Russian Journal of Earth Sciences

Special Issue: "To the 80th Anniversary of the 'Sedimentary Rocks' Section of the Moscow Society of Naturalists (MOIP)"

Jurassic and Cretaceous Glendonites of the Novoyakimovskaya-1 Borehole (Western Taimyr): Age, Morphology, Depositional Settings and Alterations of Mineral Composition

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According to biostratigraphic data, Bathonian and Callovian (Malyshevka and Tochinskoe Formations), Oxfordian (Sigovoe Formation), Volgian and Ryazanian (Yanov Stan Formation), Valanginian and Hauterivian (Sukhaya Dudinka Formation) stages were recognized in the core of Novoyakimovskaya-1 well. Characteristic species of mollusks from the Bathonian–Hauterivian are figured. For the first time, members previously established in the Bazhenovo Formation and the Lower Tutleim Subformation were traced into the Yanov Stan Formation. All studied formations except for Malyshevka Formation contain glendonites. Glendonites are pseudomorphs after cold-water mineral ikaite and can be used as indicators of cold water paleoenvironments. The size of glendonites varies from a few to 9–10 cm. Glendonites are morphologically diverse, however, no patterns in the distribution of glendonites of different shapes across the section are noted. Glendonites are abundant in the lower part of the section (Bathonian and Callovian stages), but their number decreases up the section. The stratigraphic distribution of glendonites is compared with the stages of climate cooling in the Arctic region. All studied glendonites are composed of two types of calcite; this feature is stable for glendonites of different ages and can be used for microscopic identification of glendonites.

Keywords: glendonite, climate fluctuations, sedimentary environment, Jurassic, Cretaceous, West Siberia, Yenisey-Khatanga regional depression.

Citation: Rogov M. A., Vasileva K. Y., Olenova K. Y., Ippolitov A. P., Lutikov O. A., Panchenko I. V., Kiselev D. N. (2025), Jurassic and Cretaceous Glendonites of the Novoyakimovskaya-1 Borehole (Western Taimyr): Age, Morphology, Depositional Settings and Alterations of Mineral Composition, *Russian Journal of Earth Sciences*, 25, ES4011, EDN: ypqowp, https://doi.org/10.2205/2025ES001040

Research Article

Received: 2025-06-02
Accepted: 2025-07-13
Published: 2025-09-30

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Introduction

Glendonites are pseudomorphs after metastable mineral ikaite (cold-water calcium hexahydrocarbonate, $CaCO_3 \cdot 6\,H_2O$). They are widely distributed in the Jurassic and Cretaceous sediments within the Yenisey-Khatanga regional depression and were mentioned as either "star-like calcite concretions", "concretions of brown calcite" or "antraconite" in publications and unpublished reports since the early 1960s, when drilling of numerous deep wells began here [*Baybarodskikh et al.*, 1968]. However, these pseudomorphs have not yet been studied in the region, and information about their occurrences is mainly limited to stratigraphic distribution, while data on location, morphology, and composition of the host sediments are not available.

The parametric well Novoyakimovskaya-1 was drilled in 2020 in the western part of the Yenisey-Khatanga regional depression (coordinates 71.75347°N, 90.90119°E, Figure 1), reaching a depth of 5020 m and penetrating a thick succession of Middle Jurassic–Lower Cretaceous deposits (Bajocian–Bathonian to Hauterivian), represented within the core. Since stratigraphic subdivision, as well as age and position of formation boundaries differ significantly in publications [see *Rogov et al.*, 2024; *Skvortsov et al.*, 2025], data on glendonite distribution in this study was complemented with information on lithological composition, finds of characteristic mollusk taxa allowing for precise dating of the studied deposits, and also confirming the identification of formations.

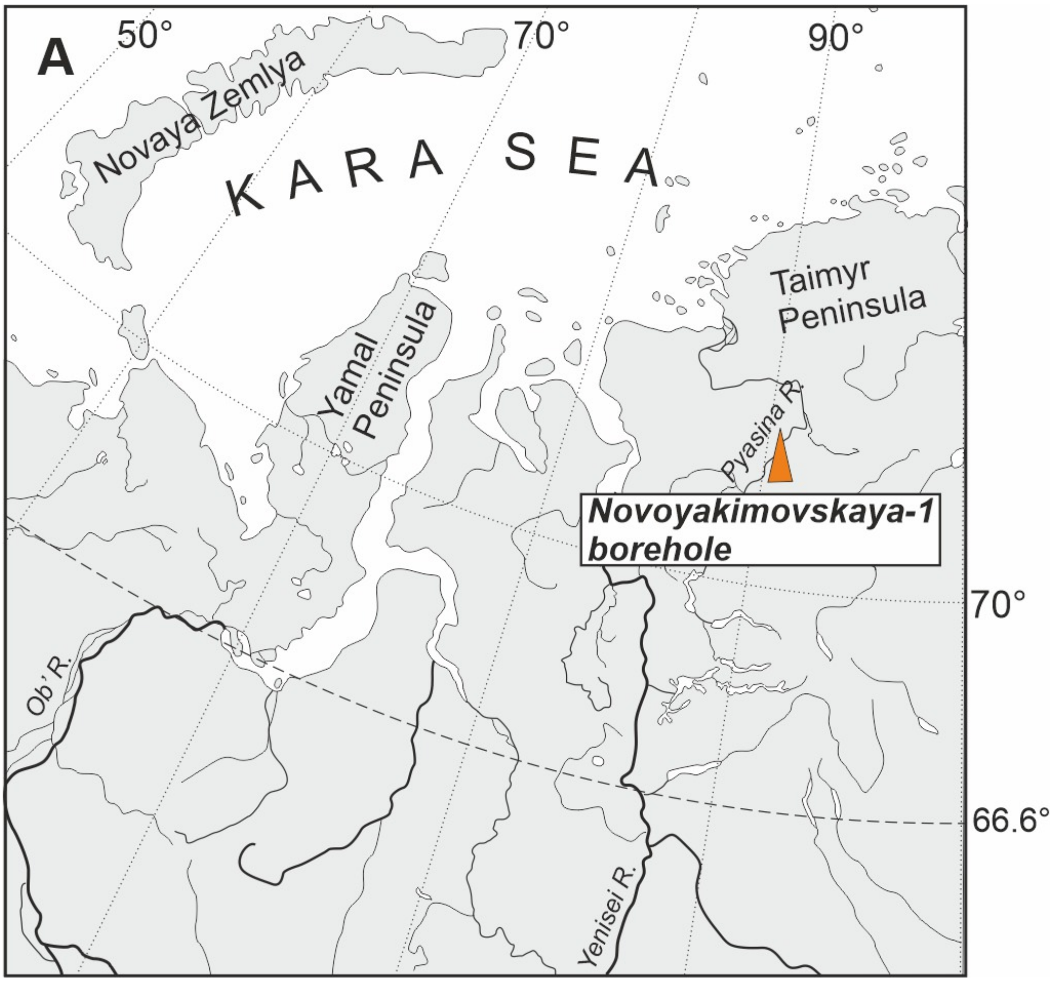


Figure 1. Map showing the studied borehole.

The section of the Novoyakimovskaya-1 well is unusually rich in glendonites, which are associated with deposits of different ages. The glendonites have different morphologies, belonging to three main morphotypes known from the Phanerozoic [see *Rogov et al.*, 2023], and are found in different facies. These features make this well unique, and the study of glendonite finds from the core of this well is promising for clarifying the factors that control the distribution of these pseudomorphs, which have not yet been completely understood.

During the Middle Jurassic–Early Cretaceous, the studied area was located on the periphery of the West Siberian sea and was adjacent to land; throughout the Late Jurassic, coastal-marine sedimentation settings dominated here [*Kontorovich et al.*, 2013]. In the end of the Middle Jurassic and in the beginning of the Late Jurassic (when Tochinskoe and Sigovoe formations, containing most abundant glendonites, accumulated), the sedimentation depths were probably 25–50 m or less [*Kontorovich et al.*, 2013]. The extensive Late Jurassic transgression had almost no effect on the depositional environments in the marginal area of the basin, and the Yanov Stan Formation apparently also accumulated in the shallow part of the sea, with depths comparable to those which existed at the end of the Middle Jurassic [*Kontorovich et al.*, 2013]. The mentioned paleoclimatic reconstructions show that after a significant and prolonged cooling in the Middle Jurassic, a gradual warming of the climate occurred throughout the Late Jurassic, with the peak of warming during the Volgian, while the Ryazanian was probably cooler. This is consistent with the presence of glendonites in the Ryazanian stage of Western Siberia [*Vasileva et al.*, 2025]. Shallow marine depositional environments dominated during Berriasian, Valanginian and Hauterivian stages. Due to ongoing regression, by the beginning of Barremian continental environments established in the study area [*Kontorovich et al.*, 2014].

