Foraminifera and ostracodes across the Pliensbachian–Toarcian boundary in the Arctic Realm (stratigraphy, palaeobiogeography and biofacies)

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Abstract: The analysis of samples from numerous Pliensbachian and Toarcian sections from the northern regions of Russia and northern Alaska, as well as published data, allow us to estimate the correlative significance of foraminifera and ostracodes, and to develop an Arctic zonal standard based on these microfauna. During the Late Pliensbachian–Early Toarcian depositional period in the Arctic Basin and northwestern seas of Western Europe, a succession of almost simultaneous biotic and abiotic events occurred: widespread development of black bituminous shale at the beginning of the Early Toarcian, and a microbiota crisis (mass extinction event) in the Northern Hemisphere. The Early Toarcian microbiotic crisis was very sharp in both Arctic and Western European palaeobasins. In the Arctic seas, the generic and family composition of ostracode communities was completely replaced by new taxa. The species composition of foraminiferal assemblages changed considerably, while the generic composition of the foraminifera is only characterized by partial changes. In the Western European seas, the Early Toarcian microbenthos crisis caused taxonomic changes generally at the species level among foraminifera and at the generic level among ostracodes. The comprehensive analysis of the biogeographical distribution of Late Pliensbachian and Early Toarcian foraminifera and ostracodes, as well as Jaccard cluster analysis, allow us to define several biogeographical units within the Arctic and Boreal–Atlantic realms. A pattern of ecological distribution of microbenthos in bathymetric zones in Siberian palaeobasins has been developed, providing the basis for palaeoenvironmental reconstructions.

Upper Pliensbachian and Lower Toarcian deposits are widespread in both the Arctic Basin and in NW Europe (Fig. 1). Numerous sections of Upper Pliensbachian–Lower Toarcian microfossils (foraminifera and ostracodes) from the Barents Sea shelf, NW and eastern Siberia, NE Russia and northern Alaska have been investigated by the authors. For comparative analysis, the published data on lithostratigraphy, biostratigraphy and micropaleaeontology of Upper Pliensbachian–Lower Toarcian sections from the NW portion of Western Europe, the North Sea, the Barents Sea shelf and Arctic Canada were included in this study (Norling 1972; Bate & Coleman 1975; Souaya 1976; Lofaldli & Nagy 1980; Copestake & Johnson 1981, 1984, 1989; Wall 1983; Riegraf 1985; Ainsworth 1986, 1987; Gramberg 1988; Malz & Nagy 1989; Basov et al. 1989; Nagy & Johansen 1991; Leith et al. 1992; Embry 1993; Dibner 1998; Arias 2000).


Data on the Pliensbachian–Toarcian microfauna of Arctic regions are not so numerous: mainly comprising descriptions of the foraminifera and ostracodes, as well as taxonomic lists of microfauna from the Pliensbachian–Toarcian

The aim of this paper is to summarize all the data on the distribution of foraminifera and ostracodes in the Upper Pliensbachian and Lower Toarcian deposits of the Arctic regions, evaluate the correlative potential of the foraminifera and ostracodes, and develop an Arctic zonal standard based on these data. Also, we will describe and characterize the Pliensbachian–Toarcian microfaunal turnover of the Arctic region. Despite the fact that the foraminifera and ostracodes are the most widespread groups of Jurassic microfossils present in the differing facies (from brackish to normal marine), these groups are very seldom utilized for palaeobiogeographical purposes (Gordon 1970; Basov 1983). This necessitates the analysis of the biogeographical distribution of the foraminifera.
and ostracodes at the end of the Late Pliensbachian–earliest Toarcian in the Arctic regions on the basis of well-developed biostratigraphy, as well as the development of the patterns of ecological distribution of the microfauna in bathymetric zones in the studied palaeobasins, and the reconstruction of palaeoenvironments.

Stratigraphy

Upper Pliensbachian–Lower Toarcian deposits, both from the Arctic and northwestern areas of Western Europe, are characterized by a succession of sedimentological cycles caused by eustatic events in the world's oceans. The widespread development of Lower Toarcian organic-rich shales allows us to divide the Upper Pliensbachian–Lower Toarcian deposits of the NW areas of Western Europe and the Arctic into two parts: Upper Pliensbachian and Lower Toarcian (Fig. 2). The Lower Toarcian bituminous clays are now regarded as an interregional stratigraphic marker-level, due to typical homogeneous argillaceous composition and comparable thickness (20–40 m) over the vast territory of the Arctic and Europe.

Any stratigraphic and palaeobiogeographical reconstructions are only possible on the basis of reliable and detailed biostratigraphic information. All the deposits of the different Arctic regions are characterized by rich assemblages of foraminifera, ostracodes and palynomorphs, as well as less-abundant ammonites and bivalves, allowing for the definitive correlation of these deposits.

Northeastern Siberia and northeastern Russia

Pliensbachian–Toarcian deposits in northeastern Siberia and northeastern Russia are distributed in numerous outcrops and well-sections, and are characterized by macrofaunas, including ammonites, belemnites and bivalves, and also rich and diverse foraminiferal and ostracode assemblages. During the 1990s, zonation schemes for both Siberia and northeastern Russia based on the foraminiferal (f-zones) and ostracode (o-zones) have been developed and correlated with each other, and tied into the Boreal Ammonite zonal standard (Nikitenko 1992, 1994; Nikitenko & Shurygin 1994a, b; Zakharov et al. 1997; Shurygin et al. 2000). The combination of Jurassic zones based on foraminiferal and ostracode data has allowed us to calibrate the sections of Arctic Russia (Nikitenko 1992, 1994; Nikitenko & Shurygin 1994a, b; Shurygin et al. 2000).

The Upper Pliensbachian in the northern portion of central Siberia is represented by sediments of the upper part of the Zimnyay Formation comprising marine and near-shore sandstones, mudstones and siltstones (Fig. 3). In the west, the Zimnyay Formation is overlain by argillites and clays with pebbles, and thin layers of organic-rich shale of the Levinskiy Formation. In the central areas, it is overlain by clays and silt clays of the lower part of the Airkat Formation, while in the eastern areas (lower reaches of the Lena River) it is overlain by clays and silts of the Kyra Formation. In the upper part of the Zimnyay Formation, and lower parts of the Levinskiy, Airkat and Kyra formations, the *Ammodiscus siliceus* JF3 Zone (uppermost Lower Pliensbachian–basal Upper Pliensbachian) has been established. Foraminiferal assemblages of this zone are characterized by an abundance of *Ammodiscus siliceus* (Fig. 3). *Trochammina inusitata* is subsidiary, while other foraminifera (*Turritellina volubilis*, *Jaculella jactatica*, *Spiroplectammina* sp. 1, *Astacluba varianis*, *Geinitzinita tenera* and *Marginulinosita hatangensis*) are rare. In this part of the section, the ostracodes (*Ogmoconcha longula*, 'Mandelstamia' sp.) are rare, characterizing the *Ogmoconcha longula* JO2 Zone (Hettangian–basal Lower Toarcian) assemblage (Figs 4 & 5).

The foraminiferal assemblage of the overlying *Trochammina lapidosa–Frondiculinita dubiella* JF5 Zone (middle *stokesi* Ammonite Zone) is more diverse (Fig. 6h, n & r). *Dentalina gloria*, *Neobulimina* sp., *Nodosaria turgida*, *Marginolina spinata* orbicularis, *M. prima*, *M. quinta* and *Ichthyolaria lustrata* have their inceptions in this zone. The assemblage is dominated by *Trochammina lapidosa*, while *Ammodiscus siliceus*, *Hyperammina odiosa* and *Glomospira ex gr. gordialis* are subsidiary. In some horizons, *Neobulimina* sp. dominate the assemblage. The *Trochammina lapidosa–Frondiculinita dubiella* JF5 Zone occurs in the lower part of the Levinskiy, Airkat and Kyra formations in NE Siberia (Shurygin et al. 2000). In the upper part of the *Trochammina lapidosa–Frondiculinita dubiella* JF5 Zone, the diversity of the ostracodes increases. The lowest occurrence of the *Ogmoconcha oleneakensis*, *Ogmoconcha nordvikensis*, 'Mandelstamia' linearis and *Nanacythere costata* (Fig. 71, o, p, s, r, u & w) was observed in the *Nanacythere costata* JO3 Zone (uppermost *stokesi* Ammonite Zone–lower part of *viligaensis* Ammonite Zone) (Fig. 5).

