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Cryoaridic Soils as a Genetic Type in the Russian Soil Classification System: Geography, Morphology, Diagnostics

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Abstract—Cryoaridic soils were proposed to be identified as an individual genetic soil type by Vladimir Volkovintser in the 1970s. Volkovintser argued that the specific properties of these soils are in good agreement with the soil-forming factors: ultracontinental climate, cryoxerophytic steppe or tundra-steppe vegetation, dry permafrost, and skeletal parent material. In cryoaridic soils, the properties of chestnut and pale soils are combined, but their individual features are due to the specific cryohumus AK horizon and secondary carbonates dominated by pendants. Cryoaridic soils were not included in the soviet soil classification system of 1977; in the Russian soil classification system, the type of cryoaridic soils with the AK–BPL–BCA–Cca horizons is included in the order of pale-metamorphic soils with the pale-metamorphic BPL horizon as diagnostic for all soil types of this order. However, our field research, analysis of publications, and the study of soil in the Central Soil Museum give us grounds to verify diagnostic criteria, to change the profile type formula of cryoaridic soils, and to review their taxonomic position in the classification system. We argue that the BPL diagnostic horizon should be replaced by the diagnostic property (pl), which means that cryoaridic soils should be transferred into another order, presumably, the order of humus carbonate-accumulative soils. Some additional subtypes are proposed. On highly skeletal shallow parent materials, cryohumus soils belonging to the order of organo-accumulative soils are developed.

Keywords: cryoxerophytic steppes, climatic niche, cryohumus diagnostic horizon, root detritus, coatings, processes and subtypes. Skeletic Someric Kastanozems (Cambic?), Eutric Skeletic Cambisol (Protocalcic), Skeletic Cambic Calcisol (Yermic)

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INTRODUCTION

Cryoaridic soils were introduced into the world of Siberian soils as a special geographical and genetic formation by Volkovintser in the 1970s [9, 11–13]. Based on a small number of publications characterizing the properties of soils and their special "ecological niche," cryoaridic soils were included in the classification of Russian soils as a type in the order of pale metamorphic soils [22, 39]. In the WRB system, these soils are not distinguished as a separate group and fall into three major reference groups of Kastanozems, Cambisols, and Calcisols. The most widespread cryoaridic soils can be described in the WRB system as follows: Skeletic Someric Kastanozems (Cambic), Eutric Skeletic Cambisols (Protocalcic), and Skeletic Cambic Calcisols [59].

Cryoaridic soils remain insufficiently studied; their distribution is associated with two groups of remote and difficultly accessible landscapes: (a) cold dry steppes in the intermountain basins of mountain systems in southern Siberia and Central Asia: Altai, Sayan, Tuva, Transbaikalia, Tien Shan, and Mongolia and (b) "islands" of cryoxerophytic steppes (tundra-steppes, in the terminology of geobotanists) on the high plateaus and south-facing slopes of mountains systems in the East Siberia and Northeastern Asia [4, 8, 10, 13, 19, 43, 54, 56]. In the foreign literature, cryoaridic soils have not been described as a separate genetic type, although they are distinguished under different names in the territory of Mongolia by Russian authors [13, 38, 61]. Taking into account geographical analogues, these soils should be present in the continental part of Alaska and in Tibet [57, 60].

Despite such a relatively wide distribution, cryoaridic soils are rarely reflected on soil maps as judged from previous publications [2, 8, 13, 43, 47]. Thus, on the soil map of the Russian Federation on a scale of 1 : 2.5 M [40], the areas of these soils can be found in the mountainous territories (Eastern Sayan, Central and Southeastern Altai) under the name of mountainous steppe soils; under the name of cold steppe soils, they are included as accompanying soils in some soil polygons in the sharply continental regions of Eastern Siberia with pale (palevye) soils, taiga and tundra podburs, and tundra gley soils as the dominant soils. The legend to this map contains soils that are most likely associated with cryoaridic soils: "high-mountain steppe soils." However, these soils are absent on the map. It is probable that they were put into the original legend to the planned soil map of the entire Soviet Union [1], for some high-mountain territories in eastern Kazakhstan and Central Asia. In the main areas of cryoaridic soils—intermountain basins of Altai, Tuva, and Transbaikalia—these soils are shown on the map as dark chestnut, chestnut, and light chestnut soils. Steppe cryoaridic soils are shown as an individual group of soil on the soil map of the Magadan region on a scale of 1 : 2.5 M [33] as accompanying soils among eluvial-gley tundra soils in the Anadyr River bend and among mountainous podburs in the upper reaches of the Kolyma River. On the soil map of the northeast of Eurasia on a scale of 1 : 2.5 M [31], cryoaridic steppe soils are also shown as accompanying soils in the areas with a dominance of pale (palevye) soils and podburs in the upper reaches of the Yana, Indigirka, and Kolyma rivers and their tributaries.

Dry steppe vegetation, low precipitation (110–250 mm/yr), low moistening coefficient (aridity index), as well as some characteristic features of the profile—a humus-accumulative horizon with a poorly formed structure, a relatively low content of organic matter, and the presence of a carbonate-accumulative horizon—were the reasons for classifying these soils as chestnut and mountainous chestnut soils. In the zonal paradigm, other solutions were unlikely taking into account this particular combination of the soil forming agents. However, it was noted that chestnut soils in cold ultracontinental regions have some specific features [34, 35, 41]. These soils were assigned to the facies subtype of chestnut soils with long-term seasonal freezing [23].

However, the differences between the soils of ultracontinental cold dry steppes and the central image of chestnut soils of dry steppes, upon a closer examination, turned out to be so significant that it was necessary to speak about the need for their isolation into a separate genetic type [9, 11, 12, 15]. The proposed new type was substantiated by Volkovintser based on the specifics of landscape conditions, including the composition and functional features of the biota, as well as the morphological and analytical features of soils [13].

In this paper, we analyze the concept of cryoaridic soils as a genetic soil type and the position of these soils in the new Russian soil classification system on the basis of previously published and newly obtained data. The particular goals are: (1) to substantiate the status of cryoaridic soils as a genetic soil type taking into account the presence of diagnostic horizons and diagnostic features (in agreement with the rules of this classification system) and the specificity of soil forming agents, (2) to consider the main morphogenetic features and the genetic and geographical diversity of cryoaridic soils, (3) to verify and refine diagnostic criteria for the horizons of cryoaridic soils, and (4) to consider variants of the subtype division of cryoaridic soils.

OBJECTS AND METHODS

Consideration of the classification position of cryoaridic soils was based on three groups of approaches and sources of information. In the tradition of geographic and genetic studies, the analysis was based on the authors' own field observations. The collection of field material was preceded by a purposeful analysis of the factual material contained in Volkovintser's basic monograph *Steppe Cryoaridic Soils* [13]. Its data were used not only to verify the morphogenetic "portrait" of cryoaridic soils but also to select the key objects for further field studies, since it was this monograph that provided the basis for the inclusion of cryoaridic soils into the Russian soil classification system [22, 39].

For each of the 39 soil profiles described by Volkovintser, the ecological niche—a combination of soil-forming factors at the particular site—was characterized, and the morphological descriptions of the profiles were analyzed with an emphasis on the diagnostic criteria used in the new Russian soil classification system. The same principles were used in field studies and in the analysis of full-profile cores (soil monoliths) of cryoaridic soils from the Dokuchaev Central Soil Science Museum in St. Petersburg [20]: soil forming conditions, profile horizonation, and diagnostically significant morphological characteristics of each horizon were identified.

