

Faunal and facies changes at the Early–Middle Frasnian boundary in the north-western East European Platform

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Multidisciplinary study of the Early–Middle Frasnian boundary in the north-western East European Platform (Main Devonian Field) allows evaluation of changes in facies, brachiopod, ostracod, and conodont associations, as well as carbon isotope composition. Brachiopod and ostracod faunas, characterized by predominance of rhynchonellids, spiriferids, podocopids, and platycopids in the Early Frasnian, and by predominance of spiriferids, palaeocopids, and kloedenello-copids in the Middle Frasnian, demonstrate significant changes in dominance and diversity likely caused by regression-transgression couplets in the extremely shallow-water environment. Changes in diversity of the conodont associations, represented mainly by shallow-water polygnathids and spathognathids, are controlled by sea-level fluctuations as well; however significant evolutionary turnover is absent. Deepening pulses lead to an increasing in diversity of both the benthic and nectic groups, whilst regressions cause diversity fall due to progressive habitat reduction. Most prominent decreasing in the fauna diversity is observed in the late Early Frasnian (Dubnik time) coinciding with the regressive phase of the Late Givetian to Early Frasnian eustatic cycle. Positive-negative $\delta^{13}\text{C}$ excursion, detected in brachiopod calcite from the early interval of the Middle Frasnian, can be correlated with global isotopic perturbations near the Frasnian substage boundary: the positive 2.6‰ $\delta^{13}\text{C}$ excursion is probably linked with enhanced primary production in high-nutrient regimes in the epeiric sea.

Key words: Conodonta, Brachiopoda, Ostracoda, facies, correlation, carbon isotopes, Frasnian, Main Devonian Field, East European Platform.

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Introduction

Early–Middle Frasnian boundary (= *Palmatolepis transitans*–*Palmatolepis punctata* zonal boundary, as proposed by the Subcommission on Devonian Stratigraphy; Ziegler and Sandberg 2001), is a time of significant abiotic events. This stratigraphic level is known as Middlessex Event (Becker et al. 1993), global transgression corresponding to initial phase of the Ilc cycle (Johnson et al. 1985). Recent study of the stable isotope composition shows a significant positive $\delta^{13}\text{C}$ excursion at this level in Belgium, Poland, and South China (Yans et al. in press) that may be a good chemostratigraphic marker of the Mid-Frasnian boundary.

The Early–Middle Frasnian (E–MF) boundary level has been studied mostly in open-marine carbonate (middle shelf) facies, where no significant biotic changes were detected (e.g., Racki 1993; Piszczowska et al. 2006; Yans et al. in press). In the Main Devonian Field Basin in the north-west of the East Euro-

pean Platform (Fig. 1) this interval is represented by differentiated shallow-marine shelf deposits. Moreover, significant facies and faunal diversity changes, caused by regression-transgression couplets, mark the E–MF transition in this area (e.g., Sorokin 1978; Tikhomirov 1995). This paper describes facies changes, isotope changes, and dynamics of selected faunal associations in the E–MF interval in the Main Devonian Field (MDF), as well as at comparison with southerly Central Devonian Field (CDF) of the East European Platform.

Institutional abbreviation.—CNIGR, The Academician F.N. Chernyshev Central Scientific Geological and Prospecting Museum, St. Petersburg, Russia.

Other abbreviations.—BI, brachiopod interval; CAI, Colour Alteration Index of conodonts; CDF, Central Devonian Field; CI, conodont interval; CIS, cell imprint size; EEP, East European Platform; E–MF, Early–Middle Frasnian; MDF, Main Devonian Field; OI, ostracod interval.

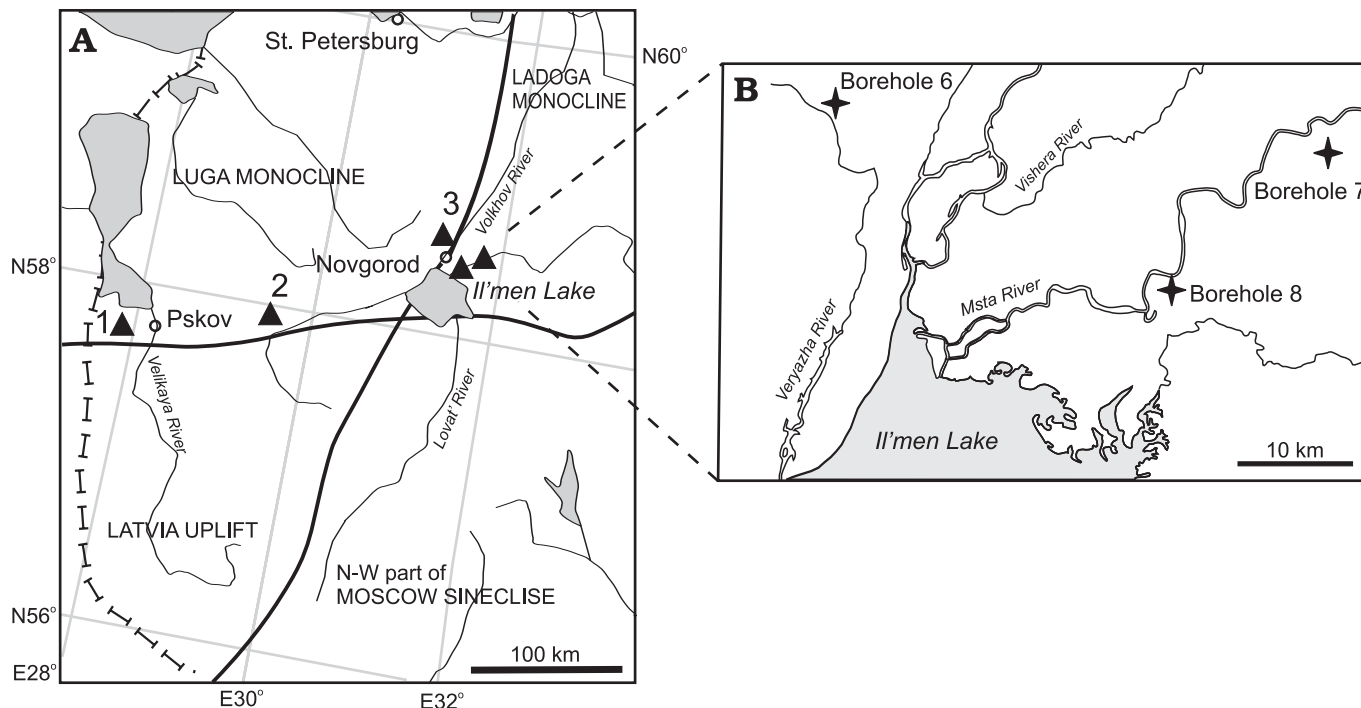


Fig. 1. A. Overview map of the studied Frasnian localities in the St. Petersburg region: 1, Stary Izborsk vicinity; 2, Porkhov town; 3, Il'men Lake area. B. Details of the borehole location in the Il'men Lake area (see Fig. 3).

