On frozen chernozem genesis and evolution at lacustrine plains in the southern Vitim plateau (Eastern Siberia, Russia)

A Gyninova¹, N Badmaev¹, D Andreeva¹, W Zech² and A Syrenzhapova³

¹ Institute of General and Experimental Biology SB RAS, Ulan-Ude, 670047 Russia
² Institute of Soil Science and Soil Geography, Bayreuth, 95440 Germany
³ V R Philippov Buryat State Academy of Agriculture, Ulan-Ude, 670034 Russia

E-mail: ayur.gyninova@mail.ru

Abstract. To clarify the probable role of the stage of the post-lake soil in the evolution of clay-illuvial frozen chernozem the studies were carried out in the southern Vitim plateau of Transbaikalia. The research covers soils in the area of ancient currently dried lakes and the lakeside plain of the Yeravninskaya depression. The obtained data evidence the dissimilarity of parent rocks, as well as radical differences in the soils’ characteristics and properties.

1. Introduction

The Yeravninskaya depression (YD) is located at the Vitim Plateau southern margin in the Transbaikalia permafrost zone with flat-wavy topography and numerous shallow lakes [1, 2]. Climate warming has greatly affected soils and lake ecosystems [3, 4]. The depth of permafrost in the study area has deepened from 170 to 270 cm over 70 years, the lakes have shallowed, and the shallowest lakes have dried up [5, 6].

Chernozem, often formed from lacustrine sediments, predominates in the YD [7, 8]. R V Desyatkin [9] associates the formation and disappearance of lakes within the cryolithic zone with the temporal dynamics of permafrost thawing and restoration and refers it to the alas process as a whole.

Soil studies in the area of dried lakes in the YD due to aridization processes over the past 20 years [10, 11] have been carried out to ascertain issues related to their genesis, the possibility of post-lake soil evolution into frozen Chernozem [5, 7]. Modern soils combine features and properties formed by the current and past environments [12]. Recognizing the polygeneticity and heterochronism means that the profile of the current soils is not always monogenetic [13].

The work objective is to study the properties and compare the diagnostic signs of frozen chernozem and soils of the bottoms of dried lake in the YD (a case of Lake Khaimisan).

2. Models and Methods

YD topography, like the entire Vitim plateau, was formed in close relationship to orogenic processes taken place here at different geological periods [8]. This area is composed of ancient crystalline rocks: granites, diorites, gneisses covered with thick eluvium, deluvium, proluvium, alluvium, and lacustrine sediments. The climate is extremely continental with little snow, long and frosty winters, short and hot summers. Mean annual precipitation varies between 253-313 mm. Long duration of sunshine is typical, and the mean annual temperature is ~4.1°C [14].
We studied 1) alluvial (limnic) soddy immature soils classified as Calcaric Humic Fluvisol Limnic Turbic, developed under a forb-sedge community at the dried-up Lake Khaimisan bottom, and 2) clay-illuvial frozen Chernozem, classified as Luvic Chernozem (Tonguic), developed under meadow steppe forming in the central lakeside basin. According to the \(\delta^{13}C\) values (−29‰ to −25‰) the vegetation cover consists of C3 plants [15]. Soil diagnostics and classification was carried out according to the Field Guide to Soils of Russia [16] in correlation with the World Reference Base of Soil Resources [17]. Soil morphological description techniques [18], physical, physical-chemical, and chemical analyses of soils were used in the work [19, 20]. Radiocarbon analyses were carried out with AMS using a Mini Carbon Dating System coupled online to an Elementar Analyser [21].

Most of the lakeside plain is covered by Chernozem characterized by 7DKh19 section (52°030’53.0” N, 111°032’44.3” E), 948 m height a.s.l. (figure 1). The vegetation is represented by a grass-wheatgrass-herb community, the grass cover is 70-80%.

The Chernozem under study shows the following horizons: AUdern (0-10 cm) – AU (10-25 cm) – AUBI (25-45 cm) – BI (45-75 cm) – BCA (75-95 cm) – BCca (95-150 cm) – Cq (150-180 cm). Soil: Luvic Chernozem (Tonguic).

8DKh19 section is in the bottom of dried-up Lake Khaimisan (52°55’42.2” N, 111°35’46.5” E), 947 m height a.s.l.). The vegetation is represented by a herb-sedge community, the grass cover is about 10% (figure 2). The following soil horizons were identified:

AUtern (0-15 cm) – AU (15-40 cm) – C[A’G]cr (40-70 cm) – A’ (morphon 70-90 cm) – C”cr (70-85 cm) – DCR (85-160 cm). Soil: Calcaric Humic Fluvisol Limnic Turbic.

