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Biotic Paleothermometry Constrains on Arctic Plates Reconstructions: Carboniferous and Permian (Zhokhov Island, De-Longa Group Islands, New Siberian Archipelago)

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Key Points:
- The document in New Siberian Archipelago fusulinid fauna never occurring north from the forbiddance line, i.e., 30–35°N/S
- The biota paleothermometry provided latitudinal constrains on the paleogeography and tectonics
- The paleogeography of New Siberian and Wrangelia terranes and surrounding regions reconsidered

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2

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Biotic paleothermometry constrains on Arctic plates reconstructions: Carboniferous and Permian (Zhokhov Island, De-Longa Group Islands, New Siberian Archipelago)

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Abstract A warm-water fauna and flora from a Carboniferous limestone xenolith that was captured during penetration of deep intraplate Cenozoic basalts through a Paleozoic carbonate platform have been found on Zhokhov Island, New Siberian Archipelago (NSA). This limestone xenolith contains a very high taxonomic diversity of Moscovian (Middle Pennsylvanian) tropical foraminifera and calcareous algae. As this warm-water biota never occurs north of the forbiddance line, i.e., 30–35°N/S, this fauna and algal flora constrain the paleogeography and interpretation of the paleotectonics in the region. Thus, the location of the most of the New Siberian Archipelago islands at that time must have been within tropics or subtropics. Analyses of the existing data on fusulinid distribution within the Arctic region indicate that Zhokhov and Wrangel Islands were still a part of Alaska-Chukotka composite terrane as late as in the Artinskian. Both fusulinid and detrital zircon provenance data suggest that the Chukotka microplate, NSA, and Wrangel Island probably were close to Arctic Alaska until Triassic time. The fusulinids from the Mankomen Formation and other formations in Wrangelia show a strong affinity with the Uralo-Franklinian province regions including the Sverdrup Basin, Spitsbergen, Barents Sea, and Timan-Pechora and the northern-central Urals rather than with northern Panthalassa.

1. Introduction

A number of recent Late Paleozoic paleogeographic maps show the Siberian Craton and various arctic islands positioned outside the tropic belt at 40° to 70°N paleolatitudes [*Scotese*, 2004; *Cocks and Torsvik*, 2007; *Blakey*, 2008; *Golonka*, 2011; *Lawver et al.*, 2011]. These reconstructions, which were developed from paleomagnetic data, zircon provenance, and lithofacies distribution, generally lack biogeographic data. Paleomagnetic reconstructions, of course, can provide a very precise paleogeographic position of any measured location relative to the appropriate paleopole. However, the existing published reconstructions vary significantly largely due to postsedimentary alteration and other complexities associated with the recovery of the primary magnetic signal. Thus, reconstructions based on paleomagnetic data cannot always be relied upon. Compounding this problem, the chronostratigraphic constraints utilized in the paleomagnetic reconstructions are often poor (examples in *Pisarevsky* [2005]).

Recently developed methods of assessing detrital zircon provenance have produced plausible paleogeographic models and reconstructions [*Kuzmichev*, 2009; *Drachev et al.*, 2010; *Miller et al.*, 2013; *Pease et al.*, 2014; *Ershova et al.*, 2015]. These zircon provenance studies show the distribution of the sediment possessing these zircons and point to the possible source region but do not give any information on the exact paleoposition and paleoenvironments of the sampled sandstones. In addition, there can be poor chronostratigraphic control on the samples due to lack of recent biostratigraphy in many Arctic localities. For example, the sequence with the sample (WR-35B) in Wrangel Island that has been considered as Late Devonian-Lower Mississippian in age [*Miller et al.*, 2010] in accordance with the geological map [*Kos'ko et al.*, 1993] yielded fusulinid of Moscovian age (the author personal data). The distribution of the ages of the detrital zircon population from this sample contrasts sharply with the data from other Mississippian sequences in Wrangel but has strong similarity with Middle Pennsylvanian and Lower Permian sequences in Wrangel and particularly with the detrital zircon populations from Upper Paleozoic strata of the Seward Peninsula and Brooks Range-North Slope of northern Alaska [*Miller et al.*, 2010]. Similarly, the consideration of the age of the rocks from

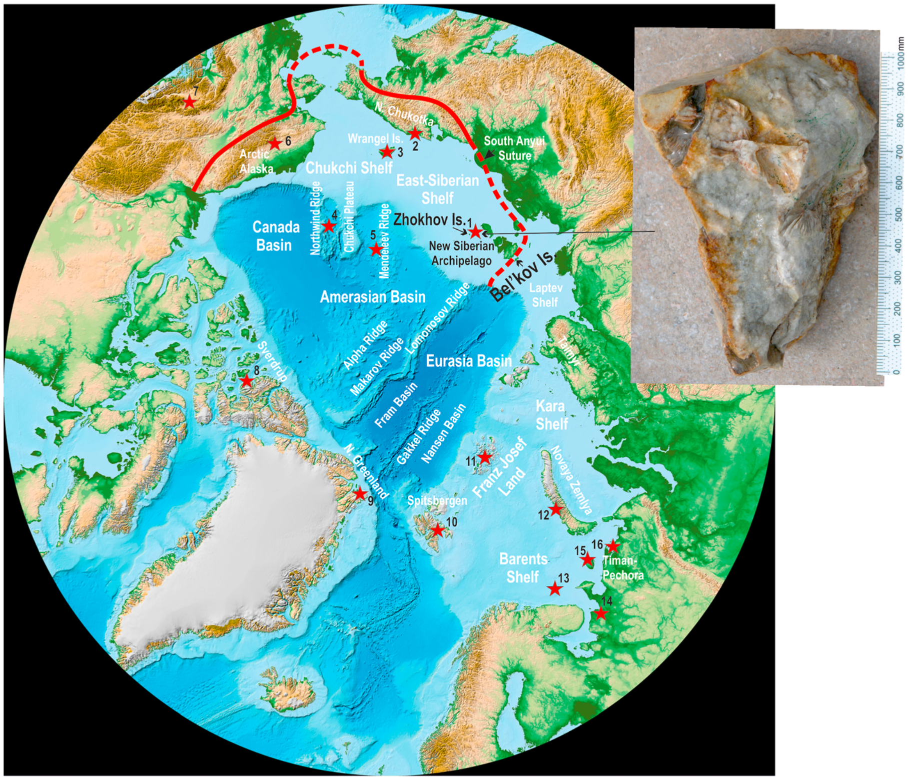

Figure 1. Bathymetric map of Arctic Ocean and surrounding areas. Locations mentioned in the text: 1, Zhokhov Island, NSA [*Makeev et al*., 1991 and this paper]; 2, North Chukotka [*Solovieva*, 1975]; 3, Wrangel Island [*Kos'ko et al*., 2013]; 4, Northwind Ridge [*Stevens and Ross*, 1997]; 5, Mendeleev Ridge [*Kaban'kov et al*., 2008]; 6, Alaska, Brooks and Lisburne Ridges [*Ross*, 1967]; 7, Delta River (Wrangelia terrane) [*Petocz*, 1970]; 8, Sverdrup Basin [*Harker and Thorsteinsson*, 1960; *Davydov*, 1991; *Groves et al*., 1994]; 9, North Greenland [*Nilsson et al*., 1991; *Davydov et al*., 2001]; 10, Spitsbergen [*Nilsson and Davydov*, 1997]; 11, Franz Josef Land [*Davydov*, 1997]; 12, Novaya Zemlya [*Nakrem et al*., 1991]; 13, Barents Sea Shelf [*Ehrenberg et al*., 2000]; 14, Mezen' depression [*Kashik et al*., 1969]; 15, Kolguev island [*Davydov*, 1997]; and 16, Timan-Pechora [*Grozdilova and Lebedeva*, 1961; *Konovalova*, 1991]. The thick red line is South Anyui Suture (modified from *Kuzmichev and Pease* [2007]) that divides Arctida from the rest of the terranes.

where detrital zircon populations are studied, as a rule, is done in accordance of older geological maps and rarely, if at all, checked with the current biostratigraphy from these sequences [*Miller et al*., 2013; *Pease et al*., 2014; *Ershova et al*., 2015]. However, as in case with age deviation of the sample WR-35B from Wrangel Island, the lack of chronostratigraphic control may produce significant errors in the interpretation of detrital zircon populations and consequently incorrect paleotectonic interpretations and reconstructions.

In contrast to geophysical (paleomagnetic) results that are very sensitive to samples subjected to even moderately high temperatures and pressures, the biota is preserved even in samples subjected to greenschist facies metamorphism. In addition to chronostratigraphic constrains, biota captures paleoenvironmental information, especially factors such as water salinity, depth, and temperature. At the margins of the paleoclimatic belts and/or biogeographic provinces, where the shift from a warm to a temperate fauna occurs quite sharply, the biota provides or may provide the precise paleolatitudinal position of climatic zones and associated provinces. Biotic data, therefore, provide information on the paleoposition of continental/microcontinental masses or parts of such masses if they are displaced from their original position. The aim of this paper is to document the foraminiferal fauna from Zhokhov Island, New Siberian Archipelago (NSA), assess the paleogeography of the archipelago during the Pennsylvanian, and provide some insights regarding the paleolatitudinal position of NSA, Wrangel Island, and N-W Chukotka regions at this time.