Geological setting

The Main Devonian Field is located in north-west of the East European Platform (EEP). According to the tectonic structure, the region is subdivided into the Latvia Uplift, Luga Monocline, Ladoga Monocline, Onega Monocline, and north-western part of Moscow Syncline (Fig. 1). The area of investigation covers the Luga and Ladoga monoclines. Total thickness of the Middle and Upper Devonian siliciclastic and carbonate succession is about 770 m (Ivanov et al. 2005). The Upper Devonian, mainly Frasnian, deposits are represented in this area by a mixture of carbonate and terrigenous sediments containing numerous and well preserved brachiopods, ostracods, conodonts, bivalves, echinoderms, and vertebrates.

The systematic investigation of the Devonian strata of the MDF began in the 19th century by Heltmersen (1840), Buch (1840), Eichwald (1841), Murchison et al. (1845), Venjukov (1884, 1886), continued in the 20th century by Hecker (1933, 1941, 1983), Nalivkin (1941), Sorokin (1978), and Zhuravlev et al. (1997). The Early–Middle Frasnian deposits, in the regional stratigraphic scheme of EEP related to the Sargaev and Semiluki horizons, were subdivided into numerous sub-regional units named “Beds”. The units were based on the lithological features and occurrence of the specific brachiopod and, partly, vertebrate associations (Snetnaya Gora, Pskov, Chudovo, Shelon', Svinord, Il'men, Buregi, and Snezha beds; Fig. 2). The cyclicity of sedimentation and succession of the main groups of fossils, mainly brachiopods, allowed subsequent subdivision of the Shelon' Beds into the Dubnik and

Porkhov beds (Hecker 1964; Fig. 2). The lower boundary of the Porkhov Beds, corresponding to the lower boundary of the Semiluki Horizon, approximates the proposed boundary between the Early and Middle Frasnian (Ivanov et al. 2005; see also Ziegler et al. 2000).

Material and methods

The Early and Middle Frasnian deposits had been sedimentologically studied and sampled for isotopic composition and fossils: brachiopods, ostracods, and conodonts, in course of the middle-scale geological mapping of the area.

Brachiopods, ostracods, and conodonts were obtained from several outcrops and boreholes located in the north-central part of the MDF. Outcrops representing E–MF boundary interval are situated in the Shelon' River Basin and in the Pskov region (Fig. 1). Boreholes penetrating this stratigraphic level were drilled in the Il'men Lake area (Fig. 1).

Isotopic study used the rhynchonellid and spiriferid brachiopod shells; all these specimens, 11 shells, taken from seven samples, were collected from successive E–MF stratigraphic levels (Table 1). Calcitic brachiopod shells were collected from mostly clay-rich lithologies and are perfectly preserved, with microornamentation details, concentric growth microlines, and without significant deformation and allochemical diagenetic changes.

The measurements of carbon and oxygen isotopic composition were made on a Finnigan MAT Delta plus mass

Table 1. Isotope composition of brachiopod shells from Main Devonian Field (see Fig. 5).

Taxon and stratigraphical position	Sample #	$\delta^{13}\text{C}$ ‰ PDB
<i>Ladogia meyndorfii</i> Pskov Beds	CNIGR 1/13163 5173	+0.025 +0.022
<i>Ripidorhynchus livonicus</i> Chudovo Beds	CNIGR 2/13163 5168-A	+0.222
<i>Eleutherokomma muralis</i> Lower part of the Chudovo Beds	CNIGR 3/13163 5168-A	-0.317 -0.269
<i>Eleutherokomma muralis</i> Middle part of the Chudovo Beds	CNIGR 4/13163 5158-1	+0.615
<i>Cyrtospirifer schelonicus</i> Svinord Beds	CNIGR 5/13163 5140	+2.626 +1.311
<i>Cyrtospirifer schelonicus</i> Il'men Beds	CNIGR 6/13163 1003-5	-0.913
<i>Cyrtospirifer schelonicus</i> Il'men Beds	CNIGR 7/13163 1003-2	-0.263
<i>Cyrtospirifer tentaculum</i> Lower part of the Buregi Beds	CNIGR 8/13163 1007-1	-0.754 -0.977
<i>Cyrtospirifer tentaculum</i> Middle part of the Buregi Beds	CNIGR 9/13163 1009-A	+0.992 +1.390

spectrometer equipped with Isodat 6.0 software at the Light Stable Isotopes Laboratory of the Institute of Geological Sciences and Institute of Paleobiology, Polish Academy of Sciences, Warsaw. Every gas sample was introduced into the spectrometer in dual inlet mode and the measurement was repeated eight times, with the mean values treated as results. The standard error of the spectrometer measurements was 0.02‰.

The results are reported in per mil deviation from the Vienna Pee Dee Belemnite (VPDB) standard using δ (delta) notation. The precision (reproducibility of replicate analyses) of both carbon and oxygen isotope analysis was usually better than $\pm 0.1\%$. Data are normalized to the VPDB scale using National Bureau of Standards NBS-19 ($\delta^{18}\text{O} = -2.20\%$ and $\delta^{13}\text{C} = +1.95\%$). The results are expressed in ‰ and controlled by replicate measurements of NBS 19 and an internal standard and was $\pm 0.02\%$ for $\delta^{13}\text{C}$ and $\pm 0.04\%$ for $\delta^{18}\text{O}$.

Account of facies development

The interval studied is represented by carbonate-siliciclastic deposits (Fig. 2). The Snetnaya Gora Formation includes dolomitic marls and clays, the Staryi Izborsk Formation is dominated by limestones and dolomites, the Rdeyskoe Formation is represented mainly by marls, clays, and silts, whilst the Buregi Formation comprises shelly and micritic limestones. The topmost Sneza Formation is represented by sands, silt, and clay. In the eastern part of the area, the Buregi and Rdeyskoe formations are partly replaced by the Malaya Vishera Formation composed of sands, silts, clays, and rare limestone lenses. In the western region a gypsum unit occurs

in the upper part of the Staryi Izborsk Formation. Eastwardly the dolomitic and clayey sediments laterally replace the sulfate evaporitic strata.

Study of the Frasnian sections of the MDF indicates the presence of four general facies types:

- facies A—silts, silty sands and silty clays, flat- and wave-bedded, locally cross-bedded; fossils are scarce and include the charophytes, lingulate brachiopods, ostracods, fish remains, small gastropods, rarely conodonts, tentaculites, and echinoids;
- facies B—clays, commonly laminated, with lenses and layers of fossiliferous marls and crinoidal packstones and biorudites;
- facies C—brachiopod-pelmatozoan packstones with high silt and clay content; wavy bedding and presence of diverse benthic fossils are characteristic;
- facies D—wacke- and packstones containing abundant benthic fossils (brachiopods, gastropods, bivalves, etc.).