According to our morphological studies the Fluvisols reveal less-developed humus accumulation and aggregation, as well as distinct cryoturbation within. The terrestrial period of soil formation lasts about 20 years in the “Khaimisan” section. Pedogenesis has affected only the upper 40 cm of the profile, forming a humus layer, which consists of two horizons: AUdern (0-15) and AU (15-40), that retain the layered structure and carbonate content – signs of sediment lacustrine genesis. Loamy and sandy layers alternate. Living roots penetrate 15 cm depth. Mull humus predominates, indicating active humification of plant residues. A’ cryogenic morphon stretches from the surface to 90 cm depth. The morphon formation is obviously related to cryogenic heaving during freezing under dried lake conditions. According to Melnichuk [22], the Yeravinsky artesian basin underground water does not freeze, and loose deposits remain thawed under lakes.
The parent material is a stratified layer (40-75 cm) C formed under water, which is underwater soil \([A'G]_{cr}\) of a bluish-grey colour due to the presence of underwater humus and deep gleying. The horizon is layered: medium-loamy bluish-grey layers dominate; between them, there are thin (1-2 cm) light-brown sandy and sandy loam interlayers often with grus. Radiocarbon dating of the bluish-grey horizon between 50-70 cm depth has shown that organic matter age varied between 8.9 and 9.5 cal ka BP, corresponding to the early Holocene.

The morphological structure diagnostics of Chernozem under study corresponds to the given type [16, 17]. The humus layer consists of the surface turfed AUdern and dark grey AU horizons. The humification trend to form mull humus is a common feature of the studied soils. The similarity is occurring grus inclusions, which can be explained by residual origin after rock weathering. However, the sod horizon soil mass of the Chernozem is characterized by good structuredness, homogeneous medium loamy composition, lack of stratification, and carbonate signs.

Heavy loamy horizon BI is formed under the humus horizon at a depth corresponding to \(C[A'G]_{cr}\) horizon in Luvic Chernozem (Tonguic). It has a yellowish-brown colour (10 YR 5/6), a lumpy structure with nutty elements, there is a thin cutan along structural part edges. Chernozem granulometric composition is similar to parent rocks of the “Khaimisan” section, a gritty medium loam with semi-rolled large fractions.

Assuming that the Chernozem under study derived from the Fluvisol, it is obvious that the bluish-grey horizon should be transformed into the yellowish-brown BI one, and the carbonates should move to the underlying horizon. At the same time, the sandy-grus soil mass will further become clayey and structured, and the structural units are covered with a thin clay cutan. In the process of transforming clay matter mineral composition, Fe\(^{2+}\) is converted into Fe\(^{3+}\) as a result of the oxidation with \(O_2\) of air, carbonates are carried down the profile. These processes characterize the transition from a hydrogenic water regime to a terrestrial one.

The Fluvisol under study shows between 70-85 cm depth a light-yellow cryogenically deformed layer of fine-grained crumbly structureless well-sorted carbonated sand \(\text{C}^{-\text{cr}}\). This likely indicates sorting by water, which could occur under conditions of melting and intensive water flow movement. According to the radiocarbon dates this layer developed between 9 and 14.5 cal ka BP during the late Sartan stadial, characterized by melting glaciers (table 1). The layer thinness (15-20 cm) is likely to indicate a small stock of ice of the Sartan Glacial.

### Table 1. Dominant pedogenetic processes.

| Horizon, Depth, cm | Chernozem Processes | Horizon, Depth, cm | Fluvisol Processes | \(^{14}\text{C ka BP calibrate}\) |
|--------------------|---------------------|--------------------|--------------------|----------------------|
| AUdern 0-10        | Humification, humus accumulation, aggregation, cracking | AUdern 0-15        | Humification and humus accumulation initial stage |
| AU 10-25           |                     | AU 15-40           |                    |
| AUB 25-45          | Aggregation         | \(C[A'G]_{cr}\) 40-70 | Low aggregation    | 8.9-9.5              |
| BI 45-75           | Cryogenic aggregation, low illimerization | \(A''\) (morphon) 70-90 | Cryoturbation       |                     |
| BCA 75-95          | Low cryogenic aggregation, carbonate lens formation | \(C^{-\text{cr}}\) 70-85 | Cryoturbation       | 14.5                 |
| BCca 95-150        | Low aggregation, carbonate concretion formation, hydrometamorphism | DCR 85-160        |                    | 19.9±3.8             |
| Cq 150-180         |                     | D 160-170          |                    |                      |
In Chernozem, carbonates are found at 75 cm depth in the BCA horizon (75-95). Forming (2.5Y 8/2 paleyellow) carbonate lenses of morphons occur here, which is confirmed by the thawing depth when they are accumulated above the permafrost.

