

The Oldest Trace Fossils in Association with an Ediacara-Type Biota in the Upper Vendian of the South Urals

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Abstract—Trace fossils and palaeopascichnids have been studied in the Basa Formation of the Vendian Asha Group of the South Urals (southwestern periphery of the Suleiman Anticline, Shubino quarry in Ust'-Katav, Chelyabinsk Region of Russia). The general morphology and preservation of ichnofossils have been shown to be similar to the Late Vendian–Early Cambrian subhorizontal bilobate burrows of *Didymaulichnus*. The paleontological remains have been found to be confined to extremely shallow deposition settings and located stratigraphically below the volcanic tuff layer with a zircon U–Pb isotopic age of 578 ± 7 Ma. Until now, the first occurrence of ichnofossils and the associated “Agronomic Revolution” were dated at ~560–550 Ma. According to our study results, mobile benthos and biological mixing of sediments could have occurred 20–30 Ma earlier. The hypothesis that the onset of the “First Agronomic Revolution” and the “Cambrian Explosion” were far from being close in time was confirmed.

Keywords: Vendian, South Urals, ichnofossils, Ust'-Katav, Ediacara biota, *Palaeopascichnus*, *Didymaulichnus*

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The beginning of the Cambrian period was related to an important stage in the evolution of life on the Earth with the restructuring of the Proterozoic-type biosphere into the Phanerozoic [1]. One of the major reasons for the observed changes was the global distribution and active consumption of sediments by burrowing organisms in the Precambrian–Cambrian transitional interval [2]. The occurrence of crawling and burrowing bilateria in the sea basins at the time mark of ~550 Ma and the subsequent increase in the depth and intensity of sediment processing led to a substantial decrease in the role of microbial mats in the sea ecosystems and the almost complete disappearance of soft-bodied Ediacara-type organisms [3, 4]. This event has received a special designation in the literature as “the First Agronomic Revolution” [5]. Despite the obvious progress in the field of studying the Precambrian and Cambrian boundary deposits, the insufficient knowledge and the lack of information from key sections still make it impossible to estimate accurately the occurrence time of the “first agronomists” in the Precambrian fossil record.

Until now, the most ancient paleontological evidence of ichnofossils was represented by primitive

horizontal traces and vertical burrows with an approximate age of 560–565 Ma [6, 7]. In this paper, we report the study data on Ediacara-type macroscopic remains (palaeopascichnids) and ichnofossils from the Basa Formation section of the Vendian Asha Group, located in the southwestern part of the Suleiman Anticline and partially exposed in the Shubino quarry in the northern outskirts of Ust'-Katav (Chelyabinsk Region of Russia). These remains are much older than previous finds.

The Asha Group consists of the youngest Proterozoic deposits of the Bashkir Meganticlinorium on the western slope of the South Urals (Fig. 1a). It includes the Bakeevo, Uryuk, Basa, Kuk-Karauk, and Zigan formations [8]. The Vendian age of this group was already indicated by the first glauconite K–Ar dates from sandstones of the Bakeevo, Uryuk, and Basa formations dated at 625–615, 590, and 570 Ma, respectively [9]. In addition, Ediacara-type fossils were found in the Basa and Zigan formations [10]. The index taxon *Palaeopascichnus linearis* was identified among them. Its distribution range, in chronostratigraphic terms, corresponded to the Vendian System (~600–535 Ma) [11]. In 2011, a zircon U–Pb age of 548.2 ± 7.6 Ma was obtained from a layer of volcanic (ash) tuffs in the Asha Group section in the northern outskirts of Ust'-Katav [12]. Later, zircon from this tuff layer was reanalyzed and dated at 547.6 ± 3.8 Ma [13]. Nevertheless, the stratigraphic position of this

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part of the Ust'-Katav section with tuff layers was a matter of debate. According to some researchers, it referred to the Zigan Formation [12, 13], while according to others, it was attributed to the Basa Formation [14].

