# Upper Permian paleosols (Salarevskian Formation) in the central part of the Russian Platform: Paleoecology and paleoenvironment

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**ABSTRACT**

*Ten to twelve pedosedimentary stages were identified within the Upper Permian red clayey sediments of the Sukhona and North Dvina drainage basins. Paleosols formed at these stages are generally similar in their profile arrangement and pedogenic features. The main pedogenic processes occurring in the area during the Upper Tatarian appear to have been: (1) eluviation and gleying (reduction and mobilization of non-silicate-bound iron and removal of some fine clay) in the upper parts of soil profiles; (2) illuvial accumulation of iron, and some clay in the subsoil; (3) formation of secondary carbonates; and (4) generation of complex soil structure. These processes are interpreted to have taken place in a semiarid climate with sharp seasonal and long-term fluctuations in precipitation. Upper Tatarian plant communities at that time probably consisted mostly of shoreline hygrophytes and halophytes, and xerophyllous conifers living on relatively elevated areas.*

*Key words:* *paleoclimate, sediments, paleosols, soil horizons, plant macrofossils, Upper Permian, Russian Platform.*

**RESUMEN**

*Se identificaron de diez a doce etapas pedosedimentarias en los sedimentos arcillosos rojos del Pérmico Superior de las cuencas de drenaje de Sukhona y North Dvina,. Los paleosuelos formados durante estas etapas generalmente son similares en perfil y características pedogénicas. Los principales procesos pedogénicos que ocurrieron en el área, durante el Tatariano Superior parecen haber sido: (1) eluviación y gleización (reducción y movilización de hierro libre y remoción de alguna arcilla fina) en las partes superiores del perfil del suelo; (2) acumulación iluvial del hierro y alguna arcilla en el subsuelo; (3) formación de carbonatos secundarios; y (4) generación de la estructura compleja del suelo. Se interpreta que estos procesos tuvieron lugar en un clima semiárido, con fluctuaciones agudas estancionales y de larga duración en la precipitación. En ese tiempo, las comunidades de plantas del Tatariano Superior, probablemente consistieron principalmente en higrófitos y halófitos de costa, y de coníferas xerofilosas presentes en áreas relativamente elevadas.*

*Palabras clave: paleoclima, sedimentos, paleosuelos, horizontes de suelo, macrofósiles de plantas, Pérmico Superior, Plataforma Rusa.*

## INTRODUCTION

The Late Permian has attracted scientific attention for a long time because it marks the beginning of the longest nonglacial period in the Earth's history, and one of the main crises in the history of the biosphere occurred between the Permian and Triassic (Wang, 1993; Ziegler *et al.*, 1997; Zharkov and Chumakov, 1998). The crisis was reflected in a catastrophic decrease in biodiversity, but the cause of this is still uncertain.

Historically, interdisciplinary investigations of paleosols have focused mostly on the Quaternary. Investigations of more ancient paleosols, especially in Russia, are very scarce and unsatisfactory, even though studies of paleosols may provide additional and valuable information about environments of the deep past. Only in recent decades, pre-Quaternary paleosols have been studied in detail on regional scales (Allen, 1974a, 1974b; Retallack, 1986; Freytet *et al.*, 1992), along with attempts to classify the main types of Paleozoic and Mesozoic soils (Pfefferkorn and Fuchs, 1991), and to characterize general trends of paleosol development during the geological past (Retallack, 1981, 1986).

In Russia, investigations of paleosols have been focused mainly on those of the Quaternary. There is little information on pre-Quaternary paleosols, and often questions arise as to whether a feature is a buried soil or diagenetically transformed sediments. However, being developed from unconsolidated parent materials under the action of climate and biota, a soil can record in its memory (*i.e.*, soil properties) information about environmental conditions at the time of their initial formation, later evolution, and transformation following burial (diagenesis). This is why reconstruction of terrestrial paleolandscapes is satisfactory only with evidence derived from paleosols.

Permian and Triassic deposits are well represented and almost unaltered in the extended area of the Russian Platform and Central Urals, and contain numerous paleosol layers. These layers not only mark depositional discontinuities, but also indicate terrestrial (at least temporarily) environments (Minikh and Minikh, 1981; Strock *et al.*, 1984; Tverdokhlebov, 1996; Arefjev and Naugolnykh, 1998). Records of paleosols in the red clayey sediments of the Late Permian are briefly described in many papers discussing the geology and stratigraphy of this region (Ignatjev, 1963; Lozovskiy and Yesaulova, 1998), however detailed investigations on these paleosols have never been undertaken.

The main objectives of this investigation are: (1) to identify pedogenically processed layers in the Upper Permian geological sequences; (2) to distinguish the most persistent soil properties containing information about the paleoenvironment; (3) to understand the nature of these paleosols and the main processes formed them; and (4) to reconstruct the paleo-environment before and after soil burial.

## SITES DESCRIPTION

Investigations on paleosols were undertaken in the stratotype region of the Upper Tatarian sub-stage of the Late Permian, in the Sukhona and North Dvina River Basins (Figure 1). The Salarevskian Formation contains the largest number of well-expressed pedogenically processed layers within the Upper Tartarian, and we studied these paleosols in more detail.

