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Cover: sketch by Roderick I. Murchison 'The Gurmaya Hills, South Urals, approaching from the Steppes' (Murchison *et al*., 1845)

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Stratotype of the Urzhumian Regional stage in the Monastery Ravine, Kazan Volga Region, Russia

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Abstract

The Monastery Ravine section has been redescribed in detail in recent years. The results of this study refine the biostratigraphic Urzhumian (~ Wordian) – Severodvinian (~ Capitanian) boundary, paleoclimatic and paleogeographical conditions of this time interval. Magnetostratigraphic and isotopic data endorse the high correlative potential of this section.

Keywords: Monastery Ravine, Urzhumian, Severodvinian, Kiaman–Illawarra reversal, carbon and oxygen isotopes

Introduction

The Monastery Ravine is located on the right bank of the Volga River, in the vicinity of the village of Monastyrskoe (55.02619° N, 48.89192° E), 12 km upstream of the town of Tetyushi. The outcrops in the thalweg and the slopes of these ravines represent one of the most complete and readily accessible sections of the Biarmian and Tatarian series in the region of the Kazan Povolzhye [1].

The Monastery Ravine section was first described by N.N. Forsch during the geological mapping of the Volga region in 1938. He divided the section into 5 formations according to lithological criteria; these formations are used in the present work. This section was repeatedly studied in the course of stratigraphic, lithological [2], [3], [4], paleomagnetic [5], [6], [7], and paleontological [8], [9], [10] works. Recent studies, carried out on this section revealed new sedimentological and geochemical features [11], clarified the paleomagnetic data [12], [13], [14], supplemented the data on tetrapods, fish and plants [15], [16], [17], and helped to identify and describe the paleosol profiles [18], [19].

According to the Resolution of the Russian Interdepartmental Stratigraphic Committee [20], the Monastery Ravine section is a stratotype of the Urzhumian and a limitotype of the Severodvinian.

The section is represented there by all three stages – Urzhumian (~ Wordian), Severodvinian (~ Capitanian), Vyatkian (~ Wuchiapingian) – and five formations (Fig. 1); its thickness reaches 150 m.

