

Biostratigraphy and Provenance of Aalenian Deposits of the New Siberian Islands, Eastern Arctic

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Abstract—New data are presented for the Aalenian deposits of the New Siberian Islands archipelago. Based on the first findings of ammonites of the genus *Pseudolioceras* and bivalves of the genus *Retroceramus* in well cores drilled in the southeastern part of Kotelny Island and in Gedenstrom Bay, the presence of both lower and upper Aalenian strata is substantiated. The Aalenian mollusk assemblages exhibit low taxonomic diversity and are compositionally similar to coeval faunas from other Arctic regions. Palynological analysis refines the composition of high-latitude Aalenian dinocyst assemblages: the early Aalenian is characterized by a higher diversity resembling that of the late Toarcian, whereas the late Aalenian records a marked decline. These changes are interpreted as ecosystem responses to pronounced cooling events. For the first time, representative Aalenian species of bivalves, ammonites, and palynomorphs from this region are figured. U–Pb dating of detrital zircon indicates that the Grenvillian–Sveconorwegian, Timanian, Caledonian, and Hercynian orogenic belts—or reworked products of their erosion—supplied clastic material to the Aalenian sedimentary basin. A comparison of detrital zircon age spectra from Jurassic deposits across the Arctic reveals strong similarity to those of the Barents Sea region. This supports a tectonic connection between the New Siberian Islands and the Barents Shelf during the Jurassic.

Keywords: Aalenian, Arctic, bivalves, ammonites, dinocysts, detrital zircon

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INTRODUCTION

The New Siberian Islands are an archipelago located in the northeastern part of the Laptev Sea. The islands are covered by Paleozoic and Mesozoic deposits that have been deformed to varying degrees, and these are overlain by undeformed or weakly deformed Cenozoic deposits (Kos'ko et al., 1985; Trufanov et al., 1986; Kos'ko and Korago, 2009; Kuzmichev et al., 2018; Popova et al., 2022a; and references in these works). This archipelago is a key object for paleogeographic and geodynamic reconstructions of the Eastern Arctic. In recent years, research has focused mainly on the study of Paleozoic deposits and the geodynamics of the region during the Paleozoic (Danukalova et al., 2015, 2019; Ershova et al., 2015a, 2015b, 2016, 2018; Prokopyev et al., 2018a). The study of the Mesozoic geological history has focused on understanding the stratigraphic sequence (Kuzmichev et al., 2009a, 2009b, 2018; Nikitenko et al., 2017, 2022; Konstantinov et al., 2022) and structural and tectonic investigations (Brandes et al., 2015; Prokopyev et al., 2018b).

There are almost no outcrops of Jurassic deposits on New Siberian Islands, and therefore they remain poorly studied. The Lower Jurassic deposits crop out

on the left bank of the middle course of the Balyktakh River (the central part of Kotelny Island). These deposits are represented by mudstones with interbeds of siltstones and sandstones (Kuzmichev et al., 2018; Nikitenko et al., 2022). The Lower Jurassic deposits were also uncovered by two test wells on Bunge Land, where they are represented by sandstones with subordinate interbeds of siltstones and mudstones. The recovered thickness of the deposits is 110 m. The Middle Jurassic deposits on the New Siberian Islands were penetrated only by wells. Except for the loose concretions with late Bathonian mollusks in the basin of the Dragotsennaya River (Meledina, 1999), the outcrops of these deposits are unknown here. The Middle Jurassic deposits (clayey siltstones, mudstones, and subordinate sandstone interbeds) were penetrated by the test well 9 on the left bank of the middle reaches of the Balyktakh River. The most complete section of the Middle Jurassic deposits was uncovered by a series of test wells (12, 13, and 25) in the southeast of Kotelny Island and in the Gedenstrom Bay (Trufanov et al., 1986; Nikitenko et al., 2017). Here, the Middle Jurassic deposits are composed of siltstones with separate interbeds of sandstones and mudstones, with an recovered thickness of more than 200 m. Undifferentiated

Jurassic deposits have also been penetrated by six test wells on New Siberia Island (Trufanov et al., 1986).

Except for the late Bathonian ammonites found in the Dragotsennaya River basin, other Middle Jurassic fossils from the New Siberian Islands have not yet been described or figured. Therefore, the age of the deposits remains insufficiently reliable.

The geodynamic evolution of the region is still debatable. There are several tectonic models of the affiliation of the New Siberian Islands archipelago and the surrounding shelf, which can be divided into three groups:

(1) According to the first group of models, the Peri-Siberian origin of the area under study is assumed (Kuzmichev and Pease, 2007; Kuzmichev, 2009; Danukalova et al., 2014a, 2014b, 2015; Danukalova and Kuzmichev, 2017, 2018; Kuzmichev and Danukalova, 2023).

(2) According to the second group of models, the archipelago is considered as an exotic block in relation to Siberia and is correlated with the Baltic, Laurentia, and/or the Arctic–Alaska–Chukotka microplate (Till et al., 2014; Akinin et al., 2015; Ershova et al., 2015a, 2015b, 2016, 2018; Davydov, 2016; Piepjohn et al., 2018; Prokopiev et al., 2018a, 2018b).

(3) According to the third group of models, the region represented a separate microcontinent (Vernikovskiy et al., 2013; Metelkin et al., 2016, 2017; Zhdanova et al., 2016; Chernova et al., 2017a, 2017b).

It is worth noting that most reconstructions were based on the study of Paleozoic complexes, while previous studies overlooked the Early Mesozoic geodynamics and the position of the archipelago.

This study aims to clarify the biostratigraphic characteristics of the Aalenian deposits of the New Siberian Islands, compare the identified fossil assemblages with coeval faunas and floras from adjacent Arctic regions, reconstruct sediment provenance based on U–Pb dating of detrital zircons, and refine Middle Jurassic geodynamic models for the Arctic realm.

MATERIALS AND METHODS

Materials

The material for the study consisted of samples of faunal remains from two test wells (nos. 12 and 25), drilled in the southeast of Kotelny Island and in Gedenstrom Bay (Fig. 1). Unfortunately, the cores of wells drilled in the late 1970s on the New Siberian Islands archipelago have not been preserved. We were only able to find individual samples of mollusks collected by E.S. Ershova and stored in VNIIOkeanogeologiya. This makes their study a unique opportunity to characterize the Aalenian deposits in the study region, especially considering that the Middle Jurassic deposits are not present in outcrops here. In addition to the revision of the mollusks, we performed palynological analysis for four samples from the core of

wells 12 and 25 and U–Pb dating of clastic zircons from four samples from well 25.

The studied collection of mollusks is stored in the Aprelevka branch of VNIGNI (Aprelevka, Moscow oblast) under reference number RMA-50.

Methods

Palynology. For the palynological analysis, four samples were collected for chemical treatment and examination: 25f-22, 25f-14, and 25f-12 from well 25 and 12f-2 from well 12 (Fig. 2). Palynomorphs were extracted from core samples containing macrofaunal remains. The sample numbers correspond to those used in the original study (Trufanov, 1978).

The palynological samples were processed in accordance with the standard procedure adopted in the Laboratory of Paleofloristics of the Geological Institute of the Russian Academy of Sciences (GIN RAS), including (1) treatment of samples with 10% hydrochloric acid (HCl) to remove carbonates; (2) treatment of samples with a hot sodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7 \times 10\text{H}_2\text{O}$) solution for dispersion of clay material with washing every 2 h to remove clay particles; (3) centrifugation of samples in a heavy liquid (K_2CdI_4) with a density of 2.25 g/cm^3 to separate the organic fraction from heavier mineral particles; (4) treatment of samples with 70% hydrofluoric acid (HF) to dissolve siliceous components; (5) treatment of samples with 10% hydrochloric acid to remove fluorosilicate gels; (6) washing the sample in distilled water and filling with glycerin. The macerate was not sieved.

U–Pb dating of detrital zircons. The extraction of heavy fraction minerals was carried out at the GIN RAS (Moscow). The zircon monofraction was extracted following a standard regimen: grinding, sieving into dimensional fractions. Then, the fraction $<0.25 \text{ mm}$ was passed through a centrifugal concentrator, and the resulting heavy fraction was processed using an electromagnet. The final treatment of the concentrate was carried out in a heavy liquid.

The U–Pb (LA-ICP-MS) dating of zircons was performed at the Center for Stable Isotope Mass Spectrometry of the University of Texas (Austin, USA).

Zircon grains were (mounted without polishing) on double-sided adhesive tape on epoxy-resin disks 1 inch in diameter. By eliminating polishing and preserving the complete structure of the grains, it became possible to analyze the grains perpendicular to the growth zone, from the rim to the core (depth profiling). U–Pb dating of zircon was performed by the method of laser ablation on a Fischer 2 mass spectrometric thermocouple using an excimer laser Photon Machines Analyte.G2 ATLex 300si ArF 193 nm. The data obtained were processed using Iolite™ (Paton et al., 2011) from Wave-metrics Igor Pro™ and software data processing schemes from VizualAge™ (Petrus and Kamber, 2012). GJ-1 ($601.7 \pm 1.3 \text{ Ma}$; Jackson et al., 2004) and Pak1 ($43.0 \pm 0.1 \text{ Ma}$; own standard) were used as stan-



Fig. 1. Geographical setting of the study area (a), and a schematic map of Kotelny Island showing the locations of the wells that penetrated Middle Jurassic strata.

dards. The methods used for data analysis and processing are described in detail in (Marsh and Stockley, 2015). Additional information is provided in ESM1 (Supplementary Information).