Field studies were planned according to the principle: "following the objects described by V.I. Volkovintser" when it was possible to georeference the soil pits described in the monograph [13]. Additional soil pits were studied in the same areas. Satellite images were used to map the "classical" soil profiles and to select additional objects; for some regions (Tuva, Transbaikalia), sheets of the State Soil Map were used. The accuracy of positioning of soil pits in Volkovintser's monograph is very different. For example, profile 108-Yu (initially described by O.V. Yurlova and published by V.A. Nosin (1963)) has the following address: Tuva Autonomous Soviet Socialist Republic, Chaa-Kholsk district, 20 km of the road from the village of Chaa-Khol to the city of Chadan. Profile 14-EN (Naumov and Andreeva, 1963) was studied... "420 km east of the city of Khandyga and 30–40 km west-northwest of the settlement of Oymyakon." This is followed by a detailed description of the position of the given soil profile in the relief, microrelief of the surface, phytocenosis, and character of the soil surface (presence of cracks, crust, rock fragments, etc.). In a number of cases, the address provided by the authors and a detailed description of the landscape made it possible to identify the latter in nature and to study new soil pits "in the same position" as the classical profiles, at a distance of no more than 1–2 km. In other cases, we could identify with certainly only the administrative region. In such cases, we analyzed landscape descriptions provided by Volkovintser especially carefully and tried to find analogous landscapes. As a result, we studied 12 soil profiles that corresponded (with a certain degree of conventionality) to the profiles described in the monograph by Volkovintser, and only 7 of these 12 soil profiles were verified by us as cryoaridic soils.

When choosing additional points for the study, we were guided by the factual material from regional monographs [34, 35, 41]. Five additional soil profiles in Tuva were studied "following the objects described by V.A. Nosin" [35]. Two of them were diagnosed as cryoaridic soils. Three profiles were also studied in the central part of Mongolia, in the area, where Volkovintser considered medium-humus cryoaridic soils to be predominant [13]. In total, in the course of field studies, we described more than 50 soil profiles under cryoxerophytic steppes in river valleys, intermontane depressions, and on mountain slopes in the range of absolute heights from 175 m a.s.l. (Central Yakutian Plain) to 2400 m a.s.l.. (high mountains of southeastern Altai), of which 39 soil profiles were identified as cryoaridic soils (Fig. 1).

A novel approach in our study was the identification of cryoaridic soils on the basis of the analysis of full-profile undisturbed soil monoliths from the collection of the Dokuchaev Central Soil Science Museum. In particular, we managed to get acquainted with the morphology of cryoaridic soils in the northeast of Russia, where we did not perform field work [20]. The work with the museum collection was focused on a comparative analysis of diagnostically significant morphological features of cryoaridic soils and related soils: pale (palevye) soils, dark-humus pale soils, chestnut soils, and brown arid soils [20]. All soil cores presented in the collection and identified as soils of the pale-metamorphic and light-humus accumulative-carbonate orders (according to the new Russian soil classification system) were studied.

For most of the studied profiles of cryoaridic soils, the main analytical chemical and physicochemical characteristics were obtained [16, 36]. However, within the framework of this article, we only discuss analytical properties related to the key feature of the main diagnostic horizon of cryoaridic soils, i.e., its richness in root detritus. To estimate the proportion of plant detritus in the organic matter of cryohumus horizons, the content of easily decomposable organic matter—plant residues and detritus (light organic matter, LOM)—was determined [18]. The LOM fraction was isolated by fractionation in a heavy liquid with a density of 1.8 g/cm^3, followed by reflotation in a heavy liquid with a density of 1.6 g/cm^3. The isolated LOM was further fractionated on sieves and examined at low magnification under a binocular microscope in reflected light.

RESULTS AND DISCUSSION

Identification of the type of cryoaridic soils according to specific soil-forming conditions. Soil formation in the cryoxerophytic steppes of the Central and Northeast Asia is determined by an exceptionally harsh climate: subzero mean annual temperatures (from –17°C to –1.5–2°C), large seasonal and daily temperature amplitudes (seasonal amplitudes are above 40°C; in Yakutia, above 60°C), and short frost-free period (from 30 to 115 days) [13]. However, even under the most severe climatic conditions (near the Oymyakon weather station), the southern slopes warm up well in summer: the soil temperature in the upper part of the humus horizon at the time of the study (August 28–31, 2017) was +17...+19°C, which is quite comparable with the temperatures of the upper horizons of cryoaridic soils in the southeastern Altai, where the maximum temperatures recorded by us in the annual cycle ranged from +23 to +31°C for soils at different absolute heights.

The mean annual precipitation ranges from 110 mm/yr (Kosh-Agach weather station, southeastern Altai) to 250–280 mm/yr (Selenginsk weather station, southern Transbaikalia; Ostrovnoe and Omolon weather stations in the continental regions of Chukotka). The maximum precipitation occurs in July–August. In the remaining months, there is little precipitation. Thus, the soils freeze in a relatively dry state; in the spring months, there is a particularly acute soil moisture deficit. Summer precipitation is often showery, and the root system of cryoxerophytic vegetation is near-surface. Thus, atmospheric precipitation quickly flows down the slope and is absorbed by plants in the upper horizons. As a rule, deep wetting of the soil profile does not take place even during intense rains [3]. On average, the soil is moistened to a depth of 20–30 cm [19].

The warm period is distinguished by prolonged sunshine and a large sum of active daily temperatures,