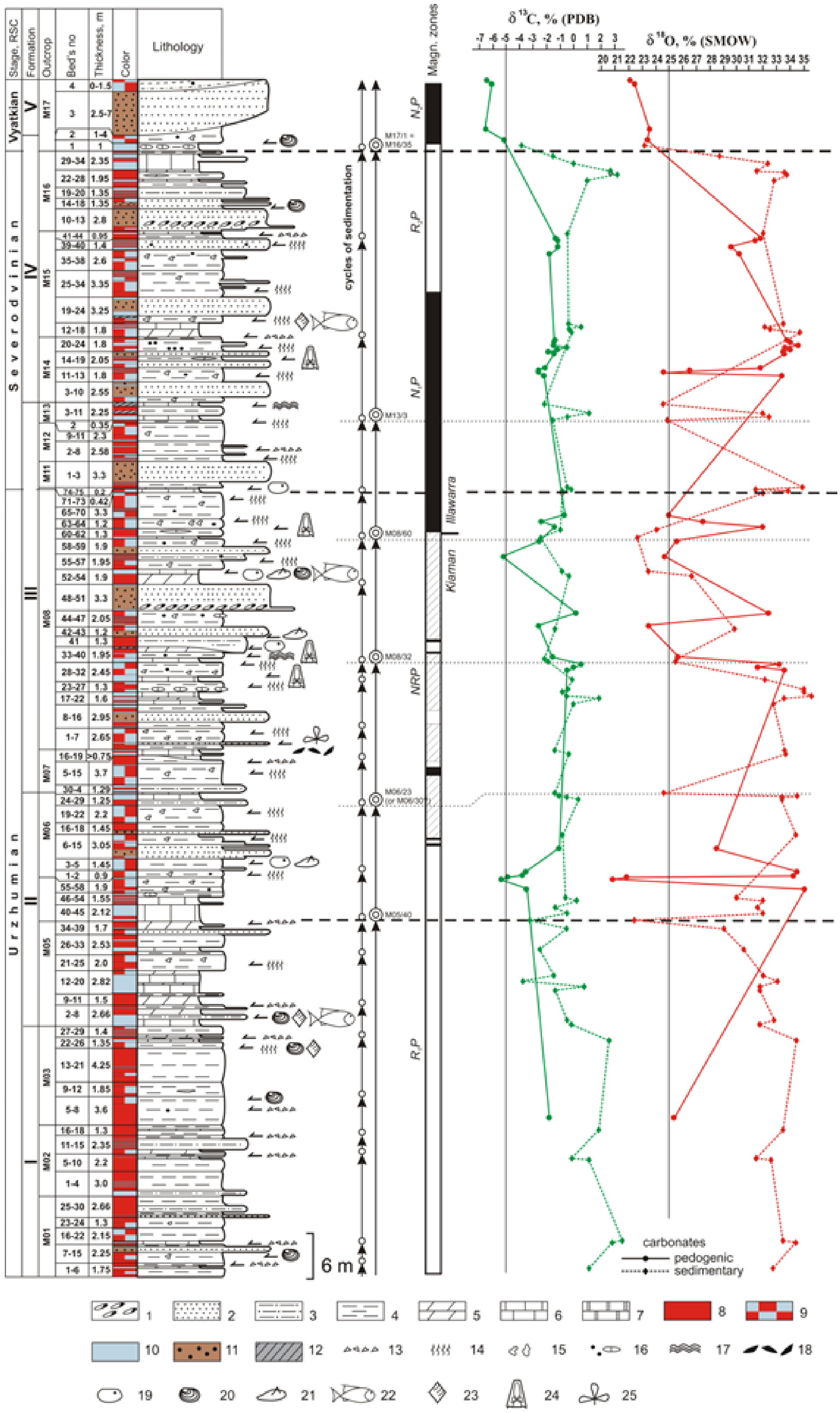

Fig. 1. Urzhumian and Severodvinian succession in the Monastery ravine (modified from [1]): (1) gravel, (2) sandstone, (3) siltstone, (4) claystone, (5) marl, (6) limestone, (7) dolomite, (8) redstone, (9) speckled rock, (10) gray and gleyed rock, (11) brown fluvial sand, (12) dark gray rocks, (13) clayey breccias, (14) paleosol, (15) gleyed spots, (16) soil nodules, (17) thrombolitic, (18) carbonized plant detritus, (19) non-marine ostracodes, (20) conchostracans, (21) non-marine bivalves, (22) fishes, (23) fish scales, (24) tetrapods, (25) plants.

Results and discussion

The Urzhumian

The Urzhumian includes three Formations: The First, the Second and the lower part of the Third Formation [1].

The First Formation is composed of red-bed clays and is distinctly subdivided into two parts.

The clays of the lower part of the Formation are gypsiferous, containing many interbeds (3-20 cm thick) of gray and pink marls and clayish dolomites, more rarely of brown siltstones and sandstones.

In the upper part of the Formation, clays are more homogenous and contain a few interbeds of siltstones and carbonate rocks. The clays often bear thin lenses of palygorskite. The overall thickness of the Formation is ca. 45 m.

Fossils occur rarely in the Formation and mostly in its upper part. The first bed with fossils lies 10 m below the top of the Formation and is composed of reddish-brown thinly bedded clays containing small (3-4 mm) distorted valves of conchostracans. Seven meters above this bed, dull-red massive clays, along with conchostracan species *Pseudestheria* cf. *itiliana* (Novojilov, 1950), contain isolated scales of the fishes *Platysomus biarmicus* Eichw., *Kargalichthys efremovi* Minich, *Eurynotoides* sp., *Palaeostrugia rhombifera* (Eichwald), *Uranichthys pretoriensis* A. Minich, *Alvinichthys curtus* Esin, *Varialepis orientalis* (Eichw.), *Varialepis bergi* A. Minich, *Elonichthys* sp., *Eurysomus* sp., and Sphenacanthidae gen. indet.

The Second Formation is exposed in the second right tributary, and also in the thalweg and slopes of the Monastery Ravine [1]. The thickness of the Formation is ca. 35 m.

The Second Formation is distinct in its cyclic structure and high content of carbonates. The section contains three clayish-carbonate members: at the bottom, in the middle, and at the top. These members are separated by two members of sandy-clayish rocks. The clayish-carbonate members are composed of greenish and pinkish-grey dolomites, clayish limestones and marls (0.2-1.5 m thick), containing thin (usually 10-30 cm) interbeds of red clay. The sandy-clayish members are composed of reddish-brown clays and siltstones with lenticular interbeds of brownish sandstones (up to 2 m).
Fossils are represented by non-marine ostracodes, bivalves, fishes, amphibians, and plants.

