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The Basal Unit of the Verkhoyansk Sedimentary Complex, Northern Kharaulakh: Lithostratigraphy, Biostratigraphy, and Deposition Environments

N.V. Sennikov[a,b,✉], R.A. Khabibulina[a], T.V. Gonta[a,b], O.T. Obut[a,b]

[a]*Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090. Russia*

[b]*Novosibirsk State University, ul. Pirogova 1, Novosibirsk, 630090. Russia*

Abstract—The origin and biostratigraphic constraints of the Krestyakh conglomerate remain among most controversial issues in the Late Paleozoic history of the Northern Kharaulakh basin. The Krestyakh conglomerate is a sequence of coarse sand to pebble-size sediments at the base of the Late Paleozoic Verkhoyansk clastic complex. According to geological, lithological, and sedimentation data, the Krestyakh conglomerate in the Atyrdakh Formation is composed of debrites i.e., deposits carried by debris flows that fill submarine canyons. The Verkhoyansk clastic deposition began at the middle Visean stage of the Early Carboniferous.

Keywords: Carboniferous; Visean; stratigraphy; lithology; Northern Kharaulakh

INTRODUCTION

Stratigraphy and sedimentology of junctions between major cratonic and orogenic provinces have always attracted the attention of geoscientists. The Northern Kharaulakh area (Northern Verkhoyansk region) in the lower reaches of the Lena River is a junction of the Verkhoyansk orogenic belt and the Siberian craton (Drachev, 2011; Klett et al., 2011; Prokopiev et al., 2013). Heavily deformed Devonian and Carboniferous sediments of the area are exposed in the right bank of the lower Lena (Figs. 1, 2) downstream of Tit-Ara Island and in the Lena Delta at the source of the Bykovsky Channel in the Krestyakh Cape (Krest-Tumsa Cape at the northwestern foot of Krest-Khaya mount) near a polar weather station of Sokol (Khabarov). The local Late Paleozoic stratigraphy was quite reliably constrained by data on brachiopods (Lapina, 1962; Kashirtsev et al., 1966; Abramov and Grigorieva, 1986; Klets, 2005), ostracods (Bushmina, 1970), corals (Koksharskaya, 1965), goniatites (Andrianov, 1985), foraminifera (Bogush et al., 1965), and other fauna groups. The stratigraphic range of the Devonian and Carboniferous units has been updated recently from conodonts, brachiopods, and ammonoids (Yazikov and Sobolev, 2013; Yazikov et al., 2013, 2015; Izokh and Yazikov, 2017).

The Northern Kharaulakh Carboniferous sediments (Fig. 3) span the Bastakh, Atyrdakh, Tiksi, and Tugasir formations exposed in large outcrops (Mezhvilk, 1958; Bogush et al., 1965; Bulgakova, 1967; Zanina and Likhareva, 1975; Geological Map, 1979, 2014; Klets, 2005; Koren' and Kotlar, 2009; Kutygin, 2009; Yazikov and Sobolev, 2013; Yazikov et al., 2013, 2015; Izokh and Yazikov, 2017). The Ebelyakh (Ebelekh) Formation beneath the Bastakh Formation was previously considered (Mezhvilk, 1958; Kashirtsev

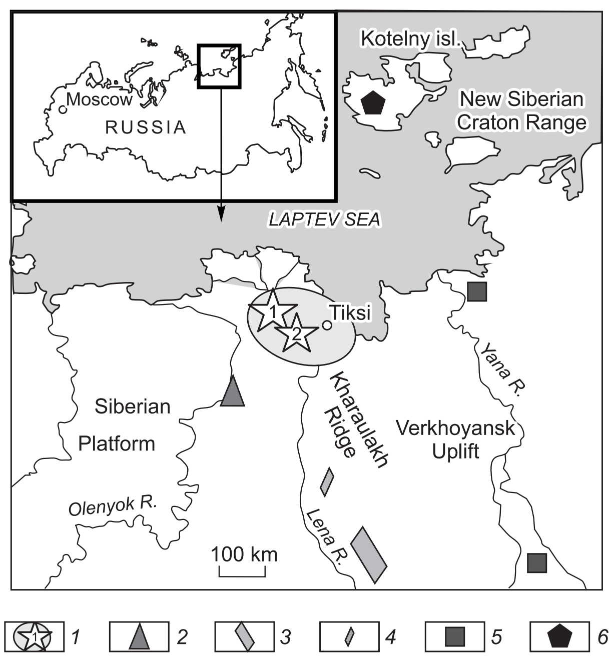


Fig. 1. Location map of Lower Carboniferous sediments exposed in large outcrops in the northeastern Siberian craton, Verkhoyansk area, and Arctic islands of the Laptev Sea. *1*, Northern Verkhoyansk area, Kharaulakh Range and sampling sites in the Krestyakh Cape, upper Lena Delta (1) and in the Lena right bank near the mouths of the Taba-Bastakh-Yurege and Kasym creeks (2); *2*, Kyutyungde graben, Siberian craton; *3* and *4*, Uel-Siktyakh and Orulgan subzones of the Central Verkhoyansk facies zone, respectively; *5*, Northern Verkhoyansk area, upper and lower reaches of the Yana River; *6,* Kotelny Island.

✉Corresponding author.
E-mail address: SennikovNV@ipgg.sbras.ru

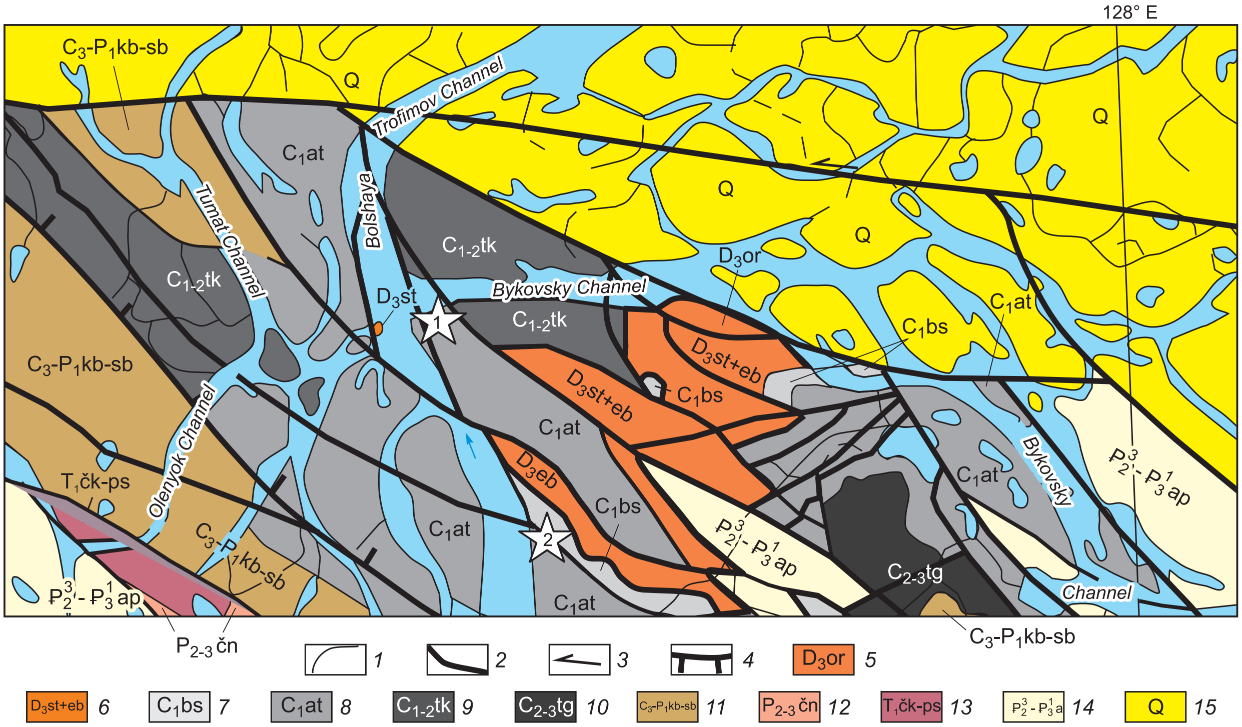


Fig. 2. Geological map of Northern Kharaulakh, lower reaches of the Lena River, simplified after Geological Map (2014). Stars are sampling sites (see Fig. 1 for location). *1*, stratigraphic boundaries; *2–4*, faults, including strike-slip (*3*) and thrust (*4*) faults; *5*, Orto-Khaya Formation; *6*, Stolb Formation + Ebelyakh Formation; *7*, Bastakh Formation; *8*, Atyrdakh Formation; *9*, Tiksi Formation; *10*, Tugasir Formation; *11*, undifferentiated Kubalakh, Tuora, Sakha, and Soubol formations; *12*, Chink Formation; *13*, Chekanov, Ystannakh, and Pastakh formations; *14*, Apanasov sequence; *15*, Quaternary sediments.

et al., 1966; Abramov and Grigorieva, 1986) as the lowermost Carboniferous stratigraphic unit. At present its full range has been officially correlated with the Upper Devonian (Geological Map, 2014), but the upper strata may be Tournaisian, or Lower Carboniferous (Izokh and Yazikov, 2017). The total thickness of the Carboniferous formations reaches 2 or 2.5 km.

We report new data of two field campaigns (2017 and 2018) from several Carboniferous sections in the lower Lena, with special focus on the Krestyakh conglomerate and typical outcrops of the Atyrdakh Formation. Two sites were studied in detail (Figs. 1, 2): one at the source of the Bykovsky Channel in the Krestyakh (Krest-Tumsa) Cape near the Sokol weather station and the other on the right bank of the Lena, at the mouths of the Taba-Bastakh-Yurege and Kasym creeks (Sites 1 and 2, respectively). The outcrops of Site 1 were documented layer-by-layer (Figs. 4–8) and sampled for biostratigraphy. Autochthonous and redeposited fauna assemblages were sampled, respectively, from the matrix and cement of conglomerates and from large boulders and pebbles. Each boulder and pebble sample was labeled as an individual fauna location and prepared in laboratory to extract ostracods and conodonts; additionally, many coral samples were collected. At Site 2 we sampled corals from the Bastakh Formation limestone, for comparison, and examined the Atyrdakh Formation in search for features and markers of deposition environments (chert, coarse rocks, etc.) which would be similar to those in the Krestyakh conglomerate near the Sokol station. Their probable occurrence was mentioned in early publications (Mezhvilk, 1956, 1958; Bogush et al., 1965; Bulgakova, 1967) and shown in Geological Maps (1979, 2014).

HISTORIC BACKGROUND

The origin of the Krestyakh conglomerate named according to its location at the Krestyakh Cape (Mezhvilk, 1958) remains one of most controversial issues in the Late Paleozoic basin history of the lower Lena River. A key point in this respect is the source of sand- to cobble-size carbonate sediments (Mezhvilk, 1958; Bogush et al., 1965; Bulgakova, 1967, 1976; Bulgakova et al., 1969). The Krestyakh conglomerate strata are located near the Sokol polar weather station at the source of the Bykovsky Channel in the Lena Delta. They were first described as a local geological body and a separate stratigraphic unit by Mezhvilk (1956, 1958) and were later identified as the Krestyakh Formation (Bogush et al., 1965; Lungersgauzen and Solomina, 1966). The Krestyakh Formation was mentioned in many publications (Bulgakova, 1976; Petrov, 1980; Abramov and Grigorieva, 1986; Matukhin, 1991; Klets, 2005; Kutygin, 2009), but its validity as a separate formation was doubted in some stratigraphic models (Kashirtsev et al., 1966; Bushmina, 1970; Geological Map, 1979, 2014) which interpreted the Krestyakh unit as a coarse facies of the Atyrdakh Formation. On the other hand, the stratigraphic volume of the Krestyakh conglomerate was equated (fully or partly) to the Atyrdakh Formation in a section 15–16 km south of the Bykovsky Channel outcrop, on the Lena right bank, at the mouths of the Taba-Bastakh-Yurege and Kasym creeks (Bogush et al., 1965; Kashirtsev et al., 1966; Abramov and Grigorieva, 1986; Yazikov and Sobolev, 2013; Izokh and Yazikov, 2017).