2. Geological Setting

Zhokhov is a very small island (10 × 15 km, 76°8′N, 152°54′E) belonging to the De-Longa groups of islands in the northeastern part of the New Siberian Archipelago, Russia (Figure 1), the latter being the western part of

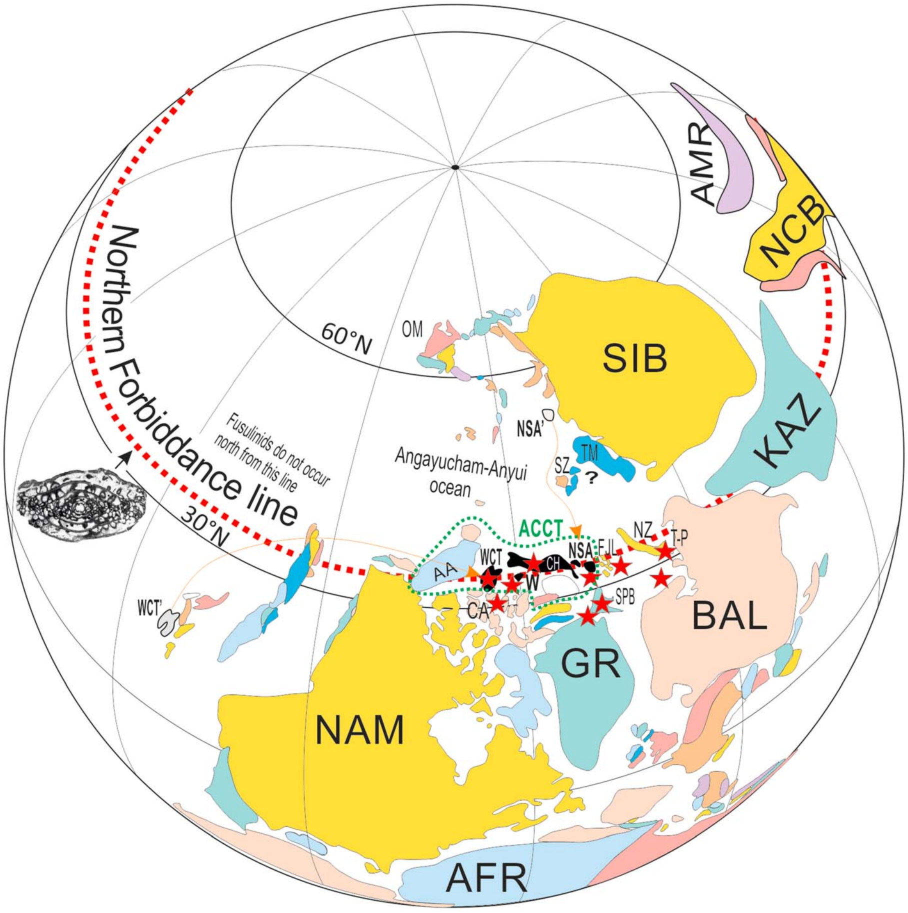

Figure 2. Paleogeographic reconstruction of Northern Hemisphere (slightly modified from *Lawver et al.* [2011]). Forbiddance line, the line of the maximum northward (and southward in Southern Hemisphere) distribution of warm-water fusulinids and green algae. The position of the line is given for the global warming event during earliest Moscovian time. AA, Arctic Alaska; ACCT, Alaska-Chukotka composite terrane marked by the green line; AFR, Africa; AMR, Amuria; B, Barents Sea Shelf; BAL, Baltica Shield; CA, Sverdrup; CH, Chukotka terrane; FJL, Franz Josef Land; GR, Greenland; KAZ, Kazakhstania; NAM, North American Craton; NCB, North China Block; NSA, New Siberian Archipelago, including Zhokhov Island; NSA abbreviation used for two potential positions, one (NSA′) for the position of the Archipelago (~50°N) on the common paleogeographic maps [*Scotese*, 2004; *Cocks and Torsvik*, 2007; *Blakey*, 2008; *Golonka*, 2011] and NSA proposed here position south from forbiddance line (~35°N); NZ, Novaya Zemlya; SIB, Siberia Craton; SP, Spitsbergen; SZ, Severnaya Zemlya; TM, Taimyr; T-P, Timan-Pechora; W, Wrangel Island; WCT, Wrangelia Terrane; WST (WCT) abbreviation used for two potential positions, one (WCT′) for the position of the terrane on the common paleogeographic maps (~0–35°N and 3–5 thousand kilometers west from Laurentia) [*Nokleberg et al.*, 2000; *Belasky et al.*, 2002; *Scotese*, 2004; *Cocks and Torsvik*, 2007; *Blakey*, 2008; *Colpron and Nelson*, 2009; *Golonka*, 2011], and second—WCT—proposed here position south from forbiddance line (~30°N) and within the Alaska-Chukotka composite terrane. The terranes under discussion highlighted with black color. Ural Mountains (or orogenic belt) developed between Baltic Shield (BAL) and Kazakhstania (KAZ).

the Alaska-Chukotka composite terrane (ACCT) (Figure 2), named in the Russian literature as New Siberian-Chukchi fold belt or New Siberian Platform [*Kuzmichev*, 2009; *Kos'ko et al.*, 2013]. The ACCT in general or its different parts were also named in the literature as Hyperborea [*Shatsky*, 1935] or Arctida [*Zonenshain and Natapov*, 1987] or as Crockerland [*Embry*, 1988].

The oldest Paleozoic strata in the archipelago are Cambrian and Ordovician shallow-water siliciclastics and limestone replaced upward by Devonian turbidites in Bennett and Henriette islands, which are located near Zhokhov Island [*Kos'ko et al.*, 2013]. These sequences are overlain by thin Lower Cretaceous sandstone and carbonaceous mudstone followed by alkaline basaltic lava sheets with thin lenses of tuffaceous mudstone. The mudstone contains spore and pollen characteristic of the late Early Cretaceous [*Kos'ko et al.*, 2013]. Zhokhov Island itself consists of Cenozoic (Miocene-Pleistocene) basalts with xenoliths of Neoproterozoic

Table 1. Algae (Light Brown) and Foraminifera Recovered From the Limestone in Zhokhov Island[a]

No	Genus	Species	Author	Year
1	*Donezella*[b]	*Lunaensis*	Racz	1966
2	*Eflugelia*[b]	*Johnsoni*	Flugel	1966
3	*Epimastopora*[b]	*Grandis*	Tchuvashov and Anfimov	1988
4	*Epimastopora*[b]	sp.		
5	*Palaeoberesella*[b]	sp.		
6	*Stacheoides*[b]	cf. *Meandriformis*	Mamet and Rudloff	1972
7	*Stacheoides*[b]	*Tenuis*	Petryk and Mamet	1972
8	*Maslovoporidium*[b]	*Delicata*	Berchenko	1982
1	*Ammovertella*	*Vaga*	Reitlinger	1950
2	*Bradyina*	cf. *Venusta*	Reitlinger	1950
3	*Climacammina*	*Aljutovica*	Reitlinger	1950
4	*Cribrostomum*	sp.		
5	*Eofusulina*[c]	cf. *Triangula*	Rauser and Belyaev	1938
6	*Eostaffella*	*Postmosquensis*	Kireeva	1951
7	*Globivalvulina*	*Granulosa*	Reitlinger	1950
8	*Globivalvulina*	*Mosquensis*	Reitlinger	1950
9	*Globivalvulina*	*Pulchra*	Reitlinger	1950
10	*Globivalvulina*	*Minima*	Reitlinger	1950
11	*Globivalvulina*	*Syzranica*	Reitlinger	1950
12	*Globivalvulina*	*Granulosa*	Reitlinger	1950
13	*Mediocris*[c]	*Breviscula*	Ganelina	1951
14	*Mediocris*	*Cupellaeformis*	Ganelina	1951
15	*Millerella*	*Umbilicata*	Kireeva	1951
16	*Millerella*	*Carbonica*	Grozdilova and Lebedeva	1950
17	*Millerella*	*Symmetrica*	Manukalova	1969
18	*Monotaxinoides*	*Subplanus*	Brazhnikova and Jartseva	1956
19	*Novella*	*Primitiva*	Rauser	1951
20	*Novella*	*Evoluta*	Grozdilova and Lebedeva	1950
21	*Novella*	cf. *Intermedia*	Rauser	1950
22	*Omphalotis*	cf. *Omphalotis*	Rauser and Reitlinger	1940
23	*Palaeonubecularia*	sp.		
24	*Palaeotextularia*	*Angusta*	Reitlinger	1950
25	*Palaeotextularia*	*Gibbosaeformis*	Reitlinger	1950
26	*Palaeotextularia*	*Longissima*	Reitlinger	1950
27	*Palaeotextularia*	*Primitiva*	Reitlinger	1950
28	*Profusulinella*[c]	aff. *Prisca*	Deprat	1912
29	*Pseudoammodiscus*	cf. *Minima*	Brazhnijkova and Potievskaya	1952
30	*Pseudoammodiscus*	cf. *Compactus*	Brazhnijkova and Potievskaya	1952
31	*Pseudoglomospira*	*Pusiliformis*	Reitlinger	1950
32	*Pseudoglomospira*	*Elegans*	Reitlinger	1950
33	*Pseudoglomospira*	*Pusiliformis*	Reitlinger	1950
34	*Pseudostaffella*	cf. *Kyselensis*	Grozdilova and Lebedeva	1950
35	*Pseudostaffella*	aff. *Paracompressa*	Safonova	1951
36	*Reitlingerina*	*Preobrajenskyi*	Dutkevich	1934
37	*Reitlingerina*	*Mirabilis*	Rauser	1951
38	*Reitlingerina*	*Variabilis*	Rauser	1951
39	*Schubertella*	*Procera*	Rauser	1951
40	*Schubertella*	*Gracilis*	Rauser	1951
41	*Schubertella*[c]	*Magna*	Lee and Chen	1934
42	*Schubertina*	*Pseudoglobulosa*	Safonova	1951
43	*Staffellaeformis*	*Staffellaeformis*	Kireeva	1951
44	*Tetrataxis*	*Corona*	Cushman and Waters	1928
45	*Tolypammina*	*Complicata*	Reitlinger	1950
46	*Trepeilopsis*	*Minimus*	Dain	1958