The *Anmarginulina gerkei* JF7 Zone ranges from the upper part of the *stokesi* Ammonite Zone to the lower part of the *margaritatus*
Fig. 2. Lithostratigraphic summary showing Lower Jurassic deposits and the age of organic-rich marine mudrock units in diverse geographical areas. Dark fill: Lower Toarcian organic-rich marine mudrock units.
Fig. 3. Summary of the distribution of selected Upper Pliensbachian-Lower Toarcian foraminifera, NE Siberia and NE Russia (part 1). For legend, see Fig. 2.
Fig. 4. Summary of the distribution of selected Upper Pliensbachian-Lower Toarcian foraminifera, NE Siberia and NE Russia (part 2). For legend, see Fig. 2.
Fig. 5. Summary of the distribution of selected Upper Pliensbachian–Lower Toarcian foraminifers and ostracodes, NE Siberia and NE Russia. For legend, see Fig. 2.
Ammonite Zone (upper part of Levinskiy Formation, middle part of Airkat and Kyra Formations). It is characterized by a considerable change of the foraminiferal assemblages, with the inceptions of *Involuita liassica sibirica*, *Citharina fallax*, *Marginulina ventrosa*, *Marginulina spinata interrupta*, *Saratencaria sublaevis*, *Ichthyolaria terquemi* and *Conorboides buliminoides* (Fig. 6a, d, e & q). Among the foraminifera, a large number of migrant taxa are recognized.

The foraminiferal assemblage from the overlying *Ammarginulina arctica* JF8 Zone (upper part of *margaritatus* Ammonite Zone–lower part of *viligaensis* Ammonite Zone) is characterized by a high diversity of the calcareous foraminifera, which sometimes dominate over the agglutinated foraminifera. This assemblage is characterized by *Lenticulina margarita*, *Pyruinoides anabarenensis*, *Ichthyolaria sulcata*, *Pseudonodosaria pseudovulgata*, *Grigilis aphelilocula* and *Frondiculinita lobata* (Fig. 6b, c, g, i, k, l, o, p, s, w, y, z & aa). The most diverse ostracodal assemblage of the *Nanacythere costata* JO3 Zone is found in this part of the section, *Mandelstamia lubrica* and *Ogmoconchella ornata* (Fig. 7t & v) having their inceptions in these assemblages. These foraminifera (JF8 Zone) and ostracodes (JO3 Zone) occur in the clays at the top of the Levinskiy Formation and from the overlying siltstones with interbedded sandstone of the Sharapovo Formation, and also in the Airkat Formation and in the top of the Kyra Formation.

The *Recurvoides taimyrensis* JF9 Zone ranges from the uppermost Upper Pliensbachian to the lowermost Lower Toarcian (upper part of *viligaensis* Ammonite Zone–*propinquum* Ammonite Zone). At the base of foraminiferal zone (JF9), foraminifera greatly decrease in diversity. *Recurvoides taimyrensis* (Fig. 8a, b & c) becomes the dominant taxon, while *Kutsevella barrowensis* and locally *Trochammina lapidosa* are subsidiary. The characteristic feature of the foraminiferal assemblages from this Zone is the extinction of many of the most typical Pliensbachian species and the inception of the first Toarcian elements in the upper part of *Recurvoides taimyrensis* JF9 Zone (Figs 4 & 5).

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**Fig. 6.** The foraminiferal assemblages of Upper Pliensbachian (a, b, c, d, e, f, g, h, i, j, k, l, o, p, q, r, s, t, u, v, w, y, z & aa) and lowermost Toarcian (m & x) from NE Siberia, NE Russia and the Franz Josef Land archipelago. Measurements (in brackets): length of specimens in micrometres.

(a, d, e, q, r & t & u) Northeastern Siberia, Anabar Bay, outcrop 12; Airkat Formation. (a, d, e & q) Upper Pliensbachian, *stokesi* Ammonite Zones, *Ammarginulina gerkei* JF7 Zone. (r) Upper Pliensbachian, *stokesi* Ammonite Zones, *Trochammina lapidosa–Frondiculinita dubiella* JF5 Zone. (t & u) Upper Pliensbachian, *margaritatus* Ammonite Zones, *Ammarginulina arctica* JF8 Zone. (b, c, g, i, j, k, l, n, o, p, s, w, y, z & aa) Northeastern Siberia, Yuryung–Tumus Peninsula; Airkat Formation. (b, c, g, i, j, k, l, o, p, s, w, y, z & aa) Upper Pliensbachian, *margaritatus* Ammonite Zones, *Ammarginulina arctica* JF8 Zone. (h & n) Upper Pliensbachian, *Trochammina lapidosa–Frondiculinita dubiella* JF7 Zone. (y & x) Northeastern Siberia, left Kedon River basin, Astronomicheskaya River, outcrop 2.

(a & b) *Saratencaria sublaevis* (Franke 1936). (a) (883.1); 1048/302. Bed 50, sample 6. (b) (646.7); 1048/306. Outcrop 8, bed 1, sample 1. (c) *Citharina fallax* (Payard 1947) (1686); 892/31. Outcrop 8, bed 1, sample 3. (d, e & f) *Ammarginulina gerkei* Nikitenko, 1992. (d) (1050); 1048/101. Bed 50, sample 1. (e) (980.2); 1048/102. Bed 50, sample 1. (f) (555.6); 1048/103. Northeastern Siberia, Yuryung Peninsula, Cape Tsevetkova, outcrop 7, bed 32, sample 2; Airkat Formation, Upper Pliensbachian, *Ammarginulina gerkei* JF7 Zone. (g) *Frondiculinita lobata* (Gerke 1957) (810.5); 892/39. Outcrop 5, bed 1, sample 2. (h & n) *Frondiculinita dubiella* (Gerke 1957). (h) Microspheric test (1309.3); 892/37. Outcrop 10, bed 3, sample 1a. (n) Megalospheric test (1297.3); 892/38. Outcrop 9, bed 3, sample 3. (i, j & k) *Ammarginulina arctica* (Schleifer 1961). (i) Megalospheric test (752.9); 1048/90. Outcrop 5, bed 1, sample 4. (j) Microspheric test, ventral view (737.2); 1048/96. Outcrop 5, bed 1, sample 1. (k) Megalospheric test (324.9); 1048/99. Outcrop 5, bed 1, sample 1. (l, o & p) *Pseudonodosaria pseudovulgata* (Gerke 1961). (l) Microspheric test (509.3); 1048/89. Outcrop 5, bed 1, sample 1. (o) Microspheric test (624.4); 1048/91. Outcrop 5, bed 1, sample 3. (p) Megalospheric test (619.2); 1048/93. Outcrop 5, bed 1, sample 3. (m) *Textularia areolecta* Tappan 1955. (710.4); ZFI1/5. Franz Josef Land archipelago, Bell Island, outcrop 1, bed 5, sample 1/5; Tegetthoff Formation (upper part), uppermost Pliensbachian–lowermost Toarcian, *Recurvoides taimyrensis* JF9 Zone. (q, r & v) *Trochammina lapidosa* Gerke & Sossipaturova, 1961. (q) Microspheric test (886.2); 1048/69. Bed 50, sample 2. (r) Megalospheric test (788.9); 1048/74. Bed 45, sample 7. (v) Megalospheric test (422.3); 2N16/2. Bed 4, sample 16; Upper Pliensbachian, *viligaensis* Ammonite Zone, *Recurvoides taimyrensis* JF9 Zone. (s, t & u) *Pyruinoides anabarenensis* Nikitenko 2000. (s) Megalospheric test, (1157.9); 1048/122. Outcrop 5, bed 1, sample 1. (t) Microspheric test (536.2); 1048/119. Bed 55, sample 2. (u) Megalospheric test (1333.6); 1048/118. Bed 53, sample 2. (w) *Marginulina spinata interrupta* Terquem 1866. Megalospheric test (748.5); 1048/310. Outcrop 5, bed 1, sample 2. (x) *Lenticulina gotttingensis* (Bornemann 1854) (567.2); 1048/301. Bed 6, sample 43; lowermost of Lower Toarcian, *propinquum* Ammonite Zone, *Recurvoides taimyrensis* JF9 Zone. (y, z & aa) *Conorboides buliminoides* (Gerke 1961). (y) Ventral view (291.2); 1048/125. Outcrop 5, bed 1, sample 2. (z) (370.6); 1048/127. Outcrop 5, bed 1, sample 3.
In many sections from the northern regions of eastern Siberia, the lowermost Toarcian (propinquum Ammonite Zone) is often eroded or absent. Therefore, the boundaries between foraminifer and ostracodal zones in these sections are rather sharp and are associated with an almost complete change of microfaunal assemblages. Where this part of the lowermost Toarcian is present in the sections (NE Russia), the transition between the assemblages is gradual, with the complete change of microfaunal assemblages occurring at the boundary between the propinquum and falciferum Ammonite Zones. In the lowermost Toarcian, the highest occurrences of the Pliensbachian foraminifera (Trochammina lapidosa, Recurvoides tainyrensis, Lenticulina margarita, Nodosaria claviformis and Marginulina spinata interrupta) (Fig. 6x; Fig. 8p & q) and the ostracodes (Ogmoconcha longula and Ogmoconchella conversa), as well as the lowest occurrence of the Toarcian microfauna (Trochammina kiselnina, Amphoeculites lobus, Ammodiscus ghumaeus, Nodosaria regularis, Globulina sibirica, Triplasia kingakensis, Reinholdella pachyderma and Kinkelinella sermosiensis) (Fig. 8f, g & r, Fig. 9n, o & p) characteristic for the upper part of this section have been observed. Depletion of the ostracode assemblages begins in the uppermost part of the Upper Pliensbachian, with the extinction of both Nanacythere and ‘Mandelstamia’. The Recurvoides tainyrensis JF9 Zone and the upper parts of Ogmoconcha longula JO2 Zone are present in the upper silty and sandy deposits of the Sharapovo and Airkat Formations, and probably into the base of the clayey deposits of the Kiterbyut Formation in some sections from NE Siberia, and in the Pliensbachian–Toarcian deposits of NE Russia.