Environmental interpretation of the facies is based on reconstructed water dynamics, sediment composition, and fossil associations. Facies A corresponds to near-shore extremely shallow-water and agitated environment with high terrigenous influx. The interpretation is supported by sediment composition and structure, as well as by poor fossil associations of specific composition. Facies B is characterized by influx of the finer terrigenous material and quiet-water regime and can be identified as partly restricted (by submarine bars or shoals) shelf deposits. This interpretation is based on sediment structure and composition associated with presence of numerous marine fossils. Facies C represents active-water open-marine bar or shoal deposits marked by traces of wave activity. Facies D represents the offshore, open shelf low-energy environment supported by fine sediment texture and abundant marine fossils.

System	Stage	Subst.	Regional scale		Local stratigraphical units Main Devonian Field (Verbitsky et al. 1999)		
			Horizon	Beds	SW	NE	
Devonian	Frasnian	Middle	Rechitsa	Snezha	Snezha Fm.		
				Buregi	Buregi Fm.	Malaya Vishera Fm.	
			Il'men	Rdeyskoe Fm.			
			Svinord				
			Shelon'			Porkhov	
		Lower	Sargaevo	Dubnik	Stary Izborsk Fm.		
							Chudovo
				Pskov			
				Snetnaya Gora			Snetnaya Gora Fm.

Fig. 2. Local stratigraphical chart of the north-central part of the Main Devonian Field.

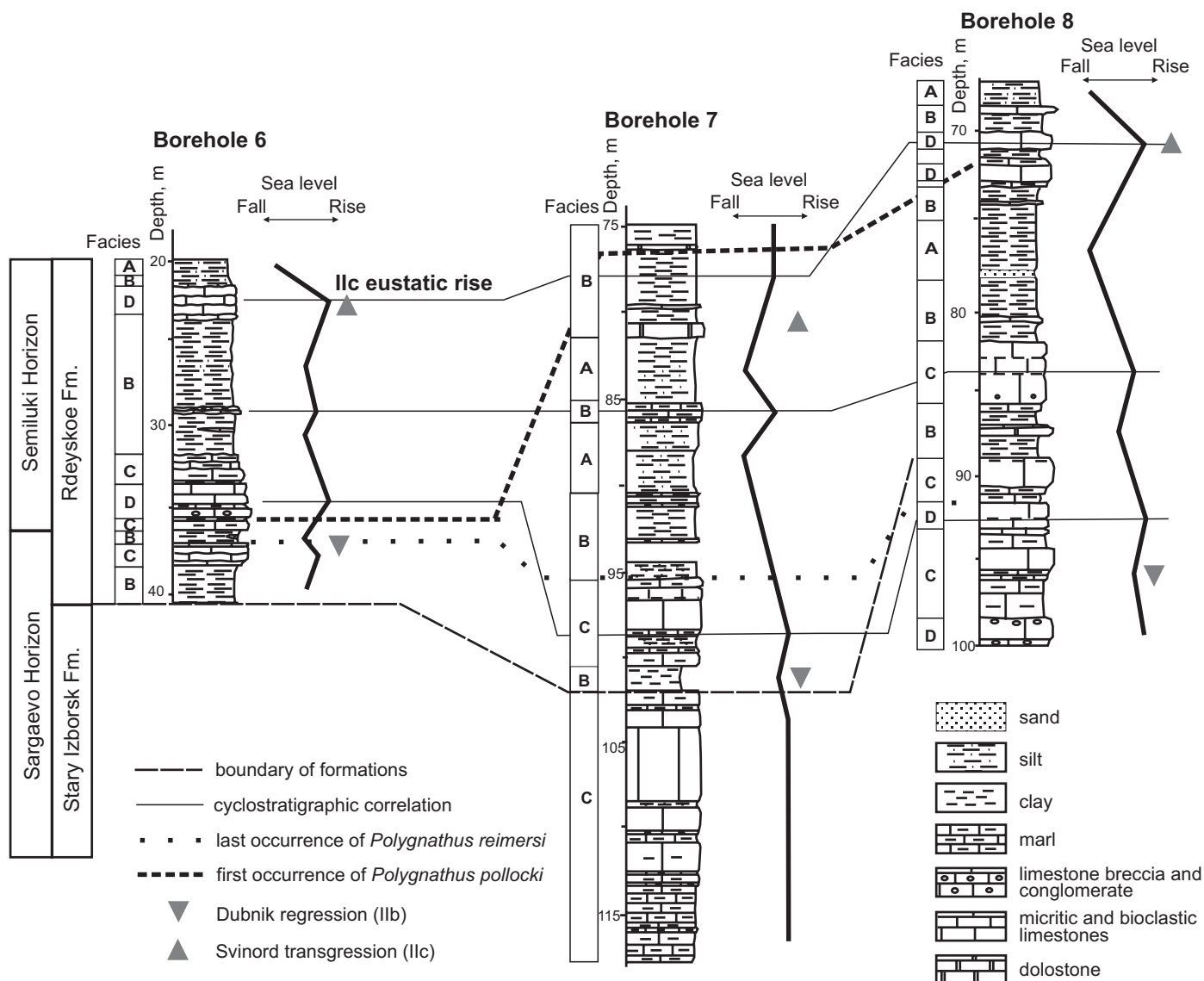


Fig. 3. Facies and sea level changes across the Early–Middle Frasnian transition in boreholes located in the Il'men Lake area (see Fig. 1).

Stratigraphic succession of the facies types are interpreted as a record of sea level cyclic changes, with largest deepening pulses recorded by facies D. Hecker (1954, 1983) and Sorokin (1978) described at length the cyclicity of facies changes over the extensive area of the MDF. Their facies model was based, however, on salinity and substrate character as the main features. Therefore their facies types can not be directly translated into facies model proposed herein, which is based mainly on distance from shore and water dynamics. Only facies types A (decreased) and rarely B (increased) sometimes indicate specific abnormal salinity.

In the area of our study, facies C and D characterize the Stary Izborsk Formation (Pskov and Chudovo beds), and facies A and B are typical for the Rdeyskoe Formation (Dubnik, Porkhov, and Il'men beds). Facies changes demonstrate clear regressive-transgressive sequences (Fig. 3) comparable with those proposed by Sorokin (1978). Most commonly the

cyclic facies successions are C–A–D, C–B–C, and B–A–B. Prominent shallowing marks the upper part of the Dubnik Beds, and subsequent transgression corresponds to the lower part of the Porkhov Beds (Figs. 3, 4). This regression-transgression couplet is traceable in all the sections studied. In the western part of the area, specific lithologies, represented by clay and gypsum intercalations (variation of facies B), appear in the upper part of the Dubnik Beds. These fossil-barren facies correspond to completely isolated restricted shelf or hypersaline lagoon settings (see also Sorokin 1978).

