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ORIGINAL ARTICLE

Soil variability of denudation landforms on eluvium and diluvium of Devonian red rocks (Lake Belyo basin, Republic of Khakassia, Russia)

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Lithological heterogeneity and dissected relief are the main factors that determine trends of soil development and diversity of soil cover within cuesta ridges and slopes of the Lake Belyo basin (Republic of Khakassia, Russia). Hyperskeletic Mollic Leptosols on eluvium of bedrock are predominant within the eluvial landscape position of local watersheds and upper parts of slopes. These soils have a shortened profile and an incomplete set of genetic horizons. Leptic Petrocalcic Chernozems (Endosalic) form on eluvial-deluvial rocks in the eluvial-accumulative positions of local depressions whereas Calcic Chernozems (Endosalic) occupy the transeluvial-accumulative positions of gently sloping lower part of the macroslope of the lacustrine basin. Less developed soils (Leptosols) have a reddish color, small thickness of humus horizons with rather high content of organic matter and high alkalinity of the entire profile with a close bedding of dense calciferous rocks. Chernozems differ by the nature of underlain sediments. Slight sulfate-chloride and sulfate salinization of the profile, which does not hinder the development of vegetation, is typical for these soils. Relatively small thickness of humus profile is characteristic for the studied Chernozems. Humus accumulation in the upper part of the profile turns into sharp decrease in the content of organic carbon with the depth. The presence of soils with different degrees of development on corresponding surfaces reflects certain stage of denudation alignment of elevated forms of relief. Leptosols and Chernozems are different parts of single evolutionary series of soils in a context of continuous translational process of physical weathering within the macroslope of the lacustrine basin. Although Leptosols gradually change to Chernozems at the mesolevel of the entire macroslope, there are areas within the aerials of Chernozems where less developed soils form on fine-grained sediments, which complicates the structure of the soil cover of the whole territory.
Keywords: Steppe; red-colored deposits; cuestas; Chernozems; Leptosols

Introduction

Features of soil-forming rocks exert a considerable influence on both direction of soil-forming processes and the stability of soils to various types of anthropogenic activities. The results of numerous studies carried out for areas with dismembered foothill relief in arid and semi-arid conditions showed that lithological heterogeneity has a significant effect on general patterns of the soil cover organization (Kutiel et al., 1998; Läßiger et al., 2008; Karchegani et al., 2012; Mehnatkesh et al., 2013; Amundson et al., 2015; Mahmoodi et al., 2016; Tazikeh et al., 2017; Meng et al., 2018). The role of lithological variability as a basis for use and protection of soils is very important for territories with dissected relief and continental climate, such as steppe intermountain depressions of Khakassia and other regions of the south of Western Siberia.

The steppe zone of Khakassia is characterized by a number of features associated with geological history of the territory. Eluvial-deluvial Devonian red-colored loams confined to marginal zones of lake basins are among the most widespread soil-forming rocks for the Minusinsk depression. Weathering products of these sediments are characterized by a special texture, mineralogical and chemical composition that have significant effect on the development of soils and adjacent landscapes (Tanzybaev, 1993; Lesovaya et al., 2003). Properties of reddish Devonian loams result in lower intensity of humus accumulation in chernozems formed on these deposits in comparison to similar soils on Quaternary sediments (Aparin et al., 2010). In addition, red-colored rocks of Khakassia as a rule contain soluble salts. This fact should also be taken into account when planning measures for treatment and protection of these soils. Geomorphological conditions also play an important role in the formation of soil diversity within the steppe depressions of Khakassia. The cuesta-ridge relief and general tendency to leveling of the territory because of the denudation and weathering of bedrock deposits predetermine diversity and variability of the soils within this area (Tanzybaev, 1993; Kulizhskii et al., 2009; Kulizhskiy & Rodikova, 2009)

The paper is dedicated to studying the soil heterogeneity in a long lithocatena for the area of Lake Belyo depression with wide distribution of Devonian reddish sediments and cuesta-ridge relief.