In this area, the Salarevskian Formation is 80–85 m thick and consists largely of non-laminated red clayey sediments that are variably calcareous. Limestone and marl layers rarely occur in the section (Figure 2). Sandy lenses varying from 15 cm to a few meters in thickness and tens to hundreds of meters wide cut deeply into underlying deposits. The origin of these polymineral sand lenses is related to the deposits of temporary riverbed floods (Arefjev and Naugolnykh, 1998). Most likely, the Salarevskian formation was formed on an alluvial plain that was repeatedly over flooded (Ignatjev, 1963). The Salarevskian Formation contains abundant fossils of terrestrial and fresh shallow water organisms, including ostracods (*Sukhonellina parallel*), fishes (*Amblypterina, Tojemia, Mutovina, Palaeoniscum*c), Stegocephalian amphibians (*Dvinosaurus, Jugosuchus*), reptiles (*Scutosaurus, Kotlassia, Dicynodon,*

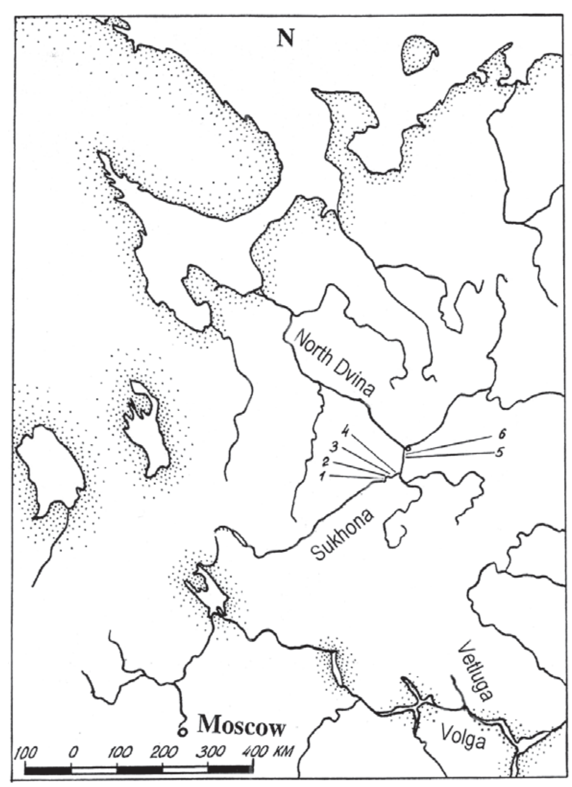



Figure 1. Geographic map of the region and location of the studied sites. 1: Mutovino; 2: Skorjatino; 3: Klimovo; 4: Salarevo; 5: Zavraje; 6: Sokolki.

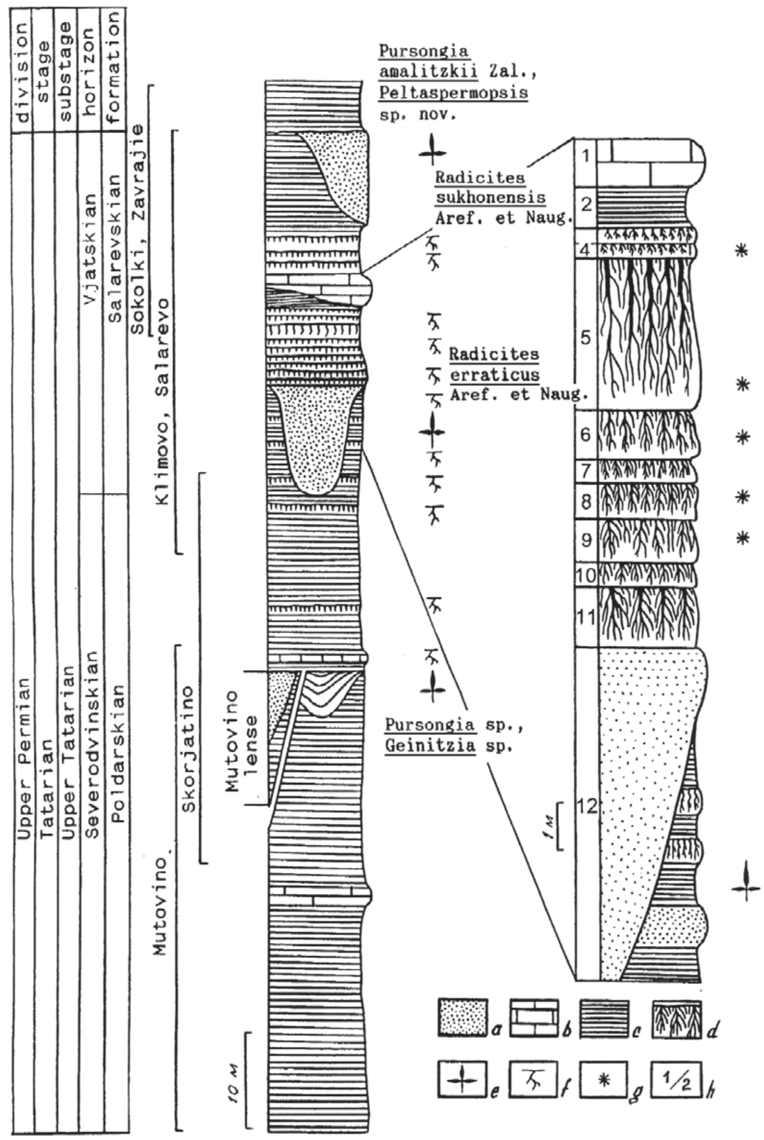



Figure 2. Stratigraphy of the studied sites. a: sand; b: limestone; c: shales; d: paleosol horizons; e: plant macrofossils; f: fossil roots; g: carbonate nodules; h: layer number.

*Inostrancevia*), and plant macrofossils.

Paleosols lie between marker beds of limestone (above) and sandstone (below). Ten to 12 individual profiles of varying morphological expression were marked out and described. The whole sequence is well preserved, has not been disturbed tectonically or glacially, and is represented by multiple uniform red colored, bleached and mottled layers (Figure 3).

Paleosols were studied in two well-correlated exposures on the left bank of the Sukhona River, where they occur in the middle part of the exposed section. They differ from the uniform red sediments by their mottled appearance. The most detailed investigations were carried at Klimovo, the most complete and representative section.