[a] Data from *Makeev et al.* [1991]. Trilobites: *Griffithinoides kasykurti* Weber, *Griffithinoides longicepts* Weber. Rugosa corals: *Caninia irinae* Gorskyi early Moscovian age (identification of Dr. O. Kossovaya).

[b] Algae.

[c] Species that were found in both NSA and Melville Island, Canadian Arctic [*Rui et al.*, 1991].

and Paleozoic rocks, suggesting a Neoproterozoic basement in Zhokhov and the other islands of NSA [*Kos'ko and Korago*, 2009; *Kuzmichev*, 2009]. The Carboniferous limestone block that is the object of this study is interpreted as a xenolith in basalt, representing a fragment of the same carbonate platform exposed in Kotel'ny and Bel'kovsky Islands of the NSA. This xenolith was captured during the assent of the deep intraplate Cenozoic basaltic magma through the Paleozoic carbonate platform [*Kos'ko et al.*, 2013]. Geological and geophysical constraints suggest that the ACCT extends as far west as the NSA and includes most of the immense and poorly known east Siberian continental shelf and Taimyr [*Parfenov et al.*, 1993; *Drachev et al.*, 1998; *Sokolov et al.*, 2002]. The alternative model suggests the extension of the Uralian structure directly into Taimyr and NSA or through Novaya Zemlya [*Scott et al.*, 2010]. Some of the recent detrital zircon provenance studies in the NSA suggest that the Late Paleozoic, synorogenic foreland basin deposits of the Uralian orogen are continuous through Taimyr toward the NSA [*Scott et al.*, 2010; *Pease et al.*, 2014]. Another suggestion is that the paleoposition of NSA was along the northern margin of Laurentia-Baltica, at least during the Late Devonian-Mississippian [*Ershova et al.*, 2015]. According to *Miller et al.* [2013], the Triassic of the Lisburne Hills of Alaska, Chukotka, and Wrangel Island possesses nearly identical sources for the detrital zircon populations, whereas the absence of Precambrian 1100–1800 Ma zircons populations in those areas allies them with Bol'shoi Lyakhov Island of NSA and Siberia.

3. Material

During an expedition to Zhokhov Island in 1990, Prof. Mikhail A. Anisimov from the Arctic and Antarctic Research Institute, St. Petersburg, Russia, found a small limestone block (xenolith) in the volcanic Cenozoic breccia near the meteorological station. There were several other Paleozoic and Precambrian xenoliths in Zhokhov and other NSA islands reported from these volcanic rocks of intraplate origin with the depth of the melting exceeding 60 km [*Kos'ko et al.*, 2013]

Having observed many fossils on the surface of the limestone, Prof. Amisimov brought this block back to paleontologists (including the writer) for investigation. The limestone is completely silicified, but preservation of the fossils is good enough for the identification and recognition of the original rock texture. The rock is a light grey to white silicified bioclastic limestone (Figure 1, photo in the upper right corner) rich in fossils, including brachiopods, trilobites, corals, and foraminifera [*Makeev et al.*, 1991]. The entire list of the fossils can be found in Table 1. The recognized fossils include 6 genera and 7 species of algae and 25 genera and 46 species of foraminifera in the studied thin sections (Table 1).

4. Discussion

4.1. The Biostratigraphy and Age Constraints

Due to strong silicification of the rock, the preservation of the fossils is not always good, but many important features of the foraminifera are well manifested. Red and green algae (Figure S1 in the supporting information) have been identified, suggesting a warm, shallow-water environment. The algae are known to characterize tropical, Middle and Upper Pennsylvanian in many regions globally [*Mamet*, 1991]. *Palaeoberesella*, *Donezella*, *Efluegelia*, and *Stacheoides* are long-ranging genera. *Donezella lunaensis* in the Urals is an index zone of upper Bashkirian, although it also ranges into the Moscovian [*Ivanova*, 2013]. The green algae *Epimastopora* are most common in the Permian and are also known in Bashkirian and Moscovian [*Ivanova*, 2013].

The majority of the foraminifera in the studied sample are small so the sample could be interpreted as temperate environment carbonates [*Solovieva*, 1975; *Dixon and Haig*, 2004; *Ivanova*, 2008; *Davydov and Arefifard*, 2013] (Figures S1 and S2). However, the presence of warm-water green algae and typical tropical fusulinids (*Novella*, *Eofusulina*) suggests that the dominance of smaller foraminifera in the studied collection is determined by the preservation mode rather than cool-water environments. The preservation of the morphology of the larger forms in the studied collection is medium to poor, due to great silicification of the limestone. The majority of the forms identified at the species level but often with *cf.*, *aff.*, and *ex gr.* qualifiers (Figures S1 and S2). The interpreted age of the studied sample, nevertheless, is very solid.

Most of smaller foraminifera are long-ranging forms and in general characterize the Late Mississippian to Pennsylvanian. The important fusulinid taxa are *Novella*, *Schubertella*, *Pseudostaffella*, *Profusulinella*, *Staffellaeformis*, and *Eofusulina*. The first appearance datum (FAD) of *Novella* is upper Bashkirian. The identified species (Figures 4.24–25), which are characteristic for the upper Bashkirian and lower Moscovian, occur in the vast area that extends from the Arctic to Tethys [*Grozdilova and Lebedeva*, 1960; *Ivanova*, 2008; *Manukalova-Grebenyuk et al*., 1969; *van Ginkel*, 2010]. *Schubertella* FAD, which is upper Bashkirian as well, is very rare in this sample. The genus is very common in the Moscovian, becomes rare in Upper Pennsylvanian, and ranges through the Permian [*Davydov*, 2011; *Rauser-Chernousova et al*., 1996]. The recognized *Schubertella* species appears in the Moscovian and ranges upward into the Kasimovian [*Davydov*, 2009, 2011; *Nikolaev*, 2011; *Rauser-Chernousova et al*., 1996]. *Pseudostaffella* is a very characteristic middle-upper Bashkirian and lower Moscovian genus. It is rare in the upper Moscovian where it is replaced by *Neostaffella* and *Hanostaffella*. The *Pseudostaffella* species recognized in the sample are characteristic for upper Bashkirian and lower Moscovian [*Dzhenchuraeva*, 1997; *Manukalova-Grebenyuk et al*., 1969; *Nikolaev*, 2005]. *Staffellaeformis* is a very common genus in the upper Bashkirian of Timan-Pechora and Urals and is also widely distributed in Tethys [*Grozdilova and Lebedeva*, 1950; *Ivanova*, 2008; *Leven et al*., 2006; *Nikolaev*, 2005; *Ueno et al*., 2007]. The upper range of that genus is lowermost Moscovian. *Profusulinella prisca* (Deprat) is known in a vast territory from the Canadian Arctic to Japan and China/Indo-China. In the Russian Platform and Urals this species is generally considered to be early Moscovian [*Rauser-Chernousova et al*., 1951; *Kulagina et al*., 2009], although it is also documented from what is considered as uppermost Bashkirian [*Ivanova*, 2008]. The latter interpretation, however, among other taxonomic complications, is also related to the problem of the definition of the Bashkirian-Moscovian boundary that has been debated in the international working group for the last 20 years [*Davydov et al*., 2012].

The last and very important form identified in the collection is *Eofusulina* cf. *triangula* (Rauser and Belyaev). Two specimens (Figures 4.49–50) are oblique and incomplete, and the exact identification is not possible. These forms have a relatively large elongate and triangular shape, very large initial chamber, deep and intensely fluted septa, and relatively loose coiling. No foraminifera with such attributes are known in the upper Bashkirian and lower Moscovian other than *Eofusulina*. This morphology best fits with the above mentioned genus; the species are identified with the cf. qualifier. In terms of biogeography, the genus is a typical tropical taxon, widely distributed within the Tethys from Cantabrian Mountains to Donets Basin, in Turkey Taurids, Central Asia, China, and Japan [*Davydov*, 2009; *Dzhenchuraeva and Okuyucu*, 2007; *van Ginkel*, 1965; *Rumyantseva*, 1974; *Toriyama*, 1953]. The single specimen of *Eofusulina* was documented in lower Canyon Fiord Formation in Melville Island, Canadian Arctic [*Rui et al*., 1996], and occurred in an assemblage that closely resembles that of Zhokhov Island. In Spitsbergen and in North Greenland, *Eofusulina* was found in slightly younger upper lower Moscovian (Kashirian) deposits [*Forbes*, 1960; *Ross and Dunbar*, 1962].

