

# Modern and relict features in clayey cryogenic soils: Morphological and micromorphological identification

*Rasgos modernos y actuales en suelos criogénicos arcillosos: identificación morfológica y micromorfológica*

*Características modernas e ancestrais de solos criogénicos argilosos: identificação morfológica e micromorfológica*

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## ABSTRACT

The research was performed in the south-eastern part of Russia. Soils were formed on clayey parent materials under an extreme continental climate favorable for the deep freezing and maintenance of permafrost. Based on morphological, micromorphological, physical and chemical attributes, the soils represent a soil complex that includes Vertic Luvic Phaeozems (Clayic and Turbic) and Luvic Phaeozems (Clayic and Turbic). Decomposition, aggregation, eluviation, illuviation, pedoturbation, mineralization and hardening result from accumulation and transformation of organic matter, freeze-thaw, shrink-swell, and translocation processes, and cryoturbation. The soil complex is interpreted as polygenetic. Interpretations were made in order to differentiate modern soil processes from relict ones. The most ancient features correspond to the cold Pleistocene glacial period and include cryogenic wedges, permafrost involutions, disrupted soil horizons, cryogenic sorting of coarse material, and accumulation of the organic matter above the permafrost. A subsequent stage of pedogenesis under a warmer and wetter environment is reflected by black humus crack infillings, black humus aggregates deep in the subsoil, vertical translocation of mobile organic matter, and the formation of clay coatings. Finally, the current climate is a warmer but more arid pedoenvironment. It is recorded in the soil complex by brownish fulvic humus and the formation of vertic features. Even in this last relatively warm climatic stage, vertic features formed by shrinking and swelling processes co-exist with annual deep freezing of the soils and subsoil permafrost at a depth of about ~300 cm.

## RESUMEN

*Este estudio se llevó a cabo en el sureste de Rusia. Los suelos están formados sobre materiales arcillosos bajo un clima continental extremo que favorece la congelación de los niveles profundos y mantiene el permafrost. De acuerdo con sus características morfológicas, micromorfológicas, físicas y químicas, los suelos representan un complejo edáfico que incluye Phaeozems Vérticos Lúvicos (Argílicos y Túrbicos) y Phaeozems Lúvicos (Argílicos y Túrbicos). Los procesos de descomposición, agregación, eluviación, iluviación, edafoturbación, mineralización y endurecimiento resultan de la acumulación y transformación de la material orgánica, hielo-deshielo, contracción-expansión, translocación y crioturbación. El complejo edáfico se interpreta como poligenético. Las interpretaciones se han realizado para diferenciar los procesos de edafogénesis modernos de los relictos. Los rasgos más antiguos están datados del periodo glacial frío del Pleistoceno e incluyen cuñas criogénicas, involuciones del permafrost, horizontes edáficos desorganizados, distribución criogénica del material grueso y acumulación de materia orgánica sobre el permafrost. Una posterior edafogénesis asociada a un ambiente más cálido y húmedo se refleja en rellenos de grietas con humus negro, presencia de agregados de humus negro en profundidad, translocación vertical de materia orgánica y formación de revestimientos de arcilla. Finalmente, el clima actual es más cálido pero más árido y esto se refleja a través de humus fúlvico pardo y la formación de rasgos vérticos. Incluso en este último periodo cálido los rasgos vérticos formados por procesos de contracción y expansión coexisten con la congelación anual en profundidad de los suelos y el desarrollo de permafrost a una profundidad de ~300 cm.*

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## RESUMO

*Esta investigação foi realizada na parte sudeste da Rússia, e os solos em causa formaram-se sobre materiais parentais argilosos em condições de clima continental extremo favorável à congelação dos níveis profundos do solo e à manutenção do permafrost. De acordo com as suas características morfológicas, micromorfológicas, físicas e químicas, os solos representam um complexo que inclui Phaeozems Vérticos Lúvicos (Argílicos e Túrbicos) e Phaeozems Lúvicos (Argílicos e Túrbicos). Os processos de decomposição, agregação, eluviação, iluviação, pedoturbação, mineralização e endurecimento resultaram da acumulação e transformação de material orgânico, congelação-descongelação, contração-expansão, translocação e crioturbação. Interpretou-se o complexo do solo como sendo poligenético. As interpretações foram feitas para diferenciar os processos de pedogénese modernos dos antigos. As características mais antigas remontam ao período glacial frio do Pleistocénico e incluem cunhas criogénicas, involuções do permafrost, horizontes edáficos desorganizados, distribuição criogénica do material grosseiro e acumulação de matéria orgânica sobre o permafrost. Uma pedogénese posterior associada a um ambiente mais quente e húmido reflecte-se no aparecimento de fendas preenchidas com húmus negro, presença de agregados de húmus negro em profundidade, translocação vertical de matéria orgânica e formação de películas de argila. Finalmente, o clima actual é mais quente e mais árido e esse facto reflecte-se no aparecimento de húmus fúlvico pardacento e características vérticas. Mesmo neste último período mais quente as características vérticas formadas por processos de contração e expansão coexistem com a congelação anual dos solos em profundidade e com o desenvolvimento de permafrost a uma profundidade de ~300 cm.*

## 1. Introduction

TransBaikal region or Zabaikalie is situated to the south-east of Lake Baikal in the Buriatia republic. The remoteness of this region, severe climate and shallow permafrost restrict detailed field studies of soils, and result in a limited knowledge about the pedodiversity of this territory. Previous research papers and monographs were published describing the soils and landscapes of Buriatia (Nogina 1964; Ufimtzeva 1967; Makeev 1968; Korsunov 1989; Badmaev et al. 2006).

Buriatia is predominantly a mountain and highland region and the parent material is mostly represented by Early Paleozoic hard rocks with limited occurrences of sedimentary material of different geneses and compositions (calcareous rock, volcanic rock, sandstone and siltstone) (Goryachkin et al. 2009). As a result, soils are generally coarse textured, with limited occurrences of moderately fine and fine-textured clayey soils. The main features of most soils in Buriatia are coarse-textures, high gravel and stone contents, variability in cryogenic features, and specificity of the organic matter. Published overviews mostly discuss the specificity of Chernozems, Kastanozems and Luvisols in cryogenic environments (Nogina 1964; Ufimtzeva 1967; Korsunov 1989).

Silty-clay and clayey soils are rare in this region (Goryachkin et al. 2009). Only limited information exists about these clayey soils of Buriatia, which were most commonly classified as Solonetz (Nogina 1964; Ufimtzeva 1967). Meanwhile, some soils did not have the characteristically high exchangeable Na<sup>+</sup>, features of Solonetz soils, and were described as low-sodium Solonetz soils (Khantulev 1954; Nogina 1964). The most well-studied clayey soils were investigated in the Chita region, the very eastern part of Zabaikalie. These soils were formed in lacustrine and colluvial parent materials in the Nerchinsk depression (Nogina 1964; Ufimtzeva 1967; Alifanov et al. 2010).

### KEY WORDS

Soil forming processes, evolution, permafrost, cryogenesis, shrinking and swelling, TransBaikal

### PALABRAS

#### CLAVE

Procesos de edafogénesis, evolución, permafrost, criogénesis, contracción y expansión, TransBaikal

### PALAVRAS-

#### CHAVE

Processos de pedogénese, evolução, permafrost, criogénese, contracção y expansão, TransBaikal

## 2. Materials and Methods

The purpose of the present research was to provide a detailed investigation of clayey soils in western Trans Baikal, considering current concepts of modern soil science. This will help to provide a better understanding of specific pedogenic pathways in clayey soils under extreme continental environments. We were interested in verifying possible shrink-swell activity in these clayey soils as differentiated from features associated with freeze-thaw phenomena of volume change.