Rare valves of conchostracan species *Pseudestheria exigua* (Eichwald, 1860) were found About 5 m above the base of the Formation in brownish clays.

The bed of the greenish-gray siltstone (5-20 cm), 6.5 m above the base of the formation, contains numerous scales of the fishes *Platysomus biarmicus* Eichw., *Eurynotoides* sp., *Uranichthys pretoriensis* A. Minich, *Varialepis bergi* A. Minich, *Elonichthys* sp., *Eurysomus* sp., *Varialepis bergi* A. Minich, *Elonichthys* sp., *Eurysomus* sp., and Sphenacanthidae gen. indet, Discordichthyidae gen. indet. The large (0.5-3.0 cm) reddish-brown scales occur parallel to the bedding planes and mainly concentrate in the thin (3-5 mm) bed, which also yields small amphibian bones.

Eight meters below the top of the Formation, the bed (0.1 m) of reddish-brown evenly and thinly laminated clay contains molds of the ostracodes *Palaeodarwinula* cf. *fragiliformis* (Kash.) [4], the bivalves *Palaeomutela castor* (Eichw.), *P. doratioformis* Gusev, *Prilukiella subovata* (Jones), scales of the fishes *Varialepis* cf. *orientalis* (Eichw.), *Platysomus* sp., *Elonichthys* sp., fragments of the small-leafed plant *Phylladoderma tscheremushca* Esaul., and the remains of *Paracalamites frigidus* Neub. and *Stomochara diserta* Kis.

The Third Formation is well exposed in the first right tributary and in the thalweg of the mainstream of the Monastery Ravine. The thickness of the Formation is ca. 45 m. Its lower boundary is drawn at the top of the upper dolomitic bed of the Second Formation.

The Third Formation is distinct in the predominance of sandstones and siltstones in the succession (Fig. 1). Carbonate beds are rare and thin. Reddish-brown clays and siltstones are most widespread and are usually intercalated by thick lenses of yellowish-brown, cross-bedded sandstones. Carbonate rocks are represented by gray, nodular, and muddy limestones and marls.

The cyclicity of the Formation is distinct.

Different levels within the Formation contain the remains of non-marine bivalves, ostracodes, conchostracans, fishes, and tetrapods, and imprints and fragments of plants [1]. Gray and brown siltstones 1-1.5 m above the base of the Formation contain coaly remains of the trunks of *Sphenophyllum stouckenbergii* (Schm.) and *Paracalamites frigidus* Neub.

The mass occurrences of the conchostracan species *Pseudestheria exigua* (Eichwald, 1860) appear in the greenish siltstone of fish layer (bed M08/54, Fig. 1). All the specimens found are well preserved. They are represented by various deformations of the growth lines at the anterior-ventral and posterior-ventral margins. There are also the examples in this section without deformations on the margins.

The bed of reddish-brown and greenish-gray siltstone, eight meters higher than the previous one contains the ostracodes *Paleodarwinula chramovi* (Schn.), *P*. ex gr. *aronovae* (Bel.), *P*. ex gr. *fainae* (Bel.), *P. fainae* (Bel.), *P. fragiliformis* (Kash.), *P. pseudopertebrata* (Bel.), *P. teodorovichi* (Bel.), *P. elongata* (Lun.), *Prasuchonella nasalis* (Schn.) [4], the bivalves *Palaeomutela ulemensis* Gusev, *P. wöhrmani* Netsch., *P. numerosa* Gus., *P. marposadica* Gus., and *P. subparallela* Amal., rare scales of the fishes *Varialepis orientalis* (Eichw.) and *Kichkassia* sp., and rare amphibian vertebrae. The clayish limestone, four meters above, contains the ostracodes *Paleodarwinula chramovi* (Schn.), *P. aronovae* (Bel.), *P. fainae* (Bel.), *P. elongata* (Lun.), *Prasuchonella nasalis* (Schn.) [4], the remains of complete fishes *Platysomus biarmicus* Eichw., *Kargalichthys efremovi* Minich, *Varialepis bergi* A. Minich, *V. orientalis* (Eichw.), *Eurynotoides costatus* (Eichwald), *Kichkassia furcae* Minich, *Isadia suchonensis* A. Minich, *Suchonichthys molini* A. Minich, *Alvinichthys curtus* Esin, *Uranichthys pretoriensis* A. Minich, Sphenacanthidae gen. indet., *Discordichthys spinifer* Minich, a few small bivalves of *Palaeomutela* sp. and conchostracans.