DESCRIPTION OF SECTIONS AND THEIR CHARACTERISTICS

The faunistically characterized Aalenian deposits located in the southeast of Kotelny Island under the cover of loose Quaternary deposits were penetrated

below depths of 4.5–22 m by test wells 12 and 13 (Fig. 1) (Trufanov, 1978). Their bedding varies from inclined (at an angle of about 45°) in well 13 to subvertical in well 12. Taking into account the steep dipping of rocks, the actual thickness of the Aalenian deposits in these wells is less than 100 m, and taking into account the probability of tectonic juxtaposition, their thickness probably does not exceed 50 m.

In the Gedenstrom Bay, the inclined Aalenian deposits have been recovered by the well 25 in the depth

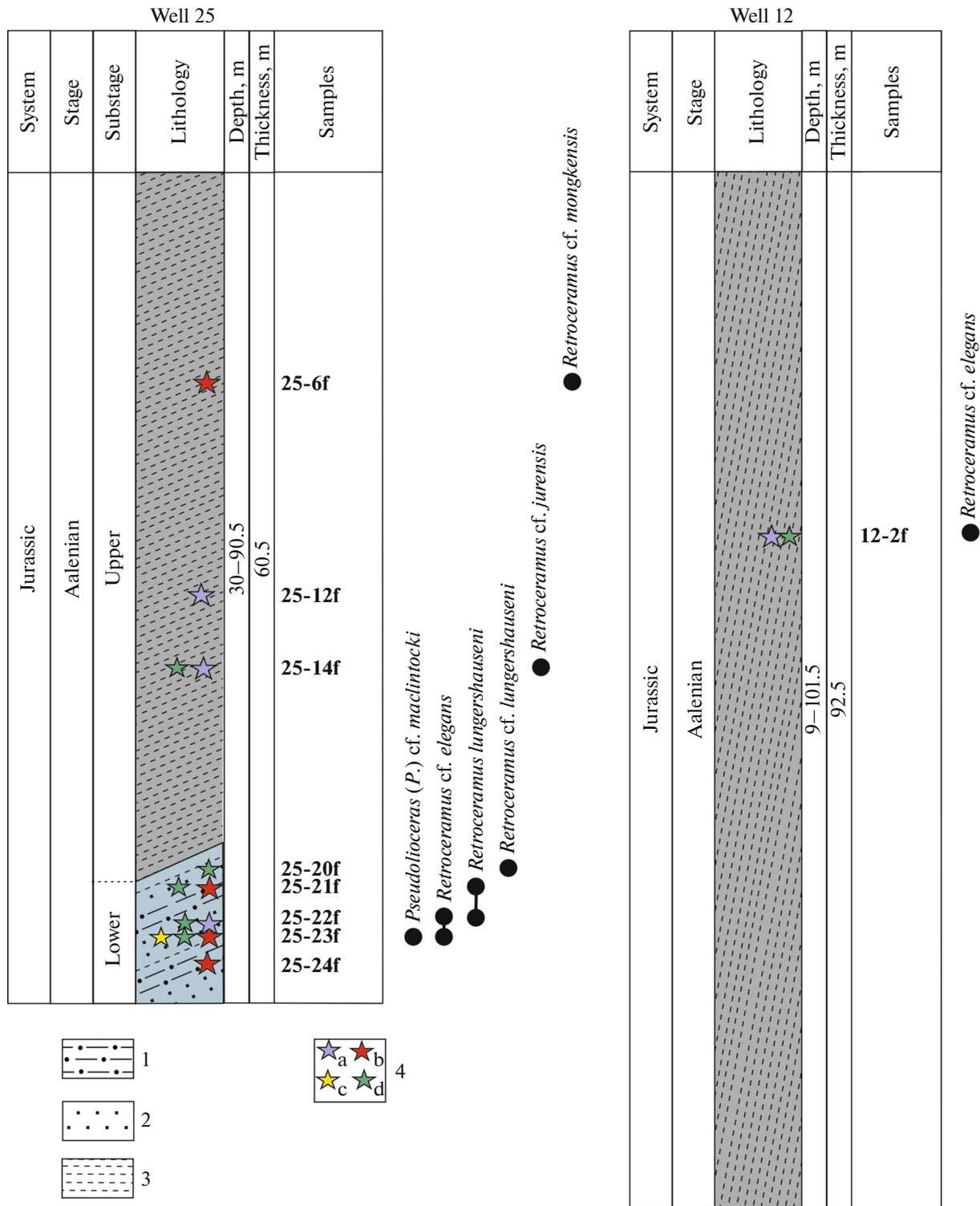


Fig. 2. Lithological columns of wells 12 and 25 with the position of the samples. Legend: (1) siltstones; (2) sands, sandstones; (3) clays, mudstones; (4) position of the samples: (4a) spores and pollen, (4b) detrital zircon, (4c) ammonite, (4d) bivalves.

of 30.0–90.5 m. The pattern of the relationship of the Middle Jurassic deposits with older strata by test wells in the studied area has not been established.

According to Trufanov (1978), the Middle Jurassic terrigenous stratum has a homogeneous lithological

composition and is represented by siltstones, enclosing separate beds of sandstones and mudstones with thickness from several millimeters to 0.1–0.3 m.

Siltstones are gray, dark gray, and brownish gray, slightly lithified, clayey, less often sandy, with a mas-

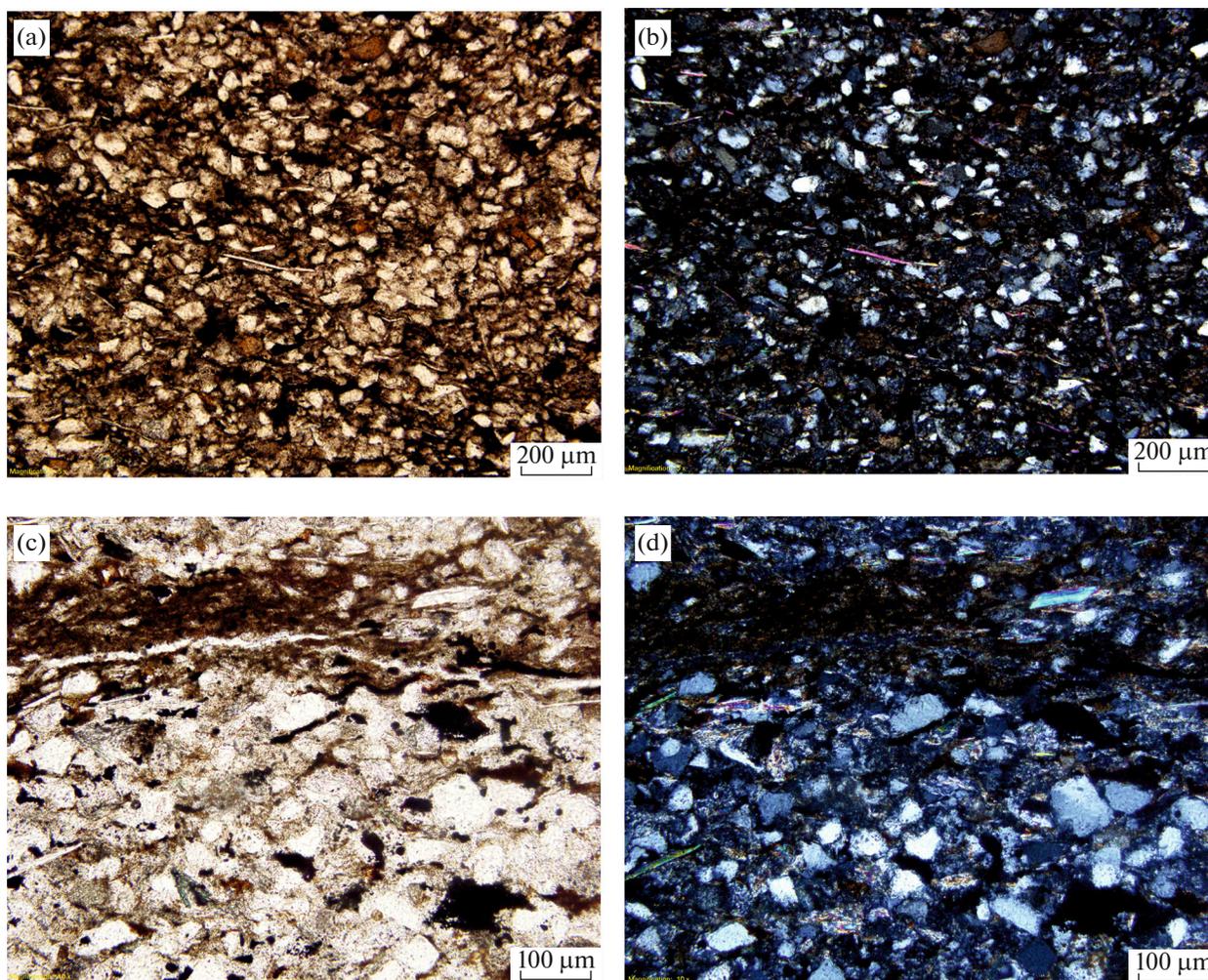


Fig. 3. Images of thin sections of rocks from well 25. (a, b) Sample 25-6f, fine-grained feldspar-quartz sandstone; (c, d) Sample 25-22f, feldspar-quartz sandy siltstone.

sive or thinly layered structure. The composition of the detrital part of siltstones is polymictic and is represented by quartz, feldspar, mica, and rock fragments (Fig. 3). The rocks contain single siderite nodules up to 5 cm in size.