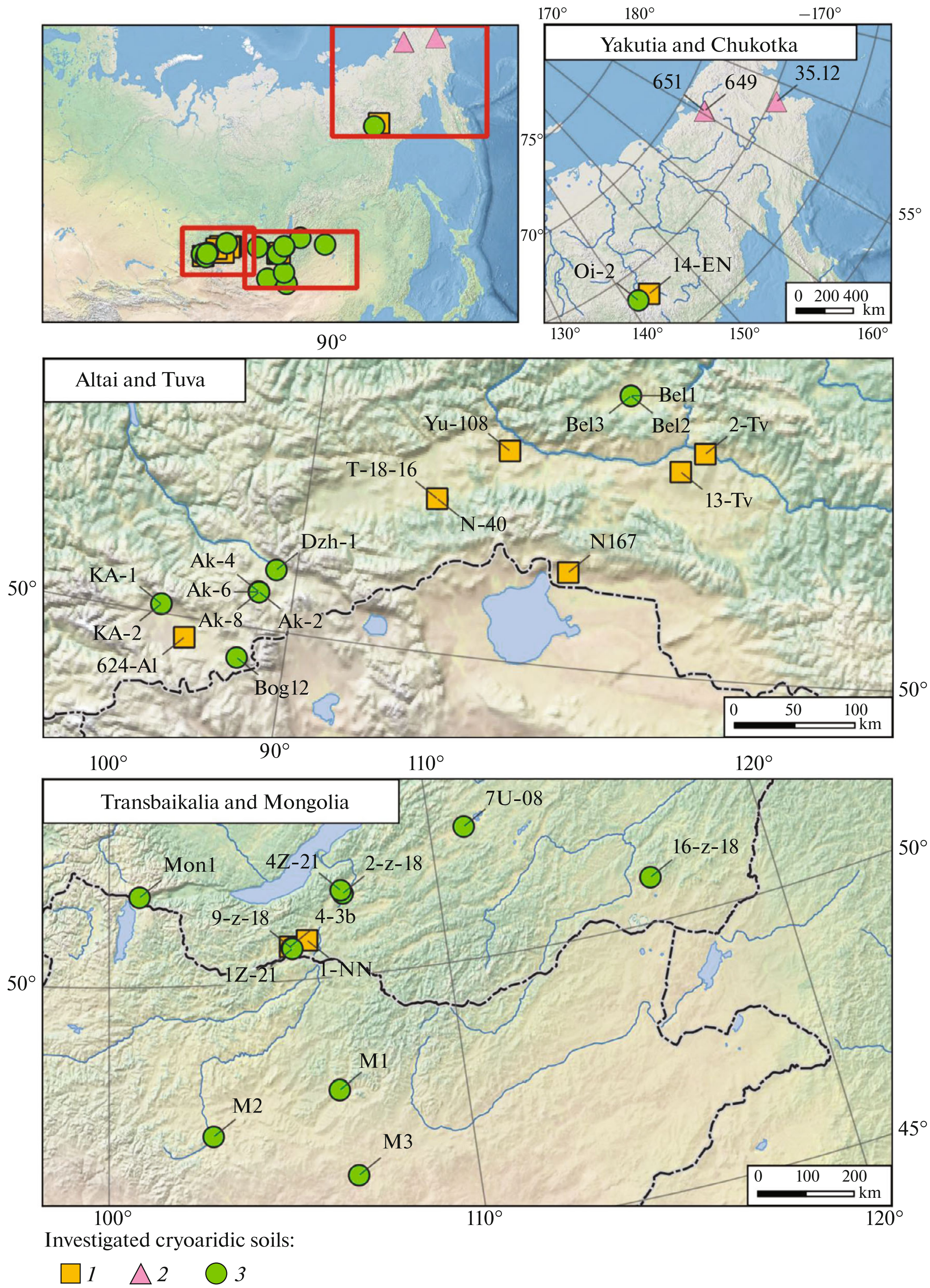

Fig. 1. Distribution of cryoaridic soils: (*1*) classical soil profiles described by V.I. Volkovintser and V.A. Nosin, (*2*) full-profile soil monoliths from the museum collection, and (*3*) soil profiles described during fieldwork in 2010–2021.

Evaporation from the soil surface is strong, especially in the driest part of the area of cryoaridic soils. In the Ubsunur depression—one of the driest places—annual precipitation has decreased significantly in the past 60 years: the aridity index[1] decreased from 0.34 to 0.18–0.23. Thus, the aridity category changed from arid to strongly arid [38, 46]. The hydrothermal coefficient[2] ranges from 0.2 (Chuya steppe) to 0.6 (Transbaikalia, Yakutia) [19].

All areas of cryoaridic soils are located either in the permafrost area (mostly, discontinuous permafrost) or in the territory subjected to very long seasonal soil freezing [55]. Soils freeze deeply (to 3–4 m) [13]. However, in none of the studied pits, permafrost was found within the soil profile (field studies were carried out in July–August). In some cases (profile Ak-8, southeastern Altai), subzero temperatures and ice lenses were found at a considerable depth (230 cm) at the end of July. It is known that full soil thawing is reached in September).

Cryoaridic soils are usually developed from various colluvial and alluvial deposits of debris cones and alluvial fans in the depressions and from colluvium on slopes. These heterogeneous and usually gravelly sediments with loamy sandy or sandy loamy fine earth and a considerable content of gravelly material. Often, they contain lithogenic carbonates: clastic material of carbonate-bearing rocks in fractions from coarse silt to boulders. The content of coarse clastic material varies greatly along the profile and usually increases with depth. In the hyperskeletic soils (often, >80% of fractions >1 mm), fine earth may have a light clayey or clay loamy textures.

Evaluation of the "biological efficiency" of atmospheric precipitation in terms of climatic parameters and textural characteristics of the soil performed by Rukhovich with coauthors [45] singled out the dry steppes of the south of Central and Eastern Siberia as cryoaridic steppes, or cold semideserts (Fig. 2). One of the starting points was the well-known fact that the coarse texture and relatively high gravel content dictate the high water permeability and low water-holding capacity of soils, which reduces the efficiency of atmospheric precipitation. The approach proposed by these authors to the zoning of the dry steppes of Eurasia was based on calculations of the sums of active temperatures and the sums of the excess of precipitation over evapotranspiration, corrected for the soil texture, solonetzic features, and the presence of carbonates. Cryoaridic steppes, or cold semideserts, were delineated in the southeastern Altai and in the intermontane basins of Tuva. Dry steppes were shown in Transbaikalia [45]. However, it follows from our field observations that cryoaridic soils in Transbaikalia are confined mainly to solar slopes, where soil formation occurs on highly skeletal substrates, and their better heating during the growing season reduces the soil moisture.

Plant communities on cryoaridic soils are mainly composed of species ubiquitous in the ultracontinental cold dry steppes of Asia. Sod-forming grasses are most typical: feather grass (*Stipa krilovii* Roshev., *S. glareosa* P.A. Smirn.), fescue grass (*Festuca lenensis* Drobow., *F. valesiaca* Gaudin), bluegrass (*Poa attenuate* Trin.), wheatgrass (*Agropyron cristatum* L.), Junegrass (*Koeleria cristata* (L.)Pers.), molinia grass (*Cleistogenes squarrosa* (Trin.) Keng); wormwood (*Artemisia frigida* Willd., *A. caucasica* Willd.); cinquefoil (*Potentilla acaulis* L., *P. conferta* Bunge, *P. bifurca* L.); gray-haired speedwell (*Veronica incana* L.); edelweiss (*Leontopodium*); sedges (*Carex diriuscula* C.A. Mey, *C. pediformis* C.A. Mey). In the most arid parts of the area of cryoaridic soils and/or on strongly gravelly rocks, shrubs and cushion-forming herbs are found: *Caragana pigmaea* (L.) DC., *C. bungei* Ledeb., *C. aurantiaca* Koehne; *Ephedra* sp., and *Nanophyton grubovii* U.P. Pratov. Especially gravelly soils are characterized by the appearance of *Goniolimon* sp., *Gypsophyla desertorum* (Bunge) Fenzl, and *Orostachys spinosa* (L.) C.A. Mey. In the highlands, cryophytic and alpine associations are represented by gentian (*Gentiana*), alpine aster (*Aster alpinus* L.), forget-me-not (*Eritrichium pectinatum* (Pall.) DC.), cobresia (*Kobresia myosuroides* (Vill.) Fiori), snow cinquefoil (*Potentilla nivea* L.).

Cryoaridic soils host shortgrass steppes, with a 3–10-fold predominance of underground phytomass over aboveground phytomass [17, 42]. We carried out single determinations of phytomass[3] at three sites with cryoaridic soils in the southeastern Altai. The aboveground phytomass varied from 0.02 kg/m^2 under the most arid conditions (Fig. 3, *3*) under the desertified steppe with a low (20–30%) projective cover (Chuiskaya Depression) to 0.154 kg/m^2 in the high-mountain steppe landscape (Fig. 3, *1*) with a significant proportion of alpine species and a projective cover of 70–80% (valley of Bogutin lakes). In the most typical cryoxerophytic steppe (Fig. 3, *2*) with a projective cover of 50% (Lake Ak-Khol basin), the aboveground phytomass was 0.041 kg/m^2. The phytomass reserves of the least arid areas with cryoaridic soils are comparable with those in the continental warm dry steppes of the European part of Russia and Kazakhstan, while the phytomass in the most arid area of our study—the deserted steppe of the Chuiskaya Depression—is extremely small for steppe phytocenoses.

[1] The aridity index was calculated as the ratio of the mean annual precipitation to the potential evapotranspiration for the same period [46].

[2] The hydrothermal coefficient is the ratio of precipitation (mm) during the period with active (>10°C) daily temperatures to the accumulated sum of active temperatures (Σt) and is a quantitative characteristic of the water supply of plants.

[3] Phytomass was determined as an absolutely dry mass of living plants cut from a test plot of 1 × 1 m and the mass of dead plants (mortmass) sampled from the same test plot.