The Severodvinian

The Severodvinian includes the upper 12 m of the Third Formation and almost the entire Fourth Formation [1].

The Fourth Formation is exposed in the thalweg and the slopes of the first left tributary of the Monastery Ravine. It is represented by the alternation of siltstones, clays and sandstones with marls and limestones showing the distinct cyclicity. Sandstones are usually bluish or yellowish-gray and recognized in three levels as lenses 2.5-8.0 m thick. Together with clays and siltstones, they form three clayish-sandstone members. Carbonate rocks concentrate mostly in the lower and upper parts of the Formation, where they, together with clays, form separated clayish-carbonate members 4.5 m thick at the bottom and 7.8 m at the top of the Formation [1]. The lower boundary of the Formation is drawn at the base of the bed of light-gray clayish limestone with a distinct vertical structure overlying the upper clayish-sandstone member of the Third Formation. The thickness of the Formation is ca. 33 m.

The Formation contains few fossils. At the base of the Formation, there are the ostracodes *Suchonellina inornata* (Spizh.), *S. inornata macra* (Lun.), *S. parallela* (Spizh.), *S. perlonga* (Schn.), *S.* ex gr. *parvaeformis* (Kash.), *Prasuchonella nasalis* (Shar.), *P. stelmachovi* (Spizh.) [33], the charophytes *Cuneatochara vjatkensis* Kis. and *C. amara* (Said.). Upwards in the section, five meters below the top of the Formation, the bed of bluish-gray marl, apart from the similar ostracode assemblage, contains large conchostracan shells, fragments of the bivalve *Palaeomutela* sp., scales of the fishes *Isadia suchonensis* A. Minich, *Suchonichthys molini* A. Minich, *Platysomus* sp., *Kargalichthys efremovi* Minich, *Varialepis stanislavi* A. Minich, *Strelnia insolita* (Esin), *Sludalepis* sp., *Kichkassia furcae* Minich, *Lapkosubia* cf. *uranensis* A. Minich, *Uranichthys pretoriensis* A. Minich, Sphenacanthidae gen. indet [16]. Ostracodes occur in more calcareous part of the marl, whereas fish scales occur in more clayish part. The intermediate type of marl contains conchostracans and fragments of bivalvian shells.

The rare juvenile specimens of *Pseudestheria exigua* (Eichwald, 1860) were found in the reddish siltstones (beds M16/14-15). The presence of *Pseudestheria exigua* at different levels in the section indicates that during the sedimentation period, the living environment changed insignificantly or was repeated after certain intervals of time. The variability of the valve morphology in the section is not significant. The presence of juveniles of the species *P. exigua* indicates that the depth became extremely small, and the pool turned into a drying pond (puddle), which prevented the crustaceans developing into adults.

The Fifth Formation and its boundary with the Fourth Formation is exposed 2 km southwest, in the upper reaches of the Ilyinsky Ravine (55.01297° N, 48.86517° E) [1]. In this locality, the section of the Formation is represented by a member (10-15 m) of yellowish-brown obliquely laminated sandstones, with conglomerate lenses, consisting of fragments of local rocks. Sandstones frequently contain silicified lenses and interbeds of red-bed siltstones, clays and marls. The apparent thickness of the Formation is 25 m.

The lower part of the Formation (clays and marls) contains ostracodes and fragments of bivalves.

Ostracodes are characteristic of the boundary beds of the Vyatkian and Severodvinian Horizons and represented by *Wjatkellina fragilis* (Schn.), *Suchonellina parallela* (Spizh.), *S.* cf. *futschiki* (Kash.), *S.* cf. *inornata* Spizh., *S. inornata macra* (Lun.), *Suchonella typica* Spizh., *Volganella magna* (Spizh.), *V. laevigata* Schn. and *Placidea lutkevichi* (Spizh.) [4]. Sandstones contain bones of labyrinthodonts (*Dvinosaurus*), chroniosuchids (*Chroniosaurus*), leptorophids (*Raphanodon),* pareiasaurs (*Praelginia* and others) and numerous therapsids [1].