Eofusulina has recently been proposed as an index of the Bashkirian-Moscovian boundary in the International time scale [*Davydov*, 2009; *Groves*, 2011]. The upper range of the species is upper Moscovian [*Ivanova*, 2008].

Taking into consideration the above mentioned taxonomic information, it is clear that the studied limestone belongs to the lower Moscovian, Vereian, or Kashirian Regional Stage of Russian Platform and the Urals. This age is consistent with the previously published coral data [*Makeev et al*., 1991]. The presence of diverse algae, fusulinids, and rugose corals suggests the occurrence of this location within the warm-water tropics-subtropics of the early Moscovian global interglacial warming episode [*Davydov*, 2014].

4.2. Paleobiologic and Environmental Constraints of Foraminifera and Algae

Two major shallow-water assemblages exist in Carboniferous and Permian foraminifera: warm-water tropical-subtropical larger foraminifera and cool-to-cold water smaller calcareous and agglutinated foraminifera. The latter foraminifera represent a large group of long-ranging protozoans (over 750 genera) possessing the longest stratigraphic ranges among the foraminifera, with no lateral and/or bathymetrical limits in distribution [*Gerke*, 1961; *Bogush and Yuferev*, 1966; *Yuferev*, 1968; *Dixon and Haig*, 2004; *Kaminski et al*., 2010] except for the rarity in normal marine shallow warm-water settings.

Late Paleozoic fusulinids and green algae were shallow-water organisms living in healthy considered to have been symbiont-bearing organisms similar to the modern larger benthic foraminifera [*Ross*, 1995; *Lee*, 1996; *Vachard et al*., 2004]. Water temperature and light availability (depth) are the most important factors controlling the distributions of larger symbiont-bearing foraminifera in seas of normal salinity [*Hohenegger*, 2004]. Temperature determines the geographic and bathymetric distribution of larger foraminifera by the development of a shallow thermocline that truncates the distribution of shallower species and excludes species adapted to the deepest euphotic zone [*Davydov et al*., 2013]. Larger foraminifera are also restricted to those geographical regions or water depths characterized by temperatures never falling below 14°C for more than several weeks [*Hohenegger*, 2004]. The optimal water temperatures for shallow-water assemblages of recent larger foraminifera range from 20 to 30°C [*Hohenegger*, 2004].

The taxonomy and diversity of fusulinids directly correlates with the latitudinal distribution of tropical-subtropical temperature changes [*Ross*, 1995; *Buzas et al*., 2002; *Davydov et al*., 2013]. During global warm (climatic optimum) episodes, symbiont-bearing foraminifera could migrate to higher latitudes. By contrast, cooling led to emigration of parts of the foraminiferal fauna from higher to lower latitudes, stepwise extinction of some of the taxa, increasing provincialism, and the preferential survival of faunas adapted for a broader range of facies. Fusulinid faunas are a particularly sensitive index of climate change in midlatitude regions, where the changes are quite dramatic [*Davydov and Arefifard*, 2013; *Davydov et al*., 2013].

Recent larger, symbiont-bearing foraminifera are limited in general to a worldwide tropical-subtropical climatic belt defined by winter minimum isotherms between 15° and 20°C, i.e., approximately 30° south and north latitudes [*Langer and Hottinger*, 2000; *Goldbeck and Langer*, 2009]. Only very few larger warm-water foraminifera are known to occur outside of this climatic belt due to the local paleogeography and climate fluctuations. Similar biogeography within 30° south/north latitudes is reflected in Carboniferous and Permian fusulinid distribution [*Mamet*, 1977; *Ross*, 1995]. Two transitional subbelts with temperate water fusulinid fauna are designated in both Northern [*Rui et al*., 1991] and Southern Hemispheres [*Davydov and Arefifard*, 2007; *Ueno*, 2006]. These subzones extended from approximately 25° to 35° south/north latitudes. Eventually, the 35° south/north latitudes could be designated as north/south *forbiddance lines* for fusulinid distribution (Figure 2) that is absolute limit of their midlatitude occurrences. Therefore, in paleotectonic/paleogeographic reconstructions where fusulinids are located north (in the Northern Hemisphere) or south (in the Southern Hemisphere) of the forbiddance lines, corrections need to be made.

4.3. Biotic Paleothermometry Constraints on the New Siberian Archipelago Paleoposition

Most of the Late Paleozoic Arctic paleotectonic/paleogeographic reconstructions, particularly the most recent ones, were developed from paleomagnetic, paleoenvironments/paleolithofacies distribution and detrital zircon provenance studies [*Drachev et al*., 2010; *Ershova et al*., 2015; *Khramov and Ustritsky*, 1990; *Kuzmichev*, 2009; *Metelkin et al*., 2015; *Miller et al*., 2013; *Pease et al*., 2014]. The biotic constrains were generally not considered in these studies. The existing faunistic records in the Arctic region are poor. Also faunas are very sensitive to paleoclimate and quickly respond to any climate fluctuations by way of migration and changes in latitudinal distribution [*Buzas et al*., 2002; *Davydov and Arefifard*, 2013; *Davydov et al*., 2013]. On regional and interregional scales and within a refined chronostratigraphy climatic changes could be very significant. This is particularly true along the latitudinal gradient in the midlatitudes where the changes associated with climate fluctuations in foraminifera distribution are most dramatic and may vary up to ±10° latitudes [*Buzas et al*., 2002]. Consideration of faunal data for paleotectonic/paleogeographic reconstructions at glacial and interglacial episodes without an understanding of fauna-climate interaction at the regional and interregional scales might produce significant errors in the reconstruction. Two stratigraphically successive assemblages one of which is taxonomically related to tropics and the other to temperate environments could be interpreted in two different ways. In general, it is interpreted as a tectonic movement of the location from tropics to higher latitudes. However, this might be also due to global climate shift from global warming into cooling episodes. Therefore, the records of paleoclimate dynamics must be a part of the paleotectonic/paleogeographic reconstructions. Taking into account that early Moscovian perhaps was the time of global warm climate [*Davydov*, 2014], we can suppose the paleoposition of Zhokhov Island at this time around 35°N. Also, in order to correctly understand the biogeography of the regions, only assemblages proved to be isochronous must be analyzed.

In the southern Taimyr and Verchoyansk along the Moscovian Siberian shelf, shallow-water siliciclastic sequences possess boreal cold-water brachiopods and agglutinated smaller foraminifera attesting to the cold temperature even in shallow-water environments in these regions [*Klets*, 2005]. This strongly contrasts with typical warm-water assemblage recovered from Zhokhov Island. In terms of the taxonomy of fusulinids, the assemblages of Zhokhov island are most similar to synchronous assemblages known in Spitsbergen, Greenland, Canadian Arctic Archipelago, Novaya Zemlya, and the Timan-Pechora province [*Grozdilova and Lebedeva*, 1961; *Nakrem et al*., 1991; *Rui et al*., 1991]. Thus, Zhokhov Island and perhaps the other islands of the NSA during Moscovian time were located south of the forbiddance line that is south of about 30–35°N (Figure 2). The upper Bashkirian and perhaps lower Moscovian fusulinids were also documented in Wrangel Island and northern Chukotka [*Kos'ko et al*., 1993; *Solovieva*, 1975]. These two regions were part of the ACCT and were located very close to Spitsbergen and North Greenland during Pennsylvanian time.

In previous Late Paleozoic continental reconstructions including data from lithofacies/paleoenvironmental proxies and detrital zircon provenance [*Scotese*, 2004; *Cocks and Torsvik*, 2007; *Blakey*, 2008; *Golonka*, 2011; *Lawver et al*., 2011] the transitional temperate water zone in Northern Hemisphere includes North Greenland, Sverdrup Basin in Canada, Spitsbergen, Franz Josef Land, and Novaya Zemlya, whereas Wrangel Island, North Chukotka, NSA, Taimyr, and Anvil-Anui terranes are positioned around 45–50°N (Figures 3c and 3d). Part of Wrangellia terrane (at least that south from Denali fault) according *Colpron and Nelson* [2009] was positioned within tropics-subtropics and far west from the Sverdrup Basin, Spitsbergen, and other regions of the temperate northern climatic subbelt (WCT' in Figure 2).