The study site was located in the large intermountain depressions with bedrock of Mesozoic age, characteristic for the southern part of Eastern Siberia. Lacustrine sediments cover the central part of the basin and surrounding slopes, where they are combined with eluvial and deluvial material of the hard rocks. Our investigations were performed on a south-facing slope of a local watershed near the Bol'shoe Eravnoe lake in Eravninskaya depression, 52°38'433 N and 111°25'080 E (Figure 1). Soil parent materials are represented by Paleogene-Neogene lacustrine, alluvial and alluvial-colluvial deposits. The slopes of local ridges are usually covered by lighter-textured sediments, which result in the formation of complex polygenetic soil-lithological sequences.



Figure 1. Site location (indicated by star) in TransBaikal region, Buriatia, Russia.

The vegetation of the area is represented by birch-larch forest in the top and northern slopes of the local ridges, changing into steppe grass/herbaceous vegetation along the warmer southern slopes. The pit was excavated under the sparse forbs-grass vegetation including *Artemisia*, *Agropyron*, *Cleistogenes*, *Bromopsis*, *Potentilla*, *Leymus* etc. The soil surface was slightly wavy and dissected by a polygonal network of cracks that were closed at the time of field investigations. The climate of this area is extra continental with MAT -4 °C, low precipitation (MAP ~300 mm with the maximum at the end of August-September), short warm dry summers (mean  $T_{Jul}$  19 °C), cold winters (mean  $T_{Jan}$  -26.5 °C) and little snow cover. The end of the 20th century was marked by increased temperatures and precipitation (Shimarev et al. 2002).

Due to the cold winter temperatures (up to -45... -55 °C) and little snow cover, TransBaikal represents the territory with maximal seasonal freeze-thaw phenomenon in the soils (Epstein 1962). Other pedogenic processes are active mostly during summer 2.5-3 months. The severe winters with little snow cover result in deep annual freezing of soils up to 300-400 cm. Soil excavations at the end of August revealed the permafrost at a depth of about 240-280 cm. There has been a trend for the depth of permafrost to increase during the last 100 years from about 100-150 cm in depth at the beginning of 20<sup>th</sup> century up to about 200-250 cm at the end of century (Kulikov 1987). This may be explained by global warming processes as well as natural oscillation.

The specific environmental characteristics for the pedogenic processes in these soils are an extremely cold environment, permafrost, deep freezing, and clayey parent materials that contain pockets of gravel and stone inclusions.

### 2.1. Field studies

A soil pit 120 x 150 cm in cross-section by 140 cm deep was dug with a shovel in the well-drained, convex, middle hillslope of a local ridge facing south-east towards a lake, at an absolute

elevation of about 976 m a.s.l. Strong differences in morphology were found between three soil profiles from the central, left and right walls of the pit (Figure 2). These three soil profiles were described and sampled separately. In spite of differences among these profiles, because of paper space limitations most of the data presented herein are for the central profile. Bulk samples for physical and chemical analyses in the laboratory, and undisturbed soil clods for thin sections were taken from the genetic horizons. Soil morphology was described according to USDA (Schoeneberger et al. 2002). Soils and horizons were identified using the World Reference Base (IUSS Working Group 2006).

### 2.2. Laboratory studies

Samples were finely crushed after all roots were removed. Soil pH values were determined with soil-to-water ratio of 1:2.5, and particle size distribution – by pipette method. X-ray diffraction (XRD) was performed using XZG-4A Carl Zeiss Jena X-ray diffractometer (40 mA, 30 kV) on oriented specimens of the clay fraction (< 1 µm) after Mg and ethylene glycol saturation, and heating at 550 °C. Clay minerals were identified using d-spacings on a standard base.

Oxalate- ( $Fe_o$ ) and dithionite citrate bicarbonate- ( $Fe_d$ ) extractable Fe were determined according to Soil Survey Staff (1996). Chemical analyses were performed on bulk samples collected from each horizon. Total organic carbon ( $C_{org}$ ) was determined by wet combustion with potassium dichromate and concentrated sulfur acid, and exchangeable cations according to the procedure of Shollenberg (Vorob'eva 2006).

Soil organic matter fractions were determined on the basis of extractability in NaOH and solubility upon acidification of alkaline extracts into humic acids (HA), fulvic acids (FA) and insoluble humin according to Ponomareva and Plotnikova (1980). Parameters of humus status, including the degree of humification ( $C_{HA}/C_{org} \cdot 100\%$ ), type of humus according to  $C_{HA}/C_{FA}$  were calculated using Orlov et al. (1996).

Bulk chemical composition was analyzed using energy-dispersive X-ray fluorescence (XRF) after the preliminary determination of the loss on ignition in the specimens by heating at 900 °C. Concentrations of major chemical elements are presented for the unheated specimens. Stable isotopic composition of carbon in soil organic matter was determined for 27 bulk samples of soil matrix collected from each soil profile and along the cracks that were filled with black humus-rich material. Stable isotope composition of carbon in soil organic matter was determined using IRMS Finnigan Delta V<sup>+</sup> in A.N. Severtsov Institute of Ecology and Evolution, RAS. Organic remnants of roots and debris were hand picked from soil samples prior to analysis. Dried soil samples were powdered and reacted with 10% HCl to remove any inorganic carbon, washed with deionized water and centrifuged until neutral reaction, dried and powdered again. The isotopic ratios of carbon are reported in standard  $\delta$ -per mille notation relative to V-PDB.

Undisturbed oriented blocks were impregnated with polysynthetic resin, mounted on 4 x 4 cm glass slides, polished to 30  $\mu$ m thickness and covered by glass for micromorphological descriptions according to Stoops (2003). Optical examinations of microfabrics were made under plane (PPL) and crossed-polarized (XPL) light modes at magnifications of 25x to 100x.