Comparison of the transgressive-regressive cyclicity observed with the sea-level curve elaborated by Johnson et al. (1985) allows us to correlate the Pskov transgression with transgressive phase of cycle IIb (= IIb/c subcycle of Racki, 1993; see discussion in Piszarszowska et al. 2006), the Dubnik regression with the regressive ending phase of cycle IIb, and the Porkhov–Buregi transgression with the transgressive

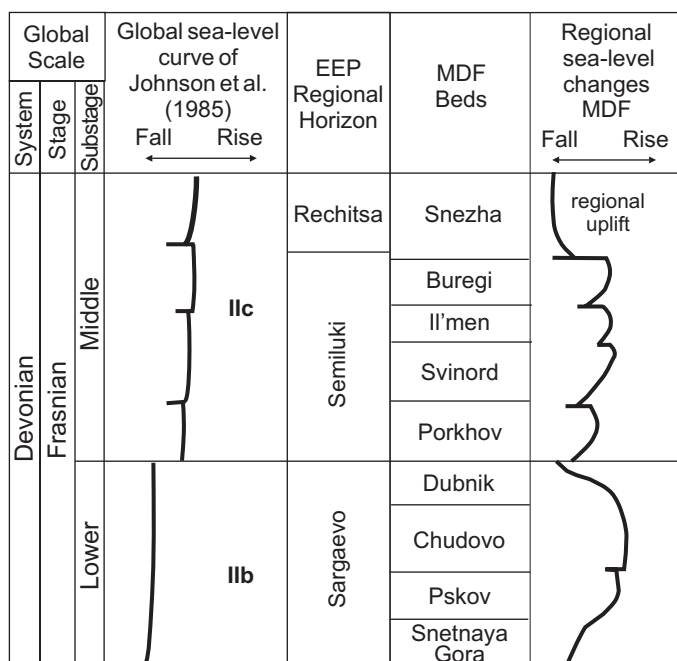


Fig. 4. Comparison of the global sea-level curve and regional sea-level fluctuations in the Early–Middle Frasnian interval of the Main Devonian Field (see Fig. 3).

phase of cycle IIc (Fig. 4). The prominent Snezha regression is probably of regional scale. It may be caused by the regional tectonic uplift of the northern and central parts of the EEP, including the Moscow Syncline, coinciding with the initiation of the Pripyat-Dnieper-Donetsk rifting (Alekseev et al. 1996; Nikishin et al. 1996).

Geochemical data

Perfectly preserved brachiopod calcite is commonly judged as adequate to reflect the primary isotopic record of the ancient seas (see Brand 2004; Yans et al. in press). Rhynchonellid and spiriferid brachiopod shells from the MDF demonstrate significant variation of $\delta^{13}\text{C}$ near the E–MF boundary. The negative excursion of $\delta^{13}\text{C}$ noted in the Il'men and lower part of the Buregi beds (-0.9‰) follows the maximum ^{13}C enrichment ($\delta^{13}\text{C} = 2.6\text{‰}$) in the Svinord Beds (i.e., negative shift of -3.5‰ ; Fig. 5). The similar $\delta^{13}\text{C}$ shift from 2.38‰ to -0.18‰ was obtained for brachiopod calcite samples from the E–MF interval of the CDF (Dorofeeva et al. 2002).

According to study of brachiopod calcite by Yans et al. (in press), the very high-amplitude $\delta^{13}\text{C}$ excursion, preceded by long-lasting positive anomaly from 5.85‰ to -1.20‰ was detected in the upper *Palmatolepis punctata* Zone in Belgium and, probably from 5.47‰ to -0.72‰ , in Poland, confirmed by whole-rock isotopic record (Pisarzowska et al. 2006). Furthermore, similar isotopic data from Moravia and China suggest that the prominent positive and negative excursions across E–MF transition might be signature a global

biogeochemical perturbation (Yans et al. in press). Reported data from the MDF also demonstrate “heavy carbon” enrichment with the highest $\delta^{13}\text{C}$ values above 2‰ in the Svinord Beds, which can be reasonably correlated with the positive anomaly detected in the early *Pa. punctata* Zone in other Laurussian and Chinese shelves.

Faunal distribution

Brachiopods.—The Early–Middle Frasnian deposits of the MDF yield the brachiopods at some levels. Generally, the Early Frasnian brachiopods of the MDF differ significantly from those of the Middle Frasnian. The Early Frasnian is characterized mostly by rhynchonellids with *Ripidiorhynchus livonicus* (Buch, 1834), *R. aldogus* (Nalivkin, 1941), *Ladogia meyendorffii* Verneuil, 1845 and a spiriferid *Eleutherokomma muralis* (Verneuil, 1845), which constitute low-diversity but frequently medium or high-density shelly benthos (Fig. 5). High-density monospecific shelly banks of *L. meyendorffii* occur in the Pskov Beds. *R. livonicus* and *E. muralis* compose clumps or aggregations in the Pskov and Chudovo beds.

In addition to *Schizophoria tulliensis* (Vanuxem, 1842), “*Gypidula*” *biplicata* (Schnur, 1854), *Comiothechia bifera* (Phillips, 1841), *Elita fimbriata* (Conrad, 1842), and several species of atrypids (*Pseudoatrypa*, *Radiatrypa*, *Anatrypa*, *Heckerella*), rarely also *Cyrtospirifer* and *Anathyris* are present in this Early Frasnian fauna (Nalivkin 1941; Sorokin 1978; Sokiran 2002). Significant diversity reduction took place in early Dubnik time. Only *Ripidiorhynchus livonicus* and rare *Eleutherokomma muralis* compose shoal assemblages in this interval.

The new wave of brachiopod immigration to the NW region of the EEP took place at the beginning of the Middle Frasnian, with the onset of the IIc transgression. Representatives of *Cyrtospirifer* were widely distributed over the EEP seas at this time; furthermore, *Theodossia* had its first appearance in the region. *Cyrtospirifer schelonius* (Nalivkin, 1941) becomes the dominant species over the wide spectrum of facies, and it may form both low- and high-density assemblages. Thus, these biogeographically new brachiopods filled the former *Ripidiorhynchus* benthic niches. In addition to the dominant *Cyrtospirifer schelonius* and *C. tentaculum* (Verneuil, 1845; see Sokiran 2006), the Middle Frasnian brachiopod fauna of the MDF is represented by productids (*Productella*, *Rhytidlosia*) rhynchonellids (“*Pugnax*”, “*Hypothyridina*”), spiriferids (*Cyrtina*, *Theodossia*), athyrids (2 species of *Anathyris*) and atrypids (e.g., *Pseudoatrypa*, *Spinatrypa*) according to data of Nalivkin (1941) and Sorokin (1978).