Materials and Methods

The material for the research included descriptions of cores, photographs, macroscopic descriptions of glendonites, extracted specimens of fossils, as well as selected samples of glendonites. Glendonites from different stratigraphic levels were photographed, and the size, orientation and morphology of the encountered glendonites were noted during core description. Mollusks, which were used to determine the age of the deposits, are present in all the formations, but are most numerous in the Yanov Stan Formation [*Rogov et al.*, 2024]. The selected mollusk specimens (stored in the Aprelevka branch of the All-Russian Research Geological Oil Institute, VNIGNI) were photographed after coating with ammonium chloride. Transparent polished sections of glendonites were made from the samples on epoxy resin; petrographic and cathodoluminescence studies were carried out on an Olympus BX-53 microscope with an attachment for “cold” cathodoluminescence (CITL) Mk5, Cambridge Image Technology Ltd. (Department of the Regional Geology, St. Petersburg State University). Scanning electron microscopy and microprobe analysis were carried out on a Hitachi S-3400N microscope with analytical attachments, at the Centre for Geo-Environmental Research and Modelling (GEOMODEL) (for samples NYa-9 and NYa-11). Glendonite studies using methods including visual description in core, examination of samples under a stereomicroscope, and stained petrographic sections under an optical microscope were also carried out at the Aprelevka branch of the All-Russian Research Geological Oil Institute (VNIGNI), and some of the results of these studies were previously published [*Olenova et al.*, 2023].

Results

Lithostratigraphy, Biostratigraphy and Glendonite Distribution

During the study of the core of the Novoyakimovskaya-1 well, several options of subdivision into formations were proposed by different specialists based on the logging data and the results of the core study. The subdivision used in this work is based on a comprehensive interpretation of the lithological structure of the intervals according to the core, as well as the obtained biostratigraphic data.

Upper Bajocian–Lower (? Middle) Bathonian (Malyshevka Formation, Depth ~ 4955–5020 m)

The Malyshevka Formation comprises the lowermost part of the section and is composed of sandstones with subordinate siltstone beds (Figure 1). The boundary between the Malyshevka and Tochinskoe Formations is drawn by the disappearance of massive sandstone layers. Macrofossils in the Malyshevka Formations are rare, and it was possible to identify a single belemnite from the depth 4988.16 m. Despite poor preservation, it is tentatively identified as *Paramegateuthis* sp. (mid-Bajocian to Lower Bathonian in Siberia, Figure 3.1) due to laterally compressed alveolus combined with wide alveolar angle (26°) characteristic for the members of this genus. Glendonites are not recorded, although their presence in the Malyshevka Formation was noted for neighboring areas [*Baybarodskikh et al.*, 1968].

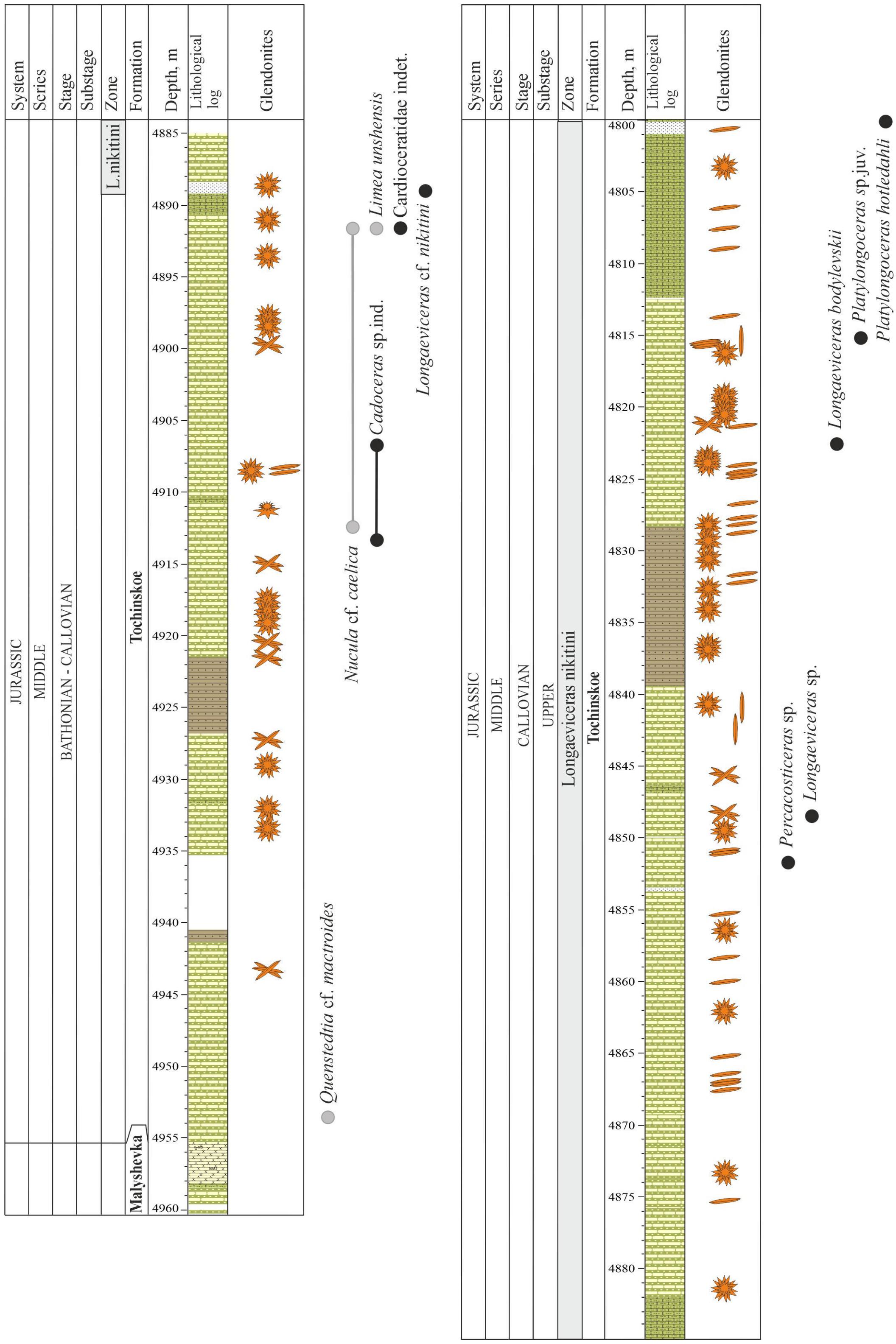
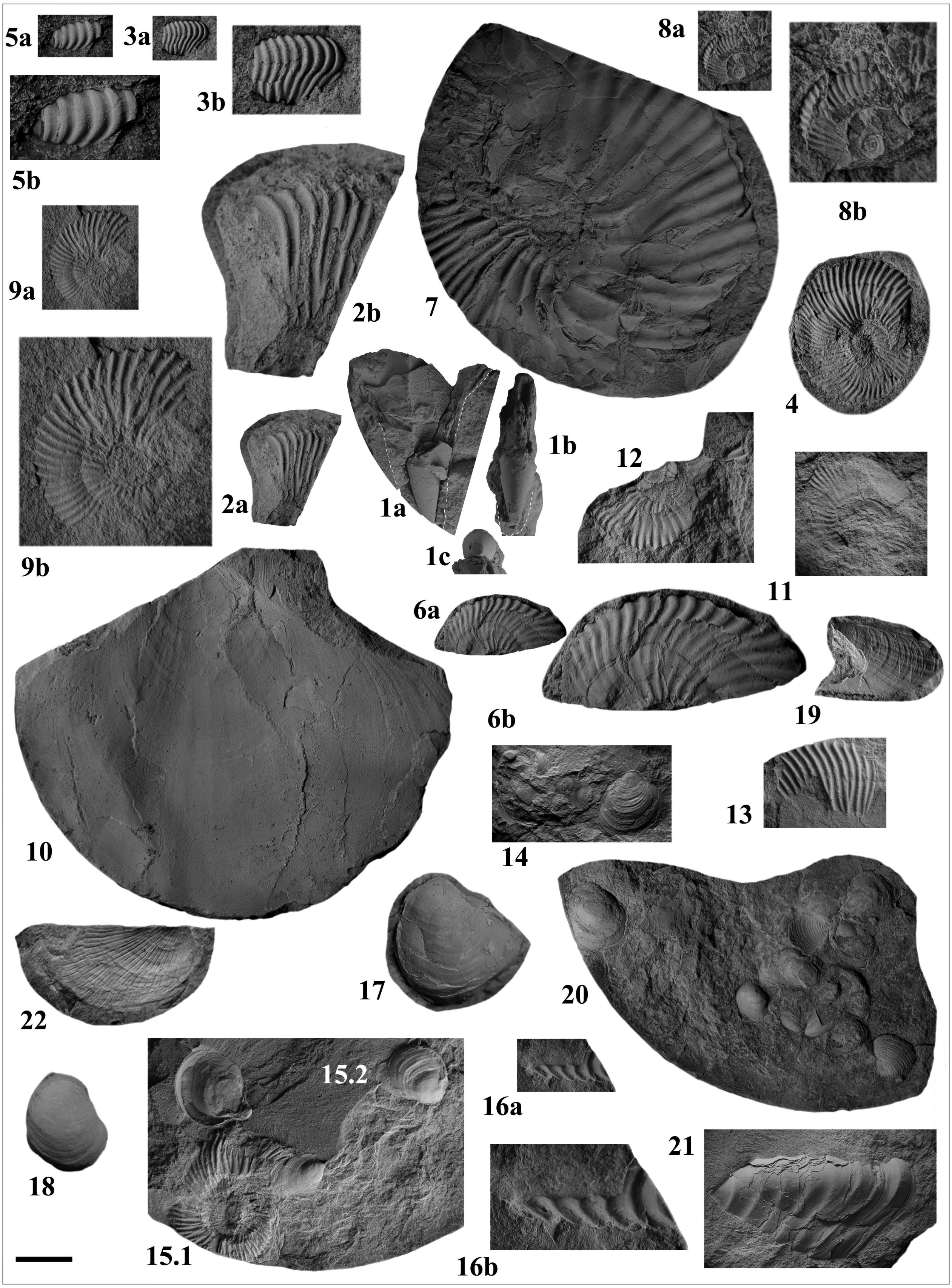


Figure 2. Biostratigraphy and glendonite occurrences in the Middle Jurassic Tochinskoe Formation (for captions see Figure 4).