The relatively "young" U–Pb age of volcanic zircon and the absence of classical representatives of the Ediacara-type biota, such as *Dickinsonia*, Rangeomorpha, *Tribrachidium*, and others, made it possible to attribute most of the Asha Group, starting from the Uryuk Formation, to the Vendian Kotlinian Stage of the East European Platform (EEP) [12, 14]. Alongside that, the more "ancient" Rb–Sr isochron age of authigenic glauconite from sandstones of the Bakeevo Formation (642 ± 9 Ma) [15] suggested a break between the Bakeevo and Uryuk formations in the Asha Group section. In addition, in 2020, the U–Pb isotope age of 573 ± 2 Ma was obtained for zircon from ash tuffs of the Basa Formation on the western flank of the Alatau Anticlinorium (a new road from Petrovskoe to Kulgunino) [16]. In 2022, zircon from the following localities was re-dated: ash tuffs of the Basa Formation on the southwestern flank of the Suleiman Anticline (578 ± 7 Ma, northern margin of Ust'-Katav), the eastern flank of the Alatau Anticlinorium (570 ± 2 Ma, Tolparovo Settlement), and ash tuffs of the Zigan Formation on the western flank of the Alatau Anticlinorium (566 ± 5 Ma, the new road from Petrovskoe to Kulgunino) [17]. All these zircon dates obtained in ash tuffs eventually made it possible to correlate confidently the structurally separated sections of the Asha Group of the Bashkir Meganticlinorium. The new data do not confirm the previous isotope age of zircon from volcanic tuffs of the Basa Formation ($\sim 548 \pm 4$ Ma) [12, 13], which, according to [17], is erroneous, but do not contradict the earlier dates obtained from the Bakeevo (642 ± 9 Ma) [15] and Basa (573 ± 2 Ma) formations [16].

In 2022, we additionally studied fragments of sections and outcrops of the Asha Group in the vicinity of Ust'-Katav (Figs. 1a, 1b) to clarify the structure of Uryuk and Basa formations, as well as to reveal the position of ash tuffs with an age of 578 ± 7 Ma [17] and paleontological remains in the section.

The Bakeevo Formation overlies unconformably stromatolitic limestones of the Upper Riphean Uk Formation and is represented best on an outcrop in a railroad excavation pit on the eastern outskirts of Ust'-Katav and the southern slope of Mount Medved (Fig. 1b). This formation is dominated by a sequence (40 m) of interbedded fine-grained greenish gray sandstones with siltstones and mudstones. No paleontological remains were found in the Bakeevo Formation.

The Uryuk Formation overlies conformably, without visible signs of a break, the Bakeevo Formation. The contact of these formations on the southwestern slope of Mount Medved and the eastern slope of

Mount Shikhan is grass-covered (Fig. 1b). The most representative sections are exposed on the slopes and top of Mount Shikhan, as well as in the northeastern outskirts of Ust'-Katav, along the road to the village of Minka. The lower and middle parts of the formation are composed of a sequence (115 m) of medium- and coarse-grained cross-bedded arkose sandstones. The upper part of the Uryuk Formation is exposed in numerous ridges, trenches, and a range of outcrops along the streets of the suburbs lined by small houses, in the northeastern outskirts of the city. It is dominated by a sequence (45 m) of interbedded arkose sandstones with siltstones and rare mudstone layers. According to our data, the total thickness of the Uryuk Formation is ~ 160 m; earlier it was estimated at 125 m [14]. Paleontological remains were not found in the Uryuk Formation.