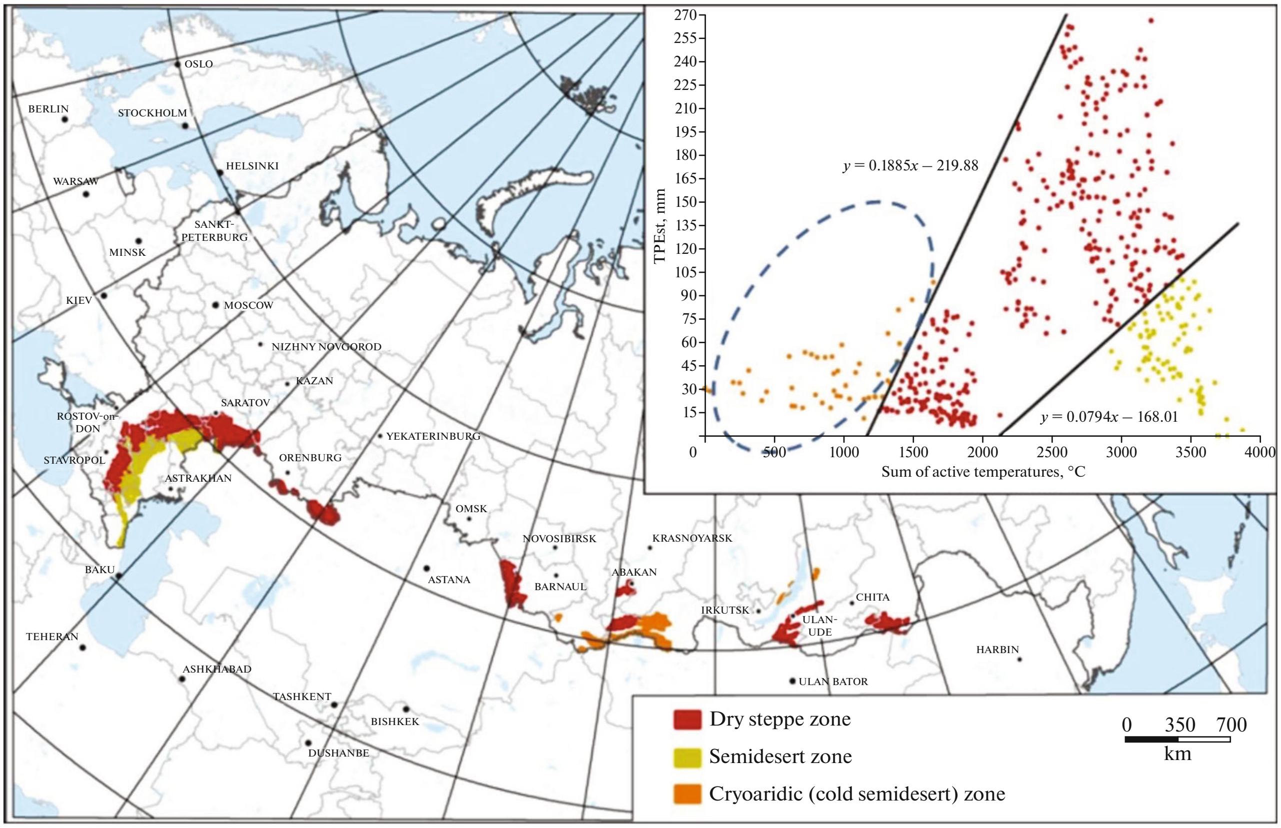

Fig. 2. Zones of the distribution of chestnut soils as determined by the sum of monthly excesses of precipitation over potential evaporation with a correction for soil texture (TPEst, mm) and the sum of active temperatures (taken from [45]).

Soil forming conditions favor the development of root mass; in general, the underground phytomass can exceed the aboveground phytomass by 3–20 times [42]. Against the background of exceptionally low winter temperatures, low precipitation, highly permeable gravelly substrate with low water retention capacity, and low diversity and population density of soil fauna, this distribution of phytomass creates specific conditions for the formation of humus-accumulative horizon of cryoaridic soils. In the new Russian soil classification system [22, 39], this horizon was called the *cryohumus* (AK) horizon.

Having given the cryoaridic soils of the cryoxerophytic steppes the status of a genetic soil type and separating them from the type of chestnut soils of warmer and less continental regions, V.I. Volkovintser argued that these two soil types are different because of the differences in their ecological niches (factors of soil formation). However, despite the factor-oriented approach of Volkovintser towards separation of a new soil type, he also pointed to specific features of cryoaridic soils that were later used as their diagnostic criteria in the new classification system of Russian soils.

Substantiation of the identification of the type of cryoaridic soils according to soil properties. *Diagnostic horizons.* According to Volkovintser, characteristic features of cryoaridic soils include the predominance of warm, reddish brown (chestnut) rather than gray hues in the color of the humus horizon, the weakly expressed structure of all genetic horizons, the presence of a more or less clear horizon of carbonate accumulation with a predominance of calcitic coatings (pendants) on lower surfaces of rock fragments. The depth of effervescence varies greatly, the content of carbonates varies from 0.5 to 50%, and there are no horizons with the accumulation of gypsum and soluble salts. According to Volkovintser, the morphological manifestation of cryogenic processes in these soils is weak because of the lack of moisture despite the severe temperature regime [13].

These properties served as the basis for diagnosing cryoaridic soils in the Russian soil classification system. In accordance with its principles, the soil type level is diagnosed by a certain set of diagnostic horizons, i.e., the profile formula; the type of cryoaridic soils is characterized by the following horizonation: AK–BPL–BCA–Cca [22, 39]. The parent material of cryoaridic soils can also be carbonate-free, so it is more expedient to change its index to C(ca). Below, we consider the features of the diagnostic horizons of cryoaridic soils (Fig. 3, Figs. S1–S3).

The cryohumus horizon (AK) was introduced into the classification for cryoaridic soils and cryohumus soils from the order of organo-accumulative soils as