Upper Bathonian (?)–Upper Callovian (Tochinskoe Formation, Depth 4800–~4955 m)

The Tochinskoe Formation is composed of gray and dark gray siltstone (Figure 2). The glendonites are abundant as well as ammonites and bivalves (Figure 3.2–9). The ammonite occurrences allow the recognition of the upper part of the Lower–Middle Callovian Cadoceras milaschevici Zone (depth 4888.97 m) and the Upper Callovian Longaeviceras nikitini


5a
3a
3b
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8a
8b
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7
4
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11
6a
6b
19
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14
17
20
22
15.2
16a
18
21
15.1
16b

Figure 3. Bajocian–Hauterivian mollusks from Novoyakimovskaya-1 borehole. Scale bar is 1 cm except ammonite specimens marked with letter "b", which are enlarged by two times (×2). All specimens were coated with ammonium chloride. 1 – *Paramegateuthis* sp., incomplete cast of alveolus surrounded by fragments of the rostrum; specimen 427/NYa-1, Malyshevka Fm, Upper Bajocian–Lower Bathonian, depth 4988.16 m (a – right side view; b – dorsal view; c – cross-section from posterior side; white dotted line denotes rostrum fragments, crushed anteriorly due to lateral compression); 2, 3 – *Cadoceras* sp. indet., Tochinskoe Fm., Upper Bathonian–Lower Callovian, 2 – specimen 423/NYA-1, depth 4913.33 m; 3 – specimen 419/NYA-1, depth 4906.8 m; 4 – *Pseudocadoceras* ex gr. *nanseni* (Pompeckj, 1899), specimen 416/NYA-1, Tochinskoe Fm., Upper Callovian, Nikitini Zone, depth 4888.97 m; 5 – *Percacosticeras* sp., specimen 412/NYA-1, Tochinskoe Fm., Upper Callovian, Nikitini Zone, depth 4851.85 m; 6 – *Longaeviceras* cf. *nikitini* (D. Sokolov, 1912), specimen 423/NYA-1, Tochinskoe Fm., Upper Callovian, Nikitini Zone, depth 4848.33 m; 7 – *Longaeviceras* cf. *bodylevskii* Meledina, 1977, specimen 406/NYA-1, Tochinskoe Fm., Upper Callovian, Nikitini Zone, depth 4822.4 m; 8 – *Platylongoceras* sp.juv., specimen 405/NYA-1, Tochinskoe Fm., Upper Callovian, Nikitini Zone, depth 4815.2 m; 9 – *Platylongoceras hotledahli* (Salfeld et Frebold, 1924), specimen 403/NYA-1, Tochinskoe Fm., Upper Callovian, Nikitini Zone, depth 4800.35 m; 10 – *Mclearnia* cf. *broenlundi* (Ravn, 1911), specimen 323/NYA-1, Sigovoe Fm., Oxfordian, depth 4471.24 m; 11 – *Amoeboceras* cf. *mansoni* Pringle, 1936, specimen 324/NYA-1, Sigovoe Fm., Upper Oxfordian, Serratum Zone (?), depth 4469.31 m; 12 – *Amoeboceras ovale* (Quenstedt, 1845), specimen 326/NYA-1, Sigovoe Fm., Upper Oxfordian, Serratum Zone (?), depth 4467.95 m; 13, 15a – *Prohomolsomites* cf. *petschorensis* (Bogoslowsky, 1902), Sukhaya Dudinka Fm., Valanginian/Hauterivian boundary beds, Bojarkensis Zone; 13 – specimen 26/NYA-1, depth 3155.95 m; 15 – specimen 29/NYA-1, depth 3141.15 m; 14, 15b,18 – *Buchia sublaevis* (Keyserling, 1846), Sukhaya Dudinka Fm., Valanginian-Hauterivian boundary beds, 14 – specimen 27/NYA-1, depth 3148 m; 18 – specimen 44/NYA-1, depth 3115.05 m; 16, 21 – *Prohomolsomites* sp. Sukhaya Dudinka Fm., Valanginian/Hauterivian boundary beds, Bojarkensis Zone; 16 – specimen 35/NYA-1, depth 3129.81 m; 21 – specimen 187/NVK-1, depth 3088.1 m; 17 – *Buchia crassicollis* (Keyserling, 1846), Sukhaya Dudinka Fm., Valanginian/Hauterivian boundary beds, specimen 37/NYA-1, depth 3126.87 m; 19 – *Solemya* cf. *woodwardiana* (Leckenby, 1859), Sukhaya Dudinka Fm., specimen 176/NVK-1, depth 3112.91 m; 20 – *Buchia* cf. *sublaevis* (Keyserling, 1846), *Thracia* cf. *lata* (Muenster, 1839), Sukhaya Dudinka Fm., specimen 178/NVK-1, depth 3111.59 m; 22 – *Meleagrinella* ex gr. *subovalis* (Zakharov, 1966), Sukhaya Dudinka Fm., Lower Hauterivian (?), specimen 198/NVK-1, depth 3078.8 m.

Zone (depth 4850–4885 m), underlain by the interval with Upper Bathonian (?)–Lower Callovian cadoceratins. Both zones have wide spatial distribution in the Arctic and adjacent regions and form part of the Callovian scale included in the latest version of the Boreal Standard zonation [*Kiselev*, 2022]. The Milaschevici Zone of the Arctic corresponds to the uppermost Lower Callovian (Enodatum Subzone) and the lower part of the Middle Callovian (Kosmoceras jason Zone) of the Subboreal sequence. In the studied section, the presence of only the Middle Callovian part of the zone is paleontologically justified by the finding of *Pseudocadoceras* ex gr. *nanseni* (Pompeckj). This species is a characteristic taxon of the *Cadoceras arcticoides* biohorizon (lower part of the Middle Callovian). This microconch, together with the corresponding macroconch *Cadoceras* (*Protolongaeviceras*) *arcticoides* Kiselev et Meledina, is widely distributed in the Panboreal Superrealm (Kosmoceras jason Zone / upper part of the Cadoceras milaschevici Zone), primarily in the European Russia, Franz Josef Land, East Greenland, and East Taimyr [*Kiselev*, 2022].

The Nikitini Zone is characterized by numerous finds of ammonites of the genera *Platylongoceras* (Figure 3.8–9), *Longaeviceras* (including *L.* cf. *nikitini* (Sokolov), Figure 3.6 and *L.* cf. *bodylevskii* Meledina, Figure 3.7, as well as finds not identified to species level), and *Percacosticeras* (Figure 3.5).

Below the Milaschevici Zone, juvenile *Cadoceras* s. str. were found (Figure 3.2–3; depth 4906.8 m and 4913.33 m). These finds suggest a Late Bathonian–Early Callovian age of the deposits. The bivalves are abundant, but represented by taxa of a wide stratigraphic range, belonging to the genera *Nucula*, *Limea* and *Quenstedtia*.

Upper Oxfordian (Sigovoe Formation, Lower Subformation, Depth 4400–4500 m)

The Sigovoe Formation is represented by interbedded greenish sandstones and siltstones (Figure 4). The cored interval is presumably attributed to the Lower Sigovoe Subformation by analogy with the sections of wells located nearby [*Borisov*, 2019, Figure 6]. Fossil finds are rare in the Sigovoe Formation. Ammonites are found in a narrow range in the middle part of the interval (4467.95–4469.31 m). These ammonites referred to as genus *Amoeboceras*, which, despite the small size of the specimens, can be identified to the species level and allow us to accurately date this part of the section to the Serratum ammonite Zone. A single specimen (*Amoeboceras* cf. *mansoni* Pringle, Figure 3.11) has weakened sculpture on the internal whorls – a characteristic feature for *Amoeboceras* associated with *Prionodoceras serratum–P. koldeweyense*, that are diagnostic for this ammonite zone [*Sykes and Callomon*, 1979]. Additionally, the age is confirmed by findings of *A. ovale* (Quenst.) (Figure 3.12), another species characteristic for the Serratum Zone [*Mesezhnikov et al.*, 1989]. Bivalves *Mclearnia* cf. *broenlundi* (Ravn) that have a wide stratigraphic distribution were also observed in the interval (Figure 3.10), along with a single fragment of *Buchia*. The lowermost part of the interval contains glendonites.

