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# Main Features of Sedimentogenesis and Ecogenesis in Late Paleozoic Sea Pools of Northeast Asia

*Victor Gdal'evich Ganelin*

## Abstract

The main characteristics of the Late Paleozoic sediments and ecogenesis in the Late Paleozoic basins of Northeast Asia are considered. The authigenic bacterial nature of carbonate bodies, previously considered as detrital, was revealed. The assumption about the lithotrophic nature of the Late Paleozoic ecosystems of the region is substantiated, the basis of the trophic chains of which are prokaryotes. As it turned out, a feature of the Late Paleozoic benthic biota is associated not with climatic factors but with the trophic nature of the communities. Similar types of paleoecosystems in the same age layers of Gondwana are indicated.

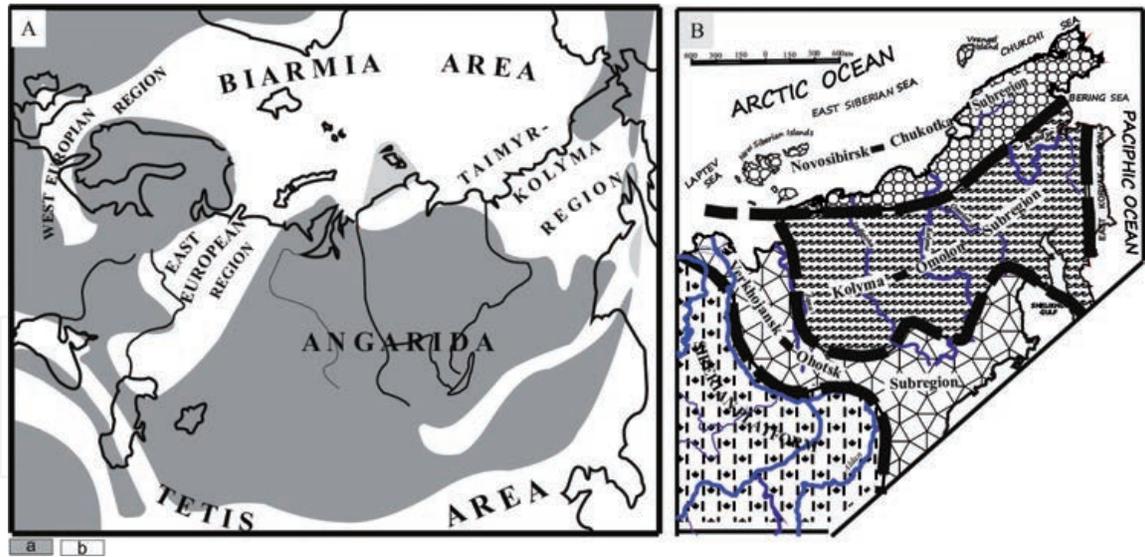
**Keywords:** Northeast Asia, Gondwana, late Paleozoic basins, rifting, black shale sedimentology, bacterial carbonate rocks, autolithotrophy, fluidolites, benthic biota

## 1. Introduction

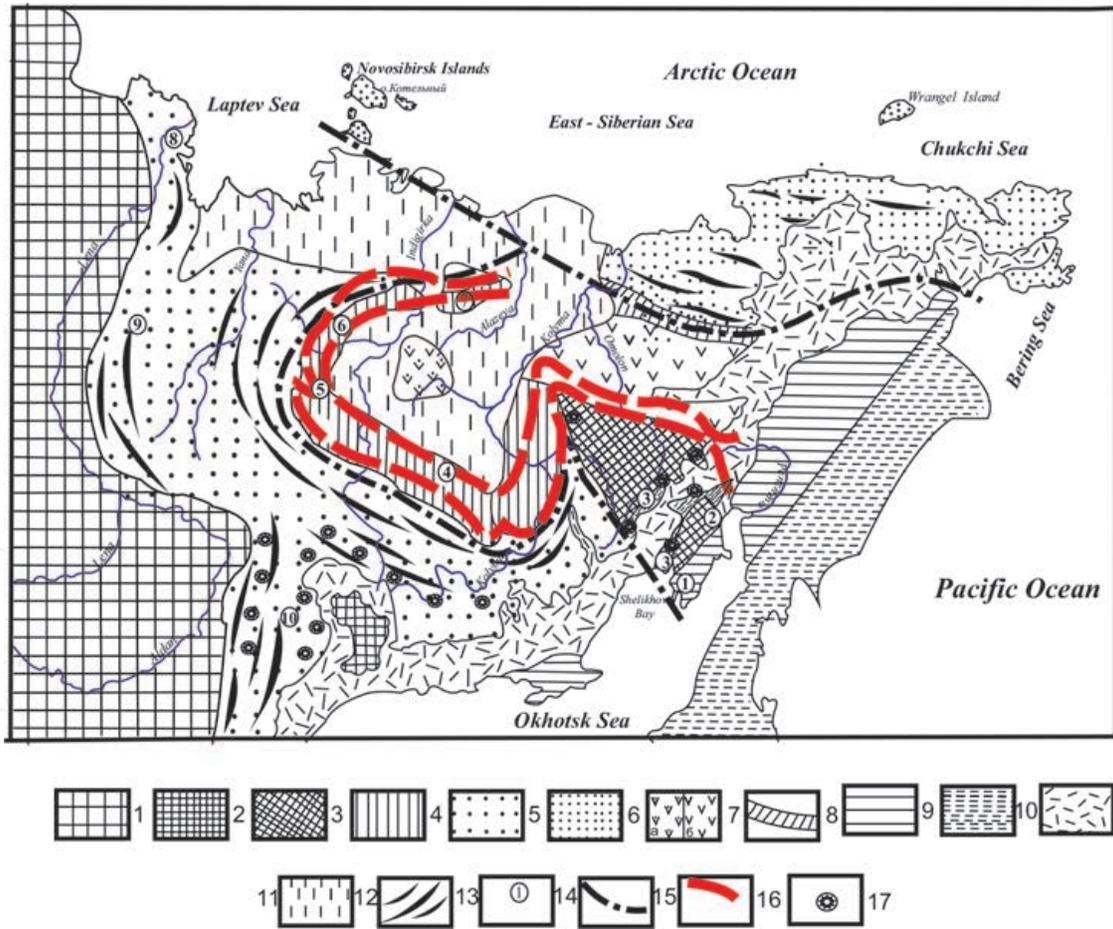
Throughout the Late Paleozoic, there was a large marine basin at the northeast of Asia, with a total area covering about 2,500,000 square meters. Together with the southern part of Taimyr Peninsula, this territory represented a biogeographically and sedimentologically integral system of sedimentary basins, also known as “Taimyr-Kolyma” paleogeographic region, also including Transbaikalia and Northern Mongolia. From the mid-Early Permian, the Taimyr-Kolyma, East European, and West European paleogeographic regions are considered as parts of the Biarmian subregion, framing the modern Arctic [1] (**Figure 1A**). In its main outlines, this system of basins is apparently preserved during the Early Mesozoic.

The main features of sedimentary and biotic evolution of the Late Paleozoic basins of the northeast of Asia were connected with the destruction of the Middle Paleozoic continental shelf by establishing rift basins across it [2]. This process started in the mid-Early Carboniferous and, up to the end of the Early Permian, had been accompanied by intense mafic magmatism—the Omolon-Selenyakh volcanic belt of Lychagin and Lyckman [3] (**Figure 2**). By the mid-Middle Carboniferous time, these processes foreordained the general paleogeographic patterns of the Late Paleozoic basin system.

According to the features of sedimentation and the appearance of fossil assemblages, three paleogeographic areas can be distinguished within the northeast of Asia: Verkhoyansk-Okhotsk, Kolyma-Omolon, and Novosibirsk-Chukotka subregions [4, 5] (**Figure 1B**). Despite biota was very close in all of them, there are differences



**Figure 1.** Zoning of the late Paleozoic basins of northern Eurasia. (A) Zoning of perm basins of northern Eurasia (after Ganelin, modified by Kotlyar [1]). (a) land, (b) sea. (B) Zoning of the late Paleozoic basins of Northeast Asia (after Ganelin, Tschernjak [5]).



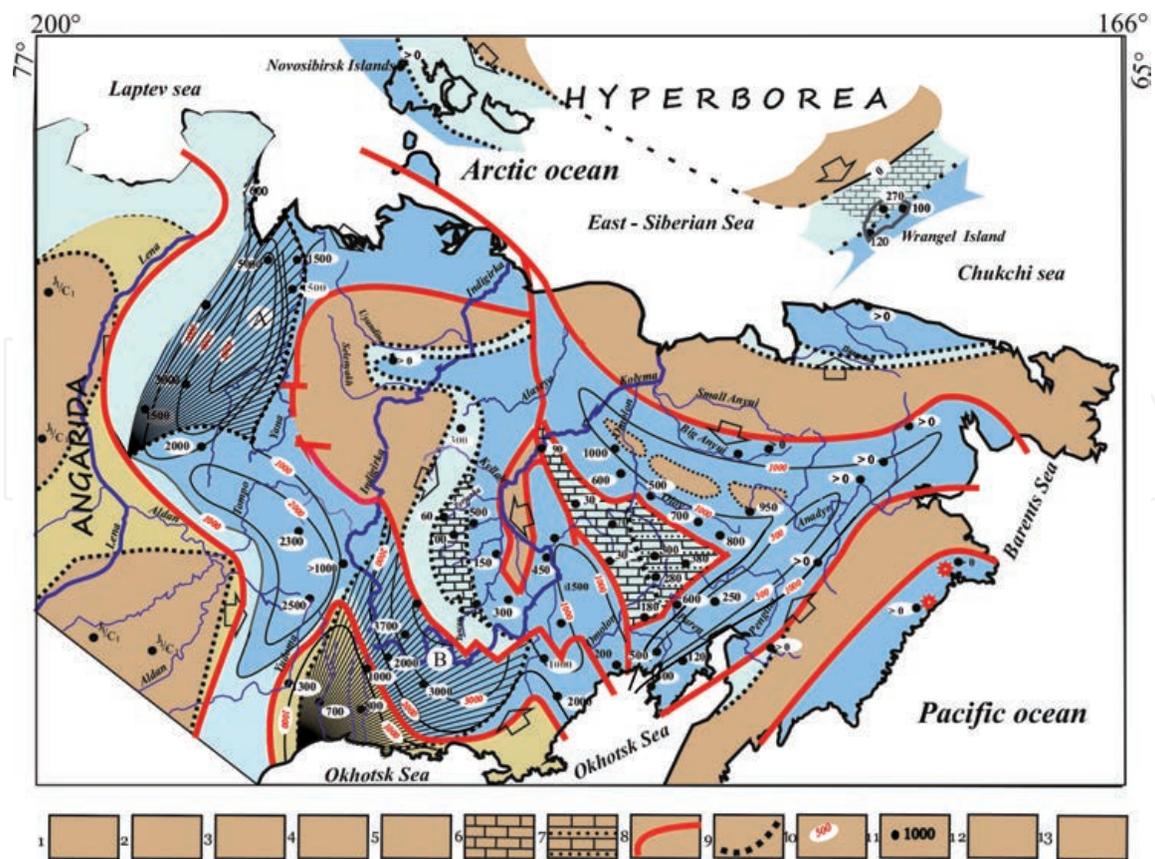
**Figure 2.** Principal tectonic elements of Northeast Asia and the position of the late Paleozoic magmatic belt. 1 Siberian platform, (2 and 3 massifs) 2 Okhotsk, 3 Omolon, 4 uplifts, composed mainly of Paleozoic, (5–10 orogens) 5 Yana-Kolyma, 6 Novosibirsk-Chukotka, 7 Alazey-Oloy [(a) Alazey and (b) Oloy parts], 8 south Anyui, 9 Taiganos, 10 Koryak-Kamchatka, 11 Okhotsk-Chukotka volcanic belt, 12 Kolyma-Indigirka and Primorye lowlands covered by quaternary, 13 stretch of folds, 14 smaller tectonic structures, mentioned in the text (1 Taiganos, 2 Avekov block, 3 Gizhiga deflection, 4 Arga-Tass block, 5 Tas-Hayakhtakh uplift, 6 uplift of the Selenyakh and Polousny ridges, 7 Ulakhan-sis uplift, 8 Kharaulakh zone, 9 Orulgan zone, 10 South Verkhoyansk synclinorium), 15 borderline between Yana-Kolyma, Indigirka-Omolon, and Novosibirsk-Chukchi regions, 16 boundaries of the late Paleozoic Omolon-Selenyakh magmatic belt of Lychagin and Lyckman [3], and 17 presumed areas of fluid-explosive activity.