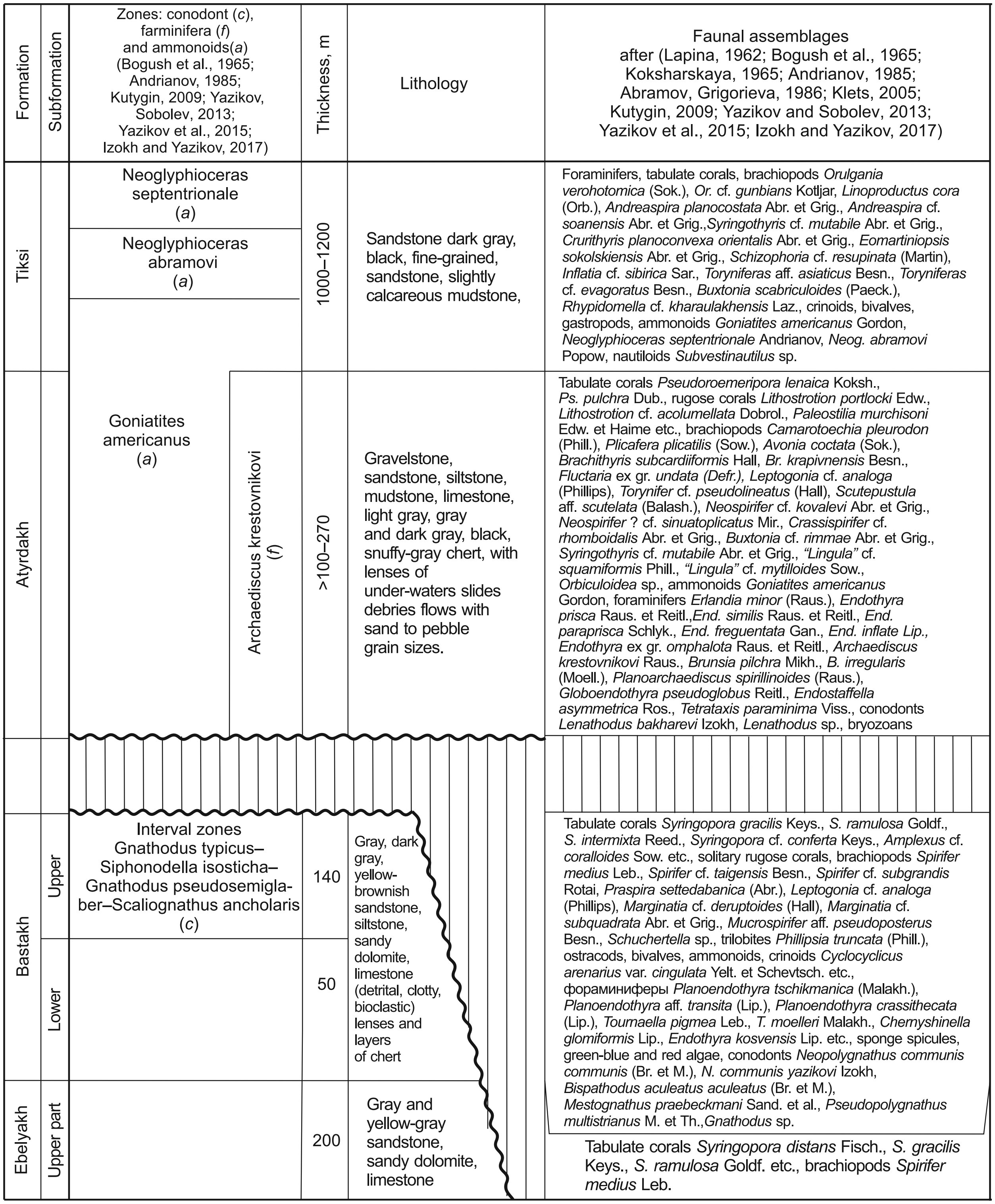


Fig. 3. Lithology and fauna assemblages in the Lower Carboniferous of Northern Kharaulakh.

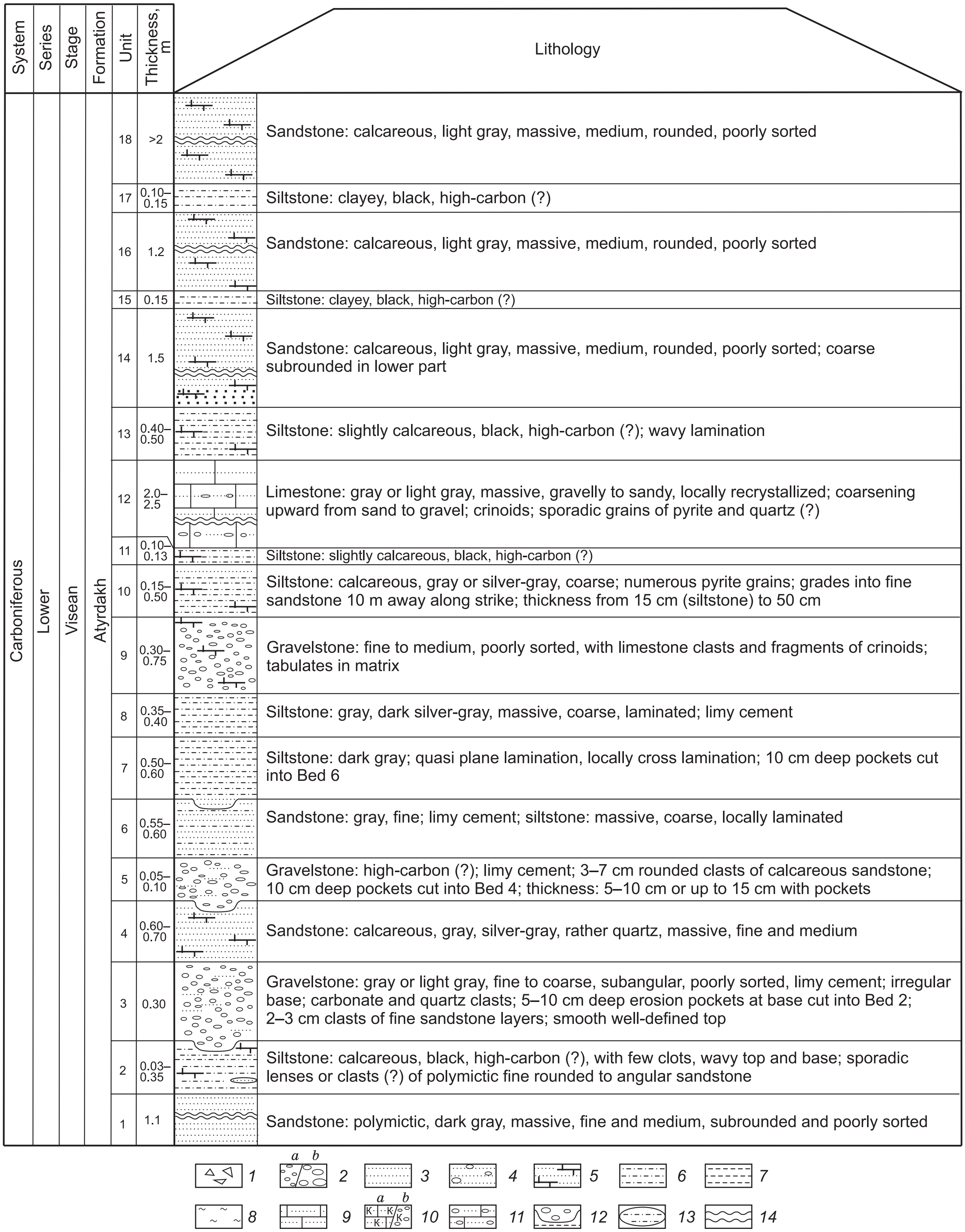


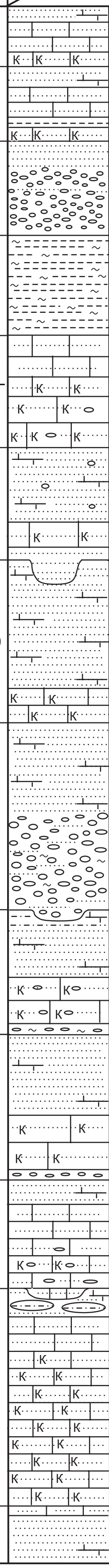
Fig. 4. Lithology of the Krestyakh conglomerate, basal strata (S-1870, head of Bykovsky Channel, 72°24′15″ N; 126°47′35″ E). *1*, breccia; *2*, gravel/conglomerate; *3*, sandstone; *4*, sandstone with floating pebbles; *5*, calcareous limestone; *6*, siltstone; *7*, mudstone; *8*, chert; *9*, sandy limestone; *10*, calcarenite/calcirudite; *11*, gravel-sand-size limestone; *12*, erosional pockets cut into underlying beds; *13*, lenses; symbol *14* means *not to scale*.

System	Series	Stage	Formation	Unit	Thickness, m	Lithology
Carboniferous	Lower	Visean	Atyrgakh	28	0.8	Sandstone: calcareous, gray, massive, fine, subrounded and well sorted, flaggy (10 cm); 1–2 mm gray banded pyrite grains
				27	0.35	Siltstone: calcareous, black, high-carbon (?)
				26	0.8	Conglomerate: fine pebbles of gray limestone (50 %) in a matrix of fine and medium well sorted subrounded sandstone, in lower 3–5 cm; grades upwards to 15–20 cm of gravelstone (30 % or more clasts) and further to sandstone; coarsening upward from sand to gravel (15–20 cm thickness); all rocks are calcareous
				25	0.03–0.05	Mudstone: calcareous, black, high-carbon (?)
				24	0.8–0.9	Conglomerate: 3-5 cm rounded to subangular pebbles of gray limestone (more than 50 %) in a matrix of fine and medium sandstone with limy cement in lower 5–10 cm;: fine, subrounded gravel (5 %) in middle 30 cm; coarse and medium sandstone at the top
				23	0.04	Mudstone: calcareous, black, high-carbon (?)
				22	0.2	Sandstone: calcareous, gray, massive, fine and medium, poorly sorted, subrounded
				21	0.05–0.07	Mudstone: calcareous, black, high-carbon (?)
				20	0.25	Sandstone: calcareous, gray, massive, fine and medium, poorly sorted, subrounded
				19	0.4	Sandstone: calcareous, gray, dark gray, massive, medium, subrounded, laminated (1–2 mm)
				18	0.8–0.9	Sandstone: calcareous, dark gray, almost black, fine (3–10 %), with floating subrounded gravel and rounded limestone pebbles with crinoids and ostracods; random orientations
				17	0.4	Sandstone: calcareous, light gray, massive, fine, well sorted
				16	1.1	Siltstone: calcareous, black, high-carbon (?), massive, with poorly pronounced quasi-horizontal 2-5 mm lamination; sporadic 3–4 cm pebbles at bed base
				15	0.35–0.40	Sandstone: calcareous, dark gray, massive, fine and medium, rounded, poorly sorted, flat quasi-horizontal top and base
				14	0.20–0.25	Siltstone: calcareous, black, massive, coarse; quasi parallel cross lamination and twisting (rolling) microstructures
				13	0.5	Sandstone: calcareous, gray, massive, fine, well sorted; quartz in clasts
				12	0.4	Mudstone: calcareous, black, high-carbon (?), massive, foliated
				11	2.7	Sandstone: fine; floating clasts of sand and gravel conglomerate; small pockets at bed base; randomly oriented 5–10 cm clasts of gray medium sandstone (up to 50 %, 20–25 % on average); rounded 5 cm pebbles; 15 cm thick black high-carbon (?) laminated clayey siltstone, with rolling structures
				10	0.35–0.4	Sandstone: black, slightly calcareous, fine, alternated with black high-carbon (?) calcareous siltstone (3–5–7 cm layers)
				9	2.5	Wavy base with erosion pockets cut into Bed 8; gravel to conglomerate (50 %), with limestone and sandstone pebbles, in a matrix of gray coarse calcareous siltstone at member base; 10–15 cm clasts of medium sandstone (50 % rounded and 50 % angular) oriented along or across the bedding, decreasing in number upward; clasts contain crinoids, rugose and tabulate corals and bivalves
				8	0.8	Siltstone: calcareous, black, massive, coarse, 0.1–0.2 mm lamination; sporadic pyrite crystals (grains?)
				7	1.7	Sandstone: highly calcareous, gray, massive, fine and medium; crinoids
				6	0.25	Siltstone: calcareous, black, high-carbon (?), massive, poorly pronounced lamination at the top
				5	1.3	Siltstone: calcareous, occasionally sandy, dark gray, massive, fine
				4	0.2	Siltstone: calcareous, black, high-carbon (?), massive, laminated (0.1–0.2 mm)
				3	0.8	Sandstone: carbonate (calcarenite-calcirudite), gray, dark gray, fine and medium, subangular, moderately sorted; limestone clasts; laminated (0.1–0.2 mm) and weakly flaggy in cross section
				2	0.10–0.15	Siltstone: clayey, black, high-carbon (?), massive; slightly wavy base
				1	1.7	Sandstone: carbonate (calcarenite-calcirudite), gray, dark gray, fine and medium, subangular, moderately sorted; limestone clasts; 0.1–0.2 mm banding at member top

(*continued on next page*)