Lower Toarcian black, locally bituminous shales of the Kiterbyut Formation occur throughout northern Siberia (Shurygin et al. 2000). Their stratigraphic analogues in western Siberia are the black mudstones of the Togur Formation, while in northeastern Russia these comprise clayey silty deposits. In sections of the coastal facies from the Anabar River and the lower sublittoral facies (Eastern Taymyr), the

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Fig. 7. The ostracode assemblages of Upper Pliensbachian (l, p, q, o, r, s, t, u, v & w) and Lower Toarcian (a, b, c, d, e, f, h, i, j, k, m & n) from northeastern Siberia and northeastern Russia. Measurements (in brackets): length of specimens in micrometres.

(a, b, c, d, e, f, h, i, k, m & n) Northeastern Siberia, Taymyr Peninsula, Cape Tsvetkovka, outcrop 7. (a, c & f) Bed 1, sample 2; Korotkiy Formation, Lower Toarcian, commum–monestieri Ammonite Zones, Camptocythere ocellata JO6 Zone. (d, e, h, i, k, m & n) Bed 7; Kiterbyut Formation, Lower Toarcian, Trachycythere verrucosa JO5 Zone. (v) Bed 13, Airkat Formation, Upper Pliensbachian, Nanacythere costata JO3 Zone. (g, l, p & s) NE Siberia, Anabar Bay. (g) Female, left valve, internal lateral view (893.5); 648/2. Sample 9. (e) Female, right valve, internal lateral view (914.1); 1048/2. Sample 2. (g) Female, left valve, internal lateral view (873.4); AB1113. Sample 3. (j) Female carapace, dorsal view (914.1); 1048/2. Sample 2. (g) Female, left valve, internal lateral view (873.4); AB1113. Sample 3. (j) Female carapace, left side, lateral view (598.1); 2N51/1. Northwestern Russia, Lower Kedon River basin. Astronimchekskaya River, outcrop 2, bed 3, sample 7; Kiterbyut Formation, Upper Pliensbachian, Nanacythere costata JO5 Zone.

(a, b, c & f) Camptocythere ocellata Gerke & Lev, 1958. (a) Male carapace, left side, lateral view (792.3); 1050/32. (b) Female, right valve, internal lateral view (810.3); M5524. East Siberia, Vilyuy Basin, Markha river, outcrop 5, bed 5, sample 23; Suntury Formation, Toarcian, Camptocythere ocellata JO6 Zone. (c) Female, right valve, lateral view (963.8); 1048/5. (f) Female, right valve, internal lateral view (978.9); 1048/6. (d, e, g, j, k & n) Camptocythere mandelstami Gerke & Lev, 1958. (d) Female carapace, right side, lateral view (893.6); 1048/1. Sample 2. (e) Female carapace, dorsal view (914.1); 1048/2. Sample 2. (g) Female, left valve, internal lateral view (873.4); AB1113. Sample 3. (j) Female carapace, left side, lateral view (598.1); 2N51/1. Northwestern Russia, Lower Kedon River basin. Astronimchekskaya River, outcrop 2, bed 3, sample 7; Kiterbyut Formation, Upper Pliensbachian, Nanacythere costata JO5 Zone. (k) Male, carapace, left side, lateral view (1130.4); 1048/3. Sample 2. (m) Male carapace, dorsal view (1117.9); 1048/4. Sample 2. (h & i) Trachycythere verrucosa Triebel & Klingler 1959. (h) Carapace, dorsal view (845.9); 1048/16. Sample 2. (h & i) Trachycythere verrucosa Triebel & Klingler 1959. (h) Carapace, dorsal view (845.9); 1048/16. Sample 2. (h) Carapace, right side, lateral view (845.9); 1048/16. Sample 2.

(l & p) Nanacythere costata (Gerke & Lev 1958). (l) Carapace, left side, lateral view (427); 1048/17. stokesi Ammonite Zone, Bed 50, sample 9. (p) Carapace, dorsal view (426.5); 1048/18. Bed 50, sample 2. (m) Polyscope petra Fischer 1961. Carapace, lateral view (204.1); 1048/240. Sample 2. (o & r) Ogmoconchella olenakensis (Gerke & Lev 1958). (o) Carapace, right side, lateral view (641.3); 7/3a. (r) Right valve, internal lateral view (631.5); 7/4a. (q & s) Ogmoconcha longula Gerke & Lev 1958. (q) Carapace, right side, lateral view (684.5); 1048/28. Northeastern Siberia, Yuryung–Tumus Peninsula, outcrop 1, bed 6, sample 1; Airkat Formation. Upper Pliensbachian, margaritatus Ammonite Zone, Ogmoconcha longula JO2 Zone. (s) Carapace, dorsal view (823.5); 1048/26. Bed 52, sample 2. (t & v) Ogmoconchella ornata (Gerke & Lev 1958). (t) Carapace, right side, lateral view, (731.6); 1048/236. Northeastern Siberia, Anabar River, outcrop 3, bed 7, sample 7; Airkat Formation, Upper Pliensbachian, Nanacythere costata JO3 Zone. (v) Carapace, right side, lateral view (792.8); 7/4a. Bed 12, sample 2. (u) Ogmoconcha nordvikensis Gerke & Lev 1958. Carapace, right side, lateral view, (621.8); 7/4b. (w) ‘Mandelstamia’ linearis Gerke & Lev 1958. Carapace, left side, lateral view, (470); 1/7v.
maximum content of the pelitic fraction varies between 91% and 97%. A high concentration of organic carbon is also characteristic of these sediments (Kaplan 1976; Levchuk 1985). The thicknesses of the Kiterbyut Formation are between 22 m and 25 m and are remarkably consistent over the vast territory of the Siberian Platform (Shurygin et al. 2000).

