Diversity of soils in the karst sinkholes in the Pre-Ural forest-steppe

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Kungur insular forest-steppe is the northern vanguard of forest-steppe landscapes in Europe, and it may be explained by the impact of calcareous rocks and complicated history of regional flora. In the Pleistocene, invasion of Siberian xerophytic pine forests was followed by another invasion in the Mid-Holocene, and these were European feather grass steppes (Buzmakov, Sannikov, 2014). Accordig to De Waale et al. (2009), calcareous rocks are responsible for soil moisture deficit; hence, fir-spruce forests surrounding the Kungur region could not survive there (Kadebskaya, Naumkin, 2012). The area is very famous for its karst phenomena, which most impressive result is the Kungur Cave with its picturesque and bizarre carvings, halls, tunnels, columns. Since 1965, the area was declared as a nature monument. It is under control of State authorities.

Fig. 1. Location

Lithology and topography

The origin and evolution of karst topography within the whole Pre-Ural region is related to the Caspian Sea level – its fluctuations in the Pleistocene and the Holocene, resulting in well-known transgressions and regressions; hence, the age of karst topography is considered to be several thousands years (Gorbunova et al., 1992; Kungur Ice Cave…, 2005). Karstic rocks – Low Permian (Artinskian stage) limestone and dolomite occur directly on the surface: at the depth of 10-15 m they are underlain by gypsum and anhydrite of the Kungurian stage. Thus, parent rocks are represented by stony eluvium of limestone on the main subhorizontal surface and colluvium on the slopes of sinkholes.

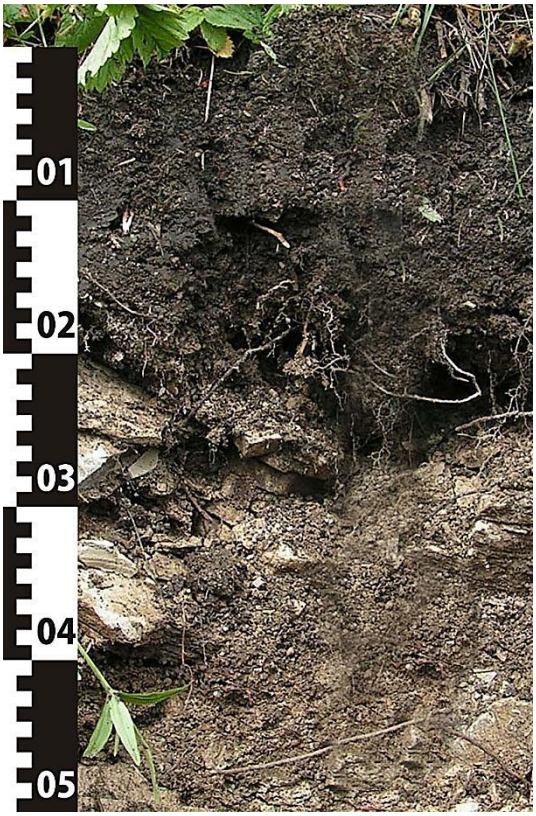
The sinkhole studied has a distinct conical shape, weakly undulating slopes, which are 20 m long and have an average slope gradient of 33º. The depth of the sinkhole is 11 m, diameter – 33 m. There is a ponor in its bottom: it means that the sinkhole is connected with an underground hollow. All these features permit to qualify the sinkhole as a solution doline.

Land use

The sinkhole was located in the territory of protected area «Ice Mount» near the town of Kungur. Natural vegetation is rather modified owing to the proximity of the town; ruderal species are not uncommon. Mesophytic steppe communities alternate with the meadows ones, and the admixture of hygrophytes in sinkholes, sometimes bushes, was recorded.

Profile 1 - Calcaric Rendzic **Leptosol** (Siltic, Humic)

Location: subhorizontal inter-sinkhole main surface (152 m a.s.l.). Steppe with feather grass (*Stipa pennata*), fescue (*Festuca valesiaca*), wormwood species and forbs: *Fragaria vesca, Filipendula vulgaris*, *Trifolium repens, Sanguisorba officinalis*, *Echinops ritro*, etc.
N 57°26'29.2" **E** 57°7'30.9"



Morphology:

Ah – 0–20 cm, *mollic* horizon, silt loam, very dark gray (10YR 3/1), weakly moist, weakly compact, fine angular blocky to crumbly structure, weak effervescence, many fine roots, few fine fragments of calcareous rocks, abrupt boundary;

R – 20–(47) cm, hard weakly weathered limestone (85%), light gray (10YR 7/1) with light yellowish brown (10 YR 6/4) fine earth (15%).