System	Series	Stage	Formation	Unit	Thickness, m	Lithology
Carboniferous	Lower	Visean	Atyrgakh	43	>3	Gravelstone: dark gray or gray, fine; subangular gravel (up to 80 %) in a fine- and medium-grained sandstone matrix; similar to calcirudite
				42	0.9	Sandstone: gray or steel-gray, medium to coarse, highly calcareous, poorly sorted, subangular; sporadic fine gravel; black (high carbon?) calcareous siltstone in upper 5–10 cm
				41	0.4	Sandstone: highly calcareous, gray or steel-gray, medium to coarse, poorly sorted, subangular, with sporadic fine gravel; black (high carbon?) calcareous siltstone in upper 5–7 cm
				40	0.45	Sandstone: highly calcareous, gray or steel-gray, medium to coarse, poorly sorted, subangular, with sporadic fine gravel; black (high carbon?) calcareous siltstone in upper 15 cm; traces of wavy cross lamination
				39	0.8	Sandstone: highly calcareous, gray or steel-gray, medium to coarse, poorly sorted, subangular, with sporadic fine gravel; black (high carbon?) calcareous siltstone in upper 15 cm; wavy cross lamination
				38	0.6	Sandstone: highly calcareous, gray or steel-gray, medium to coarse, poorly sorted, subangular, with s poradic fine gravel; fragments of fauna; lenses of black (high carbon?) calcareous siltstone and cross lamination in upper part
				37	1.6	Limestone (calcarenite): detrital, dark gray, slightly recrystallized in lower 50 cm; grades to light gray subangular sandstone with carbonate cement and carbonate grains; 1–5 cm thick lens-like layers of black high carbon (?) siltstone in upper part
				36	1.6	Conglomerate and gravelstone with up to 50 % gravel in lower 10 cm, grading upward into medium sandstone; medium-grained sandstone matrix; sporadic rounded poorly sorted pebbles; flaggy sandstone in upper 3–5 cm; all rocks dark gray to black; calcareous high carbon (?) mudstone at the top
				35	3.5	Sandstone: light gray, fine and medium, subrounded and rounded, in lower 20–30 cm; grades upward to 70–80 cm of gravelstone composed of rounded and subangular medium to coarse gravel (up to 50 %), with up to 5 cm rounded floating pebbles; quite sharp horizontal boundary between sandstone and gravelstone; grades further upward to sandstone with sporadic floating gravel; black high carbon (?) calcareous mudstone of variable thickness in upper 5–10 cm
				34	1.5	Limestone: detrital, dark gray; or carbonate sand-gravel-size subangular and angular gravelstone (calcirudite ?) in lower 30 cm, with up to 50–60 % gravel; grades further upward to dark gray medium-grained and on to calcareous fine moderately sorted subrounded sandstone; 5 m away along strike: gravel with poorly sorted subangular floating pebble locally changing to light gray fine conglomerate (up to 80 % pebble); 3 cm long and 0.2–0.3 cm thick fragments of calcareous sandstone layers; black calcareous laminated siltstone in upper 15 cm
				33	1.5	Gravelstone lying on a relatively smooth surface, with 30–35 cm deep erosion sand pockets cut into Bed 32; gravel in a matrix of gray or dark gray medium and coarse poorly sorted subrounded and rounded carbonate (calcarenite-calcirudite) sandstone with fauna detritus; no gravel and more abundant fauna (crinoids, rugose and tabulate corals) in upper part; black calcareous (high carbon?) mudstone in upper 20–25 cm
				32	2.1	Gravelstone in lower 50 cm, up to 70 % gravel in a matrix of gray fine and medium poorly sorted subangular calcareous sandstone; gray sandstone with lenses of black (high carbon?) calcareous mudstone in middle and upper parts; colonies of tabulate corals in matrix; 5–7 cm away along strike: dark gray platy (3–5 cm) coarse siltstone in upper 30–40 cm
				31	0.05	Mudstone: clayey, black (high carbon ?), foliated
				30	3.6	Coarse clastics lying on a relatively smooth surface, with 60–70 cm deep erosion pockets cut into Bed 29, in a matrix of gray fine and medium poorly sorted subangular calcareous sandstone; breccia-conglomerate and gravelstone in lower 1.5 m; well sorted angular 5–7-cm pebbles (up to 50 %); 5–7- cm long and 1–2 cm thick lenses of fine-medium laminated sandstone; pebbles and gravel disappear gradually upward and grade to light gray calcareous sandstone 2 m above the base; massive or rarely laminated (1–2 mm) sandstone at the top
				29	13	Sandstone: calcareous, gray or light gray, medium to coarse, massive, poorly sorted, subangular; 2–3 cm thick layers and up to 1 m long lenses of black (high carbon?) calcareous mudstone and 0.5–1.5 m thick lenses of rounded gravelstone in the middle; 10 cm thick lenses of black (high carbon?) calcareous laminated mudstone at the top

Fig. 5. Lithology of the Krestyakh conglomerate, lower strata (S-1871, head of Bykovsky Channel, 72°24’15” N; 126°47’00” E). Legend same as in Fig. 4.



System	Series	Stage	Formation	Unit	Thickness, m	Lithology
Carboniferous	Lower	Visean	Atyrgakh	13	0.50	Limestone (calcarenite): detrital, coarse and sand-size in lower 5 cm; grades upward to medium and fine limestone, and further to fine calcareous sandstone and at the top
				12	0.65	Limestone (calcarenite): detrital, coarse and sand-size in lower 5–7 cm; grades upward to medium and fine limestone, and further to fine calcareous sandstone at the top; 1–1.5 cm layers of dark gray calcareous mudstone inside the bed
				11	0.35	Gravelstone, fine, in a sandy matrix; grades into fine and medium moderately sorted subrounded sandstone; brachiopods, crinoids, rugose corals; dark gray fine platy (0.5–1 cm) well sorted subrounded sandstone in upper part
				10	1.20	Mudstone (chert): siliceous, light gray to black lying on a wavy bedded surface; 1–2 cm, rarely 3–5 cm, bedding according to color; a wavy surface of sliding (or submarine erosion) in the middle
				9	1.30–1.45	Limestone (calcarenite): dark gray, sand-size, massive, subangular and subrounded, poorly sorted; floating gravel at the base, on a weakly wavy surface; grades upward to lighter gray fine to coarse moderately sorted subrounded limestone; fragments of fauna at the top
				8	1.20	Sandstone: calcareous, light gray, fine and medium, lying on a wavy surface with 2–3 cm deep pockets; limestone (calcarenite): sand and fine gravel sizes, massive; 1–1.5 cm pebbles, at 10 cm above the base; 5 m downstream the Lena River: gray or silver-gray massive fine and medium moderately sorted and subrounded homogeneous sandstone
				7	2.10	Limestone (calcarenite): gray or dark gray, coarse, moderately sorted and subangular, slightly recrystallized; fragments of fauna; above 50 cm grades into slightly calcareous massive fine and medium poorly sorted and subrounded sandstone
				6	1.30	Sandstone or conglomerate-gravelstone, 60–70 cm thick, lying on a surface with wavy bedding, in 20 cm deep erosion pockets filled with rounded poorly sorted 3–5 cm pebbles and gravel (50 %); gravel and pebbles locally reach jointly 80 %; 5 cm long fragments of calcareous sandstone layers, oriented across or along the bedding; crinoids and rugose and tabulate corals, a coral colony on pebbles; fragments of black massive chert; fine well sorted rounded calcareous sandstone at the top
				5	1.35	Limestone (calcirudite): detrital, light gray, massive, fine gravel size, subrounded, in lower 25–30 cm; crinoids, rugose and tabulate corals and bryozoans; 2–3 cm or rarely 5 cm pebbles; black chert; sandstone: calcareous, gray or light gray, fine and medium, rounded and subrounded, in the middle of the bed; siltstone: calcareous, dark gray, almost black in upper 10–15 cm
				4	1.80	Limestone (calcarenite): detrital, gray, massive, coarse sand; dispersed fragments of crinoids and brachiopods; medium moderately sorted subrounded carbonate gravel in lower 1–2 cm; above 1 m grades into gray fine moderately sorted subrounded calcareous sandstone; laminated (1–2 mm) sandstone in upper 5 cm
				3	0.90	Limestone (calcirudite): detrital, gray, medium, gravel size, moderately sorted and subrounded; 3–5 cm deep erosion pockets at base; fragments of brachiopods and tabulates; coarsening upward from gravel in lower 10 cm to gray fine well sorted subrounded calcareous sandstone; wavy lamination at the top
				2	3.30	Limestone (calcarenite): gray or dark gray, organic-detrital, locally recrystallized; fragments of crinoids, tabulate corals, and other faunas; 0.5–1 cm clasts in lower 25–30 cm; grades into massive fine and medium moderately sorted subrounded calcareous sandstone (sandy limestone); lenses of black slightly calcareous laminated (1–3 mm) siltstone in upper 30–50 cm
				1	0.70	Sandstone: calcareous, gray or light gray, massive, fine and medium, well sorted, rounded; farther along strike: sandy limestone, locally recrystallized; sporadic fragments of crinoids and tabulates

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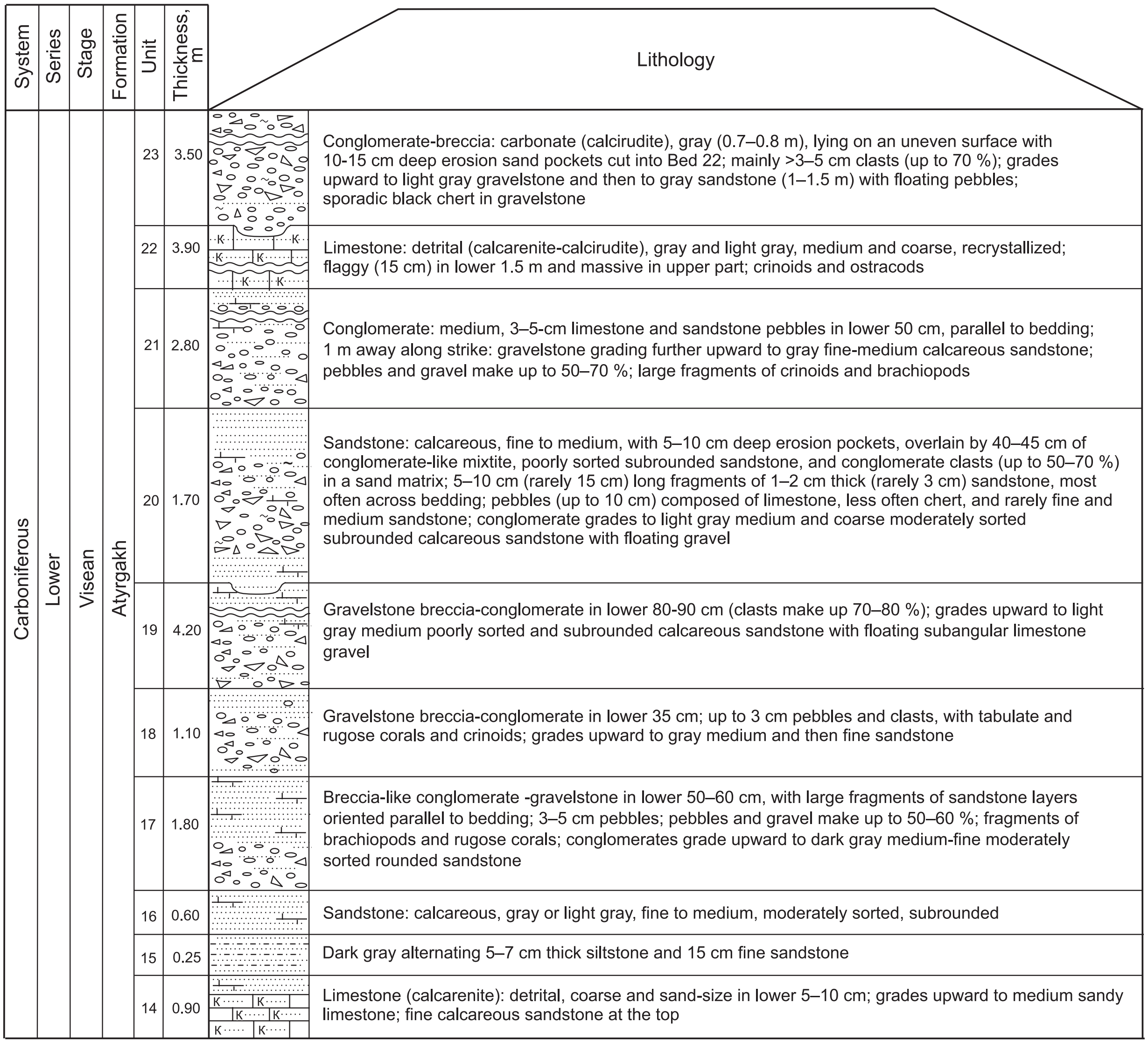


Fig. 6. Lithology of the Krestyakh conglomerate, middle strata (S-1872, head of Bykovsky Channel, 72°24’10” N; 126°46’45” E). Legend same as in Fig. 4.