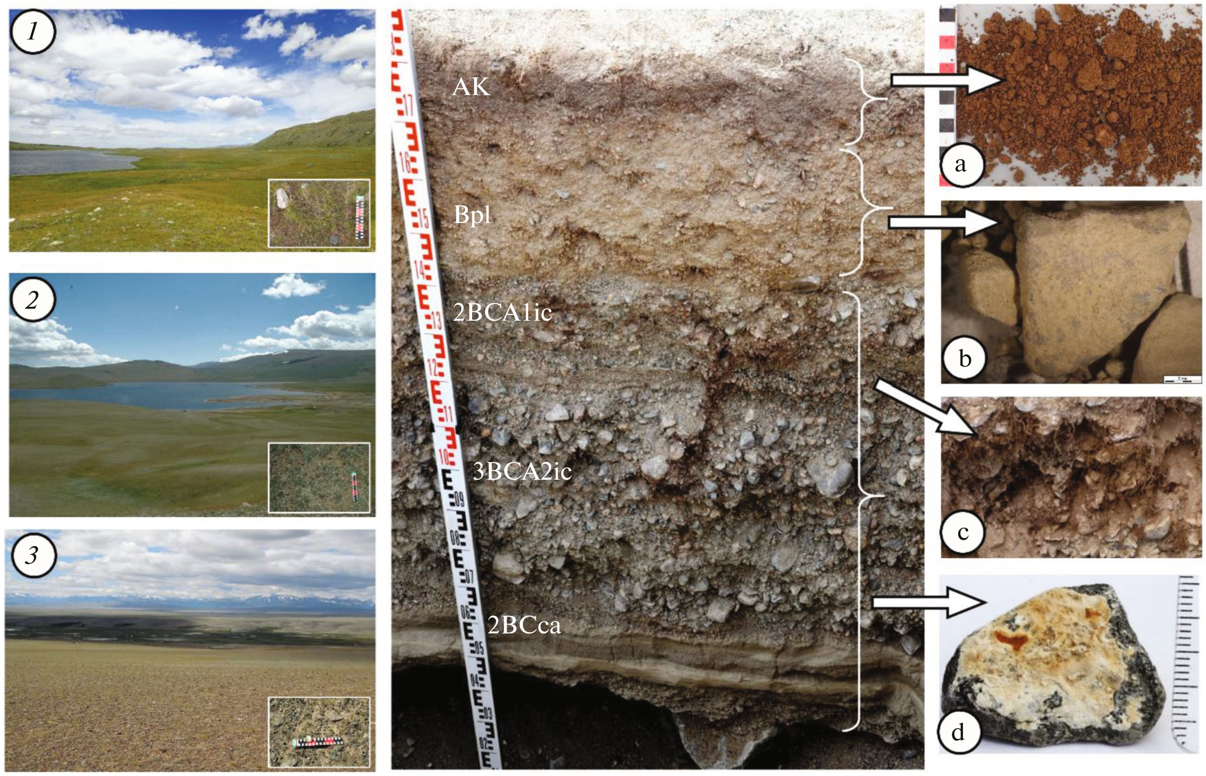

Fig. 3. Characteristic landscapes, typical; profiles, and major morphological features of cryoaridic soils. Landscapes: (*1*) southeastern Altai, the Boguty River valley, 2400 m a.s.l., cryoxerophytic steppes with participation of alpine flora; (*2*) southeastern Altai, Lake Ak-Khol area, 2230 m a.s.l., cryoxerophytic steppes; (*3*) southeastern Altai, Chuiskaya Steppe, 1900 m a.s.l., desertified cryoxerophytic steppe. Key morphological features of cryoaridic soils: (a) AK horizon of brown color, fine granular-subangular blocky structure, and with abundant plant remains; (b) Bpl horizon of pale color and clay–silty coatings on mineral grains; (c) accumulations of dead root detritus at the lithollogical contact between the Bpl and 2BCAic horizons; and (d) layered pendants on rock fragments in the BCAic horizon.

the horizon reflecting their specificity and unique formation conditions. Based on the morphological analysis of the studied objects, the following features of the cryohumus horizon should be noted (Fig. 3a, Fig. S1). The thickness of the AK horizon is more than 5 cm and is usually 10–20 cm. In its upper part, either a medium-dense sod layer is found, or there is a thin, brittle crust (0.5–2 cm) on the soil surface. The crust is most often porous (Fig. S4-n) and is underlain by a layer of structureless, loose, silty sandy material, sometimes stratified, of 1–2 cm in thickness. It is considered to be a diagnostic *akl* feature (Fig. S4-l). In non-soddy areas, gravels and rock fragments of various sizes are often found on the soil surface (Fig. S4-l, Fig. S4-o). In the presence of a crust, the clastic material on the surface often has the features of desert varnish (Fig. S4-m). As a rule, AK horizons with a crust (AKakl) effervesce from the surface and contain various sinter forms of carbonates: coatings, pendants (feature *ic*).

One of the main differences between the cryohumus horizon and other humus-accumulative humus horizons is the reddish or reddish brown rather than gray tones of color [22, 39]. However, they are not as bright as indicated in the diagnostics [39]; as a rule, the color of the horizon is dark brown or reddish brown: according to the Munsell scale, the hue is 10YR[4], the value is in the range of 3–4, and the chroma is in the range of 2–4; hues of 7.5YR or 5YR are also found in some profiles (Table 1, Fig. 3).

The structure of the fine earth is loose fine granular and subangular blocky (Fig. 3a, Fig. S1-a). In some cases, subangular blocky aggregates (0.5–2.0 cm) are arranged into weak prismatic units; very fine granular aggregates are usually less than 1 mm in size (Fig. S1-b). A peculiar and diagnostically significant feature of cryohumus horizon, which was not previously given due importance, is the abundance of small (<0.5 mm) weakly decomposed plant detritus (Fig. S1-c), mainly root remains, scattered over the entire horizon and determining many of its physical and chemical properties, including a peculiar color [20]. Brownish detritus covers the surface of crumb granular and subangular

[4] The soil color according to the Munsell scale was determined at the field moisture varying from dry to slightly wet soil.

Table 1. Characteristic features of the horizons of cryoaridic soils according to literature data and field observations*

Characteristic	Diagnostic horizons		
	cryohumus AK(A)	pale-metamorphic BPL (AB/B)	carbonate-accumulative BCA(BC)
Color	V.I. Volkovintser [9–14]		
	Brown (chestnut); light or dark brown with reddish tint	Brown (chestnut), with grayish tint; lighter than the AK horizon	Whitish or pale brown; uneven color pattern with yellowish or brownish tints
	Classification and diagnostic system of Russian Soils [22, 39]		
	Reddish brown (chestnut); the darkest in the profile; 5YR or 7.5YR 5–6/2–4 in Munsell's notation (for dry samples)	Pale; 10YR 7–8/3 (dry state)	Pale or brownish pale: 10YR 7–8/3–6 (dry state)
	Generalized data from 39 studied soil profiles		
	Dark brown, brown, reddish brown; chestnut; grayish tint is weakly pronounced; in Munsell's notation, hue: 10YR (most often), 7.5YR (rarely), or 5YR (single samples) with values of 3–4(5) and chroma of 3–4	Brown, pale brown, yellowish brown; hue: 10YR (most often); 7.5YR (rarely; in the case of soil development from red-colored parent materials); 5YR (single samples); value 3–5 (usually) or 6–7 (rarely); chroma 3–4	The lightest in the profile; brownish pale, light pale, yellowish. whitish; hue:10YR, 2.5YR; rarely 7.5YR; value 5–7, chroma 2–4
Structure	V.I. Volkovintser [9–14]		
	Structureless or single-grain, or weak fine granular or subangular blocky	Structureless, or weak subangular blocky with elements of platy structure; rarely coarse blocky	Indistinct, or cryogenic (platy, lenticular, granular; post-schlieren structure
	Classification and diagnostic system of Russian Soils [22, 39]		
	Indistinct or structureless	Weak subangular blocky structure or structureless	Weakly pronounced; inherited from the parent material; subangular blocky elongated aggregates with uneven cavernous surface
	Generalized data from 39 studied soil profiles		
	Loose, weak, fine or very fine granular or subangular blocky	Weak, usually, prismatic-blocky, rarely subangular blocky, or granular with elements of cryogenic granules and post-schlieren organization of the soil mass	Indistinct; loose; cryogenic blocky prismatic, or fine angular blocky
Presence of forms of carbonate concentrations	V.I. Volkovintser [9–14]		
	Generally, carbonate-free	Carbonate-free; in some cases, effervescent, but without distinct morphological forms; there are also soils with carbonate impregnation of the fine earth and calcitic pendants on rock fragments	Strongly effervescent; carbonate impregnation of the fine earth and calcitic films, pendants, and crusts on rock fragments
	Classification and diagnostic system of Russian Soils [22, 39]		
	May effervesce from the surface or at some depth	May effervesce	Strongly effervescentl carbonate impregnation of the fine earth; calcitic pendants on rock fragments

Table 1. (Contd.)

Characteristic	Diagnostic horizons		
	cryohumus AK(A)	pale-metamorphic BPL (AB/B)	carbonate-accumulative BCA(BC)
	Generalized data from 39 studied soil profiles		
	Usually, carbonate-free; may contain carbonate pendants on rock fragments	Carbonate-free, or unevenly effervescent; in some profiles, carbonate impregnation of the fine earth and carbonate pendants on rock fragments in the Bpl/BCA horizons	Strongly effervescent; diffuse carbonates; carbonate pendants on rock fragments

* Symbols of soil horizons are given according to [22, 39] and, in parentheses, according to the original publications. Munsell color for the studied soil profiles was determined at the field water content corresponding to a range from dry soil to slightly wet soil.

blocky, rock fragments, and is dispersed in the nonaggregated soil mass (Fig. S1-d).

The presence of plant detritus explains an increased content of organic carbon (1–5%; on average, 3.5% (for the studied 39 soil profiles)) and a very high proportion of the nonhydrolyzable residue fraction in the composition of organic matter. According to the classification, it should be 40–50%. According to data on three profiles of cryoaridic soils from the southeastern Altai [21, 24, 50], it may vary from 40 to 80% and even more. An additional characteristic of the organic matter of the cryohumus horizon is a high content of easily decomposable light organic matter (LOM) fraction: 3–5% (in the sod layer, it is significantly higher). This is several times higher than the LOM content in the chestnut soils of the European part of Russia (0.7%) [5].