Materials and methods

Field studies were carried out for the territory of Lake Belyo intermountain depression (Republic of Khakassia, Russia). The basin of Lake Belyo is covered with red-colored clastic rocks of the Oydanovo formation of the Upper Devonian. Soil-forming rocks are gray-colored limestones and marls with the subordinate development of calcareous red-colored siltstones and sandstones (Parnachev & Degermendzhy, 2002). Climate of the research area is sharply continental, with significant fluctuations in annual temperatures, low annual precipitation (less than 250 mm), low thickness of snow cover and strong winds. Different steppe plant formations are predominant within the study area (Makunina, 2010; Zorkina & Zhukova, 2012).

We studied soil variability within a long catena from the top of the cuesta ridge to the beach barrier of Lake Belyo through a hilly-cuestic slope of the southeastern exposure (Figure 1). The surface of the slope is complicated by numerous micro-terraces. The objects of the study were soils developing on weathering products of red Devonian rocks in elevated and transit landscapes positions (Figure 2). The Soil description was carried out according to the Classification and Diagnostics of Soils of Russia (Shishov et al., 2004); the names of soils are also given according WRB. Determination of the color for genetic horizons was carried out using the Munsell scale in a wet and dry state, the pH of the aqueous extract by the potentiometric method, the content of organic carbon by the Tyurin titrimetric method of wet oxidation (Vorobyova, 2006). The content of individual ions of soluble salts was determined in an aqueous extract (1:5) (Vorobyova, 2006): HCO_3- by titration with 0.01 N; H_2SO_4 with methyl orange (CO_3^{2-} ions were not detected in the extracts); Cl^- by argentometric method; SO_4^{2-}, Ca^{2+}, Mg^{2+} with complexometric methods; Na^+, K^+ with flame photometry using the atomic absorption spectrometer NOVAA300 "Analytik Jena" (Germany). The calculation of toxic and non-toxic salts was carried out according to the method described by N.I. Bazilevich and E.I. Pankova (1968).

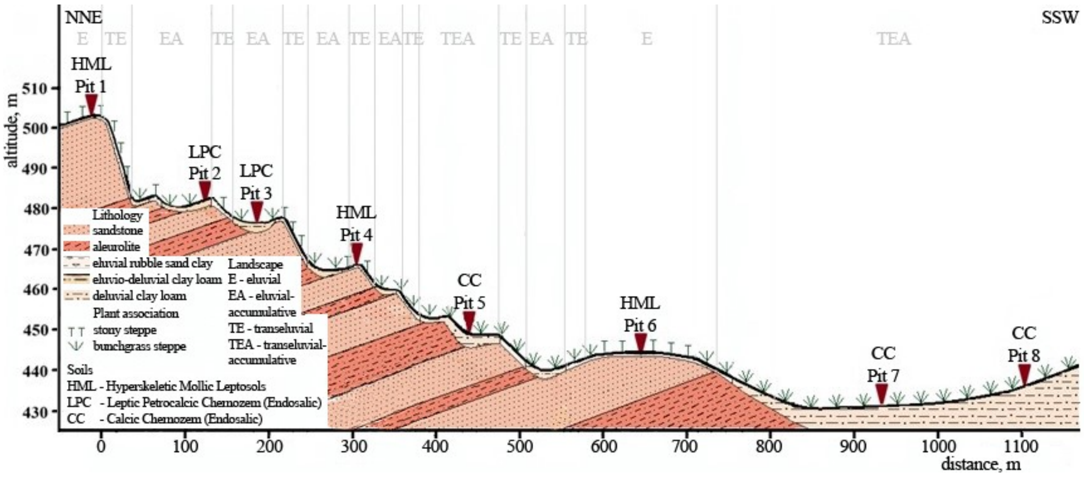

Figure 1. Studied soil catena of Lake Belyo.