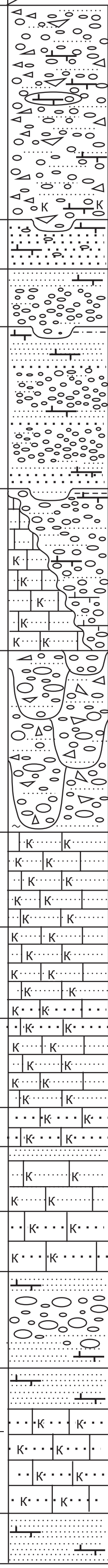
Some models (Petrov, 1980; Abramov and Grigorieva, 1986) distinguished another separate stratigraphic unit of the Sokol Formation near the Sokol station, which would comprise strata equated to the upper third of the Atyrdakh Formation and the lower Tiksi Formation (Kovalevskii, 1991; Klets, 2005; Kutygin, 2009). The Krestyakh and Sokol formations were recommended for use in geological surveys (Resolutions, 1978) but were not included in the recent Geological Map (2014).

LITHOFACIES

The Krestyakh conglomerate strata in the Krestyakh Cape sections comprise several lithofacies (Figs. 9–12). Previously (Bulgakova, 1967) the rocks were described as coarse breccia, conglomerate, and brecciated conglomerate, diamictite, sandstone, siltstone, limestone, and silicic tuff types.

Lithofacies 1 (base of section S-1870): rhythmically alternated layers of gray subrounded gravel (0.30–0.75 m), gray fine to medium sandstone (0.55–1.10 m), and calcareous siltstone (0.3–0.6 m), with uniform thicknesses along the strike. The rhythms were apparently produced by pulse-like inputs of clastics which were carried by submarine debris flows and deposited as the flows slowed down.

Lithofacies 2 (upper part of section S-1870 and lower quarter of S-1871): rhythmically alternated black clayey siltstone (0.10–0.15 m) and light gray rounded medium calcareous sandstone (1.2–2.0 m) uniform in thickness along the strike. Judging by dark color (high carbon?), lack of fauna, and the presence of pyrite crystals in siltstone, the deposition was in anoxic conditions at sea depths below the photic zone, i.e., deeper than 250–300 m. Sand was transported with attenuating flows of turbidite-like material.



System	Series	Stage	Formation	Unit	Thickness, m	Lithology
Carboniferous	Lower	Visean	Atyrgakh	15	6.70	Breccia-conglomerate (calcirudite) in lower 60 cm; up to 50 cm deep pockets cut into Bed 14 at base; pebbles and cobbles up to 1 to 10 cm and 15 cm in size, respectively, composed of black, gray or white limestone; pebbles (70–80 %) are roughly parallel to bedding; sporadic 5–7-cm long and 1.5 cm thick fragments of medium-grained laminated sandstone; 0.5 m deep erosion pockets at base; 20 m upstream the Lena River: ostracods and tabulates in 60-80 cm thick conglomerate; conglomerate pinches out to zero and grades rapidly to gravel (25–30 cm) and sand (>5 m); 5 m long and 30 cm thick lens of limestone conglomerate with 50 % of pebbles at 4 m above base
				14	1.90	Sandstone: calcareous, yellowish gray, massive, coarse to gravel, poorly sorted, subangular; clasts of carbonates and quartz
				13	1.20	Gravelstone: yellowish gray, fine and medium, subangular, poorly sorted; farther along strike: yellowish gray fine and medium poorly sorted subangular highly calcareous sandstone
				12	2.65	Rhythmic alternation: (*a*) 60 cm of coarse to fine and medium sandstone, (*b*) 85 cm of poorly sorted gravel grading to coarse and then fine and medium sandstone, and (*c*) 1.2 m of poorly sorted gravel grading to coarse and then fine and medium sandstone; 3 cm long and 1 cm thick clasts of calcareous sandstone oriented along bedding in rhythms (*b*) and (*c*); black calcareous siltstone at the top; signatures of erosion on the top; 10–15 cm deep erosion pockets at base
				11	2.90	Limestone (calcarenite): detrital, gray, sand size, slightly recrystallized; tabulates. The lithology changes 10 to 20 m off the main section line upstream the Lena River. 10 m upstream: medium (70 % pebble) carbonate conglomerate in lower 40 cm grade upward to dark gray fine and medium poorly sorted subrounded calcareous sandstone; 20 m upstream: conglomerate thickness increases to 80 cm and then decreases to 50 cm 10 m away along the strike; dark gray calcareous siltstone in upper 5 cm; signatures of submarine erosion at the top
				10	4	Conglomerate of rounded pebbles, up to 10 cm (no more than 5 %), in a gravel and sandstone matrix; sporadic angular carbonate clasts and fine subrounded pebbles; several pulses of pebble deposition; traces of gullies filled by coarse material, 40 cm deep and up to several meters wide; brachiopods and crinoids in coarse clasts; sporadic randomly oriented 10 cm long and 1 cm thick fragments of fine to coarse sandstone layers
				9	1.60	Limestone (calcarenite and calcirudite): detrital, dark gray, gravel size in lower part and fine to medium sand size in upper part
				8	1.40	Limestone (calcarenite and calcirudite): detrital, dark gray, gravel size in lower part and fine to medium sand size in upper part; corals
				7	1.40	Limestone (calcarenite and calcirudite): detrital, dark gray, gravel size in lower part and fine to medium sand size in upper part
				6	0.80	Limestone (calcarenite and calcirudite): detrital, dark gray, gravel size in lower part and fine to medium sand size in upper part
				5	1.10	Limestone (calcarenite): detrital, dark gray, massive, sand size; grades to gray, fine, moderately sorted subrounded sandstone in upper part
				4	1.30	Limestone (calcarenite): detrital, dark gray, massive, sand size, slightly recrystallized
				3	1	Sandstone: calcareous, gray, massive, medium, moderately sorted, subrounded in lower 15–20 cm; gravel conglomerate, with clasts of pebbels and randomly oriented 0.5 cm thick and 5–7 cm long fragments of layers, lying upsection on a slightly wavy surface; number of clasts decreasing gradually from base to top; sandstone at the top similar to that from the base
				2	0.45–0.50	Limestone (calcarenite): organic detrital, dark gray, massive, medium, slightly recrystallized in lower 10 cm; 5 cm long and 1 cm thick fragments of coarse sandstone layers quasi parallel to bedding; brachiopods; clasts fining from base to top; fine and medium highly calcareous sandstone in upper part, with up to 3 cm deep wavy bedding, enclosing 5 cm long and 2 cm wide clasts of black limestone
				1	1	Sandstone: calcareous, gray, snuffy to light gray, fine and medium, moderately sorted, subrounded, on an eroded surface; flaggy (to 10 cm); tabulates; foraminifera detected in thin sections

(*continued on next page*)

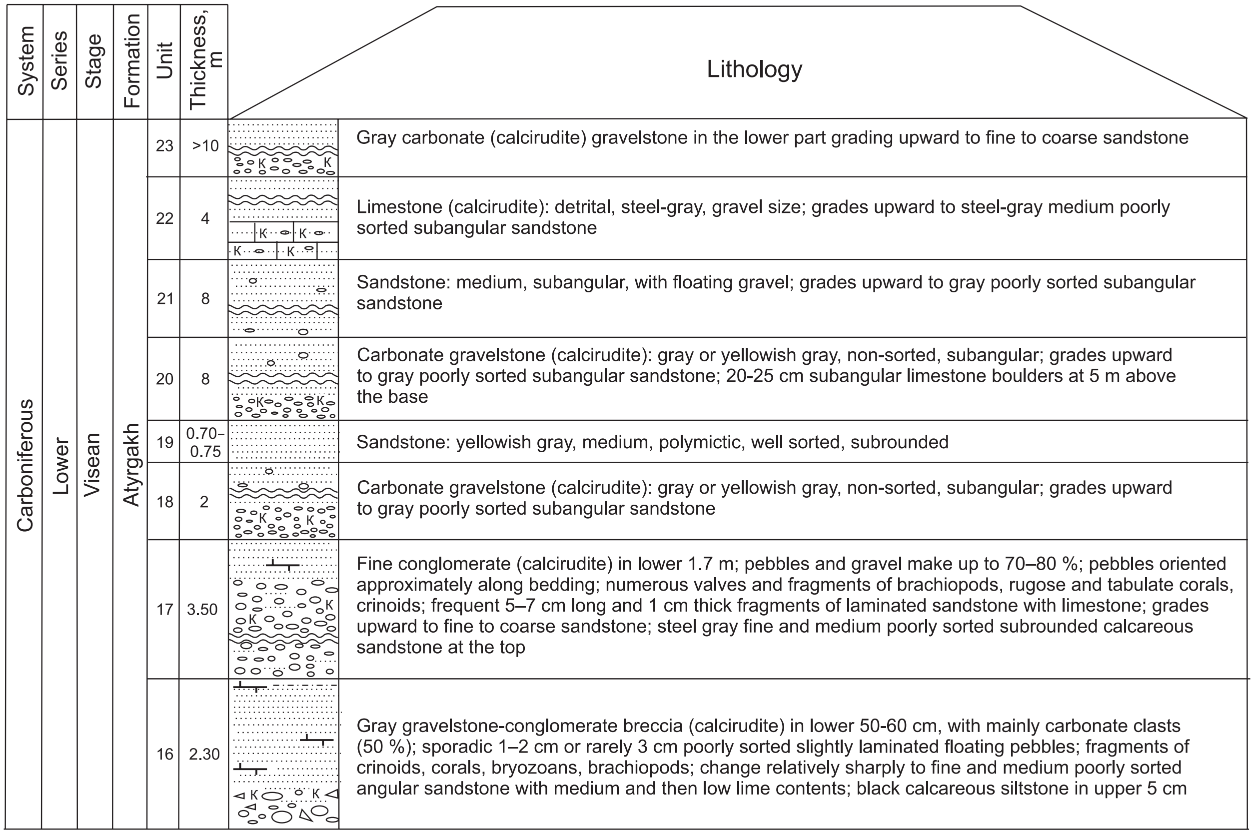


Fig. 7. Lithology of the Krestyakh conglomerate, upper strata (S-1876, head of Bykovsky Channel, 72°24’10” N; 126°46’40” E). Legend same as in Fig. 4.

Lithofacies 3 (upper quarter of section S-1871): 0.6 to 3.0 m thick layers of gray medium to coarse highly calcareous sandstones with wavy bedding and uniform thicknesses along the strike, and with lenses of black siltstone, which were deposited at weak water circulation.

Lithofacies 4 (second quarter of section S-1871): irregularly alternated lithologically diverse layers of conglomerate, gravel, fine to coarse sandstone , siltstone, and mudstone, all calcareous, with variable thicknesses from 0.4 to 1.0 m; sporadic fragments of underlying poorly lithified sandstone layers disturbed by debris flows; local rolling structures in sand-size rocks, possibly, resulting from sliding down steep sides of submarine canyons or from the edges to the bottom of canyons.

Lithofacies 5 (lower and upper parts of section S-1872 and third quarter of section S-1871): quasi-rhythmic detrital calcarenite and calcirudite limestones, calcareous sandstone, gravel, conglomerate, and breccia-conglomerate; fragments of underlying poorly lithified sandstone layers disturbed by debris flows in the sides of submarine gully-like channels; layers of different lithologies vary in thickness along the strike from 1.5 to 3.0 m; erosion pockets filled with coarse rocks deeply cut into the underlying beds.

Lithofacies 6 (section S-1872): single 1.2 m thick layer of gray and black siliceous mudstone (till chert) in the middle of the section; black chert pebbles (flat layer fragments?) in the lower and upper strata; no fauna. The presence of chert pebbles indicates that the lithofacies had a broader occurrence in the past. Lithofacies 6 builds almost the whole stratotype section of the Atyrdakh Formation. The presence of chert rules out shallow-water origin of the sediments. No organic remnants have been found in specially treated chert samples. The lack of fossils in the Krestyakh chert was explained (Bulgakova, 1967) by a volcanic (hyaloclastic) origin. Another possible explanation for the lack of common Late Paleozoic radiolarian plankton and benthic sponges from the siliceous sediments of the basin is that the silica skeletons became completely dissolved at depths below 250–350 m (Sennikov et al., 2011). Silica tests of shelf radiolarians can sink slowly to the basin bottom and rapidly dissolve in seawater which is silica-undersaturated near the surface.

Lithofacies 7 (upper section S-1876 and lower section S-1878): massive medium-grained sandstone with floating gravel or pebbles. Layer thicknesses are relatively uniform along the strike and vary within 8.0–10.0 m. The rocks of lithofacies 7 coexist with those of lithofacies 8 and make up jointly the terminal part of the composite Krestyakh conglomerate section.