Specimens of fossil roots and paleosols were collected in the layers 4–11 (Figure 2) and from sediments above and below at the Klimovo, Salarevo, Sokolki, and Zavraje localities.

## METHODS

Part of the section containing soil layers was subdivided into sediment layers and what we presume to be soil profiles composed of soil horizons. The pattern of root channels was the main criteria used to distinguish the top and bottom of each paleosol. Mesomorphological features were described in the field and under binocular microscope; micromorphological characteristics were studied in thin sections of intact samples. Bulk samples taken from soil

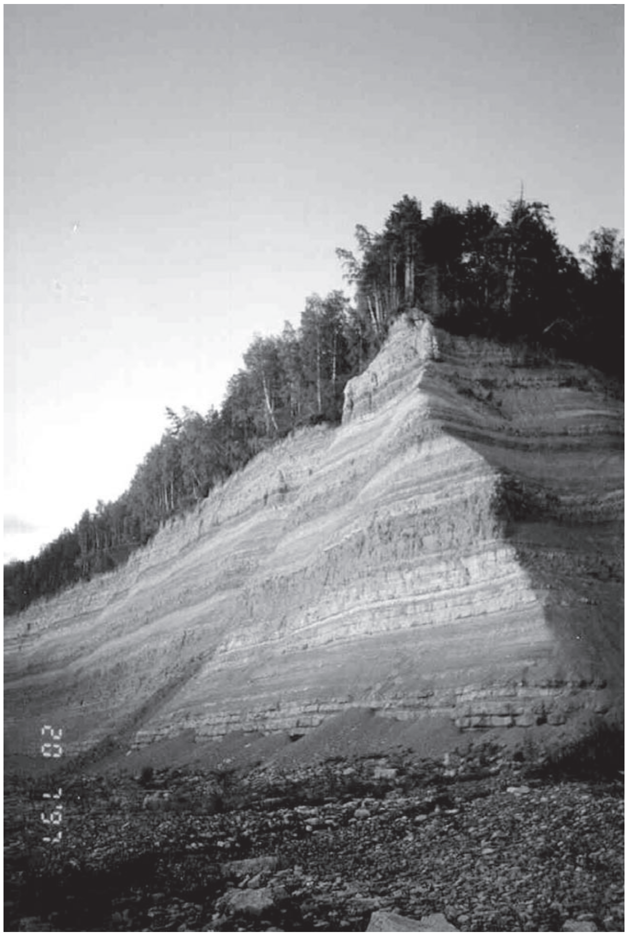


Figure 3. General view of the Upper Permian sediments in the Sukhona river basin (Klimovo).

horizons and soil parent materials beneath were analysed for: (1) Particle-size composition, performed in decalcified samples (treated with HCl, pH 3), dispersed in 25% sodium pyrophosphate ($Na_4P_2O_7$). (2) Total chemical composition (silicate analysis). (3) Non-silicate iron by dithionite extraction (Mehra and Jackson, 1960). (4) Mineralogical composition by immersion method; mineral grains were identified using a petrographic microscope with specimens immersed in a liquid with refraction index of 1.546. (5) Plant macrofossils (roots and compressed leaves, and generative organs or impressions) were studied with a binocular microscope and by SEM (Stereoscan).

## RESULTS

### Paleosol characteristics

Ten to twelve profiles, likely representing different pedosedimentary stages, were separated in the sections. Some profiles are well developed (Figure 4), multi-horizontal (3–4 horizons could be distinguished), whereas others are not fully preserved or developed enough to be subdivided into genetic horizons.

All the soils in the sequence could be divided into two groups: calcareous and those almost free of carbonates. In the sections studied, older soil profiles (the approximately five lower paleosols) are enriched in carbonate (up to 35–38%), while the younger paleosols have much lower concentrations of carbonates (ordinarily 1–2%), but are overlain by a highly calcareous clay layer and limestone.

In our descriptions, we use ‘g’ to indicate that Fe reduction and mobilization has occurred, without connotation of the percentage of soil volume with low chroma colors.

### Morphology

The profiles of studied paleosols do not have the surface organic horizons typical for the most modern surface soils, an observation commonly attributed by paleopedologists to later erosion or post-burial mineralization. However, we consider the possibility that humic horizons did not exist at all in these soils, as the herbaceous vegetation known to be mostly responsible for their formation had not yet evolved in the Upper Permian. Figure 5(a–f) shows the variety of paleosol profile arrangements described at this area. Only one paleosol profile had a bluish-grey horizon of lower density (Aeg), similar to a paleohumic or histic horizon (Figure 5a). The strongest developed and well preserved buried soils, regardless of the carbonate content, have a thick, variously bleached E horizon, interfingering into the underlying B horizon. The thickness of both transitional and B horizons may vary across a wide range (cm – m). Some parts of the sections described contain overlapping, incomplete or poorly developed soil profiles (sub-profiles), or individual horizons (Figure 5-f). However all of the soil horizons from studied paleosols, fit into one of the following four major

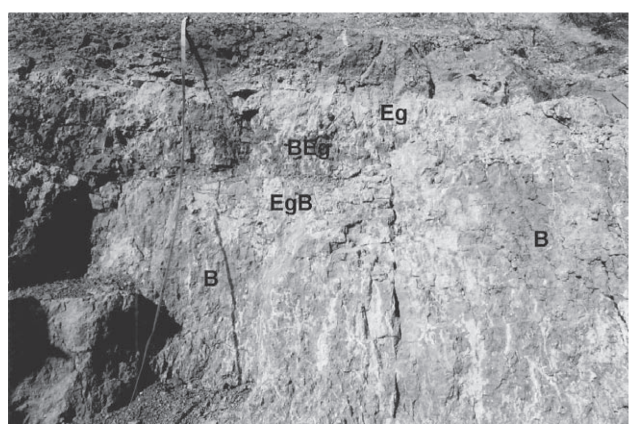



Figure 4. Detail of the Klimovo section (middle part). Well expressed genetic paleosol horizons (layers 7–8).