The Basa Formation overlies conformably, without visible signs of a break, the Uryuk Formation. The contact of these formations can be seen in a small outcrop (fringe) approximately 100 m east of the small-house suburbs (ul. Fenicheva) of Ust'-Katav (54.940783° N, 58.195957° E). The lower and middle parts of the Basa Formation are exposed in numerous ridges on the northeastern and northern outskirts of the city. In total, they exposed a thick (up to 390 m) sequence of interbedded brownish gray mudstones and greenish gray siltstones with rare interlayers of thin (up to 20 cm) greenish gray sandstones. The upper part of the formation is exposed in the northern (Shubino quarry) and northwestern outskirts of the city. A site (40 m) of finely interbedded (biolaminite) siltstones and sandstones was uncovered in the Shubino quarry. A sequence (9 m) was exposed (Figs. 1d, 1e) in the eastern part of the quarry, in one of its walls. It contains numerous well-diagnosed trace fossils and palaeopascichnids.

This sequence comprises greenish gray thin-layered biolaminite siltstones (beds of 0.3–1.5 m thick), dark- and greenish gray parallel-layered biolaminite fine-grained sandstones (0.1–0.4 m), greenish gray sandstones with cross bedding, in rare cases, with multistage cross bedding (0.05–0.3 m), and sandstones of the same color with convolute bedding (0.5–0.6 m) (Fig. 1d). At the base of the sandstone beds there are numerous molds of desiccation cracks, small cubic salt crystals, and microbially induced sedimentary structures (shagreen surfaces, "elephant skin" structures, and pimple forms of microbial mats). Small flat mud pebbles are occasionally present in the lower part of sandstones. The observed structural features of this interval of the Basa Formation section are characteristic of extremely shallow environment, tidal plains, and lagoons that have undergone short-term periodic drainage. Three-dimensional casts of palaeopascichnids (Fig. 3) and trace fossils of the organisms moving in the sediment (Fig. 4) were found on the lower surfaces of parallel-layered biolaminated sandstones (Fig. 1d, interval 1.47–1.72 m).