In the Kiterbyut Formation, the lower part of the Kelimyar Formation, and at the base of the overlying sandy silts of the Nadoykh and Eren Formations, foraminiferal assemblages of the Ammobaculites lobus–Trochammina kisselmanni JF11 Zone (lower part of the Lower Toarcian, *falciferum* Ammonite Zone–lower half of the *commune* Ammonite Zone) have been found. The foraminiferal assemblages of the relatively deep-water facies are dominated by *Trochammina kisselmanni*, Bulbobaculites strigosus and *Triplasia kingakensis* (Fig. 9a, b, c, j, k, l, q & r), while *Ammobaculites lobus* (Fig. 9d & g) and *Ammogloboigerina cunningensis* are subdominant species. *Evoluitinella taimyrensis*, *Globulina sibirica* and *Spiroplectammina* sp. 2 and *Lagenammina jurassica* are also common (Figs 4 & 5). The characteristic feature of this assemblage is the presence of migrant species from southern palaeobasins (*Palmula deslongchampsi*, *Cyclogyra Hasina*, *Citharina gradata*, *Evolutinella zwetkovi*, and *Triplasia kingakensis*) (Fig. 9e, h, i, n & s). In the deeper-water facies, migrant species from the west European basins occur (*Trachycythere verrucosa*, *Kinkelinella sermoensis* and *Polycype pelta*) (Fig. 7d, e, k & n). In the deeper-water facies, migrant species from the west European basins occur (*Trachycythere verrucosa* JF11 Zone, defining the *Trachycythere verrucosa* JF11 Zone (*falciferum* Ammonite Zone–lowest part of *commune* Ammonite Zone).

In the later part of the Early Toarcian, the differentiation of palaeoenvironments begins. The sandy silts of the Nadoykh and Eren Formations accumulated in the coastal areas of the Siberian palaeobasin, while the clayey silts of the Kelimyar Formation and their analogues were deposited in the more offshore areas. Foraminiferal assemblages of the *Lenticulina multa–Astacolus praefolius* JF12 Zone, upper part of the Lower Toarcian–lower part of the Lower Aalenian (upper part of *commune* Ammonite Zone–lower part of *maclintocki* Ammonite Zone) are characterized by *Lenticulina multa*, *Astacolus praefolius*, *Nodosaria pulchra*, *Catharina gradata*, *Evoluitinella zwetkovi*, *Ammodiscus glumaceus* and *Saccammina inanis* (Fig. 8h, j, k, m & s; Fig. 9s & t). Rather

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Fig. 8. The foraminiferal assemblages of uppermost Pliensbachian (*a, b, c & o*), lowermost Toarcian (*d, e, f, g, l, p, q & r*), Lower (*h, i, m, n & s*) and Upper (*j & k*) Toarcian from NE Siberia, NE Russia and the Franz Josef Land archipelago. Measurements (in brackets): length of specimens in micrometres.


impoverished ostracodal assemblages of the *Camptocythere ocellata* JO6 Zone, upper part of the Lower Toarcian to lower part of the Upper Toarcian (upper part of *commune* Ammonite Zone—lower part of *wurtembergeri* Ammonite Zone), are mostly represented by rare occurrences of the index species (Fig. 7a, b, c & f).

When the data are insufficient (specific facies, rare samples) to distinguish this detailed Upper Pliensbachian–Lower Toarcian foraminiferal zonation, f-zones of a wider stratigraphic range have been established. For example, in the coastal shallow-water deposits at the base of the Upper Pliensbachian, the f-zone *Trochammina insititata–Turritellella volubilis*, JF2 (Upper Sinemurian—lower part of Upper Pliensbachian) has been recognized. Above the *Ammodiscus siliceus* JF3 Zone, due to impoverished foraminiferal assemblages, an Upper Pliensbachian and lowermost Toarcian biostratton of wide stratigraphic range, the *Trochammina lapidosa* JF4 Zone, can be established. It is overlain by the *Trochammina kisselmani* JF10 Zone (Lower Toarcian). In the more offshore shallow-water facies, above the *Trochammina lapidosa–Fondalinita diabili* JF5 Zone, the *Conorboides buliminoides* JF6 Zone has been distinguished. This corresponds with the upper part of the Upper Pliensbachian.

**Northwestern Siberia**

In northwestern Siberia, Pliensbachian and Toarcian sediments have only been described from boreholes. Conventional core samples from these subsurface strata contain relatively rich foraminiferal and ostracodal assemblages and rare bivalves. Autonomous Jurassic zonations based on the foraminifera and ostracodes, which have been developed from the ammonite-dated coastal outcrops of northeastern Siberia, are present over the northern regions of western Siberia. Some marker levels can be observed in central and even southern regions of western Siberia. The detailed (as in northern Siberia) subdivision of the Lower and Middle Jurassic of western Siberia based on microfauna is difficult to duplicate, due to the rare and incomplete recovery of microfaunal assemblages in core samples. However, marker levels are rather distinct and occur across the region (Nikitenko et al. 2000).

At the base of the Upper Pliensbachian, in the uppermost part of the Zimnay Formation and lowermost part of the Levinskiy Formation, the *Ammodiscus siliceus* JF3 Zone has been identified (Fig. 10). The foraminiferal assemblages are characterized by abundant *Ammodiscus siliceus* and *Trochammina insititata*, in association with rare *Pseudonodosaria dea*, *Marginulina prima* and *Verneulinoides pudica* (Nikitenko et al. 2000).

In the central part of NW Siberia, clays of the Cherchinskoe Formation and sandy silts of the Sarapovo Formation were deposited in subcontinental to nearshore marine palaeoenvironments. In layers of marine genesis, rare *Trochammina lapidosa*, *Ammodiscus siliceus*, *Hyperammina* ex gr. *odiosa*, *Saccammina* sp. and *Jaculella jactatica* have been recovered, characterizing the *Trochammina lapidosa* JF4 Zone, upper part of Upper Pliensbachian–basal Lower Toarcian (Nikitenko et al. 2000). In the more northern regions, where coastal marine environments were more stable, this part of the...
Fig. 10. Summary of the distribution of selected Upper Pliensbachian–Lower Toarcian foraminifera and ostracodes, NW Siberia. For legend, see Fig. 2.
section can be further subdivided. For example, from the Levinskiiy Formation and lower part of the Sharapovo Formation, *Trochammina lapidosa*, *Lenticulina gottingensis*, *Anmargulina gerkei*, *Verneuilinoidea* sp., *Marginulopsis hatangensis*, *M. schleiferi*, *Pseudonodosaria pseudovulgata* and *Frondiculinita lobata* have been recovered (Glinskikh 2001). These taxa are typical of the undivided *Anmargulina gerkei–A. arctica* JF7–JF8 Zones (middle part of Upper Pliensbachian). In the uppermost part of the Sharapovo Formation, and in its analogue (Chernichnoe Formation) plus the base of the Togur Formation, the foraminifera characterizing the *Recurvoides taimyrensis* JF9 Zone have been recovered, notably *Recurvoides taimyrensis*, *Recurvoides* sp. ind. *Kutsevella barrowensis* and *Trochammina* ex gr. *kisselmani* (Komissarenko 1989). In the Pliensbachian sections of western Siberia, ostracodes are rather rare and represented only by the index species of the *Ogmoconcha longula* JO2 Zone (Fig. 10).

The Togur Formation (stratigraphic analogue of the Kiterbyut Formation, lower part of the Lower Toarcian) occurs in the central regions of western Siberia and consists of black, sometimes bituminous, mudstones. The foraminiferal assemblages of the *Ammobaculites lobus–Saccammina inanis* JF11 Zone, an analogue of the northern Siberian lower Toarcian *Ammobaculites lobus–Trochammina kisselmani* JF11 Zone, occur in the Togur, Kiterbyut, the lowermost parts of the Novogodnyay, and the Nadoyakh Formations. Taxa present include *Ammodiscus glumaceus*, *Ammobaculites lobus*, *Saccammina inanis*, *Trochammina kisselmani*, *Globulina sibirica* and *Kutsevella* ex gr. *barrowensis*.