Results and discussion

Dark-humus Carbolitozems (Hyperskeletic Mollic Leptosols) develop within autonomous and transeluvial landscape positions under stony steppes with a close bedding of bedrock (Figure 1). The soil forming rocks is charly-gritty loamy eluvium of dense calcareous sandstones (Figure 2). Studied soils have a different set of genetic horizons depending on the intensity of dense rocks weathering and lithological heterogeneity. Generally, they can be characterized as incompletely developed soils. Leptosol of the top of the cuesta ridge (Figure 2a) has a following structure of the profile: AUro [0-10 cm]-ARro [10-20 cm]-Ric, ro [20-70 cm]. Organic horizons form directly on the dense rock in soil that develop below the slope at the top of the elongated terrace (Figure 2d). While the soil at the top of the micro-terrain within the lower slope of the macroslope has the most complicated soil profile AUro [0-8 cm]-AU/Cs, ca, ro [8-20 cm]-Cs, ca, ro [20-35 cm]-R (s), ic, ro [35-40 cm] (Figure 2e).

Figure 2. Soils of the hilly-cuestic slope of the southeastern exposure within Lake Belyo: a-Hyperskeletic Mollic Leptosol (pit 1); b-Leptic Petrocalcic Chernozem (Endosalic) (pit 2); c-Leptic Petrocalcic Chernozem (Endosalic) (pit 3); d-Hyperskeletic Mollic Leptosol (pit 4); e-Calcic Chernozem (Endosalic) (pit 5); f-Hyperskeletic Mollic Leptosol (pit 6); g-Calcic Chernozem (Endosalic) (pit 7); h-Calcic Chernozem (Endosalic) (pit 8).

The reddish color and alkalinity of studied Leptosols is inherited from the soil-forming rocks. Color differentiation of the profile is characteristic only for the most developed soils (Table 1). Pedogenic carbonates are absent; the soil profiles contain a considerable amount of carbonate crushed stone and gruss, while in the least developed soil (pit 4) there are large rock fragments. Pedogenic processes lead to the mineral mass conversion which results in depletion of carbonate rock fragments down the profile (pit 1) and their intensive weathering (pit 6). The soil reaction varies with depth from slightly alkaline to alkaline (Table 1). Formation of the humus profile depends on the degree of mineral mass conversion and, consequently, the depth of root system penetration. According to the thickness of humus horizons (Shishov et al., 2004), studied Leptosols belong to the short type: from 13 cm in the least developed and 20 cm in the most developed. Correspondingly, the content of organic carbon in these horizons also increases: from 2.1 % to 3.9 % (Table 1). The distribution of humus in carbolitozems has a clear accumulative type. Analysis of soluble salts (Table 1) showed that weak chloride salinity associated with lateral transfer of salts or their pulverization from the lake surface is typical only for the Hyperskeletic Mollic Leptosol developed on the top of the terrace in the lower gently sloping part of the macroslope (pit 6). The reason of this is the fact that all investigated soils from this group develop on weathering products of non-saline calcareous rocks. In non-saline Hyperskeletic Mollic Leptosols, nontoxic $Ca(HCO_3)_2$ prevails in upper horizons, while toxic Na_2SO_4, $MgSO_4$ and $MgCl_2$ prevail in the rock. The amount of toxic salts does not exceed the values critical for the development of vegetation. In the slightly saline Hyperskeletic Mollic Leptosol (pit 6), the toxic salts represented by Na_2SO_4 and $MgSO_4$ prevail throughout the profile, their maximum content is observed in the AU/Cs,ca,ro (0.34 %) horizon, which probably has a negative effect on vegetation.

Table 1. The physicochemical characteristics of soils of the hilly-cuestic slope of the southeastern exposure within Lake Belyo.