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–20	13	3	17	17	7	5	16	18	14	3	SiL

Table 2. Chemical and physicochemical properties

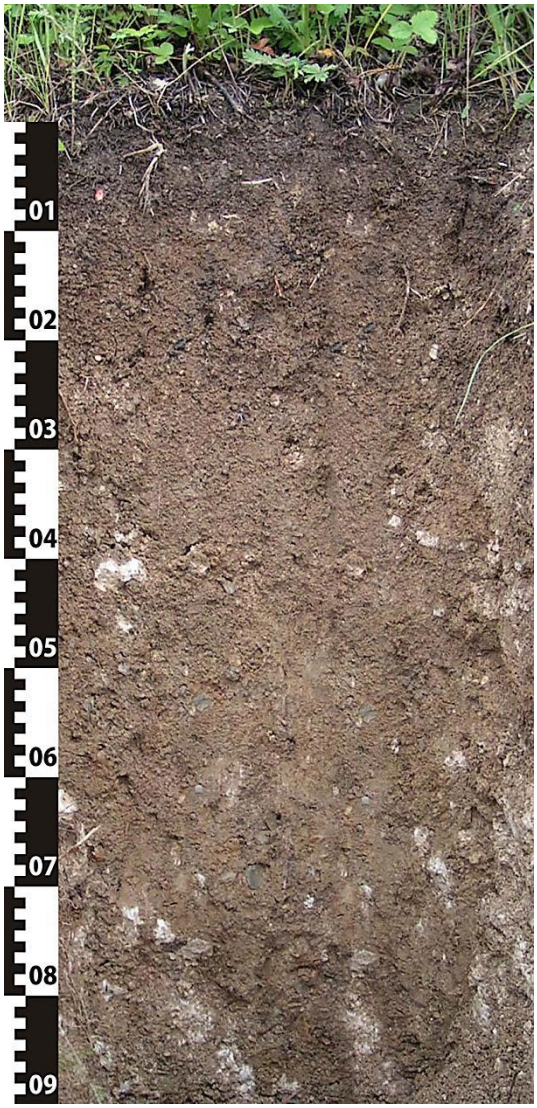
Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH H_2O	$CaCO_3$ [$g \cdot kg^{-1}$]
Ah	0–20	32	4.1	7.9	7.3	11

Table 3. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
Ah	0–20	50.51	10.42	8.21	19.65	8.03	0.18	0.65	1.80	0.27

Profile 2 - Calcaric Cambic **Phaeozem** (Siltic, Colluvic, Protocalcic)

Location: upper part of the sinkhole slope (3 m from the edge and 17 m down to the bottom; 151 m a.s.l.), inclination 33°. Grass-forb community dominated by wild strawberry (*Fragaria vesca*), feather grass (*Stipa pennata*), (*Poa pratensis L.*) and dropwort (*Filipendula vulgaris*).
N 57°26'29.2" **E** 57°7'30.9"



Morphology:

Ah – 0–9 cm, humus horizon, silt loam, dark grayish brown (10YR 3/2), weakly moist, friable, fine crumbly to subangular blocky structure, weak effervescence starting at 6 cm, densely pierced by fine roots, very few fine fragments of calcareous rocks, clear transition and wavy boundary;

Ahk – 9–25 cm, silt loam, grayish brown (10YR 3/3) with darker mottles, some of them vertical (earthworm passage ways), weakly moist, fine subangular blocky, visible effervescence, many fine roots, very few fine fragments of calcareous rocks, clear transition and wavy boundary;

ABwk – 25–42 cm, silt loam, light yellowish brown (10YR 5/4), weakly moist, friable, fine subangular blocky, visible effervescence, few fine soft carbonate concretions and pseudomycelium, very few fine roots, few fragments of calcareous rocks (up to 2x3x5 cm in size), gradual transition by the abundance of fragments, diffuse boundary;

BCk – 42–(90) cm, silt loam, light yellowish brown (10YR 5/4), weakly moist, similar to the above horizon but has more limestone fragments, rather firm, weak subangular blocky structure, visible effervescence, no carbonate pedofeatures.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–9	14	4	16	16	7	6	19	19	11	2	SiL
Ahk	9–25	16	3	17	18	8	7	20	16	9	2	SiL
ABwk	25–42	21	5	14	14	5	5	14	19	20	4	SiL
BCk	42–(90)	27	6	15	15	5	5	13	17	19	5	SiL