The New Siberian Archipelago (NSA) terrane with its Precambrian basement and Middle to Late Paleozoic carbonate platform is the key for the paleotectonic/paleogeographic reconstructions of the Arctic (Figure 1). Many

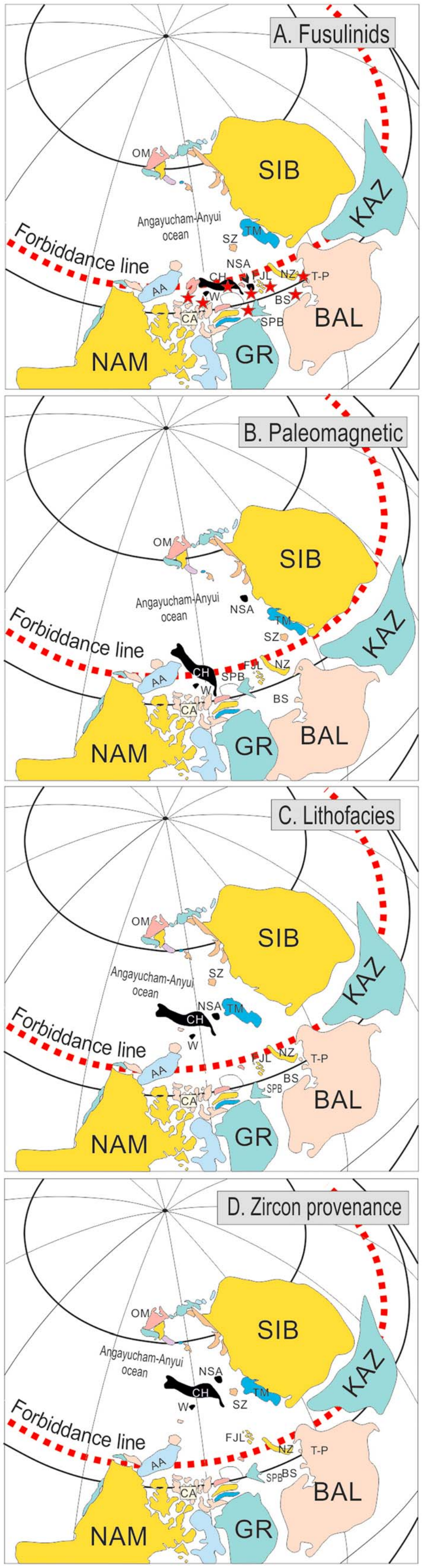

Figure 3. Northern Hemisphere paleogeographic reconstructions (315 Ma, Early Moscovian) established with different data sets and approaches: (a) according to fusulinid occurrences in different terranes, the position of NSA, Alaska-Chukotka composite terrane, and Wrangel Island (shown as black masses) has to be south of the forbiddance line (~30–35°N at the Early Moscovian global warming); (b) reconstruction proposed from the paleomagnetic studies [*Metelkin et al*., 2015]; (c) the same terranes with a reconstruction developed from lithofacies and paleoenvironmental proxies [*Golonka*, 2011]; and (d) the reconstruction developed from detrital zircon provenance studies [*Kuzmichev and Pease*, 2007; *Colpron and Nelson*, 2009; *Miller et al*., 2013; *Pease et al*., 2014; *Ershova et al*., 2015]. In all reconstructions except Figure 3a, NSA, Alaska-Chukotka composite terrane, and Wrangel Island positioned north from the northern forbiddance line at around 45–60°N.

disagreements regarding the NSA paleoposition exist among the researchers. According to recent paleomagnetic studies in the Early Paleozoic NSA occurs north of the Siberian Craton, but by the Late Carboniferous it is suggested to be within the distal northeastern margin of Siberian Craton (NSA in Figure 3b) [*Metelkin et al.*, 2015] and somewhat north of the position suggested by the fusulinids (Figure 3a). According to these authors the NSA was the separate and independent terrane located during Early to Middle Paleozoic nearby the passive margin of Siberian Craton near its northwest corner. During Carboniferous the terrane was docking to Siberia in the southwest and since that time becomes essentially permanent part of the Siberia and North Kara cluster [*Metelkin et al.*, 2015].

Utilizing lithofacies analyses, *Golonka* [2011] placed the Chukotka, Wrangel Island, NSA, and Taimyr between North American and Siberian Cratons. At Tournaisian time, according to his analyses, NSA was located at approximately 30–35°N and was a part of the carbonate platform extended from eastern margin of Barentsia to the western margin of Siberian Craton. During Carboniferous Chukotka, Wrangel Island, NSA, and Taimyr migrated north toward Siberia and by Middle Pennsylvanian they proposed to be at approximately 40–45°N, i.e., about 10–12°N from the forbiddance line (Figure 3c). By the early Permian, according to this model the NSA was docked to Taimyr and to Siberian Craton [*Golonka*, 2011].

The reconstruction based on detrital zircon provenance studies (Figure 3d) proposes a sub-Baltica position for the clustered paleoposition of Chukotka, NSA, and Wrangel Island during Devonian-Mississippian time. This composite terrane then shifted to the Uralian zircon provenance during Late Carboniferous-Permian and Triassic [*Kuzmichev and Pease*, 2007; *Miller et al.*, 2013; *Pease et al.*, 2014; *Ershova et al.*, 2015]. The major shift to Uralian sources during Pennsylvanian-Triassic time is explained by the rifting of Chukotka, Wrangel Island, NSA, and Severnaya Zemlya from Baltica/Laurentia and their eastward drifting and collision and suturing to Siberian continent around the Triassic (Figure 3d). This contradicts the fusulinid data, which suggests that during Middle Pennsylvanian time, Chukotka-Wrangel Island and NSA terrane, including Zhokhov Island, were located close to the Sverdrup Basin, Arctic Alaska (Brooks and Lisburne Ridges), Spitsbergen, Franz Josef Land, Barents Shelf, and Timan-Pechora (Figure 2). The remnants of this composite terrane occur in Northwind Ridge [*Stevens and Ross*, 1997; *Grantz et al.*, 1998] and possibly in Mendeleev Ridge [*Kaban'kov et al.*, 2008; *Morozov et al.*, 2014]. The youngest fusulinids from Northwind Ridge and Mendeleev Ridge (late Artinskian *Parafusulina*) indicate that ACCT could still be south of the forbiddance line at least until the late Artinskian (Figures 2 and 3a). The nearly identical sources of the Triassic detrital zircon populations of the Lisburne Hills of Alaska with the Triassic of Chukotka and Wrangel Island have been reported [*Miller et al.*, 2013], although Lisburne Hills in the Triassic was separated from Chukotka and Wrangel Island by the paleohigh and is of different facies (shelf versus basinal). This might be an additional argument for the stability of ACCT and its sub-Baltica position until Triassic time.

The Lower Triassic sills and other small hypabyssal gabbro and dolerite intrusions in the Bol'shoi Lyakhov Island of NSA reveal some geochemical similarity with the traps of the Siberian Craton [*Kuzmichev and Pease*, 2007]. If they belong to the Siberian trap magmatism, it would mean that westernmost part of the NSA may be related to Siberian Craton and that the South Anuyi Suture was located between Bel'kov and Bol'shoi Lyakhov islands and the rest of the NSA (Figure 1), which is consistent with the provenance data [*Miller et al.*, 2013; *Pease et al.*, 2014].

It is worth noting that the paleoposition of the Wrangelia arc terrane during Late Paleozoic time is highly variable in different publications. In the most popular reconstruction [*Belasky et al.*, 2002], Wrangelia is placed in the Panthalassa, close to Stikinia and Eastern Klamath terranes, and about 2000–3000 km west of Arctic Alaska because of a strong generic level similarity among corals, brachiopods, and fusulinids. The latter group shows a particularly strong similarity between Wrangelia and other Panthalassa terranes [*Belasky et al.*, 2002, Table 2]. But at the species level there is a strong dissimilarity between fusulinids of those regions. The fusulinid records in Wrangelia are still poor. One excellent study of fusulinids of Wrangelia in which the early Permian fusulinid fauna is described in great detail was accomplished over 40 years ago [*Petocz*, 1970]. At the species level, the fauna there shows strong affinity with that of North Greenland [*Nilsson et al.*, 1991], Canadian Arctic [*Harker and Thorsteinsson*, 1960; *Davydov*, 1991], Arctic Alaska [*Ross*, 1967], Kolguev Island [*Davydov*, 1997], Timan-Pechora, and northern Urals [*Grozdilova and Lebedeva*, 1961; *Konovalova*, 1991]. In fact, many species originally described in Timan-Pechora are recognized in the Mankomen Formation of Wrangelia [*Petocz*, 1970] but have never been found in Panthalassa terranes. Similarly, the Lower Permian colonial corals also show high similarity at the species level [*Stevens*, 2008], although the proposed paleoposition based on the corals [*Stevens*, 2008] is different from what is suggested here.

Douglass [1971] provides the only other paper dealing with Wrangelia Moscovian fusulinids. Although the majority of the fusulinid species in this paper are described as new, they resemble fusulinids known in Urals and Russian Platform. *Pseudostaffella rotundata* Douglass is very close to *Pseudostaffella gorskyi* (Dutkevich) known from upper Bashkirian and lower Moscovian in Russian Platform, Urals, and Timan-Pechora. *Fusulinella pinguis* Douglass resembles *Fusulinella* (*Pulchrella*) *subpulchra* (Putrja) from Kashirian to Myachkovian of Russian Platform, Urals, Timan-Pechora, Spitsbergen, and Sverdrup. *Fusulinella alaskensis* Douglass is very similar to *Fusulinella* (*Pulchrella*) *eopulchra* Rauser, and *Fusulina flexuosa* Douglass could be interpreted as *Fusulina cylindrica* (Moeller) [*Rauser-Chernousova et al*., 1951; *Lebedeva*, 1966; *Rui et al*., 1991; *Nilsson and Davydov*, 1997; *Ivanova*, 2008]. *Pseudostaffella gorskyi* and *Fusulina cylindrica* have never been reported from northern Panthalassa, and certainly, the Wrangelia fusulinids have affinity with Uralo-Franklinian province [*Rui et al*., 1991]. The record from both the fusulinid and colonial corals strongly suggests that the paleoposition of Wrangelia was close to North Greenland, Canadian Arctic, and Sverdrup rather than with northern Panthalassa (Figure 2). In any case, the Carboniferous and Permian paleontological record of Wrangelia-Alexandria terranes requires further and extensive development.