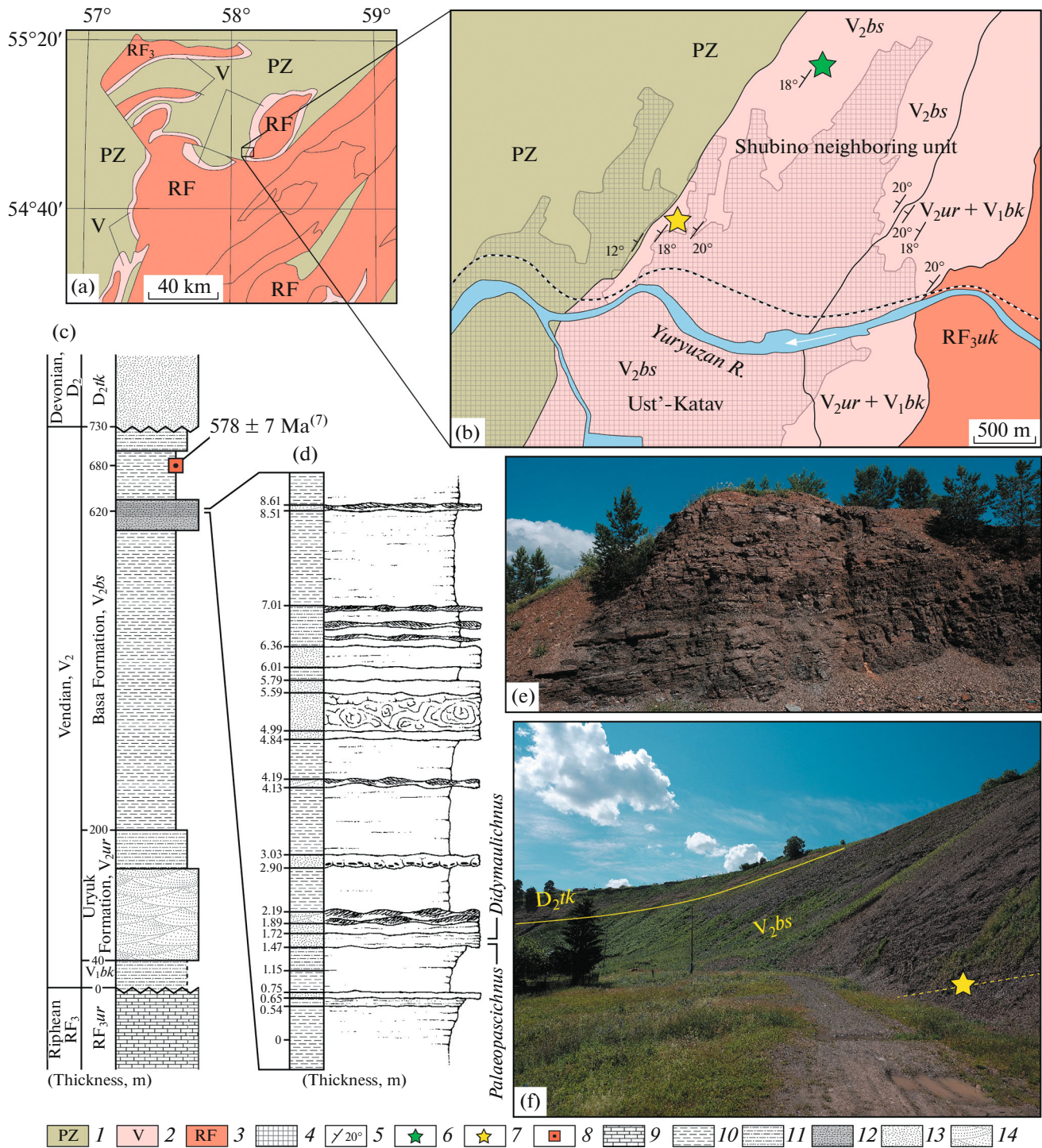


Fig. 1. Location of trace fossils and Ediacara-type biota in the southeastern flank of the East European Platform: (a) northwestern part of the Bashkir Meganticlinorium; (b) geological structure of the vicinity of Ust'-Katav; (c) Asha Group section in the vicinity of the city; (d) fragment of the Basa Formation outcrop indicating the level of paleontological findings; (e) studied outcrop of the Basa Formation in the Shubino quarry; (f) exposed upper part of the Basa Formation in the northwestern outskirts of the city. (1) Paleozoic sequences; (2) Asha Group, Vendian; (3) Riphean sequences; (4) urban area; (5) occurrence elements of sedimentary rocks; (6) location of the studied outcrop of the Basa Formation in the quarry; (7) location of the sampling point of ash tuffs dated at 578 ± 7 Ma [17]; (8) position of ash tuffs in the Asha Group section; (9) limestone; (10) mudstone and siltstone interbedding; (11) mudstone, siltstone, and sandstone interbedding; (12) biolaminite siltstone and sandstone; (13) sandstone; (14) cross-bedded sandstone. Designation of the formations on the column and geological map: (RF_{3uk}) Uk, (V_{1bk}) Bakeevo, (V_{2ur}) Uryuk, (V_{2bs}) Basa, and (D_{2tk}) Takaty.

