ISSN 1028-334X, Doklady Earth Sciences, 2011, Vol. 440, Part 1, pp. 1222–1226. © Pleiades Publishing, Ltd., 2011.
Original Russian Text © D.V. Grazhdankin, V.V. Marusin, J. Meert, M.T. Krupenin, A.V. Maslov, 2011, published in Doklady Akademii Nauk, 2011, Vol. 440, No. 2, pp. 201–206.

GEOLOGY

Kotlin Regional Stage in the South Urals

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Received April 26, 2011

DOI: 10.1134/S1028334X11090170

According to the current tradition that has remained unchanged since 1977, the Upper Vendian of the East European Craton is subdivided into three regional stages (horizons): Redkino, Kotlin, and Rovno. It is generally believed that the Redkino Regional Stage is characterized by casts and molds of soft-bodied organisms; the Kotlin, by diverse assemblages of carbonaceous compressions; the Rovno, by the appearance of diverse ichnocoenoses [1]. It turned out that carbonaceous compressions also occur in the Redkino Regional Stage as a distinctive fossil assemblage [2, 3], whereas almost all casts and molds of soft-bodied organisms in the Mezen Basin and South Urals are confined to a stratigraphic interval wedged between the Redkino and Kotlin and not represented in the Moscow Basin [4]. It appears that the Redkino lower boundary is older than previously thought: during our fieldwork in 2009, we discovered volcanic tuffs in the Perevalok Formation of the Sylvitsa Group in the Krutaya Gora section on the Us'va River (Central Urals) that yielded a U–Pb-zircon date of 567.2 ± 3.9 Ma (Fig. 1). Considering a Rb–Sr (Cpx + bulk) date of 608 ± 3 Ma for the explosive picritic breccia intruded into the Kernos Formation (which underlies the Staropechny Formation of Redkino Regional Stage in the Central Urals) and a Sm–Nd (Cpx + bulk) date of 569 ± 42 Ma for picrobasalts, trachybasalts, and trachyandesites of the Dvorets volcanogenic complex of Upper Kernos Formation [5], the Redkino lower boundary age can be placed as 570–600 Ma.

Fossils have been rather freely used to subdivide the Upper Vendian into the regional stages, which inevitably led to inflation of the paleontological characteristic and correlation of heterochronous deposits. By analogy with the Redkino Regional Stage [3, 4], we propose to restrict the stratigraphic range of the Kotlin Regional Stage and match its lower boundary with the marine flooding surface (mfs) that is traced across the entire East European Craton (Fig. 2). This surface transgressively overlies the Redkino and older strata (locally, the crystal basement) on the southern slope of the Baltic Shield. In some sections (Valdai Borehole), the Redkino shales preserve evidence of subaerial exposure in the form of kaolinite. We place the lower Kotlin boundary in the base of a thin (4.7–7.6 m) unit of coarse-grained quartz and quartz–micaceous, rarely arkosic sandstones of the Gdov Formation. The main bulk of the Kotlin Regional Stage consists of gray, variegated, and red-brown clay and thin-alternating sandstones, siltstones, and shales [6].

The lower Kotlin boundary on the southeastern slope of Baltic Shield (southeastern White Sea area) is drawn at the base of the Erga Formation. In the sections along the Bol'shaya Torozhma and Zimn'yaya Zolotitsa rivers, the lower Erga Formation comprises interstratified variegated wave-bedded sandstones, siltstones, and shales of the highstand systems tract (HSST) transgressively overlying various parts of the Zimnegory Formation. The base of this unit is marked by a marine flooding surface and packages (up to 2 m) of wave-bedded quartz sandstone with conglomerate lenses. In the sections of Zimnie Gory, the lower Erga Formation consists of a cyclic stratification of units of dark gray thin-bedded shales, packages of yellowish gray sandstones, and intervals of alternating siltstones and shales. This succession (reaching 30 m in thickness) represents a gentle incised valley fill constrained by a marine regression surface (mrs) from below and a marine flooding surface from above and is interpreted as a transgressive system tract (TST) of the Erga sequence. The overlying unit of variegated interstratified wave-bedded sandstones, siltstones, and clays is coeval with a similar unit at the base of Erga Formation in the adjacent sections. The sharp facies change allows direct tracing of the marine flooding surface at the base of the highstand system tract of Erga sequence in outcrops and boreholes. We propose to match this surface with the lower boundary of the Kotlin Regional Stage in the southeastern White Sea area.