## 3. Results and Discussion

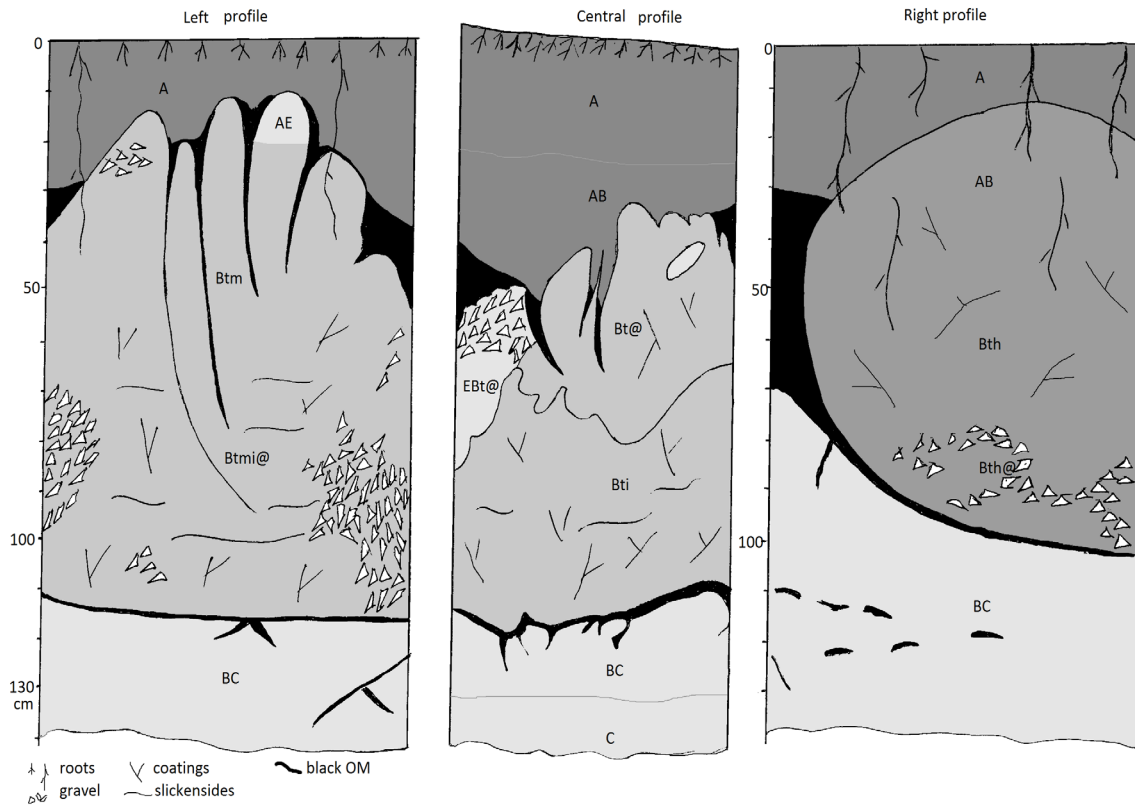
### 3.1. Morphology

Based on field morphology three types of soil profiles were identified, which we referred to as 1) “cryogenic” – in the *central* pit’s wall, 2) “organic” – on the *right* side and 3) “consolidated” – on the *left* side of the soil pit (Figure 2). Morphological features are shown in the Table 1. All three profiles have generally similar set of horizons with variations

in color, texture and structure with depth. They lack any carbonate, gypsum or Fe/Mn pedofeatures, but have large light-gray gravelly inclusions of irregular form, fine to medium fissures and cracks, sandy lower horizons, clayey subsurface horizons and strong clay-organic coatings on ped surfaces. Fragments of bleached zones or horizons may occur below the organic-rich horizons, but these features are the most developed in the left part of the *central* profile. The bleached groundmass has a tendency to be platy in structure and is enriched in quartz. The middle part of all three profiles has a fine granular structure that is covered with prominent brown humus-clay coatings.

The unique characteristics of each soil profile are discussed below. The *central* profile has the most prominent cryogenic features. At a depth of ~40 to 80 cm it is strongly disturbed and the horizons are fragmented by cryoturbation and solifluction. A number of sub-parallel fine black linear features are interpreted as the termini of the cracks and fissures marked by black organic matter that has fallen down from overlying horizons and filled the cracks. The lowest and more pronounced dark sub-parallel linear features are ~3-5 cm thick and at a depth of between 110-120 cm. The cumulative thickness of the humus-rich horizons varies from 30 to ~70 cm. The upper part is more brownish in color, while organic matter at greater depths becomes darker and turns black in color at the greatest depths. Small shiny wavy surfaces similar to slickensides were found at a depth between 90 and 130 cm.

The *left* “consolidated” soil profile is remarkable in terms of its extreme density in the middle part. It has weaker evidence of cryoturbation than the other profiles but does show several zones of cryogenically-sorted and enriched coarse fraction. It also exhibits clear straight fissures from the surface to a depth of 50-80, (with a maximum up to 100 cm). The humus horizon is about 12 cm thick, brownish without black in color. This profile is the lightest in color among the three profiles examined. It has common faint slickensides and very fine wedge-shaped peds in the middle part of subsoils.



**Figure 2.** Left, central, and right profiles of the soil pit. The gradation of gray color corresponds to three main layers of different texture and color.

The *right* soil profile also has slight cryogenic and pedoturbation features, but is the most “organic-enriched”. Its color is the most monotonous due to the deepest penetration of roots, humus impregnation of the groundmass, and expression of dark-brown clay-humus coatings. It is less compact and less consolidated compared with the *left* profile. It is without straight fissures. But the large cryogenic wedge associated with the long curved crack is infilled with black organic matter. It was observed in the left corner of the *right* profile connecting with the *central* profile. Apparently this part of the soil pit reflects the wetter pedoenvironment.

### 3.2. Micromorphology

Micromorphological features follow same pattern as the soil features at the macroscale. The major features are represented in [Table 2](#). Most of the features support the role of active cryogenic processes. Pedality is strongly developed in all horizons. The small and complex granular and crumb aggregates of the upper part are replaced by a simple large subangular and angular blocky structure with some elements of platy and lenticular (wedge) pedality at depth. Granular and subangular blocky microstructures with compact peds are typical for clayey cryosols. This is the result of abrupt cooling and freezing of the originally water-saturated unconsolidated

**Table 1.** Morphological properties of studied soils (central profile)

Horizon, Depth, cm	Munsell color (dry)	Texture / Field consistence / Stickiness	Structure	Mottles / Special features / Boundary	Rock fragments / Roots
Central					
A 0-5	7.5YR2.5/1	Silty loam / Loose / NSTC	Sts	Abs / Abs / Gradual, smooth	Vf fine gravel / Mn fine
A 5-25	7.5YR2.5/1	Clay / soft / NSTC	Weak Sbc	Abs / Black Fs and Cr / Gradual, smooth	Cm fine gravel / Mn fine
AB 25-45/50	7.5YR2.5/1 & 7.5YR2.5/2	Clay / Slightly hard / NSTC	Sbc, Pr	Dark ft / Black Cs and Cr / Gradual, irregular	Mn fine gravel / Cm fine
Bt@ 45/50-70	7.5YR2.5/1	Clay / Very hard / NSTC	Abc	Dark ft / Vf SS, Black Fs and Cr / Clear, broken	Cm fine gravel / Mf fine
EBt@ 37/70-80	7.5YR7/1 & 2.5Y5/3, 2.5Y3/2	Sandy clay loam / hard / NSTC	weak Pr & thin Pt elements	Dt white silica powdery Ct and mottles / Gravel concentrations, Black Fs and Cr / Clear, smooth	Few fine gravel / Mf fine
Bti 80-110/117	2.5Y5/3	Silty clay / Very hard / SSTC	Pr, strong medium Gr	Str Ct 7.5YR3/2 / Very fine black Fs / Abrupt, irregular	Vf fine gravel / Mf fine
BC 110/117-130	2.5Y5/3	Clay / hard / SSTC	Strong medium Gr	Dt Fe 10YR5/3 / Terminus of black Fs, Fe stains, F SS / Clear, smooth	Abs / Vf fine
C 130-140	2.5Y6/3	Clay loam, Slightly hard / SSTC	Ms	Dt Fe 2.5Y6/8 / Terminus of black Fs, Fe stains, Vf weak SS	Abs / Vf fine

Structure: Abc – angular-blocky, Sbc – subangular blocky, Gr – granular, Pr – prismatic, Ms – massive, Wd – wedge, Pt – platy, St – structureless; Mottles: Ft – faint, Pr – prominent, Dt – distinct, Str – strong; Stickiness: STC – sticky, SSTC – slightly sticky, NSTC – non sticky; Abundance: Vf – very few, F – few, Mf – Moderately few, Mn – many, Cm – common; Other: – Fs – fissures, Cr – cracks, CrWd – cryogenic wedge, SS – slickensides, Ct – coatings, Abs – absent.

clays (Van Vliet-Lanoë et al. 1984, 2004). The formation of wedge-shaped and angular-blocky aggregates in this particular set of soils more likely reflects their vertic nature, even though the cryogenic impact on their formation cannot be completely excluded. Lenticular aggregates are better presented in the *left* profile and are interpreted as the result of the transformation of initially granular and subangular blocky peds.

The *right* profile exhibits perfect subrounded (granular and subangular blocky) microstructure with ultramicroaggregation, and a specific pattern that can be interpreted as frost shattering of clay coatings and aggregates. These features suggest the rotation of soil particles favored by solifluction under saturated conditions in soil horizons just above the active permafrost zone in the convex hillslope position.