When the data are insufficient (specific facies or poor recovery from the core) to distinguish this foraminiferal zonation, foraminiferal biostratons of wider stratigraphic range have been established. At the base of the Upper Pliensbachian, the *Trochammina insitata* JF2 Zone (Lower Pliensbachian–lower part of Upper Pliensbachian) has been recognized. The *Ammodiscus glumaceus* JF12 Zone is considered a biostratigraphic subdivision ranging from Lower Toarcian to Lower Aalenian (Fig. 10). However, in its lower part, there is a well-defined marker level: *Ammobaculites lobus–Saccammina inanis* JF11 Zone. The undifferentiated middle part of *Ammodiscus glumaceus* JF12 Zone can be correlated with the middle Siberian *Astacolus praefoliaceus–Lenticulina multa* JF12 Zone. At this level, in the Novogodnyay Formation and Nadoyakh Formation, rare *Ammobaculites praefoliaceus*, *Lenticulina* sp. ind. and *Ammodiscus glumaceus* occur. In the Kiterbyut Formation and lowermost part of the Nadoyakh Formation the single ostracode species *Camptocythere mandelstami* (JO4 Zone) has been recognized (Fig. 10).

**Barents Sea Region**

There is much less information about the Pliensbachian–Toarcian microfaunas from the Barents Sea region. The oldest foraminiferal assemblages of Pliensbachian age have been described from mudstones occurring in the Wilhelm Island, Spitsbergen, area. This assemblage is represented by *Ammodiscus siliceus*, *Trochammina lapidosa*, *Gloomspera* ex gr. *gordialis*, *Saccammina* sp., *Gaudryina* sp. and *Textularia* ex gr. *areolepta* (Klubov 1965), which are characteristic of the *Trochammina lapidosa* JF4 Zone, upper part of the Upper Pliensbachian–lowermost Toarcian (Fig. 11). Diverse *Ammodiscus* sp. (Löfaldli & Nagy 1980) were recovered from the clayey silts of the Wilhelmoya Formation, Passet Member, dated as Upper Sinemurian–Toarcian (Kongsøya, Kong Karls Land). These deposits are overlain by Middle and Upper Jurassic sediments, often beginning with a layer of phosphorite concretions, which contain Toarcian and Aalenian ammonites (Pchelina 1965, 1967). The microfauna from the sandy silts of the upper part of the upper Tegetthoff Formation (Bell Island, Franz Josef Land) comprises the foraminifera *Ammodiscus siliceus*, *Trochammina lapidosa*, *Saccammina* sp., *Gloomspera* ex gr. *gordialis*, *Recurvoides taimyrensis*, *Reophax metensis* and *Textularia areolepta* (Fig. 6m; Fig. 8d, e), which are characteristic of the *Recurvoides taimyrensis* JF9 Zone.

In the Barents Sea region, in the overlying deposits of the lowermost Toarcian, no foraminifera have been found. In the central areas of the Barents Sea shelf, the rare ostracode *Camptocythere mandelstami* JF4 Zone has been recovered from ditch-cutting samples only. Impoverished foraminiferal assemblages comprising *Astacolus praefoliaceus* and *Dentalina aff. forta* from the *Astacolus praefoliaceus* JF12 Zone from the upper part of the Lower Toarcian (Fig. 11), have been recovered in well sections from the central areas of the Barents Sea shelf (Gramberg 1988; Basov et al. 1989).

**Arctic Canada**

In the northern Yukon and northern Richardson Mountains, only one occurrence of foraminifera (*Trochammina* sp. 5264 and *Trochammina* sp. 5271) has been described (Poulton
Fig. 11. Summary of the distribution of selected Upper Pliensbachian–Lower Toarcian foraminifera and ostracodes, Barents Sea area. For legend, see Figure 2.

Fig. 12. Summary of the distribution of selected Upper Pliensbachian–Lower Toarcian foraminifera, Canadian Arctic. For legend, see Figure 2.
et al. 1982) from sandy silts of the Almstrom Creek Formation, dated as Late Pliensbachian by the occurrence of the ammonite Amaltheus. In the overlying silty clays and mudstones of the Manuel Creek Formation, a richer foraminiferal assemblage has been recovered (Trochammina sp. 5267, Trochammina sp. cf. T. canningensis (= Ammobaculites lobus-Trochammina kisselmanni JF11 Zone, which is based on the occurrence of the ammonite Ammonite Zone-lower part of the Post-Trochammina kisselmanni JF11 Zone, which is based on the occurrences of these foraminifera and the ammonite Dactylioceras sp. (Poulton et al. 1982).

In sections from the Canadian Arctic archipelago, in the shales of the Jameson Bay Formation, Wall (1983) established the Flabellammina sp. assemblage, which has been dated to Toarcian. The foraminiferal assemblages, however, include Saccammina sp. 1 (= S. inanis), Kutsevella barrowensis, Flabellammina sp. 1 (= Triplasia kingakensis), Haplophragmium sp. 1 (= Bulbobaculites strigosus) and Eoguttulina? sp. (= Globulina sibirica). These are diagnostic of the northern Siberian Ammobaculites lobus-Trochammina kisselmanni JF11 Zone, which is characteristic of the lower part of the Lower Toarcian (Fig. 12). Therefore, the stratigraphic range of the Flabellammina sp. assemblage can now be dated as the lower part of the Lower Toarcian (falciferum Ammonite Zone-lower part of the commune Ammonite Zone).

In the central part of the Canadian Arctic archipelago, Souaya (1976) established two foraminiferal zones based on ditch-cutting samples, namely Ammodiscus sp. cf. A. rugosus (Pliensbachian-Toarcian) and Ammodiscus sp. cf. A. baticus (Pliensbachian—lower part of the Bathonian), from sediments now envisaged to be Pliensbachian-Lower Aalenian. The foraminifera from these zones are characterized by similar assemblages comprising both Pliensbachian and Toarcian species, and taxa typical of the Middle and Upper Jurassic (Ammodiscus thomsi, Flabellammina? sp., Ammobaculites venustus, A. vetusta, A. alaskensis, A. barrowensis, Gaudryina dyserita, Haplophragmoides kingakensis, Kutsevella barrowensis, Trochammina sp. cf. T. sablei, Pseudobolivina sp. C and Astacolus ectypus).

At present there are no published data on Pliensbachian and Toarcian ostracodes from Arctic Canada. The Pliensbachian and Toarcian sediments from Arctic Canada and northern Siberia are rather similar (Figs 2, 3–5 & 12). For example, in the northern Yukon and northern Richardson Mountains, the Pliensbachian sandy silts of the Almstrom Creek Formation are overlain by Lower Toarcian clays and clayey siltstones of the lower part of the Manuel Creek Formation (Poulton et al. 1982). In the Canadian Arctic archipelago, the Lower Toarcian Jameson Bay Formation, sometimes containing bituminous clays, overlies the Pliensbachian sandy silts of the uppermost part of the Heiberg Formation (Embry 1993). A gradual change of Lower Toarcian siltstones and silty clays to Toarcian bituminous clays can only be recognized in the Pliensbachian–Toarcian part of the Jameson Bay Formation.

Arctic platform of Alaska

In northern Alaska, the Upper Pliensbachian is represented by the lower member of the Kingak Formation, comprising mudstones, interbedded with siltstones and sandstones (Fig. 2). Some sections, however, are characterized by mudstones or organic-rich mudstones with rare interbedded siltstones. The Lower Toarcian deposits of the lower member of the Kingak Formation are represented by bituminous mudstones, which in turn are overlain, and, in some cases, replaced by, alternating non-bituminous mudstones and siltstones (Mickey & Haga 1987).