in sedimentation type and, also, in the composition of benthic assemblages at certain stratigraphic intervals, especially for the Novosibirsk-Chukotka subregion. Clearly aside these three was the East Koryak subregion, characterized by Tethyan fusulinid assemblages, which are unique for the territory under consideration. East Koryak subregion still remains poorly studied and is not considered in the present paper.

## 2. Paleogeographic and sedimentological structure

The Verkhoyansk-Okhotsk subregion was a passive margin of Angarida continent, with intense accumulation of material brought here by prograding deltaic systems. This resulted in the formation of thick clastic sequence—so-called Verkhoyansk complex Cheraskov [6]. Two particular areas are characterized by the most intensive accumulation—these are Yana-Indigirka area and Ayan-Yuryakh area. The Novosibirsk-Chukotka subregion corresponds to the marginal basins of another continent, the hypothetical Hyperborea (Arctida). Kolyma-Omolon subregion, separating two subregions mentioned above, looks to be an offshore area, containing shallow sediments of mid-ocean elevations and deep-sea formations framing them (Figure 3).

A remarkable characteristic is predominant black shale sedimentation. It is defined by the presence of carbon-rich, clayish, carbon-siliceous, and ash-siliceous deposits, sometimes manganese-bearing and mostly sulfide-bearing within the succession, and these types of sediments are regionally distributed. All these features were previously explained by the author as connected with the influence



**Figure 3.** Thickness and facies of the middle Permian in Northeast Asia: 1 presumable land (no deposit), 2 continental facies, 3 shallow-water facies, 4 offshore facies, 5 prodelta ((A) Yana-Indigirka, (B) Ayan-Yuryakh), 6 limestone facies, 7 limestone facies, intercalating with terrigenous rocks, 8 tectonic boundaries of structural zones, 9 facial boundaries, 10 isopachytes of the middle Permian, 11 total thickness of the middle Permian, 12 volcanic facies, and 13 clastic material transport direction.

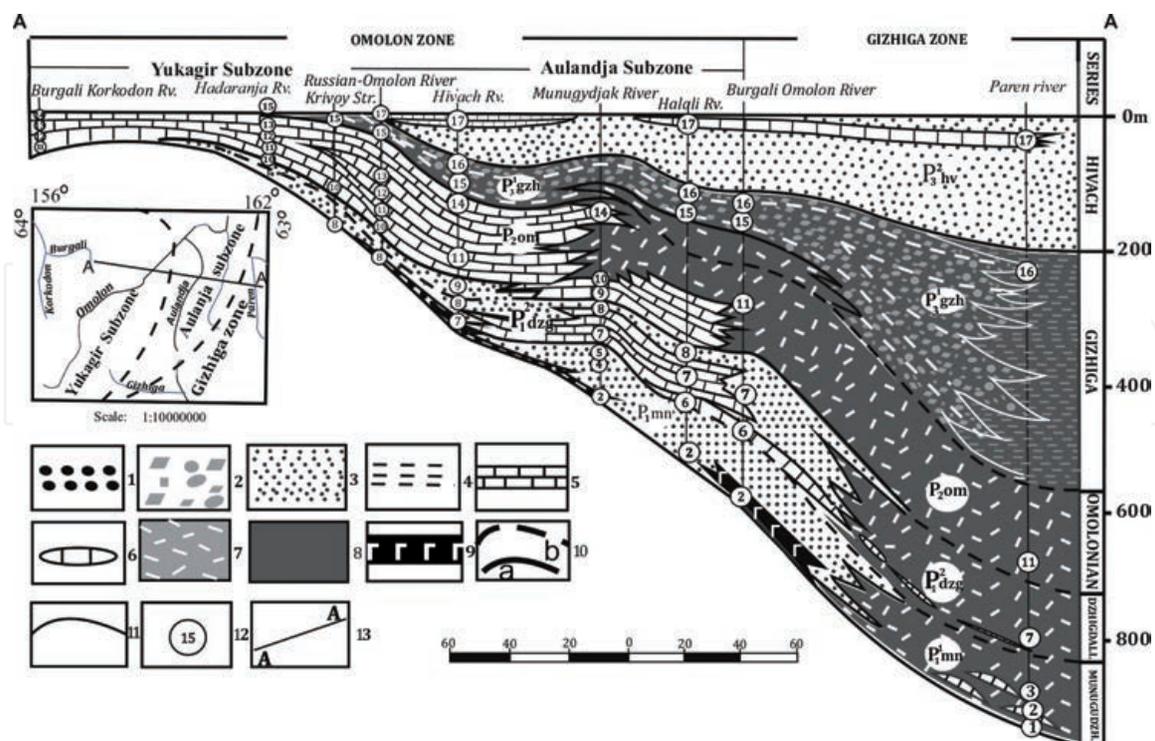
of low-temperature hydrotherms, which caused the formation of the carbon-rich, substantially siliceous, sulfide-bearing sediments in the basin of euxinic type [7].

## 2.1 Carbonate rocks of the upper Paleozoic black shales

Considering the interpretation discussed above, particularly interesting are the carbonate rocks reported from the black shale successions. Those are represented both by isolated bioherms and biostromes inside the black shale series and by fully carbonate intervals within the succession, sometimes reaching 1000 m thick and replacing the black shales laterally (Figure 4). Such intervals are widely spread in the Kolyma-Omolon and Novosibirsk-Chukotka subregions. Within the shallow-water facies of mid-elevations (Omolon massif, Prikolymye), carbonate facies are characterized by the greatest variety of shelly benthic fauna, which makes it possible to consider them as centers of diversifications for the corresponding communities. The isotopic studies of these rocks, along with the analysis of their macro-, micro-, and ultramicrostructures, revealed the microbial origin of carbonates. Moreover, we have two different groups of these carbonate formations, which replace each other over time.

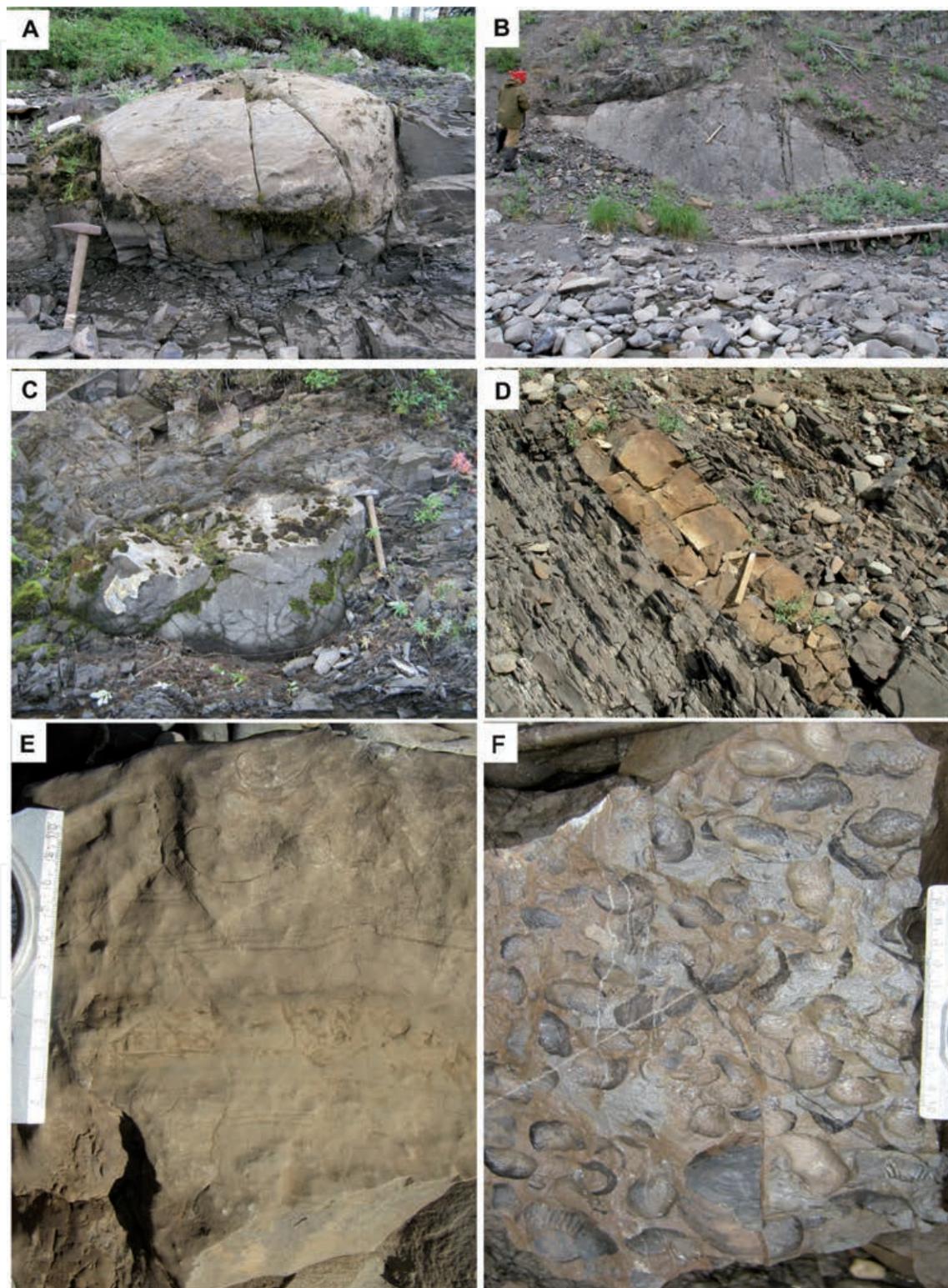
Carbonate formations of the first group are distributed from Middle Carboniferous to the first half of the Lower Permian. Biofacies of the Verkhoyansk type of fossil communities are associated with them. Carbonate rocks of the second group occupy the age interval from the second half of the Early Permian to the end of the Permian period. This second interval is characterized by the fossil assemblages of the so-called Kolyma-Omolon type [9].