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According to this correlation, the transgressive systems tract of Erga Formation with a diverse assemblage of casts and molds of soft-bodied organisms is not part of the Kotlin Regional Stage.

In the Moscow Basin, the marine flooding surface is traced at the base of quartz and arkosic sandstones of the Pereslavl' beds of Lubim Formation [7]. In the Central Urals, we place this surface at the lower boundary of dark gray and variegated siltstones and shales of the Konovalovka Member of the Chernokamen Formation that overlies various parts of the Chernokamen Formation. The marine flooding surface is difficult to trace in the Mezen Basin characterized by the highest subsidence rates on the craton. We draw the lower Kotlin boundary by the appearance of variegated rocks in the "Mezen Formation."

We therefore propose to establish the Kotlin Regional Stage as an equivalent of the highstand systems tract of the Erga sequence bounded by the marine flooding surface below and the marine regression surface above. In order to preserve the correlation function of the Kotlin for the Upper Vendian stratigraphy, we suggest exclusion from the Kotlin Regional Stage of the Padun Formation of Mezen Basin (and the lithologically similar Reshm Formation of Moscow Basin) that contains trace fossils *Diplocraterion* of the Lontova Regional Stage [8].

The Kotlin Regional Stage is characterized by a specific assemblage of fossil soft-bodied organisms. The highstand systems tract of the Erga sequence (southeastern White Sea area, Mezen Basin, western slope of the Central Urals) yielded fossil arumberiamorph organisms. Three-dimensional casts of rangeomorphs and psammocorals, casts and molds of dickinsoniomorphs, bilateromorphs, and tribrachiomorphs found in the upper part of Winter Mountains (Zimnie Gory) sections, as well as fossil dickinsoniomorphs, petalonamae, and rangeomorphs in Konovalovka and Krutikha members of the Chernokamen Formation in the Sylvitsa Rivers sections of the Central Urals all have the Kotlin age. Strata cropping out in the middle reaches of the Onega River on the southeastern margin of the Vetrenyi Poyas Ranges and yielding three-dimensional casts of petalonamae, tribrachiomorphs, and rangeomorphs are also related to the Kotlin Regional Stage [9].

The lower part of the highstand systems tract of the Erga sequence is characterized by trace fossils, of which the most important is *Psammichnites* found in the lower Erga Formation in the coastal cliffs of the Winter Mountains (southeastern White Sea area). It is preserved as a pair of ridges (hyporelief and epirelief) formed as a result of burrow collapse that was made within the sediment by bilaterian organisms. These organisms moved in the horizontal plane and had a vertical snorkel for collecting detritus from the surface. When cross-cutting of *Psammichnites* is observed, an older trace is not obliterated but instead is superimposed by a successive trace implying an intrasedimentary origin. Apart from *Psammichnites*, the ichnocoenoses also include relatively large vertical burrows of sedentary polypoid organisms *Bergaueria* and *Astropolichnus* and vertical burrows of worm-like organisms *Scolithos*, as well as trace fossils from the underlying strata: meandering horizontal meniscate traces *Nenoxites*, small epirelief pairs of ridges *Archaeonassa*, meandering horizontal traces *Planolites*, and small *Bergaueria*.