Sandstones are polymictic, ultra-, fine-, and medium-grained, as a rule, inequigranular, massive, and cross-stratified, brownish gray to greenish gray in color (Trufanov, 1978). Quartz grains are angular, semi-rounded, rarely well-rounded; feldspars are angular. Siliceous rocks predominate among the lithic fragments; felsic and intermediate volcanics and metamorphic schists are less common. Mudstones are massive, unstratified, weakly lithified, with, as a rule, an admixture (from 5 to 30–40%) of silty and sandy grains (Trufanov, 1978).

According to Trufanov (1978), abundant remains of bivalves (from Sample 25f-1 to Sample 25f-25) are present throughout the section of the well. According to E.S. Ershova, among them are *Mytiloceramus ele-*

gans (Kosch.),¹ *M. lungershauseni* (Kosch.), *M. jurensis* (Kosch.), *M. cf. elegans* (Kosch.), *M. cf. lungershauseni* (Kosch.), *M. cf. jurensis* (Kosch.), *M. cf. menneri* (Kosch.), *M. sp. indet.*, *M. sp. juv.*, and *Dacryomya cf. lacrima* (Sow.). In addition, a fragment of the lateral side of the ammonite mold (Sample 25f-23) of *Pseudolioceras* sp. (aff. *maclintocki*. (Haught.)) was found at the base of the section. According to E.S. Ershova, similar bivalves are found in the Aalenian deposits of the Priverkhoyansk Foreland Basin trough and in the Kolyma and Omolon river basins.

In addition, V.A. Basov and N.V. Sharovskaya studied 19 samples from well 25 and identified diverse foraminifera belonging to the upper part of the lower Aalenian—middle Aalenian assemblage with *Saccamina ampullacea* and *Lenticulina nordvikensis* (Trufanov, 1978).

¹ Hereinafter, the determination given in the literature are given in their original version.

In well 12, a subvertical unit of weakly cemented layered clay siltstones containing individual brown siderite nodules of up to 5 cm across was penetrated in the depth range of 9–101.5 m. The layering of the deposits is determined by the presence of thin (up to 3 mm) layers of lighter sandy siltstone.

Poorly preserved shells of bivalves (specimens 12f-1–12f-5) *Mytiloceras elegans* (Kosch.) (determination by E.S. Ershova) and foraminifers (specimens 12f-4, 12f-5) *Nodosaria candela* Franks and *Lingulonodosaria fimbriata* Scharov. (determination by N.V. Sharovskaya) were found in the siltstones (Trufanov, 1978).

The Aalenian silty-clayey deposits were referred by Nikitenko et al. (2017) as the Zeeberg unit (Fig. 2) with a stratotype in the 30.0–90.5 m interval of the well 25 section. The contacts of this unit with the underlying deposits have not yet been found; it is overlain by Cenozoic terrigenous deposits. Three zonal foraminiferal assemblages, in which calcareous species are quantitatively dominant and taxonomically diverse, have been identified in the sections of wells that penetrate the Zeeberg unit. In the lower part of the well 25 section, in the unit of frequent alternation of siltstones and sandy siltstones (Nikitenko et al., 2017, 2018) (Fig. 2), abundant foraminifera, typical of the upper part of the upper Toarcian–lower Aalenian *Astacolus praefoliaceus*–*Lenticulina multa* (JF12) Zone, were identified. The higher horizons of the Zeeberg unit are attributed to the *Astacolus zwetkovi* (JF16) Zone (upper part of the lower Aalenian–upper Aalenian), while the upper part of this unit is attributed to the *Lenticulina nordvikensis* (JF17) Zone (upper part of the upper Aalenian).

In addition, Nikitenko et al. (2018) attributed the Murunnakh unit to the upper Toarcian. This formation contains the foraminiferal assemblage of the *Trochammina taimyrensis* (JF13) Zone; in the lower part, there are dinocysts of the *Phallocysta eumekes* and *Susadinium scrofoides* (JD3) zones and spore-pollen assemblage of the upper Toarcian *Piceapollenites variabiliformis* Palynozone (*Cyathidites minor*, *Osmundacidites* spp., Dipteridaceae, *Marattisporites scabratus* (JSP7)). Considering that the upper part of the foraminiferal JF12 Zone and the JF13 Zone correspond to the same upper Toarcian–lower Aalenian stratigraphic interval (Nikitenko, 2009, p. 220; Nikitenko et al., 2013, p. 1066), one can suggest that the lower part of the Zeeberg unit and the upper part of the Murunnakh unit are coeval.

RESULTS

Ammonites

The collection includes a single small ammonite, which was found in the lower part of the section of well 25 (specimen 25-23f, Plate I, fig. 1). This specimen, represented by an internal mold and imprint, was defined by E.S. Ershova as *Pseudolioceras* sp. (aff.

maclintocki (Haught.)). We have reidentified this species as *P. (P.) cf. mclintocki* (Haught.) and its description is given below. *P. (P.) mclintocki* is common in lower Aalenian deposits of the Arctic. Its findings are known in Svalbard, Franz-Josef Land, the north of Eastern Siberia, and the Northeast and Far East of Russia, as well as in Canada and Northern Alaska (Imlay, 1976; Repin, 2017). Lower Aalenian ammonite assemblages from the above regions are characterized by low taxonomic diversity. Only in Arctic Canada *Leioceras opalinum* and *Tmetoceras* occur together with *P. (P.) mclintocki*/*P. (P.) cf. mclintocki* (Friebold, 1960; Poulton, 1991). It is probable that, in Svalbard, *P. (P.) mclintocki* and *Leioceras* were found in the same stratigraphic interval. However, all Aalenian ammonites were found in conglomerate bearing a Toarcian–Aalenian mixed faunal assemblage (Ershova and Repin, 1983).

SUPERFAMILY HILDOCERATOIDEA HYATT, 1867

FAMILY HILDOCERATIDAE HYATT, 1867

SUBFAMILY HARPOCERATINAE NEUMAYR, 1875

Genus *Pseudolioceras* Buckman, 1889

Subgenus *Pseudolioceras* Buckman, 1889

Pseudolioceras (Pseudolioceras) cf. mclintocki (Haughton, 1858)

Plate I, fig. 1

Description. The specimen is represented by an impression and the internal mold of an incomplete (less than half a whorl has been preserved) juvenile specimen. Shell small-sized (the preserved part of about 3 cm in diameter), with moderately narrow umbilicus. Sculpture is represented by well-defined single primary ribs (~7 per quarter whorl). The ribs, inclined towards the mouth, appear slightly above the umbilical seam. Above the lower third of the lateral side, they curve, becoming sickle-shaped, and then weaken and almost disappear near the ventral side. Owing to the high degree of compression of the specimen, it is difficult to determine the cross section of the whorls. The keel is well defined, suture line is not preserved.

Comparison. The specimen we have studied differs from typical *P. (P.) mclintocki* (Haught.) (see, for example, the specimens figured in (Krymholtz, 1977; Sey and Kalacheva, 1980; Repin, 2017)) in slightly pronounced ribs in the upper part of the whorls, while this species is characterized by a strongly pronounced sculpture in the upper part of the lateral side. At the same time, there are findings of *P. (P.) mclintocki* that also have more pronounced ribs in the umbilical part of the whorl, at least on the internal whorls (Kalacheva and Sey, 1972, pl. III, figs. 1, 2, 8; Sey and Kalacheva, 1980, pl. V, figs. 9, 13; Knyazev, 1991, pl. 12, fig. 15). In terms of well-defined primary ribs, it resembles some specimens belonging to the younger subgenus *Pseudolioceras (Tugurites)* (Knyazev et al., 2007a, pl. 2, figs. 7, 11–14), but differs from them in an indistinct umbilical seam.

Remarks. In most publications, this species is called *P. maclintocki*. However, Haughton (1858, p. 244) described this taxon as ammonites *M'Clintocki*. According to the Code of Zoological Nomenclature (*Mezhdunarodnyi...*, 2004, Article 32.5.2.3), the name *M'Clintocki* should be corrected to *maclintocki*. The type specimen of *P. (P.) maclintocki* (the holotype according to the monotypy, represented by a fragment of a whorl) was known until recently only from the drawing (Haughton, 1858, pl. IX, figs. 2–4) and was considered lost (Repin, 2017). This specimen, however, was recently discovered in the collection of the Royal Dublin Society Museum and re-figured (Monaghan, 2009, fig. 8). Although the drawing in Haughton's work is somewhat idealized, it generally accurately illustrates the features of this type of sculpture.

Material. The collection contains a compressed fragment of ammonite (less than half a whorl) and its impression, field number 25f-23/1. Collections: New Siberian Islands, Bunge Land, Gedenstrom Bay, well 25, depth ~86 m, Middle Jurassic, lower Aalenian.

Bivalves

In the core of well 25, a sequence of bivalves of the genus *Retroceramus* was identified that makes it possible to distinguish two assemblages. Specimens similar to *Retroceramus elegans* (Kosch.) (Plate I, figs. 2–4) and *Retroceramus lungershauseni* Kosch. were found in Samples 25-23f, 25-22f, 25-21f, and 25-20f (Plate I, figs. 7–9). The species *Retroceramus elegans*, which is characterized by oval valves, oblique, equivalve, and non-equilateral shapes of a shell, has been described in Beds with *Pseudolioceras maclintocki* in the Moto-rchuna and Molodo river basins in Eastern Siberia. *Retroceramus lungershauseni*, which is characterized by rounded-oval valves, apices not protruding above the hinge line, and a short hinge line, is known from the lower Aalenian deposits in the Molodo River basin (Koshelkina, 1963).