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH H_2O	$CaCO_3$ [$g \cdot kg^{-1}$]
Ah	0–9	34	6.1	5	7.6	23
Ahk	9–25	12	1.5	8	7.7	39
ABwk	25–42	-	-	-	8.0	86
BCk	42–(90)	-	-	-	7.4	46

Table 6. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
Ah	0–9	47.07	11.85	3.84	21.98	12.53	0.17	0.69	1.69	0.18
Ahk	9–25	40.34	12.15	4.54	26.32	13.82	0.12	0.67	1.65	0.17
ABwk	25–42	38.81	11.15	3.82	30.2	13.6	0.13	0.62	1.52	0.15

Profile 3 - Cambic Someric **Phaeozem** (Siltic, Colluvic, Hyposkeletic) over Cambic Someric **Phaeozem** (Siltic, Colluvic, Hyperhumic, Hyposkeletic) over **Cambisol** (Siltic, Colluvic)

Location: medium part of the sinkhole slope (10 m down from the edge, and 10 m to the bottom; 148 m a.s.l.), slope gradient 33°. Plant community with fern (*Gymnocarpium dryopteris*) and herbs: *Aegopodium podagraria*, *Alchemilla vulgaris, Galium aparine, etc.*
N 57°26'29.2" **E** 57°7'30.9"

Morphology:

Ah – 0–13 cm, *mollic* horizon, silt loam, very dark gray (10YR 2/2), moist, friable to slightly firm, fine crumbly and subangular blocky structure, weak effervescence at 10 cm, common fine roots, few fine fragments of calcareous rocks, clear and smooth boundary;

ABwk – 13–40 cm, transitional horizon, silt loam, dark grayish brown (10YR 3/3), moist, rather firm, subangular blocky (fine and medium blocks), visible effervescence, common fine roots, many fragments of calcareous rocks, clear and smooth boundary;

2Ahkb – 40–53 cm, buried *mollic* horizon, silt loam, black (10YR 2/1), moist, firm, fine crumbly and granular structure, visible effervescence, pierced by fine roots with fine aggregates hanging on them, few fine fragments of calcareous rocks of different weathering degree, clear and smooth boundary;

2ABwkb – 53–72 cm, transitional horizon, silt loam, dark brownish gray (10YR 3/2), moist to weakly wet, firm, fine crumbly, visible effervescence, few fine roots, abundant fragments of calcareous rocks of different weathering degree, clear and smooth boundary;

3Akb – 72–79 cm, buried humus horizon, silt loam, very dark grayish brown (10YR 3/2), moist to weakly wet, firm, weak subangular blocky structure, visible effervescence, few fine roots, abundant fragments of calcareous rocks, clear and smooth boundary;

3Bwb – 79–(110) cm, buried *cambic* horizon, loam, brown (10YR 4/3), moist to weakly wet, firm, weak subangular blocky structure, weak effervescence, few fragments of calcareous rocks in upper 10 cm.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–13	11	4	14	13	7	7	20	19	14	2	SiL
ABwk	13–40	23	3	18	18	5	6	23	15	10	2	SiL
2Akb	40–53	9	3	12	15	7	6	21	18	15	3	SiL
2ABwkb	53–72	26	6	16	17	8	6	25	14	6	2	SiL
3Akb	72–79	20	6	17	16	8	6	17	17	10	3	SiL
3Bwb	79–(110)	6	7	15	17	8	7	21	17	6	2	SiL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH H_2O	$CaCO_3$ [$g \cdot kg^{-1}$]
Ah	0–13	46	3.7	12	7.4	17
ABwk	13–40	19	2.6	7	8.1	41
2Akb	40–53	37	3.4	11	7.5	38
2ABwkb	53–72	-	-	-	8.1	52
3Akb	72–79	-	-	-	7.5	49
3Bwb	79–(110)	-	-	-	7.9	45

