform to oxide forms. This process goes on rather actively. Fe is accumulated on the oxygen barrier. Slight ferrugination occurs in the *Salic-Stagnic Gleysols* (*Thionic, Arenic*). The soils of ridges (the *Salic Gleysols* (*Alcalic, Arenic*)) are usually free of ferrugination. The signs of ancient oxide ferrugination, probably of a similar lagoon-marsh genesis, are preserved as ferruginous layers within the New-Caspian sediments (Figure 7).

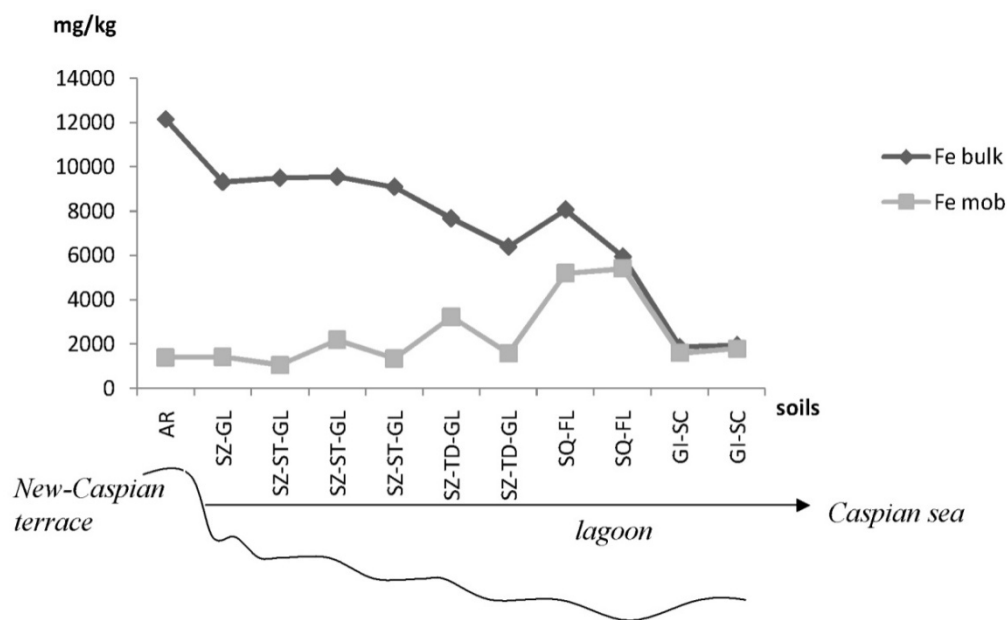


Figure 6. The distribution of the bulk and mobile forms of Fe in the soils of the Caspian salt marshes

AR- Arenosols, SZ-GL- Salic-Gleysols (Alcalic, Arenic), SZ-ST-GL- Salic-Stagnic-Gleysols (Thionic, Arenic), SZ-TD-GL- Salic-Tidalic-Gleysols (Thionic, Siltic), SQ-FL-Subaquatic Fluvisols, GI-SC- Gleic-Solonchaks (Chloridic, Arenic)

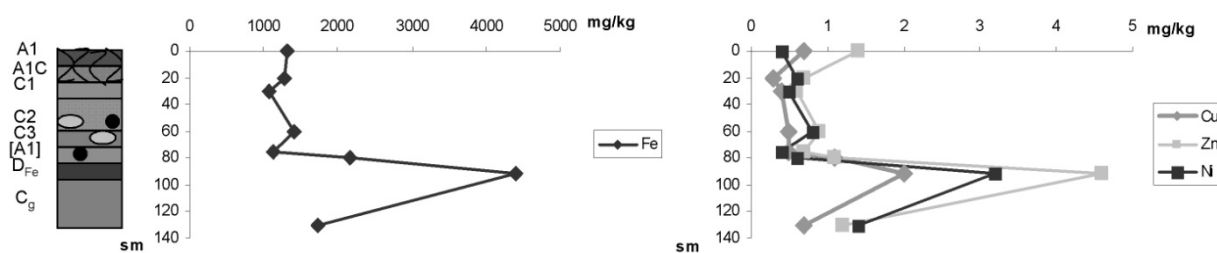


Figure 7. The accumulation of Fe, Cu, Zn, Ni in the ferruginous horizon of the New-Caspian sediments