Carbonate bodies of the first type are very rare. Findings of shell benthos, which belong to the Verkhoyansk type of communities, are also noted only locally. The carbonatolites of this age interval were studied by us in the upper reaches



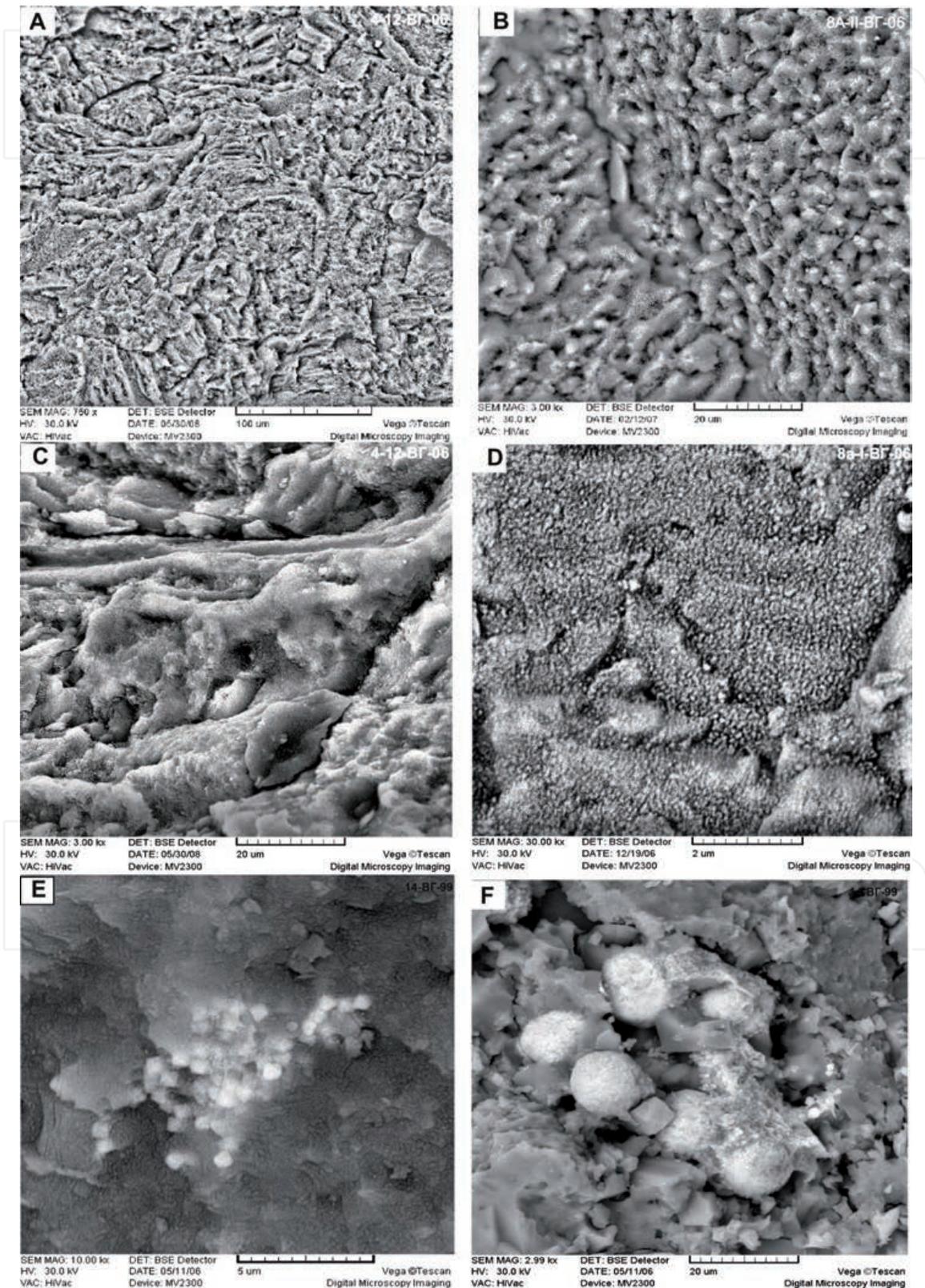
**Figure 4.** Facies profile for the Permian deposits of the Omolon massif and Gizhiga zone. 1 conglomerates, 2 mixtites, 3 sandstones and siltstones, 4 flysch, 5 hydrogen sulfide limestones, 6 bioherms and biostromes, 7 fine pyroclastics, 8 carbon-rich black shales, 9 basalts, 10 boundaries of series, 11 boundary of formations, 12 stratigraphic zone numbers (Ganelin, Biakov [8]), 13 profile line of the map.  $P_L^{1mn}$ , lower Permian and Munugudzhak series;  $P_1^2 dzg$ , lower Permian Dzhigdali series;  $P_2 om$ , middle Permian, Omolon series, Kolyma series;  $P_3^1 gzh$ , upper Permian; Gizhiga regional stage;  $P_3^2 khv$ , upper Permian, Khivach regional stage.

of the Paren' River (**Figure 4**). Here they are represented by bioherms, which have a lenticular, dome-shaped, and loaf-shaped form (**Figure 5A–D**). Their size reaches up to 7x0.7 m and they lie among carbon thin clastic tuffs. Tuffs contain an increased amount of organic carbon—up to 5%. A characteristic feature of these limestone bodies is their very thin layering, which, apparently, was formed by bacterial mats (**Figure 5E**). The rocks are saturated with finely dispersed pyrite,



**Figure 5.** Carbonatolites of the middle carboniferous-early Permian. (A, B) bioherms in siliceous pyroclastic-rich rocks of the Olcha formation, middle carboniferous of the upper reaches of Paren' river, (C) bioherm in carbon-rich siliceous rocks of the Magiveem formation, early Permian, same location, (D) biostrome in carbon-rich siliceous rocks of the Magiveem formation, early Permian, (E) the same, showing thin bedding, (F) the same as (D), showing assemblage of brachiopods and bivalves.

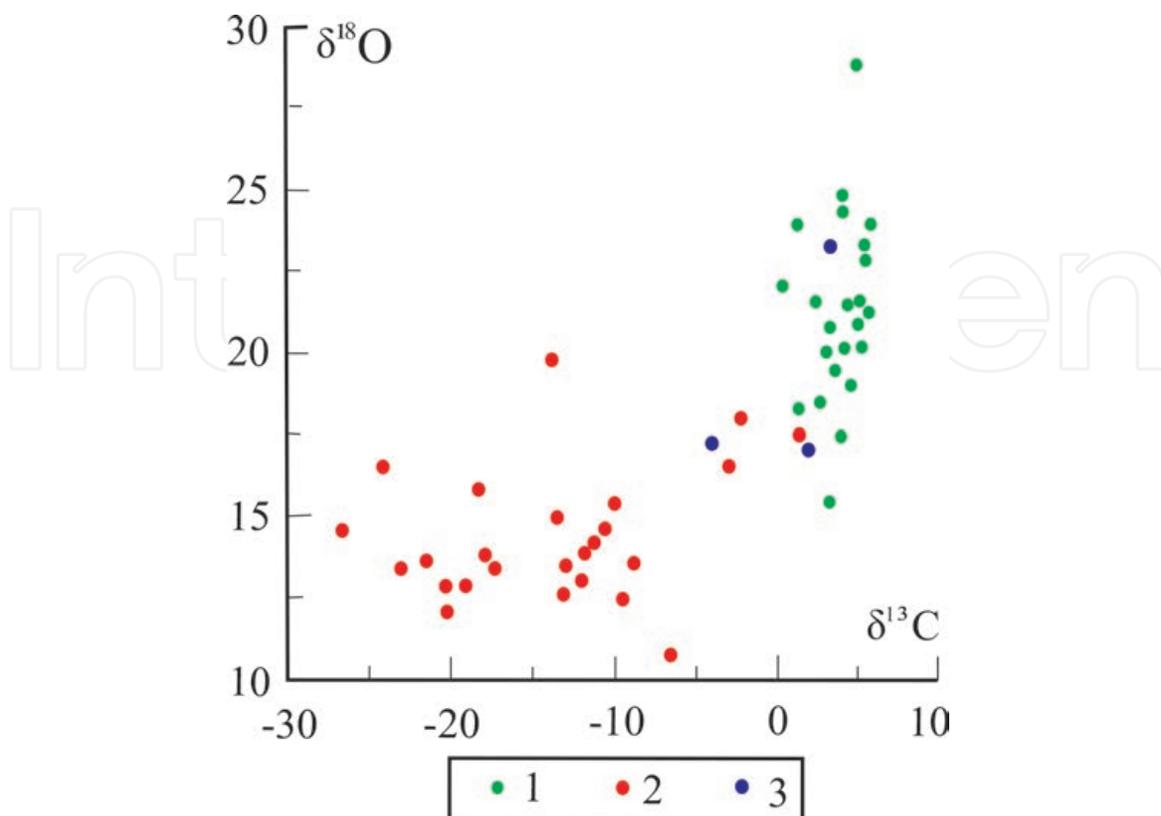
which is often framboidal. Although benthic fossils are extremely rare in this interval (especially the Middle and Upper Carboniferous), some bodies are real “oases of life” (**Figure 5F**). Dense settlements of brachiopods, sometimes bivalve mollusks and, to a lesser extent, gastropod mollusks, conularia, hyolites, as well as attached agglutinated foraminifers. Under scanning electron microscope (SEM), the microbial structure of the matrix is clearly visible (**Figure 6**). Isotopic data