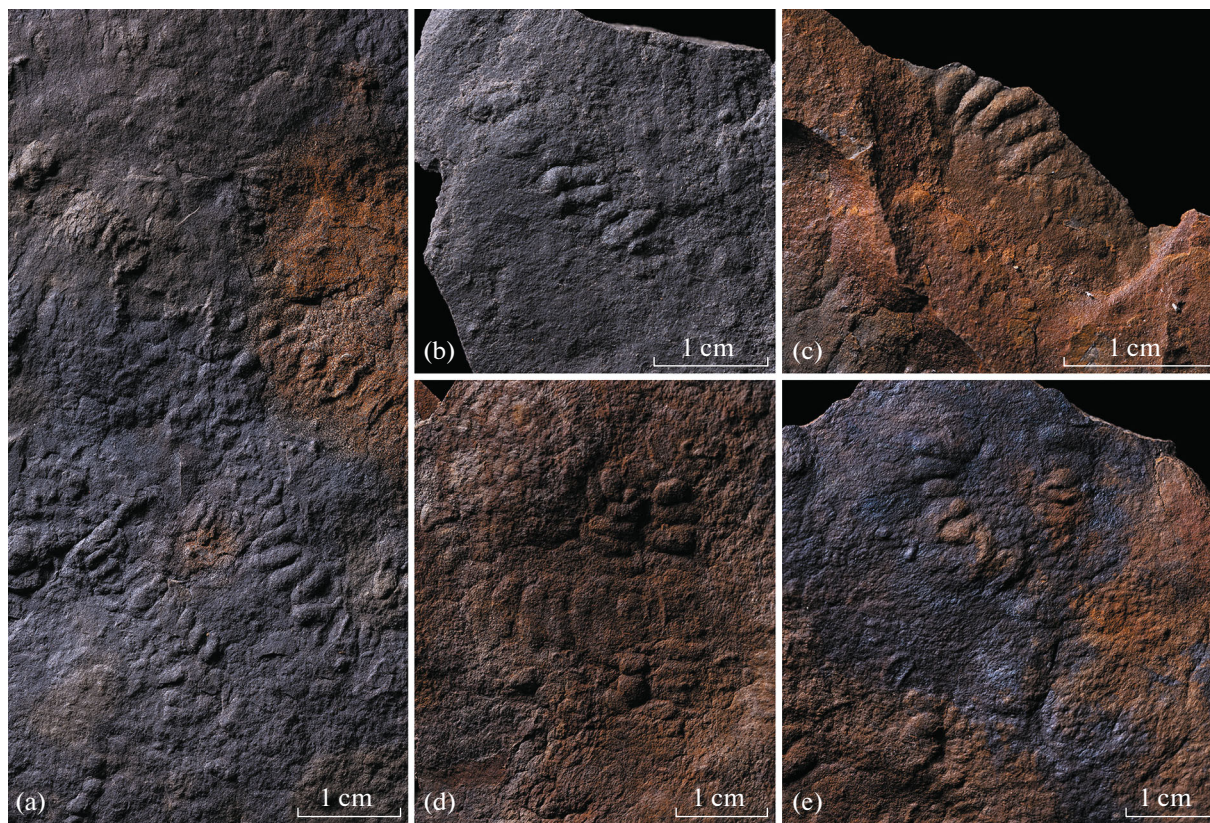


Fig. 2. Representatives of the Ediacara-type biota (palaeopascichnids) from the Basa Formation in the Shubino quarry: (a) sample no. SU22/21-3, *Palaeopascichnus linearis*; (b) sample no. SU22/21-4, *P. linearis*; (c) sample no. AG-2019-53, *P. linearis*; (d, e) sample no. SU22/21-2, *P. delicatus*.

The uppermost part of the Basa Formation section in the vicinity of Ust'-Kataev is exposed on its north-western margin. It is represented by a sequence (65 m) of interbedded brownish gray mudstones and greenish gray siltstones with rare interlayers of thin (up to 10 cm) greenish gray sandstones. At the level of 480 m from the base, the formation contains a few layers of volcanic (ash) tuffs (Fig. 1f); the U–Pb age of 578 ± 7 Ma was obtained for one of them [17]. Above, the exposed sequence of interbedded greenish gray mudstones, siltstones, and sandstones (35 m) is overlain with a parallel unconformity by terrigenous rocks of the Middle Devonian Takaty Formation. The total thickness of the Basa Formation is 530 m in the vicinity of Ust'-Kataev. It should be noted that the Basa Formation is likely not exposed completely in the area studied. Its maximum thickness, according to various estimates, reaches 800 m [8, 9, 14, 17].