Table 9. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
Ah	0–13	50.51	10.42	6.13	17.65	12.21	0.19	0.65	1.80	0.27
ABw	13–40	48.56	11.31	5.83	17.37	14.27	0.19	0.66	1.47	0.18
2Akb	40–53	53.03	10.81	6.92	15.81	10.01	0.33	0.75	1.85	0.21
2ABwkb	53–72	50.30	11.10	6.20	18.10	11.20	0.21	0.71	1.20	0.17
3Akb	72–79	51.20	10.80	5.90	16.30	10.43	0.26	0.69	1.33	0.23
3Bwb	79–(110)	63.77	9.81	4.40	10.61	6.79	0.12	0.49	1.37	0.20

Profile 4 - Cambic **Phaeozem** (Siltic, Colluvic, Pachic)

Location: lower part of the sinkhole slope (17 m from the edge and 3 m to the bottom of the sinkhole; 144 m a.s.l.), slope gradient 33°. Grass-forb community with leguminous plants and predominance of *Aegopodium podagraria*. **N** 57°26'29.2" **E** 57°7'30.9"

Morphology:

Ah1 – 0–35 cm, *mollic* horizon, silt loam, very dark gray (10YR 3/1), moist to weakly wet, friable, fine subangular blocky and crumbly structure, weak effervescence at 20 cm, densely pierced by fine roots, few coarser roots, few fragments of calcareous rocks of different weathering degree, clear and wavy boundary;

Ah2 – 35–60 cm, humus horizon, silt loam, heterogeneous in color: dark gray (10YR 3/1) and dark yellowish brown (10YR 3/4) mottles, moist, rather firm, subangular blocky structure, visible effervescence, few roots of any diameter, few fragments of calcareous rocks of different weathering degree, clear and wavy boundary;

ABwk – 60–(100) cm, colluvial silt loam, heterogeneous in color: dark gray (10YR 3/1) and dark yellowish brown (10YR 3/4) mottles, moist, rather firm, weak subangular blocky structure, visible effervescence, few fragments of calcareous rocks of different weathering degree.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah1	0–35	16	7	18	16	7	7	17	17	9	2	SiL
Ah2	35 – 60	13	6	16	17	6	5	16	18	13	3	SiL
ABwk	60–100	7	8	19	17	7	5	14	16	11	3	SiL

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH H_2O	$CaCO_3$ [$g \cdot kg^{-1}$]
Ah1	0–35	38	3.5	10.9	7.1	12
Ah2	35 – 60	-	-	-	7.3	18
ABwk	60–100	-	-	-	7.7	31

Table 12. Elemental composition

Horizon	Depth [cm]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	TiO_2	K_2O	P_2O_5
		[%]								
Ah1	0–35	53.33	13.08	6.49	14.80	8.52	0.20	0.82	2.28	0.21
Ah2	35 – 60	53.30	12.22	6.84	15.53	7.86	0.15	0.83	2.39	0.20
ABwk	60–100	53.39	13.06	6.98	15.98	6.99	0.14	0.83	2.42	0.18

Climate

The study area is located in the fully humid zone with a long period with snow cover and warm summer (Kottek et al., 2006). Mean annual air temperature equals 1.8ºC, mean temperature of July is +21.6ºC (absolute maximum +37.5ºC), that of January –11.2ºC (absolute minimum –45ºC); the frost-free period lasts 115 days. Mean annual precipitation is equal to 532 mm. The snow cover is preserved during 170 days, and its average depth reaches 60 cm (water reserve in the snow is estimated as 130 mm). Soil is freezing to the depth of 65 cm on average. Strong winds in winter affect the snow cover pattern: sinkholes accumulate snow blown off from the main surface (Kungur Ice Cave…, 2005).