A1 – humus horizon, A1C, C1-C3 – horizons, [A1] – buried humus horizon, D_{Fe} – ferruginous horizon, C_g – horizon

As shown in Figure 7 the Fe content in the ferruginous horizon is 4 to 7 times higher than in containing sediments, i.e. the intensity of this accumulation may be related to the process of recent ferrugination. Free metal ions may subsequently be co-precipitated and adsorbed to Fe and Mn oxides and hydroxides in aerobic zones

(Williams et al., 1994). Changes of Eh values control the distribution of trace elements.

In sediments, the transition between the aerobic and anaerobic zones is called the redoxcline or redox discontinuity and is identified by a visual change in color from red-brown oxidized surface deposits to dark grey-black of reduced sediment zones (Williams et al., 1994). This color change is synonymous with the presence of ferric oxide precipitates in surface layers and precipitation of insoluble FeS₂ (pyrite) at depth (Lyle, 1983). Consequently, the position of the redoxcline shifts from surface layers under saturated soil conditions to deeper sediment layers following soil water drainage. Salt marshes which are flooded frequently have a dynamic water table, leading to short-term fluctuations of the redox boundary. During the transgression of the Caspian Sea, the redoxcline in the marsh soils lay below 5-10 cm. After the sea level stabilization and partial drainage of the territory, it dropped to below 15-20 cm.

Cycling of Fe and Mn may partly control the vertical profile distribution of Cu, Pb, and Zn, with the maxima occurring in the zone of Fe and Mn enrichment (Cundy et al., 2005; Zwolsman et al., 1993). In the upper oxic horizons of the *Salic-Tidalic Gleysols (Thionic, Siltic)*, the total Cu, Pb, and Zn show enrichment. This suggests that there has been significant re-mobilization of these metals associated with the diagenetic cycling of Fe and Mn. The subsurface maxima of Co, Cd, Cu, Ni, Cr, Pb, and Zn are located in the zone of diagenetic Fe and Mn enrichment, which may indicate re-adsorption by Mn and Fe oxyhydroxides (Tessier, Rapin, & Carignan, 1985). Compared to the containing sediments, the ferruginous horizon accumulates the following elements: Fe (the coefficient of the concentration is 4.6), Co (8.0), Cu (3.1), Mn (3.0), Ni (2.7), Zn (1.6), Cr (1.6), Pb (1.3). In the anoxic sediments, Fe and Mn oxyhydroxide phases are reduced leading to the release of the trace elements that were co-precipitated or adsorbed by them (Blasco, Saenz & Gomez-Parra, 2000). That leads to the trace element mobility in the coastal zone.

4.3 Organic Matter Accumulation

The process is closely related to the type of vegetation. The vegetation of the Caspian salt marshes is a successional system that worked out well in the process of evolution and adapted to the variable regime of the Caspian Sea level. The coastal succession series is presented by the following stages: A – shoal stage with the dominance of *Juncus species*, *Phragmites australis*; from the water edge – B – halophylous stage with the dominance of *Salicornia europea*, *Limonium gmelini*, *Puccinellia dolicholepis*; C – meadow stage with the dominance of *Cynodon dactylon*, *Elytrigia repens*; D – subzonal (pre-climatic) stage with the dominance of *Artemisia scoparia*, *Astragalus hircanicus*.

During the transgression phase, the plant associations change in the reverse order but excluding halophytic vegetation. Instead of halophytic vegetation, the coastal associations were replaced by meadow-solonchak vegetation. The development of hydromorphic vegetation leads to humus accumulation in the upper layers of soils.