Lithofacies 8 (upper part of section S-1878 and section S-1883): boulder- or less often pebble-size breccia conglom-

System	Series	Stage	Formation	Unit	Thickness, m	Lithology
Carboniferous	Lower	Visean	Tiksi	(1)	>20	Interbedded black platy-flaggy (3 cm to 10 cm) siltstone and mudstone, less often fine well sorted sandstone
						Fault
			Atyrgakh	6	>30	Breccia-conglomerate in 1.5–2 m deep erosion pockets at base, with angular (up to 60 cm) and more abundant rounded non sorted (up to 30 cm) carbonate clasts (80 %); three or four submarine channels, 5–7 to 8–10 m deep, superposed one upon another, filled with sand and coarse clastic material; 0.5–1 m thick lenses of dark gray massive calcareous gravel and sandstone between the channels; tabulate corals
				5	0.3–2.5	Gravelstone breccia-conglomerate: calcareous, gray or snuffy gray lying on a wavy surface with up to 1 m deep erosion pockets; 1.5 m long and 20–30 cm thick fragments of sandstone layers roughly parallel to bedding; 10 m downstream the Lena River: 10 cm thick dark gray calcareous siltstone-mudstone in upper part; Bed 5 has up to 80 cm deep erosion pockets cut through Bed 4 and thus lies immediately over Bed 3; with 80 cm deep erosion sand pockets at base of Bed 5 cut into Bed 3; gray or yellowish gray gravelstone with 5–7 cm round subangular floating pebbles in lower part, locally grading to detrital calcarenite limestone; pebbles (50 %) become more numerous upsection; 50 cm long and up to 3 cm thick fragments of yellowish gray fine and medium calcareous sandstone layers; tabulate and rugose corals, crinoids
				4	1.5–2.8	Gravelstone: polymictic, dark snuffy gray, massive, fine to coarse; grades into medium calcareous sandstone and calcarenite limestone; clasts of rugose corals and brachiopods
				3	1.5	Sandstone: calcareous, snuffy light gray or dark gray, polymictic, massive, medium, well sorted, subangular
				2	~3	Gravelstone, coarse, with floating limestone pebbles, clasts of corals, and 10–15 cm long and 1–1.5 cm thick fragments of fine-medium sandstone layers, lying on a slightly wavy surface in 30–80 cm erosion pockets cut into Bed 1; 10–20 cm floating cobbles 1 m above the base; gravel conglomerate with up to 30 cm cobbles and boulders of gray limestone (70 %) at the base, found 20 m upstream the Lena River; isolated up to 1 m long lenses of yellowish gray calcareous gravestone; black calcareous siltstone-mudstone in upper 1 to 5 cm; crinoids, brachiopods, bivalves, tabulate and rugose corals
				1	3	Limestone (calcirudite): detrital, crystallized, coarse to gravel size; grades into gray calcareous gravelstone-sandstone along strike; sandstone is yellow or dirty yellow on weathered surfaces and gray or dark gray on cleavage planes; sporadic subangular limestone cobbles (10–15 cm); yellow or gray massive polymictic sandstone, with vague 1–2 cm bedding, in upper part; 15 cm long and 1–2 cm thick bedding-parallel flattened carbonate concretions at the top
						Fault
				2	15–25	Conglomerate material filling a large (at least 170–180 m wide) submarine canyon cut into Bed 1, varying in depth from 15 m at the side exposed in the outcrop to 25 m in the axis; conglomerate is composed of poorly sorted rounded and subrounded, rarely angular, boulders (50–60 % in lower part to 10 % in upper part), cobbles and pebbles (20–30 % in lower part to 60–80 % in middle and upper parts), from 50 cm to 10 cm in size, composed of gray or dark gray detrital and oolitic limestone, gray medium calcareous sandstone; sporadic 50 cm long and 10 cm thick fragments of fine sandstone, oriented quasi parallel to lamination
				1	20–25	Sandstone: gray, massive, coarse and medium; floating pebbles

Fig. 8. Lithology of the Krestyakh conglomerate, composite top strata (S-1878 below and S-1883 above, right bank of Lena River upstream of Bykovsky Channel; S-1878: 72°23′15″ N; 126°44′05″ E; S-1883: 72°23′05″ N; 126°44′25″). Legend same as in Fig. 4.

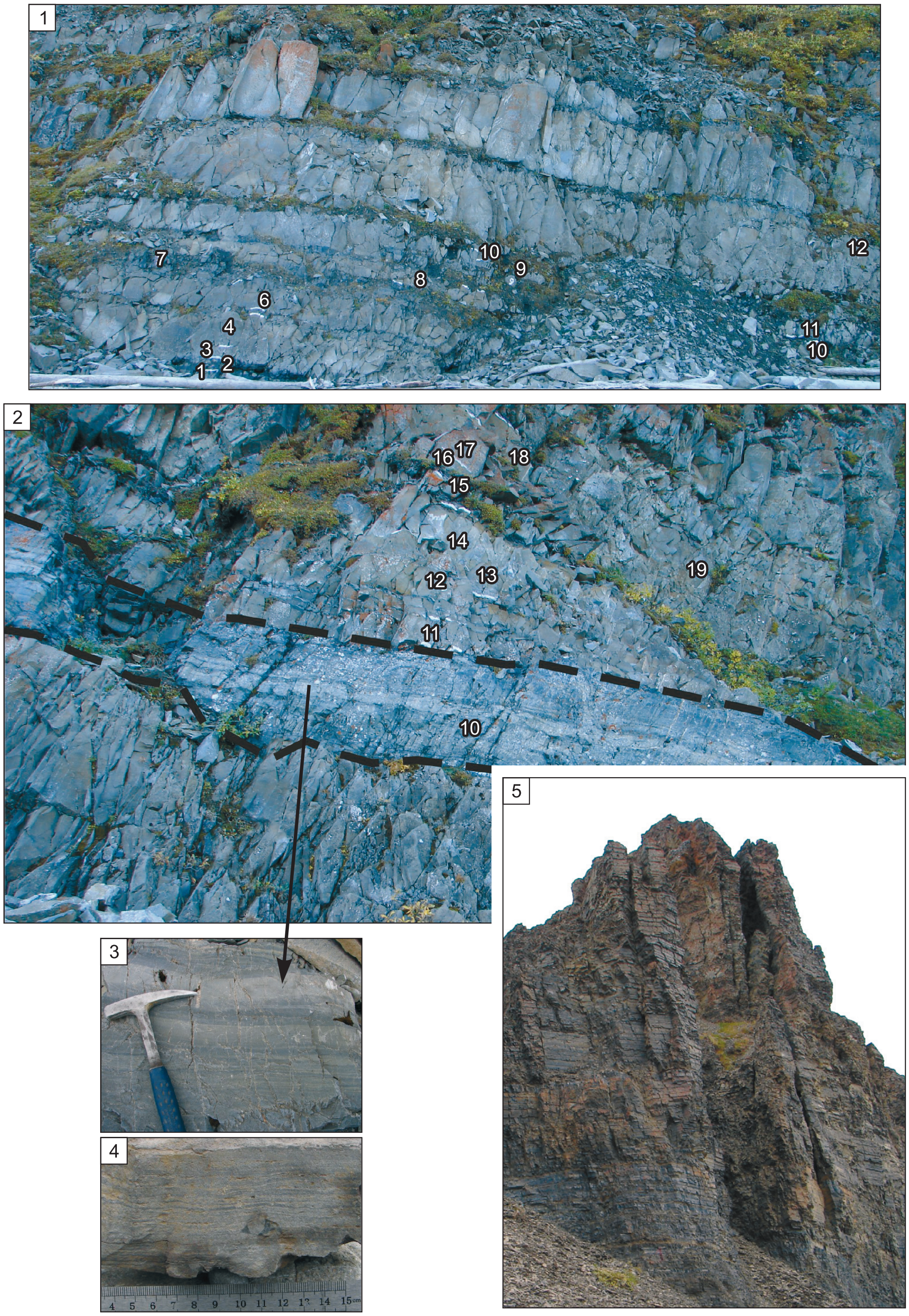


Fig. 9. Krestyakh conglomerate sections in the Lena right bank, head of Bykovsky Channel, near Sokol station: general view. Plate 1: section S-1870; Plate 2: section S-1872; Plate 3: chert in section S-1872; Plate 4: siliceous mudstone in the Atyrdakh Formation stratotype section near Taba-Bastakkh-Yurege creek mouth. Hereafter dash line delineates base of a bedset; dotted lines are bed boundaries.

erates with numerous fragments of underlying poorly lithified layers disturbed by debris flows. Lithologically heterogeneous sediments varying in thicknesses from 3.0 to 30.0 m.

The rock clasts are subrounded in lithofacies 1 and 2 and subangular in the others; all are poorly or moderately sorted.

According to our data, which confirm the previous estimates (Bulgakova, 1967), rocks of different grain sizes in the Krestyakh sections are lithologically diverse: mainly carbonates (70–80%), calcareous clastics (10–15%), quartzites (3–5%), and igneous rocks (1–2%) in pebbles, cobbles,

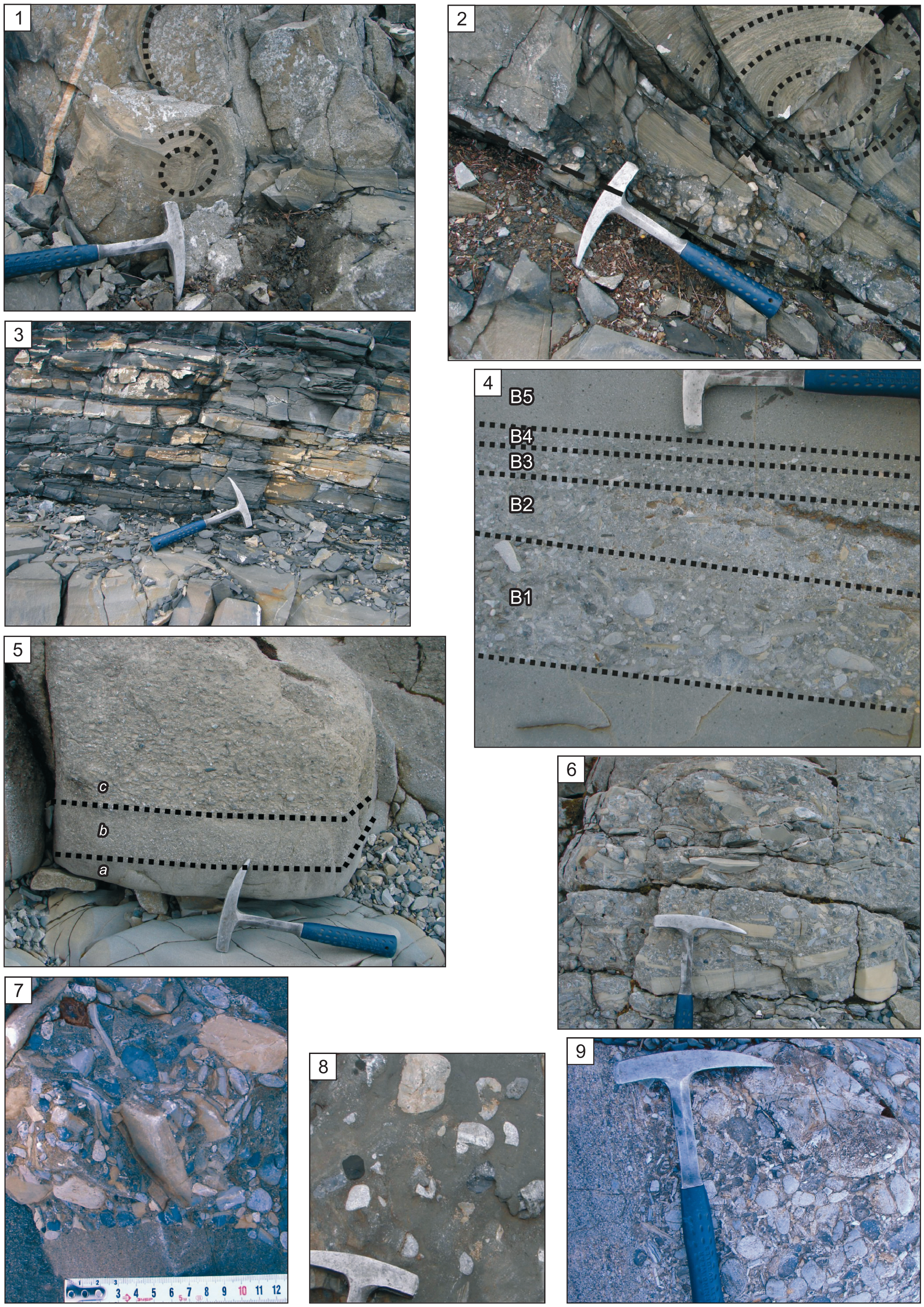


Fig. 10. Sedimentary structures. Plates 1, 2: rolls of unlithified sediments slid from the side of a submarine channel; Plate 3: alternating thin layers of black siltstone and sandstone in an isolated block, possibly, lower Tiksi Formation lying over gray sandstone of the Krestyakh conglomerate; Plate 4: a cyclic feature (B1-B5) produced by a slow debris flow; Plate 5: three-component structure composed of sandstone (*a*), fine gravel (*b*), and coarse gravel (*c*), produced by a rapid debris flow; Plate 6: angular fragments of disintegrated unlithified layers slid down low-angle sides of a submarine channel; Plate 7: chaotic breccia conglomerate; Plate 8: subangular unsorted floating pebbles in sandstone; Plate 9: a large redeposited boulder in conglomerate consisting of subangular mainly carbonate pebbles similar to nearby limestone pebbles.