**Figure 6.** (A–D) Bacteriomorph structures of the carbonatolites of the Magiveem formation; (E, F) Framboidal pyrite in the same rock; Lower permian, Magiveem formation, upper Paren river. Scanning electron microscope (SEM) photos at different magnifications.

are especially important for correct interpretation of these rocks. Pokrovsky [10] found that the bulk samples are characterized by very low values of  $\delta^{13}\text{C}$ , ranging from  $-9.4$  to  $-26.4\text{‰}$ , and values of  $\delta^{18}\text{O}$  ranging from  $12.5$  to  $15.9\text{‰}$  (Figure 7). Since brachiopod shells from the same rocks demonstrate isotopic ratios, typical for normal marine environment, it can be assumed that low  $\delta^{13}\text{C}$  values in bulk samples should be explained by the fractionation of carbon by sulfate-reducing and methanotrophic prokaryotes. The intense sulfate reduction, as can be assumed, brought additional impact on the development of euxinia within the basin. According to B.G. Pokrovsky, low values of  $\delta^{18}\text{O}$  can be explained by untypically intense fluid regime at the moment of rock formation, associated with hydrothermal activity. There is reason to believe that benthic organisms were rare due to rapidly changing redox conditions in the thin and mobile redox zone. As an analogy, we can turn to modern sedimentation in the Black Sea [11, 12]. Here, prokaryotes form an integrated symbiotic system in which methane oxidation is inextricably linked to sulfate reduction. Under anaerobic conditions in microbial mats, active sulfate reduction and anaerobic oxidation of methane occur due to the activity of archaea and sulfate-reducing bacteria. It was found that during the oxidation of the methane, part of the produced carbon is spent for the formation of carbon dioxide. The latter is fixed in carbonates that constitute nodules, bioherms, and continuous beds. At the same time, intensive sulfate reduction generates the huge amount of hydrogen sulfide. It can be suggested that the rarity of occurrence of fossil shelly benthos can be explained by unstable and quickly changing redox conditions within the thin and versatile redox zones.

The wide distribution of Middle-Upper Permian carbonates is associated with regional transgression, which began at the end of the Early Permian and ended by the end of the period. Carbonate crusts, bioherms, biostromes, as well as normally bedding limestones are ubiquitous all over the region (Figure 8). Bioherms and biostromes are normally 1–3 m high, rarely reaching 30 m, while their length



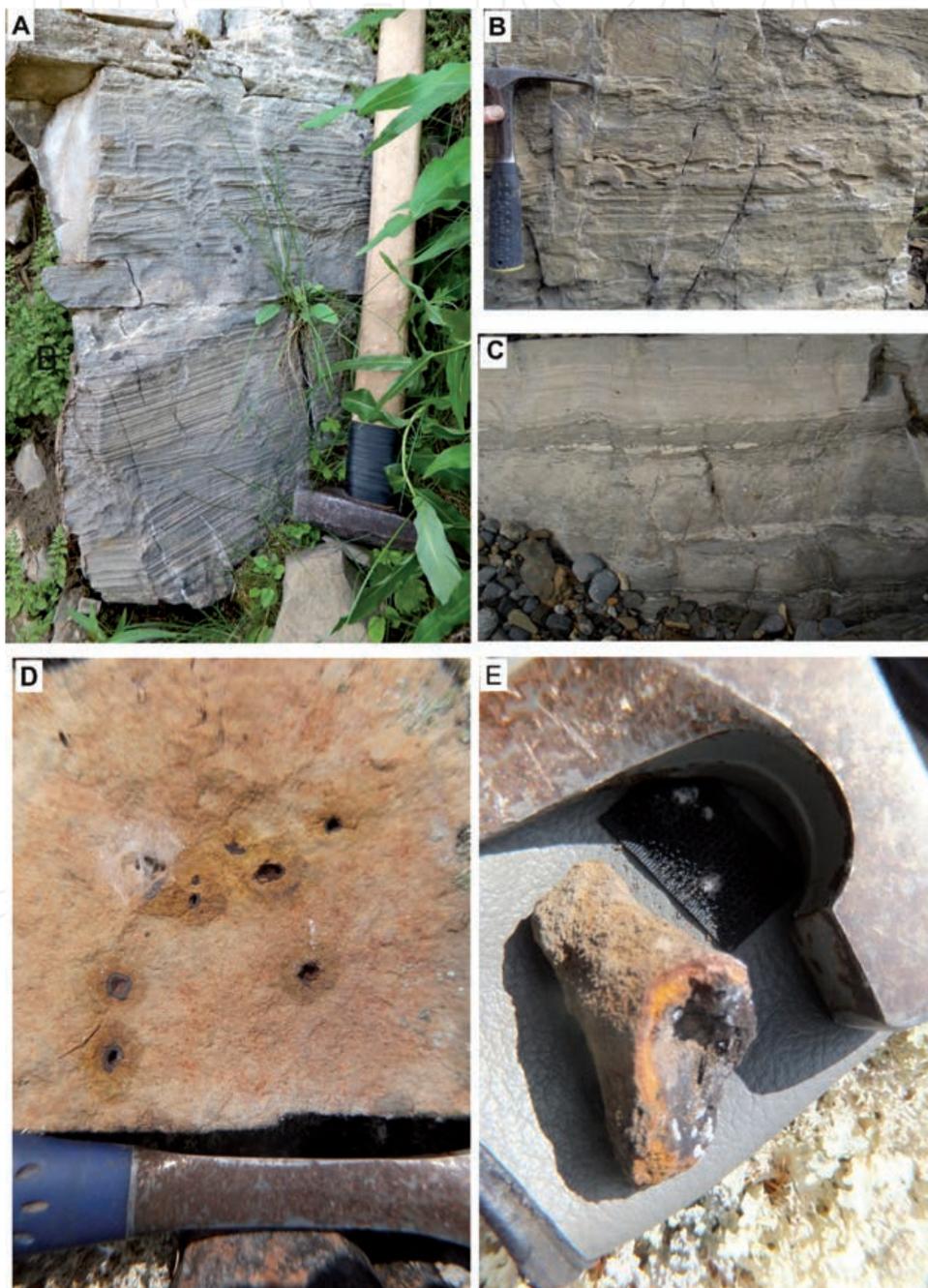
**Figure 7.** Stable isotope ratios  $\delta\text{C}$  (‰ PDB) and late Paleozoic carbonates of the Kolyma-Omolon basin. 1 middle-late Permian limestones, 2,3 late carboniferous-early Permian (2 bulk carbonate, 3 brachiopod shells).



**Figure 8.**

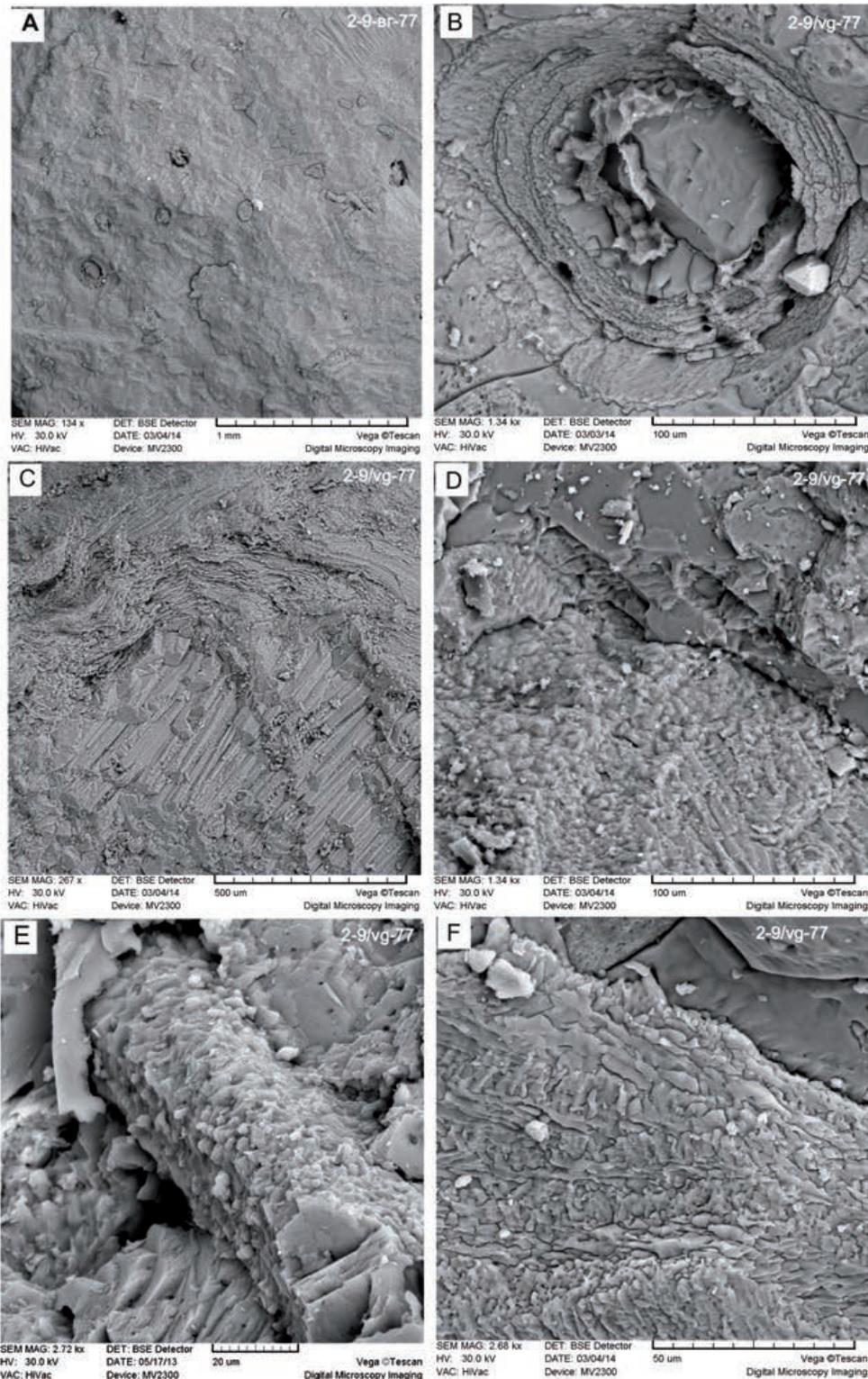
(A) Omolon massif. Bacterial limestones of the Omolon formation (1,2,3 indicate the members of the Omolon formation), middle Permian, northern Priokhotye, Khivach River basin (photo by I.L. Vedernikov). (B–E) Sugoi synclinorium. Bacterial limestones of the Taktay-Yuryakh formation. (B, C) Biostromes and bioherms of the Taktay-Yuryakh formation. D Biostromes overlying each other demonstrate strongly dissected upper surface, inverted bedding. (E) Bacterial crusts of prismatic calcite in limestones of the Taktay-Yuryakh formation. Middle Permian, middle reaches of the Kolyma River. (F) Omulevka uplift. Bacterial crusts of prismatic calcite in carbonaceous clay-silty rocks of the Rogachev formation. Upper perm, Kolyma river basin, Tuscan River. Photo by I.L. Vedernikov. (G) Gizhiga deflection. Bacterial crusts of prismatic calcite in carbon siltstone Fedorov formation. The second half of the lower perm; northern Priokhotye, upper course of the Paren' river. (H) for comparison, bacterial crusts among modern sediments of the Black Sea (A. Mazzini, M.K. Ivanov and others [9]).