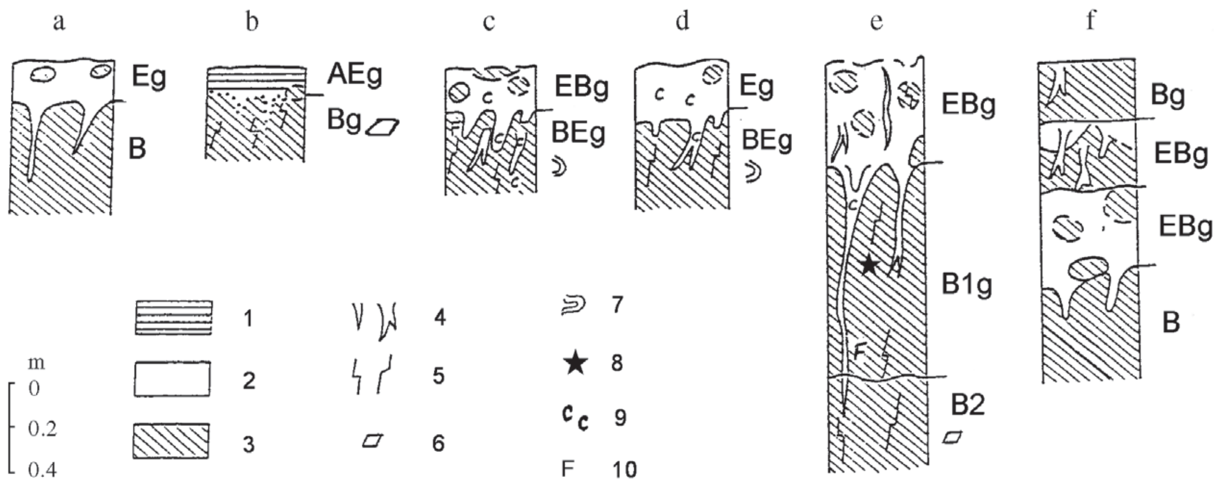



Figure 5. Typical profiles of the Late-Permian paleosols in the Sukhona river basin. Coloration: 1: dark gray; 2: bluish-gray; 3: red-brown. Features: 4: drab-haloed root traces; 5: multi-ordered prismatic-blocky angular structure; 6: slickensides; 7: clay coats; 8: carbonate nodules. Composition: 9: calcareous; 10: ferruginous zones.

morphological types:

1) Eg (eluvial-gley) bleached horizons, which do not exist in every profile. Varying in thickness from 10 to 20 cm, they are completely bluish-grey or contain a few pale-red residual spots of altered red clay material. Paleoroot channels, which are partly filled with lighter colored material, can be distinguished in the soil mass. These soil horizons are massive or have weak platy structure, are dense, and usually have silt loam texture. The finest material is represented by calcareous (in the case of calcareous sediments) – clayey or iron-clayey plasma with weak birefringence. Silt and fine-sand fractions are composed mostly of quartz, feldspars, and muscovite, with a mixture of epidote, analcime, and rarely calcite, amphiboles and pyroxene. Accumulation of sandy grains can occur in the pore space, but more often pores of these horizons are not filled, and free of any coatings. Typically there is an interfingering contact with the subjacent horizon.

2) EBg (transitional) horizons are usually 30–60 cm thick and stand out because of their strong mottling. Against a background of red, bluish-grey (gleyed) zones develop mainly along root traces, creating a sub-vertical branching net of bleached tubes depleted in iron and clay. The red matrix of the horizon has a complex multi-ordered prismatic-angular blocky structure with rare coatings on the ped faces. Material of the near-root tubes (varying in diameter from 1 to 15 mm) is composed of loamy, bleached, gleyed (pedogenic or post-pedogenic) clay. In thin sections, plasma of the non-calcareous red zones is optically well oriented (flake-stream or orientated around skeleton grains), has good birefringence, and partly forms micro-aggregates enriched in iron. In the red material of highly calcareous layers, the plasma has weak optical orientation. Fabric of the bleached zones within calcareous layers is free of iron, impoverished in clay, also weakly oriented, and has cross-fibrous orientation. Skeleton grains are free of films. Bleached zones of non-calcareous EBg horizons have more complicated microstructure. Their fabric is better aggregated, and porous microstructure is typical for the plasma, unlike dense microstructure of the surrounding red material. Solid carbonate nodules (0.5 x 1.0 cm) occur in some of these horizons. They are located both within the soil mass, and in the pore space, possibly indicating a different origin. A smooth irregular boundary with the underlying horizon is typical. Irregular gleyed zones within horizons occur in some cases between roots, indicating other natural gleyzation processes (possibly abiotic).

3) Btg (illuvial) horizons (40 cm to 1 m thick) are uniformly red with rare thin bleached tubes. B-horizons are the densest in the profiles; they are relatively enriched in clay and have fewer skeleton grains. In less calcareous soil material, often aggregated and enriched in iron, plasma has high birefringence; the presence of carbonates causes a significant decrease in plasma birefringence and optical orientation. The soil mass of Btg horizons has a multi-ordered prismatic-angular blocky structure with slickensides and clay coatings on the surfaces of structural units. Clay coatings have an iron-clay composition, non-laminated, thin, and usually do not demonstrate high plasma birefringence. Slickensides are characterized by abundant well micro-oriented clay material. In some profiles, the B-horizon can be subdivided on the basis of differences in coloration, density, or structure. Carbonate nodules of 0.5 x 1.0 cm and 1.0 x 2.0 cm are more common in these horizons, and occur in the soil mass, and pores.