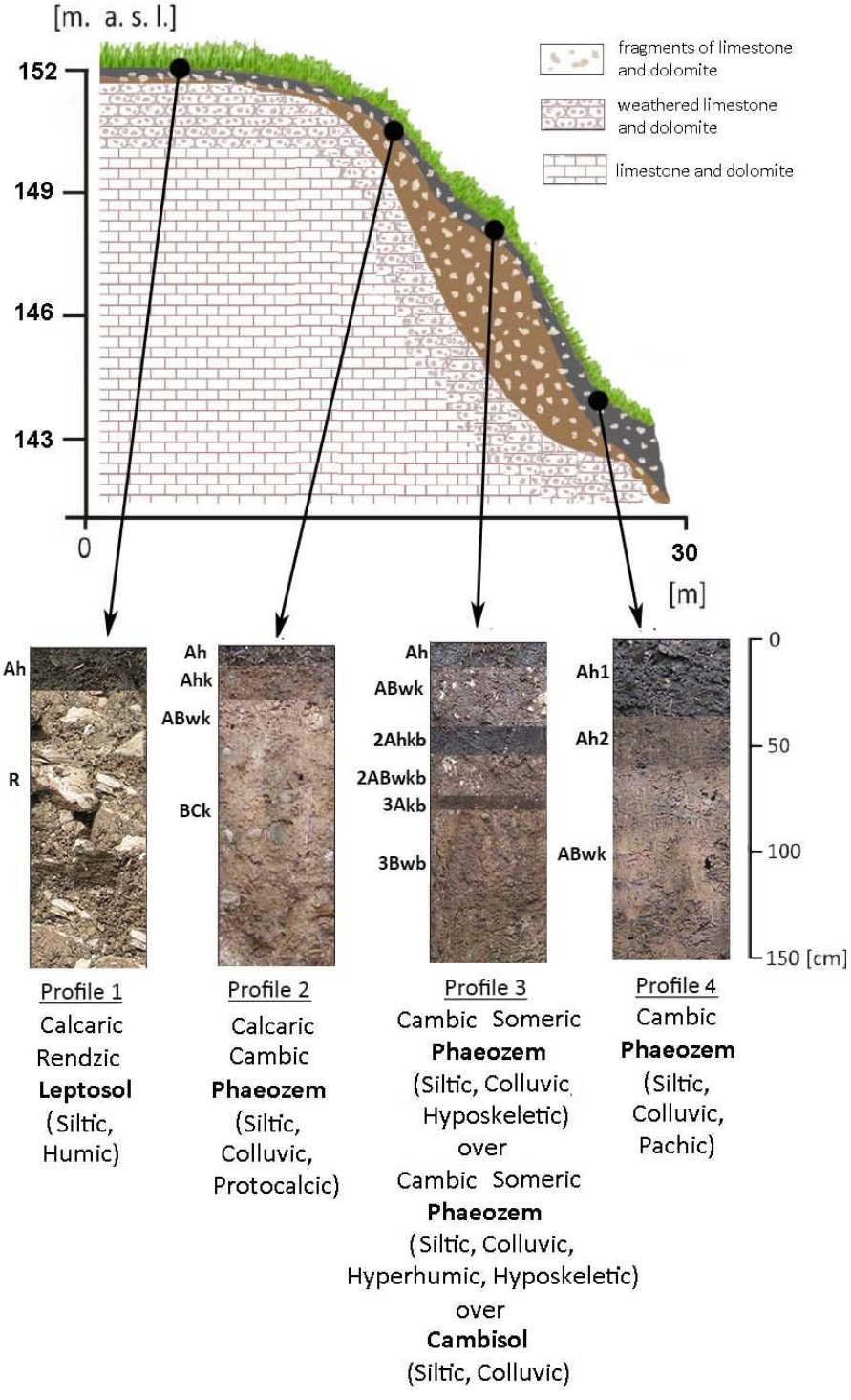


Fig. 2. Toposequence of soils on the slope of karst sinkhole in forest-steppe

Soil genesis and systematic position

Among pedogenic processes that have formed soils in this sinkhole, located in forest-steppe with its **Phaeozems**, **Chernozems** and **Luvisols** (IUSS Working Group WRB, 2015), accumulation of humus is the main process; it is manifested in all soils of the studied sinkhole as a mollic horizon. Slope processes – mass movements within the sinkhole were intensive, so the colluvial material is rather deep, poor in rock fragments and contains well preserved buried soils.

The bulk of soils within the sinkhole – **Phaeozems** – strongly differ of the shallow soil on the main surface on hard calcareous rock: it is rich in humus, has a strong structure, and perfectly fits its definition: ***Rendzic*** **Leptosol** with ***Humic*** and ***Calcaric*** qualifiers.