The parent rock of Chernozem BCca (95-150) is carbonate, heavy loamy, dense with carbonate pedofeatures clearly delimited of the total mass. The structure is lumpy-cloody with elements of nuttiness, with clay cutans at structural unit edges. There is an abundance of large grus and fine gravel inclusions. The bedrock D (at 150 cm depth) does not contain grus and gravel and is characterized by the absence of carbonate. For the rest, the bedrock is similar to horizon C.

The Fluvisol shows under a pale-yellow sandy layer in 70-90 cm a stratum of carbonate bedrock with a variegated colour: alternating bright ocher, bluish-grey and brownish parts of different stoniness and various granulometric composition. These layers form a vortex pattern as a result of cryoturbation. A grusy part has bright ocher colour, clay one – bluish-grey, a grusy clay part is brownish. The size of cryoturbated morphons reaches 1-2 m. These features indicate the hydromorphism and good aeration of rocks formed under freezing conditions, which could correspond to weathering under cooling, and moisture preserving in both solid and liquid states. The organic matter age was determined for a sample at the soil profile bottom (170 cm), it corresponds to 19.9±3.8 cal ka BP, typical for the mid-Sartan Glacial (table 1).

According to Volkova and Orlova [23], the climate at the late Sartan stadial was humid in the West Siberian Plain, and similar intermontane depressions of East Siberia were non-covered with glaciers. Khotinsky [24] noted that the late Sartan Glacial and the early Holocene were humid in Siberia as well. As cryogenic deformation forming a vortex pattern (below 85 cm) has occurred in the Sartan Glacial, the horizons located above 70 cm are of Holocene age. The sandy layer between refers to the final Glacial stage or the Holocene initial humid stage. The overlying mid-loamy and heavy loamy layers were accumulated as lacustrine ones, under conditions of less active water movement, which carried mainly fine dispersed fractions, and, accordingly, causing slow accumulation of sediments with heavy granulometric composition. Glacial deposits are characterized by grusy, carbonate, and cryoturbation, which is observed in alluvial (limnic) soddy immature soils.

There is no vortex pattern among the cryogenesis signs of Chernozem. Frost cracks are marked, which penetrate an average 60-70 cm depth and are filled with AU horizon soil mass. Morphological cryogenic features are not observed in the parent rocks. Therefore, they were formed on neither cryogenic deposit of the Sartan stadial, nor lacustrine deposits, but rather on fine-grained-stony rocks of proluvial-deluvial genesis. Forming these soils is most likely related to the influence of the Pleistocene and Holocene climate under other landscape conditions.

Thus, the obtained information on the morphological structure reveals profound distinctions in the pedogenesis between soil profiles under study, Chernozem, and Fluvisol.

The granulometric analyses show that the Chernozem is light-textured in the surface horizons, becoming gradually heavier textured down the profile (table 2). On the contrary, the surface horizon of Fluvisol has a heavy loamy composition, which is replaced by a medium loamy one (AU weakly developed and C [A’G] cr), and then with a sandy loam layer C’’’cr up to 85 cm, which is due to the sediment origin. The most clearly indicated regularity is shown by data on the content of physical clay. Obviously, the C’’’cr layer characterizes a separate phase of sedimentation in the Khaimisan section, which sharply differs from the underlying one. Below a depth of 170 cm, there is a change in the horizons of heavy loamy and clayey compositions. The clay layer has a high silt fraction content.

The extremely low content of silt and clay minerals in the Fluvisol and the absolute predominance of pulverescent fractions compared to those in the Chernozem, prevent the soil mass aggregation and deteriorate soil physical properties. Under growing aridization, it will contribute to deflation, and the Fluvisol stage duration will depend on climatic conditions.

Physical and chemical characteristics data also reveal significant variations in all indicator parameters as well. The humus content in Fluvisol upper 40-50 cm layer is 2 times lower, and ECE – nearly 4-5 times. The content of Fe free forms is several times lower, which could contribute to its accumulation by binding to humus and serve as an agent to aggregate the soil mass as well.
The pH is alkaline, which indicates a high probability of the presence of sodium ions with dispersing properties. Determination of the sum of salts reveals some accumulation of salts, more clearly expressed in the surface horizons.