4) BC or C layers are represented by a nearly pedogenically unaltered clay mass, structureless, solid, and free of any new formations.

Several of the paleosols were characterized by abundant fossil roots of *Radicites erraticus* Aref. et Naug., with drab-colored haloes. In part of the profile, these root systems form a dense branching three-dimensional net. The roots gradually diverge downwards and decrease in diameter. Some of the root channels are filled with secondary carbonates. The distribution patterns of roots and other plant macrofossils suggests that one of the main plant communities in the region during the Upper Tatarian were water-proximal associations, consisting of ephemerals and halophytes such as *Acanthopteridium spinimarginalis* Naug. et Aref., and including a dense root net of *Radicites* sp. type (Arefjev and Naugolnykh, 1998). Some anatomical details, including well-preserved roots containing tissues and peridermal structures occur (Figure 6). Another type of plant communities is a xerophyllous association, including *Geinitzia* and other gymnosperms, which are well adapted to arid or even extra arid climates.

**Substantial paleosol composition**

The paleosol profiles studied are nearly uniform in their particle-size composition (Table 1). In general, the paleosols are silty clays containing very little sand (1%). There are no significant differences within the soil profiles except for slight increases in the clay content of the illuvial horizons, and (within the same horizons) red coloured zones, which also show some increase in the content of particles <0.005 mm. In the fractions of 0.25–0.05 and 0.05–0.01 mm, quartz predominates (Figure 7a), and feldspars, muscovite, and analcime are less abundant. Minerals less resistant to weathering, such as epidote, pyroxenes and amphiboles are present only in the 0.05–0.01 mm size fraction of certain paleosol layers (Figure 7b). Traces of analcime occur in both the silt and fine sand fractions of almost all the samples. Illite and smectite predominate in the <0.001 mm fraction for most of the selected samples (Figure 7c). Chlorite usually does not exceed 25%. Mineral composition of the selected samples did not show any difference in mineral distribution among the soil profiles.

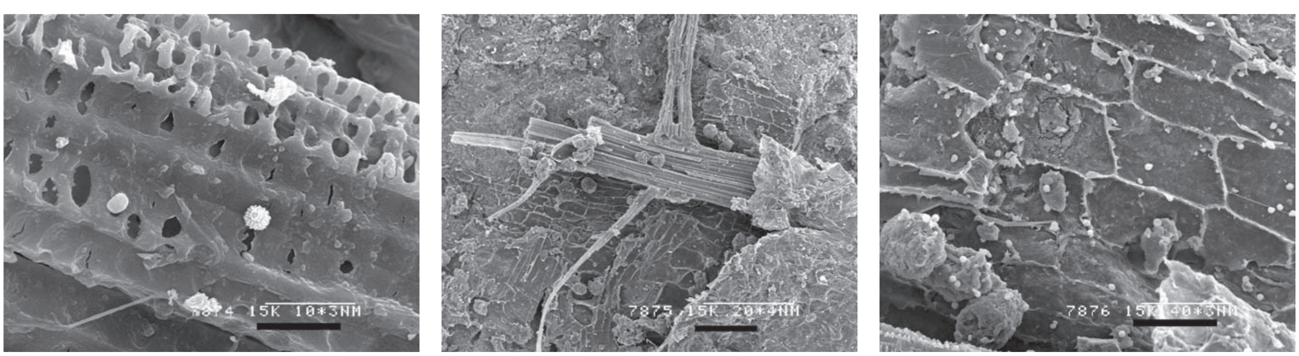
Despite the horizontation of the paleosols, the down-profile chemical composition is irregular (Figure 8). The older profiles are significantly more calcareous, even containing ostracods that were probably inherited from the parent material. Carbonates consist mostly of low-Mg calcite.

There are no notable trends in the soil chemical composition across profiles and within horizons except for iron. Bleached horizons or zones within horizons are impoverished in non-silicate iron, while Bt (illuvial) horizons or red masses within others are enriched in iron (Figure 8).

The most altered areas within soil horizons are located along root traces. Root traces are tubes that usually penetrate paleosols to depths of 30–80 cm or more, with some extending downward into the underlying paleosol. In horizontal cuts it is obvious that the material composing these root tubes is different from that of the soil matrix and often has different zones. The central parts of the tubes (2–3 mm wide) are hollow or filled with authigenic white, pure, coarsely crystalline secondary calcite (Figure 9a,c) while the outer parts (1–2 to 5 cm from the center of the tubes) are bleached bluish-grey matrix, impoverished in iron and clay. In some cases, analcime grains occur in the intermediate positions in between the calcite "zone" and the pore walls (Figure 9c). The contact of the bleached zones of the tubes with the enclosing red material is irregular and ranges from diffuse to sharp. In thin sections, the ferruginous and calcified zones are clearly separated, especially with increasing distance from the large channels (Figure 9b). They partly alternate, indicating that processes of iron removal and calcification were temporally separated during pedogenesis.

## DISCUSSION

Our study shows, that the most pronounced features of the described paleosols, and consequently the most persistent properties allowing us to distinguish soils from sediments, were: (1) dense, branching fossil root channels;



a) b) c)

Figure 6. Fragments of plant residues from paleosols in the Klimovo section observed under a SEM. a) Mineralized root fragment of *Radicites* sp. preserved *in situ* in the B1g horizon, scale bar: 30 µm; b) Epidermal structure of the root *Radicites* sp., the epidermal cells are clearly visible, scale bar: 10 µm; c) Microstructure of the root containing tissues of *Radicites* sp., scale bar: 5 µm.