extensively varies from the first meters to tens of meters and probably more. The contacts between individual bioherms are of the baselap type. Sometimes the top of bioherms demonstrates complex relief with column-like structures [column heights up to 1.5–2 m (**Figure 8D**)]. Carbonate crusts are especially common. They are present both in shallow facies (limestones) and in the deepwater facies—in the carbon-rich siliceous shales (**Figures 8D–G** and **9C**). A comparison of these crusts with similar bacterial formations in modern sediments of the Black Sea is indicated in **Figure 8H**. Limestones are always thin-layered (**Figure 9A–C**), fetid (with a pungent smell of hydrogen sulfide), and often saturated with finely dispersed pyrite and locally bituminous. Tubular fossils, composed of hematite and



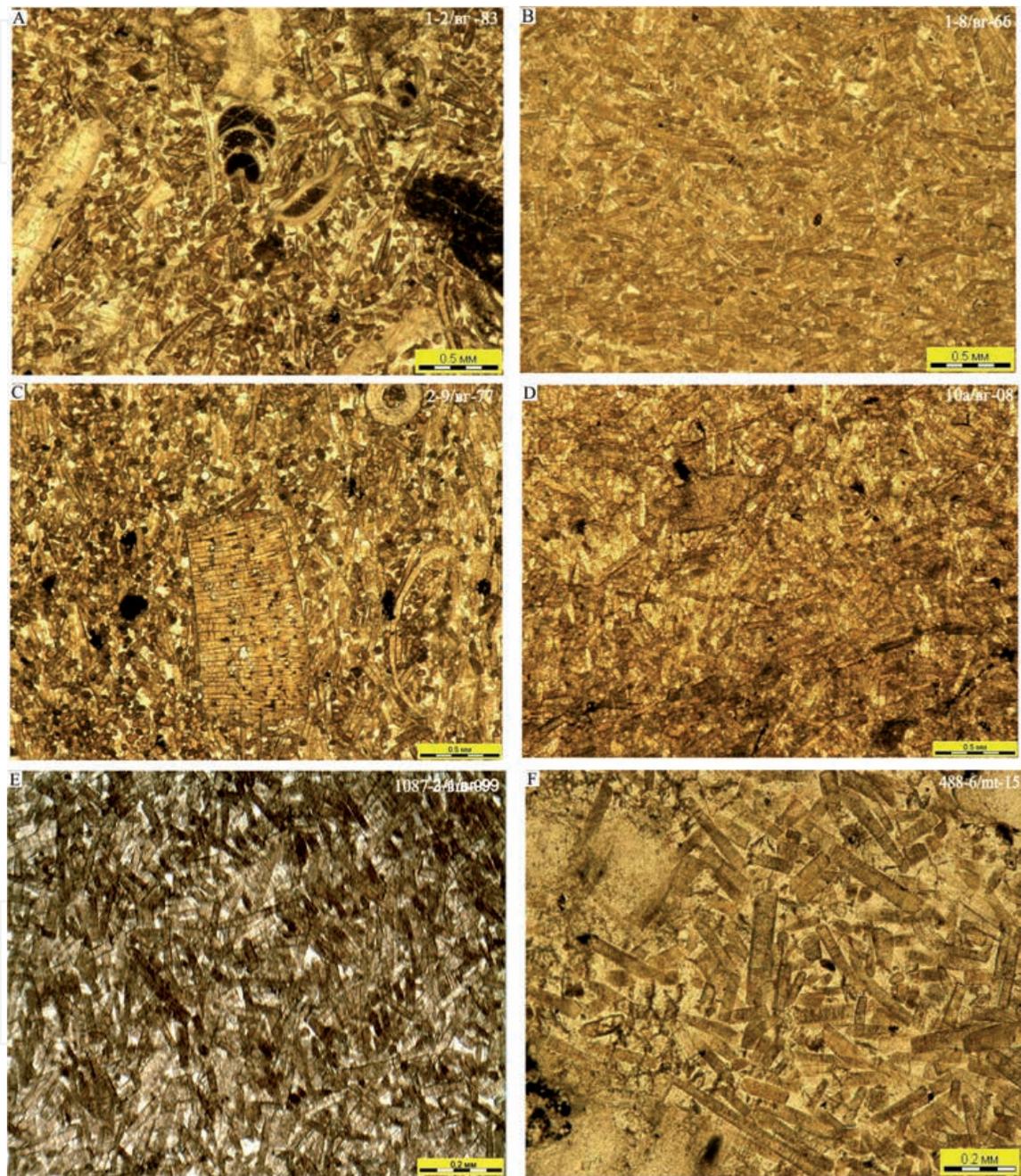
**Figure 9.** Structures of limestones of the Omolon series. (A–C) thin bedding of bacterial limestones of the middle Permian Omolon formation at Omolon massif: (A) upper member of the Omolon formation, zone 14 (*Magadania bajkurica*), Omolon River; (B) middle member of the Omolon formation, Khivach River; (C) bedding in the limestones of the Turin formation, Omulevka zone, Taskan River (photo by I.L. Vedernikov); (D, E) tubes in the bacterial limestones of the folk formation, the second half of the early Permian, zone 9 (*Kolymaella-Bocharella*), Omolon massif, Munugudzhak River (photo by T.V. Filimonova).

apparently formed during the oxidation of pyrite, can be met here (**Figure 9D, E**). In some samples of Permian limestones, quite numerous rounded transverse sections of presumable organisms with multilayered shell can be observed under SEM (**Figure 10B**). One can assume that these structures belong to organisms related to siboglinids—annelid worms, having the gut filled with chemosynthetic bacteria—serving as food for the host.



**Figure 10.** Limestones of the Omolon formation (sample 2–9/vg-77) under SEM. (A) cross sections of microbial tubular structures; (B) the same, enlarged; (C) overlying prismatic crust and multilayered bacterial sheath; (D) another location of the same sample; (E) isolated prismatic colony, with no glycocalyx membrane and its cellular structure (with presumable cells  $>2\ \mu\text{m}$ ) is clearly visible; (F) differently oriented rod-shaped and spindle-shaped lithified cells forming elongated clusters; middle Permian, zone 12 (*Terrakea borealis*); Omolon massif, Omolon River.

The thickness of limestone bodies varies from centimeters to hundreds of meters. Microstructural features of these rocks (**Figure 11**), composed of the smallest calcite prisms, gave rise to an erroneous opinion about their detrital origin. Over the centuries, it was believed that calcite prisms are fragments of the destroyed prismatic layer of shells of inoceramid-like mollusks of the Colymiidae family, and therefore they are often called “Kolymiidae limestones” in the literature.