Horizon	**Depth, cm**	**Munsell soil color**		**pH**	**The content of organic carbon, %**	**The content of individual ions (cmol/kg)**							**Total**
		Dry	**Moist**			**HCO_3^-**	**Cl^-**	**SO_4^{2-}**	**Ca^{2+}**	**Mg^{2+}**	**K^+**	**Na^+**	**salt content, %**
Pit 1. Hyperskeletic Mollic Leptosol													
AUro	0-10	5YR 4/2	5YR 3/1	7.9	3.1	0.6	0.2	0.27	0.5	0.25	0.12	0.19	0.08
ARro	44105	2.5YR 5/2	2.5YR 3/2	8.3	1.2	0.67	0.2	0.09	0.25	0.5	0.04	0.17	0.07
Ric.ro	40-50	2.5YR 5/2	2.5YR 4/2	8.5	0.7	0.61	0.3	0.19	0.5	0.37	0.03	0.2	0.08
Pit 2. Leptic Petrocalcic Chernozem (Endosalic)													
AUro	43497	5YR 4/3	5YR 3/2	7.8	2.3	0.8	0.4	0.27	0.87	0.12	0.19	0.29	0.11
AU/CATro	20-30	5YR 4/3	5YR 3/2	7.9	1.3	0.79	0.3	1.26	0.63	0.75	0.15	0.82	0.17
CATs.ro	40-50	2.5YR 4/3	2.5YR 3/3	8	0.9	0.5	1	12.58	5.87	5.5	0.18	2.54	0.92
	60-70	2.5YR 5/3	2.5YR 3/3	8.8	0.3	0.74	0.75	2.19	0.37	1.12	0.1	2.08	0.25
Pit 3. Leptic Petrocalcic Chernozem (Endosalic)													
AUro	43378	5YR 3/1	5YR 2/1	7.6	5.7	0.38	0.2	0.58	0.87	0	0.14	0.15	0.08
	20-30	5YR 4/2	5YR 3/1	8	2.8	0.78	0	0.79	0.63	0.38	0.13	0.43	0.12
AU/CATro	50-60	5YR 4/2	5YR 3/2	8.4	1.7	0.92	0.95	2.19	1.12	0.37	0.03	2.53	0.28
CATs.ro	60-70	5YR 4/2	5YR 2/2	8.5	1.4	1.03	0.95	2.78	1	0.75	0.03	2.98	0.33
	80-90	2.5YR 5/3	2.5YR 3/3	8.7	0.5	1.03	0.7	2.02	0.63	0.88	0.04	2.21	0.26
CATro	100-110	2.5YR 5/3	2.5YR 3/3	8.9	0.2	0.89	0.5	1.25	0.75	0.37	0.04	1.48	0.19
Pit 4. Hyperskeletic Mollic Leptosol													
AUro	0-13	5YR	5YR	8	2.1	0.61	0.	0.1	0.	0.1	0.	0.	0.07