Volgian–Ryazanian (Yanov Stan Formation, Depth 3822–4112 m)

The biostratigraphic characteristics and composition of the Yanov Stan Formation were previously discussed in detail by the authors [*Rogov et al.*, 2024]. The same article provides information on stratigraphic distribution of glendonites and their photographs. In addition to the published materials, it should be noted that in the studied section of the Yanov Stan Formation, it is possible to identify members that were previously identified in the contemporary Bazhenovo and Tutleim Formations of Western Siberia [*Panchenko*, 2023; *Panchenko et al.*, 2015, 2022] (Figure 5). In the Lower Volgian–lowermost part of the Middle Volgian of the Yanov Stan Formation there are numerous phosphorite concretions with a lenticular shape, similar to those developed in the Lower Middle Volgian member 1 (phosphate-clay-siliceous, lenticular-layered) and in the Middle Volgian member 2a (siliceous lenticular-layered) of the Bazhenovo and Tutleim formations (West Siberian platform). Such a comparison is also confirmed by macrofaunal associations: inoceramids and *Buchia* bivalves recorded together with ammonites Dorsoplanites and Pavlovia and relatively frequent belemnite rostra (in the Bazhenovo Formation they are common present in member 1 and 2a, becoming extremely rare higher in the section).

The Lower Volgian interval of the Yanov Stan Formation with homogeneous lithology in the depth range of 4110–4092 m can be compared with member 1 of the Bazhenovo and Tutleim formations, and the overlying alternation of argillites, siltstones with carbonate interlayers in the depth range of 4092–4041 m is an analogue of member 2a. Above (4041–4020 m) in the studied section of the Yanov Stan Formation there is a homogeneous interval of thin-layered argillites with the ubiquitous presence of pyrite, while the remains of macrofauna are extremely rare. This interval can be correlated with the member 2b of the Bazhenovo Formation (high-siliceous and horizontally layered), which was formed during the next sea level rise [*Panchenko*, 2023]. In the overlying interval of 4020–4006 m, in similar argillites with lens-shaped fabric and relatively high amount of pyrite, ammonites *Epivirgartites* and *Laugeites* are recorded, while benthic fauna was not found. Such features correspond to the member 3 of the Bazhenovo Formation (high-carbon, siliceous, and lens-shaped).

Still higher, at 4006–3980 m, clayey deposits with the most homogeneous lithology and with the maximum concentration of organic matter are developed, which is reflected in the comparatively high values of gamma-ray logging. The indicated interval can be quite confidently correlated with the Bazhenovo Formation member 4a (high-carbon, homogeneous), where the most condensed layers were deposited during the maximum sea

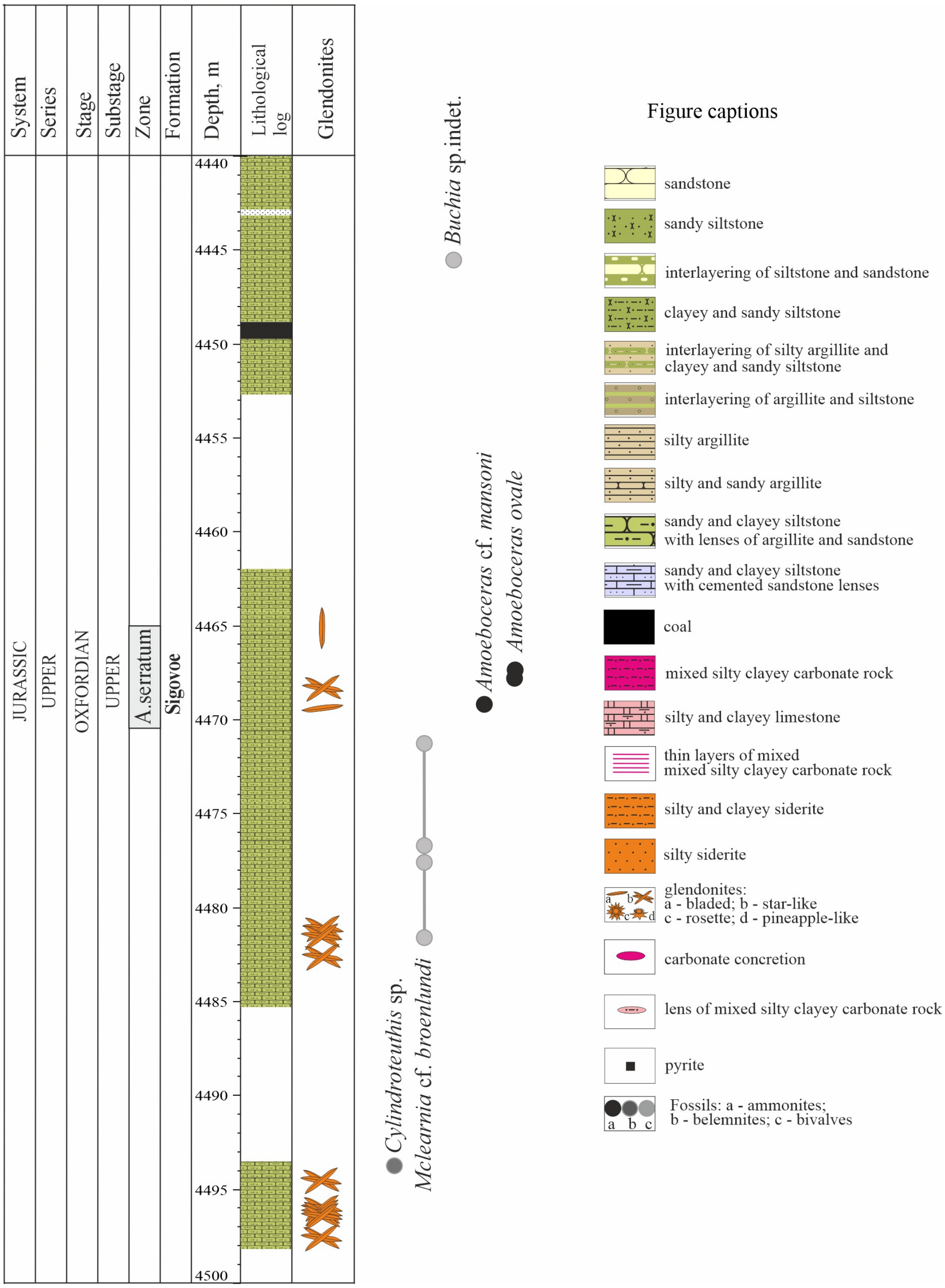

Figure 4. Biostratigraphy and glendonite occurrences in the Upper Jurassic Sigovoe Formation.

level rise. It is noteworthy that both in the Bazhenovo and Tutleim Formations, as well as in this part of the Yanov Stan Formation, ammonites occur quite often, among which *Praechetaites* are most typical. *Buchia* bivalves are also present here. In the Yanov Stan Formation, the boundaries of this member are highlighted by pyritization and high radioactivity levels (high-amplitude peaks on gamma-ray logging) (Figure 5), similarly to the Bazhenovo Formation of Western Siberia, and is interpreted as microhiatuses [*Panchenko*, 2023].

A lithological shift (increase in silt content and appearance of carbonate layers), as well as presence of inoceramid bivalves in the interval of 3980–3944 m, in which the fundamental logging characteristics are inherited from the underlying unit, allows us to recognize the member 4b of the Bazhenovo Formation. The presence of ammonites *Praetollia* in this unit confirms this correlation.

The level of disappearance of inoceramid bivalves and appearance of relatively large *Buchia* shells and ammonites of the Hectoroceras kochi Zone, together with the formation of rhythmically arranged and carbonate-containing deposits, allows for a reliable comparison with the base of the 5a member of the Bazhenovo and Tutleim Formations. In the black shale basin of West Siberia, the most significant faunal change takes place at this level, which is apparently reflected in the Yenisey-Khatanga regional depression. Based on the presence of numerous *Buchia* shells in the core together with ammonites *Hectoroceras kochi*, *Borealites* spp., *Surites* spp. and uniform lithological composition, the interval 3944–3822 m is ascribed to the member 5a (Figure 5). In the Bazhenovo and Tutleim Formations, this member is, as a rule, one of the thickest, which is also true for the studied section of the Yanov Stan Formation.

Higher levels of the Yanov Stan Formation are not represented in the core. However, in the very top of the Yanov Stan Formation, there is an increase in gamma-ray logging and resistivity values from the bottom to up, which allows us to assume that there are analogs of the member 5b of the Bazhenovo Formation, but without the support from lithological and biostratigraphic data, this remains speculative.

Thus, the detailed comparison of the Upper Jurassic and Lower Cretaceous sequences in the Yenisey-Khatanga regional depression and West Siberia shows that in this time interval in the Yenisey-Khatanga regional depression, glendonites occur at levels correlated with members 1, 2a, 2b, and 5a, whereas in the Bazhenovo Formation of West Siberia, glendonites were found only in the Ryazanian member 5a [*Vasileva et al.*, 2025].