A specimen similar to *Retroceramus jurensis* (Kosch.) was found in Sample 25-14f (Plate I, fig. 10). The species *Retroceramus jurensis*, which is characterized by

elongated-oval outlines and well-separated apices, is known from the upper Aalenian in the Anadyr River basin (Northeastern Russia) from Beds with *Tugurites* cf. *tugurensis* Kalatsheva et Sey (Koshelkina, 1969). In the Anabar Bay section (Eastern Siberia), this species is described in upper Aalenian *Pseudolioceras* (*Tugurites*) *whiteavesi* Zone (Meledina and Shurygin, 2000). An incomplete specimen from Sample 25-6f was determined as *Retroceramus* cf. *mongkensis* Kosch. *Retroceramids* with narrow, elongated-oval shells, typical of *R. mongkensis*, and frequent rounded dichotomous concentric folds covering the entire shell surface are known from the lower part of the upper Aalenian deposits in the Mongke River basin, Northeastern Russia (Koshelkina, 1969, 1980), and from the upper Aalenian of the Anabar Bay, Eastern Siberia (Meledina and Shurygin, 2000).

One incomplete and one juvenile specimen were described in Sample 12-2f from well 12 and were referred as early Aalenian *Retroceramus elegans*.

The distribution of retroceramids across well 25 allows us to distinguish zones that are conventionally correlated with lower Aalenian (*R. elegans* Zone) and upper Aalenian (*R. jurensis* Zone). In well 12, only early Aalenian taxa of the *R. elegans* Zone were recognized.

Aalenian Stage of the Arctic and Problems of Its Bivalve Zonation

The substantiation of the boundaries of the Boreal Aalenian and its correlation with Tethyan equivalents is one of the difficult issues of Jurassic stratigraphy. Epicontinental seas in Siberia and the Far East were a part of the Pan-Boreal Superrealm in the Jurassic in the rank of the Arctic Realm (Saks et al., 1971; *Paleogeografiya...*, 1983; Zakharov et al., 2003). From the late Toarcian to the Bathonian, there were endemic ammonites here. According to this, a direct correlation of local zonal subdivisions with the standard stratigraphic charts of Europe is hardly possible.

The zonal scheme of the Aalenian Stage for the Boreal Jurassic of Russia was first proposed by I.I. Sey and E.D. Kalacheva in the Far East when studying the

Plate I. Aalenian mollusks from the core samples. (1) *Pseudolioceras (P.)* cf. *maclintocki* (Haught.), specimen 25f-23/1, internal imprint, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-23, Middle Jurassic, lower Aalenian; (2–6) *Retroceramus* cf. *elegans* (Kosch.): (2) specimen 25f-23/2, internal molds of left valves, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-23, Middle Jurassic, lower Aalenian; (3) specimen 25f-22/1, internal mold of left valve, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-22, Middle Jurassic, lower Aalenian; (4) specimen 25f-22/2, internal mold of right valve, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-22, Middle Jurassic, lower Aalenian; (5) specimen 12f-2/1, internal mold of left valve with broken apex, ×1; New Siberian Islands, Bunge Land, well 12, sample 12f-2, Middle Jurassic, lower Aalenian; (6) specimen 12f-2/2, internal mold of right valve of a juvenile specimen, ×1; New Siberian Islands, Bunge Land, well 12, sample 12f-2, Middle Jurassic, lower Aalenian; (7, 8) *Retroceramus lungershauseni* (Kosch.): (7) specimen 25f-22/3, internal mold of left valve, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-22, Middle Jurassic, lower Aalenian; (8) specimen 25f-21/1, internal mold of right valve, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-21, Middle Jurassic, lower Aalenian; (9) *Retroceramus* cf. *lungershauseni* (Kosch.), specimen 25f-20/1, internal mold of left valve, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-20, Middle Jurassic, lower Aalenian; (10) *Retroceramus* cf. *jurensis* (Kosch.), specimen 25f-14/1, internal mold of the left valve of a juvenile specimen, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-14, Middle Jurassic, upper Aalenian; (11) *Retroceramus* cf. *mongkensis* Kosch., specimen 25f-6/1, internal mold of the left valve with a broken upper part, ×1; New Siberian Islands, Bunge Land, well 25, sample 25f-6, Middle Jurassic, upper Aalenian.



sections of the Torom trough (Kalacheva and Sey, 1972; Sey and Kalacheva, 1980). Ammonite assemblages were traced here and the ammonite zonation, including the *Pseudolioceras* (*P.*) *beyrichi*, *P.* (*P.*) *mclintocki*, and *P.* (*Tugurites*) *tugurensis* zones, was developed for the Aalenian. These subdivisions became the basis of the Aalenian zonal scale of the Northeast of Russia and Siberia (*Zonal'naya...*, 1991).

Pseudolioceras beyrichi is the only ammonite species described from Toarcian–Aalenian boundary deposits in the Tethyan and Boreal sections. Kalacheva and Sey (1967), who studied the Jurassic sections of the Western Okhotsk region, came to the conclusion that this species in Western Europe, the Caucasus, and the East of the Soviet Union is predominantly of early Aalenian age. At the 2nd Far Eastern Interdepartmental Stratigraphic Meeting, Beds with *Pseudolioceras beyrichi* were included in the lower Aalenian *Pseudolioceras mclintocki* Zone (*Reshenie...*, 1971). This decision led to the adoption of the Aalenian age of the Beds with *Pseudolioceras beyrichi* in the stratigraphic schemes of Northeast of the Soviet Union (*Resheniya...*, 1978) and Siberia (*Resheniya...*, 1981).

Later, it was established that *Pseudolioceras beyrichi* in sections of Western Europe appear in the late Toarcian. In sections of Britain, *Pseudolioceras beyrichi* is distributed in the upper Toarcian *Dumorteria levesquei* Zone and lower Aalenian *Leioceras opalinum* Zone (Howarth, 1992). In France, *P. beyrichi* was found in the upper subzone of the upper Toarcian *Dumortieria pseudoradiosa* Zone (Elmi et al., 1997). Recently, there has been information about the presence of *Pseudolioceras beyrichi* in the *Pleydellia aalenis* Subzone in Germany (Arp, 2010; Arp et al., 2021).

According to Repin (2017), *P. (P.) beyrichi* from Siberia and the Northeast and Far East of Russia differs from the European representatives of this species in a more weakly pronounced sculpture. This suggests that it should belong to the subspecies *P. (P.) beyrichi orientale* Repin, 2017. Yu.S. Repin believes that *P. (P.) beyrichi orientale* is characteristic of the lowermost Aalenian. However, there is no direct evidence of the age of these ammonites in the Arctic, and the *Beyrichi orientale* Zone proposed by Repin may be fully or partially attributed to the upper Toarcian.

On the basis of the material from Northern Siberia, a continuous phylogenetic sequence of closely related species—*P. (P.) falcodiscus* (Quenst.) and *P. (P.) beyrichi* (Schloen.)—was noted in the terminal Toarcian (Knyazev, 1991; Knyazev et al., 2007a, 2007b). Therefore, V.G. Knyazev proposed to distinguish the Toarcian–Aalenian boundary in Northeast Asia on the basis of the first occurrence of “typical *P. (T.) mclintocki* (Haught.), which is characterized by a ‘ribbed stage’ spanning more than two whorls, including a living chamber” (Knyazev et al., 2007b, p. 40).

Since *P. (P.) beyrichi* and *P. (P.) mclintocki* occur rarely in the Boreal sections and their stratigraphic position is unclear, data from other fossil groups can be used to establish the boundary of the Lower and Middle Jurassic. In the Boreal regions of Russia, a bivalve scale based on the genus *Retroceramus* has been developed and it is widely used together with the ammonite scale. However, the correlations between retroceramid scales have so far been based only on data from ammonites (Fig. 4). Accordingly, the position of individual bivalve zones in the scales is unstable. The *Retroceramus elegans* Zone in Siberia is placed in the middle part of the upper Aalenian (*Reshenie...*, 2004). In Northeast Russia, this zone corresponds to the upper Aalenian (*Resheniya...*, 2009), whereas according to Z.V. Koshelkina, *Retroceramus elegans* is of early Aalenian age (Koshelkina, 1963).

The ancient retroceramids in the sections of Eastern Siberia belong to *menneri* and *elegans* groups (Koshelkina, 1963). Their first occurrence was reliably recorded in Beds with *Pseudolioceras (P.) mclintocki* in the Motorchuna and Molodo river sections (Koshelkina, 1963; *Stratigrafiya...*, 1976). In the Kelimyar River section, the interval with *Pseudolioceras (P.) beyrichi* is at a lower level compared to the level of the first occurrence of *Retroceramus elegans* (Lutikov, 2024). In the Viliga River basin, the level with *Pseudolioceras beyrichi* is also lower in the section compared to Beds with *Retroceramus elegans* and *Pseudolioceras mclintocki* (Koshelkina, 1980). In the Mongke River sections, *Retroceramus elegans* was found together with ammonites *Pseudolioceras mclintocki* in the same beds (Koshelkina, 1980). In the Far Eastern sections, the specific oldest retroceramids occur together with *P. (P.) beyrichi* (Sey, 1972; Sey and Kalacheva, 1980). It should be noted that *Retroceramus mytiliformis* (Fantini) and *R. elburzensis* (Fantini), which appear together with *Pseudolioceras (P.) beyrichi*, were first described in the Toarcian deposits in Iran and were recorded in the assemblage together with late Toarcian ammonites *Polyplectus* sp. ind., *Pleydellia* sp. ind., *Grammoceras* cf. *fluitans* (Dumortier), and *Dumortieria* cf. *tabulata* Buckman (Fantini Sestini, 1966). The first occurrence of *Retroceramus elegans* was noted in *Pseudolioceras mclintocki* Zone in the Tugur Bay and the Bureya River basin (Sey and Kalacheva, 1980). Taking into account the fact that the occurrence of *Pseudolioceras (P.) beyrichi* in the upper Toarcian is confirmed by the joint occurrence with zonal late Toarcian ammonites in the European sections, the lower boundary of the Middle Jurassic in Eastern Siberia and Northeast Russia can be correlated with the base of the *Pseudolioceras mclintocki* Zone and the first occurrence of retroceramids from the *elegans* group in sections. Despite the fact that the identification of the Toarcian–Aalenian boundary may seem somewhat arbitrary, there is an objective advantage to using this boundary compared to the boundaries used in existing regional schemes, as the boundary is distin-