An analysis of the share of detritus (LOM isolated by fractionation in a heavy liquid [18]) in various size fractions showed that the fraction 0.2–0.5 mm absolutely predominates and accounts for about 40% of the detritus mass. The next largest fraction, 0.1–0.2 mm, constitutes about 20% of the total LOM mass. The abundance of such small weakly and moderately decomposed plant remains in the cryohumus horizon explains a relatively high organic carbon content in this horizon (as determined by the wet combustion (Tyurin's) method) [25], because it is practically impossible to remove this plant detritus from the sample together with roots during preparation of the samples for the analysis.

The noted properties of the cryohumus horizon correlate well with the characteristic soil forming conditions. An increased amount of plant residues is explained by the dominance of root phytomass, which is concentrated in the surface layer, which is typical of cryoxerophytic steppe phytocenoses. Humification processes are limited not only by the harsh climate but also by the properties of the plants themselves—grasses, wormwood, and shrubs, as well as by the low biological activity, which limits the mechanical and biochemical destruction of mortmass. Cryogenic fragmentation seems to be an important mechanism of the comminution of plant remains and their transformation into fine detritus [44]. The very name of the horizon —cryohumus—reflects a special complex of processes forming it. In other words, the morphology and properties of the AK horizon reflect the features of the transformation of organic remains of cryoxerophytic vegetation under conditions of heat and moisture deficiency and low biological activity. This humus horizon differs from humus horizons forming in warmer and less continental steppes. It can be regarded as a modification of the steppe type of humus formation. A specific nature of humus horizon in steppe cryoaridic soils was noted by Volkovintser; following A.V. Kuminova, he considered the process of "mummification" of plant remains that decompose very slowly because of the unfavorable climatic conditions [10, 28].

Pale-metamorphic horizon (BPL) is the middle-profile horizon of cryoaridic soils. It was not distinguished by Volkovintser as a special genetically and diagnostically significant horizon; in morphological descriptions, it appears as a transitional horizon AB. In the new Russian soil classification system, the first middle-profile horizon of cryoaridic soils is designated as the pale-metamorphic BPL horizon [39]. It can be carbonate-free or carbonate-bearing, with carbonate pedofeatures (carbonate pendants and dispersed calcite grains). According to [39], the BPL horizon has a dull pale yellow color; it is less colored than the iron-metamorphic BFM horizon and is "practically structureless" compared to the structural-metamorphic (BM) and cryometamorphic (CRM) horizons (Table 1). It is believed that the BPL horizon "reflects the specifics of soil transformation (metamorphism) processes under ultracontinental climatic conditions; it is characteristic of the soils of taiga landscapes of Central Yakutia and of cold steppes and tundra-steppes in the mountain systems of Siberia" [39, p. 50]. The BPL horizon is given a diagnostic value for the types of cryoaridic and pale (palevye) soils, and it serves as the basis for their association in the same order of pale-metamorphic soils [22, 39]. The idea of close relationships between cryoaridic and pale soils was put forward long ago. For example, while studying the soils of the steppe slopes of the Yana-Oymyakon Highlands, Naumov and Andreeva wrote about their similarity with neutral soddy forest soils (at present, palevye soils) of Central Yakutia [32]. A similar genesis was also supposed for the soils of the steppe and tundra-steppe landscapes of continental Chukotka and the pale soils of taiga landscapes in the ultracontinental permafrost regions of Eastern Siberia [8].

The new materials obtained by us and the results of discussions made it possible to clarify the characteristic properties of the first middle-profile horizon of cryoaridic soils and to question the presence of BPL horizon in cryoaridic soils. The analysis of morphological descriptions and color determinations on the Munsell scale indicates that the BPL horizon of pale and cryoaridic soils is darker and "more brown" than indicated in the classification: its color in the studied soils, as a rule, varies within 10YR 3–5/2–4 (earlier, in the description of the horizon, it was supposed to be lighter: 10YR 7–8/3 (Table 1, Fig. 3; Fig. S2). This horizon has a poorly pronounced structure in comparison with that in the middle-profile horizons of chestnut and brown arid soils (Table 2). However, it is also not completely structureless as indicated in [39]. It is characterized by the weak angular blocky or prismatic aggregates (Fig. S2-a); less often, there are cryogenic lenticular post-schlieren structures (Fig. S4-f).

At the level of aggregates of the first order in the BPL horizon, there are significant differences between pale (palevye) and cryoaridic soils. Very fine (up to 1 mm) cryogenic aggregates were described in the BPL horizons of pale soils: granules (ooids) with a characteristic orientation of clay along the aggregate periphery and fine layering associated with the formation of thin ice lenses during the soil freezing [27, 30, 48, 58]. These cryogenic features, though not mentioned as diagnostic in [39], reflect the specificity of the BPL horizon along with its pale yellow color and weak aggregation. In cryoaridic soils, coarse skeletal grains are covered by clayey–silty coatings composed of the material of the enclosing horizon (Fig. 3b, Figs. S2-b, c, d). The cryogenic granular (ooid) structure characteristic of pale soils is, as a rule, less pronounced in cryoaridic soils, except for the least arid soils of this group (Figs. S2-c and S2-d). Even under these conditions, post-schlieren structures may be absent in cryoaridic soils [25]. The weak expression of features reflecting the cryogenic nature of the paleo-metamorphic horizon raises doubts about the need to identify it as a diagnostic middle-profile horizon for cryoaridic soils. It would be more correct to attribute the elements of the paleo-metamorphic horizon present in cryoaridic soils to the level of the diagnostic feature and to indicate it by small letters *pl*. At present, this feature is considered to be diagnostic of the subtype of pale-metamorphized cryozems having the cryometamorphic CRM middle-profile diagnostic horizon [39]. The use of this symbol for other soils, including cryoaridic soils, supposes some extension of its diagnostic criteria. It is suggested that the *pl* feature should not be associated only with cryozems. The presence of cryogenic features—fine granular (ooid) structure and silty–clay coatings on coarse fragments—should be added to the list of diagnostic characteristics of the *pl* feature.

Thus, the first middle-profile horizon of cryoaridic soils has not very clearly expressed characteristic features of the paleo-metamorphic (BPL) horizon. It only displays the features of "pedogenic transformation of the parent rock" [39, p. 47], which is characteristic of the structural-metamorphic BM horizon (Table 2). How to correctly designated this horizon? According to the rules of the new Russian soil classification system, diagnostic features (in contrast to diagnostic horizons) are used to separate genetic subtypes of soils. Their symbols should be added to the symbols of corresponding diagnostic horizon, or transitional horizon, or parent material. The question arises, to which horizon should the index *pl* be added in order not to lose information about the cryoaridic soil? The first middle-profile horizon of cryoaridic soils is most often free of pedogenic carbonates, so it cannot be indexed as the carbonate-accumulative (BCApl) horizon. It also does not fit criteria for the metamorphic BM horizon, as this horizon is separated for clay loamy and clayey soils and should have distinct structure [22, 39]. An alternative and perhaps more correct option is to add a small pl symbol to the transitional nondiagnostic B horizon, which does not have the features of other middle-profile diagnostic horizons. The use of several non-diagnostic horizons to represent subtype features is proposed as part of an update of the Russian soil classification system [52].