Upper Valanginian–Lower Hauterivian (Sukhaya Dudinka Formation, Depth 3160–3060 m)

The Sukhaya Dudinka Formation is composed of gray siltstones (Figure 5); ammonite finds are much less common than in the Yanov Stan Formation. However, ammonites of the genus *Prohomolsomites* (Figure 3.13, 15.1, 16, 21), characteristic for the *Prohomolsomites* bojarkensis Zone (Upper Valanginian–Lower Hauterivian) were found (depth 3088.1–3155.95 m). Although the first *Prohomolsomites* specimens appear already in the upper part of the Upper Valanginian Bidichotomoides Zone, are they not accompanied by other genera of ammonites only in the Bojarkensis Zone. We suppose that species bojarkensis can be as well be assigned to the genus *Prohomolsomites*. Despite some of its differences from typical *Prohomolsomites* (more pointed cross-section, strengthening of the ribs on the ventral side, the appearance of the ribs on the middle whorls), the North American species of *Homolsomites*, to which the type species of the genus *H. poecilochotomus* Crickmay belongs [see *Imlay*, 1956], differ even more strongly from the Siberian *Prohomolsomites* and "*Homolsomites bojarkensis*". The age of the Bojarkensis Zone is accepted herein considering the newly published Sr isotope ages [*Efremenko et al.*, 2025], but allowing the possibility that the base of the zone is located in the Valanginian.

In the Sukhaya Dudinka Formation *Buchia sublaevis* and *B. crassicollis* zones were identified (Figure 3.15.2, 17, 18, 20); the boundary between these two zones is estabshed by the first appearance of *B. crassicollis* (Keyserling) (depth 3126.87 m). The uppermost part of the Sukhaya Dudinka Formation (above 3111.59 m) lacks *Buchia* findings and is characterized by an assemblage of various bivalves (genera *Oxytoma*, *Meleagrinella*, *Nuculoma*, *Thracia*, *Entolium*, *Solemya*, Figure 3.21), which do not allow making conclusions about the age of the sediments. In the Sukhaya Dudinka Formation, glendonites are rare; they are found only in the upper part of the interval characterized by the core, above the ammonite and *Buchia* findings.

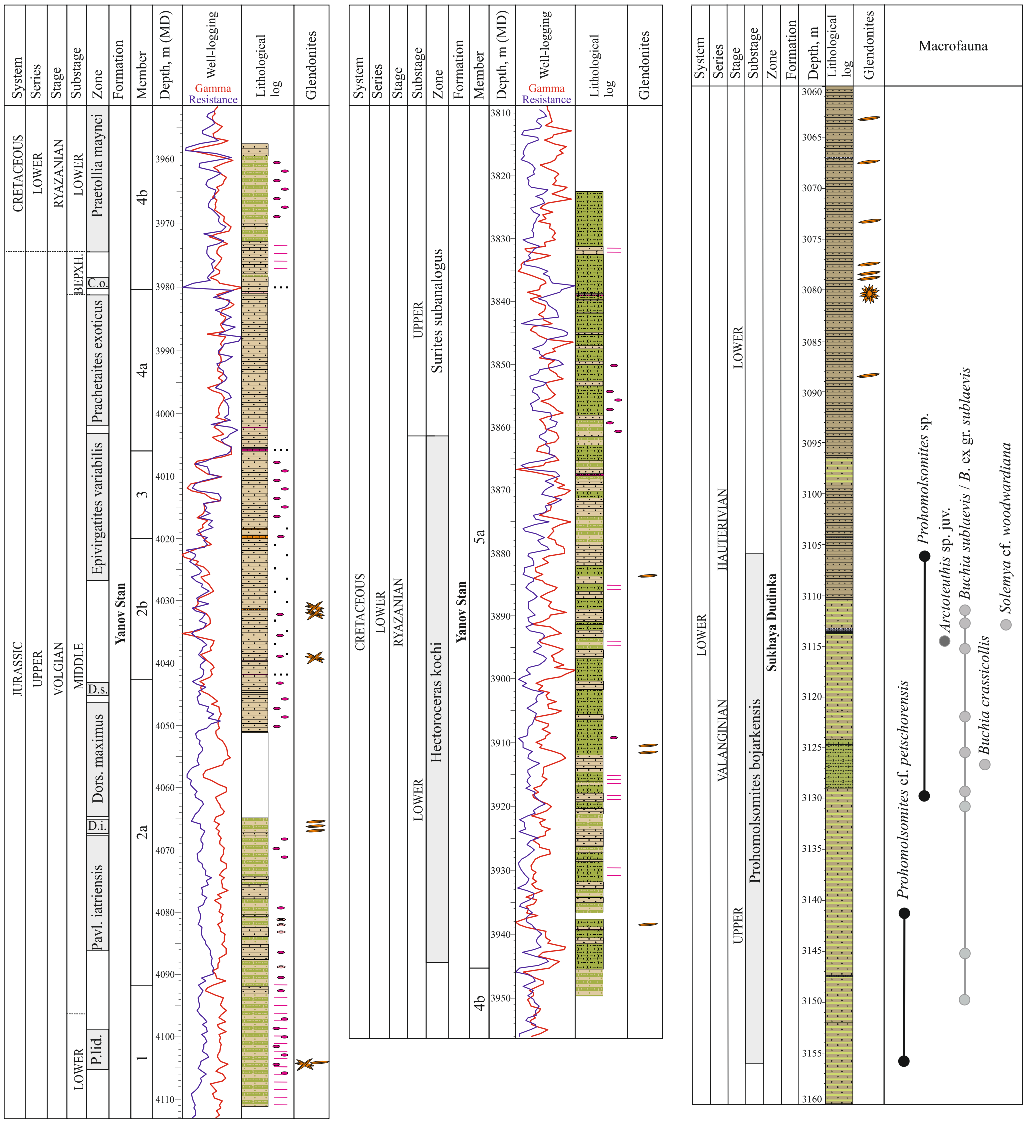

Figure 5. Upper Jurassic–Lower Cretaceous glendonite occurrences in the Yanov Stan and Sukhaya Dudinka formations.

Morphology, Size and Facial Distribution of Glendonites

Although glendonites are found in all formations across the large interval from the Upper Bathonian (Tochinskoe Formation) to the lower Hauterivian (Sukhaya Dudinka Formation), their frequency and distribution of morphotypes, as well as size of specimens, vary significantly. The glendonite findings in the Tochinskoe Formation are abundant, they appear through almost core interval (glendonites are absent in the lowermost 20 m of the Tochinskoe Formation only). The glendonites are predominantly small (2–5 cm in diameter) and are represented by rosette morphotype, including pineapple-like specimens (Figure 6.3, 6, 8–16). Some specimens are flattened (Figure 6.10–11, 14, 16). Stellate glendonites (Figure 6.2, 5, 7) are also found, but less common, while certain levels contain bipyramidal (bladed) glendonites, which can reach relatively large size (up ~15 cm in length, Figure 6.1). Glendonites of the latter morphotype are oriented either vertically or horizontally (Figure 6.1, 6.4). At the same time, there is no regularity in size or morphology of glendonites across the section. As in other cases described previously [*Rogov et al.*, 2023], different glendonite morphotypes may appear within the certain thin intervals. Glendonite finds are confined to dark gray siltstones.

In the Sigovoe Formation, glendonites are rarer than in the Tochinskoe Formation and less variable morphologically. They belong to the stellate morphotype and have an average size slightly smaller than the core diameter. All the glendonites are oriented parallel to bedding planes (Figure 7.11–14); they are found within both clayey sandy siltstones and silty argillites within 3 intervals: in the lowermost part of the formation (~4494.5–4497.7 m and ~4480–4482 m) and in the its middle part (~4467–4469 m).

Glendonites had never been mentioned from the Yanov Stan Formation before the present study, and their findings were a surprise. Glendonites from the Yanov Stan Formation are confined to six narrow stratigraphic intervals: one in the Lower Volgian, two levels in the Middle Volgian, and three levels in the Ryazanian [*Rogov et al.*, 2024, Figures 2–3]. Glendonites here are medium-sized, with blade-like morphology (Figure 7.3, Figure 3.5, 8–10). Stellate glendonites appear in the Volgian (Figure 7.4, 6, 7.). The glendonites occur in clayey sandy siltstones with lenses of calcitic argillites, as well as in argillites. They are horizontal-oriented, parallel to bedding planes, while vertically-oriented glendonites are rare (Figure 7.10). As in underlying deposits, shape and size of glendonites in the Yanov Stan Formation is irregular.

In the Sukhaya Dudinka Formation, glendonites are rarer and smaller than in older deposits (Figures Figure 7.1, 2). Here they are found within two narrow intervals above the ammonite and *Buchia* findings, likely of the Early Hauterivian age. These glendonites are either bladed or stellate (Figure 7.1, 2), and are found within argillitic siltstone.

Petrographic and Cathodoluminescence Characteristic of the Glendonites

Petrographic and cathodoluminescence studies revealed differences in composition of the glendonites form different intervals of the Novoyakimovskaya-1 well. Glendonites from the Yanov Stan and the Sigovoe formations are composed of two calcite generations: the first-generation calcite forms tabular, isometric or rosette-shaped crystals, often zoned in transmitted light with a colorless central part and a darker edge (Figure 8A–D); the second calcite generation forms brownish xenomorph crystals filling space between calcite of the first generation. The cathodoluminescence of these types of calcite also differs: the first generation of calcite is characterized with zonal cathodoluminescence colors (dark brown center and bright yellow edges); the second type of calcite has a dark brown cathodoluminescence colors.