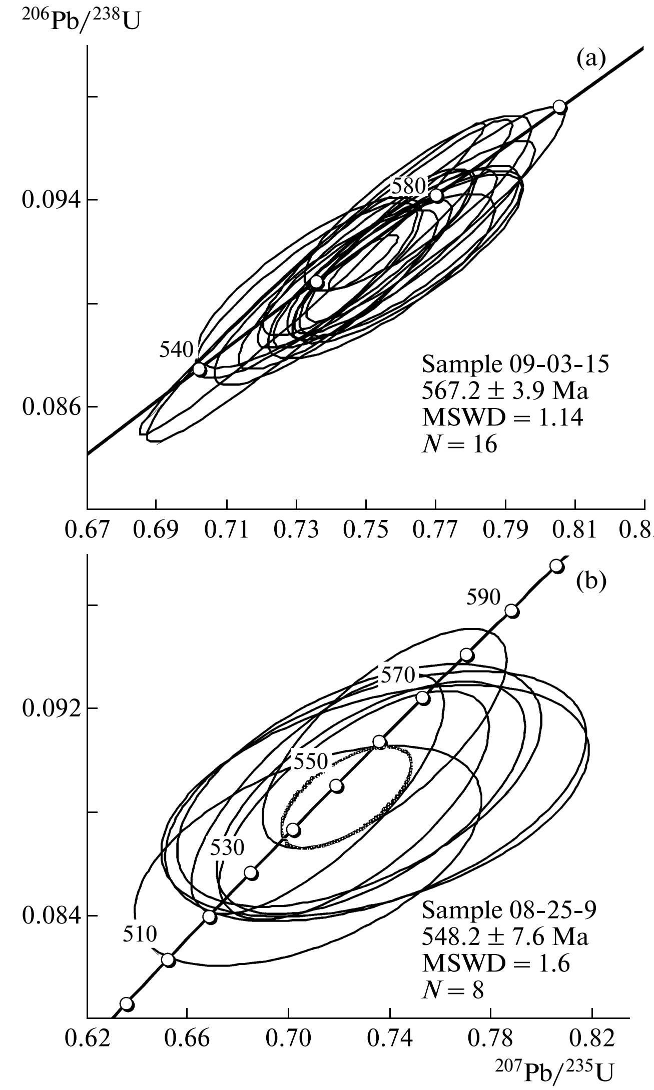

Fig. 1. U–Pb-zircon date of volcanic tuffs from Perevalok Formation of the Sylvitsa Group, Central Urals (a), and from the Zigan Formation of the Asha Group, South Urals (b).

The paleontological characteristic of the Zigan Formation of Asha Group (western slope of South Urals) is also very interesting. Based on the discovery of casts and molds of soft-bodied organisms, the strata are correlated with the Redkino Regional Stage [10]. Sedimentological analyses of Zigan sections demonstrate that this formation is part of a highstand systems