International Stratigraphic Chart	General Stratigraphic Chart	Boreal Atlantic Realm (northwestern Europe)		Arctic area (Northeast Asia)		Boreal zonal ammonite standard	Bivalve zonal scale of Northeast Russia	Bivalve zonal scale of Siberia	New Siberian Islands			
Cintini et al., 1997	Zony..., 1982	Howart, 1992; Contini et al., 1997		Repin, 2016, 2017	Knyazev, 1997; Knyazev et al., 2007	Zakharov et al., 1997	Repin and Poluboko, 2004; Resheniya..., 2009	Resheniya..., 2004; Shurygin et al., 2011	This work			
Stage	Sub-stage	Stage	Sub-stage	Zone	Subzone	Zone	Zone	Zone	Zone, Beds*	b-Zone	Zone	b-Zone
Aalenian	Upper	Aalenian	Upper	Grafoceras concavum	Graphoceras formosum	Pseudolioceras (Tugurites) whiteavesi	Pseudolioceras (Tugurites) whiteavesi	Pseudolioceras (Tugurites) whiteavesi	Retroceramus elegans—Retroceramus jurensis	Retroceramus jurensis	No units have been established	Retroceramus jurensis
					Graphoceras concavum							
				Brasilia bradfordensis	Brasilia gigantea							
	Brasilia bradfordensis											
	Ludwigia murchisonae			Ludwigia murchisonae								
				Ludwigia haugi								
Lower	Lower	Leioceras opalinum	Leioceras bifidatum	Pseudolioceras maclintocki	Pseudolioceras maclintocki	Pseudolioceras maclintocki	Retroceramus priscus, Retroceramus menneri*	Retroceramus priscus, Retroceramus menneri*	Mclearnia kelmyarensis	Pseudolioceras maclintocki	Retroceramus elegans	
			Leioceras opalinum	Pseudolioceras beyrichi orientale								Pseudolioceras beyrichi
Toarcian	Upper	Toarcian	Upper	Dumorteria levesquei	Pleydellia aalensis	Pseudolioceras replicatum	Pseudolioceras falcodiscus	Pseudolioceras falcodiscus	Arctotis marchaensis	Dacryomya gigantea	No units have been established	No units have been established
					Dumorteria moorei							
					Dumorteria levesquei							
	Phyloseogrammoceras dispansum											
	Grammoceras thouarsense			Pseudo-grammoceras fallaciosum	Pseudolioceras danilovi	Pseudolioceras wuerttenbergeri	Pseudolioceras wuerttenbergeri	Pseudolioceras wuerttenbergeri	Mytiloceras (Lenoceras) elongatus	Mytiloceras (Pseudo-mytiloides) marchaensis	Arctotis marchaensis	
				Grammoceras striatulum	Pseudolioceras rozenkrantzi							

Fig. 4. Correlation scheme of the ammonite and bivalve zonal scales of the upper Toarcian (without the lower zone) and Aalenian.

guished on the basis of two groups of fauna. Guided by the data obtained from the sections in Germany, which are the most similar to the Arctic sections of the Russian Toarcian, not only for ammonites but also for bivalves (Lutikov, 2024), it can be assumed that the first occurrence of *Pseudolioceras beyrichi* in the sections in Eastern Siberia and Northeast Russia corresponds to the upper Toarcian Pleydellia aalensis Subzone.

The first occurrence of *Retroceramus jurensis* in sections of Eastern Siberia was reliably recorded on the western shore of the Anabar Bay in upper Aalenian Beds with *Pseudolioceras* (Tugurites) *whiteavesi* (Meledina and Shurygin, 2000). In Northeast Russia, this species is found in upper Aalenian Beds with *P. (Tugurites) cf. tugurensis* in the Anadyr River basin (Koshelkina, 1969). Guided by these data, it seems that the *Retroceramus elegans* Zone in the sections of Eastern Siberia and Northeast Russia should be assigned to the lower Aalenian, and the *Retroceramus jurensis* Zone should be assigned to the upper Aalenian, although the substantiation for the position of the boundary between the Aalenian substages in the Arctic remains largely conditional.

On the basis of analysis, the authors' version of the zonal division of the Aalenian of Eastern Siberia is proposed (Fig. 4).

Palynology

The extracted palynomorphs are represented by plant spores and pollen, dinocysts, acritarchs, prasinophytes, and organic linings of foraminifera, which indicates the coastal-marine genesis of the studied deposits. Palynomorphs from well 12 are satisfactory preserved; those from well 25 are poorly preserved; many of them are broken. There are a large number of plant tissue fragments and carbonaceous particles. In general, the palynospectra of the samples from both wells are similar, with the main difference being a decrease in the amount of microphytoplankton and the diversity of spores and pollen and an increase in bisaccate gymnosperm pollen abundance in samples from well 25.

The spore-pollen spectra identified in the core samples are characterized by a high content of bisaccate gymnosperm pollen (Coniferales) and *Osmundacidites* spp. spores (Plate II). *Gingkoecyadophytus*, *Inaperturpollenites*, *Piceapollenites*, *Alisporites*, *Podocarpidites*, and *Schasmatosporites* are the most abundant among gymnosperm pollen. *Cycadopites*, *Quadraeculina limbata*, *Pinuspollenites*, *Sciadopytisipollenites multiverrucosus*, and *Callialasporites* occur sporadically in the form of single specimens. The spores in the samples from both wells have a relatively low diversity.

Along with frequent *Osmundacidites*, various *Stereisporites* (*S. psilatus*, *S. congregatus*, *S. compactus*), *Leiotriletes* sp., and *Lycopodiumsporites* sp. occur relatively constantly (Table 1).

The spore-pollen part of the palynospectra in core samples from wells 12 and 25 are combined into a single palynocomplex, which, according to its systematic and quantitative composition, correlates with the palynocomplex 7b, including *Piceapollenites* spp., *Stereisporites* spp., *Quadraeculina limbata*, *Dictyophyllidites* spp., and *Marattisporites scabratus* and dating back to the late Toarcian–early Aalenian (Ilyina, 1985, 1997; Ilyina et al., 2011; *Reshenie...*, 2004). A special feature of palynospectra of samples from well 25 is a gradual increase from bottom to top along the section in the number of *Cyathidites* spores. The latter are abundant in the upper Aalenian deposits, in the north of Central Siberia (Ilyina, 1985). The fact indicates a relatively higher stratigraphic position of the deposits in well 25, corresponding to the transition from the early to late Aalenian. This is consistent with the data on foraminifera (Nikitenko et al., 2017, 2018) and the above data on bivalves.

Microphytoplankton is abundant and most diverse in sample 12f-2 (well 12), while in samples from well 25, its amount and diversity are lower and significantly reduced up the section (Plate II). The dinocyst complex is characterized by frequent *Phallocysta* (*P. arctica*, *P. eumekes*, *P. elongata*) and *Nannoceratopsis* (mainly *N. gracilis*) with their approximately equal quantitative ratio, which is observed in wells 12 and 25. *Caddasphaera halosa* is common. *Parvocysta* cf. *bullula*, *Parvocysta* cf. *bjaerkei*, *Batiacasphaera* sp., and *Scrinioicassis* cf. *limbicavatus* are present only in the core of well 12. In addition to dinocysts, microphytoplankton is represented by frequent acritarchs, prasinophytes, and organic linings of foraminifera.

The assemblage of dinocysts of the *Phallocysta eumekes* and *Susadinium scrofoides* (JD3) Zone recognized on Kotelny Island in the lower part of the Murunnakh unit (Nikitenko et al., 2018) is similar at the generic level to that identified in Sample 12f-2 (well 12). However, the quantitative ratios in these assemblages are different. Thus, the assemblage of dinocysts from the Murunnakh unit is dominated by *Phallocysta eumekes*, with a small amount of *Phallocysta elongata*, *Mancodinium semitabulatum*, *Nannoc-*

eratopsis spp. (*N. deflandrei senex*, *N. deflandrei*, *N. gracilis*, *N. sp.*), *Valvaeodinium* sp., and *Mencodinium* sp. As in the microphytoplankton complex from wells 12 and 25, frequent acritarchs and prasinophytes are present in the Murunnakh unit.

The assemblage of dinocysts identified in wells 12 and 25 is similar to the assemblages found in the lower Aalenian sections of Eastern Siberia (Kelimyar River) and Taimyr (well Tulai-Kiryakskaya 1) (Goryacheva, 2020, 2022, 2023), which are characterized by extremely low taxonomic diversity (*Phallocysta* spp., *Valvaeodinium* spp.) and the occurrence of dinocysts. In the studied core samples from wells 25 and 12, the composition of acritarchs and prasinophytes, including the rare colonial algae *Botryococcus* sp., is similar to the early Aalenian strata in Eastern Siberia.