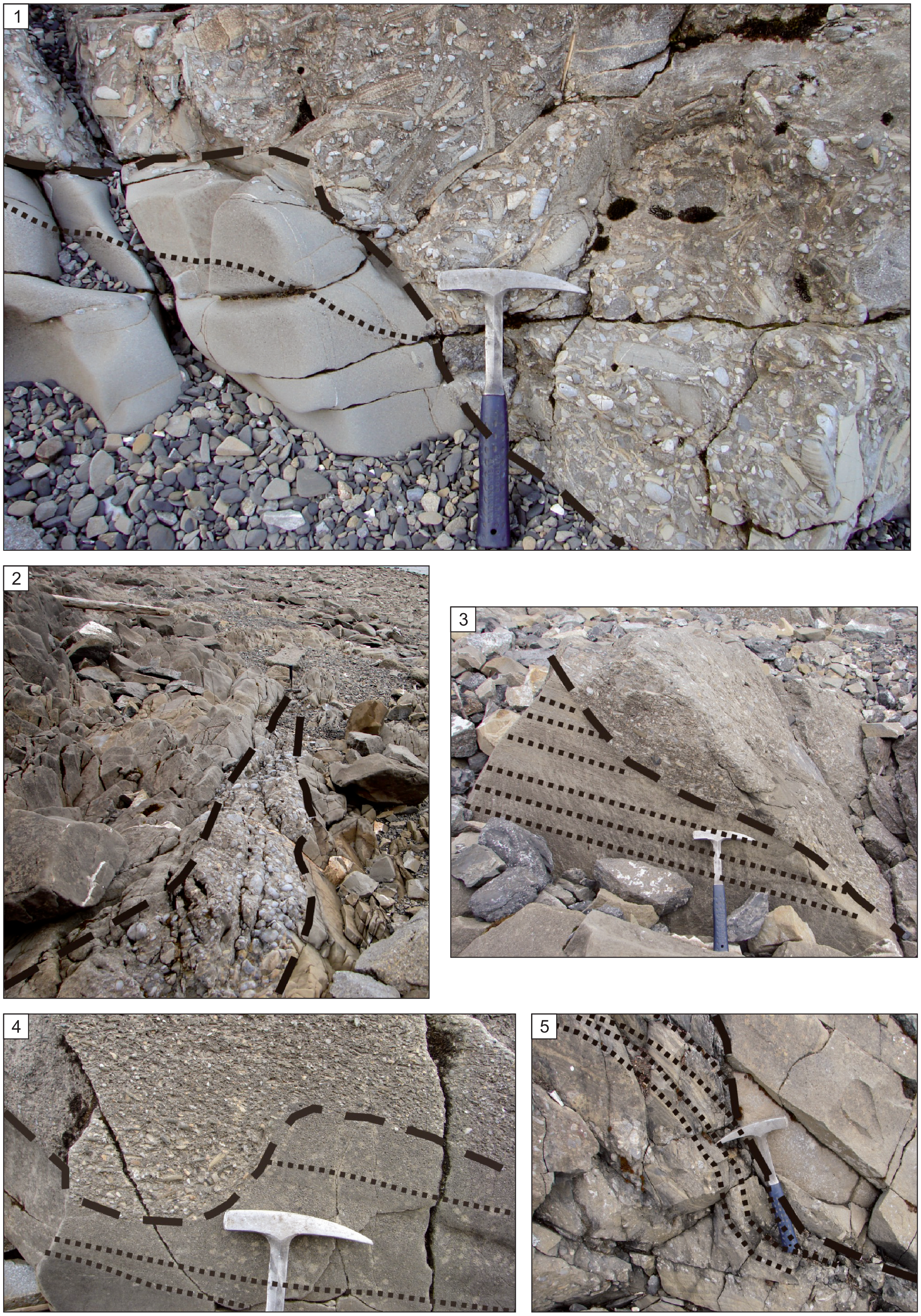


Fig. 11. Erosional features scoured by debris flows in bottoms of submarine canyons (channels). Plate 1: two beds meeting in the side of a submarine canyon; Plate 2: a conglomerate bed pinching out on a low-angle side of a submarine channel; Plates 3, 5: pockets cut into underlying beds; Plate 4: quasi-parallel bedding in two eroded beds with pockets cut into the underlying beds.

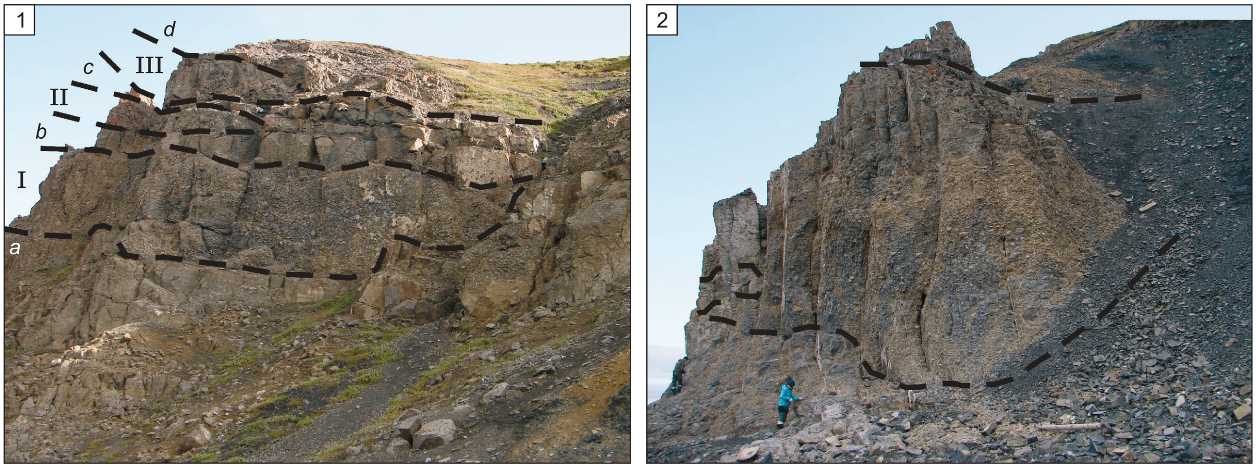


Fig. 12. Fill of large submarine canyons (channels). Plate 1: repeated inputs of coarse (I, II, III) and sand-size (*a*, *b*, *c*, *d*) material filling a large submarine canyon; Plate 2: coarse material filling a large submarine canyon.

and boulders; carbonate (50–60%), quartz (15–20%), clastic (10–15%), feldspar (5–10%), chert (3–5%), and igneous (1–2%) compositions in gravel and sand-size rocks.

The sedimentary structures observed in different beds of the Krestyakh conglomerate sections include graded bedding; traces of submarine erosion by debris flows; sediments that fill depressed parts of submarine canyons and channels; broken and dragged fragments of lithified layered rocks, which are either aligned and parallel to the bed base or are chaotically oriented; contorted bedding and recumbent folds; submarine gravity slides; rolled up or twisted slid sediments; flat-bottomed submarine channels and canyons. Some structures were previously attributed to wave action (Bulgakova, 1967).

Some beds were deposited over uneroded surfaces and have a smooth base, which is evidence of background rather than pulse-like clastic deposition. Some other beds display signatures of four successive processes: (i) erosion by debris flows and formation of wavy surfaces and pockets in underlying beds; (ii) deposition of transported clastic material; (iii) insertion of clasts from eroded steep sides of canyons or channels into unconsolidates rocks; (iv) contortion and rolling of poorly lithified sediments subject to sliding down the canyon sides.

BIOSTRATIGRAPHY

The Atyrdakh Formation laminated calcareous siltstone and sandstone (including the Krestyakh conglomerate sections) contain diverse faunas (Fig. 3). Brachiopod taxa are especially numerous and frequent, with the species *Camarotoechia pleurodon* (Phill.), *Plicafera plicatilis* (Sow.), *Avonia coctata* (Sok.), *Brachithyris subcardiiformis* Hall, *Br. rapivnensis* Besn., *Fluctaria* ex gr. *undata* (Defr.), *Leptogonia* cf. *analoga* (Phillips), *Torynifer* cf. *pseudolineatus* (Hall), *Scutepustula* aff. *scutelata* (Balash.), *Neospirifer* cf. *kovalevi* Abr. et Grig., *Neospirifer* ? cf. *sinuatoplicatus* Mir., *Crassispirifer* cf. *rhomboidalis* Abr. et Grig., *Buxtonia* cf. *rimmae* Abr. et Grig., *Syringothyris* cf. *mutabile* Abr. et Grig., "*Lingula*" cf. *squamiformis* Phill., "*Lingula*" cf. *mytilloides* Sow., *Orbiculoidea* sp. Foraminifera make another group of high taxonomic diversity: *Erlandia minor* (Raus.), *Endothyra prisca* Raus. et Reitl., *End. similis* Raus. et Reitl., *End. paraprisca* Schlyk., *End. freguentata* Gan., *End. inflate* Lip., *Endothyra* ex gr. *omphalota* Raus. et Reitl., *Archaediscus krestovnikovi Raus., Brunsia pilchra* Mikh., *B. irregularis* (Moell.), *Planoarchaediscus spirillinoides* (Raus.), *Globoendothyra pseudoglobus* Reitl., *Endostaffella asymmetrica* Ros., *Tetrataxis paraminima* Viss. Conodonts in the Atyrdakh Formation appear as few taxa of *Lenathodus bakharevi* Izokh. The coral species are restricted to *Pseudoroemeripora pulchra* Dub., *Ps. lenaica* Koksharskaya tabulates and *Lithostrotion portlocki* Edw., *Lithostrotion* cf. *acolumellata* Dobrol., and *Paleostilia murchisoni* Edw. et Haime rugoses (Lapina, 1962; Bogush et al., 1965; Koksharskaya, 1965; Andrianov, 1985; Abramov and Grigorieva, 1986; Klets, 2005; Kutygin, 2009; Yazikov and Sobolev, 2013; Geological Map, 2014; Yazikov et al., 2015; Izokh and Yazikov, 2017). The Krestyakh conglomerate contains also *Goniatites americanus* Gordon ammonoids (Abramov and Grigorieva, 1986) (see below).

In addition to the autochthonous faunas, the Krestyakh conglomerate sections bear redeposited Ordovician, Silurian, and Devonian brachiopods and corals known since long ago (Mezhvilk, 1958; Bogush et al., 1965; Lungersgauzen and Solomina, 1966; Geological Map, 2014).