Complex packing and planes are the most common voids. The micromass varies from isotropic very dark brown in the upper part, through yellow-brown to light gray at depth. Dark brown characterizes the micromass at depth in the *right* profile, while the *left* soil profile has the lightest micromass. The c/f related distribution pattern of the upper horizon is enaulic which turns to porphyric at depth with corresponding increases in the clay fraction. Prominence of b-fabric increases with depth, and striated patterns are present including poro-, grano-, mono-, cross- striated, strial and mosaic. Most of these b-fabrics are typical for cryosols (Van Vliet-Lanoë 2010), but are also typical for clayey soils of other origins and environments (Blokhuis et al. 1990; Kovda and Mermut 2010).

The coarse fraction exhibits a variety of alternation patterns including irregular and cross linear, dotted, and complex. Some zones are characterized by enaulic c/f distribution consisting predominantly of coarse fraction that occurs frequently in all horizons. There

are a variety of pedofeatures occur consisting of excrements and rare ferrous nodules in the upper horizons, combined with common infillings and coatings in subsoil horizons. Coatings are the most commonly observed pedofeature for these soils, but they have variable composition including silty, clayey, or clayey enriched with organic matter and/or iron compounds. Limpid colorless optically isotropic coatings were identified alone or combined with clayey coatings associated with aggregates and voids; these were interpreted as opaline films (Stoops 2003).

### 3.3. Physical and chemical properties

Laboratory investigations confirm the combination of common and unique features of the three profiles. Selected properties for the *central* profile are presented in Tables 3 and 4. *Left* and *right* soil profiles generally have similar trends with some variations according to the depths of horizons and degree of horizon development.

Table 2. Main micromorphological characteristics (*central* profile)

Horizon	Depth cm	Microstructure and Porosity										Groundmass					Organic and inorganic components of biological origin					Pedofeatures																															
		type		aggregation				voids		c/f <sub>2um</sub>		c/f distribution			micromass		b-fabric			color		weathering pattern			biological origin			ct	sc	oc	de	if	Fe	ex																			
		gr	cr	sb	ab	pl	lt	lg	sm	si	co	str	pl	spv	cpv	en	cph	dph	oph	un	sp	gs	ps	cs	ms	mo	me	al	dt	cl	il	pt	ph	hy	or	ce	am	pu	pi														
A	5-10	x	x					x	x	x	x	x	x	x	x	6/1	x			x							bb		x	x	x	x	x	x	x	x	x	x	x						x	x	x						
AB	45-50	x	x	x	x			x	x	x	x	x	x	x	2/3		x			x	x	x			x		wb	x	x	x	x															x	x						
EBt@	56-61	x	x	x	x	x		x	x	x	x	x	x	x	2/1	x		x		x	x	x			x		wb	x																		x	x						
Bti	85-90	x	x	x	x	x		x	x	x	x	x	x	x	2/5			x		x	x	x			x		lb	x	x	x	x															x	x	x					
BC	110-115	x	x					x	x	x	x	x	x	x	2/5			x		x	x	x			x		lb	x																		x	x	x					
C	130-135	x						x	x	x	x	x	x	x	3/5	x		x		x	x	x			x		gr																				x	x	x				

**voids:** pl – planes, spv – simple packing voids, cpv – complex packing voids.  
**Microstructure**  
**Type:** gr – granular, cr – crumb, sb – subangular blocky, ab – angular blocky, pl – platy, lt - lenticular.  
**Pedality:** str – strong  
**Aggregates:** si – simple, co – complex, lg – large, sm – small.  
**Groundmass**  
**c/f distribution:** en – enaulic, cph – close porphyric, dph – double spaced porphyric, oph – open porphyric.  
**b-fabric:** un – undifferentiated, sp – speckled, gs – granostriated, ps – porostriated, cs – crosstriated, ms – monostriated, mo – mosaic speckled.  
**Color:** bb – blackish-brown, wb – wellowish-brown, lb – light brown, gr – gray.  
**Weathering pattern:** me – mesomorphous, al – alteromorph, dt – dotted, cl – cross linear, il – irregular linear, pt – patchy, pl – pellicular.  
**Organic and inorganic**  
**Components of biological origin:** ph – phytoliths, hy – hyphae, or – organ residues, ce – cell residues, am – amorphous fine organic material, pu – punctuations, pi – organic pigments.  
**Pedofeatures:** ct – coatings, sc - silt coatings, oc - opal coatings, de - depletion, if - infillings, Fe - iron nodules, ex - excrements.

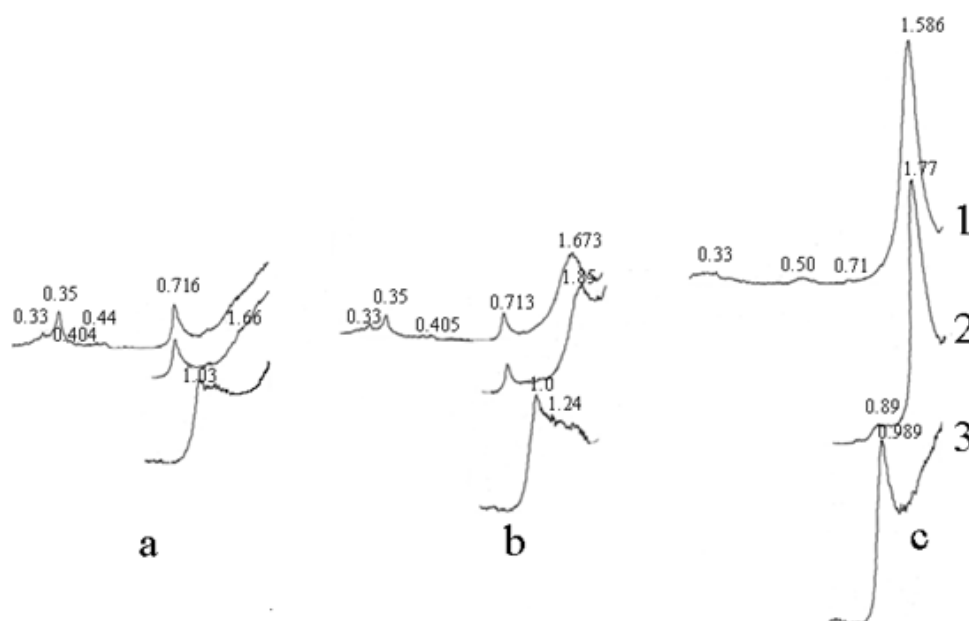


All soils have acid pH values. They range from 6.45-6.9 in upper horizons but decrease with depth to 5.25-5.55. The sum of exchangeable cations roughly corresponds to the cation exchange capacity and ranges between 20-26  $\text{cmol kg}^{-1}$ . In bleached, coarser-textured zones, the CEC drops to 8.7  $\text{cmol kg}^{-1}$ .  $\text{Ca}^{2+}$  dominates in the exchangeable complex (78-86% of total),  $\text{Mg}^{2+}$  is the next most abundant and ranges from 14-22%, while  $\text{Na}^{+}$  is less than 2.1%. Identification of the EBt@ horizon and its fragments by color and platy structural elements was confirmed by laboratory data including low exchangeable cations, clay-depleted texture, low R2O3 values, and increased  $\text{SiO}_2$  contents (Table 3, 4).

Soil texture changes within the profile, from clay in surface organic-enriched horizons to loam and silty clay in subsoils (Table 3). The upper part of the *central* and *right* profiles is enriched in coarse skeleton grains and gravelly fragments. This forms irregular-shaped concentrations in the middle part of all three profiles and is interpreted as a result of cryogenic sorting. The

hardest and most consolidated of the horizons investigated are enriched in up to 30-60% clay ( $< 1 \mu\text{m}$ ) fraction. Except for the upper soil horizons, the clay mineral composition of all three profiles is smectitic. The organic-enriched surface horizons are predominantly kaolinite-smectite in composition with high content of weakly-ordered hydromica (Figure 3). Such mineralogical and textural changes confirm the lithological discontinuity. The specificity of the *right* profile is the increased kaolinite-smectite and decreased smectite portion in the specimen from 80-90 cm depth i.e. from the zone above the crack ending.