**Figure 11.**

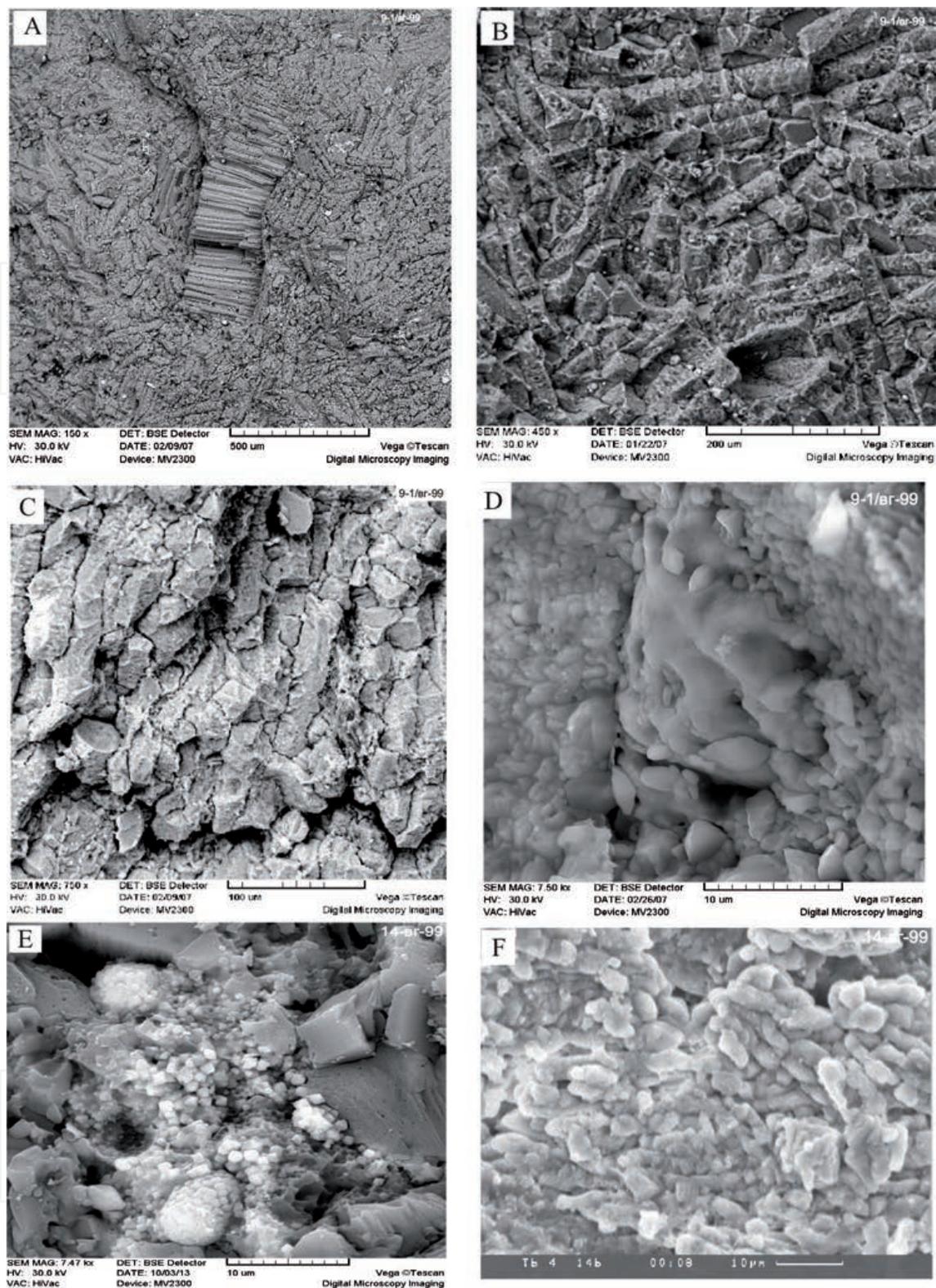
Microstructures of limestone in transmitted light. (A) Ozerny formation, sample 1–2/ВГ-73; fragments of foraminifera and brachiopods are visible; upper lower Permian, Dzhigdali series, zone 9 (*Megousia kuliki*); Omulevka uplift, Kolyma river pool, upper course of the Zyryanka River. (B) Middle member of the Omolon formation, sample 1–8/ВГ-66, zone 13 (*Terrakea korkodonensis*), middle perm, Omolon massif, Khivach River basin. Sample 1–8/vg-66, zone 13 (*Terrakea korkodonensis*). (C) Middle member of the Omolon formation, sample 2–9/ВГ-76, zone 12 (*Terrakea borealis*), middle Permian, northern Priokhotye, Omolon massif, the left tributary of the Omolon River is the Russian River. (D) Taktay-Yuryakh formation, sample 10a/ВГ-08, middle Permian, the middle reaches of the Kolyma River. (E) Tupicovy formation, sample 1087–3/ВШ-09, the second half of the lower Permian, possibly the middle perm; Indigirka River basin (materials by V.S. Shulgina). (F) Mochov formation, sample 488–6/МТ-15; fragments of shells of brachiopods and crinoid stems are present; upper lower Permian; Wrangel Island, the upper reaches of the Hishchnikov River (material by M.I. Tuchkova).

However, our detailed studies of these structures have undoubtedly shown the autigenicity of these rocks and their microbial nature. In addition to studying the morphology of these bodies, this is confirmed by a detailed study using SEM and thin sections, which leaves no doubt about this conclusion. Carbonate rocks have a well-preserved mineralized microbial structure. With a significant increase in SEM conditions, the breed looks like a set of fossilized colonies represented by prismatic and cup-shaped forms (**Figures 11, 12**). Prismatic colonies (up to 500  $\mu\text{m}$  long and up to 30  $\mu\text{m}$  wide) fit tightly against each other, and the matrix is completely absent. These colonies have a wrinkled and nostril surface—a membrane. It is formed, apparently, by the mineralized glycocalyx, which surrounds a cluster of mineralized cells 1–2 microns in size. Cells have a coccoidal, less often rod-shaped or ovoid shape (**Figures 12D, E, 13E, and 10D, E**). When these structures are more strongly mineralized, the shell is covered with an even layer of porcelain calcite, and often prismatic colonies acquire a columnar appearance (**Figures 12D and 10C**). In some places you can see fragmented cells, sometimes forming bundles or a complex interweaving of threads, branched, or rosette-like clusters (**Figures 13F and 10F**). The rock is saturated with fine pyrite, which is often framboidal (**Figure 12E**). The surface of the colonies also has pores (gas vacuoles), with a diameter of up to 1  $\mu\text{m}$  (**Figure 13C**).

Pokrovsky [10] established a significant difference in the isotopic composition of these rocks and limestones of the Middle Carboniferous-Early Permian era described above. The rocks of the Middle and Late Permian are characterized by a relatively high average content of  $\delta^{13}\text{C} = 4.1 \pm 1.4\text{‰}$  (in the range from 1.5 to 5.9‰) and a wide range of  $\delta^{18}\text{O}$  values: from 15.5 to 28.8 (in average  $21.4 \pm 2.8$ ) (**Figure 7**). When interpreting these data, it should be borne in mind that the formation of rocks occurred during the widespread transgression. Therefore, it can be assumed that this violation caused the influx of deepwater sulfide water masses into the aerobic zone. Their mixing with oxygenated water masses, as can be assumed, caused changes in the composition of the bacterial biota. The methanotrophic anaerobic ecosystem of Middle Carboniferous-Early Permian was probably replaced by the chemotrophic sulfide ecosystem of Perm. It can be assumed that the trophic basis of this ecosystem was colorless sulfur bacteria and (possibly) archaea. They oxidized reduced sulfur compounds and produced carbon using seawater carbon dioxide. This explains the relatively high  $\delta^{13}\text{C}$  for these limestones. It can be assumed that in addition to obligate aerobes, facultative prokaryotes were also present in the bacterial consortium. The latter explains the formation of rocks at different levels of the stratified basin. They are formed in the photic, oxygen zone, as well as in the deepwater aphotic zone with a low oxygen content.

## 2.2 Mixtites of the upper Paleozoic black shale series

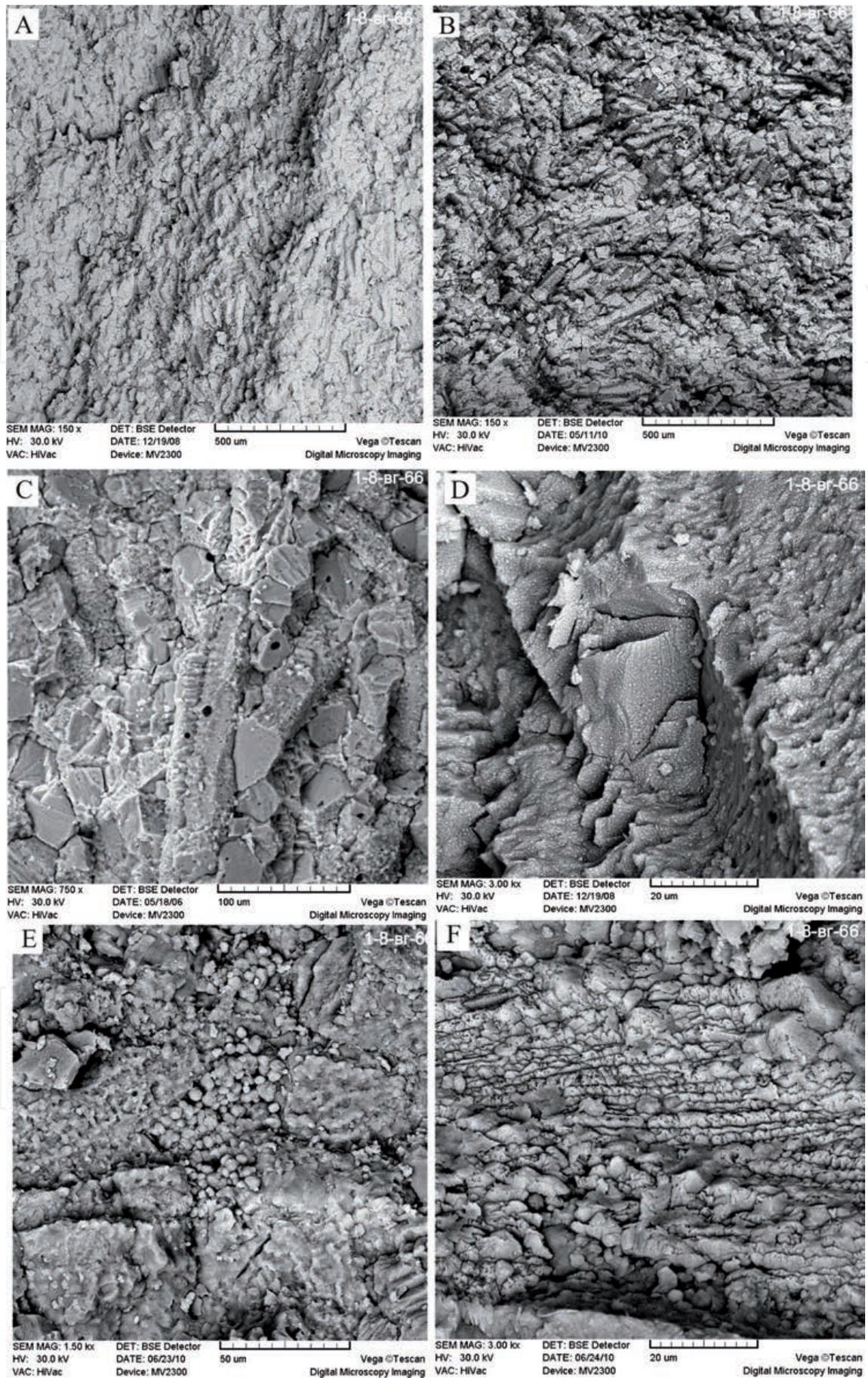
Of no less interest than the carbonate rock, another characteristic member of the black shale series are the Late Permian mixtites, which form a belt along the Angarida margin. This belt extends from the Southern Verkhoyanie to Northern Priokhotye. Another belt of similar type extends along the southeastern margin of the Omolon massif and the Gizhiga trough. In Verkhoyanie and Priokhotye, mixtites are confined to thick (up to 1500 m) clay-shale sequences along the Angarida passive margin. Within the latter, the Late Paleozoic rocks are ore-bearing—they include large and very large gold stockwork-type mine fields. At the Omolon massif, the thickness of strata containing mixtites is 30–60 m, increasing up to 200–300 m in its marginal parts and areas surrounding the Gizhiga trough. A feature of stones is that they look like a drill: sand, gravel-pebble, and boulder materials are randomly dispersed in a dark gray and black clay-silty matrix, which is usually not layered but often has a characteristic of