Urzhumian-Severodvinian boundary, biostratigraphical criteria

The Severodvinian boundary is suggested at the base of bed M08/74 by the first appearance of the ostracode *Suchonellina* and the index species *Suchonellina inornata* marked the basement of *Suchonellina inornata-Prasuchonella nasalis* zone [1], [21]. Urzhumian ostracode species of *Palaeodarwinula* genus, on the contrary, occur just below this boundary. This level is close to *Platysomus biarmicus-Kargalichthys efremovi* and *Toyemia tverdochlebovi-Platysomus biarmicus* ichthyozones boundary [21]. Five meters below the Severodvinian boundary, in beds M08/64-66, there have been found the remains of the fishes *Isadia suchonensis*, *Suchonichthys molini* and *Uranichthys* sp. belonging to the *Toyemia tverdochlebovi-Platysomus biarmicus* ichthyozone.

The same species as well as transitional *Platysomus biarmicus* and *Xenosynechodus* sp. have been identified in bed M14/16 and upper. Here, in this bed, the isolated bones of the terrestrial amphibians *Microfon exiguus* have been found [15]. Non-marine bivalves of the Severodvinian complex appear in the section 20 m below the Urzhumian-Severodvinian boundary. Species such as *Palaeomutela numerosa* and *P. marposadica* have been traced in Severodvinian deposits throughout the vast territory of Volga-Ural basin [4], [22].

The Kiaman-Illawarra reversal boundary lies 5-6 m below the Urzhumian-Severodvinian biostratigraphic boundary (Fig. 1) and practically coincides with *Toyemia tverdochlebovi-Platysomus biarmicus* ichthyozones boundary [1]. The negative excursions of carbon and oxygen isotope values of sedimentary and pedogenic carbonates can be suggested as an additional marker of the Kiaman-Illawarra reversal boundary.

Chemostratigraphy

Stable isotope ($\delta^{13}C$, $\delta^{18}O$) studies have been carried out on all stratigraphic levels in the Monastery Ravine section. The values of $\delta^{18}O$ vary from 22.3 to 35.5‰ SMOW (Fig. 1). Variations of $\delta^{18}O$ values apparently reflect the evolution of local ‘lacustrine’ basins. Intervals with the lightest oxygen structure may correspond to the spread of freshwater environments and to the active influx of meteoric water from the land during humidization and cooling [23]. Intervals with the heaviest oxygen structure may correspond to episodes of warming, when the basin waters were heavy due to evaporation. It is also possible that episodes of heavy oxygen composition may indicate the impact of marine ingression of the Boreal sea. These events could be reflected in the flow of heavier water from closed or semi-enclosed lagoon environments [24]. Decrease in $\delta^{18}O$ values in pedogenic carbonates is also associated with cooling, as is well demonstrated for Quaternary soils [25], [26].

Significant facilitation of $\delta^{13}C$ values fixed in the lower part of the section up to the mid-Urzhumian (Wordian) from 3.5 ‰ to -3.8‰ in sedimentary carbonates and from -1.8‰ to -5.2‰ in pedogenic ones (Fig.1). These negative excursions of carbon isotope values could reflect global geochemical changes and may potentially be good stratigraphic markers. In the upper part of the section, a marked decrease of $\delta^{13}C$ values have been identified on the Severodvinian-Vyatkian (Capitanian-Wuchiapingian) boundary (Fig. 1). The same facilitation of carbon isotopic composition is typical for terrestrial deposits of the central parts of East European Platform [27].

Magnetostratigraphy

Paleomagnetic studies were repeatedly conducted in the Monastery Ravine section [5], [6], [11], [12], [13]. Rocks of the First Formation and the lower part of the Second Formation are characterized by reversed polarity and belong to R_1P magnetic zone (Fig. 1). The upper part of the Second Formation and the lower part of the Third Formation, with the total thickness of 35 m, have a strong metastable magnetism which is commonly a characteristic feature of weak-magnetic rocks.

This interval was specified as the alternating-sign zone (NRP zone, Fig. 1).

The Kiaman-Illawarra reversal boundary is located in the upper part of the Third Formation, at 5 m below the Urzhumian-Severodvinian biostratigraphic boundary (Fig. 1). The upper part of the Third Formation and the lower part of the Fourth Formation belong to the N_1P magnetic zone of Illawarra Hyperzone. The upper part of the Fourth Formation shows reversed polarity. This interval of the section corresponds to the largest part of the R_2P magnetic zone. Geomagnetic latitudes calculated for samples with normal polarity, are from 18° to 29°N for the overall succession.