5. Conclusions

1. The studied limestone block from Zhokhov Island, New Siberian Archipelago, reveals very high taxonomic diversity of Middle Pennsylvanian Moscovian tropical foraminifera and algae.
2. The faunal and floral (algae) paleothermometry constrains the paleogeography and paleotectonics in the region because these warm-water biotas never occur north of the forbiddance line, i.e., 30–35°N/S and undoubtedly indicate the location of the most of New Siberian Archipelago islands at that time within tropic-subtropics.
3. The analysis of the existing data on the fusulinid distribution within the Arctic region indicates that by Artinskian time, Zhokhov Island as well as Wrangel Island were still within the Alaska-Chukotka composite terrane.
4. If the Lower Triassic sills and intrusions in Lyakhov Island of the New Siberian Archipelago belong to Siberian trap magmatism, it suggests that the South Anuyi Suture lay between Bel’kov Island and the rest of the New Siberian Archipelago.
5. The detrital zircon provenance data might be interpreted to suggest the paleoposition of the Alaska-Chukotka composite terrane, including New Siberian Archipelago and Wrangel Island close to Arctic Alaska probably until Triassic time.
6. The fusulinids from the Mankomen Formation and other formations in Wrangelia show strong affinity with the Uralo-Franklinian province regions such as the Sverdrup Basin, Spitsbergen, Barents Sea, Timan-Pechora, and northern-central Urals rather than with northern Panthalassa.

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References

Belasky, P., C. H. Stevens, and R. A. Hanger (2002), Early Permian location of western North American terranes based on brachiopod, fusulinid, and coral biogeography, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *179*(3–4), 245–266.

Blakey, R. C. (2008), Gondwana paleogeography from assembly to breakup: A 500 m.y. odyssey, *Spec. Pap. Geol. Soc. Am.*, *441*, 1–28.

Bogush, O. I., and O. V. Yuferev (1966), *Foraminifery Karbona i Permi Verkhoyanya [Carboniferous and Permian foraminifers From Verkhoiansk]* [in Russian], pp. 1–208, Akad. Nauk SSSR, Sib. Otd., Inst. Geol. i Geofiz., Nauka, Moscow.

Buzas, M. A., L. S. Collins, and S. J. Culver (2002), Latitudinal difference in biodiversity caused by higher tropical rate of increase, *Proc. Natl. Acad. Sci. U.S.A.*, *99*, 7841–7843.

Cocks, L. R. M., and T. H. Torsvik (2007), Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic, *Earth Sci. Rev.*, *82*(1–2), 29–74.

Colpron, M., and J. L. Nelson (2009), A Palaeozoic northwest passage; incursion of Caledonian, Baltican and Siberian terranes into eastern Panthalassa, and the early evolution of the North American Cordillera, *Geol. Soc. Spec. Publ.*, *318*, 273–307.

Davydov, V. I. (1991), Vozrast verkhney chasti formatsii Belcher Chenell v stratotipe po fuzulinidam [The age of the upper Belcher Channel Formation in the type-section on the ground of fusulinids], in *Stratigraphy and Paleontology of Paleozoic of the Arctic*, *Trans. of SEVMORGEO* [in Russian], edited by V. I. Bondarev, pp. 16–29, Sevmorgeo House, Leningrad.

Davydov, V. I. (1997), Fusulinid biostratigraphy of the Upper Paleozoic of the Kolguev Island and Franz Josef Land Archipelago, in *Biostratigraphy of the Oil-Bearing Basins*, *Trans. of First Int. Symp*. [in Russian], edited by M. D. Belonin et al., pp. 40–59, VNIGRI, St. Petersburg.

Davydov, V. I. (2009), Bashkirian-Moscovian transition in Donets Basin: The key for Tethyan-Boreal correlation, in *The Carboniferous Type Sections in Russia, Potential and Proposed Stratotypes: Proceedings of the International Conference, Ufa - Sibai, 13–18 August, 2009*, pp. 188–192, Inst. of Geol., Bashkirian Acad. of Sci., Ufa.

Davydov, V. I. (2011), Taxonomy, nomenclature and evolution of the early schubertellids (Fusulinida, Foraminifera), *Acta Palaeontol. Pol.*, *56*(1), 181–194.

Davydov, V. I. (2014), Warm water benthic foraminifera document the Pennsylvanian–Permian warming and cooling events—The record from the Western Pangea tropical shelves, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *414*, 284–295.

Davydov, V. I., and S. Arefifard (2007), Permian fusulinid fauna of Gondwanan affinity from Kalmard Region, East-Central Iran and its significance for the tectonics and paleogeography, *Palaeontol. Electron.*, *10*, 1–40. [Available at http://palaeo-electronica.org/2007_2/00124/index.html.]

Davydov, V. I., and S. Arefifard (2013), Middle Permian (Guadalupian) fusulinid taxonomy and biostratigraphy of the mid-latitude Dalan Basin, Zagros, Iran and their applications in paleoclimate dynamics and paleogeography, *GeoArabia*, *18*(2), 17–62.

Davydov, V. I., I. Nilsson, and L. Stemmerik (2001), Fusulinid zonation of the Upper Carboniferous Kap Jungersen and Foldedal Formations, southern Amdrup Land, eastern north Greenland, *Bull. Geol. Soc. Den.*, *48*, 31–77.

Davydov, V. I., D. Korn, and M. D. Schmitz (2012), The Carboniferous Period, in *The Geologic Time Scale 2012*, vol. 2, edited by F. M. Gradstein et al., pp. 603–651, Elsevier, Amsterdam.

Davydov, V. I., D. W. Haig, and E. Mccartain (2013), A latest Carboniferous warming spike recorded by a fusulinid-rich bioherm in Timor Leste: Implications for East Gondwana deglaciation, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *376*, 22–38.

Dixon, M., and D. W. Haig (2004), Foraminifera and their habitats within a cool-water carbonate succession following glaciation, Early Permian (Sakmarian), Western Australia, *J. Foraminiferal Res.*, *34*(4), 308–324.

Douglass, R. C. (1971), Pennsylvanian fusulinids from Southeastern Alaska, *U.S. Geol. Surv. Prof. Pap.*, *706*, 1–42.

Drachev, S. S., L. A. Savostin, V. G. Groshev, and I. E. Bruni (1998), Structure and geology of the continental shelf of the Laptev Sea, eastern Russian Arctic, *Tectonophysics*, *298*(4), 357–393.

Drachev, S. S., N. A. Malyshev, and A. M. Nikishin (2010), Tectonic history and petroleum geology of the Russian Arctic shelves: An overview, *Pet. Geol. Conf. Proc.*, *7*, 591–619.

Dzhenchuraeva, A. V. (1997), Biostratigraphy of Middle and Upper Carboniferous deposits of Tien-Shan, *Spec. Publ. Cushman Found. Foraminiferal Res.*, *36*, 37–40.

Dzhenchuraeva, A. V., and C. Okuyucu (2007), Fusulinid Foraminifera of the Bashkirian-Moscovian boundary in the eastern Taurides, southern Turkey, *J. Micropalaeontol.*, *26*(1), 73–85.

Ehrenberg, S. N., N. A. H. Pickard, T. A. Svana, I. Nilsson, and V. I. Davydov (2000), Sequence stratigraphy of the inner Finnmark carbonate platform, Barents Sea: Correlation.

Embry, A. F. (1988), Middle-Upper Devonian sedimentation in the Canadian Arctic Islands and the Ellesmerian Orogeny, in *Devonian of the World*, vol. 2, edited by N. J. McMillan and D. J. Glass, pp. 15–28, Canadian Society of Petroleum Geologists, Memoir 14.

Ershova, V. B., A. V. Prokopiev, A. K. Khudoley, N. N. Sobolev, and E. O. Petrov (2015), Detrital zircon ages and provenance of the upper Paleozoic successions of Kotel'ny Island (New Siberian Islands Archipelago), *Lithosphere*, *7*(1), 40–45.

Forbes, C. L. (1960), Carboniferous and Permian Fusulinidae from Spitsbergen, *Palaeontology*, *2*(2), 210–225.

Gerke, A. A. (1961), Foraminifers of Permian, Triassic and Liassic petroleum strata of northern central Siberia, in *Trudy Instituta Geologii i Mineral'nykh Resursov Mirovogo Okeana, VNII Okeangeologiya* [in Russian], vol. 120, pp. 1–518, Nedra, Leningrad.