**Figure 12.**

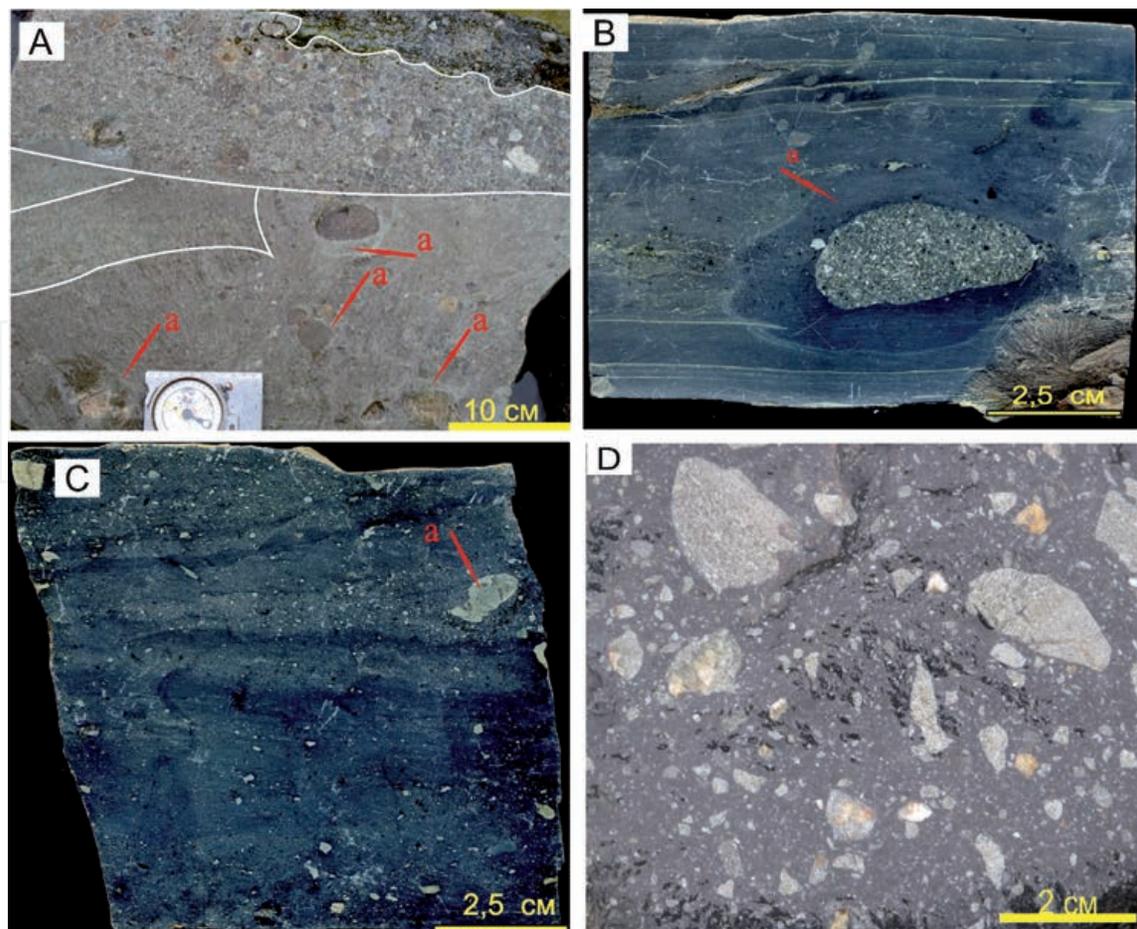
*Limestones under a SEM. (A–D) Rulon formation. (A–C) accumulation of prismatic microbial structures, at different magnifications (in a, a small carbonate crust is visible among clusters of prisms), (D) the accumulation of grains of bacterial carbonate and a whitened colony covered with porcelain calcite, sample 9–1/Br-99. Omolon massif, the upper half of the lower Permian, Dzhigdali series, zone 7 (Megousia aagardi). Left tributary of the Omolon River, the Munugujak River. (E, F) folk formation, sample 14–1/Br-99. (E) Framboidal pyrite, (F) rod-shaped microbial structures. Omolon massif, the upper half of the lower Permian, Dzhigdali series, zone 8 (Megousia kuliki). Same location.*

concentric layered parting (**Figure 14**). Another feature of the rocks is the predominantly volcanic composition of the clastic elements—andesit-dacite, less often liparite. Light, decayed, and altered fragments of volcanic rocks, scattered over the dark matrix, provide spotty appearance for the rocks. This served as a basis for their



**Figure 13.**

(A–C) accumulation of prismatic microbial structures, depicted in different planes under different magnifications. (D) Surface of the prismatic structures, apparently covered by the mineralized glycocalyx. (E) Aggregates of microbial filaments formed by splitting cells and coated by a thickened mineralized glycocalyx. (F) Longitudinal section of a prismatic structure with distinct coccoid bacteriomorph structure; sample etched with HCl. Middle member of the Omolon formation. Middle Permian, zone 13 (*Terrakea korkodonensis*); Omolon massif, Khivach River.



**Figure 14.**

Polished surfaces of Permian mixtites, showing their principal features. (A–C) Mixtites (diamictites) of the Permian of Northeast Asia: (A) fractal nature of diamictite (diamictite in diamictite; “a” letters indicate areas of mineral transformation around xenoliths); middle-upper Permian, Atkan formation; upper reaches of the Nelkoba River, basin of the upper reaches of the Kolyma River (materials by I.L. Vedernikov). (D) variable roundness of xenoliths; upper Permian, Atkan formation; Burgagylkan River, a tributary of the Chelomdzha River, the basin of the upper reaches of the Kolyma River (materials by A.S. Byakov).

naming in the geological slang as “hazel grouse rocks.” The predominant size of the clasts is 0.5–5 cm, although fragments up to 20 cm can be observed. The clasts normally occupy 5–10% of the total rock volume, locally reaching 60–70%. Their roundness is variable, but often they are well-rounded. The silty-clayish matrix is unsorted, has chlorite-siliceous-clay composition, and apparently derives from the pyroclastic material (Mikhailov, 1971 — unpublished; Byakov, Vedernikov [13]). Intervals with clasts normally interbed with pure clayish-silty intervals, which locally demonstrate well-visible graded bedding and soft-sediment flow structures. Fluid textures are also noted. The mineralogical composition of the heavy fraction from the Omolon mixtites is represented by three types: (1) associated with rocks of acid and intermedium composition, (2) associated with rocks of basic and ultrabasic composition, and (3) deriving from metamorphic rocks (Mikhailov, 1971). The most peculiar thing is the presence of large amount of pyroclastic materials, while the corresponding effusive analogues remain unknown. This gave rise to different hypotheses on the origin of clasts. Since the late 1950s, there was a widespread opinion that the clasts were brought by the drifting seawater ice, while the source of clasts was from some hypothetical land in the Sea of Okhotsk [14]. Ustritsky [15] linked the transport of volcanogenic material with synchronous volcanism within his hypothetical “Shelikhovsky volcanogenic belt.” Rejecting the ice transportation hypothesis, Byakov and Vedernikov, following Ustritsky, explained the origin of clasts by synchronous volcanism outside the territory, renaming the hypothetical “Shelikhovsky belt” into the equally hypothetical

“Okhotsk-Taigonos volcanic arc.” These authors correctly marked the widespread presence of debris flows within the succession, which offer to be the main transportation agent. Recent special studies by Isbell et al. [16] have also rejected the hypothesis of the ice origin of these deposits. Obviously, the problem requires further study. However, several additional considerations should be made.

Noteworthy is the spatial distribution of the rocks along the continental margin, which was the zone of increased fluid permeability. For such areas fluid flows are one of the significant factors of sedimentogenesis. This suggests that the rocks under consideration may belong to the fluid-explosive type, the recognition and study of which receives more and more attention today. In recent years, the role of fluid systems has been recognized as the universal mechanism of the formation and transformation of the earth's crust, as well as of the localization of many currently known mineral resources. Fluid is a substantially aqueous, water/gas, vapor or gas medium, enclosed or transported by the rocks within the lithosphere. The components of the fluid systems react with petrogenic, ore, and other elements [17]. Fluidolites are a resulting association of rocks, varying from breccias and conglomerates to aleuropsammites and carbonates. Cases of erroneous interpretation of fluidolites as glacial formations are not rare at all [18]. The formation of such rocks was not associated with the magma intrusion. It happened due to drastic releases of gas-water solutions and more or less gradual intrusion of gas and water solutions into the crust. These solutions, having separated from their maternal extremely gas-saturated magma, brought various types of pyroclastic debris, from ash to psephtes. The development of fluid systems was accompanied by a wide range of phenomena, such as mud volcanism.

The fluid-explosive-mud origin of the debris in mixtites of Northeast is confirmed by the structural position of these formations; sedimentation of black slate background; lack of a clear (and not hypothetical) surface source; sharp lateral disappearance, which can be explained by the presence of several foci of eruption; the presence of fluid textures; and the presence of stockwork type of mineralization. The interbedding of diamictites and pure silt-clay intervals, as we can assume, indicates the alternation of different phases: explosive (short-term explosive emissions of gases, debris, and dirt) and griffin (prolonged and quiet penetration of liquid mud). It can be assumed that the hazel grouse and the associated gold mineralization are syngenetic.

The characteristics of the Late Paleozoic sedimentation in Northeast Asia, considered above, suggest that a significant role in the Late Paleozoic riftogenesis was played by the endogenous activity, which generated ascending fluid flows of various compositions. The discharge of these flows resulted in the black shale sedimentation, the presence of peculiar mixtites within the succession, and the presence of carbonate bodies of bacterial genesis. The association of benthic fauna within bacterial carbonates indicates that the basin was characterized by autolithotrophic ecosystems, where the role of primary producers was played by methanotrophic and chemotrophic bacteria. Data indicating the significant role of similar processes in recent water reservoirs are quickly increasing ([11, 12, 19–22] and others). Lein described the problem as “life on methane and hydrogen sulfide” [23]. A summary on these processes is reflected in the Belenitskaya's concept of “fluid lithogenesis” [24] as a special type of rock formation processes (Yudovich [25]).