		4/2	2/2				15	1	5	2	09	17	
Ric.ro	30-40	2.5YR 4/3	2.5YR 2/4	8.3	0.2	0.94	0.2	0.28	0.62	0.37	0.05	0.37	0.11
	40-50	2.5YR 5/2	2.5YR 3/2	8.4	0.1	0.7	0.2	0.3	0.25	0.75	0.02	0.16	0.08
	70-80	2.5YR 4/3	2.5YR 3/2	9	0.1	0.81	0.5	2.06	0.25	0.75	0.03	2.35	0.24
Pit 5. Calcic Chernozem (Endosalic)													
AUro	44105	5YR 3/2	5YR 2/2	7.7	4.1	0.49	0.55	0.01	0.35	0.35	0.18	0.17	0.07
AUnc.ro	22-32	5YR 4/2	5YR 2/2	8.1	4	0.77	0.3	0.23	0.37	0.62	0.05	0.25	0.09
AU/CATs.ms.ro	50-60	5YR 4/2	5YR 3/3	8.2	1.7	0.8	0.7	3.53	1.13	1.88	0.02	2	0.33
CATs.ro	80-90	2.5YR 5/3	2.5YR 3/3	8.4	0.9	0.7	1.1	3.71	0.5	2.13	0.05	2.83	0.36
	110-120	2.5YR 4/3	2.5YR 3/3	8.5	0.9	1.02	0.65	3.78	0.5	2.37	0.07	2.51	0.37
	140-150	5YR 5/4	2.5YR 3/3	8.5	0.8	0.65	0.5	3.09	0.62	1.37	0.07	2.18	0.29
Pit 6. Hyperskeletic Mollic Leptosol													
AUro	0-8	5YR 5/2	5YR 3/2	8.1	3.9	0.88	0.2	0.37	0.25	0.88	0.14	0.19	0.1
AU/Cs.ca.ro	44044	5YR 5/2	2.5YR 3/2	8.2	2.5	0.84	0.35	5.12	1.13	2.38	0.32	2.48	0.43
Cs.ca.ro	25-35	2.5YR 4/3	2.5YR 3/2	8.6	1	0.69	0.45	3.02	0.5	1.13	0.29	2.24	0.29
Pit 7. Calcic Chernozem (Endosalic)													
AUro	0-10	5YR 4/2	5YR 2/2	7.9	5.4	1	0.1	0.21	0.62	0.37	0.12	0.19	0.1
	15-25	5YR 4/2	5YR 2/2	8.2	4.3	1.16	0.15	0.31	0.87	0.5	0.05	0.19	0.12
AU/CATs.ro	40-50	5YR 4/2	5YR 3/2	8.2	2.2	0.87	0.15	0.97	0.37	0.62	0.02	0.97	0.14
CATs.ro	70-80	2.5YR 4/3	2.5YR 3/2	8.2	1.2	0.6	0.2	3.1	0.5	2	0.05	1.36	0.26
	100-110	2.5YR 5/3	2.5YR 3/2	8.4	1.1	0.73	0.1	4.27	0.5	1.87	0.08	2.65	0.35
CATs.ro/Cro	120-130	2.5YR 5/2	10YR 3/3	8.1	1.2	0.49	0.15	11.72	3.62	6.11	0.11	2.52	0.81
	150-160	2.5YR 5/2	2.5YR 3/2	8	1	0.45	0.15	14	2.37	9.23	0.13	2.86	0.93
Pit 8. Calcic Chernozem (Endosalic)													
AUro	0-10	5YR 4/2	5YR 2/3	7.9	5.1	0.88	0.15	0.39	0.75	0.38	0.12	0.17	0.11
	20-25	5YR 4/3	5YR 2/3	8.2	3.8	0.91	0.25	0.87	1.12	0.25	0.06	0.59	0.15
AU/CATs.ro	45-55	5YR 4/3	2.5YR 3/2	8.3	2.1	0.71	0.25	3.36	1.37	0.75	0.05	2.14	0.3
	70-80	2.5YR 4/2	2.5YR 3/2	8.4	2.3	0.75	0.55	3.49	0.75	1.87	0.07	2.11	0.32
CATs.ro	100-110	2.5YR 5/3	2.5YR 4/3	8.4	0.6	0.85	0.35	2.19	1	0.37	0.07	1.94	0.24
CATs.ro/Cro	130-140	2.5YR 4/3	2.5YR 3/2	8.5	0.6	1.09	0.35	2.57	0.75	1.25	0.07	1.94	0.28

Leptic Petrocalcic Chernozems (Endosalic) with a short profile develop within the eluvial-accumulative position of the upper steep part of the catena under the cereal-fescue steppe vegetation on eluvial-deluvial red-colored loams underlain by dense calcareous sandstone (Figure 1). Chernozem (pit 2) representing graded slope of the ridge (Figure 2b) has sufficiently developed profile with a following number of horizons: AUro [2-19 cm] - AU/CATro [19-34 cm] - CATs ro [34-80 cm] - Ric,ro [80-85 cm]. The second chernozem from this group (pit 3) with better-developed profile (Figure 2c) formed below the slope within the concave surface of the microterrace: AUro [2-45 cm] - AU / CATro [45-60 cm] - CATs, ro [60-90 cm] - CATro [90-136 cm] -

Ric, ro [136-140 cm].