The brownish to black color variations of the organic matter are followed by variable humic to fulvic acid ratio, C:N ratio, degree of humification, stable carbon isotopic composition depending the location. The organic matter filling the large cryogenic wedge and curved cracks on the *right* profile has the blackest colors with associated high C:N ( $\sim 8-12$ ) and  $C_{\text{HA}}/C_{\text{FA}}$  (1.03-1.38) ratios (Table 3). Degree of humification is in the range of 20.6-26.2. The stable isotopic



**Figure 3.** Clay mineralogy of selected horizons along the *central* soil profile: **a** – 5-25 cm; **b** – 37-80 cm, **c** – 130-140 cm; **1** – Mg-saturated, **2** – Mg-saturated and ethylene glycol treated, **3** – heated at 550 °C.

**Table 3.** Main physical and chemical properties of the *central* soil profile and along the wedge crack from the *right* pit's wall

Hor.	Depth, cm	pH	C <sub>org</sub> , %	C <sub>HA</sub> :C <sub>FA</sub>	HD	C/N	$\delta^{13}\text{C}$ , ‰	Exchangeable cations, cmol <sub>c</sub> kg <sup>-1</sup>				Texture, %			Fe <sub>t</sub>	Fe <sub>d</sub>	Fe <sub>o</sub>	Fe <sub>o</sub> /Fe <sub>d</sub>	Fe <sub>d</sub> /Fe <sub>t</sub>
								Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	Total	sand	silt	clay					
A	0-5	6.9	6.3			12.0	-25.77												
A	5-25	6.5	2.72	0.51	13.2	8.7	-25.22	21.81	4.06	0	25.87	33	18	50	2.21	0.27	0.12	0.44	0.12
AB	25-45/50	6.35	1.29	0.21	7.0	5.5	-24.8	17.77	4.72	0	22.49	34	13	53	2.51	0.23	0.08	0.36	0.09
Bt@	45/50-70	5.95	1.0	0.13	4.0	5.4	-24.76	19.05	5.0	0.11	24.05	27	15	58	2.9	0.24	0.11	0.47	0.08
EBt@	37/70-80	5.8	0.48			15.2	-24.52	7.16	1.55	0.03	8.71	50	24	26	1.22	0.07	0.03	0.4	0.06
Bti	80-110/117	5.45	0.31			-	-24.56	20.07	4.04	0.27	24.11	14	45	41	2.4	0.11	0.01	0.13	0.05
BC	110/117-130	5.5	0.27			2.2	-24.43	19.36	3.22	0.16	22.58	26	42	32	2.43	0.15	0.03	0.24	0.06
C	130-140	5.55	0.18			0.5	-24.69	16.98	2.9	0.03	19.88	31	40	28	2.04	0.16	0.04	0.26	0.08
crack	5-15	6.25	4.75	1.03	20.6	9.8	-26.69												
	15-25	6.3	4.24	1.28	21.5	8.3	-25.09												
	25-35	6.25	3.26	1.33	22.4	9.1	-25.12												
	35-45	5.85	3.04	1.22	23.3	9.5	-24.90												
	45-55	5.8	2.1	1.38	26.2	12.4	-24.32												

HD – Humification degree.

**Table 4.** Major oxides (%) in the soil horizons of the 245 *central* soil profile

Horizon	IL %	Depth, cm	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	MnO	Fe <sub>2</sub> O <sub>3</sub>
A	13.46	5-25	0.40	0.66	16.70	61.47	1.76	0.85	0.99	0.034	3.16
AB	12.4	25-45/50	0.39	0.79	19.18	59.55	1.85	0.77	1.02	0.024	3.59
Bt@	12.65	45/50-70	0.44	0.90	19.88	57.92	1.86	0.82	0.95	0.023	4.15
EBt@	5.04	37/70-80	1.10	0.48	14.00	72.71	2.98	0.51	0.99	0.022	1.75
Bti	8.83	80-110/117	1.26	1.11	16.06	64.53	2.58	0.98	0.85	0.026	3.43
BC	7.19	110/117-130	1.51	1.01	15.22	66.63	2.77	1.06	0.75	0.029	3.48
C	6.38	130-140	1.58	0.91	14.19	68.91	2.92	1.06	0.70	0.026	2.92

IL – Ignition loss at 900 °C. Concentrations are presented for unheated specimens.

composition of carbon becomes slightly heavier (-24.3‰) compared with -25.8‰ in brownish topsoil organic matter. Organic matter along the *central*, *left* and *right* soil profiles has a tendency for low C:N ratio 0.5- 5.5, except for the surface horizons (8-12 cm) and subhorizontal narrow black layer at a depth ~110-120 cm (C:N=47.5). Organic matter is predominantly fulvate (C<sub>HA</sub>/C<sub>FA</sub> = 0.13-0.86 i.e. with constant domination

of fulvic acids). Degree of humification is two to three times lower comparing with the organic matter from the wedge turning into the curved crack, and does not exceed 10-16 (Table 3).

The Fe<sub>o</sub> and Fe<sub>d</sub> values, and Fe<sub>o</sub>/Fe<sub>d</sub> ratios, have low values and little variation with soil depth. Most of the total iron is in the silicate form. This is supported by the Fe<sub>d</sub>/Fe<sub>t</sub> between 0.05-0.30

indicating a low degree of weathering of the groundmass. Highest values for all forms of iron and calculated ratios ( $Fe_d/Fe_t$  and  $Fe_o/Fe_d$ ) correspond to the upper horizons and to the *right* “organic” soil profile. This suggests that the *right* profile, compared with *left* and *central* profiles, has more weathered soil material transformed by pedogenic processes. This was confirmed previously by clay mineralogy, which has shown that the *right* “organic” soil was depleted in smectite and enriched in kaolinite-smectite and poorly-ordered hydromica.

### 3.4. Modern and relict pedogenic processes

Major processes of soil formation were identified based on morphological, physical and chemical attributes, and especially micromorphology characteristics. Features related to decomposition, aggregation, eluviation/illuviation, pedoturbation, mineralization, and hardening, can be grouped according to generalized pedogenic processes of organic matter accumulation and transformation, freeze/thaw, shrink/swell, and translocation processes.

Each of the profiles is characterized by common features formed by the revealed pedogenic processes, and exhibits individuality related to the intensity of these processes. As a result the three soil profiles investigated represent a soil complex consisting of Luvic-Vertic Phaeozems (Clayic and Turbic) – illustrated in *center* and *left* walls. The *right* soil profile was classified as a Luvic Phaeozem (Clayic and Turbic). We could expect this because the complexity of the soil cover is typical pattern in cryogenic environment, where it is usually associated with cryogenic microrelief (Fridland 1976; Kimble 2004).