### 3. Stages of historical development of the benthic biota

The black shale “anomaly” of the Late Paleozoic sedimentation at the Northeast Asia is well correlated with the peculiarity of its benthic biota. The latter is very poor taxonomically and endemic for most of the Northern Hemisphere. Large animal groups such as fusulinids and trilobites are absent here. As a rule, corals are absent too,

while conodonts are unknown. The explanations for this usually imply the paleogeographic position of the region—it was located in high palaeolatitudes and ocean waters here were cold [26–29]. However, earlier, the author has shown that the distribution of the so-called “boreal, cold-water” biota is not consistent with this idea. At the same time, a correlation between the occurrence of the benthic communities and the phases of riftogenesis and formation of deep black shale basins was revealed [2]. The analysis of the corresponding ecosystems revealed their lithotrophic nature, where the role of primary producers belongs not to plants but to autolithotrophic bacteria.

In the evolution of the Late Paleozoic biota of the northeast of Asia, three large stages can be distinguished, reflected in the successive change of three types of benthic associations—Verkhoyansk, Pechora-Kolyma, and Kolyma-Omolon types [9].

The Verkhoyansk type of benthic associations (*Verkhoyania*–*Jakutoproductus* fauna) ranges from the mid-Bashkirian to the mid-Artinskian. Taxonomically these associations are very poor and sharply endemic. As a rule, fossil assemblages are confined to thin limestone bodies (bioherms, biostromes) with untypically low  $\delta^{13}\text{C}$  values. Until the Early Artinskian, this type of associations remains extremely rare and mostly local.

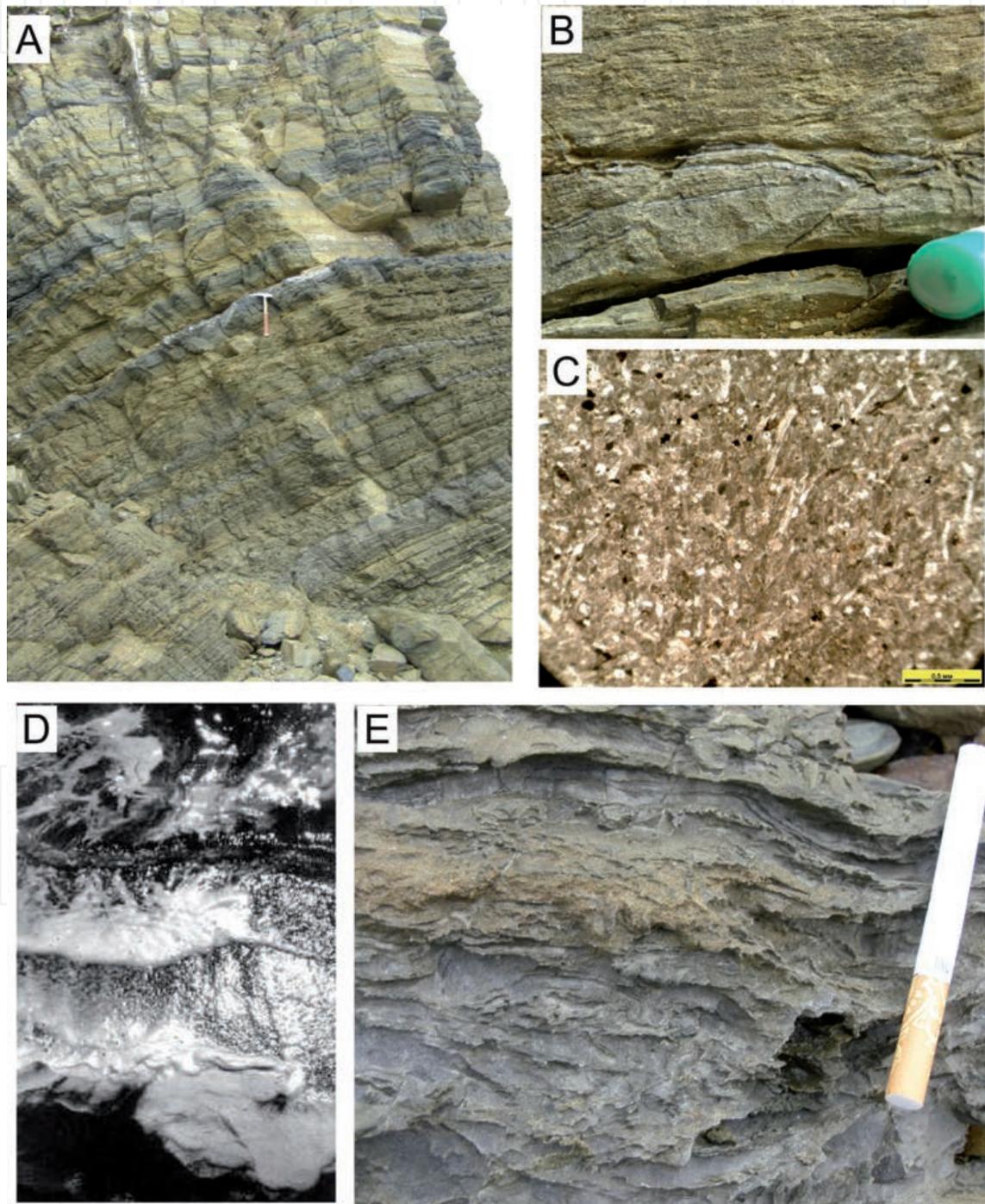
Starting from the Late Artinskian and up to the end of the Early Permian, there was a biotic turnover caused by the beginning transgression. Monotypic associations of the Verkhoyansk type were replaced by polytypic association of Pechora-Kolyma type. In the newly established associations, the presence of the elements of Ural and, especially, of Pechora affinity is very noticeable. The diversity of foraminiferas from Lagenidae’s family significantly increased after this turnover. Representatives of the genera *Waagenoconcha*, *Anidanthus*, *Striapustula*, and *Spiriferella* are the dominants of the brachiopod communities. Among mollusks, the most significant and noticeable event is the appearance of inoceramid bivalves.

The Kolyma-Omolon type of associations replaces the preceding Pechora-Kolyma type during the biotic crisis at the Early/Middle Permian transition. Its paleocenoses are confined to bacterial carbonates, forming thick bodies of limestones saturated with sulfides. This type is characterized by the highest taxonomic diversity. The foraminifera are very diverse but represented exclusively by lagenids. Among brachiopods, finely ribbed linoproductides are dominant (genera *Terrakea*, *Canocrinelloides*, and *Stepanoviella*), as well as the representatives of the family Lichareviidae. Among bivalves, the role and taxonomic diversity of inoceramid-like bivalves (the family Kolymiidae) grows. As a rule, these are large and very large (up to 70 cm) shells, suggesting endosymbiosis with bacteria, by analogy with recent *Bathymodiolus* and *Calyptogena*. The described type of associations existed throughout the rest of the Permian, completely disappearing near the Permian–Triassic boundary.

#### 4. Analogues outside the Northeast Asia

The described features of the Late Paleozoic bio- and sedimentogenesis are not limited by the territory of Northeast Asia. Similar biotopes, as well as related biomes, are fragmentarily present along the Pamir-Himalaya belt, Inner Mongolia, and Primorsky Krai of Russia. But the most striking analogues can be found in the Southern Hemisphere, associated with sedimentary basins of Gondwana. In particular, benthic associations of the Middle Carboniferous–Early Permian of the Tepuel group in Patagonia [30] are almost identical with those of Verkhoyansk type. Fossils, similar to all dominants of the Verkhoyansk association, are known from Patagonia. Among them brachiopods of the genera *Verkhoyania*, *Jakutoproductus*, *Lanipustula*, *Levipustula*, and *Costatumulus* are reported. Noteworthy is the black shale silt-clay composition of the sequence of the Tepuel group, containing several horizons of diamictites, interpreted here as a result of transportation by seawater ice.

The Perm system of New Zealand shows even more striking similarities. The thin-layer carbonate formation Wooded Peak on the South Island is built by lithified bacterial mats and consists of fetid hydrogen sulfide bacterial limestones rich in sulfides with characteristic carbonate crusts completely identical to similar rocks from Northeast Asia (**Figure 15**). Here, they are also mistakenly interpreted as clastic rocks—the result of fragmentation of bivalve mollusk shells (“*Atomodesma* limestone”) [31, 32]. In the north of the southern island, in the Nelson region, limestones appear to be deep-sea and directly contact with ophiolite rocks (Dan Mountains and D’Urville Islands) [23]. In the flat facies of shallow water in the south of the same island, these rocks contain



**Figure 15.** Limestones of the wooded peak formation (upper perm) at D’Urville Island, New Zealand, and recent bacterial formations in the Black Sea. (A–C) Limestones of the wooded peak formation. (A) Exposure of the wooded peak formation. (B) Bacterial carbonate crusts along bedding planes. (C) Thin sections in transmitted light. (D, E) comparison between recent and fossil bacterial structures: (D) modern bacterial mats on the Black Sea bottom (7) and (E) fossilized bacterial mats in the wooded peak formation.

shell benthic fossils, mostly similar with the Kolyma-Omolon association—finely ribbed linoproductides, inoceramid-like bivalve mollusks, etc.

Comparable associations of brachiopods, bivalves, and foraminifera are also characteristic of Perm Australia, especially eastern of fully occupied Australia (Bowen and Sydney basins, New England) [33]. The thick terrigenous sequence, similar to the Verkhoyansk terrigenous complex of Northeast Asia, also contains several mixtite horizons, interpreted here as glacial.

The considered materials allow us to see the similarity of some Late Paleozoic basins of Gondwana and Northeast Asia. The identical geology of these basins was the reason for the existence in these areas of peculiar ecosystems unknown in the previous eras.

## 5. Conclusion

The present brief overview allows to make some preliminary conclusions requiring further elaboration. The composition of the Late Paleozoic rocks in Northeast Asia, as well as the features of their fossil associations, suggests that the strongest agent which defined both sedimentation and development of life were the endogenous fluid processes. Those appeared, apparently, both as extrusions of cold fluids (seeps), confined to the system of regional faults (or fractures), and as mud-explosive activity caused by pressure gradients within the crust. This led to the saturation of marine waters by reduced compounds—methane and hydrogen sulfide. The result was the formation of the Late Paleozoic sulfide-rich sedimentary basins and their typical sulfide biota. This defines the peculiarity of the Late Paleozoic biosphere, where lithotrophic ecosystems played an important role along with “normal” phototrophic associations.

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