Goldbeck, E. J., and M. R. Langer (2009), Biogeographic provinces and patterns of diversity in selected Upper Cretaceous (Santonian-Maastrichtian) larger Foraminifera, *Spec. Publ. Soc. Sediment. Geol.*, *93*, 187–232.

Golonka, J. (2011), Phanerozoic palaeoenvironment and palaeolithofacies maps of the Arctic region, in *Memoirs of the Geological Society of London*, vol. 35, edited by A. M. Spencer et al., pp. 79–129 , Geol. Soc. of London, London.

Grantz, A., et al. (1998), Phanerozoic stratigraphy of Northwind Ridge, magnetic anomalies in the Canada Basin, and the geometry and timing of rifting in the Amerasia Basin, Arctic Ocean, *Geol. Soc. Am. Bull.*, *110*(6), 801–820.

Groves, J. R. (2011), Report of the Task Group to establish a GSSP close to the existing Bashkirian–Moscovian boundary, *Newsl. Carboniferous Stratigr.*, *28*, 30–33.

Groves, J. R., W. W. Nassichuk, R. Lin, and S. Pinard (1994), Middle Carboniferous Fusulinacean biostratigraphy, northern Ellesmere Island (Sverdrup Basin, Canadian Arctic Archipelago), *Bull. Geol. Surv. Can.*, *469*, 55.

Grozdilova, L. P., and N. S. Lebedeva (1950), Some species of *Staffella* from the Middle Carboniferous of the western slope of the Urals, in *Mikrofauna SSSR, Trudy, Vsesoyuznogo Neftyanogo Nauchno—Issledovatel'skogo Geologo-Razvedochnogo Instituta (VNIGRI), Sbomik 3, Novaya Seriya* [in Russian], vyp. 50, pp. 5–46, Gostoptekhizdat, Leningrad.

Grozdilova, L. P., and N. S. Lebedeva (1960), Foraminifery kamennougolnykh otlozhenii zapadnogo sklona Urala i Timana; atlas naibolee kharakternykh vidov, in *Trudy - Vsesouznyy Naucno-Issledovatelskiy Geologorazvedocnyy Neftanoy Institut, Geohimiceskiy Sbornik* [in Russian], vol. 150, 264 pp., Gostoptekhizdat, Leningrad.

Grozdilova, L. P., and N. S. Lebedeva (1961), Lower Permian foraminifers of North Timan, in *Transactions of VNIGRI* [in Russian], vol. 179, pp. 161–283, Gostoptekhizdat, Leningrad.

Harker, P., and R. Thorsteinsson (1960), *Permian Rocks and Faunas of Grinnell Peninsula, Arctic Archipelago, Mem.*, Geol. Surv. of Can., Ottawa.

Hohenegger, J. (2004), Depth coenoclines and environmental considerations of western Pacific larger foraminifera, *J. Foraminiferal Res.*, *34*(1), 9–33.

Ivanova, R. M. (2008), *Fusulinids and Algae of Middle Carboniferous of the Urals (Zonal Stratigraphy, Paleobiogeography and Paleontology)* [in Russian], Inst. of Geol. and Geochem., Ekaterinburg, Russia.

Ivanova, R. M. (2013), *Calcareous Algae of the Carboniferous of the Urals* [in Russian], Inst. of Geol. and Geochem., Ekaterinburg, Russia.

Kaban'kov, V., I. A. Andreeva, V. V. Krupskaya, D. V. Kaminskii, and E. I. Razuvaeva (2008), New data on the composition and origin of bottom sediments in the southern Mendeleev Ridge, Arctic Ocean [in Russian], *Dokl. Earth Sci.*, *419*(2), 403–405.

Kaminski, M. A., E. Setoyama, and C. Cetean (2010), The Phanerozoic diversity of agglutinated Foraminifera: Origination and extinction rates, *Acta Palaeontol. Pol.*, *55*(3), 529–539.

Kashik, D. S., I. A. Alekseeva, and A. N. Polozova (1969), The stratigraphy of lower Permian deposits of north of the Russian Platform [in Russian], *Dokl. Acad. Sci. USSR*, *187*, 399–402.

Khramov, A. N., and V. I. Ustritsky (1990), Paleopositions of some northern Eurasian tectonic blocks: Paleomagnetic and paleobiologic constraints, *Tectonophysics*, *184*(1), 101–109.

Klets, A. G. (2005), *Upper Paleozoic of the Angarida Marginal Seas* [in Russian], *Trans. of Inst. of Pet. Geol.*, GEO, Novosibirsk.

Konovalova, M. V. (1991), *Stratigraphy and Fusulinids of Upper Carboniferous and Lower Permian of Timan-Pechora Oil- and Gas Bearing Province* [in Russian], Nedra House, Ukhta Geol.-Explor. Exped., Moscow.

Kos'ko, M., and E. Korago (2009), Review of geology of the New Siberian islands between the Laptev and the East Siberian Seas, North East Russia, *Stephan Mueller Spec. Publ. Ser.*, *4*, 45–64.

Kos'ko, M. K., M. P. Cecile, J. C. Harrison, V. G. Ganelin, N. V. Khandoshko, and B. G. Lopatin (1993), Geology of Wrangel Island, between Chukchi and East Siberian Seas, northeastern Russia, *Bull. Geol. Surv. Can.*, *461*, 1–107.

Kos'ko, M. K., N. N. Sobolev, Y. A. Korago, V. F. Proskurnin, and N. M. Stolbov (2013), Geology of the New Siberian islands: A basis for interpretation of geophysical data on the eastern Russian Arctic continental shelf [in Russian], *Neftegazov. Geol. Teor. Prak.*, *8*(2), 36.

Kulagina, E. I., V. N. Pazukhin, and V. I. Davydov (2009), Pennsylvanian biostratigraphy of the Basu River section with emphasis on the Bashkirian-Moscovian transition, in *The Carboniferous Type Sections in Russia, Potential and Proposed Stratotypes: Proceedings of the International Conference, Ufa - Sibai, 13–18 August, 2009*, pp. 43–62, Inst. of Geol., Bashkirian Acad. of Sci., Ufa.

Kuzmichev, A. B. (2009), Where does the South Anyui suture go in the New Siberian islands and Laptev Sea? Implications for the Amerasia basin origin, *Tectonophysics*, *463*(1–4), 86–108.

Kuzmichev, A. B., and V. L. Pease (2007), Siberian trap magmatism on the New Siberian Islands: Constraints for Arctic Mesozoic plate tectonic reconstructions, *J. Geol. Soc.*, *164*, 959–968.

Langer, M. R., and L. C. Hottinger (2000), Biogeography of selected "larger" foraminifera, *Micropaleontology*, *46*(Suppl. 1), 105–126.

Lawver, L. A., L. M. Gahagan, and I. Norton (2011), Palaeogeographic and tectonic evolution of the Arctic region during the Palaeozoic, *Mem. Geol. Soc. London*, *35*, 61–77.

Lebedeva, N. S. (1966), Foraminifery srednego karbona Severnogo Timana, in *Trudy - Vsesouznyy Naucno-Issledovatelskiy Geologorazvedocnyy Neftanoy Institut* [in Russian], vol. 250, pp. 176–253, Mikrofauna SSSR, Nedra, Leningrad.

Lee, J. J. (1996), Symbiosis in larger foraminifera, *Spec. Publ. Paleontol. Soc.*, *8*, 1–233.

Leven, E. Y., V. I. Davydov, and M. N. Gorgij (2006), Pennsylvanian stratigraphy and fusulinids of central and eastern Iran, *Palaeontol. Electron.*, *8*(1), 1–36.

Makeev, V. M., V. I. Davydov, and V. I. Ustritsky (1991), The discovery of the Middle Carboniferous deposits with tropical fauna on De Longa Islands, in *Stratigraphy and Paleontology of Paleozoic of the Arctic* [in Russian], *Trans. of SEVMORGEO*, pp. 167–170, Sevmorgeo House, Leningrad.

Mamet, B. (1977), Foraminiferal zonation of the Lower Carboniferous: Methods and stratigraphic implications, in *Concepts and Methods of Biostratigraphy*, edited by E. G. Kauffman and J. E. Hazel, pp. 445–462, Dowden, Hutchinson & Ross, Oakland, Calif.

Mamet, B. (1991), Carboniferous calcareous algae, in *Calcareous Algae and Stromatolites*, edited by R. Riding, pp. 370–451, Springer, Berlin.

Manukalova-Grebenyuk, M. F., M. T. Il'ina, and T. D. Serezhnikova (1969), Atlas foraminifer srednego karbona Dneprovsko-Donetskoy vpadiny [Atlas of middle Carboniferous foraminifera of the Dnieper-Donets basin], in *Ukrainskiy Nauchno-Issledovatel'skii Geologorazvedochnyy Institut, Trudy* [in Russian], vol. 20, Naukova Dumka, Kiev, pp. 1–287.

Metelkin, D. V., V. A. Vernikovsky, and N. Y. Matushkin (2015), Arctida between Rodinia and Pangea, *Precambrian Res.*, *259*, 114–129.

Miller, E. L., G. E. Gehrels, V. Pease, and S. Sokolov (2010), Stratigraphy and U-Pb detrital zircon geochronology of Wrangel Island, Russia; implications for Arctic paleogeography, *AAPG Bull.*, *94*, 665–692.