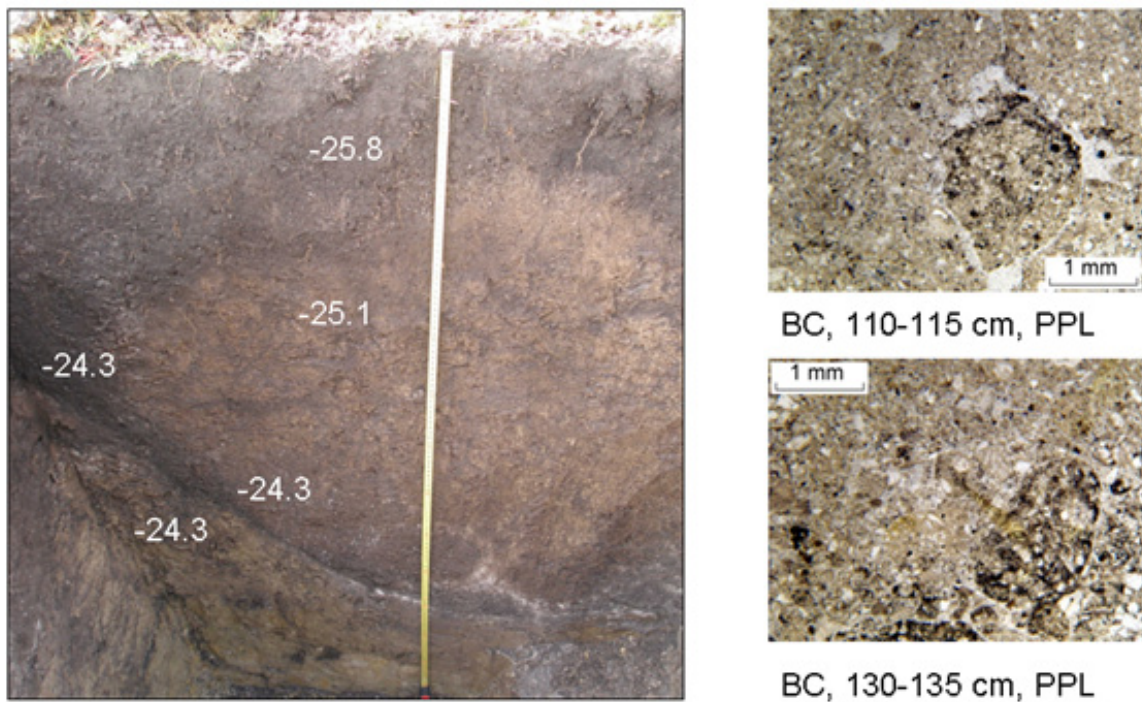
The differing intensities of the pedofeatures and attributes are interpreted to be a result of the development or “erasing” of the pedogenic processes. i.e. soil evolution. We interpret the investigated soil complex as a polygenetic formation which has recorded the processes acting at different times, with different intensities, and in different pedoenvironments. We have attempted to identify the current processes and

differentiate them from relict processes, which are “recorded” in the soil memory system.

Cryogenic processes are represented by the greatest variety of features visible at the macro- and micro-scales. Two generations of cryogenic cracks were identified in the soil complex. Large cryogenic cracks (wedges) with shoulders were found at the edges of the soil pit i.e. they were formed at a distance ~1.5-2 m apart. Wedges are large near the surface getting narrow below ~40 cm. These wedges are filled by material with voronic features. We can identify this material in thin sections (right photos on [Figure 4](#)) as well as by stable isotopic composition and other characteristics of organic matter. This is a black material ( $C_{org}$  ~3-6%) with enriched  $\delta^{13}C$  value ( $-24.3\text{‰}$ ). Such isotopic composition was found in the bottom part of the right profile along the curved deepest part of the cryogenic wedge.

The modern organic matter is brownish in color, more fulvate in composition, and has slightly depleted stable carbon isotope composition ([Figure 4](#), left photo). The relict organic matter can be easily identified in thin sections as rounded black aggregates or dispersed black fine organic material ([Figure 4](#)). We interpret the large cryogenic wedges as relict features of the coldest cryomorphic climatic phase. During the further thermokarstic stage, the melted cryogenic wedges became infilled by voronic topsoil material of the soil formed under relatively warm and wet environments.

Similar polygonal cryogenic microrelief of Pleistocene age, formed during a glacial period due to the vein ice and followed by a thermokarstic stage, were described in European part of Russia (Velichko 1973; Velichko et al. 1996). Relict polygonal microrelief in the southern part of Middle Siberia was associated with permafrost, which disappeared during the Holocene optimum (Semina 1984). The wedge shaped large cracks became infilled by the material of the ancient soil with a well-developed humus accumulative horizon. Vorob'ova (1990) supported the role of polygonal-vein ice and suggested the disappearance of ice-wedges in southern PreBaikal region in Holocene. Our data correspond to these investigations.

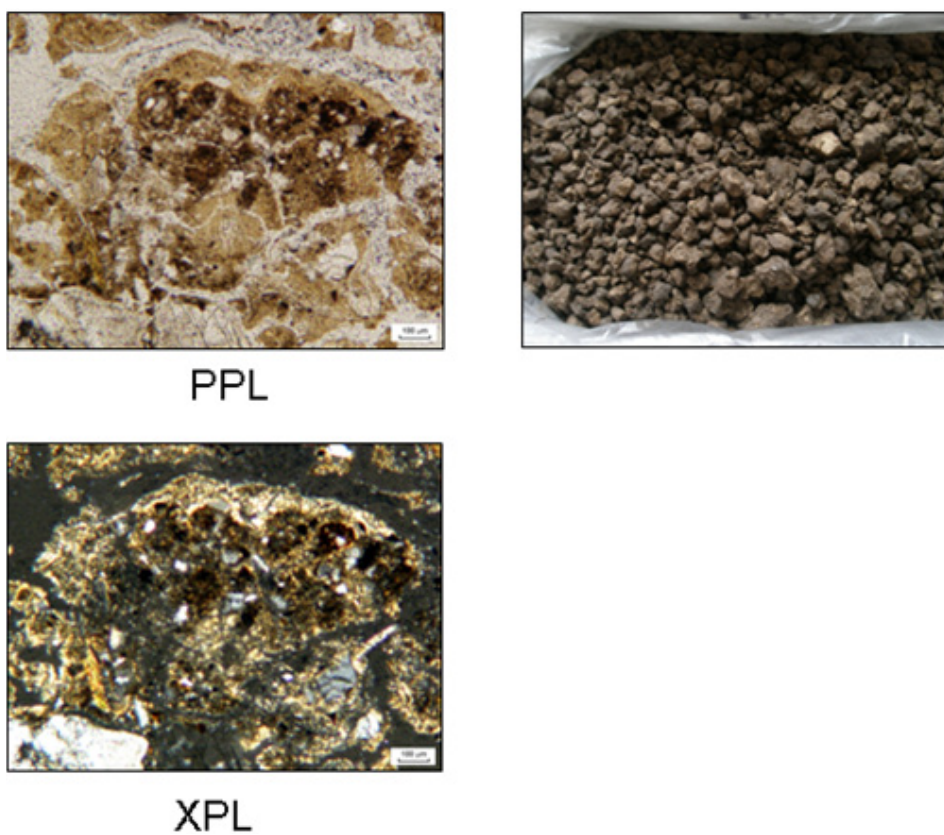


**Figure 4.** Identification of relict organic matter in thin sections as concentration of charcoal and black pigment inside the aggregates, and by stable isotopic composition of carbon enriched up to  $\delta^{13}\text{C}$  value  $-24.3\text{‰}$ . Left photo represents the *right* "organic" soil profile.

The second type of crack is represented by strait narrow fissures going down to a depth about 50 cm and deeper. Such fissures are infilled with brown organic matter and are interpreted as modern cryogenic fissures reflecting the severe winter temperatures at the present time .

At a depth of 90-100 cm the deepest cracks of both types change their orientation from subvertical to subhorizontal (Figures 2, 4). Curved forms of cracks and fissures most likely originated due to the sloping position of the soils and reflect past solifluctions and permafrost boundary. A black organic-rich sub-horizontal fine layer of about 3-5 cm thick was found at a depth of ~110-120 cm and likely indicates the accumulation of organic matter over active permafrost. Several zones consisting of coarse gravel fragments of 3 to 5 mm in diameter were described in all three profiles (Figure 2). They must be related to paleocryogenic sorting of the material. We also believe that the cryomorphic disturbances most expressed in the central profile happened at that time.