Significant changes in brachiopod diversity were detected in the E–MF interval (Dubnik–Porkhov Beds; Fig. 5). Prominent decrease in brachiopod diversity in the upper part of the Dubnik Beds is marked by disappearance of the *Ripidiorhynchus livonicus* and *Eleutherokomma muralis* assemblages and probably corresponds to the sea-level drop correlated with

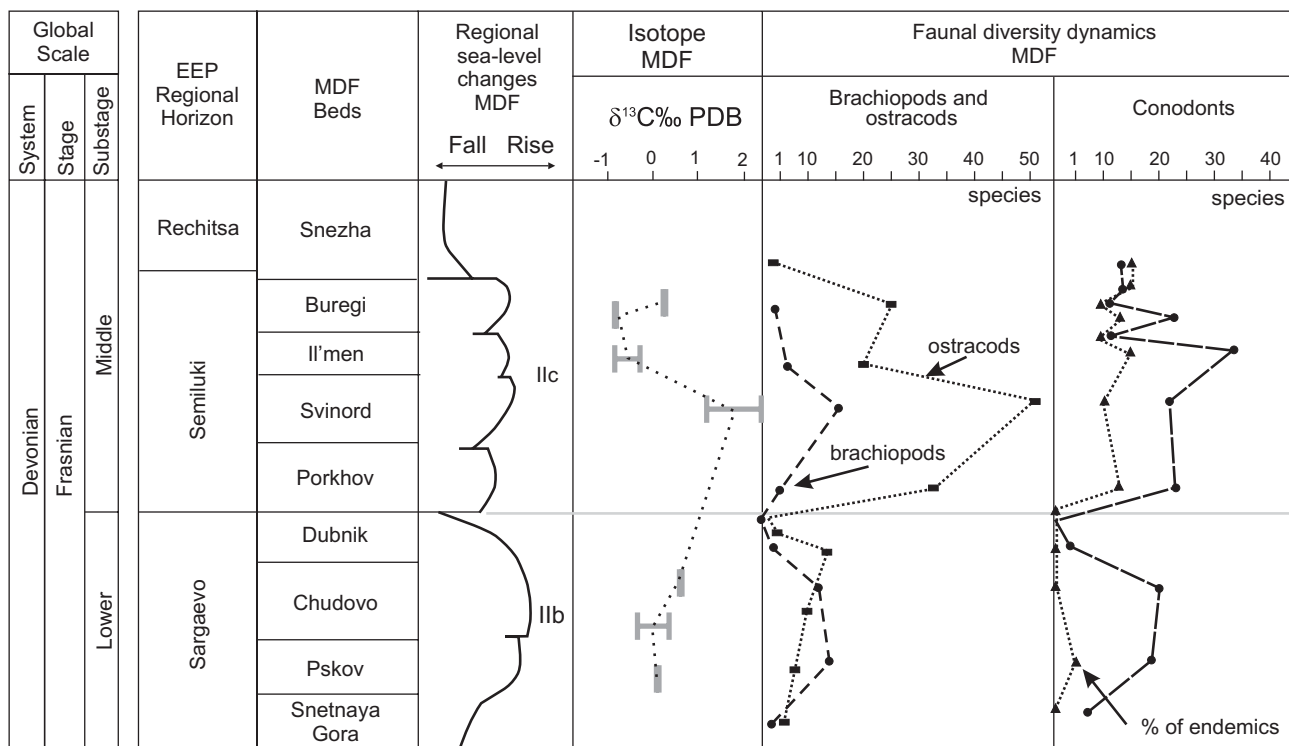


Fig. 5. Carbon isotopic composition ($\delta^{13}\text{C}$), fauna diversity dynamics, and sea level changes in the Main Devonian Field in the Early–Middle Frasnian interval (see Fig. 3).

regressive phase of the IIb cycle of Johnson et al. (1985; see Sokiran 2002). Subsequent increase in diversity during the Porkhov–Svinord time corresponds to transgressive phase of cycle IIC (Fig. 5). Tikhomirov (1995) noted that the Early Frasnian transgression was farther reaching than the Middle Frasnian one, however, brachiopods were more diverse during the Middle Frasnian. It may be explained by higher habitat diversity for shelly macrobenthos in the Frasnian time span in this region.

Conodonts.—Conodonts occur in the E–MF interval in varying abundances, ranging from zero up to 700 elements per kg of rock. Most abundant conodont associations were recovered from the shallow-water quiet-water carbonate-siliciclastic facies. Conodont elements are abraded at some levels, mainly in silts and calcarenites, but mostly they are well preserved. Conodont Colour Alteration Index (CAI) varies from 1 to 2.

The shallow-marine environment that predominated over the region during the Frasnian lead to specific conodont associations, which are represented mainly by *Polygnathus*, *Youngquistognathus*, *Mehlina*, *Pandorinellina*, and *Icriodus*. Three biofacies can be recognized on the basis of generic composition of the conodont associations: *Polygnathus* biofacies, more than 65% of *Polygnathus*, *Ancyrognathus*, and *Youngquistognathus*; “*Spathognathodus*” biofacies, more than 40% of *Mehlina* and *Pandorinellina*; and *Icriodus* biofacies, more than 20% of *Icriodus* and *Pelekysgnathus* (see also Druce 1973, Klapper and Lane 1985).

Most of the Frasnian conodont samples represent the *Polygnathus* biofacies and were collected from the facies types B and D. *Icriodus* biofacies conodonts rarely occur in the facies types C and D. “*Spathognathodus*” biofacies occurs in all the facies types and are hardly related to facies, because of the presumed nektonic life mode of the dominant species: *Pandorinellina insita* (Stauffer, 1940), *Mehlina gradata* (Youngquist, 1945), *Mehlina fitzroyi* (Druce, 1976). Three sub-biofacies can be recognized in the *Polygnathus* biofacies on the basis of predominant species:

- *Polygnathus webbi* sub-biofacies dominated by *Po. webbi* Stauffer, 1938, *Po. pseudoxylyx* Kononova, Alekseev, Barskov, and Reimers, 1996, *Po. seraphimae* Ovnatanova and Kononova, 1999, *Po. reimersi* Kuz'min, 2001, and *Po. praepolitus* Ovnatanova and Kononova, 1999 is typical of the lithofacies type B;
- *Polygnathus pollocki* sub-biofacies, where nektonic species *Po. pollocki* Druce, 1976 and *Po. ilmenensis* Zhuravlev, 2004 dominate, is common in lithofacies ranging from B to D (see also Zhuravlev 1999);
- *Polygnathus lanei* sub-biofacies, where nektonic *Polygnathus lanei* Kuz'min, 1995 and *Po. efimovae* Kononova, Alekseev, Barskov, and Reimers, 1996 are prevalent, is limited to the lithofacies type D.