In the northern regions of Arctic Alaska, the Pliensbachian–Toarcian deposits are recognized in many well sections. Micropalaeontological subdivision of these sediments is based on the analysis of conventional core and ditch cutting samples. At the base of Upper Pliensbachian section the Trochammina inusitata–Turritellella volubilis JF2 Zone (Upper Sinemurian—lower part of Upper Pliensbachian) is represented by an impoverished foraminiferal assemblage (Ammodiscus siliceus, Trochammina inusitata, Turritellella volubilis, Spiroplectammina sp. and Marginulinopsis hatangensis). In a few sections, this stratigraphic level is marked by an abundance of Ammodiscus siliceus, but it is limited to local sections and cannot be traced as widely as in eastern and western Siberia. The upper horizons of the Kingak Formation are characterized by foraminiferal assemblages of the Ammargulina arctica–A. gerkei JF7–JF8 Zone. Foraminifers are abundant and diverse in this part of section. They include Trochammina lapidosa, Lenticulina ottagensis, Ichthyolaria lustrata, Pseudonodosaria pseudovalgata, Ammargulina gerkei, Citharina fallax, Saracenaria sublaevis, Kutsevella barrowensis and Marginulinopsis quadricostata (Fig. 13).
Fig. 13. Summary of the distribution of selected Upper Pliensbachian–Lower Toarcian foraminifera, Arctic Platform of Alaska. For legend, see Fig. 2.
The Recurvoides taimyrensis JF9 Zone is represented by an impoverished foraminiferal composition. It is dominated by Recurvoides taimyrensis. Common taxa include Kusievelia barrowensis, Saccammina sp. 2 and Textularia areoplecta. In the lower part of this Zone (JF9), foraminifera from the underlying Annamarginulina arctica-A. gerkei JF7-JF8 Zone become extinct (Comorboides buliminoides, Pyrulinoides anabaresensis and Verneuilinoides ex gr. pudica). In the upper part of the Recurvoides taimyrensis JF9 Zone, the first Toarcian taxa, which are typical for the overlying Zone, are present (Trochammina kisselmani, Triplasia kingakensis and Ammodiscus glumaceus). At the boundary between the Recurvoides taimyrensis JF9 Zone and the Ammobaculites lobus–Trochammina kisselmani JF11 Zone there is a sharp change in the taxonomic composition of foraminiferal assemblages (Fig. 14). In some sections it was possible to recognize only the Trochammina lapidosa JF4 Zone characterized by a long stratigraphic range. This situation is caused by rare sample recovery and the specific facies. Foraminiferal assemblages of this zone are represented by Trochammina lapidosa, Lenticulina gottingensis, Hyperammina odiosa, Ichthyolaria lustrata, Marginulina amica, Dentalina communis and Geinitzinita tenera (Figs 13 & 14). Ostracode assemblages of the Upper Pliensbachian and Lower Toarcian (Ogmoconcha longula JO2 Zone) are rather sparse, comprising only a few taxa (Ogmoconchella ornata and Nanocythere ex gr. costata). At the boundary of the Ogmoconcha longula JO2 Zones and Camptocythere mandelstami JO4 Zones, the composition of the ostracode assemblages completely alters (Fig. 14).

It should be noted that the Pliensbachian-Toarcian boundary is similarly characterized in the northern regions of Alaska, Siberia and the northeastern regions of Russia (Figs 2, 3–5, 13 & 14). For example, in some sections in the upper part of the Recurvoides taimyrensis JF9 Zone the foraminiferal assemblages contain both Pliensbachian and Toarcian taxa, suggesting that this part of the section corresponds with the lower part of the Lower Toarcian. In several sections, it is supported by joint occurrences of the ammonite Dactylioceras aff. D. tenuicostatum and foraminifera in core samples (Tappan 1955). In other sections, foraminiferal assemblages of the Recurvoides taimyrensis JF9 Zone are represented by Pliensbachian taxa only, and the boundary with the overlying zone is very sharp. In this case, the lower zone of the Lower Toarcian has probably been eroded or was not deposited in the section.

The foraminiferal assemblages allow us to reliably identify the Ammobaculites lobus–Trochammina kisselmani JF11 Zone recovered from the bituminous mudstones of the lower member of the Kingak Formation. The foraminifera are dominated by Trochammina kisselmani, Ammobaculites lobus, Evolutinella taimyrensis and Citharina hofkeri. In the same sedimentary interval, the Camptocythere mandelstami JO4 Zone has been established and is characterized by abundant Camptocythere mandelstami and additional rare Kinkelinella sp. juv., K. ex gr. sermoisensis and Paracypris sp. 2.

The overlying part of the lower member of the Kingak Formation is comprised of siltstones and clayey siltstones. In this part of the section, the foraminifera characterizing the Astacolus praefoliaceus–Lenticulina multa JF12 Zone include the inceptions of Astacolus praefoliaceus, Lenticulina toarcense, L. multa and Nodosaria pulchra. Along with foraminifera, some ostracode species (Camptocythere ocellata and Ekropyx there cf. debilis) which are typical of the ostracode assemblage for the Camptocythere ocellata JO6 Zone have been recovered (Fig. 14).

**Biotic and abiotic events**

In the Arctic basin and northwestern seas of western Europe, during the Late Pliensbachian–Early Toarcian, several simultaneous biotic and abiotic events have been recognized (Nikitenko & Shurygin 1994b; Little & Benton 1995; Hylton & Hart 1998). One of the most striking biotic events is the Early Toarcian microbionta crisis (mass extinction event) in the Northern Hemisphere.

The beginning of the Late Pliensbachian (stokesi chron to the beginning of the margaritatus chron) is characterized by a transgression of the Arctic basin (Fig. 15). The climate was warm and wet; coal deposits accumulated in many areas of the Northern Hemisphere (Ilyina 1985; Shurygin et al. 2000). In the Arctic palaeobasin, and palaeoseas of the northwestern regions of Western Europe, the taxonomic diversity of foraminifera and ostracode assemblages gradually increases. For example, three genera of ostracodes and 20 genera of foraminifera have been defined for the stokesi chron in the Arctic seas, while the margaritatus chron is characterized by four genera of ostracodes and 29 genera of foraminifera (Fig. 16). The transgression and climatic warming caused the
Fig. 14. Summary of the distribution of selected Upper Pliensbachian-Lower Toarcian foraminifera and ostracodes, Arctic Platform of Alaska.
invasion of a number of thermophilic migrant taxa (on both species and generic levels) in the microbenthos communities of the Arctic palaeo-seas. Some foraminiferal species of the genera Neobulimina, Saracenaria, Involutina, Ichthyolarians and Geinitzinita, as well as possibly some ostracodal species of the genus Nanacythere, migrated from the west, while the foraminiferal genera Grigelis, Pyrulinoides, and Astacolus probably migrated from the Palaeopacific (Fig. 15). At that time, the palaeo-geographical differentiation of the microbenthos characterizing different ecological (bionomical) zones was distinct. In the Late Pliensbachian, foraminiferal catenae with many elements (four to five) and ostracode catena with two elements were most typical for the northern Siberian seas. A catena is the lateral succession of interrelated communities on the bathymetric profile or slope extending from the palaeoshore toward the centre of the basin (Krasilov 1972, 1977; Tesakov 1978; Bogolepov 1983; Zakharov 1988; Nikitenko & Pospelova 1996).

The regressive stage of the Arctic palaeobasin began at the end of the margaritatus chron/the beginning of the spinatum chron. In association with a eustatic fall, a rather sharp cooling has been observed, denoted by the presence of glendonites in the northern regions of eastern Siberia (Kaplan 1976). At the same time, the climate gradually became arid (Zakharov 1994).

The palaeobasins became more shallow, while the profile of the sea-bed changed. There was possibly a series of geographical barriers causing restrictions. These events apparently caused changes in the current system, which resulted in the biotic connections with Western European seas being broken. However, the migration of microbenthos inside the Arctic Basin continued, denoted by the presence of the same taxa at similar stratigraphic levels in different Arctic regions (Fig. 15). Simultaneous eustatic fall, climatic cooling, change of sea-bed profile (and consequently changes of the current system) caused microbenthos depletion at the specific and generic levels, as well as dominance shifts in the Arctic microbenthos communities.

In the earliest Toarcian, a climatic warming (Ilyina 1985) took place in association with a major eustatic rise. Analysis of the microbenthos distribution at the Pliensbachian–Toarcian boundary suggests the absence of continuity between Pliensbachian and Toarcian microbenthos communities. At the base of the Lower Toarcian (propinquum Ammonite Zone), species and some genera of Arctic foraminifera were almost completely replaced, while some families disappeared (Fig. 15). The generic compositions of the ostracodes changed completely (Figs 15 & 17) and at that level in the Siberian and Western European seas the Healldidae disappeared (Arias 2000). During this crisis, the differentiation of the ecological zones of the benthos sharply reduced two- to three-element catena, and the biodiversity also decreased in individual elements of the catena.