Palaeopascichnids. Most of them are represented by single-row entire series of convex casts of chambers on the lower surface in siltstones and fine-grained sandstones (positive hyporelief) (Fig. 2). In some cases, they are incompletely preserved as casts of collapsed chamber walls (Figs. 2a, 2e). Despite the relatively low relief of the chambers with respect to the bedding surface, they were reliably identified using a narrowly

focused light source. Two species were diagnosed among palaeopascichnids: *Palaeopascichnus linearis* consisting of single-row series of globular or slightly elongated chambers from 2 to 6 mm wide (Figs. 2a, 2b, 2e) and *P. delicatus* represented by single-row series of chambers distinguished by an allantoid shape and progressively increasing width (Figs. 2c, 2d).

Trace fossils are observed on the lower surface in the fine-grained sandstone layers in the positive hyporelief as bilaterally symmetrical linear winding, meandering, sometimes crossing each other, subhorizontal burrows of 5–15 mm wide (Figs. 3, 4). All findings are elongated ridges located close to each other, separated by a narrow longitudinal central furrow (Figs. 3, 4a, 4c, 4d). The surface of these ridges is occasionally complicated by a relatively thin (less than 0.5 mm) or larger (up to 1 mm) transverse segmentation. In the negative epirelief, the trace fossils are relatively deep furrows with fine transverse wrinkling, separated by a pointed meandering ridge (Figs. 4e, 4f). They often cross each other, but the cases of crossing themselves were not found in individual specimens. In the cross section, the burrows are trough-shaped: a longitudinal furrow is limited on the sides by two protruding ridges the lateral parts of which are characterized by sharp bevels (Figs. 4a, 4b). In general, these