Table 1. Granulometric composition of the Upper Permian paleosol sequence, %.

| Layer No. | Horizon | Thickness | Particle size classes (mm) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 – 0.25 | 0.25 – 0.05 | 0.05 – 0.01 | 0.01 – 0.005 | 0.005 – 0.001 | <0.001 |
| *Klimovo* | | | | | | | | |
| 7 | Eg (red) | 15 – 20 | 0.00 | 0.02 | 36.89 | 13.70 | 27.22 | 22.17 |
| | (bleach) | | 0.01 | 0.04 | 53.09 | 10.93 | 18.75 | 17.18 |
| 7 | BEg | 30 – 35 | 0.08 | 2.20 | 36.10 | 17.16 | 18.93 | 25.53 |
| 8 | EBg | 20 – 30 | 0.05 | 0.85 | 57.55 | 11.22 | 9.37 | 20.96 |
| 8 | BEg | 45 – 50 | 0.09 | 2.33 | 44.43 | 11.91 | 18.49 | 22.75 |
| 9 | EBg | 10 – 15 | 0.04 | 9.63 | 37.61 | 10.82 | 22.46 | 19.34 |
| 9 | B1g | 20 – 25 | 0.36 | 0.56 | 42.43 | 10.64 | 25.74 | 20.27 |
| 9 | B2 (red) | 55 – 60 | 0.02 | 0.02 | 9.4 | 23.94 | 33.49 | 32.95 |
| | (bleach) | | 0.02 | 2.01 | 39.42 | 12.93 | 23.72 | 22.20 |
| *Salarevo* | | | | | | | | |
| 6 | AEg | 12 – 15 | 0.06 | 0.28 | 23.59 | 11.24 | 33.54 | 31.29 |
| 6 | Bg | 20 – 25 | 4.28 | 0.03 | 22.35 | 8.05 | 30.59 | 38.93 |
| 7 | EBg(red) | 35 – 45 | 0.01 | 0.04 | 36.25 | 18.00 | 8.14 | 37.56 |
| | (bleach) | | 0.02 | 0.02 | 29.53 | 11.10 | 30.12 | 29.21 |
| | (mixed) | | 0.14 | 0.24 | 22.24 | 11.16 | 29.26 | 36.96 |
| 7 | B1g | 40 – 45 | 0.04 | 0.05 | 10.90 | 11.62 | 40.68 | 36.71 |
| 7 | B2 | 65 – 70 | 0.02 | 0.01 | 1.89 | 16.21 | 25.55 | 56.32 |

(2) repetitive soil horizonation; (3) complex soil structure; (4) slickensides; and (5) clay coatings.

Multiple occurrences of plant macrofossils (vegetative shoots, leaves and regenerative organs) of a water-proximal mode of preservation, and intact terrestrial tetrapods, together with the observed paleosol characteristics indicate a continental origin for the sequence, and contradict the suggestion of Verzilin *et al.* (1993) of a marine environment of deposition. During the Tatarian, the study area was probably covered with temporary lakes and rivers, and repeated flooding deposited sands and clayey sediments with varying carbonate content. The bimodal particle size distributions, with clay (<0.005 mm) and silt (0.05–0.01 mm) particles predominating, suggest a mixture of flood sediments and possibly wind-blown dust.

The hierarchical pattern of the gradual vertical root distribution (root channels), without any reorientation or breaks, indicates relative landscape stability and likely the absence of paleo-hardpans or water bearing layers in the profiles. Repeated, overlapping soil profiles, with similar sequences of homologous horizons, indicate episodic sedimentation at that time, with intervals of different duration, resulting in varying degrees of morphological expression. However, differences in the soil or horizon development could also result from varying aridity at the time. More arid conditions, especially coupled with shorter discontinuities in sedimentation, could lead to formation of more weakly expressed paleosols.

The variety in thickness and arrangement of the paleosols and the absence of full paleosol profiles may have arisen also from erosion, or phases of accretionary pedogenesis. Some paleosol horizons were evidently formed under conditions of continuing, but reduced sedimentation rates, during which pedogenic processes reworked incoming sediments. According to the mineral composition of the different soil layers, sediments apparently were already well weathered before they served as a parent material for the paleosols.

Regardless of their carbonate content, the paleosols are of the same general morphological type and have very similar pedological features. Soil coloration evidently results mostly from iron mobilization. Both bleached horizons (Eg) and bluish-grey zones (along root and other channels) within illuvial horizons show similar chemical composition except for soluble (and consequently) total iron, which occurrs in smaller amounts in these zones.

Carbonate nodules occurr mostly in the subsoil horizons of the paleosols, indicating the possibility of recurrent, mainly vertical water flow within the paleosol profiles. As these carbonate concentrations occur only in genetic soil horizons (regardless of the carbonate content distribution) and not throughout the section, it is reasonable to assume that these features are pedogenic.