### Table 2. Soil physical-chemical, some physical and chemical characteristics.

| No | Horizon, Depth, cm | Humus, % | pH | CEC, cmol kg⁻¹ | Sum of salts, % | Fe₄, % | Fe₅, % | Particle size mm | % | % |
|----|--------------------|----------|----|----------------|----------------|--------|--------|------------------|----|----|
|    |                    |          |    |                |                |        |        |                  |    |    |
| 1  | AUdern 0-10        | 11.4     | 6.9| 53.3           | 0.05           | 0.56   | 0.48   | 25.2             | 7.6| 2 |
| 2  | AU 10-25           | 8.6      | 7.1| 49.2           | 0.04           | 1.11   | 0.44   | 31.2             | 10.4| 8 |
| 3  | AUB 25-45          | 4.9      | 7.2| 44.9           | 0.02           | 0.45   | 0.32   | 43.3             | 15.7| 5 |
| 4  | BI 45-75           | 1.3      | 7.6| 33.6           | 0.04           | 1.41   | 0.12   | 51.9             | 24.7| 5 |
| 5  | BCA 75-95          | 0.8      | 8.2| 28.5           | 0.05           | 1.08   | 0.24   | 54.4             | 21.0| 4 |
| 6  | BCca, Cq 95-150    | 0.7      | 8.3| 12.4           | 0.10           | 0.78   | 0.12   | 51.8             | 19.6| 5 |
| 7  | Cq 150-180         | 0.4      | 7.9| 36.6           | 0.02           | 0.96   | 0.16   | 31.0             | 9.0 | 5 |

### Luvic Chernozem (Tonguic)

| No | Horizon, Depth, cm | Humus, % | pH | CEC, cmol kg⁻¹ | Sum of salts, % | Fe₄, % | Fe₅, % | Particle size mm | % | % |
|----|--------------------|----------|----|----------------|----------------|--------|--------|------------------|----|----|
| 1  | AUdern 0-15        | 6.2      | 8.9| 12.0           | 0.26           | 0.15   | 0.14   | 51.0             | 7.6| 2 |
| 2  | AU 15-40           | 2.3      | 8.9| 8.0            | 0.14           | 0.13   | 0.12   | 41.1             | 5.4| 2 |
| 3  | C[AG]cr 40-70      | 2.5      | 8.6| 8.0            | 0.10           | 0.11   | 0.08   | 42.4             | 5.3| 2 |
| 4  | C[cr] 70-85        | 2.3      | 8.6| 12.0           | 0.12           | 0.23   | 0.12   | 18.0             | 1.9| 2 |
| 5  | A``(morphon) 70-90 | 2.2      | 8.8| 5.0            | 0.07           | 0.13   | 0.12   | 57.7             | 6.8| 2 |
| 6  | DCR 85-160         | 1.8      | 8.7| 0.2            | 0.10           | 0.08   | 0.08   | 50.6             | 6.8| 2 |
| 7  | D° 160-170         | 2.3      | 8.8| 0.2            | 0.01           | 0.10   | 0.10   | 64.8             | 10.2| 2 |

### Calcaric Humic Fluvisol Limnic Turbic

3. Conclusion

The most striking features of Calcaric Humic Fluvisol Limnic Turbic distinguishing them from Luvic Chernozem (Tonguic) could be highlighted as follows. They are immaturity and well-conserved signs of the lacustrine sedimentation, as well as Holocene and Pleistocene cryogenic signs. The absence of these features in Chernozem indicates either their lack in the soil evolution or complete transformation of both the soil layer and parent rock. The latter assumption is unlikely, accounting permafrost, which has a conserving effect on the soil and rock structure.

Acknowledgments

The work was carried out with financial support of the RFBR, grant No. 19-29-05250 mk, and research project No. 121030100228-4. The University of Bayreuth financed travel costs and the radiocarbon analyses, which were performed by S Szidat and G Salazar (Department of Chemistry and Biochemistry, University of Bern, Switzerland) with the support of M Bliedtner (Geography, University of Jena, Germany).