The carbonate-accumulative horizons (BCA) of cryoaridic soils differ from those in other soils by the presence of a distinct (and often, the only) form of pedogenic carbonates: multilayered coatings on rock fragments (Figs. S3-b, c, d); along with them, carbonate impregnation of the soil mass may take place (Fig. S3-a). These pedofeatures were not mentioned in the general description of the BCA horizon [39, p. 51], but were included in the description of this horizon for the order of pale-metamorphic soils [39, p. 89]. Segregational forms of carbonates in cryoaridic soils are extremely rare. The presence of the BCA horizon in cryoaridic soils is beyond doubt. Most often, this horizon strongly effervesces with HCl. However, there are also low-carbonate varieties, where the fine earth of the BCA horizon contains little carbonates, but multilayered carbonate pendants are distinct on numerous rock fragments [6, 13, 14, 25, 26, 34, 35, 43].

Horizonation of the profile and position of the type of cryoaridic soils in the classification system. The above clarifications concerning the morphogenetic features of cryoaridic soils allow us to propose some

Table 2. Comparison of the diagnostic features of cryoaridic, pale, chestnut, and brown arid soils (according to published data and field materials)*

Feature	Soils			
	cryoaridic	pale	chestnut	brown arid
Humus horizon	AK	AY	AJ	AJ
Biogenic features	Present	Few	Many	Few
Color of the humus horizon	Dark brown 10YR 3(4)/3(4)	Grayish brown 10YR 3–6/2–3	Brown 10YR 4(5)/2–6	Light gray 10YR 7/2
Surface crust	May be present	None	None	May be present
First middle-profile horizon (B)	Bpl(ic) or BMpl(ic)	BPL	BMK/BM	BM
Macrostructure of middle-profile horizons	Weak or moderate	Weak	Moderate or strong	Moderate or strong
Cryogenic meso- and microstructure of middle-profile horizons	Weak or moderate	Moderate or strong	Indistinct	Indistinct
Color of the middle-profile horizons	Pale 10YR 3–5/3–4	Pale 10YR 3–6/2–4	Reddish brown (chestnut) to brown 10YR 4–6/3–6	Brown 10YR 4/6
Carbonate-accumulative horizon	BCAic(ic,dc)	BCAdc,mc	CATnc, BCAnc	BCAnc
Forms of carbonate concentrations	Effervescence of fine earth in the BCA horizons; pendants on rock fragments; dispersed calcite	Disperse carbonates and carbonate pseudomycelium	Effervescence from the AJ horizon; segregational forms of carbonate concentrations	Effervescence from the AJ horizon; segregational forms of carbonate concentrations
Cryogenic features in the profile and on the soil surface	Moderately pronounced; polygonal cracks; silty and silty–clay coatings on upper sides of rock and around small grains; ooidal aggregates; post-schlieren organization of the soil mass	Polygonal surface; cryogenic cracks; cryoturbation; post-schlieren organization of the soil mass; ooidal microstructure with skelsepic orientation of clay	Few/none	Few/none

* Munsell color was determined at the field water content corresponding to a range from dry soil to slightly wet soil.

changes to the typical profile formula. It can be represented by one of the following options: AK–Bpl–BCAic–C(ca); AK–BMpl–BCAic–C(ca), the second option, as discussed above, is less appropriate. The feature “ic” is indicative of carbonate pendants and is not obligatory, though it emphasizes the specific character of the profiles of cryoaridic soils.

If we refuse to identify the BPL horizon in the cryoaridic soils, then they should be withdrawn from the order of pale metamorphic soils, though cryoaridic soils have some common features with pale soils. For this reason, we suggest some correction to the principle of the new Russian soil classification system and introduce the diagnostic feature—subtype attribute *pl*—to the characteristic of the type of cryoaridic soils. In fact, this is not the only case in the classification system. Thus, in the orders of texture-differentiated and Al–Fe-humus soils, the symbol of gleyic feature (g) was added to the symbols of major diagnostic horizons EL, BEL, BT, E, and BHF; to characterize the type of solods, diagnostic features *ca* (residual carbonates) and *s* (soluble salts) are added to the symbols of major horizons [39].

Cryoaridic soils can also be classified within the order of light-humus carbonate-accumulative soils. This order is characterized by the carbonate-accumulative BCA middle-profile diagnostic horizon, which is typical of all soils of the order. These are the types of chestnut, brown arid, and light-humus carbonate-accumulative soils [39]. However, it we accept this decision, then we should replace the term "light-humus" by a less specific "humus" in the name of this order. In our opinion, the morphogenetic and chemical properties of cryoaridic soils and the conditions of their formation are close to those in brown arid soils of semi-deserts and chestnut soils of dry steppes than to those in pale soils of permafrost-affected taiga landscapes.

Soils with a cryohumus horizon on thin and strongly skeletal rocks of mountain slopes, as a rule, have a shortened profile with an incomplete set of diagnostic horizons. In some profiles, only cryohumus horizon is formed, and middle-profile horizons are absent. Such soils can be classified as the type of cryohumus soils in the order of organo-accumulative soils. Their typical horizonation is: AK–C [39].

Subtypes of cryoaridic soils. The subtype division of cryoaridic soils has so far been poorly developed due to insufficient data on their genetic and geographical diversity. The accumulated field material, the results of studies of cryoaridic soils in the Central Museum of Soil Science, as well as the analysis of previously published data on cryoaridic soils of Tuva, Altai, Buryatia, eastern Transbaikalia, Yakutia, northeast of Russia, and Mongolia allow us to verify the subtypes of cryoaridic soils in the classification system and to introduce new subtypes [2, 13, 14, 20, 26, 29, 37, 47, 49, 51, 54]. In the latest version of the classification [39], subtypes are not too rigidly attached to the type, and any subtype can be distinguished within any type. However, for each order, there is a list of subtypes that are most characteristic of and/or are frequently found in the soil types belonging to this order. The list of possible subtypes in the order of pale metamorphic soils includes the subtype with carbonate pendants (feature *ic*, illuviation of carbonates). For cryoaridic soils, the presence of carbonate pendants is an obligatory characteristic. Thus, there is no need in the separation of this subtype. Cryoaridic soils with carbonate pendants can be distinguished as typical cryoaridic soils (Figs. S4-a, b).

In the existing list of subtypes, three subtypes have been described by us for cryoaridic soils: dark-tonguing, surface-turbated, and postagrogenic soils.

Dark-tonguing cryoaridic soils (Fig. S4-g) were described in the highlands of Tuva and Altai and, singly, in Yakutia (on the solar slope near the settlement of Tomtor); they are relatively rare soils, and they are formed in the regions, where the deficit of soil moisture is not very sharp.

Surface-turbated cryoaridic soils were described in different regions. Mechanical disturbances can be caused by various reasons and are not specific to cryoaridic soils. Most often, these are anthropogenically disturbed soils.

In general, the set of natural conditions in the areas of cryoaridic soils is not favorable for agriculture and, accordingly, the formation of agrogenic features in the soil profile. However, *postagrogenic cryoaridic soils* have been described in the large depressions of Tuva and Transbaikalia, where these soils were widely used for arable land, especially in Soviet times. Postagrogenic cryoaridic soils are diagnosed by a relatively smooth border of the former agrohorizon. The former fields are perfectly visible on remote sensing materials, including satellite images and images taken from unmanned aerial vehicles.

Gleyic and cryoturbated subtypes of cryoaridic soils are unlikely because of low precipitation, deep and low-ice permafrost.