Our investigation show, that carbonates, and their distribution in the paleosol sequences can provide information on the succession of processes during pedogenesis and in post-pedogenic time, possibly indicating some paleoevents and changes in environmental conditions. Carbonates in the studied sequence could have originated from different sources: (1) inherited from the parent material, (2) allocthonous, (3) pedogenic, and (4) accumulated post-burial. The younger paleosols are impoverished in

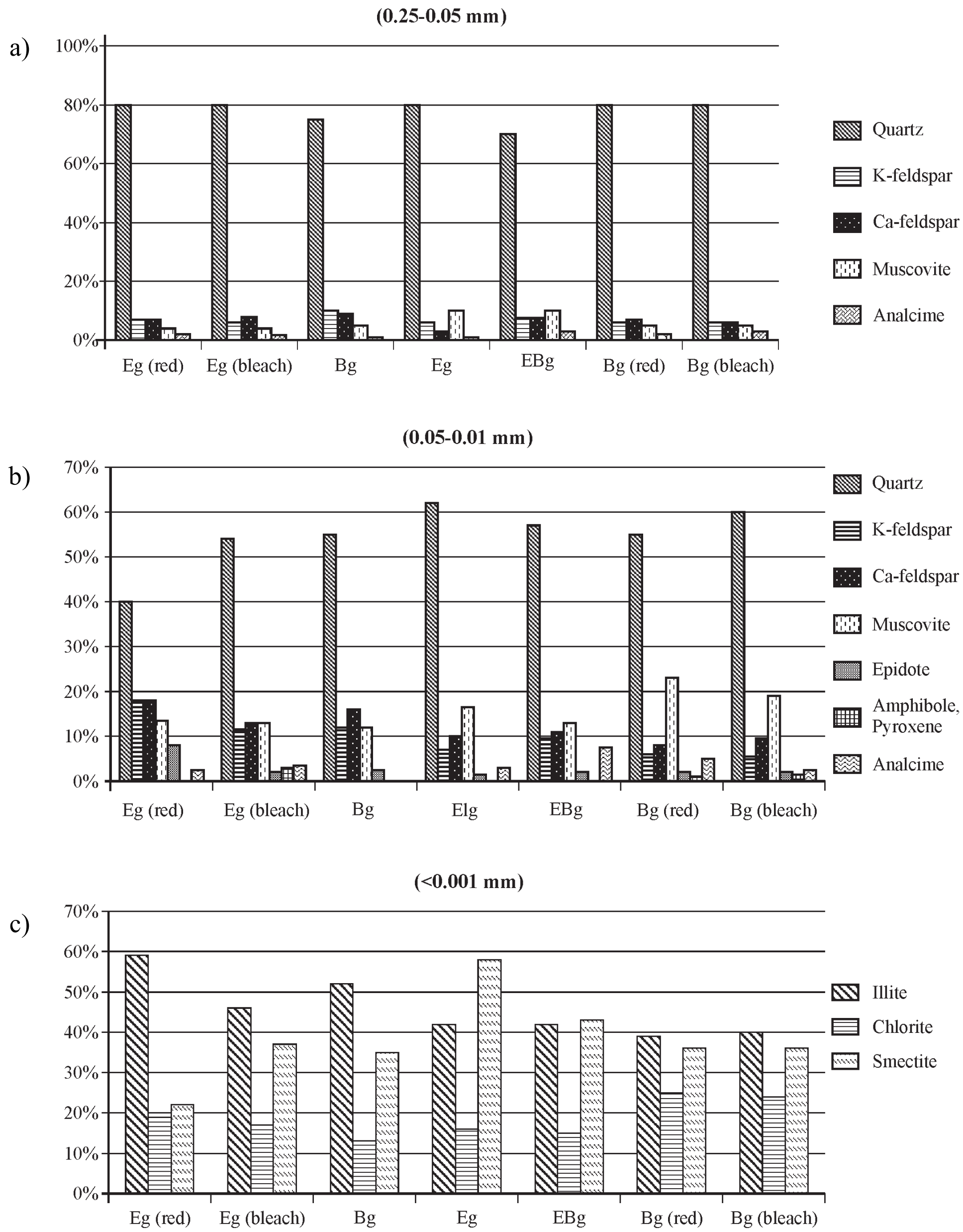



Figure 7. Mineral composition of some paleosol layers (Klimovo section) in the fractions: a) 0.25–0.05 mm; b) 0.05–0.01 mm; c) <0.01 mm.

carbonates, overlie older paleosols with high carbonate content, and are overlain by calcareous sediments. Thus, it is possible, that the carbonates in the paleosols did not result from diagenetic processes. We believe that these carbonates are pedogenic and likely indicate drier climate conditions. In the paleosols and sediments studied, carbonates are present in several forms, such as shell residues, calcite grains, carbonate nodules, clay-carbonate substances, and pure crystalline calcite. Primary carbonates, like shell remains, and calcite debris likely were inherited from the parent material, but it is difficult to determine the origin of carbonates dispersed in the soil mass. Within the soil profiles, no steady trends in carbonate distribution coincident with the soil mass coloration are observed. However greater amounts of carbonate concretions in the lower horizons may indicate carbonate redistribution due to vertical water flow either during pedogenesis or after.

Pure crystalline calcite fillings, accumulated in the center of root channels likely have a post-pedogenic origin. Calcite filled central pore (or channel) parts are represented by one pure crystalline generation, which we presume formed when the soil was buried and rates of water movement were slow enough to allow calcite crystallization. Furthermore, some pores (channels) filled with pure crystalline calcite cross through two profiles, suggesting that these floods did not happen at every pedosedimentary stage.