Reddish coloring is characteristic for chernozems as well as for carbolitozems. Profiles are well differentiated by color: boundaries between horizons are clearly distinguished by the change in hue as well as the proportion of red tones grows with the depth (Table 1). Dense carbonate rocks lying at a depth of 80 and 130 cm (pit 2 and pit 3 respectively) limit the development of soil profiles. In contrast to Leptosols, lithogenic artefacts are absent in the profiles of Leptic Petrocalcic Chernozems (Endosalic). Chernozem developed on a flat surface (pit 2) react with HCl at the depth 3-5 cm, while in the soil within a microterrace (pit 3) this depth is slightly lower probably due to the increase in moisture content. Pedogenic carbonates in the middle and the bottom parts of soil profiles are spots along the edges of the aggregates and white-eyes nodules. Soil reaction varies from weakly alkaline in the upper part of the profile to alkaline at the boundary with the rock. Occurrence of dense rocks in the bottom of the profile also influences the humus profile. Thickness of the humus horizons varies from 34 (pit 2) to 60 cm in a more developed soil (pit 3). Accumulative type of distribution is characteristic for organic carbon in both chernozems developed on the eluvial-deluvial red-colored loams underlain by dense calcareous sandstone. Thus, its content is two times higher in soil developed down the slope (Table 1). Salt profiles of both chernozems underlain by dense rocks are characterized by a sharp increase in the content of soluble salts in the midline horizons (Table 1), which is mainly due to the leaching of salt-bearing Devonian sediments. The lowering soil (pit 3) is slightly saline. There is no significant accumulation of salts due to the exchange between components of the relief. Strong salinization was observed in the chernozem (pit 2) with the high bedding of the underlying dense rock that limit deep washing of the profile and removal of salts. In the studied soils, magnesium-sodium sulfate type of salinity was determined. The humus horizons of both chernozems underlying by dense rock are not saline, the content of toxic salts is less than 0.1 %, non-toxic Ca(HCO3)2 and $CaSO_4$ prevail. The amount of toxic salts rises towards the underlying rock (Na_2SO_4 and $MgSO_4$ dominate). In general, the presence of dense bedrock significantly affects the content of soluble salts, but not their ratio and distribution (Konstantinova, 2016).

Calcic Chernozems (Endosalic) with most developed and thick profiles develop within the transeluvial-accumulative position of the lower graded part of the slope under the high-core steppe, with a predominance of feather grass on the reddish loams (Figure 1). They are the most widespread soils of the lake basins in steppe zone of Khakassia (Novokreshchennykh & Panova, 2007). Pit 5 is located in lower part of the gentle slope (Figure 2d). The studied chernozem has following horizons: AUro [1-23 cm] - AUnc, ro [23-40 cm] - AU/CATs, ms, ro [40-70 cm] - CATs, ro [70-180 cm]. Two other chernozems (pits 7 and 8) develop on reddish loams within the large depression in the lower part of the slope. These soils have a similar thickness (about 160 cm) and structure of the profile (Figures 2g and 2h): AUro - AU/CATs, ro - CATs, ro - CATs, ro/Cro.