According to specific features of humus accumulation in soils, two landscape situations can be identified. The first one includes the soils of higher surfaces where humus accumulates under sparse grass-herbal semi-desert vegetation. In 1995-1996, the humus content here was 0.3-0.5% increasing slightly to 0.7-1.3% in more hydromorphic soils. The process of slow humus accumulation continues at the phase of the sea level stabilization. In 2001-2003, the humus content increased to 0.6% in these soils and even to 2.9% in more hydromorphic soils of the depressions. Another landscape situation occurs within the marsh zone covered by abundant vegetation. The *Salic-Stagnic Gleysols (Thionic, Arenic)* and the *Salic-Tidalic Gleysols (Thionic, Siltic)* here show much more active humus accumulation. In 1995-1996, the average humus content in these soils was 2.4%; in several peaty horizons it grew to 9.0 %. The development of meadow vegetation in this zone increased the rate of humus accumulation in the soils. As a result in 2001-2003, the content of C_{org.} was 5.5% and 22% in the *Salic-Tidalic Gleysols (Thionic, Siltic)* and in the peaty horizons, respectively.

Humus and peaty horizons of soils create biogeochemical (with biogenic accumulation) and sorption (adsorption by organic colloids) geochemical barriers accumulating a number of chemical elements. In soils of marsh-lagoon zone, Zn, Pb, and Cu have typically biogenic surface maxima; to a lesser extent, this is true for Ni and Cr. According to the correlation with the humus content, the mobile forms of chemical elements form the following sequence, from the most biogenic Zn up to Ni, which is least associated with organic matter of soils (in the values of correlation coefficient): Zn 0.95> Mn, Cu 0.8-0.9> Cd 0.7-0.8> Pb, Fe, Na, Co 0.6-0.7> Ni 0.3 (Kasimov et al., 2000). The content of metals usually reaches its maximum values in the horizons enriched with organic matter. At the stabilization phase, the concentrations of the mobile forms of Fe, Mn, Zn, and Cr increased in the upper layers of the marsh zone. However, for the *Salic-Tidalic Gleysols (Thionic, Siltic)*, it is very hard to assess the leading role of humus accumulation in the distribution of the trace elements, because the upper

horizons of these soils are, at the same time, the biogeochemical and oxygen geochemical barriers.

The organic matter content is usually highly correlated with Pb, Cu, Zn, Ni, and Cd (Cundy et al., 2005; Di Giulio & Scanlon, 1985; Vestergaard, 1979). Metal enrichment normally occurs in organically rich silt-clay fractions which have high cation exchange capacities, large surface areas, and large surface charge, while sandy, organically poor sediments have low ability to retain metal ions. Organic material derived from decaying vegetation and detritus of marine and terrestrial origin may also lead to metal-organic complex formation which promotes pollutant retention within the sediment compartment.

4.4 Mobility of Trace Elements

The concentration of the mobile forms of chemical elements increases in the *Salic-Tidalic Gleysols* (*Thionic, Siltic*) and the bottom sediments of the lagoon. The mobility of trace elements is somewhat higher during the stabilization phase than at the transgression phase. A combination of factors that are unique for salt marsh sediments enhances trace metal mobilization. The principal reason for the mobilization process is the presence of a pronounced oxic sediment layer at the surface preventing precipitation of metals as sulfides. Instead, retention and mobility of the trace metals in the surface sediments are controlled by adsorption onto Fe and Mn oxyhydroxides, oxidation of sulfide and degradation of organic carbon. Moreover, periodic shifts from oxidizing to reducing conditions (during inundation) cause dissolution of the Fe and Mn carrier phases and release of associated trace metals. Metals released by dissolution of Fe and Mn oxides may also participate in reactions below the redoxcline (Zwolsman et al., 1993).