Glendonites from the Tochinskoe Formation are composed of two types of calcite, authigenic quartz, dolomite, and apatite (Figure 8E, F). The crystals of authigenic quartz are associated with thin fractures within glendonites or mark the boundary between glendonite and matrix (Figure 8A, B). The crystals of authigenic quartz have hexagonal section and are non-luminescent. The crystals of dolomite have saddle-like shape and are with dark red to brown cathodoluminescence; besides, dolomite and calcite form botryoidal aggregates (0.3 mm in width) with orange cathodoluminescence. Surprisingly, glendonites contain micron-sized authigenic apatite crystals with bright purple cathodoluminescence.

Scanning Electron Microscopy and Microprobe Analysis

Scanning electron microscopy and microprobe analysis revealed that calcite types determined by petrographic and cathodoluminescence analysis, have a slightly different elemental composition. Calcite of the 1st generation (with tabular, isometric, or rosette-shaped crystals) is low-magnesium (Mg content is up to 0.1%), while calcite of the 2nd generation (with xenomorph crystals) contains up to 1.3% Fe, 0.3 Mn and 0.2% Sr, it is often zonal and can have thin dolomite edge zone (Figure 9). Authigenic quartz crystals are hexagonal or pyramidal and contain calcite inclusions. Apatite forms slightly elongated barrel-shaped crystals, often with Fe-rich calcite inclusions within apatite crystals.

Discussion

Based on the lithology and the presence of characteristic mollusk taxa, the lithostratigraphic subdivision of the cored interval of the Novoyakimovskaya-1 well section

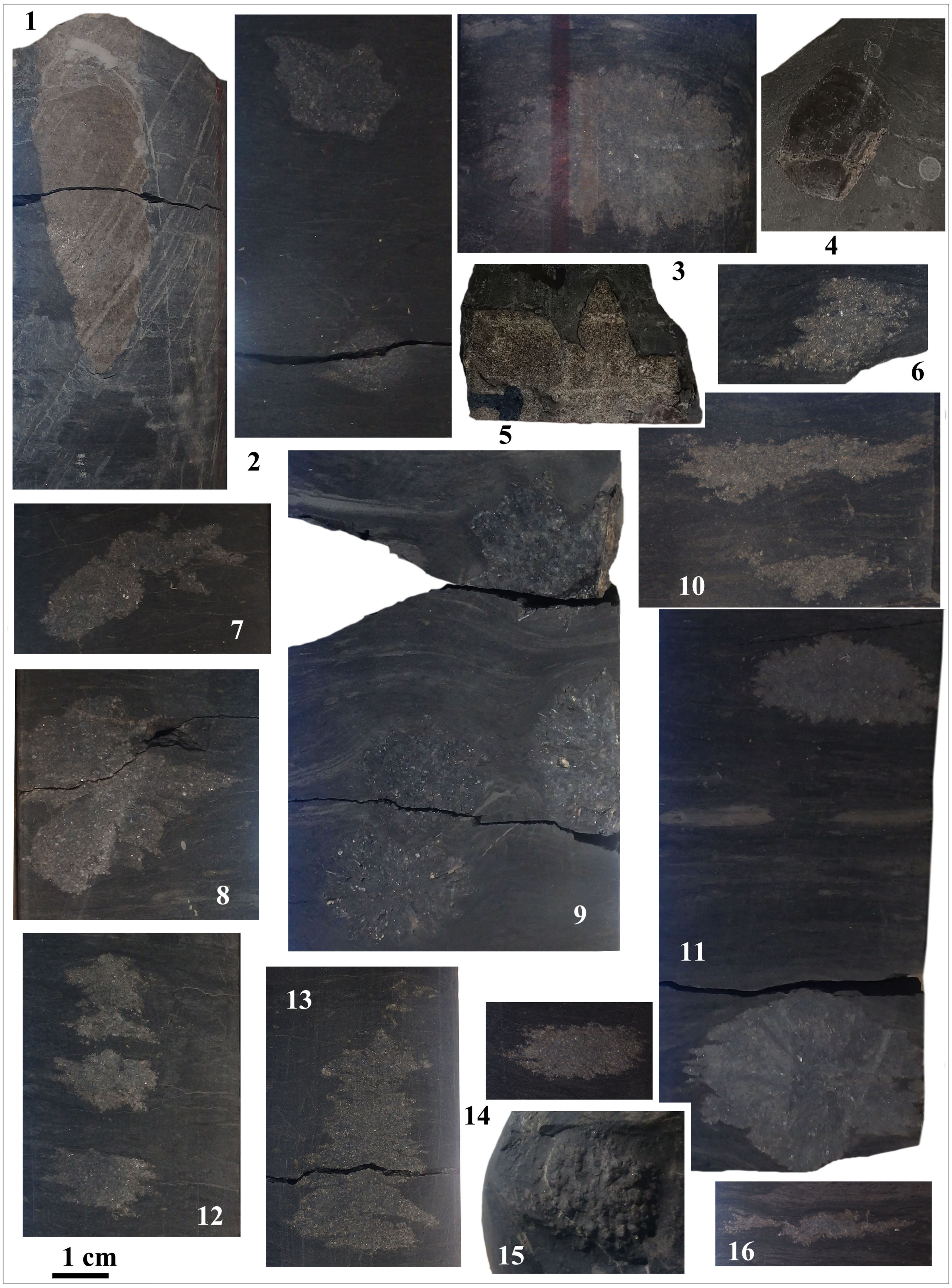

Figure 6. Glendonites from the Tochinskoe Formation (Upper Bathonian–Callovian), scale = 1 cm. 1 – depth 4815.3 m; 2 – depth 4824 m; 3 – depth 4842.45 m; 4 – depth 4860.05 m; 5 – depth 4832.7 m; 6 – depth 4919.05 m; 7 – depth 4848.3 m; 8 – depth 4873.4 m; 9 – depth 4918.0–4918.25 m; 10 – depth 4920.4 m; 11 – depth 4932–4931.1 m; 12 – depth 4898 m; 13 – depth 4911.1 m; 14 – depth 4921.5 m; 15 – depth 4929 m; 16 – depth 4933.45 m.

in the depth range of 3060–5020 m is justified. From bottom to top, the section consists of Malyshevka, Tochinskoe, Sigovoe, Yanov Stan and Sukhaya Dudinka formations. The Nizhnyaya Kheta Formation was not characterized with core material. Numerous glendonites were found in all formations except the lowermost Malyshevka Formation, with their number gradually decreasing from bottom to top; most glendonites are found within argillite and siltstone (Figure 10). Glendonites are most numerous and diverse in the