The presence of well-sorted granular macro- and micro-aggregation (Figure 5) also suggests its formation between the two fronts of freezing: lower front – shallow permafrost in the subsoil in the past, and upper front - winter freezing of soil from the surface. Ultra and very fine granules of about 1 mm in diameter are coalescent together into larger granules of about 7 mm in diameter and have organic matter and Fe inclusions. The formation of granular pedality in the middle part of all three soil profiles is believed to be active during the warmer climatic stage in the Holocene, but under conditions when the permafrost was closer to the surface than in present time. Formation of granular aggregates described at the macroscale and granular to subangular blocky peds in the thin sections is apparently related to gelifluctions, when originally platy aggregates above the permafrost were plastically deformed up to granular aggregates. We believe that close permafrost and extra deep perennial freezing in wet smectite rich soils situated at a slope position favored the gelifluction process and the transformation of structural units into granules.



**Figure 5.** Granules and fine subangular blocky structures (~3-7 mm in diameter) at a macrolevel (upper right photo) consisting of coalescent ultra and very fine granules, enriched in organic matter and iron oxides. Note the fine isotropic opaline coatings around the granule on the left photos. Bt@ horizon, 45-50 cm.

Although the climate is not as severe as it used to be in glacial times, the modern cryogenic processes have a deeper permafrost represented by the fissures described above, and display strong cryogenic weathering of mineral grains. This is illustrated by the irregular and cross-linear alteration patterns typical of feldspar and quartz grains (Figures 6a-d). These alterations are accompanied by pelletization and release of iron from selected mineral grains. Altered mineral grains occur at various depths along the profiles, but differences in the degree and type of alteration have previously been described (Table 2). Another recent pedogenic process related to winter freezing is the formation of opaline coatings around the granular aggregates (Figure 5). Limpid colorless isotropic opaline films juxtaposed on clay coatings are common in indurated B and

BC horizons, and are believed to be formed as a result of silicic acid precipitation from the soil solution under winter freezing conditions (Slavny and Vorobieva 1962; Kovda 1985; Channing and Butler 2007).

Translocation processes including eluviation and illuviation are interpreted to be younger than the paleocryogenic processes. We expect that they started to form at the initiation of the relatively warm and wet mid-Holocene stage and this process is still active today. Illuviation is strongly expressed both at macro- and micro-levels to the depth of the soil. Dark humus-clay thick coatings cover the macrostructural units, granular peds, and microaggregates (Figures 6a-h). They are especially well developed and strongly expressed in the pale indurated part of subsoil horizons but get thinner and

less well expressed in the deepest horizons up to a depth of ~130 cm. While this is our current interpretation, we cannot exclude the possibility that the formation of the pale bleached zones may be older and reflect the chemical reduction of soil material due to temporary waterlogging and gleization above the permafrost layer in the past (Figure 7a). A warmer and more humid period than at present was reconstructed for mid-Holocene in Buryatia by Andreeva et al. (2011), which correlates with our hypothesis.

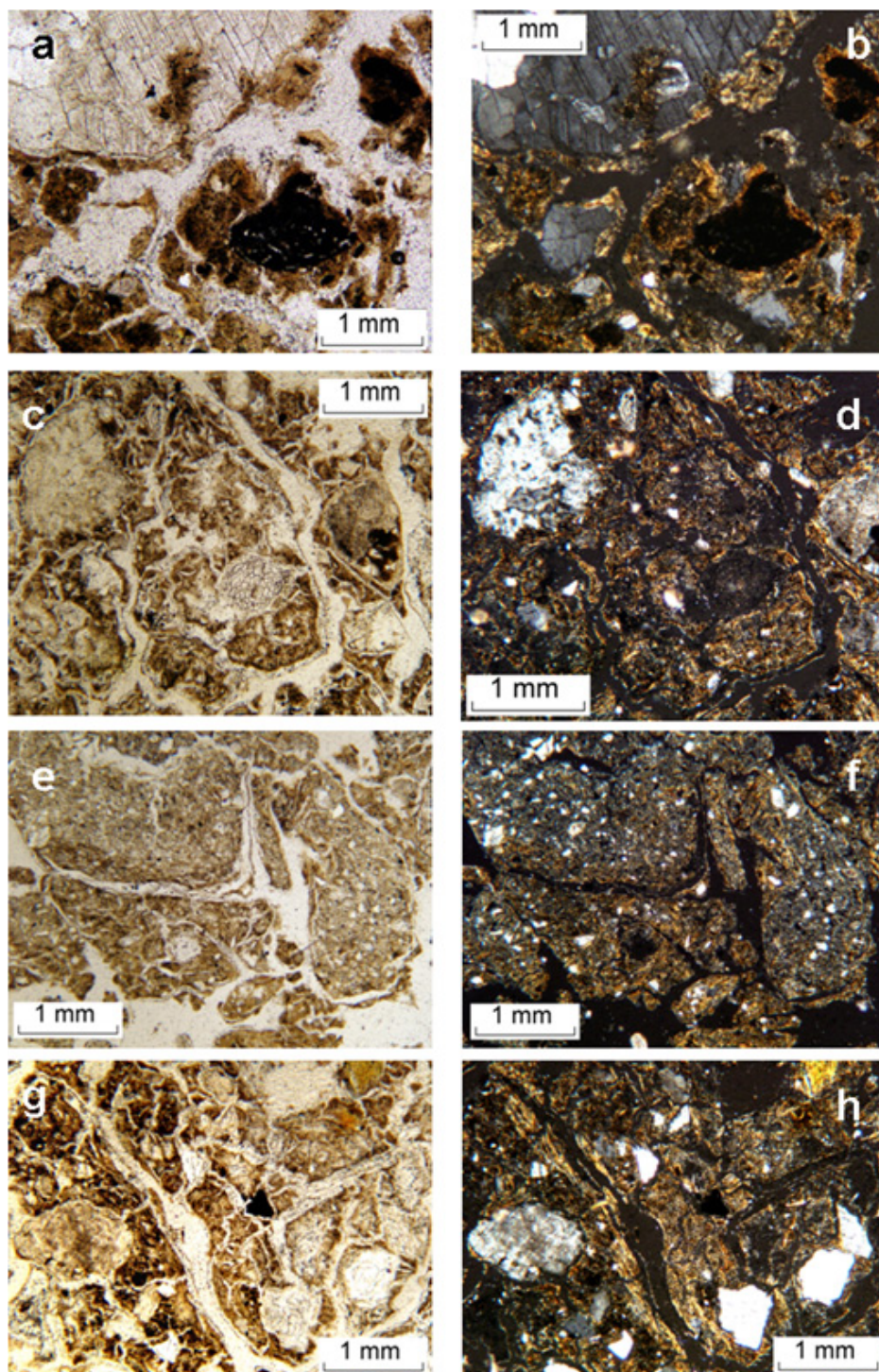
The most recent features in these soils are weakly developed vertic features identified both at the macro- and micro-level. Since 1966 attempts have been made to identify vertic features in cold environments. An "arctic equivalent" of a Vertisol was described in northern Alaska by MacNamara and Tedrow (1966). They described clayey and montmorillonite rich soil, but did not mention the main diagnostic features such as slickensides. Brierley et al. (2011) described soils of the Vertisolic order, identified recently in Canada. In the last example, Vertisolic soils are limited biogeographically to the Prairie region, which has a warmer environment and lacks the permafrost comparing with the Trans-Baikal region. Wilding (2004) mentioned that about 10% of Vertisols are in colder regions, while the Soil Taxonomy established the Cryert suborder in 1994 (Soil Survey Staff 1994), and the vertic subgroup of Gelisol order in 1998 (Soil Survey Staff 1998), even though the last one has not been really found yet.