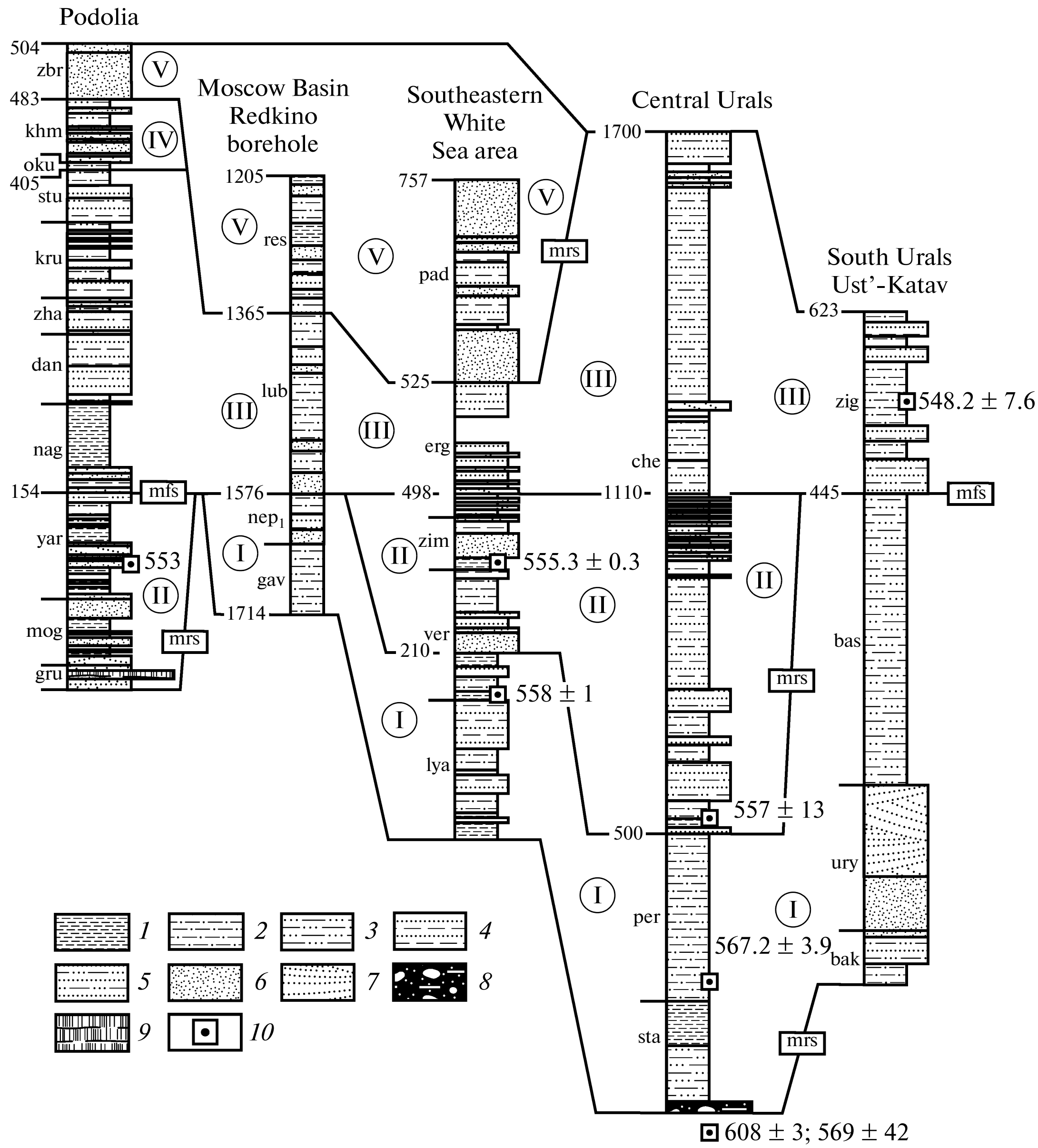

Fig. 2. Correlation of reference sections of the Upper Vendian of the East European Craton and tracing of the marine flooding surfaces at the base of the Kotlin Regional Stage. The Ust'-Katav section is based on data by V.I. Kozlov, N.D. Sergeeva, and A.N. Abramova (1995).

(*1*) Fine laminated shale; (*2*) alternating siltstone and shale; (*3*) fine laminated siltstone; (*4*) alternating shale and sandstone; (*5*) alternating siltstone and sandstone; (*6*) planar laminated sandstone; (*7*) cross-bedded sandstone; (*8*) diamictite; (*9*) flood basalts; (*10*) stratigraphic position of volcanic tuffs with U–Pb-zircon dates. Sequence boundaries: (mrs) marine regression surface; (mfs) maximum flooding surface. Formations: (gru) Grushka, (mog) Mogilev, (yar) Yaryshev, (nag) Nagoryany, (dan) Danilov, (zha) Zharnovka, (kru) Krushanovka, (stu) Studenitsa, (oku) Okunets, (khm) Khmel'nitski, (zbr) Zbruch, (gav) Gavrilov-Yam, (nep) Nepeitsyno, (lub) Lubim, (res) Reshm, (lya) Lyamtsa, (ver) Verkhovka, (zim) Zimnegory, (erg) Erga; (pad) Padun; (sta) Staropechny, (per) Perevalok, (che) Chernokamen, (bak) Bakeevo, (ury) Uryuk, (bas) Basu, (zig) Zigan. Regional Stages (numbers in circles): (I) Redkino, (II) intermediate between Redkino and Kotlin; (III) Kotlin, (IV) Rovno, (V) Lontova. Age, Ma.

tract, with the marine flooding surface as the lower boundary. This fact suggests correlation of the Zigan Formation with the Erga sequence. An assemblage of Kotlin-age fossils was discovered in 2004 in the valley of Karanyurt Creek (upper reaches of the Askyn River; western Yashkady Ridge) (Fig. 3). As in the Winter Mountains, the assemblage includes horizontal "bulldozing" traces *Psammichnites* preserved in positive hyporelief as a pair of ridges separated by a deep sinusoidal furrow that crosses the wave-ripple lamination