Cyclicity and paleosols

The Monastery ravine succession exhibits a clear multi-order cyclicity. In total, 22 complete high order cycles (HOC) have been identified in this section (Fig. 1), each of 4-12 m thick [28]. The bases of the cycles are both erosional surfaces (fluvial channels filled in sandstones and their basinal equivalents) and non-erosional surfaces (paleosols and clayey breccias). These cycles have been formed as a result of climatic temperature fluctuations evidenced by isotopic data ($\delta^{13}C$ and $\delta^{18}O$ of sedimentary and pedogenic carbonates) [10]. Each of the cycles could be interpreted as a transgressive-regressive cycle for a shallow lake basin and the adjacent fluvial plain [28].

The complete cycle of continental deposits includes: 1) the fluvial plain deposits of the transgressive phase (massive and laminated mudstones); 2) basinal terrigenous sediments of the transgressive phase (laminated mudstones, marls with lacustrine fauna); 3) carbonate basinal sediments (in some cases, pedogenically altered) with non-marine ostracodes, bivalves, fish; 4) basinal terrigenous sediments of the regressive phase (laminated mudstones with desiccation signs) and 5) flood plain sediments of the regressive maximum (massive mudstones with paleosols and fluvial channel sandstones). Fossils occur mainly in deposits of the middle phases of sedimentary cycles.

Paleosols have been identified and described in more than twenty levels of these section (Fig. 1) by the pedofeatures: *in situ* roots, slickensides, gleyed zones, carbonate nodules, blocky peds, etc.

All paleosols are classified based on pedofeatures and the presence of paleosol horizons [29] and belong to two genetic types: calcic gleysols and gleyed vertisols [18]. The typical pedofeatures of studied paleosols are wedge-shaped angular blocky peds with slickensides on their surfaces and gley spots, including the gleyed root traces. This indicate the periodical shrinking and swelling of soils on wetting and drying [30] and changes in the water table due to the seasonal rainfalls [31]. By degree of maturity, most of the studied paleosols could be attributed to moderately developed paleosols, with I to II Stage of carbonate accumulation.

An overall characteristic feature for all the studied paleosols, are: 1) lack of non-gleyed soils; 2) lack of the signs of deep soil erosion; 3) markers of seasonality of precipitation (slickensides, gley features and calcareous nodules); 4) clear soil horizonation; 5) silty-muddy host material. These features indicate settings of low relief, periodically flooded plains with rain or fluvial waters [32], where the accumulation of sediments exceeded their erosion.

Based on the depth to B_k horizon [33], the trend toward some humidization is traced from the Urzhumian to the Severodvinian time, with mean annual precipitation (MAP) estimated at 300-400 mm/year and 400-600 mm/year respectively. Similar climatic trend ("wetting phase") was detected in the Middle Permian of the tropical zone of Northern Pangaea [34] at the Wordian-Capitanian boundary (*ca.* Urzhumian-Severodvinian boundary). Thus, the paleosols in the studied section indicate a semi-arid climate with clear seasonality of precipitation during the Urzhumian and some humidization in the Severodvinian.

Conclusions

1. The biostratigraphic Urzhumian-Severodvinian boundary in the Monastery Ravine section is located within the Third Formation and coincides with the lower boundary of the *Suchonellina inornata-Prasuchonella nasalis* ostracode zone and the *Toyemia tverdochlebovi-Platysomus biarmicus* fish zone.
2. The Kiama-Illawarra paleomagnetic reversal boundary in the studied section lies just below the Urzhumian-Severodvinian biostratigraphic boundary and is a valuable marker for interregional and global correlation.
3. The Urzhumian-Severodvinian succession in the Monastery Ravine has clear cyclic construction formed as a result of temperature climatic fluctuations on a background of semi-arid climate with seasonality of precipitation. MAP estimated from the study of paleosol profiles, is 300-400 mm/year for the Urzhumian and 400-600 mm/year for the Severodvinian.
4. Cooling episodes marked by the decrease of $\delta^{18}O$ values are confined to the Middle and Late Urzhumian and to the Severodvinian-Vyatkian boundary. Negative excursions of $\delta^{13}C$ in the Mid-Urzhumian and in the Severodvinian-Vyatkian boundary could reflect global geochemical events and serve as additional correlative markers.

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