References

[1] Mukhina L 1965 *Vitim Plateau (Natural Conditions and Regionalization)* (Ulan-Ude: Buryat Publ. House) p 135 (in Russian)

[2] Badmaev N and Bazarov A 2019 Monitoring network for atmospheric and soil parameters measurements in permafrost area of Buryatia, Russian Federation *Geosciences* 9(1) 6

[3] Kulikov A, Ubugunov L and Mangataev A 2014 On global climate change and its ecosystem consequences *Arid Ecosystems* 20(3) 5–13

[4] Kulikov A, Badmaev N, Sympilova D and Gyninova A 2019 The use of the value of heat cycle to assess the energy stability of permafrost soils at the change of conditions on the surface *Geosciences* 9(3) 112
[5] Kulikov A, Dugarov V and Korsunov V 1997 *Permafrost Soils: Ecology, Heat Balance Capacity, and Productivity Forecast* (Ulan-Ude: BSC SB RAS) p 312 (in Russian)

[6] Badmaev N et al 2019 *IOP Conf. Ser.: Earth Environ. Sci.* 320 012033
doi:10.1088/1755-1315/908/1/012033

[7] Kulikov A, Panfilov V and Dugarov V 1986 *Physical Properties and Regimes of Meadow-Chernozemic Permafrost Soils in Buryatia* (Novosibirsk: Nauka) p 137 (in Russian)

[8] Olyunin V 1961 On genetic types of Quaternary deposits in the Buryat ASSR *Materials of the All-Union meeting on the study of the Quaternary period* (Moscow: AN SSSR) 3 pp 271–6 (in Russian)

[9] Desyatkin R 2008 *Pedogenesis in Thermokarst Hollows – Alases of the Permafrost Zone* (Novosibirsk: Nauka) p 324 (in Russian)

[10] Karelin D et al. 2020 Greenhouse gas emission from the cold soils of Eurasia in natural settings and under human impact: controls on spatial variability *Geoderma Regional* 22 e00290

[11] Badmaev N and Bazarov A 2020 Correlation analysis of terrestrial and satellite meteodata in the territory of the Republic of Buryatia (Eastern Siberia, Russian Federation) with forest fire statistics *Agricultural and Forest Meteorology* 297 108245

[12] Targulian V 2008 Memory of soils: formation, carriers, spatio-temporal diversity *Memory of soils: soil as a memory of biosphere-geosphere-anthropospheric interactions* (Moscow: LKI) p 24–59 (in Russian)

[13] Kulikov A and Targulian V 1985 Inherited properties of the weathering crust of granites of Siberia and the Far East Processes of soil formation and evolution of soils Pre-Holocene and Holocene evolution of soils and ESP (Moscow: Nauka) pp 74–103 (in Russian)

[14] Badmaev N 2008 *Coordinate Analysis and Principles of Soil Recognition* (Ulan-Ude: BSU Publ. House) p 206 (in Russian)

[15] Andreeva D, Zech M, Glaser B, Erbajeva M, Chimitdorgieva G, Ermakova O and Zech W 2013 Stable isotope (d13C, d15N, d18O) record of soils in Buryatia, southern Siberia: Implications for biogeochemical and paleoclimatic interpretations *Quaternary International* 290(291) 82–94

[16] *Field guide to soils in Russia* 2008 (Moscow: V Dokuchaev Soil Inst.) p 182 (in Russian)

[17] 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.

[18] *World Soil Resources Reports* 106 (FAO: Rome)

[19] Rozanov B 2004 *Soil Morphology* (Moscow: Acad. project) p 431 (in Russian)

[20] Shein E and Karpachevsky L 2007 *Theories and Methods of Soil Physics* (Moscow: Grif & Co.) p 616 (in Russian)

[21] Vorobieva I 2006 *Theory and Practice of Soil Chemical Analysis* (Moscow: GEOS) p 185 (in Russian)

[22] Wacker L, Bonani G, Friedrich M, Hajdas I, Kromer B, Nimec M, Ruff M, Suter M, Synal H-A and Vockenhuber C 2010 MICADAS: Routine and high-precision radiocarbon dating *The Arizona Board of Regents on behalf of the University of Arizona Proceedings of the 20th Int., Radiocarbon Conf.,* 52(2-3) p 252–62

[23] Melnichuk N 1966 Ground waters of the Yeravninsky and upper Uda artesian basins *Methods of hydrogeological research and groundwater resources of Siberia and the Far East* (Moscow: Nauka) pp 217–27 (in Russian)

[24] Volkov I and Orlova L 2000 Kargin-Sartan time and Holocene of SE West Siberia according to the radiocarbon dating *Geology and Geophysics* 41(6) 1426–42 (in Russian)

[25] Khotinsky N 1977 *Holocene of Northern Eurasia. Experience of Transcontinental Correlation of the Vegetation and Climate Development Stages* (Moscow: Nauka) p 200 (in Russian)