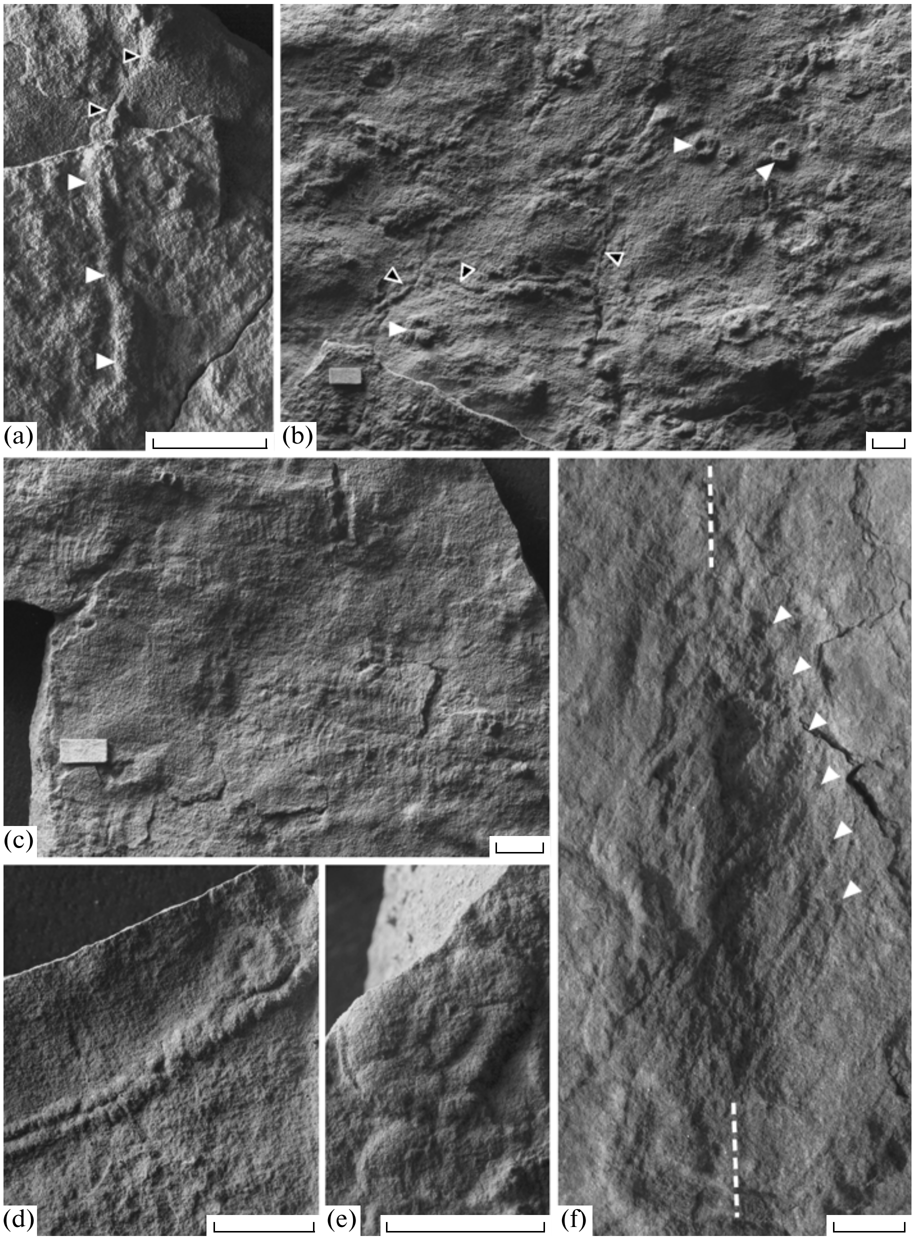

Fig. 3. Fossil assemblage from the Zigan Formation of the Asha Group of the South Urals (upper reaches of the Askyn River, western Yashkady Ridge). (a) Horizontal “bulldozing” trace fossil *Psammichnites* (hyporelief, white arrowheads), with trace of vertical snorkel within sandstone (black arrowheads); (b) trace fossils *Psammichnites* (black arrowheads) and vertical burrows *Bergaueria* (white arrowheads), hyporelief; (c) sedimentary structures “swing marks,” hyporelief; (d) trace fossil *Psammichnites*, hyporelief; (e) three-dimensional cast of holdfast of the frondomorph organism *Charniodiscus*, epirelief; (f) mold of the stem (dashed line) and segmented frond (white arrowheads mark the segments) of the frondomorph organism *Charniodiscus*, hyporelief. Scale bar: 10 mm. Depository of the Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences.

in the host sandstones, as well as trace fossils *Bergaueria*. In addition to the ichnofossils, the fossil assemblage is characterized by three-dimensional and composite negative hyporelief casts of holdfast structures and rare epirelief molds of frond structures of frondomorphs *Charniodiscus concentricus*, along with three-dimensional casts of arumberiamorphs. The bedding surfaces preserved abundant swing marks, the molds of arcuate scratches and furrows produced by a swinging motion of rooted organisms (for example frondomorphs) in a turbulent current.

A thin bed of volcanic tuffs in the lower Zigan Formation in a section located on the northern outskirts of the town Ust’-Katav yielded a U–Pb-zircon date of 548.2 ± 7.6 Ma (Fig. 1). The marine flooding surface at the base of the Kotlin Regional Stage marks a major eustatic event [4] and can be traced directly to the western margin of the East European Craton. Here, on the Lublin Slope of the craton, two U–Pb-zircon dates constrain the age of the lower Kotlin boundary from below: 551 ± 4 Ma in volcanic tuffs of the Sławatycze Formation of Poland [11] and 553 Ma in volcanic tuffs of the Yaryshev Formation of Podolia (S. Bowring, MIT, 2004, our samples). Hence, the age of the lower Kotlin boundary is confined between 551 and 548 Ma.