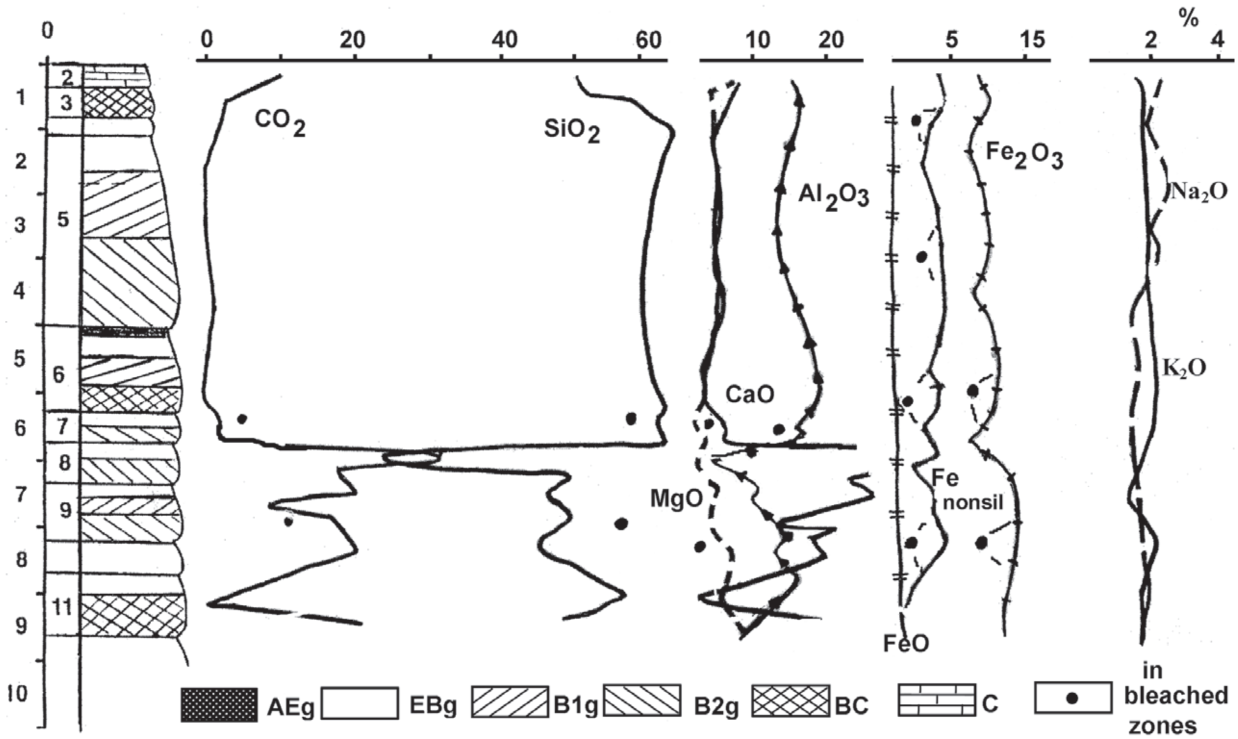


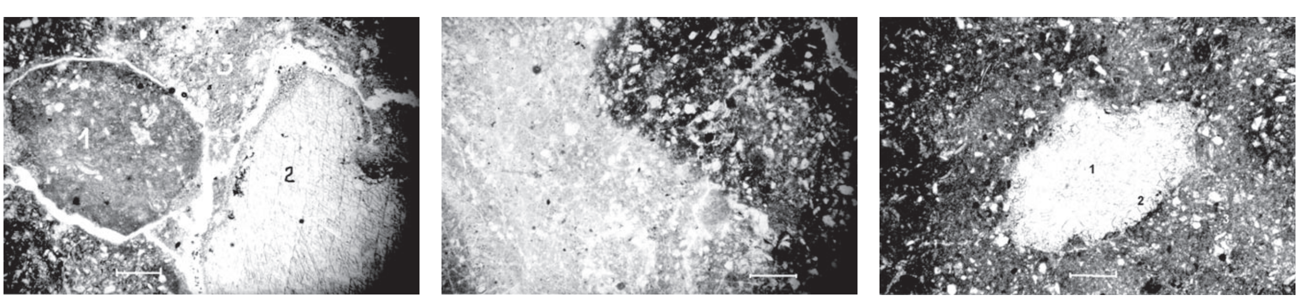

Figure 8. Chemical composition of the Upper Permian paleosol sequence (Klimovo).

The presence of analcime suggests alkaline and saline conditions in the soils, although the low total amount of $Na_2O$ and $K_2O$ indicate current low salinity (Figure 8). The stratigraphic occurrence of analcime grains between two calcite generations in some pores could suggests more alkaline conditions with higher salinity at the later stages of the soil formation, or immediately after burial.

The combination of total carbonation, bright red color, and gley bleached tubes along the deep root systems allow us to suggest that these paleopedosediments developed in strongly contrasting climatic and hydrological environments. The sedimentation likely occurred in an arid climate with oxidizing geochemical conditions followed by stages of pedogenesis governed not only by general climate aridity but also by rainy seasons with periods of surface and subsurface saturation.

## CONCLUSIONS

In the Sukhona and North Dvina drainage basins, the Salarevskian Formation was deposited in a terrestrial environment, possibly in a zone of shallow-water lakes. Part of the red sediments formed during the Tatarian were repeatedly exposed and processed pedogenically, resulting in the formation of overlapping paleosols with varying



a) b) c)

Figure 9. Micromorphological features of paleosols studied, plane polarized light, scale bar: 0.2 mm. a) Carbonate concretion (1) and pure crystalline calcite (2) adjacent to the bleached groundmass (3). b) Boundary of bleached (gleyed) and red (ferruginious) zones in EB horizon. c) Pure crystalline calcite within the pore space (1), crystals of analcime on the pore wall (2), clay calcareous bleached groundmass (3).

morphological expression. Soil macro- and microfeatures indicate similar trends in the soil formation during subsequent pedosedimentary stages, apparently due to similar climate and landscape conditions. In our opinion, the observed variable morphological expression represents variations in the duration of pedogenesis. Paleosols studied within the Tatarian sediments evidently were developed by the action of (1) eluvial-gley processes (reduction and mobilization of non-silicate iron and slight removal of fine clay from the upper part of the soil profile; (2) illuvial accumulation of iron and some clay in the subsoil; (3) formation of secondary carbonates; and (4) generation of complex soil structure.

Apparently this paleosol sequence was formed in arid or semi-arid climate conditions, and was repeatedly over flooded following burial.

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