A new stage in the development of microbenthos communities began at the falciferum chron. The taxonomic diversity, as well as the degree of differentiation of microbenthos associations and life-forms characterizing different ecological zones, gradually increased. During this stage, organic-rich black shales accumulated in the Arctic palaeobasins. Investigations of microcyclicity of the Lower Toarcian black shales indicate that the deposits at the boundaries of thin layers (2–5 mm) of organic-rich black shales were usually characterized by abundant monospecific communities of thin-shelled ostracodes with a well-developed system of pores and pore canals (i.e. Camptocythere mandelstami). In the deposits represented by the alternation of black layers with lighter grey clays, abundant and relatively diverse foraminiferal assemblages are recognized. The layers of black clays are characterized by rare eurybiontic Ammodiscus and Saccammina only. This feature of microbenthos distribution and structure in Lower Toarcian clays has been traced in numerous sections (Nikitenko 1994). It may be attributed to the alternation of periods of stagnant water and relatively well-aerated bot-
Fig. 16. Changes in taxonomic structure of foraminifera and ostracode associations
tom waters, as well as to periodic increases in the amount of organic material accumulating in the sedimentary basin.

During the post-crisis period there were reliable links between the microbenthos communities of the Arctic and Western European seas, caused by transgression and climatic warming. In the Arctic palaeobasin, this stage is characterized by periodic invasions of migrant taxa of both foraminifera (*Palmula, Cyclogyra* and *Nodosaria*) and ostracodes (*Trachycythere, Plocopote* and *Kinkelinella*), which are widespread in the Toarcian Western European palaeoceans (Fig. 15). In Arctic palaeoceans, the Western European migrant taxa are generally rare, with no descendants. At the same time, some specific Arctic forms (for example, the ostracode genus *Campylocythere*) migrated to Western European seas, giving rise to new taxa (Triebel 1950; Bate & Coleman 1975).

The Early Toarcian microbiotic crisis was very sharp in both Arctic and Western European palaeobasins, and it was the most remarkable event of the Jurassic. For example, in the Arctic seas, the genera and families of the ostracodal communities were completely replaced by new taxa (Figs 15 & 17b). The species composition of foraminiferal assemblages changed considerably, while generic composition of foraminifera is characterized by partial changes. Many families disappeared (Fig. 17a). In the Western European seas (Fig. 16), the microbenthos crisis caused taxonomic changes generally on the species level among foraminifera and on the generic level among ostracodes (Fig. 16). In the Early Toarcian, the number of foraminifera and ostracodes was reduced by more than half (Copestake & Johnson 1981, 1984, 1989; Riegraf 1985; Arias 2000).

The regressive stage of the Arctic palaeobasin began in the middle of the *commune* chron, resulting in a differentiation of sedimentation conditions. Sandy silts accumulated in coastal areas of palaeobasins, while clayey silts were deposited in offshore areas. During this post-crisis period (an interval of recovery), the diversity of Arctic foraminifera was only a half of its level in Western European seas, and the difference between the ostracode diversity in the Arctic basin and European sea was even more sharp (Figs 15 & 16) (Copestake & Johnson 1981, 1984, 1989; Arias 2000). The taxonomic diversity of Arctic foraminiferal and ostracodal communities had gradually recovered by the Toarcian–Aalenian boundary. The model of Kauffman and Erwin (1995) for the basic structure of a mass extinction event holds for the Pliensbachian–Toarcian microbiotic event.

### Palaeobiogeography

The comprehensive analysis of biotic and abiotic events and the reliable biostratigraphic data (ability to estimate isochronism or unischronism of events) allow reliable palaeobiogeographical reconstructions. Very large biogeographical assemblages characterizing all the Jurassic are proposed on the basis of foraminiferal analysis (Gordon 1970; Basov 1983). On the one hand, for the Boreal Jurassic shelf assemblages, which are characteristic for the Boreal Zone, as well as for Tethyan Assemblages (for the Tethyan Zone) some biogeographical type assemblages of Jurassic foraminifera have been established: cyclamminiids–pavonitiniids (tropical zone), nodosariids–epistominiids (subtropical and temperate zone) and nodosariids–ammendiscids (subpolar zone) (Gordon 1970; Basov 1983). On the other hand, biogeographical maps for the Volgian stage were based on the analysis of the distribution of characteristic species of foraminifera (Ivanova 1973). Such studies are rare for the Jurassic ostracodes.

The traditional principles of palaeobiogeographical zonation (Saks *et al.* 1971; Saks 1972; Westermann 2000), such as definition of ‘Realms’ based on endemic family availability, as well as the definition of ‘Provinces’ based on the distribution of endemic genera, cannot be used for the microbenthos. In the Arctic palaeobasin, the microbenthos is generally characterized by foraminiferal and ostracode families and genera of rather wide geographical distribution (cosmopolitan) only. Analysis has been carried out using genera, because opinions on the classification of some species vary considerably in different publications, while the nomenclature of the genera is more standard.

Palaeobiogeographical studies should be based on abundance data, but they are not always available from the publications. In this case they can be substituted by presence/absence data, which are usually sufficient for large-scale palaeobiogeographical studies (Shi 1993; Liu *et al.* 1998). We performed multivariate analysis (Jaccard Cluster Analysis) on the micropalaeontological data obtained from the study of Upper Pliensbachian and Lower Toarcian sections from northwestern and eastern Siberia, northeastern Russia, Franz Josef Land and northern Alaska, as well as published data on northwestern Europe, the North Sea, the Barents Sea shelf and Arctic Canada (Klubov 1965; Norling 1972; Bate & Coleman 1975; Souaya 1976; Lofaldli & Nagy 1980; Copestake & Johnson...
Fig. 17. Foraminifera (a) and ostracod (b) assemblage composition across the Pliensbachian-Toarcian boundary in northeastern Siberia and northeastern Russia.
Arctic palaeoseas may be divided into a number of ecological zones. In the northern Siberian and northern Alaskan seas, the Late Pliensbachian microfaunal communities were the richest and the most diverse among Early Jurassic microfaunal communities. During this time-frame, the palaeogeographical differentiation of microbenthos communities characterizing different ecological zones was distinct. In the Late Pliensbachian, in the northern Siberian seas (Fig. 20a) the foraminiferal catena commonly comprised many elements (four to five), while the ostracode catena were composed of only two elements.

The inner part of the upper sublittoral zone (Fig. 20a) was represented by nearly monospecific Ammodiscus communities, while Saccammina, Glomospira and some other taxa were rather rare (ecological zone F1). The agglutinated foraminiferal tests are often coarse grained. This zone is characterized by active hydrodynamics and unstable salinity.

The taxonomic diversity gradually increased with depth. For instance, in the outer part of the upper sublittoral zone (ecological zone F2), foraminifera are represented by abundant Recurvoides and numerous Kutsevella, Saccammina and Glomospira, while Ammodiscus and some other taxa are rarer. Sandy and silty grounds were settled by rare, but taxonomically diverse calcareous foraminifera, such as Lenticulina, Astacolus, Marginulina, Nodosaria, and Ichthyolaria. Large abundances of Glomospira in some areas of the palaeobasin suggest active hydrodynamic conditions, while high taxonomic diversity may indicate normal salinities. In the shallow-water offshore areas, ostracodes are rare and represented by only Ognunconcha (Fig. 20a).

The maximum taxonomic diversity of microbenthos communities (Fig. 20a) has been observed in the inner part of the middle sublittoral zone. Near-shore areas are characterized by various calcareous foraminifera (Amarginalina, Pyrulimoides, Citharina and Conorboides), although their assemblages are dominated by eurybiotic Recurvoides or Trochammina (ecological zone F3). Ostracodes are also more abundant in these areas.

Fig. 18. Palaeobiogeographical zonation of the Arctic Realm in the Late Pliensbachian on the basis of foraminifera (a) and on ostracodes (b), with dendrograms showing results of cluster analysis. (Base maps after Golonka & Scotese (1995); palaeogeographical reconstructions after Bogolepov (1983), with modifications.)
Fig. 19. Full caption on page 168.
Fig. 20. Full caption on page 168.
In the outer part of the middle sublittoral zone (Fig. 20a) the taxonomic diversity of the microbenthos slightly decreases. These assemblages are dominated by calcareous foraminifera. The population density of *Lenticulina, Marginulina, Nodosaria, Pseudonodosaria, Geinitzinita* and *Planularella* increases, whereas agglutinated foraminifera are less abundant (ecological zone F3).