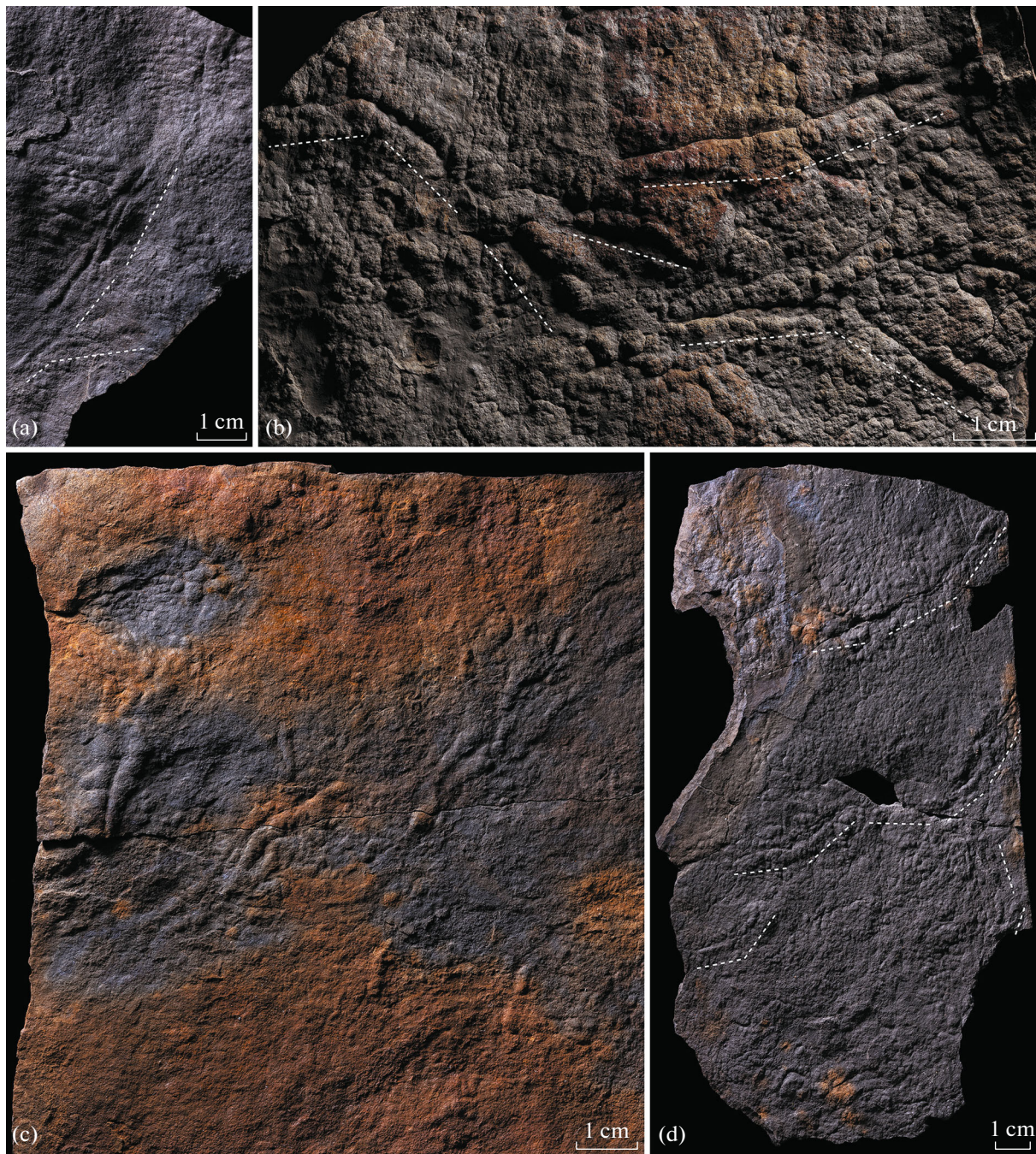


Fig. 3. *Didymaulichnus* trace fossils from the Basa Formation in the Shubuno quarry: (a) sample no. SU22/21-D27, (b) sample no. AG-2019-35, (c) sample no. AG-2019-18, (d) sample no. AG-2019-15.

bilobate trails are morphologically simple and do not demonstrate a specific strategy of the organism's behavior. Basically, this category of ichnofossils represents horizontal or slightly inclined passages not characterized by signs of nutrition in the organism, for example, passing of a sediment through itself. Poorly and incompletely preserved undulation (periodic subsidence) of burrows prevents us from identifying the paleontological remains to the ichnospecies. Never-

theless, the observed set of features is partially characteristic of bilaterally symmetrical bilobate representatives of the ichnogenus *Didymaulichnus* [18] which, according to the accepted ichnofossils classification, is included in trails (Repichnia) [19].

The fossil record of the complex life on the Earth is full of hints and contradictory evidence with the main drawbacks being the narrow provincialism of findings and the incomplete geological (and paleontological)