Thus, there are several factors of mobilization: (1) presence of a distinct oxic top layer; (2) acidification in the top layer due to oxidation of Fe sulfides and organic matter; (3) high pore water salinity near the surface due to sediment desiccation; (4) periodic shifts from oxidizing to reducing conditions during inundation; and (5) organic matter degradation (Zwolsman et al., 1993). The mechanisms tend to keep high trace metal concentrations in solution. These features have been recorded in salt marshes all over the world; it follows that trace metal mobilization from salt marsh sediments is a general phenomenon (Allen, Rae, & Zanin, 1990). Therefore, salt marshes are the sources of dissolved trace metals to the water column.

4.5 Assessment of the Vulnerability of Coastal Soils

Based on research in the Caspian region the assessment of the vulnerability of coastal soils to the sea-level fluctuations was made. Such assessment can be used as the methodical basis for zoning of the coastal soils according to their response to extreme weather events in coastal areas. The degree of vulnerability in soil was determined by a number of soil properties: 1) the position in the coastal catena, 2) oxidation-reduction and alkaline-acidic properties, and 3) soil texture.

The position in the catena of coastal soils is divided into four groups. The first group is presented by *Arenosols* on the New-Caspian terrace. These soils are not influenced by the modern sea level fluctuations. The second group includes *Salic-Gleysols* that are slightly affected by sea-level rise. The third group consists of *Salic-Stagnic-Gleysols* and *Salic-Tidalic-Gleysols* of the marsh zone. Flooding and waterlogging of these soils is directly related to sea level changes. The fourth group is *Gleyic-Solonchaks* of the modern beach ridge, experiencing the worst effects of the sea-level fluctuations.

The redox conditions of the coastal soils are divided into a number of oxidizing soils (*Arenosols*) and soil with variable redox conditions (*Salic-Gleysols*, *Salic-Stagnic-Gleysols*, *Salic-Tidalic-Gleysols*, *Gleyic-Solonchaks*). The coastal soils of the Turali site can be divided into three main groups (high, medium and low degree of the vulnerability) according to the sea-level fluctuations (Table 5).

Table 5. Assessment of the soil's vulnerability of Caspian salt marshes

<i>The degree of vulnerability</i>	<i>Coastal soils</i>
High	<i>Salic-Tidalic-Gleysols</i>
Medium	<i>Gleyic-Solonchaks</i>
Low	<i>Arenosols</i> , <i>Salic-Gleysols</i> , <i>Salic-Stagnic-Gleysols</i>

The high degree of the vulnerability of *Salic-Tidalic-Gleysols* are due to the developing of intensive processes of sulfidization and gleyization, as well as acidification and redistribution of Fe and other elements in the upper peaty horizons of these soils as a result of sea-level fluctuations.

The medium degree of the vulnerability is typical for *Gleyic-Solonchaks* of the modern beach ridge. Strong storm surges lead to erosion of these soils. Because of the light texture and low organic matter the geochemical transformation of these soils is not very intensive. The rest coastal soils of the Caspian salt marshes have the low degree of vulnerability. In the present situation of the Caspian Sea level and frequency of occurrence and height of the surge, they are not influenced by the short-term sea-level fluctuations.

5. Conclusions

The long-term research of the coastal zone of the Central Dagestan (Turali site) made it possible to assess the environmental changes due to the complete cycle of the Caspian Sea level changes (regression-transgression-stabilization) (Figure 8).

Sea-level fluctuations	Regression	Trans-gression	Stabi-lization	Regression	Trans-gression	Stabi-lization	Regression	Trans-gression	Stabi-lization	Regression	Trans-gression	Stabi-lization	Regression	Trans-gression	Stabi-lization
Geochemical processes Soils	Salinization, mg/l			Ferrugination, mg/kg			Humus accumulation, %			Sulfidization (G _{FeS}), cm			pH		
New-Caspian sediments	20-40	20-40	20-40	500	500	500	0,1	0,4	0,6				8,5	8,5	8,5
1	20-40	20-100	20-100	500	1500	1850	0,1	0,5	1,5				8,5	8,5	8,5
2	20-40	100-1000	200-5800	500	1200	1500	0,1	0,5	2,9	10	12		8,5	8,8	8,5
3	20-40	1500-2500	1200-7100	500	4200	3100	0,1	2,4	5,5	28	20		8,5	8,3	6,8
4	20-40	2000-6000	3000-6000	500	5400	4400	0,1	9,0	22,0	30	30		8,5	6,9	6,7

Figure 8. Geochemical changes of the Caspian salt marshes under the sea level fluctuations

Soils: 1- Arenosols, 2- Salic-Gleysols (Alcalic, Arenic) and Salic-Stagnic-Gleysols (Thionic, Arenic), 3- Salic-Tidalic-Gleysols (Thionic, Siltic), 4- Subaquatic Fluvisols; numbers – the average values.