Along with the subtypes already included in the list, several new subtypes can be added as the subtypes characteristic of the type of cryoaridic soils. Thus, cryoaridic soils with brown, dark brown, and reddish brown humus pendants on clastic material in all horizons (in the BCA horizon, humus layer often lie over multi layered carbonate pendants on large gravels and boulders; Figs. S4-i, k) are widespread in the high mountains of the Altai and Sayany Ranges and also, according to previously published data [7, 8, 43, 54] and our study of soil cores in the Central Museum of Soil Science, in Chukotka. Such pendants or layers in multilayered pendants composed of collomorphic, translucent in reflected light, isotropic substance, are not always enriched in iron oxides despite their bright reddish-brown and ocherous-brown colors; their reddish hue is mainly dictated by the organic matter, and the color intensity is proportional to its content [6, 25]. There is evidence that such humus layers (pendants) reflect the Al–Fe-humus stage of profile development: illuviation of organic matter in the form of chelate complexes with iron and aluminum. Thus, their presence is a heritage of a more humid phase of soil formation in the recent Holocene past [6, 43]. None of the previously proposed genetic features reflecting the processes of organic matter illuviation—*hi* (humus illuviation), *sn* (solonetzic), or *i* (clay illuviation)—does not accurately reflect the genetic nature of humus pendats in cryoaridic soils. In fact, the presence in the profile of humus pendants formed by the colloidal migration and illuviation of organic matter corresponds to the genetic feature identified by the BH symbol (as an exception, this symbol is given in capital letters).[5] The content of organic carbon (recalculated to humus) in the horizons with humus pendants is from 0.8 to 2%, and not >3%, which is a criterion for the BH horizon; also, these pendants contain very little oxalate-soluble forms of iron (up to 0.3–0.5%). Among earlier suggested diagnostic features, these properties correspond to the humus-illuvial (*hi*) feature. However, in this case, the definition of this feature must be modified by adding the presence of dark-colored brown and reddish-brown coatings (pendants) on skeletal particles: gravel, crushed stone, boulders. Cryoaridic soils with brightly colored humus coatings are proposed to be separated as a subtype of *humus-illuvial cryoaridic soils*; the presence of the coatings themselves should be

[5] See comments in [39] (pp. 45, 60, 62) and in [52].

reflected either by the already existing small *hi* symbol (with some revision of its definition), or by a new *hc* symbol (from the English "humus coating").

Cryoaridic soils with massive accumulations of coarse root detritus in the Bpl and BCA horizons have been described in Southeastern Altai, Tuva, and Yakutia. These accumulations are usually confined to the lithological contact with highly skeletal layers that mechanically restrict root penetration (Figs. S4-h, g). Analytically, this is reflected in the second maximum of the organic matter content in the profile. Considerable accumulation of root detritus may lead to the local acidification of the host horizon. Soils with massive accumulation of coarse root detritus at lithological contacts can be distinguished as an *intraprofile-detritus subtype*, and the presence of detritus itself can be reflected by adding symbol *dr* (from detritus of roots) to the symbol of the horizon.

In some profiles of cryoaridic soils, we observed post-schlieren structures and specific cryogenic lenticular structure in the middle-profile (BCA) horizon analogous to that in the cryometamorphic (CRM) horizon. The presence of these cryogenic structural features can be indicated by symbol *crm* (cryometamorphic feature) (Fig. S4-f). These features have been described in cryoaridic soils of the high mountains of Altai and Tuva, on relatively heavy-textured parent materials with a higher water-holding capacity. Owing to this, the moisture deficiency in the soil is less pronounced, and the development of cryogenic structures becomes possible. Cryoaridic soils with a pronounced cryogenic granular and post-schlieren layered structures can be attributed to the *cryometamorphic subtype*.

In some places, in the most arid variants of cryoaridic soils (the Ubsunur and Chuiskaya depressions), there is no sod in the upper part of the profile, and a crust of up to 1–2 cm in thickness is formed on the soil surface (Fig. S4-n). This is reflected by the inclusion of the *akl* feature: single-layer friable cavernous crust with a vesicular layer, often with inclusions of gravels, underlain by loose structureless sandy–loamy material (Fig. S4-l). Fragments of hard crystalline rocks on the crust surface are usually covered by desert varnish (Figs. S4-m, o). We suggest that the most arid varieties of cryoaridic soils with the *akl* feature should be separated as a *xerohumus subtype*, which is currently reserved exclusively for the order of light-humus carbonate-accumulative soils [39]. In this order, the akl feature implies a vesicular crust and a layered subcrust microhorizons of 1–3 cm in thickness each. In the cryoaridic soils, only the vesicular crust is present; the subcrust microhorizon is loose, noncoherent, but it has no distinct layering (Figs. S4-l, n, o).

Volkovintser believed that the accumulations of gypsum and soluble salts are not characteristic of cryoaridic soils. However, according to our data, cryoaridic soils may contain small amounts (fractions of a percent) of soluble salts; this may be reflected at the subtype level: *saline soils*. Saline cryoaridic soils were described in the Chuiskaya Depression [47]. Gypsum is sometimes found in the lower carbonate-accumulative horizons (from a depth of 80–100 cm), mainly as part of layered pendants on rock fragments (Figs. S4-c, d). Thus, a *gypsiferous* subtype can be distinguished.

In addition to the carbonate coatings and pendants (the *ic* feature), that are widely distributed among cryoaridic soils, *dispersed carbonates* (the *dc* feature; fine calcite grains impregnating the soil mass without visible concentrations) have also been described in cryoaridic soils of the Transbaikal region. These soils are usually confined to the least gravelly substrates, especially to loamy sandy substrates (Fig. S4-e). Impregnating or farinaceous forms of carbonates were previously considered a facies feature of the steppe soils in this region [23, 34].

CONCLUSIONS

Detailed field studies and the study of soil monoliths from the museum collection confirmed the opinion of V.I. Volkovintser about the specificity of cryoaridic soils and their separation from chestnut soils. Cryoaridic soils have a specific cryohumus horizon, which has no analogues among other diagnostic horizons of the new Russian soil classification system, and the properties of which clearly reflect the specificity of soil forming conditions. At the same time, cryoaridic soils have common features with both pale yellow (palevye) permafrost-affected taiga soils and chestnut soils of dry steppes. In contrast to the latter, cryogenic features are distinct in the cryoaridic soils; in particular, their cryogenic microstructure. However, they are no so clearly expressed as in the pale permafrost-affected soils and are inferior to biogenic features.

The profile of cryoaridic soils in the Russian soil classification system consists of the following diagnostic horizons: AK–BPL–BCA–Cca. However, taking into account the insufficiently pronounced expression of cryogenic features characteristic of the BPL horizon, we argue that, in cryoaridic soils, it should be given the status of not a horizon, but a feature and be designated by symbol *pl*: Bpl. For pale (palevye) permafrost-affected soils, the BPL horizon is retained as a diagnostic horizon. Thus, the formula of a typical profile of cryoaridic soil should be written as follows: AK–Bpl–BCA–C(ca).

Cryoaridic soils can be introduced into the order of light-humus carbonate-accumulative soils, which also includes chestnut and brown arid soils. However, in this case, it is desirable to replace the name "light-humus" for simply "humus," because the upper (humus) horizons of the soils included in this order will be different.

In the Russian soil classification system [22], only a typical subtype of the type of cryoaridic soils was identified. In the later published field guide [39], a general list of soil subtypes in the order of pale-metamorphic soils (hosting cryoaridic soils) was suggested. Out of this list, the following subtype qualifiers can be used: dark-tonguing, surface-turbated, and postagrogenic. Other subtypes may be added: cryometamorphized, disperse-carbonate, and intraprofile–detrital. The latter subtype is unique and is only characteristic of cryoaridic soils with accumulations of coarse root detritus. The humus-illuvial subtype can also be considered unique; it is probably associated with the past more humid phase in the development of cryoaridic soils. Under the most arid conditions, subtypes of xerohumus, saline, and gypsiferous cryoaridic soils can be distinguished. The expansion of the set of subtypes makes it possible to reflect the geographic diversity of cryoaridic soils.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY INFORMATION

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Fig. S1. Morphology of the cryohumus (AK) horizon of cryoaridic soils.

Fig. S2. Morphology of the pale-metamorphic (Bpl) horizon of cryoaridic soils.

Fig. S3. Forms of carbonates in carbonate-accumulative horizons (BCA).

Fig. S4. Subtypes of cryoaridic soils.

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