Foraminiferal communities of the lower sublittoral zone (Fig. 20a) are characterized by similar features, but they are less rich and diverse. This foraminiferal association lacks any dominant species and is characterized by a lower population density (ecological zone F4). They include typical eurybiotic taxa, such as *Trochammina, Dentalina, Astacolus* and *Pseudonodosaria*. The foraminifera are smaller and their tests are much thinner in comparison with the foraminifera of the middle sublittoral communities. The tests of agglutinating foraminifera are extremely fine grained.

The characteristic feature of the outer part of the middle sublittoral zone and the lower sublittoral zone is the diversity peak of ostracodes, *Ogmoconcha, Ogmoconechella, Nanacythere* and *Mandelstamia* (ecological zone O2).

During the Early Toarcian microbiotic crisis, differentiation of the microbenthos characterizing different ecological zones (two–three elements of a catena) as well as the diversity of life-forms in the individual elements of the catena, decreased sharply (Fig. 20b). This new stage of the development of microbenthos communities began at the *falciferum* chron. The taxonomic diversity and the degree of differentiation of life-form associations characterizing different ecological zones gradually increased.

Eurybiotic *Ammodiscus, Saccammina* and rare *Trochammina* are typical of microbenthos communities (Fig. 20b) of the inner part of the upper sublittoral zone (ecological zone F1). Geochemical data (Levchuk 1985) and the specific composition of the microfossils indicate the desalination of sea-water in this zone of the palaeobasin.

In the outer part of the upper sublittoral zone (Fig. 20b) foraminiferal assemblages are also dominated by *Trochammina* and *Ammobaculites*, while the number of *Ammodiscus* and *Saccammina* decreases, and *Bulbobaculites, Kutsevella* and *Triplasia* are rare (ecological zone F1). In this zone the ostracodes are represented only by *Camptocythere*.

The most diverse assemblages of foraminifera and ostracodes have been defined for the middle sublittoral zone (ecological zones F2 and O2). Foraminiferal communities (Fig. 20b) of this zone are dominated by *Trochammina, Triplasia* and *Ammobaculites* characterized by high population densities. *Spiroplectammina, Evolutinella, Kutsevella* and some other taxa are less abundant. Calcareous foraminiferal communities (*Palmula, Dentalina, Globulina* and *Cyclogyra*) are rather diverse, but their population density is low. Ostracodes are dominated by *Camptocythere mandelstami*, whereas *Kinkelinella, Trochocythere* and *Polycope* are rare (ecological zone O2). The carapaces of *Camptocythere mandelstami* are thin walled with well-developed pores and pore-canal systems. In all ecological zones of the Siberian palaeobasin, foraminiferal tests are usually very small and thin walled, suggesting unfavourable oxygen conditions at the beginning of the Early Toarcian.

In the second part of the Early Toarcian (the second part of the *commune* chron), the inner part of the upper sublittoral (Fig. 20b) zone was settled by rare specimens of *Ammodiscus, Saccammina* and *Glomospira* with small tests. The outer part of the upper sublittoral zone is

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**Fig. 19.** Palaeobiogeographical zonation of the Arctic Realm in the Early Toarcian on the basis of foraminifera (a) and on ostracodes (b), with dendrograms showing results of cluster analysis. (Base map after Golonka & Scotese 1995; palaeogeographical reconstructions after Bogolepov 1983, with modifications.)

Fig. 22. The Circumboreal inter-regional correlation of the Upper Pliensbachian–Lower Toarcian based on ostracodes. Inter-regional correlation levels: 1. The level of the boreal crisis affecting the microbiota. Invasion of *Trachycythere verrucosa*, *Kinkelinaella sermoisensis*, *Polycythere pelta*. 2. Invasion of *Monoceratina vulsa*, *Ektyphocythere* cf. *debilis*. Invasion in NW Europe of *Camptocythere toarciana* (= *C. occalata*).
characterized by rare *Lenticulina*, *Astacolus*, *Trochammina* and *Dentalina*. According to geochemical data (Levchuk 1985) and microfauna composition, the salinity of the water was unstable – ranging from normal-marine to brackish conditions.

The assemblages of the middle sub littoral zone are dominated by *Lenticulina* and *Astacolus*, while *Globulina*, *Ichthyolaria*, *Nodosaria*, *Dentalina*, *Citharina*, *Ammodiscus* and some other taxa are less abundant. The ostracode *Camptocythere* is typical of both the outer part of the upper sub littoral zone and the middle sub littoral zone (Fig. 20b). Geochemical data indicate normal salinity in this zone of the palaeobasin (Levchuk 1985).

**Conclusions**

The results of these investigations allow us to trace Lower Jurassic ostracode and foraminiferal zonations developed from the northern regions of the eastern Siberia sections (Figs 3–5) over the whole Arctic basin: western Siberia (Fig. 10), NE Russia (Figs 3–5), Franz Josef Land (Fig. 11) and northern Alaska (Mickey et al. 1998) (Figs 13 & 14). Using published data, these zonal units or their analogues can be defined in Arctic Canada (Fig. 12) and the Barents Sea shelf (Wall 1983; Basov et al. 1989) (Fig. 11). Therefore, Lower Jurassic zonations based on foraminifera and ostracodes established for northern Siberia can be considered as an Arctic zonal standard (Figs 21 & 22). Moreover, several marker levels based on microfossils have been traced which allow us to correlate Arctic and Western European microfossil zonations of Lower and Middle Jurassic age (Figs 21 & 22).

The main abiotic and biotic events in the Late Pliensbachian and Early Toarcian of the Arctic Basin have been analysed. This allows us to conclude that a decrease of species and generic diversity of Arctic foraminifera and ostracodes began in the latest Pliensbachian, while in Western European palaeobasins the microbenthos extinction began in the Toarcian.

The Early Toarcian microbiota crisis in the Arctic was caused by several global events. At the end of the Late Pliensbachian there was an eustatic sea-level fall, climatic cooling, and changes of underwater topography. At the beginning of the Early Toarcian, there was climatic warming, a major eustatic rise, a change in the topography of the sea-bed, a change in the current system pattern and the development of anoxic environments. The alternation of these abiotic events during a short period of time resulted in a sharp decrease of microbiotic diversity followed by a new phase of development of microbenthos communities. The beginning of the *falciferum* chron is characterized by a very sharp change in the taxonomic composition of the microbenthos communities (Figs 15–17). The formation of black bituminous clays in Siberian palaeobasins, from the *falciferum* chron to the beginning of *commune* chron, correlates well with the second model of bituminous clay accumulation described by Hallam (1975). The deposits accumulated in a relatively shallow-water basin with a gently sloping sea-floor and the introduction of rather large quantities of organic material.

Mass extinction of microbenthos was simultaneous in Arctic and Western European palaeoseas and has been dated as Early Toarcian (*tenuicostatum* chron). The Early Toarcian microbiota crisis was distinct in both the Arctic and the Western European palaeobasins. For example, the genera and family composition of Arctic ostracodes completely changed, and 80% of the foraminiferal special disappeared with many families also disappearing altogether. In Western European palaeoseas, the taxonomic composition changed mainly at the species level among foraminifera and on the generic level among ostracodes (Fig. 16).

During the Late Pliensbachian and Early Toarcian there were permanent connections between the marine microbiota of the Arctic Palaeobasin, while Arctic and Western European microbiota were linked only during short periods of eustatic sea-level rise and warming.

The comprehensive analysis of the biogeographical distribution of Late Pliensbachian and Early Toarcian foraminifera and ostracodes, as well as Jaccard cluster analysis, allow us to define several biogeographical units within the Arctic and Boreal–Atlantic realms (Figs 18 & 19). The boundaries of provinces and realms based on the palaeogeographical distribution of ecological groups of microbenthos, as one would expect, change their position during geological time.

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