Miller, E. L., A. V. Soloviev, A. V. Prokopiev, J. Toro, D. Harris, A. B. Kuzmichev, and G. E. Gehrels (2013), Triassic river systems and the paleo-Pacific margin of northwestern Pangea, *Gondwana Res.*, *23*(4), 1631–1645.

Morozov, A. F., M. Y. Shkatov, and S. N. Kashubin (2014), Geologic-geophysical expedition "Arctica-2012" for the documentation of continental nature of Mendeleev Ridge in the Arctic Ocean [in Russian], *Explor. Monit. Bowels Earth*, *3*, 22–27.

Nakrem, H. A., I. Nilsson, and B. T. Simonsen (1991), Moscovian (Carboniferous) microfossils (Bryozoa, Conodonta, and Fusulinida) from Novaya Zemlya, Arctic U.S.S.R., *Polar Res.*, *9*, 45–64.

Nikolaev, A. I. (2005), Foraminifers and zonal stratigraphy of Bashkirian Stage in the east of Timan-Pechora province [in Russian], *Bull. Paleontol. Collect. VNIGRI*, *2*, 1–120.

Nikolaev, A. I. (2011), *Fusulinoids of Moscovian Stage in the Precaspian Basin* [in Russian], 168 pp., VNIGRI, Sankt-Petersburg.

Nilsson, I., and V. I. Davydov (1993), *Middle Carboniferous-Lower Permian Fusulinid Stratigraphy in Spitsbergen, Arctic Norway: A Framework for Correlation in the Arctic*, 223 pp., Can. Soc. of Pet. Geol., Calgary, Alberta.

Nilsson, I., and V. I. Davydov, (1997), Fusulinid biostratigraphy in Upper Carboniferous (Gzhelian) and Lower Permian (Asselian-Sakmarian) successions of Spitsbergen, *Arctic Norway: Permophiles*, *30*, 18–24.

Nilsson, I., E. Hakansson, L. Madsen, S. A. Schack Pedersen, and L. Stemmerik (1991), Stratigraphic significance of new fusulinid samples from the upper Palaeozoic Mallemuk Mountain Group, North Greenland, *Rapp. - Groenl. Geol. Unders.*, *150*, 29–32.

Nokleberg, W. J., L. M. Parfenov, J. W. H. Monger, I. O. Norton, A. I. Khanchuk, D. B. Stone, C. R. Scotese, D. W. Scholl, and K. Fujita (2000), Phanerozoic tectonic evolution of the Circum-North Pacific, *U. S. Geol. Surv. Prof. Pap.*, *1626*, 1–122.

Parfenov, L. M., L. M. Natapov, S. D. Sokolov, and N. V. Tsukanov (1993), Terranes and accretionary tectonics of Northeastern Asia [in Russian], *Geotectonics*, *27*, 62–72.

Pease, V. L., A. B. Kuzmichev, and M. K. Danukalova (2014), The New Siberian islands and evidence for the continuation of the Uralides, Arctic Russia, *J. Geol. Soc. London*, *172*(1), 1–4.

Petocz, R. G. (1970), Biostratigraphy and Lower Permian Fusulinidae of the Upper Delta River Area, East-Central Alaska Range, *Spec. Pap. Geol. Soc. Am.*, *130*, 1–94.

Pisarevsky, S. A. (2005), New edition of the global palaeomagnetic database, *Eos Trans. AGU*, *66*, 170, doi:10.1029/2005EO170004.

Rauser-Chernousova, D. M., N. D. Gryzlova, G. D. Kireeva, G. E. Leontovich, T. P. Safonova, and E. I. Chernova (1951), *Middle Carboniferous Fusulinids in the Russian Platform and Adjacent Area. The Guide-book* [in Russian], Acad. of Sci. of the USSR, Moscow.

Rauser-Chernousova, D. M., F. R. Bensh, M. V. Vdovenko, N. B. Gibshman, E. Y. Leven, O. A. Lipinia, E. A. Reitlinger, M. N. Solovieva, and I. O. Chediya (1996), *Sprovochnik po Sistematike Foramininfer Paleozoya (Endothyroidi, Fusulinoidi). The Guide on the Systematic of Paleozoic Foraminifera (Endothyroids and Fusulinids)* [in Russian], Nauka, Moscow.

Ross, C. A. (1967), Late Paleozoic Fusulinacea from northern Yukon Territory, *J. Paleontol.*, *41*(3), 709–725.

Ross, C. A. (1995), Permian fusulinaceans, in *Permian of Northern Pangea*, *Paleogeogr., Paleoclim., Stratigr.*, vol. 1, edited by P. A. Scholle et al., pp. 167–185, Springer, Berlin.

Ross, C. A., and C. O. Dunbar (1962), Faunas and correlation of the late Paleozoic rocks of northeast Greenland: Part 2, Fusulinidae, *Medd. Groenl.*, *167*(5), 1–55.

Rui, L., C. A. Ross, and W. W. Nassichuk (1991), Upper Moscovian (Desmoinesian) Fusulinaceans from the type section of the Nansen Formation, Ellesmere Island (Sverdrup Basin, Canadian Arctic Archipelago), *Bull. Geol. Surv. Can.*, *418*, 1–121.

Rui, L., W. W. Nassichuk, and R. Thorsteinsson (1996), Middle Carboniferous fusulinaceans from the Canyon Fiord Formation, Northwestern Melville Island (Sverdrup Basin, Canadian Arctic Archipelago), *J. Foraminiferal Res.*, *26*(1), 27–52.

Rumyantseva, Z. S. (1974), *Stratigraphy and Foraminifers of Middle Carboniferous of Central Kyzylkums* [in Russian], Fan House, Tashkent.

Scotese, C. R. (2004), A continental drift flipbook, *J. Geol.*, *112*(6), 729–741.

Scott, R. A., J. P. Howard, L. Guo, R. Schekoldin, and V. Pease (2010), Offset and curvature of the Novaya Zemlya fold-and-thrust belt, Arctic Russia, in *Petroleum Geology: From Mature Basins to New Frontiers-Proceedings of the 7th Petroleum Geology Conference*, edited by B. A. Vining and S. C. Pickering, pp. 645–647, Geol. Soc., London.

Shatsky, N. S. (1935), On the tectonics of the Arctic, in *Geology and Mineral Resources of the North of the USSR* [in Russian], edited by A. D. Arkhangel'sky, pp. 149–168, Glavsevmorput' House, Leningrad.

Sokolov, S. D., G. Y. Bondarenko, O. L. Morozov, V. A. Shekhovtsov, S. P. Glotov, A. V. Ganelin, and I. R. Kravchenko-Berezhnoy (2002), South Anyui suture, Northeast Arctic Russia: Facts and problems, *Spec. Pap. Geol. Soc. Am.*, *360*, 209–224.

Solovieva, M. F. (1975), Foraminiferal biostratigraphic subdivisions lower and middle Carboniferous Chukotka, Kotel'ny and Wrangel Islands, in *Transactions of Sevmorgeo* [in Russian], pp. 42–53, SEVMORGEO House, Leningrad.

Stevens, C. H. (2008), Permian colonial rugose corals from the Wrangellian Terrane in Alaska, *J. Paleontol.*, *82*(5), 1043–1050.

Stevens, C. H., and C. A. Ross (1997), Fusulinids from piston cores, Northwind Ridge, Amerasia Basin, Arctic Ocean, *J. Paleontol.*, *71*(3), 357–360.

Toriyama, R. (1953), New peculiar fusulinid genus from the Akiyoshi limestone of southwestern Japan, *J. Paleontol.*, *27*(2), 251–256.

Ueno, K. (2006), The Permian antitropical fusulinoidean genus *Monodiexodina*; distribution, taxonomy, paleobiogeography and paleoecology, *J. Asian Earth Sci.*, *26*(3–4), 380–404.

Ueno, K., T. Charoentitirat, Y. Kamata, H. Hara, M. Ichise, P. Charusirf, K. Khampha Vong, and K.-I. Hisada (2007), A new Pennsylvanian fusuline fauna from Northern Laos, *Acta Micropalaeontol. Sin.*, *24*(4), 359–369.

Vachard, D., A. Munnecke, and T. Servais (2004), New SEM observations of keriothecal walls: Implications for the evolution of Fusulinida, *J. Foraminiferal Res.*, *34*(3), 232–242.

van Ginkel, A. C. (1965), Carboniferous fusulinids from the Cantabrian mountains (Spain), *Leidse Geol. Meded.*, *34*, 1–225.

van Ginkel, A. C. (2010), Systematics of the Eostaffellidae, *Spec. Publ. Cushman Found. Foraminiferal Res.*, *42*, 1–130.

Yuferev, O. V. (1968), Zones of middle and upper Carboniferous of the northeastern USSR and the generally accepted stages of the Carboniferous system [in Russian], *Dokl. Acad. Sci. USSR, Earth Sci. Sect.*, *183*, 103–106.

Zonenshain, L. P., M. I. Kuzmin, and L. M. Natapov (1990), Geology of the USSR; a plate-tectonic synthesis, *Geodyn Ser.*, *21*, 242.