Soils on the slopes and in the bottom formed on colluvium have deeper profiles, and this may be explained by their parent material on one hand, and by their moisture regime, on the other hand: they receive additional moisture of the melting snow wind-blown down to the sinkhole. The second soil contains limestone fragments and has few elements of cambic horizon (pedogenic structure, although weak, dissolution of calcareous rock fragments; moreover, few secondary carbonates were recorded, testifying to the current character of the dissolution process). However, all these phenomena are not conspicuous, so "cambic" may be applied only as a qualifier for **Phaeozem** RSG, hence, we have ***Calcaric Cambic*** **Phaeozem (*Siltic, Colluvic, Protocalcic*)**. The profile of the third soil is peculiar and comprises three soils: recent ***Someric Cambic*** **Phaeozem (*Siltic, Colluvic, Hyposkeletic*)**, which properties well agree with the image of a humus-accumulative soil with pedogenic modifications of its mineral subsoil. Similar is the first buried soil – ***Cambic Someric*** **Phaeozem (*Siltic, Colluvic, Hyperhumic,* Hyposkeletic)**. The small difference of the recent soils concerns its humus horizon, which has low chroma and depth, as it is common in buried soils (Gennadiev, 1990). The lowermost soil was defined as **Cambisol**; it has a weak humus horizon and, presumably, enough time to become a **Cambisol**. All humus horizons display a weak shift of pH along their profiles. The fourth soil in the sinkhole bottom is also a ***Cambic*** **Phaeozem (*Siltic, Colluvic, Pachic*)**, its deep *mollic* horizon (***Pachic*** qualifier) being in agreement with its accumulative position.

Soil sequence

The diversity of soils in this sequence is not high. Unlike the soil sequence in the karst sinkhole filled with sands in taiga zone (Smirnova and Gerasimova, 2018) here there is "a harmony" of parent material and climate, so the differentiation of the soil cover of the sinkhole is due only to slope processes. They cause either soil burial on less steep, or flattened, parts of the slope, or gradual additions of loamy material modified by pedogenesis to produce **Phaeozems** with more or less prominent cambic features.

The influx of moisture, which generally is not abundant in the forest-steppe, to the sinkhole maintains favorable conditions for the processes of pedogenic modifications of the mineral material, while their intensity is governed by topography and age. Thus, "trapping" of snow by the sinkhole results in catenary differentiation of soil properties: pH values and the content of carbonates decrease down slope parallel to increasing moisture. The most prominent *cambic* features were recorded in the oldest the buried soil.

Formation of ***Rendzic*** **Leptosols** on the outcrops of calcareous rock (without any additions of mineral material) is in good agreement with forest-steppe environment, which may be aggravated by moisture deficit owing to percolation of atmospheric moisture through cavities and cracks in the calcareous rocks. Most favorable conditions for humus accumulation process (*mollic* horizon) fall on

the middle part of the slope, since in the bottom part, the hydrothermal regime is recorded as too wet and cold.

References

Andrejchuk, V.N., 1996. Gypsum karst of the pre-Ural region. Int. Journal of Speleology. 25 (3-4). 285–292.

Buzmakov, S.A., Sannikov, P. Yu., 2014. Landscape and biological diversity of protected areas network in Perm Krai. Advances in environmental biology, 8(13), 2014 P. 473–479.

De Waele, J., Plan, L, Audra, L, 2009. Recent developments in surface and subsurface karst geomorphology: An introduction. Geomorphology 106: 1–8.

Ford, D.C., Williams, P.W., 2007. Karst Hydrogeology and Geomorphology. Wiley, Chichester.

Gennadiev, A.N., 1990. Soils and Time: evoluton models. Moscow Univ.Publ., Moscow, 576 pp. (in Russian).

Gorbunova, K. A., Andreychuk, V.N., Kostarev, V.P., Maximovich, N.G., 1992. Karst and caves in the Perm oblast: Perm Univ.Publ. Perm, 232 pp. (in Russian).

IUSS Working Group WRB, 2015. World Reference Base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report No. 106. FAO, Rome.

Kadebskaya, O.I., Naumkin, D.V., 2012. Crucial landscape areas of Kungur island forest-steppe (Perm region) Steppes of Nothern Eurasia. Proceedings of the VI Internationsl Simposium. 142–144

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. 2006. World Map of Köppen-Geiger Climate Classification. updated. Meteorol. Z., 15, 259–263.

Kungur Ice Cave: experience of regime observations, 2005. Ed.by V.N.Dublianskiy. Ural Division of RAS, Ekaterinburg, 246 pp. (in Russian).

Smirnova, M., Gerasimova, M., 2018. Soil sequence on sands filling the karst sinkhole in the north of the East European Plain. [in:] Soil Sequences Atlas, (eds.) Świtoniak, M., Charzyński, P., Toruń: 111–120.

Waltham, T. F., Bell, F. M., Culshaw, M., 2005. Sinkholes and Subsidence. Karst and cavernous rocks in engineering and construction. Springer, Chichester, 382 pp.