The presence of various *Phallocysta* species among the dinocysts indicates that the age of the deposits is no older than the late Toarcian (Ilyina, 1997; *Reshenie...*, 2004; Goryacheva, 2017; Nikitenko et al., 2018). It was previously shown that the dinocyst assemblages of the Siberian Toarcian are similar to those found in the north of England, the Sverdrup Basin, and Svalbard (Ilyina, 1994). In the material we have studied, various small cysts with an intercalary archaeopyle of the “Susadinium Group” (Wille, 1982) or the “Parvocysta Formation” (Riding, 1984), whose frequent occurrence is characteristic of the late Toarcian in Northern Siberia (Ilyina, 1985, 1994, 1997; Goryacheva, 2017, 2023), were found in single specimens only from well 12. The last occurrence of *Parvocysta* cf. *bullula*, and the first occurrence of *Batiacasphaera* sp. and *Scrinioicassis* cf. *limbicavatus* in sections of Sub-Boreal and Boreal areas of Northwestern Europe established in the well 12 are dated to the early Aalenian (Riding, 1984; Riding and Thomas, 1992; Poulsen and Riding, 2003; Feist-Burkhardt and Pross, 2010). This allows the host deposits to be attributed to the lower Aalenian.

It should be noted that *Nannoceratopsis*, which are common in the upper Lower Toarcian in sections of Siberia, are abundant in the material we have studied. At the same time, the presence of *Scrinioicassis* cf. *limbicavatus*, *Valvaeodinium* cf. *cavum*, *Batiacasphaera* sp., and *Caddasphaera halosa* (Plate II), which were not identified in the Siberian Toarcian (Plate II), indicates that the dinocyst assemblages from wells 25 and 12 are similar to the early Aalenian dinocyst assemblage from

Plate II. Typical palynomorphs from Aalenian deposits of the New Siberian Islands. (1, 2) *Phallocysta arctica* (Below) Riding, well 12, sample 12f-2; (3) *Caddasphaera halosa* (Filatoff) Lent. et Will., well 12, sample 12f-2; (4) *Scrinioicassis* cf. *limbicavatus* Prauss, well 12, sample 12f-2; (5) *Phallocysta elongata* (Beju) Riding, well 12, sample 12f-2; (6, 7, 12) *Nannoceratopsis gracilis* Alberti: (6, 7) well 12, sample 12f-2; (12) well 25, sample 25f-22; (8) *Valvaeodinium* cf. *cavum* (Davies) Below, well 12, sample 12f-2; (9, 15) *Baltisphaeridium* spp., well 12, sample 12f-2; (10, 11) *Parvocysta* cf. *bullula* Bjaerke, well 12, sample 12f-2; (13) *Parvocysta* cf. *bjaerkei* Smelror, well 12, sample 12f-2; (14) *Micrhystridium* sp., well 12, specimen 12f-2; (16) *Cyathidites* sp., well 12, sample 12f-2; (17) *Campotriletes tenellus* Sachanova, well 12, sample 12f-2; (18) small spherical phycomata green algae, well 12, sample 12f-2; (19) *Stereisporites psilatus* (Ross) Pflug in Thomson et Pflug, well 12, sample 12f-2; (20) *Stereisporites congregatus* (Bolchovitina) Schulz, well 12, sample 12f-2; (21) *Osmundacidites* sp., well 12, sample 12f-2; (22) *Inaperturipollenites* sp., well 12, sample 12f-2; (23) *Sciadopytisipollenites multiverrucosus* (Sachanova et Iljina) Iljina, well 12, sample 12f-2; (24) *Piceapollenites variabiliformis* (Maljavkina) Petr., well 12, sample 12f-2. All images are presented at the same scale.

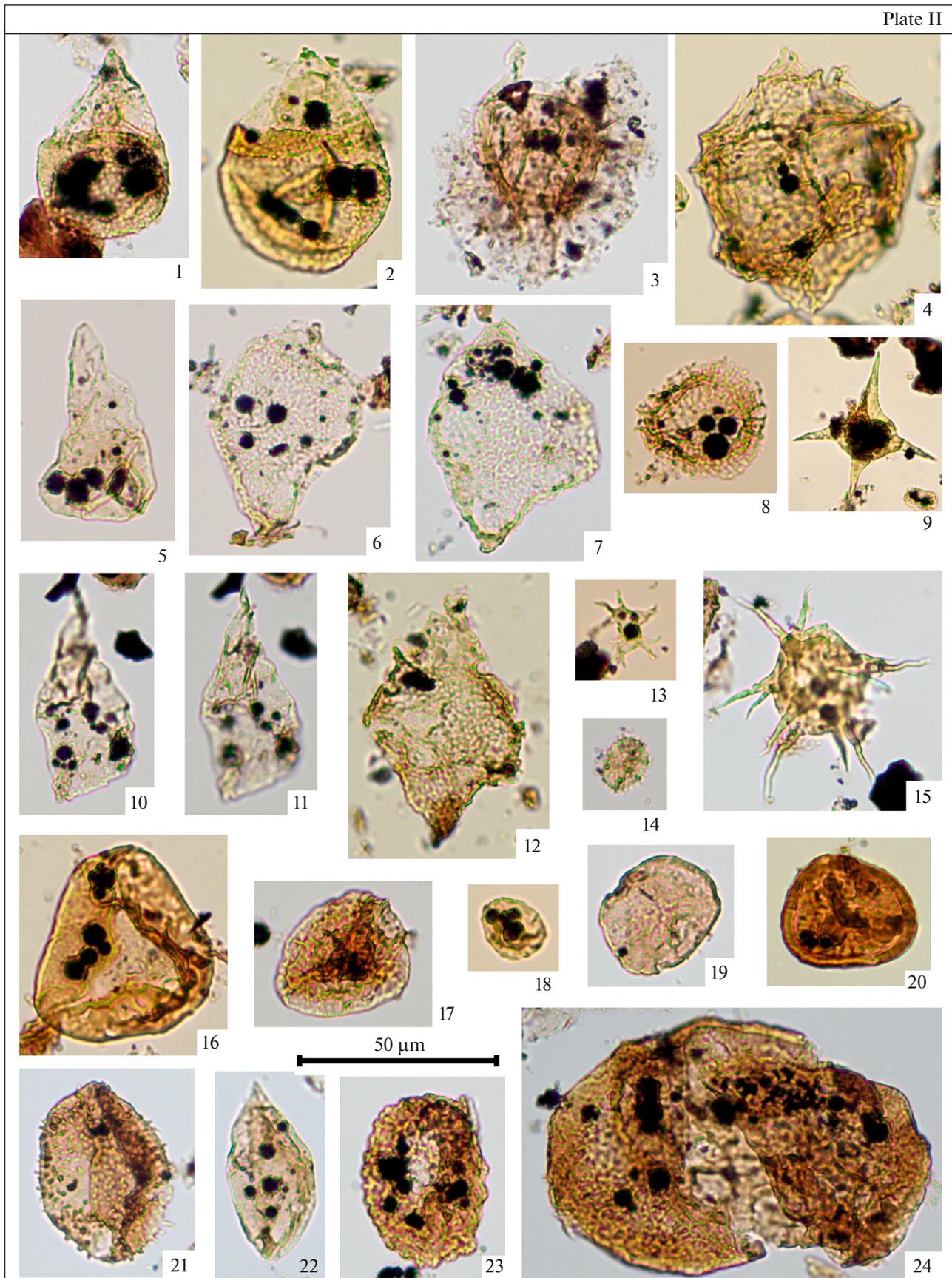


Table 1. Distribution of palynomorphs

System	Jurassic			
Stage	Aalenian			
Palynozone, after (Ilyina, 1997)	7— <i>Piceapollenites variabiliformis</i> , <i>Cyathidites minor</i> , <i>Osmundacidites</i> spp., <i>Marattisporites scabratus</i> , Dpteridaceae			
Beds with spores and pollen, after (Ilyina, 1997)	7b— <i>Piceapollenites</i> spp., <i>Stereisporites</i> spp., <i>Quadraeculina limbata</i> , <i>Dictyophyllidites</i> spp., <i>Marattisporites scabratus</i>			
Beds with dinocysts (this work)	<i>Phallocysta arctica</i> , <i>Caddasphaera halosa</i>			
Samples	25f-12	25f-14	25f-22	12f-2
GYMNOSPERM POLLEN				
<i>Cycadopites</i> sp.	1			1
<i>Gingkokocycadophytus</i> spp.	1	1	1	3
<i>Inaperturpollenites</i> sp.	4	8	8	14
<i>Perinopollenites elatoides</i> Couper				2
Coniferales	104	101	51	25
<i>Piceapollenites</i> sp.	1	3	11	4
<i>Piceapollenites variabiliformis</i> (Maljavkina) Petr.			1	3
<i>Alisporites</i> sp.	1	2	4	3
<i>Pinuspollenites</i> sp.				2
<i>Podocarpidites</i> sp.	2	1	3	1
<i>Sciadopytispollenites multiverrucosus</i> (Sachanova et Iljina) Iljina		1		1
Schasmatosporites sp.	1		2	1
<i>Quadriculina limbata</i> Maljavkina				1
<i>Callialasporites</i> sp.			1	
<i>Sciadopytispollenites</i> sp.			1	
SPORES OF MOSSES AND FERNS				
<i>Stereisporites psilatus</i> (Ross) Pflug in Thomson et Pflug				1
<i>Stereisporites congregatus</i> (Bolch.) Schulz	1	1		2
<i>Stereisporites compactus</i> (Bolch.) Iljina			1	1
<i>Stereisporites</i> sp.		2		
<i>Marattisporites scabratus</i> (Couper) Norris				3
<i>Lycopodiumsporites</i> sp.	1	4		6
cf. <i>Reticulisporites</i> sp.				1
<i>Tripartina variabilis</i> Maljavkina				1
<i>Leiotriletes</i> sp.	3	1	1	3
<i>Deltoidospora</i> sp.				1
<i>Dictyophyllidites</i> sp.				1
<i>Baculatisporites comaumensis</i> (Cookson) Potonié	1			3
<i>Osmundacidites</i> sp.	17	17	7	7
<i>Osmundacidites wellmanii</i> Couper				5

Table 1. (Contd.)