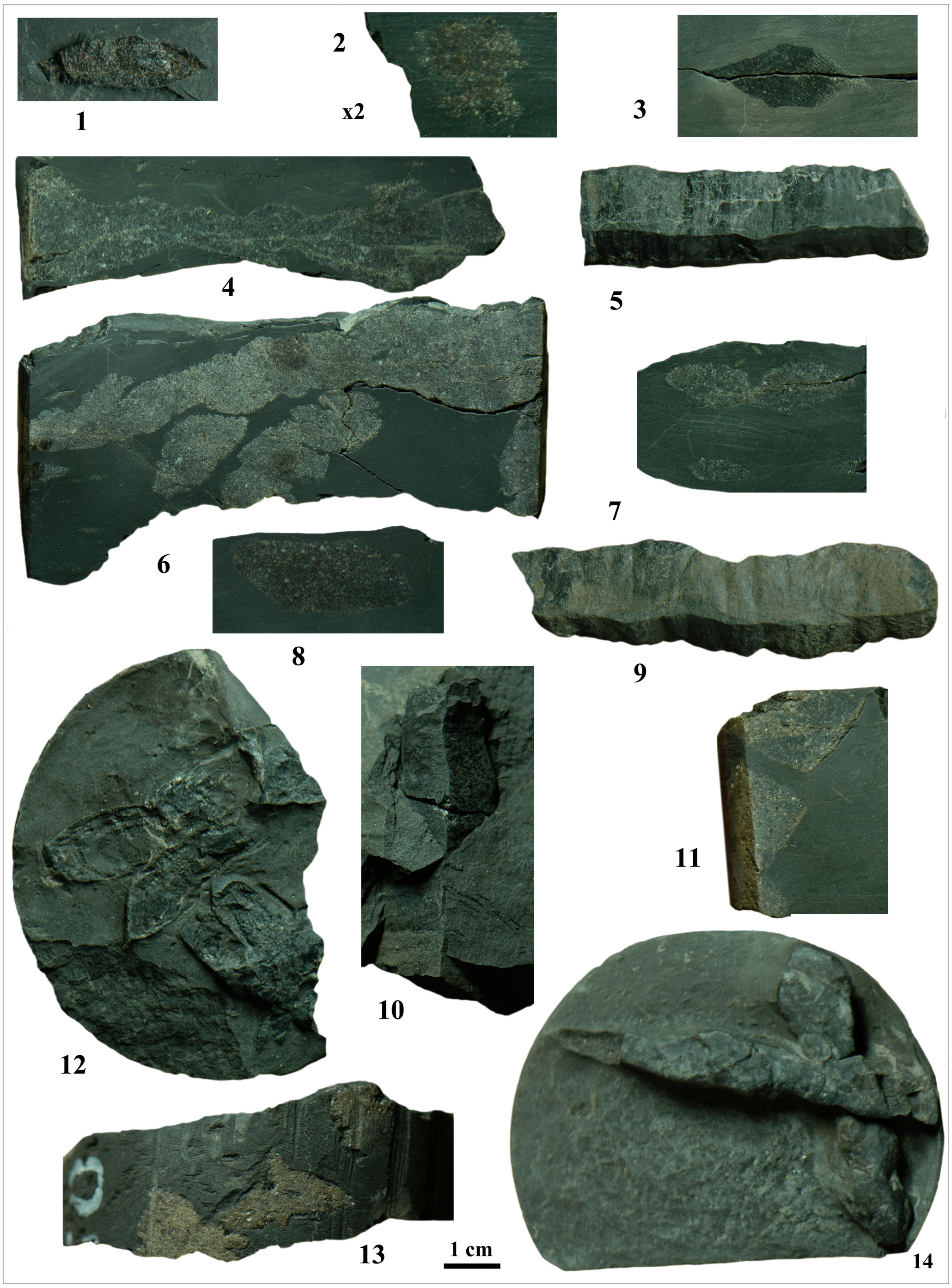

Figure 7. Glendonites from the Sigovoe Formation (Oxfordian), Yanov Stan Formation (Volgian–Ryazanian) and Sukhaya Dudinka Formation (?Lower Hauterivian), scale = 1 cm. 1–2 – Sukhaya Dudinka Fm.; 3–10 – Yanov Stan Fm.; 11–14 – Sigovoe Fm. 1 – depth 3078.5 m; 2 – depth 3080.26 m; 3 – depth 3883.49 m; 4 – depth 4031.86 m; 5 – depth 4066.01 m; 6 – depth 4038.84 m; 7 – depth 4104.65 m; 8 – depth 4065.68 m; 9 – depth 4066.16 m; 10 – depth 4066.94 m; 11 – depth 4481.55 m; 12 – depth 4496.16 m; 13 – depth 4497.64 m; 14 – depth 4494.51 m.

Tochinskoe Formation. All known morphotypes of glendonites are present here: blade-like, stellate and rosette-shaped (including the "pineapple" variant). Glendonites of different types do not occur together, but it is not possible to establish any patterns in the change of morphotypes across the section. The most common for the Tochinskoe Formation are rosette glendonites, the rarest are bladed ones. In the Sigovoe Formation, glendonites are

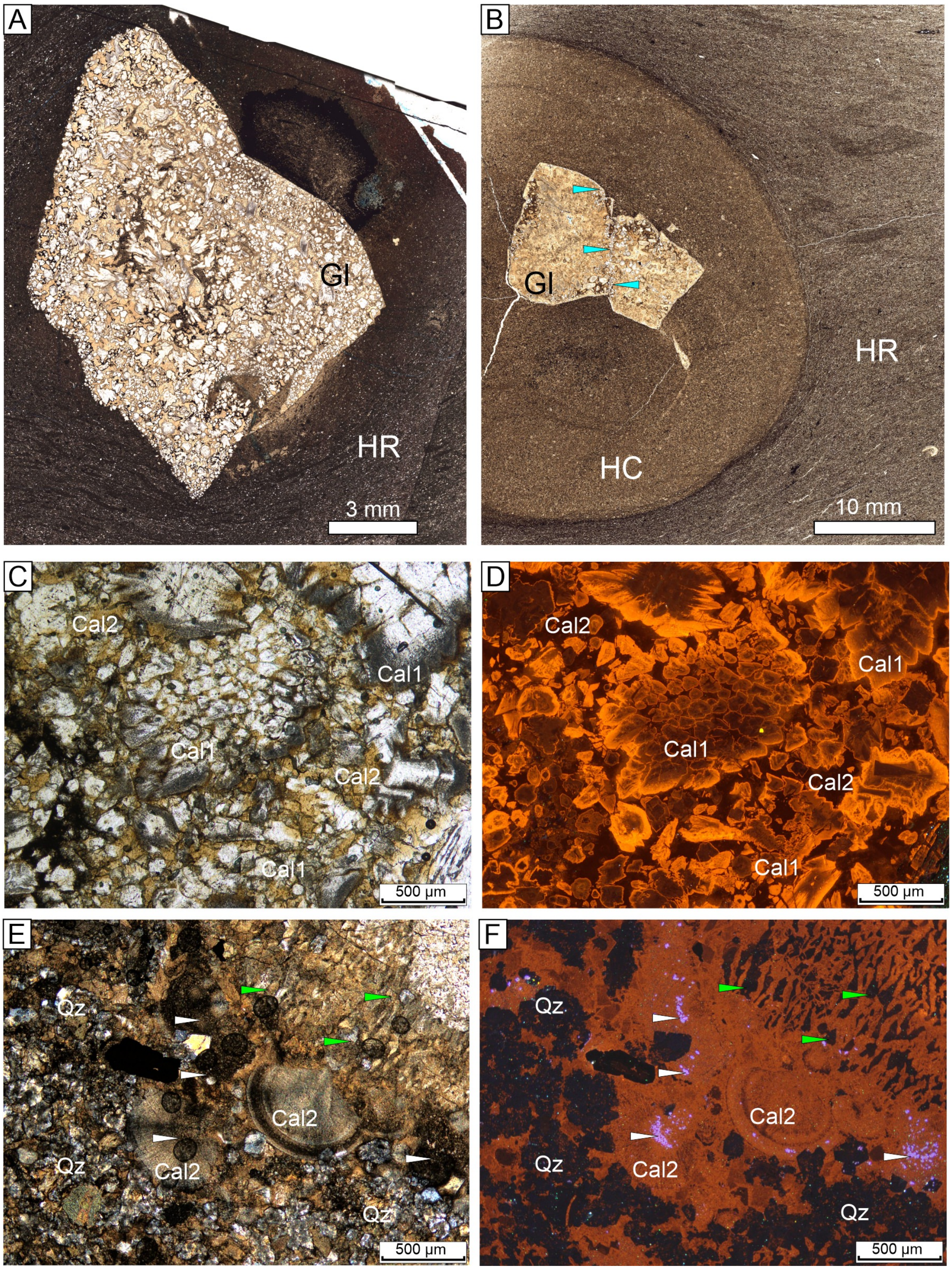

Figure 8. Petrographic and cathodoluminescence characteristics of the studied glendonites. A – panoramic photograph of glendonite thin section from the Yanov Stan Fm. (depth 3873.27 m), plane polarized light, B – panoramic photograph of glendonite thin section from the Sigovoe Fm., plane polarized light; C – photograph of NYA-1 sample thin section (Yanov Stan Fm., depth 4019.52 m), plane polarized light, D – the same under CL; E – photograph of NYA-11 sample (Tochinskoe Fm., depth 4932.09 m), plane polarized light, F – the same under CL. The photographs show: HR – host rock, HC – host concretuion, Gl – glendonite, low-magnesium calcite (Cal1, shown with green arrows in photos D and E), high-magnesium calcite (Cal2), authigenic quartz (Qz), authigenic apatite (shown with white arrows).

found more rarely, being confined to the lower half of the interval characterized by the core. Here, their morphology is more uniform, and all specimens belong to the stellate

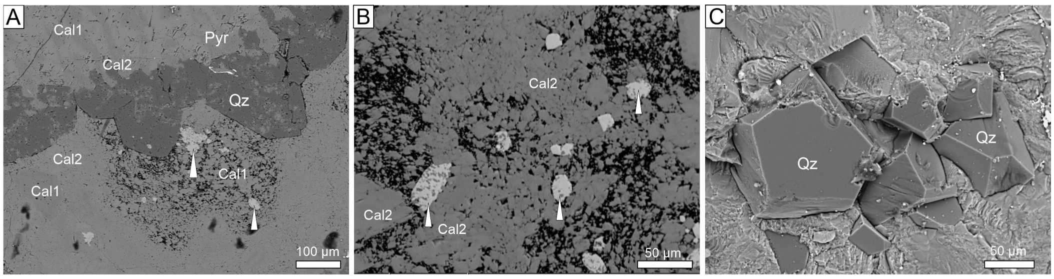

Figure 9. A, B – photos of the NYA-11 sample (Tochinskoe Fm) thin section under the scanning electron microscope: Cal1 – low-magnesium calcite, Cal2 – high-magnesium calcite, Pyr – pyrite, Qz – authigenic quartz, white arrows show crystals of authigenic apatite. C – photo of glendonite from the Tochinskoe Formation in the scanning electron microscope, Qz – authigenic quartz crystals.

morphotype. In the Yanov Stan Formation, glendonites appear in several narrow intervals, in all substages from the Lower Volgian to the Upper Ryazanian; and are absent only in the Upper Volgian interval. Here, comparatively large elongated blade-like glendonites predominate; stellate pseudomorphs are also present. In the Sukhaya Dudinka Formation, glendonites are the rarest and smallest in size; they belong to either the blade-like or rosette morphotypes.