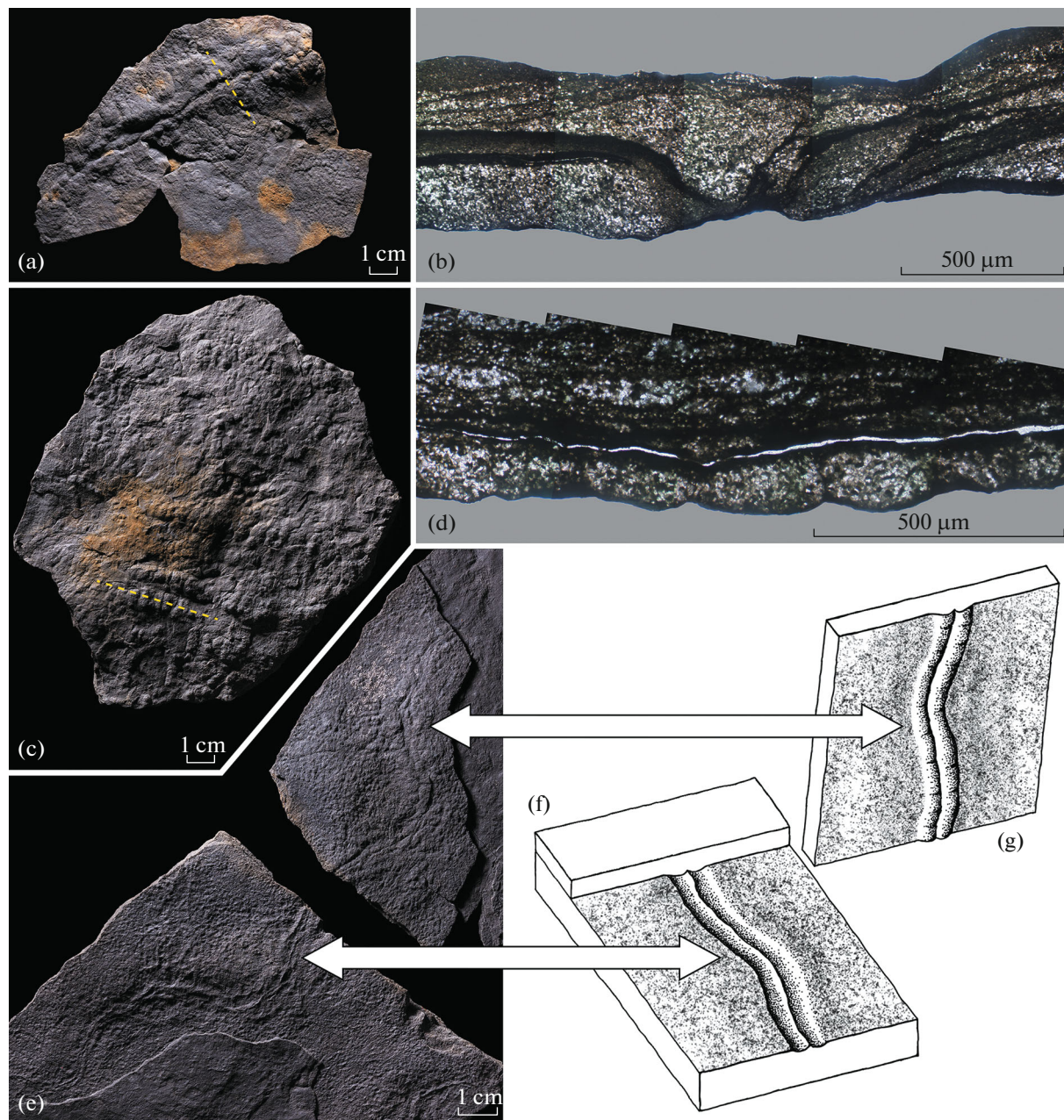


Fig. 4. Morphology and preservation of *Didymaulichnus* ichnofossils from the Basa Formation: (a) sample no. AG-2019-8, (b) transverse section along the line (a); (c) sample no. AG-2019-10; (d) transverse section along the line (c); (e) sample no. AG-2019-11; (f) reconstructed ichnofossil preserved in the negative epirelief; (g) reconstructed ichnofossil preserved in the positive hyporelief.

data. Until now, the trace fossils in the Vendian (Ediacara) were extremely rare and confined mainly to a time interval of ~560–540 Ma [18–20]. Our data obtained in the course of the study of the Basa Formation in the vicinity of Ust'-Katav, along with the dates of zircon from several stratigraphically different layers of volcanic (ash) tuffs of the Asha Group [17], convincingly prove that some palaeopascichnids, in particular, the species *Palaeopascichnus delicatus*, as well as more complex organisms with a bilateral symmetry and an ability to move and process sediments, could

have appeared already ~575–580 Ma ago, i.e., 25–35 Ma earlier than previously thought [1–5, 18–20]. Consequently, the beginning of the “First Agronomic Revolution” and the “Cambrian Explosion” of biodiversity were far from being close in time. In addition, the discovery of new fossils with a relatively good preservation in the Basa Formation of the Asha Group of the South Urals is indicative of the fact that the paleontological potential of the Upper Precambrian in the east of the EEP is far from being fully explored. The Asha Group sections of the South Urals remain one of

the most important/key objects to study the functional features of living systems at the early stages of evolution of Metazoa and to reconstruct their distribution range.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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