The geochemical conditions in the coastal soils were not highly different during the regression phase. The concentrations of chemical elements were low and their spatial distribution was homogeneous. From the beginning of the transgression phase, the variety of geochemical conditions in the coastal soils increased. It affected the mobilization and availability of both major and minor metals. The distribution of trace metals in soils and sediments has been significantly modified by new landscape-geochemical processes leading to the formation of the geochemical barriers in the soils.

The formation and gradual inland movement of the bar-lagoon system has led to additional accumulation of organic matter in the marsh soils; the development of anaerobic processes in the presence of sulfate-rich water resulted in the precipitation of sulfides in the bottom sediments of the lagoon and in the soils of the marsh-lagoon zone. The co-precipitation of Fe and heavy metals together with sulfides and the accumulation of Fe at oxidizing barrier are the main processes of the transgression phase (Kasimov et al., 2000).

After the stabilization of the sea level, the geochemical conditions of the *Salic-Tidalic Gleysols (Thionic, Siltic)* began to change slowly. The shallowing of the lagoon has resulted in a partial oxidation of sulfides in the upper horizons of these soils and the formation of sulfuric acid. This was accompanied by the acidification of the coastal soils and increased the accumulation of Fe in the upper horizons of the soils. During the period of the sea level stabilization, the redoxcline in the *Salic-Tidalic Gleysols (Thionic, Siltic)* dropped below 10-15 cm enhancing mobility of the trace elements in the upper 5-15 cm and metal accumulation at the oxygen geochemical barrier. The development of meadow vegetation in the marsh zone increased the rate of humus accumulation in the coastal soils. As a result, in 2001-2003, the rate of humus accumulation in the peaty horizons was estimated at 1.9 % of C_{org} per year.

A new rise of the sea level may lead to the landward movement of the bar-lagoon system; the width of the lagoon may decrease. It may lead to water-logging of the *Salic Gleysols (Alcalic, Arenic)* and the *Salic-Stagnic Gleysols (Thionic, Arenic)*. It may cause development of anaerobic processes, accumulation of sulfides and humus and concentration of chemical elements. Further stabilization or regression of the sea level may be accompanied by drainage of the marsh zone, oxidation of the sulfides in the upper horizons, acidification of soils, and accumulation of Fe in the soils. Accumulation of Fe oxides and hydroxides and humus can also cause accumulation of other trace elements. However, acidification of soils may enhance the mobility of heavy metals and their removal. The interaction of these two opposite processes should be studied in the future.

The salt marsh environment is a complex system. Even small changes to the surrounding environment can significantly affect the overall cycling of the metal forms. Salt marsh sediments provide a valuable tool for the study of trace metal behavior in different landscape-geochemical processes. Such study can be used in quantitative projections of risks to disastrous natural hazards (floods and droughts, degradation of soils) for different regions.

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Notes

Note 1. Investigations: 1995-1996. (n) – number of samples.

Note 2. Investigations: 2001-2003. (n) – number of samples.

Note 3. The coefficient of accumulation was calculated as a ratio of the average content of the chemical element in soils of the marsh zone to that in the soils of the New-Caspian terrace.

Note 4. The coefficient of changes of chemical elements' contents – content of the chemical element in soils during the phase of stabilization/content of the chemical element in soils during the transgression phase.

Note 5. Coefficient of changes $\leq 0,7$ and coefficient of changes $\geq 1,3$ are shown in bold.