Our studies have provided new biostratigraphic constraints (Fig. 13). According to recent views, the species *Archaediscus krestovnikovi* Raus. found in the foraminifera assemblage from the middle and upper parts of the Krestyakh conglomerate south of the Krestyakh Cape and in the upper Atyrdakh Formation near the Bastakh River mouth (Bogush et al., 1965) is an index species of the respective Arch. kre-

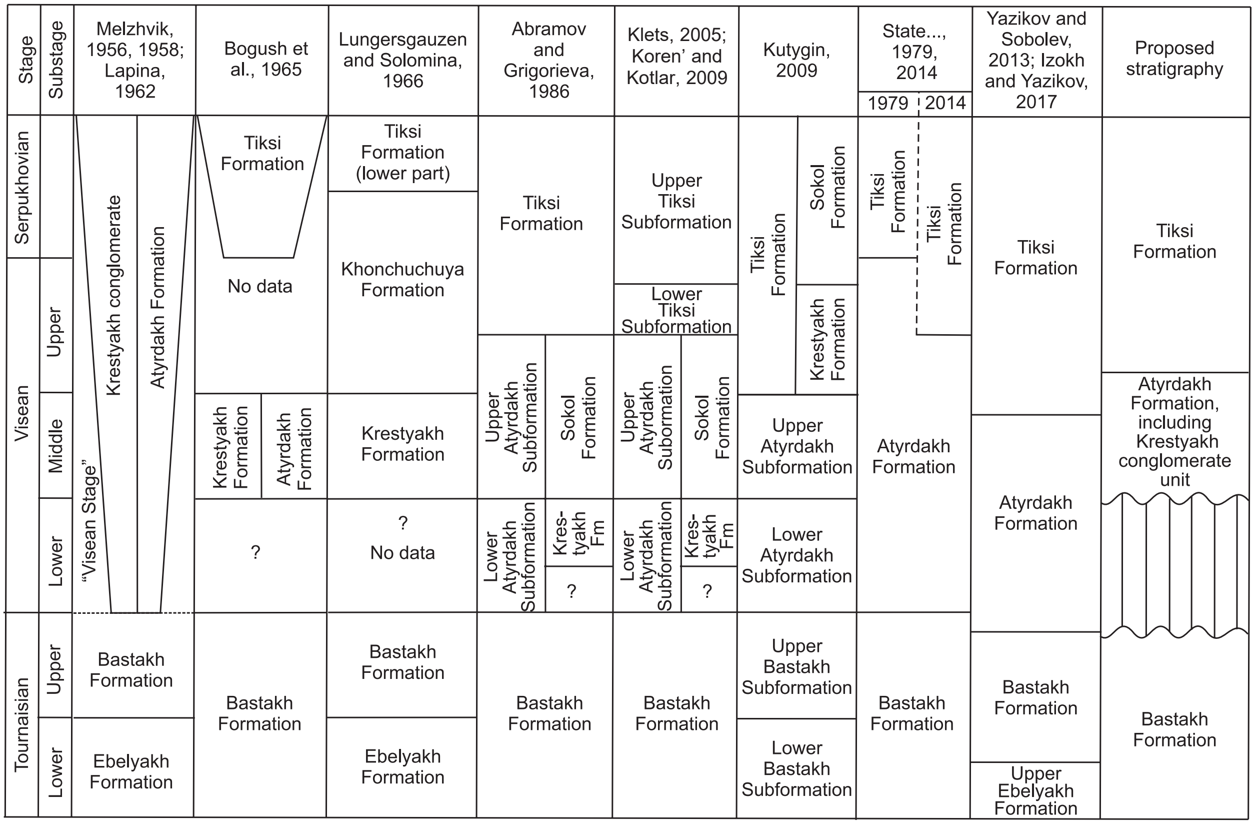


Fig. 13. Different models of Lower Cambrian stratigraphy of Northern Kharaulakh.

stovnikovi foraminifera zone (Koren', 2006) in many geological provinces of Russia: Timan-Pechora, Northern and Polar Urals, Eastern Urals, and Novaya Zemlya. The zone Arch. krestovnikovi corresponds to the lower half of the Upper Visean (if the stages are divided into two substages of upper/lower). Since the *Arch. krestovnikovi* Raus. species has a global extent, the standard foraminifera zone of Endothyranopsis compressa – Arch. krestovnikovi was included into the International Time Scale (Gradstein et al., 2012) in the middle of the Visean. In the stratigraphy of China (Wang et al., 2019), the base of the Arch. krestovnikovi zone is located slightly above the base of the Goniatites standard ammonoid genus zone, while its top falls in the middle of the upper half of the Goniatites zone. The International Time Scale (Gradstein et al., 2012) shows the Beyrichoceras/Goniatites standard ammonoid genus zone in the middle of the Visean. Representatives of *Goniatites Haan* (*G. americanus* Gordon) ammonoids were also found in the Krestyakh conglomerate of the Krestyakh Cape (collected by Prof. P. Sofronitsky, identified by M. Bogoslovskaya), as reported by Abramov and Grigorieva (1986). However, no ammonoids have been found recently in the Krestyakh conglomerate section. Summing up the available data, the stratigraphy of the Krestyakh conglomerate can be constrained as the middle and lower parts of the Upper Visean. Ammoinoids of the Beyrichoceras/Goniatites zone (Yazikov and Sobolev, 2013) and *Arch. krestovnikovi* Raus. foraminifera (Klets, 2005) are present also in the Tiksi Formation that lies over the Atyrdakh Formation. This fact suggests rapid deposition of the Krestyakh conglomerate composite section, within 1–2 myr: less than one ammonoid genus zone and less than one foraminifera zone.

Note that younger Serpukhovian ammonoids *Neoglyphioceras septentrionale* Andrianov were reported from the Tiksi Formation in the right bank of the Lena, 21 km south-southeast of Krestyakh Cape (Andrianov, 1985; Kutygin, 2009).

We found numerous tabulates, scarce rugose corals and bryozoans, few (?) ammonoids (in talus), frequent brachiopods, and numerous crinoids in the conglomerate matrix at the Krestyakh locality and revealed foraminifera in thin sections. Taphonomic analysis led to a number of inferences. The presence of marine fauna assemblages in all sampled sections of the Krestyakh conglomerate records deposition in a marine environment, whereas the mainly random orientations of the fossils with respect to bedding indicate high wave energy in the paleobasin, where near-bottom sediments were constantly moving during and after the deposition. On the other hand, there are signatures of relatively quiescent time intervals, without turbation by debris flows, which allowed stable growth of crinoids and corals. They are, namely, good preservation of whole crinoid stems as evidence of burial near the habitats; similar orientations about those of lifetime in colonies of tabulate corals; and growth of a tabulate coral colony on a boulder. Such signatures were reported from the Krestyakh conglomerate sections in early publications as well (Bulgakova, 1967).

Tabulate corals demonstrate the best preservation among all autochthonous fauna groups found in the matrix of the Krestyakh conglomerates. The identified taxa include (Figs. 14, 15): *Pseudoroemeripora lenaica* Koksharskaja (S-1871-9; S-1876-11), *Ps. pulchra* Dubatolov (C-1876-15), *Pseudoroemeripora* sp. (S-1872-2), *Multithecopora* sp. (S-1876-1; S-1883-2), *Neomultithecopora* sp. (S-1883-6),

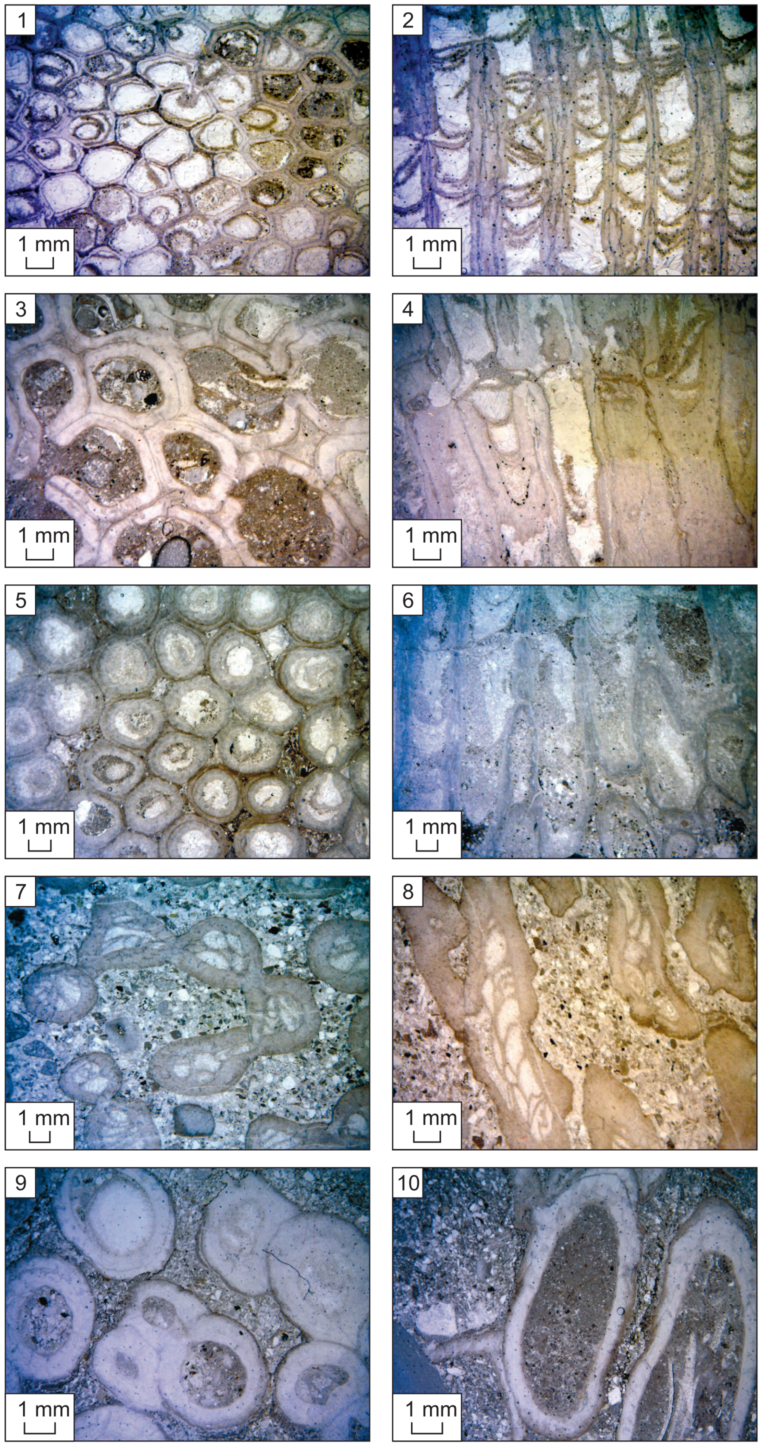


Fig. 14. Characteristic tabulate corals from the matrix of fine and coarse Krestyakh conglomerate. Plates 1, 2: *Pseudoroemiropora pulchra* Dubatolov, view along and across, point S-1876-11; Plates 3, 4: *Ps. lenaica* Koksharskaya, view along and across, point S-1871-9; Plates 5, 6: *Pseudoroemiropora* sp., view along and across, point S-1872-2; Plates 7, 8: *Montanella* sp., view along and across, point S-1876-8; Plates 9, 10: *Multithecopora* sp., view along and across, point S-1883-2.

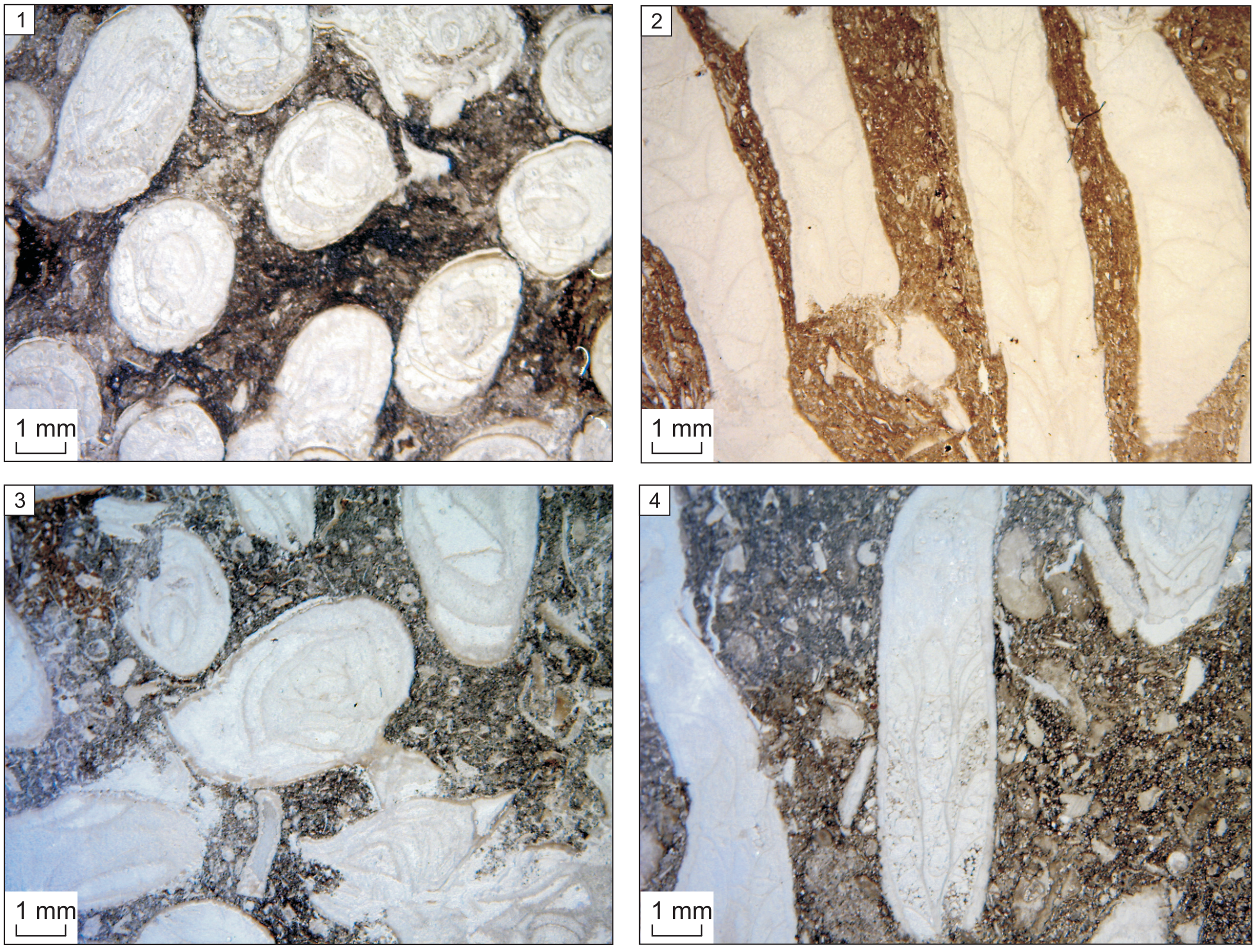


Fig. 15. Tabulate corals from the lower Bastakh Formation stratotype section. Plates 1, 2: *Syringopora rudyi* Nelson, view along and across, point S-1882; Plates 3, 4: *Neosyringopora* sp., view along and across, point S-1880.