The presence of glendonites in wide stratigraphic intervals shows that low bottom temperatures were typical for the Yenisei-Khatanga sea during Middle Jurassic to Early Cretaceous time interval, otherwise the crystallization of ikaite would not have been possible [for more details, see *Rogov et al.*, 2023]. Previous studies showed that the Arctic region in the Mesozoic was characterized by a temperate climate [*Nordt et al.*, 2024; *Price*, 1999; *Rogov et al.*, 2019]. The depth was relatively small – up to about 50 m, thus, the position of the sedimentation basin in high northern latitudes and possible penetration of cold currents were major factors controlling the establishment of low bottom temperatures and crystallization of ikaite. Glendonites are found in clayey and silty dark-colored deposits; they were not recorded in sandy deposits in the Novoyakimovskaya-1 well. The lithological control on glendonite appearance is related to the environment where ikaite is crystallized. Ikaite is associated with the processes of anaerobic diagenesis – organoclastic sulfate reduction, as a result of which prokaryotes consume a large amount of organic matter, and under anaerobic conditions it decomposes with the release of carbon dioxide. Under alkaline environment of anaerobic diagenesis, carbon dioxide combines with calcium ions leading to ikaite precipitation [*Muramiya et al.*, 2022; *Suess et al.*, 1982; *Whiticar et al.*, 2022]. In the Arctic region, glendonites have been described from relatively shallow-water deposits of similar lithology (dark-colored shales and siltstones) of the Middle Jurassic (Bajocian–Callovian) – early Cretaceous (Ryazanian–Albian) – of the Yenisei-Khatanga trough [this study], from the Spitsbergen archipelago [*Vickers et al.*, 2018; *Vickers et al.*, 2025], and Arctic Canada [*Williscroft et al.*, 2017]. The stratigraphic distribution of glendonites in the Arctic region coincides with appearance of cold-water fauna and dropstones [*Rogov et al.*, 2019].

After crystallization and stabilization, ikaite dehydrates and is replaced by calcite. The earliest phase replacing ikaite is low-magnesium calcite, which is preserved in the fossil state as tabular or rosette-shaped crystals without cathodoluminescence (Cal1 in Figures 8–9); it is surrounded by darker calcite with an orange cathodoluminescence; this calcite contains relatively high amounts of Sr, Mg and Fe (Cal2 in Figures 8–9). These two types of calcite are predominant in almost all glendonites of all the studied formations. Glendonites of the Tochinskoe Formation are also composed of the same two types of calcite, but in addition, they contain minerals that are rarely found in glendonites – authigenic quartz and apatite. Silicified glendonites that underwent post-sedimentary alterations, have been described from the Oligocene of Sakhalin Island [*Vasileva et al.*, 2021] and Ediacaran of southern China [*Wang et al.*, 2020]. In the studied glendonites of the Tochinskoe Formation, hexagonal crystals of authigenic quartz are confined either to small cracks or to contact with the matrix, so it can be assumed that the source of silica is the host rock. Crystallization of authigenic

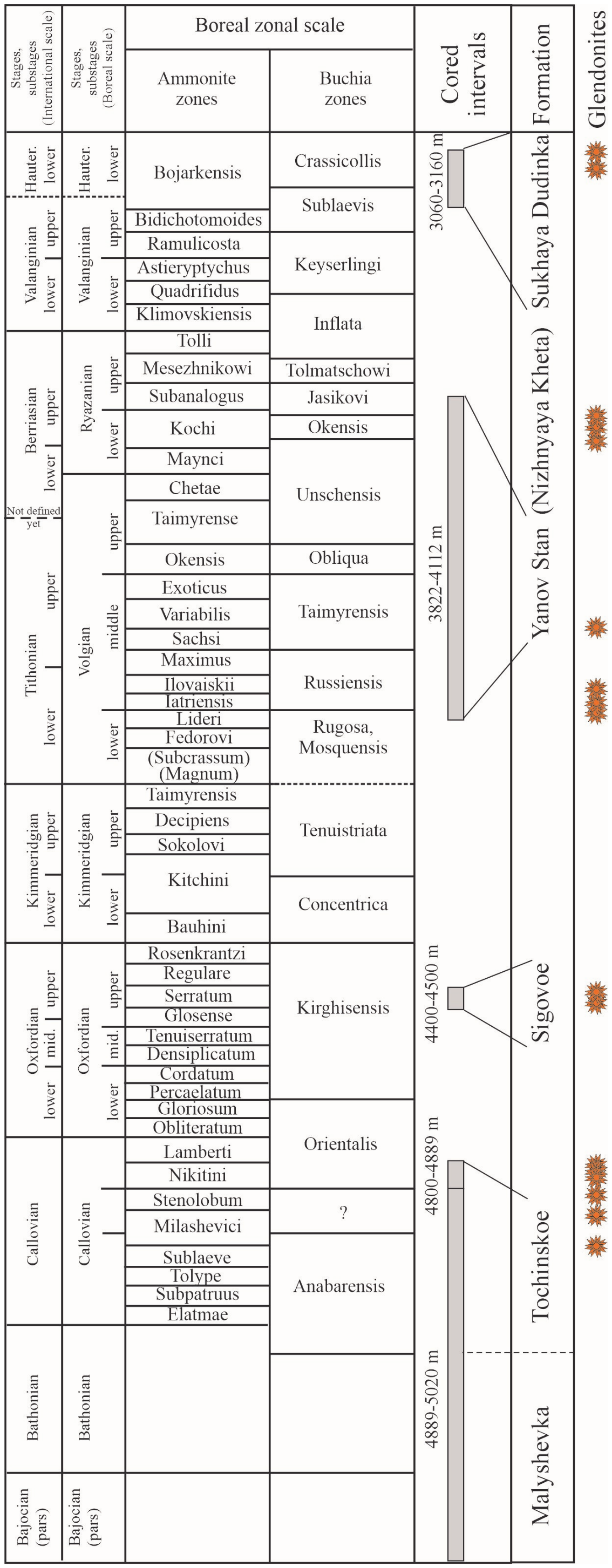

Figure 10. Summary of stratigraphic results and total range of glendonites in the Novoyakimovskaya-1 borehole.

quartz begins at temperatures of approximately 60 °C [*Allen and Allen*, 2005], i.e., it could have occurred when deposits reached depth of 2–3 km or during interactions with local heated fluids. The temperatures at which authigenic apatite crystallizes in sedimentary rocks are not entirely clear: in magmatic rocks apatite crystallization temperatures is estimated as 650–1430 °C [*Satori and Schmidt*, 2023], however, in the study region such high temperatures were not realized. The source of the phosphate is also unclear, but it is likely to have been mobilized from both the host rock and the glendonite. Phosphorus is noted in low-magnesium ikaite-derived calcite [*Vasileva et al.*, 2021], so it is possible that the processes of high-temperature replacement of glendonite (when quartz crystallized) resulted in some redistribution of the minerals within the glendonite, and phosphate crystallized into a separate phase – apatite.

Conclusion

The conducted studies of glendonites of the Novoyakimovskaya-1 well draw the following conclusions:

1. Stratigraphic studies show that the studied formations belong to the Bathonian–Callovian (Malyshevka and Tochinskoe formations), Oxfordian (Sigovoe Formation), Volgian and Ryazanian stages (Yanov Stan Formation), as well as the Valanginian–Hauterivian stages (Sukhaya Dudinka Formation) (Figure 10).
2. For the first time, a detailed correlation of units of the Bazhenovo and Tutleim formations (West Siberia) and the Yanov Stan Formation of the Yenisei-Khatanga regional depression is provided.
3. Glendonites are confined to the strata of the Bathonian (?)–Callovian, Oxfordian, Volgian, Ryazanian and Hauterivian age. The most abundant glendonite findings occurred in Tochinskoe and Sigovoe formations; their number gradually decreases up the section. The stratigraphic distribution of glendonites is consistent with the stages of cooling in the Arctic region. Thus, glendonites in the studied deposits act as an indicator of cold paleoclimatic conditions.
4. Morphologically, glendonites are represented by blade-like, rosette-shaped, and stellate forms; there is no pattern in the vertical distribution of these morphotypes by type or size.
5. Glendonites from all stratigraphic levels are composed of two types of calcite: low-magnesium (ikaite-derived calcite) and calcite with high amount of Mn, Sr, Fe (formed during cementation). This feature can be used for microscopic identification of glendonites. Apatite and quartz are present as accessory minerals, which were formed under some high-temperature influence.

Acknowledgements The authors acknowledge the Centre for Geo-Environmental Research and Modelling (GEOMODEL) of Saint-Petersburg State University for providing instrumental and computational resources. We are grateful to anonymous reviewers and the editor who helped to improve our manuscript. Studies of glendonites were supported by RSF grant no. 4-27-00415 (for MR, KV, IP) (https://rscf.ru/project/24-27-00415/).

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