Early Frasnian conodont associations are dominated by *Pandorinellina insita*, *Polygnathus reimersi*, *Po. lanei*, and *Po. webbi*. These associations correspond to the “*Spathognathodus*” and *Polygnathus* (*Po. webbi* and *Po. lanei*) sub-biofacies. Conodonts of the *Polygnathus pollocki* group,

Table 2. Average epithelial cell imprint size (CIS) in Pa elements of *Polygnathus praepolitus* Ovnatanova and Kononova, 1999. Note that the Porkhov-Svinord time span is marked by significant increase in CIS most probably indicating favourable conditions for conodont animals.

Stratigraphical position	Facies type	CIS (μm)
Porkhov Beds	B	6.7
	B	6.8
	B	6.9
	B	7.3
	C	6.1
Svinord Beds	C	6.6
	C	7.4
	C	6.0
Il'men Beds	B	5.9
	B	6.3
	B	6.4
	B	6.6
	B	6.7
	B	6.7
	B	7.1
	B	7.1
	B	7.9
	C	7.1
	C	7.6
	D	5.4
	D	5.3
Lower part of Buregi Beds	D	6.4

Mehlina, and *Icriodus* dominate the Middle Frasnian conodont associations (Ivanov et al. 2005); they mostly belong to the *Polygnathus* (*Po. pollocki* and *Po. lanei*) sub-biofacies, “*Spathognathodus*”, and *Icriodus* biofacies.

Significant changes in conodont diversity were detected in the Early–Middle Frasnian Chudovo–Il'men interval (Fig. 5). The prominent decrease in conodont diversity in the Dubnik time probably corresponds to the sea-level drop, correlated with regressive phase of cycle IIb, and subsequent increase of diversity in the Porkhov–early Il'men time corresponds to the transgressive phase of cycle IIc. This diversity rise is accompanied with increase of endemism of conodont associations from 0–5% up to 15% (Fig. 5).

It is interesting to note that the Porkhov–Svinord time span is marked by significant increase in average size of epithelial cell imprints on the surface of conodont elements (CIS), measured in *Polygnathus praepolitus* Pa elements (Table 2; for measure method see Zhuravlev 2001a, b). Average CIS value reaches 6.7–6.8 μm in the Porkhov and Svinord beds and then falls to 6.4 μm in the lower part of the Buregi Beds. CIS dynamics demonstrates accordance with $\delta^{13}\text{C}$ changes: increasing in CIS roughly coincides with positive carbon isotope excursion. The CIS increase was likely caused by favorable environment for the conodont animals, such as optimal temperature, salinity, oxygen content, and trophic conditions (Zhuravlev 2001a, b). Thus, the Middle

Frasnian transgression led to establishment of the optimal life conditions, at least for *Po. praepolitus* populations.

Ostracods.—In the Early and Middle Frasnian strata of the study area, ostracods occur nearly everywhere; however, the state of their preservation and abundance vary considerably (for more details see also Evdokimova 2006). Generally, these Frasnian ostracod assemblages belong to the Eifelian ecotype, as defined by Becker (in Bandel and Becker 1975), and indicate a well-oxygenated marine environment.

Ostracods from the Early Frasnian strata are represented mostly by podocopids and platycopids. The most common genera are *Cavellina*, the species *Cavellina batalinae* Zaspelova, 1959 is dominant in terms of numbers of individuals, and *Acratia*, which dominates in terms of numbers of species (5 species have been identified). Palaeocopids: *Buregia zolnensis* Polenova, 1952, *Amphissites irinae* Glebovskaya and Zaspelova in Egorov, 1953, *Limbatula benevoensis* Zaspelova, 1952, *Neodrepanella prisca* Zaspelova, 1952, *Pseudonodella nodosa* Zaspelova, 1952, and others occur rarely, except for facies B sediments (Dubnik Beds) interpreted as restricted shelf deposits, where palaeocopids prevail (Zaspelova 1952, 1959; Egorov 1950, 1953; Evdokimova 2002, 2006).

In the Dubnik–Porkhov boundary interval an essential renewal of ostracod fauna is marked by the appearance of abundant and diversified Middle Frasnian association coinciding with the onset of transgressive phase of cycle IIc (Fig. 5). In the strata of facies B the main elements are palaeocopids, especially nodellids, and kloedenellocopids, accompanied by infrequent podocopids. On the contrary, in the agitated-water deposits of facies C podocopids are abundant and locally, as in the Buregi Beds, dominate the assemblage. The most common genera are *Neodrepanella*, *Nodella*, *Tetracornella*, *Kloedenellitina*, *Mennerites*, *Mennerella*, *Uchtovia*, *Mossolovella*, and *Acratia* (Zaspelova 1952, 1959; Egorov 1950, 1953; Evdokimova 2002, 2006).

Regional conodont correlation

In biostratigraphic context, Early and Middle Frasnian faunal intervals, as defined by Johnson (1990), including five conodont intervals determined by polygnathid species (CI), have been distinguished in the MDF (Fig. 6; see also Ivanov et al. 2005).

Conodont interval 1.—CI 1, with *Polygnathus lanei*, is characterized by low taxonomic diversity and low element abundance. *Po. lanei* is common, *Po. pseudoxylyus*, “*Polygnathus*” *variabilis* Bischoff and Ziegler, 1957, *Youngquistognathus*, and *Mehlina* occur in some samples as well. The fauna belongs to *Po. lanei* sub-biofacies of the *Polygnathus* biofacies. Taxonomic composition of the fauna suggests Early Frasnian age for the Snetnaya Gora Beds.

Conodont interval 2.—CI 2, with *Polygnathus xylus* Stauffer, 1940 and *Po. reimersi*. *Po. xylus*, *Po. reimersi*, *Po. lanei*, *Po.*










Stage	Substage	Standard Conodont Zonation	Horizon	Beds	Faunal intervals and guide species (Main Devonian Field)					
					conodonts	brachiopods	ostracods			
FRASNIAN	Upper	<i>Pa. rhenana</i>	Rechitsa	Snezha	not studied					
		<i>Pa. jamiae</i> <i>Pa. hassi</i>		CI 5	BI 3	OI 4				
				Buregi			 <i>Polygnathus efimovae</i>	 <i>Cyrtospirifer tenticulum</i>	 <i>Milanovskya bicristata</i>	
	Middle	<i>Pa. punctata</i> MN Zone 6	Semiluki	Ilmen	CI 4	BI 2	OI 3			
				Svinord	CI 3			 <i>Cyrtospirifer schelonicus</i>	OI 2	
				Porkhov	 <i>Polygnathus pollocki</i>					 <i>Neodrepanella tricornis</i>
				Dubnik	CI 2					
	Chudovo	 <i>Polygnathus reimersi</i>	 <i>Cavellina batalinae</i>							
	Lower	<i>Pa. transitans</i>		Sargaevo	Pskov	CI 1	BI 1	rare fauna		
			Snetnaya Gora		 <i>Polygnathus lanei</i>					
			<i>M. falsovalis</i>							