Like the other studied soils, Calcic Chernozems (Endosalic) have a reddish color of the profile. Towards the underline rocks, the reddish hue becomes more pronounced (Table 1). Reaction with HCl is detected either from the surface (pits 7 and 8) or within AUro at a shallow depth (28 cm in pit 5). Pedogenic carbonates are represented by low-contrast spots along the edges of the aggregates (AUro), pseudo-mycelium on the border with the underlying horizon (AU/CATs, ms, ro in pit 5), large white-eyes nodules (CATs, ro). In all studied soils, alkalinity gradually increases with depth (Table 1). The humus profile develops to depths of 70-80 cm. Organic carbon distribution in chernozems developed on reddish loams has an accumulative type. Its content is somewhat higher in humus horizons of soils developed in the foot of the slope (pits 7 and 8), but in general, it is comparable with the values observed in the corresponding horizon of all chernozems (Table 1). Weak salinization is typical for AU/CATs, ms, ro horizons of chernozems from pits 5 and 8. Strong salinity is characteristic for the CATs, ro/Cro horizon of the chernozem developed in the bottom of the depression (pit 7). Biological processes, the intensity of bedrock weathering and the salt impulse from the lake surface are the main factors controlling ions distribution along the profile (Konstantinova, 2016). The chernozems on red-colored loams are characterized mainly by the magnesium-sodium sulphate salinization chemistry (Table 1). Nontoxic $Ca(HCO_3)_2$ predominates in the composition of salts in the upper part of the profile, while Na_2SO_4 (pits 5 and 8) and $MgSO_4$ (pit 7) dominate in the lower part.

All studied soils are characterized by a number of distinctive features associated with the lithological and bioclimatic conditions of their formation. The main factor of soil variability on slopes of the lake basin is the nature of soil-forming rocks. Similar situation is typical for areas with complex geology and dissected relief in semiarid and arid conditions (Hattar et al., 2010; Kulizhskii et al., 2012; Scarciglia et al., 2012; González-Alcaraz et al., 2014; Lybrand & Rasmussen, 2015; Pahlavan-Rad & Akbarimoghaddam, 2018; Regmi & Rasmussen, 2018). A characteristic feature of both chernozems and carbolitozems is the red color of the profile. The source of the red color in studied soils and loose redeposited weathering products is a highly dispersed clay (Evans & Hartemink, 2014; Lucke et al., 2014; Vingiani et al., 2018). The underlying dense rocks limit development of a powerful profile. Bioclimatic conditions play an important role in the formation of the soil humus profile. Long winters with low temperatures, deep-freezing and late thawing of the soil and, therefore, a shortened growing season, lead to the fact that biological processes take place over a rather short period, affecting only topsoil. However, due to the coincidence of the periods with high temperatures and maximum humidification, the microbiological activity is quite high, which leads to an intensive accumulation of organic carbon in the upper part of soil profiles. Soils developing on Devonian reddish rocks are characterized by the presence of easily soluble salts entering the soil due to leaching and weathering of rocks, with subsurface and groundwater flow and pulverization from the surface of lakes and near-shore solonchaks (Novokreshchennykh & Panova, 2007). The general trend of soil evolution from underdeveloped carbolitozems within cuesta ridges to chernozem in the lower gentle parts of the slopes and on the surface of the terraces is disturbed by lithological heterogeneity, which in turn leads to a noticeable complication of the soil cover.

Conclusion

Soil formation within autonomous and transit landscapes positions of the near-lake basins of the steppe zone of Khakassia takes place in a continental arid climate conditions. Intensive deflation of rocks characterized by varying degrees of resistance to weathering leads to the formation of conjugate series of soils from carbolitozems (Leptosols) to various Chernozems. A relatively small thickness of the humus profile is characteristic for the studied soils: accumulation of organic matter in the upper part of the profile is followed by a sharp decrease with the depth. Red color and strong alkalinity of the profiles is inherited from soil-forming rocks. Slight salinization of the profile, mainly of sulphate-chloride and sulphate types, is observed in Chernozems developed on different sediments. The properties of chernozems on eluvial-deluvial red Devonian sediments, underlain by sandstones, are generally similar to the corresponding soils not underlain by dense rocks. The presence of dense rocks in the bottom of the profiles somewhat limits the biological activity, worsens the water-salt regime. The salinity of the red Devonian deposits, as well as the heterogeneity of the soil-forming rocks, the alternation of chernozems and poorly developed Carbolitozems (Leptosols) require careful planning of measures for their protection.

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