System	Jurassic			
<i>Concavissimisorites verrucosus</i> Delcourt et Sprumont				1
<i>Undulatisporites</i> sp.				1
<i>Contignisporites</i> sp.	1			1
<i>Coronatispora perforata</i> Dettmann				1
<i>Obtusisporis junctus</i> (Kara-Murza) Pocock				1
<i>Camptotriletes tenellus</i> Sachanova				1
<i>Duplexisporites anagrammensis</i> (K.-M. ex Bolch.) Schug.			1	
<i>Cyathidites</i> sp.	5	2	1	
<i>Dicksonia</i> sp.		1		
<i>Duplexisporites</i> cf. <i>gyratus</i> Playford et Dettmann		1		
DINOCYSTS, ACRITARCHS, PRASINOPHYTES				
DINOCYSTS				
<i>Nannoceratopsis gracilis</i> Alberti			1	10
<i>Nannoceratopsis</i> sp.			2	1
<i>Phallocysta arctica</i> (Below) Riding		2	1	5
<i>Phallocysta eumekes</i> Dörhöfer et Davies				1
<i>Phallocysta elongata</i> (Beju) Riding				2
<i>Paraevansia</i> sp.				2
<i>Parvocysta</i> cf. <i>bullula</i> Bjaerke				1
<i>Parvocysta</i> cf. <i>bjaerkei</i> Smelror				1
<i>Caddasphaera halosa</i> (Filatoff) Lent. et Will.	1	1	4	2
<i>Batiacasphaera</i> sp.				1
<i>Scrinocassis</i> cf. <i>limbicavatus</i> Prauss				2
<i>Valvaeodinium</i> cf. <i>cavum</i> (Davies) Below				1
ACRITARCHS				
<i>Baltisphaeridium</i> spp.	1			8
<i>Michhystridium</i> sp.			2	5
<i>Leiofusa jurassica</i> Cookson et Eisenack				1
PRASINOPHYTES				
Tasmanaceae				1
<i>Leiosphaeridia</i> sp.				1
small rounded phycomes of green algae	3			58
<i>Botryococcus</i>	1		1	1
ORGANIC FORAMINIFERAL LININGS	3	1	4	1

the type locality of the Aalenian Stage, where *Nannoceratopsis* are also abundant (Feist-Burkhardt and Pross, 2010).

The occurrence of *P. arctica* with noticeable ornamentation, which is the morphotype of the genus

Phallocysta in wells 12 and 25, is noteworthy. It was previously established that the occurrence of ornamented *Phallocysta* species (*Phallocysta frommernensis*, *Phallocysta thomasi*) is characteristic of the Aalenian deposits in different regions of the Boreal Realm, including the Arctic part of Norway and the Barents

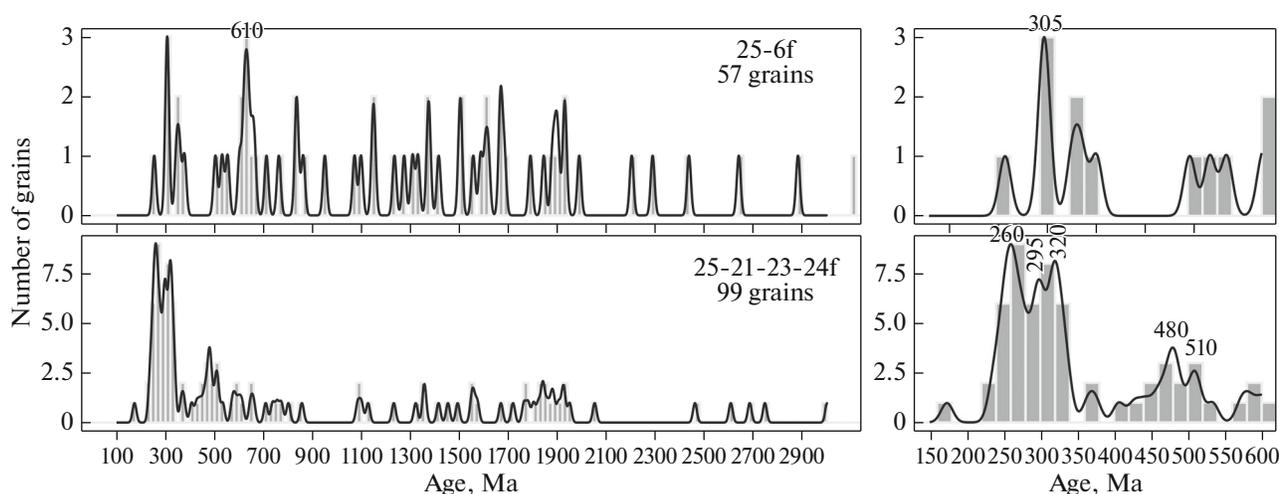


Fig. 5. Kernel Density Estimation (KDE) plots depicting the U–Pb detrital zircon data from of detrital zircons from Aalenian deposits in well 25: (a) 0–3500 Ma; (b) 100–900 Ma.

Sea (Smelror, 1991; Bujak et al., 2022), southwestern Germany, and northern Switzerland (Feist-Burkhardt and Pross, 2010).

Results of U–Pb Dating of Detrital Zircons and Reconstruction of Provenance Areas

Samples 25-21f, 25-23f, and 25-24f collected from the lower Aalenian section in well 25 (Fig. 2) show a similar distribution of detrital zircon ages, and the data obtained were used together to create plots and for further interpretation (Fig. 5). Overall, 45% of detrital zircon grains have Precambrian age, and 17% are Paleoproterozoic, forming a distinct cluster in the age range of 2000–1750 Ma. There are also single grains of Archean age. The next group of zircon grains (35%) are of Meso- and Neoproterozoic age, forming two main populations in the age ranges of 1600–1300 and 650–550 Ma. Paleozoic zircon grains account for 49% of the dated grains, with Late Paleozoic crystals being predominate. These zircons form distinct age groups of approximately 320, 295, and 260 Ma. Early Paleozoic grains are grouped about 510 and 480 Ma. Triassic grains (5%) do not form significant peaks. In the sample, one grain yielded a Jurassic age of 173.4 ± 6.7 Ma.

In the core sample 25-6f of upper Aalenian sandstones from well 25 (Fig. 2), Precambrian detrital zircons (80%) are the most abundant, with Meso- and Neoproterozoic zircons predominating. There are two zircon assemblages of Paleozoic age: Early Paleozoic with Cambrian–Early Ordovician and Carboniferous with the crystallization age ranging from 350 to 305 Ma (Fig. 5).

The age distribution of detrital zircon in the samples is very similar and indicates the same provenance area (Fig. 5). Single Archean (2900–2600 Ma) and Late Paleoproterozoic (1900–1700 Ma) zircon grains are present. The coeval magmatic and metamorphic

events are recorded in the basements of all major continents, for example, Siberia and Baltica (Smelov and Timofeev, 2007; Bogdanova et al., 2008; Donskaya, 2020). However, Late Paleoproterozoic and Mesoproterozoic zircon grains do not directly correlate with the igneous and metamorphic rocks known in the basement of Siberia, as this age interval represents the so-called Siberian amagmatic interval (Siberian Gap) (Gladkochub et al., 2010). The latter is characterized by the lack of felsic and intermediate magmatism of this age on the Siberian continent at this time.

Late Paleoproterozoic dates of detrital zircons (1800–1600 Ma) can be correlated with the age of the Trans-Scandinavian igneous belt (Larson and Berglund, 1992; Andersson et al., 2004; Gorbatshev et al., 2004). The Early Mesoproterozoic zircon ages are well correlated with the age of magmatism associated with the Telemark orogeny of Baltica that happened at 1.52–1.48 Ga (Bingen et al., 2008a, 2008b; Roberts et al., 2013; Slagstad et al., 2020). Numerous zircon ages in the range of 1500–1000 Ma likely correspond to the age of magmatic and metamorphic events widespread in the Grenvillian–Sveconorwegian orogenic belt, including older terranes that were involved in orogeny (Bingen et al., 2008a, 2008b; Rivers et al., 2012; Spencer et al., 2014, 2015).

Neoproterozoic zircon ages are of secondary importance, as they mostly fall within the range of 650–550 Ma and are well correlated with accretion-collision events in the Timanian orogenic belt (The Neoproterozoic..., 2004; Kuznetsov, 2006, 2008; Gee et al., 2008; Kuznetsov et al., 2010).