Fig. 6. Faunal intervals and guide species for the Early–Middle Frasnian in the Main Devonian Field, and correlation of the regional and local Frasnian subdivisions of the MDF with global scale and standard conodont zonation.

spatulatus Youngquist, 1947, *Polygnathus procerus* Sanneman, 1955, “*Po.*” *variabilis*, *Youngquistognathus angustidiscus* (Youngquist, 1945), *Pandorinellina insita*, and *Mehlina* predominate in the CI 2 associations. These conodonts indicate the “*Spathognathodus*” and *Polygnathus* sub-biofacies. Co-occurrence of *Po. reimersi*, *Po. procerus*, and *Po. spatulatus* suggests the Early Frasnian (Sargaevo) age of the interval. Entry of *Po. reimersi* and *Po. pseudoxylylus* possibly marks the base of the *Palmatolepis transitans* Zone according to data by Ziegler et al. (2000; see Fig. 7). *Po. xylus*–*Po. reimersi* fauna characterizes the Pskov, Chudovo, and Dubnik beds.

Conodont interval 3.—CI 3, with *Polygnathus pollocki*. Specific conodonts of this interval are *Po. pollocki*, *Po. mosquensis* Litvinova, 1996, *Po. zinaidae* Kononova, Alekseev, Barskov, and Reimers, 1996, *Icriodus*, and *Pelekysgnathus*. Conodont associations of CI 3 correspond to wide range of biofacies: *Polygnathus*, “*Spathognathodus*”, and *Icriodus*. Presence of *Polygnathus pollocki*, *Po. mosquensis*, *Po. zinaidae*, *Icriodus alternatus* Branson and Mehl, 1934, paired with absence of *Po. reimersi*, suggests correlation with the *Palmatolepis punctata* Zone (Fig. 7). This conodont fauna is present in the Porkhov and Svinord beds.

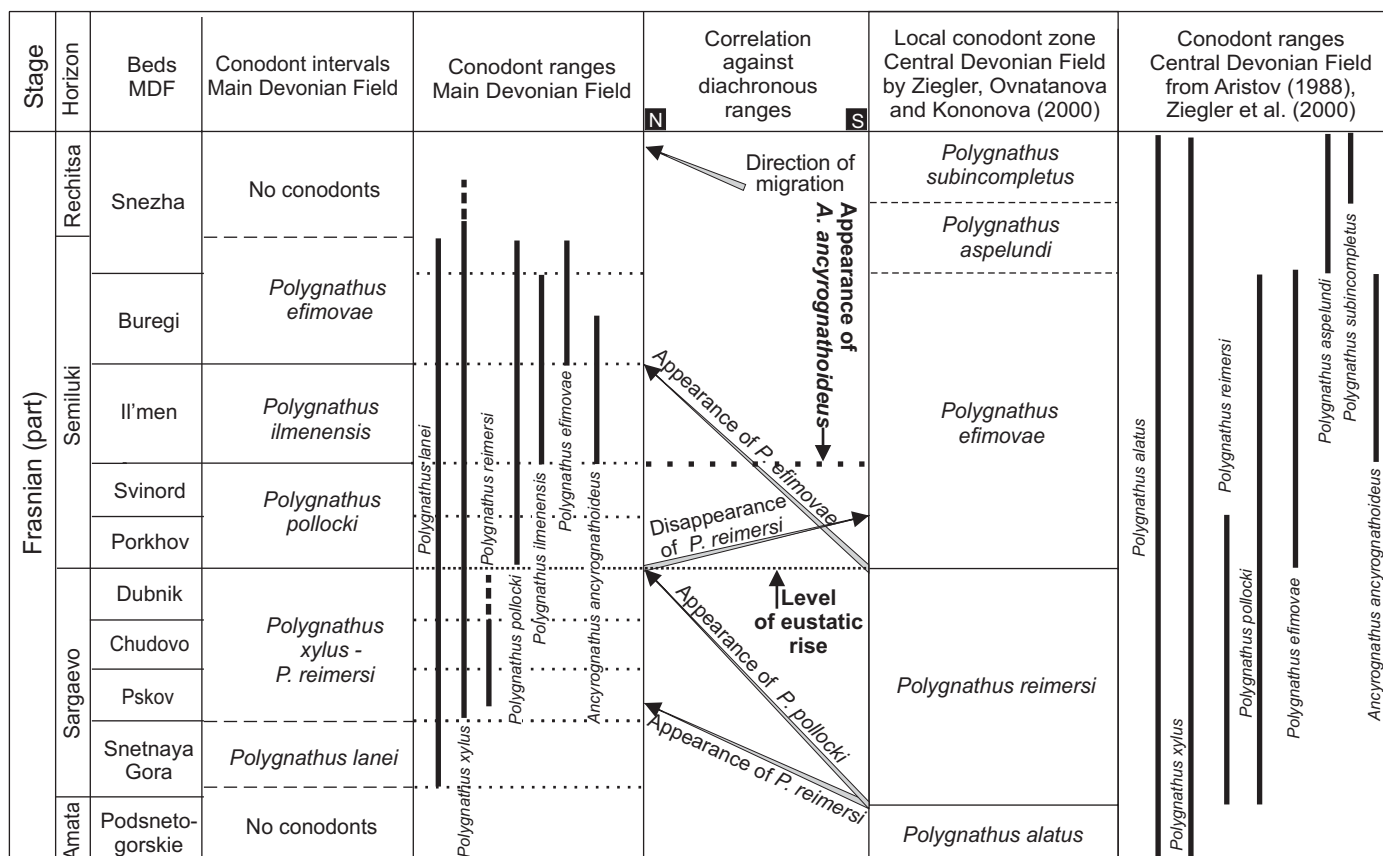


Fig. 7. Correlation of the conodont intervals of the Main Devonian Field and conodont zones of the Central Devonian Field, to show examples of northward migrations.

Conodont interval 4.—CI 4, with *Polygnathus ilmenensis*. This interval contains the highest conodont diversity in the Early–Middle Frasnian in the MDF. *Po. ilmenensis*, *Po. strictus* Kuz'min and Yurtchenkova, 1989, *Po. ukhtensis* Ovnatanova and Kuz'min, 1991, *Ancyrognathus ancyrognathoides* (Ziegler, 1958), *Icriodus symmetricus* Branson and Mehl, 1934 are specific taxa of this interval. The CI 4 corresponds to *Polygnathus* and “*Spathognathodus*” biofacies. Co-occurrence of *Po. strictus*, *Po. ukhtensis*, and *Ancyrognathus ancyrognathoides* indicates the Middle Frasnian, late *Palmatolepis punctata* Zone or MN Zone 6 of Klapper (1997). The fauna occurs in the Il'men Beds (Fig. 6).