In our case slickensides were found in the middle part of the *central* and *left* profiles starting from a depth of ~60-70 cm up to a depth of ~130 cm; this is the same depth as the cryogenic granular pedality described above. Slickensides were most distinct in the *left* indurated soil profile, but even here the surfaces of the slickensides were neither sufficiently polished nor shiny enough to indicate that the slickensides were very active in undergoing shrinking and swelling processes. The maximal size of slickensides was 5-10 cm in length. Wedge-shaped peds at the macrolevel were represented by parallelepiped, and were best expressed at

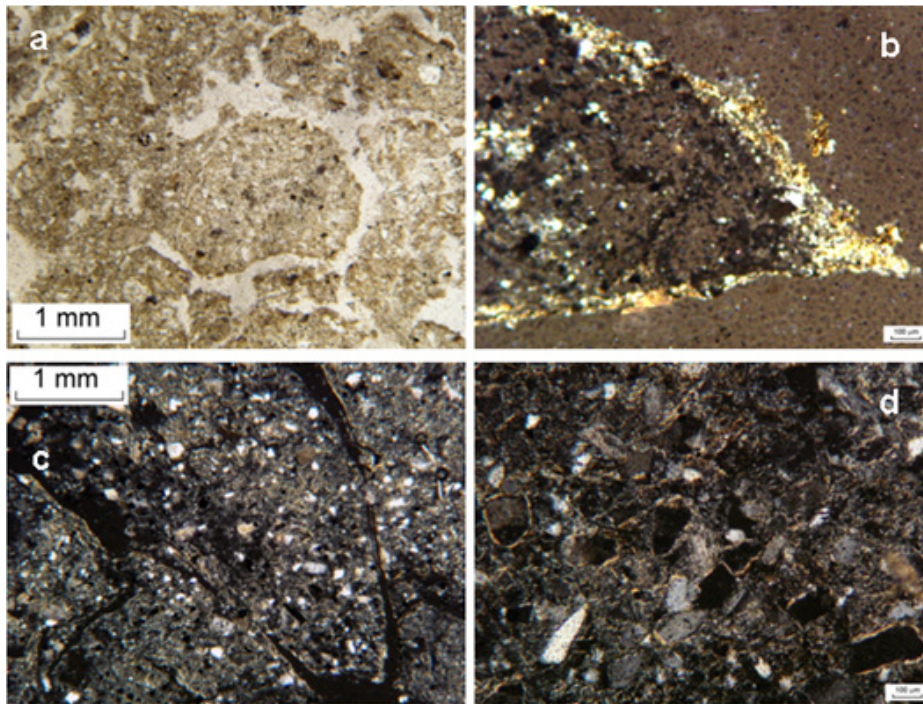
the microlevel as angular and wedge-shaped aggregates of 3-7 mm in diameter with sharp edges and highly birefringent linear zones. These are interpreted as shiny slickenside surfaces on a macroscale (Figures 6 e, f and Figures 7 b, c). In thin sections such wedge-shaped microaggregates were described in all three soils. Poro-, grano- and cross-striated, and strial b-fabrics that are characteristic for vertic processes were documented (Figures 6h, 7 b-d). However a parallel-striated b-fabric which is also common in microfabrics of modern Vertisols was not found.

We interpret the above microfabrics to be vertic features reflecting the initial stage of shrink-swell processes. Both at the macro- and micro-levels, such vertic features were observed but weakly developed. Apparently their formation started only a few decades ago. This could correlate with the fact that ~70 years ago the permafrost at this location was at a level of about 1.0-1.6 m but began to degrade and shifted downward to a depth of about 2-2.5 m (Kulikov 1987). We believe that the formation of vertic features started after the permafrost became deep enough to allow temperature and moisture oscillations to produce shrinking and swelling of the groundmass. The splitting of granular aggregates into very fine wedge-shaped, lenticular and angular blocky peds can be interpreted as the result of alternating seasonal shrinking and swelling. This is believed to be a more recent process than the microfabrics associated with gelifluction (Figures 6 c-h), but more detailed comprehensive studies are needed to clearly differentiate shrink-swell from gelifluction processes and the associated chronology.

Both vertic (shrink-swell) and cryogenic (freeze-thaw) processes reflect the alternating changes of the moisture state and could result in the formation of complex pattern of soil cover at the macro-level, deformation and strong pedality at the meso-level, and similar b-fabrics at the microscale (Van Vliet-Lanoë 2010; Kovda and Lebedeva 2012). Thus, the differentiation of cryogenic and vertic features at the micro-level is a challenge and requires additional works.



**Figure 6.** Microphotographs illustrating the pedogenic processes in the soils studied: **a** – Alteration of minerals with release of iron, Bt@ 45-50 cm, PPL; **b** – same under XPL. Note thick organo-clayey anisotropic coatings; **c** – Irregular and cross linear alteration pattern of mineral grains and limpid colorless isotropic opaline coatings around angular-blocky and wedge-shaped aggregates, Bth@ 80-85 cm, PPL; **d** – same under XPL, note the strongly developed various striated b-fabric; **e** – combination of subangular blocky, granular and lenticular (wedge-shaped) peds, Bth 70-75 cm, PPL; **f** – same in XPL clearly show alignment of clay particles near the outer aggregate's surfaces; **g** – frost-shattered transformation of the micromass, Bth@ 80-85 cm; **h** – same in XPL. Note strongly striated b-fabrics.



**Figure 7.** **a** – bleached iron depleted zone with strongly developed granular pedality, EBt@ 50-55 cm, PPL; **b** – wedge-shaped micro-aggregates with organo-clayey coating, Bt@ 55-60 cm, XPL; **c** – strongly developed pedality with acute angular aggregates, poro-, grano- and cross- striated b-fabrics, Bti 85-90cm, XPL; **d** – poro- and grano- striated b-fabrics with elements of strial, Bth@ 80-85 cm, XPL.

## 4. Conclusions

Soils studied were identified as a polygenetic soil complex. The uniqueness of this soil complex is the combination of cryogenic features, vertic features and textural differentiation. The impact of cryogenic, illuviation and vertic processes on the soils was variable both in space (i.e. laterally) and in time (present day and former relict processes), which resulted in complicated evolution of soils and formation of complex spatial pattern of the soil cover.

We reconstructed as best possible the genesis and evolution of this soil complex, and identified the relict and recent processes. The most ancient features correspond to the severe late Pleistocene glaciations period. The coldest past pedoenvironment is reflected in cryogenic wedges, past permafrost, involutions,

gelifluctions and solifluctions, disrupted soil horizons, cryogenic sorting of coarse material, and accumulation of the organic matter above the permafrost.

A later stage of pedogenesis under warmer and wetter environments is reflected by black organic matter infilling the cracks and black humus-rich aggregates deep in the subsoil, activation of vertical migration of soluble organic matter and the formation of clay coatings. A warm but more arid pedoenvironment is expected to be the most recent one. The soil complex records this stage by brownish fulvic humus accumulations and the formation of vertic features. With the “relatively warm” recent stage, we found vertic features formed by shrinking and swelling processes that co-exist with annual deep freezing of the soils



and subsoil permafrost at a depth of about ~300 cm. This hypothesis generally corresponds to the paleoreconstructions made for southern Siberia based on pollen analysis indicating higher-than-present precipitation and temperature reconstructed for the period ~10.5-7 kyrs BP (Tarasov et al. 2009); a gradual decrease in precipitation and temperatures towards their present-day values was reconstructed to start 7-6.5 kyrs BP in the Baikal region (Bezrukova et al. 2010).

Evidence of weak shrink-swell processes was found in the clayey smectite-rich soils of this cold cryoarid environment having an alternating moisture regime. Comparison and analysis of cryogenic and vertic processes have shown that in spite of various mechanisms and driving forces, they have many similarities in macro, and especially, microfeatures. Special comparative investigations are needed to better differentiate micromorphological features related to the volume changes associated with shrink/swell and freeze/thaw conditions in soils when both processes occur contemporaneously or in the past.

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