The Early Paleozoic detrital zircons yielded a wide range of ages, ranging from 510 to 420 Ma, which can be grouped into two main peaks around 510 and 480 Ma. Magmatic and metamorphic events dating back to the Early–Middle Paleozoic are widely manifested in the Caledonian fold belt (Roberts, 2003; Gee et al., 2008;

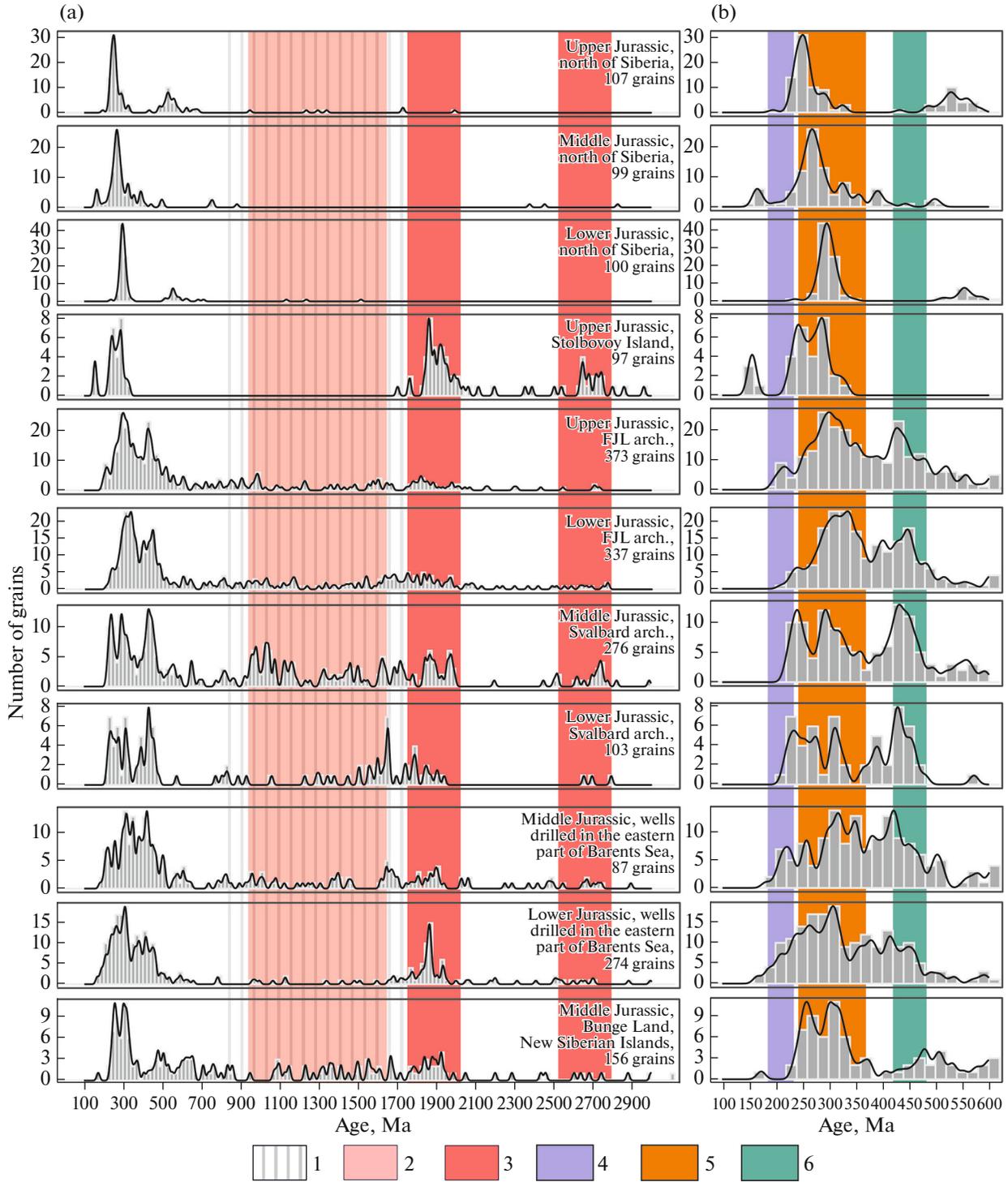


Fig. 6. Kernel Density Estimation (KDE) plots depicting the U–Pb detrital zircon data from the Jurassic deposits of the Arctic. (1) Siberian magmatic gap; (2) Grenvillian–Sveconorwegian orogeny, including metamorphic and magmatic events in the terranes involved; (3) the basement of the Siberian Platform; (4) Early Kimmerides; (5) Hercynides; (6) Caledonides. Our data were used for the Aalenian deposits of the southeast of Kotelny Island (New Siberian Islands). Published sources for other deposits: Jurassic–Cretaceous deposits from wells drilled in the Russian segment of the Barents Sea (Khudoley et al., 2019); Jurassic deposits on Svalbard (Pózer and Andresen, 2014, Røhr and Andersen, 2009); Jurassic deposits in the Frantz Josef Land (FJL) archipelago (Ershova et al., 2022b); Upper Jurassic–Lower Cretaceous deposits on Stolbovoy Island (New Siberian Islands) (Soloviev and Miller, 2014); Jurassic deposits in the north of Siberia (Vereshchagin et al., 2018). (a) 0–3500 Ma; (b) 100–900 Ma.

Corfu et al., 2014; Gee, 2015). In addition, Early–Middle Ordovician magmatic events have also been identified in the Kara Terrane (October Revolution Island, Severnaya Zemlya archipelago) (Lorenz et al., 2007; Prokopiev et al., 2019; Kurapov et al., 2020).

The Late Paleozoic dates of zircons are correlated with various magmatic and metamorphic events of the Uralides, which are manifested both in the Urals (Puchkov, 2000, 2010) and in the basement of the West Siberian Plate. Numerous Late Paleozoic intrusions are also widespread in the Taimyr–Severnaya Zemlya fold system (northeastern branch of the Uralides) (Augland et al., 2019; Vernikovskiy et al., 2020; Kurapov et al., 2021a, 2021b, 2024).

An analysis of the age distribution of clastic zircons allows us to conclude that the Grenvillian–Sveconorwegian, Timanian, Caledonian, and Hercynian orogenic belts or redeposited products of their erosion were the source of clastic material.

A comparison of the age spectra of detrital zircons from Jurassic deposits of the northern Siberian Platform, the New Siberian Islands archipelago, and the Barents Sea region demonstrates that the Aalenian deposits in the southeastern part of Kotelny Island most closely correspond to the Jurassic strata of the Barents Sea region (Fig. 6).

It is worth noting once again that the age distribution of detrital zircon from the Upper Jurassic deposits of Stolbovoy Island (Miller et al., 2008) differs significantly from that for zircons from the Aalenian deposits of the southeast of Kotelny Island (Fig. 6). This is in good agreement with the proposed location of the South Anyui suture between Stolbovoy Island and the Anjou Islands of the New Siberian Islands archipelago (for example, Prokopiev et al., 2018b).

The data obtained clearly indicate that the Jurassic deposits of Stolbovoy Island represent the distal part of the passive margin of the Siberian continent, and the Anjou Islands and the surrounding shelf, as in the Paleozoic, were located in the Middle Jurassic as part of an exotic block relative to the Siberian continent.

The similarity in the age distribution of clastic zircons from Aalenian deposits of the south-east of Kotelny Island and Jurassic deposits of the Barents Sea region (Fig. 6) supports the assumption that the Anjou Islands, part of the New Siberian Islands archipelago, were located on the Barents Sea shelf not only during the Paleozoic (Ershova et al., 2015a, 2015b, 2018) but also in the Jurassic.

CONCLUSIONS

On the basis of ammonite and bivalve findings in well cores, the presence of Aalenian deposits on the New Siberian Islands is substantiated. For the first time, representative species of bivalves of the genus *Retroceramus* and ammonites of the genus *Pseudolioceras* from this region are illustrated. Although the cor-

relation of Boreal Aalenian schemes with the standard Western European scales remains largely tentative, the newly obtained data—considered together with evidence from adjacent Arctic regions—enable recognition of both Aalenian substages in the studied succession. The Aalenian mollusk assemblages of the New Siberian Islands exhibit low taxonomic diversity but are closely comparable in composition to coeval faunas from other Arctic provinces.

Palynological analysis of lower and upper Aalenian deposits provides the first refined characterization of the high-latitude Aalenian dinocyst assemblage. The early Aalenian is marked by relatively diverse dinocyst assemblages reminiscent of those of the late Toarcian, whereas the late Aalenian shows a noticeable decline in both diversity and abundance. We infer that the reduced dinocyst counts and the presence of ornamented forms of the genus *Phallocysta* reflect a biotic response to intense and rapid global cooling accompanied by a drop in seawater temperature. This interpretation is supported by occurrences of ice-rafted debris (glendonites; Rogov et al., 2023) and a significant decrease in the diversity of marine organisms across the Aalenian in the Arctic (Meledina et al., 2005).

An analysis of the age distribution of detrital zircon indicates that the Grenvillian–Sveconorwegian, Timanian, Caledonian, and Hercynian orogenic belts, or reworked products derived from their erosion, served as the principal source areas for the siliciclastic material. A comparison of detrital zircon age spectra from Jurassic deposits of the northern Siberian Platform, the New Siberian Islands archipelago, and the Barents Sea region reveals that the spectrum obtained for Aalenian deposits in the southeastern part of Kotelny Island most closely matches that of the Jurassic strata of the Barents Sea region. This relationship supports the interpretation that the Anjou Islands represented a continuation of the Barents Sea shelf not only during the Paleozoic but also throughout the Jurassic.

SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at <https://doi.org/10.1134/S0869593825700388>.

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AUTHOR CONTRIBUTION

V.B. Ershova conducted the petrographic analysis of thin sections, dating of clastic zircons, and geodynamic analysis; D. Stockley and L. Stockley also participated in the dating of clastic zircons. The study of the collection of mol-

luses and the revision of their stratigraphy was carried out by O.A. Lutikov (bivalves) and M.A. Rogov (ammonites). Palynological studies were performed by G.N. Aleksandrova.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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