The Kotlin age is traditionally interpreted as a time of mass extinction of soft-bodied organisms, global distribution of macroscopic algae, and a low diversity of trace fossils [1]; however, these new observations necessitate a revision of the current view. Thus, the macroalgae appeared much earlier, in the Redkino time (600–560 Ma), and became widely distributed in the pre-Kotlin time [3, 12]. The ichnocoenoses of the Erga and Zigan formations suggest an increase in diversity, size, and complexity of behavior of burrowing organisms in wave- and current-agitated settings at the beginning of the Kotlin (548 Ma). There was a concurrent decrease in diversity of soft-bodied organisms in these same environments. It is established that soft-bodied organisms did not go extinct, but were excluded from the wave- and current-agitated zone by bilaterians to distributary channel systems, where a distinctive, globally recognized endobenthic ecological association formed. This association also known as "Nama-type biota" [13] is represented by petalonamae and descendants of migrants from more distal environments (such as the rangeomorph *Rangea schneiderhoehni* or the tribrachiomorph *Vendoconularia triradiata*). Distributary channels systems played the role of a refugium where the vendobionts survived until the end of the Vendian.

The maximum taxonomic and numerical diversity of casts and molds of soft-bodied organisms on the East European Craton characterizes a stratigraphic interval intermediate between the Redkino and Kotlin regional stages [3, 4]. New isotope-geochronological data allow an estimate to be made of the duration of this interval. The diversity of casts and moulds suddenly increases in the upper Verkhovka Formation in the southeastern White Sea area and in the Vilukha Member of Chernokamen Formation on the eastern slope of the Central Urals, and suddenly decreases near the base of the Kotlin [14, 15]. This stratigraphic interval equals 10 million years (557–548 Ma).

In conclusion, tracing of the marine flooding surface at the base of the Erga sequence and the new paleontological characteristic and isotope-geochronological data suggest correlation of the Zigan Formation of the South Urals with the Kotlin Regional Stage. This correlation emphasizes the importance of the lower Kotlin boundary for the Vendian subdivision. This boundary corresponds to the most important transformation of Vendian ecosystems.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 09-05-00279 and 10-05-00953).

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