Roemerolites sp. (S-1876-8; S-1883-6), *Montanella* sp. (S-1876-8), *Michelinia* sp. (S-1871-11; S-1872-3); for relation to specific beds see Figs. 5–8. We revealed a tabulate assemblage of a different facies in first five units of the Y-123 section (Izokh and Yazikov, 2017) at a stratotype locality of the Bastakh Formation (near the Taba-Bastakh creek mouth), by means of comparative analysis of samples we collected. The Bastakh Formation massive and laminated limestones contain *Syringopora rudyi* Nelson (C-1882), *Syr. bella* Tchudinova (S-1881), *Neosyringopora* sp. (S-1880), *?Syringocystis* sp. (S-1881) and *Michelinia* sp. (S-1880, S-1881). The latter tabulate taxon, which is widespread in the Bastakh Formation, occurs also in the conglomerate matrix in the lower one third of the Krestyakh sections.

DISCUSSION

Stratigraphic nomenclature. The validity of the Krestyakh Formation remains subject to discussions. Kutygin (2009) distinguished the North Verkhoyansk regional facies zone of the Lower Carboniferous sediments, divided into the Kharaulakh and Krestyakh subzones consisting of the Bastakh, Atyrdakh, and Tiksi formations in the Kharaulakh area and the Krestyakh and Sokol formations at the source of the Bykovsky Channel near the Sokol station. The Krestyakh and Sokol Formations were suggested to correlate, respectively, with the lower strata and the remaining part of the Tiksi Formation (Kutygin, 2009).

However, the Krestyakh conglomerate sections are fragmentary and lack direct evidence of stratigraphic relations with the underlying rocks, and thus can be rather a local stratigraphic unit (Body). This classification complies with the Stratigraphic Code of Russia (Zhamoida, 2019; article V.12) concerning geological data of this kind. Two editions of the Geological Map (1979, 2014) present the Krestyakh conglomerate as outcrops of the Atyrdakh Formation, which extend from its stratopyte section in the Lena right bank, near the mouths of the Taba-Bastakh-Yurege and Kasym creeks, to the Krestyakh Cape.

Assuming that the Krestyakh unit is invalid as a separate formation, it is reasonable to check the validity of the Sokol

Formation (Abramov and Grigorieva, 1986; Klets, 2005; Kutygin, 2009) distinguished between the Krestyakh and Tiksi formations near the Sokol station south of the Krestyakh Cape (Kovalevskii, 1991). According to our new data, no specific sections that would be markedly different from the lithologcally diverse Krestyakh clastic sediments or from the dark color facially uniform Tiksi Formation rocks exist at the locality near the Sokol station. The boundary between the two units may be exposed in a small isolated outcrop. The Stratigraphic Code (Zhamoida, 2019) does not recommend distinguishing new formations at the facies transitions between local stratigraphic units (article V.9, advice 9A) if their indicators are observed in different parts of a specific section. This is the case of deposits described by Abramov and Grigorieva (1986); thus, the Sokol Formation should rather be assigned to the Krestyakh unit according to our data.

The invaliditiy of the Krestyakh and Sokol formations casts doubt on the existence of the separate Krestyakh facies subzone (Kutygin, 2009) in the North Verkhoyansk facies zone.

Paleogeographic constraints and genesis of the Krestyakh conglomerate. The clastic material of the Krestyakh conglomerate facies was possibly transported under the water southward (in the present frame of reference) from a collapsed uplift. As hypothesized by Lungersgauzen and Solomina (1966), Early Visean tectonic motions in the Laptev shelf north of the Lena Delta produced a large uplift with Silurian-Devonian sediments on the top. The existence of a large isolated piece of land with an elevated plain, a plateau, and highlands between Kotelny Island in the New Siberian archipelago and the Laptev Sea coast was also inferred in large-scale reconstructions of the Devonian and Carboniferous paleogeography (Matukhin, 1991). In the Late Devonian and Early Carboniferous, it may have been a source of clastic inputs into Early Carboniferous basins of the Northern Kharaulakh and into coeval basins of the New Siberian archipelago (Matukhin, 1991). The transport of clastic material to the two basins was in the north to south and south to northeast directions, respectively (in the present frame of reference). Another Devonian-Carboniferous peninsular land source from the side of the Siberian craton was reconstructed (Matukhin, 1991) at the northeastern end of Angarida, a Late Paleozoic continent (Klets, 2005). The clastic transport of that provenance was presumably (Matukhin, 1991) into the Northern Kharaulakh Early Carboniferous basins from the southwest (in the present reference frame).

The origin of the Krestyakh conglomerate was interpreted in different ways. The multiple interpretations are: glacial deposits or tillites (Gusev and Fleishman, 1938); deposits shed to the foot of mountains and flooded by the sea (Mezhvilk, 1956); coarse deposits that formed syngenetically by wave erosion of local offshore clastic-carbonate shoals during the Bastakh and Atyrdakh deposition (Lapina, 1962); submarine seismites, including debris flows and turbidites, or pulse-like inputs of coarse clastics as a result of seismic events (Bulgakova, 1967); coastal rock slides (Bulgakova, 1967); submarine landslides and rock slides (Bogush et al., 1965); a shallow apron of coarse deposits along an uplifted land block subject to erosion (Geological Map, 2014); offshore deposits shallower than the carbonate compensation depth (CCD) of 4.5–5.0 km, judging by the presence of chert and minor amounts of fine-grained material (Bulgakova, 1976); molasse (Mezhvilk, 1958); littoral and beach deposits (for the lower part of the Krestyakh conglomerate composite section). On the other hand, the whole Atyrdakh Formation of clastic sediments (including the Krestyakh conglomerate) was often identified as a preceding or an early phase of the Upper Paleozoic Verkhoyansk clastic deposition (Bulgakova, 1967; Bulgakova et al., 1969; Geological Map, 1979; Klets, 2005; Kutygin, 2009).

The results of this study allow us to interpret the Krestyakh conglomerate as debrites: deposits of debris flows which scour and fill long submarine canyons or channels on the sea bottom.

The Lower Carboniferous stratigraphic range encompasses the Middle Tournaisian (Lower Alum Shale), Late Tournaisian, Middle Visean, Visean-Serpukhovian, and Serpukhovian-Bashkirian (Early Namurian Event) global events (Walliser, 1996; Koren' et al., 2000). In the Siberian regional stratigraphy, the Tournaisian-Visean boundary was marked by the large-scale Shcheglovo biotic-depositional event (Klets, 2005) in the beginning of the Verkhoyansk clastic deposition in Carboniferous shelf seas around the Late Paleozoic continent of Angarida. The Krestyakh conglomerate is a typical lithological marker of the early phase of this event.

Lower-Middle Carboniferous sediments occur in several areas of the landmass surroundings of the Northern Kharaulakh. Carboniferous outcrops in the Kyutyungde basin of the Siberian craton, in the middle reaches of the Olenek River, are the most proximal (less than 250 km) to the Northern Kharaulakh outcrop of Carboniferous deposits. The Kyutyungde stratigraphic units differ in lithology and thickness from the coeval Northern Kharaulakh units. The Kyutyungde Lower-Middle Carboniferous sediments comprise the Nuucha-Yurege, Toluopka, Kysyl-Khaya, and Udogan formations composed of basal conglomerate, dolomitic sandstone, dolomite, dolomitic limestone, calcareous-dolomitic siltstone, and mudstone, ~200 m of total thickness (Matukhin, 1991; Kutygin, 2009).

Lower-Middle Carboniferous sediments occur also in the Uel-Siktyakh facies subzone of the Central Verkhoyansk area located 500 km far from Northern Kharaulakh. The Carboniferous strata of this facies lie over Cambrian carbonates and are composed of limestone with siliceous concretions in the lower section and boulder-pebble and gravel-pebble conglomerates in the upper part, with clasts of Cambrian limestone (Kutygin, 2009). The limestone and conglomerate units of the Central Verkhoyansk section correlate, respectively, with the Bastakh Formation and the Krestyakh conglomerate of Northern Kharaulakh. The Lower-Middle Carboniferous deposition in the Central Verkhoyansk area produced also the Orulgan facies subzone (Bulgakova et al., 1969; Klets, 2005; Kutygin, 2009), with clastic-carbonate and carbonate beds in the lower strata overlain by Agakukan and Bylykat formations that contain abundant intraformation conglomerates. The available data on the Kyutyungde, Uel-Siktyakh, and Orulgan facies of Lower and Middle Carboniferous coarse sediments show that the Verkhoyansk clastic deposition occupied thousands of square kilometers.

The sea depths and offshore distances of the Krestyakh conglomerate (Atyrdakh Formation) deposition can be tentatively estimated from the respective depths for the Bastakh Formation below and the Tiksi Formation above. The Bastakh Formation carbonates were deposited in relatively shallow offshore regions (Geological Map, 2014). The Atyrdakh Formation, which lies over the Bastakh Formation without visible unconformity in the right bank of the Lena near the mouths of the Taba-Bastakh-Yurege and Kasym creeks (Yazikov and Sobolev, 2013; Yazikov et al., 2015), contains deepwater siliceous spongolites, like the Krestyakh conglomerate (Izokh and Yazikov, 2017). The conformably overlying Tiksi Formation (Klets, 2005; Kutygin, 2009; Yazikov and Sobolev, 2013; Yazikov et al., 2015) consists of rhythmical turbidite-like sediments deposited on a continental slope or in an outer shelf. The Tiksi Formation siltstone and limestone, with sandstone layers, often contain pyrite crystals (Geological Map, 2014). The presence of pyrite indicates offshore deposition at sea depths exceeding 100–150 m. This inference is consistent with other features of the Tiksi Formation, such as a continuous sedimentary structure over a large area from the lower Lena to the Tiksi Bay in the Laptev Sea; dark color of fine-grained rocks; absence of wave activity traces; scarce faunas in the lower part. Thus, the offshore origin appears a reasonable hypothesis for most of the Atyrdakh sections, including the Krestyakh conglomerate, given the stratigraphic succession of the three formations.

The paleobasin depths during the Krestyakh conglomerate deposition within the Atyrdakh Formation should be estimated separately for the lower, middle, and upper parts of the section. Correspondingly, the depth intervals may be approximately 150–200 m (outer shelf) for the lower strata and 200–350 m (distal outer shelf) for the middle of the section; the upper strata were deposited at depths from 50–100 m to 150–250 m that correspond, respectively, to the top and base of submarine erosional canyons.

Further constraints may be 150–250 m and 150–200 m for the lower and middle parts of the Krestyakh conglomerate sequence, with regard to a deposition gap between the Bastakh and Atyrdakh formations coeval to a short episode of low stand (a sealevel fall of at least 100 m) followed by a 80 m rise (Gradstein et al., 2012), which appears in all available data.

According to our estimates, the composite Krestyakh conglomerate section totals a thickness of 250–270 m, which differs from the previous estimates of 160 to 200 m (Bogush et al., 1965; Lungersgauzen and Solomina, 1966; Bulgakova, 1967; Geological Map, 1979; Klets, 2005; Kutygin, 2009) and 300 m (Mezhvilk, 1956, 1958). Assuming that the initial deposition depths of the Krestyakh conglomerate at least exceeded the total thickness, they can be estimated as 300–350 m, without regard to synchronous subsidence of the Early Carboniferous Kharaulakh basin or 200–250 m in the presence of the subsidence.

CONCLUSIONS

1. The documented Krestyakh sections represent a specific facies unit of the Atyrdakh Formation.

2. The Krestyakh unit largely consists of autochtonous coarse clastics that were transported by debris flows, filled submarine canyons, and were subject to gravity sliding. Thus, they are deposits of debris flows (debrites).

3. The Krestyakh sequence and other sections of the Atyrdakh Formation were deposited in an offshore environment.

4. The deposition depths were from 150–200 m (outer shelf), judging by the absence of wave ripples and roll structures, to 300 m or deeper (distal outer shelf, or even proximal continental slope).

5. The Krestyakh basal unit of the Atyrdakh Formation in the Northern Kharaulakh sedimentary complex, Verkhoyansk region was deposited in the Visean stage of the Early Carboniferous.

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