Conodont interval 5.—CI 5, with *Polygnathus efimovae*. This fauna, dominated by *Po. efimovae*, *Po. ilmenensis*, *Po. lanei*, and *Mehlina*, corresponds to *Po. lanei* sub-biofacies and “*Spathognathodus*” biofacies. Characteristic species *Po. efimovae* in association with *Ancyrognathus ancyrognathoides* confirm the Middle Frasnian, late *Palmatolepis punctata* Zone. The *Po. efimovae* fauna was found in the Buregi Beds and the lowermost part of the Snezha Beds (Zhuravlev 1999).

Direct conodonts-based correlation of the conodont intervals distinguished in the MDF with conodont zonal succession developed for the CDF (Ziegler et al. 2000) leads to some contradictions. This is probably due to diachronic na-

ture of some entries and disappearances of shallow-water conodont taxa over the basin (Fig. 7). Appearance of *Ancyrognathus ancyrognathoides* within the *Polygnathus ilmenensis* conodont interval, that marks the base of MN Zone 6 of Klapper (1997), seems to be the most reliable correlative level corresponding to the base of the Il'men Beds (Figs. 6, 7). Isochroneity of this level is chemostratigraphically confirmed by negative $\delta^{13}\text{C}$ excursion observed in the underlying Svinord Beds in both the MDF and CDF (see also Fig. 5). In general, shallow-water conodonts provide insufficient information even for regional correlation, and the need of supplementary benthos-based correlation is obvious (Fig. 6).

Brachiopod correlation

Correlation of the sub-regional units of the MDF (Beds) with the regional stratigraphic units (Horizons) is traditionally based mainly on brachiopods (Rzhonsnitskaya 2000). The oldest Frasnian brachiopods from the MDF, poorly preserved siliceous casts possibly of rhynchonellids (Ivanov et al. 2005), are known from the Amata Beds. Three brachiopod intervals (BI 1–3) were recognized in the Sargaevo and Semiluki horizons of the MDF (Fig. 6).

Brachiopod Interval 1.—BI 1, with *Ripidiorhynchus livonicus*, *Ladogia meyendorffii*, and *Eleutherokomma muralis*. This interval is marked by predominance of the index species, which form high-density assemblages at some levels. Abundance of rhynchonellids is a specific feature of this interval. *R. livonicus* and *E. muralis* compose clumps or aggregations in the Pskov and Chudovo beds. The BI 1 is characteristic for the Pskov, Chudovo, and Dubnik beds of the Sargaievo Horizon. At the EEP, the Sargaievo Horizon corresponds to *Ladogia meyendorffii*–*Hypothyridina calva*–*Eleutherokomma novosibirica* Zone *sensu* Rzhonsnitskaya (2000).

Brachiopod Interval 2.—BI 2, with *Cyrtospirifer shelonicus*. Cyrtospiriferids are particularly characteristic of the BI 2, but typically the brachiopod assemblages are of high abundance and diversity, comprising up to 15 species. Such assemblages were observed mainly in the Svinord Beds. The Porkhov and Il'men beds contain less abundant brachiopods. The *C. shelonicus* fauna is characteristic of the Porkhov–Il'men interval (Fig. 6). Presence of *Cyrtospirifer* allows correlation of the BI 2 with the lower part of the Semiluki Horizon of the CDF.

Brachiopod Interval 3.—BI 3, with *Cyrtospirifer tenticulum*. Index species and *Pseudoatrypa uralica* compose the bulk of the fauna. These species form the high-density assemblages in the facies type C of the lower part of the Buregi Beds. *Rhytiolosis petini* (Nalivkin, 1941) and *Anathyris helmersenii* (Buch, 1834) occur as well. The association occurs only in the Buregi Beds. The index species of the BI 3 suggest correlation with the upper part of the Semiluki Horizon of the CDF.

The boundary between BI 1 and BI 2 is the main brachiopod-based correlative level. It is marked by disappearance of rhynchonellids (*Ripidiorhynchus* and *Ladogia*) and appearance of abundant *Cyrtospirifer*. This brachiopod event is traceable to the CDF, where it corresponds to the base of *Cyrtospirifer rudkinensis*–*Tomestenoporhynchus rudkini* Zone of Rzhonsnitskaya (2000).

Ostracod correlation

In the Early and Middle Frasnian of the MDF four successive ostracod intervals (OI) were distinguished (Fig. 6).

Ostracod Interval 1.—OI 1, with *Cavellina batalinae*. The oldest interval is dominated by *Cavellina* (especially *C. batalinae*) and *Acratia* species, and corresponds to the Early Frasnian Snetnaya Gora–Dubnik beds interval. Only in the upper part in the Dubnik Beds some endemics recognized (Evdokimova 2006). The OI 1 can be traced within the Sargaievo Horizon of the MDF, CDF, and Timan–Pechora Basin owing to presence of *Cavellina batalinae*, *Acratia vastigata* Zaspelova in Polenova, 1955, *A. longa* Zaspelova in Polenova, 1955, as well as *Neodrepanella prisca* Zaspelova, 1952.

Ostracod Interval 2.—OI 2, with *Neodrepanella tricornis*. OI 2 occurs within the Porkov and Svinord beds and contains abundant and diverse ostracods, with Limbatulidae, Neodrepanellidae [e.g., *Neodrepanella tricornis* (Batalina, 1941)] and Nodellidae (*sensu* Abushik et al. 1990) dominant. The OI 2 displays close affinities with fauna known from the Middle Frasnian, Semiluki Horizon, of the CDF and to a much smaller extent of the Timan–Pechora Basin. The correlation is based on the presence of the index-species as well as many other species, including: *Nodella svinordensis* Zaspelova, 1952, *Kloedenellitina sygmaeiformis* (Batalina, 1941), *Milanovskya bicornis* Glebovskaya and Zaspelova in Egorov, 1950, *Menerella tuberosa* Glebovskaya and Zaspelova in Egorov, 1950, *Uchtovia elongata* Glebovskaya and Zaspelova in Egorov, 1950, and *Mossolovella philippovae* Egorov, 1953.

Ostracod Interval 3.—OI 3, with *Acantonodella lutkevichi*. The OI 3 fauna occurs in the Il'men Beds and is characterized by relatively low taxonomic diversity. Along with some species, common in the underlying strata, several new species are recognized: *Acantonodella lutkevichi* Zaspelova, 1952, *A. terciocornuta* Zaspelova, 1952, *Pseudonodella plana* Zaspelova 1952, *Buregia bispinosa* Zaspelova, 1959, *Acratia galinae* Egorov, 1953 (Zaspelova 1952, 1959; Egorov 1950, 1953; Zhuravlev et al. 1997).

Ostracod Interval 4.—OI 4, with *Milanovskya bicristata*. Kloedenellocopids and podocopids, including abundant and diverse *Bairdia*, dominate the OI 4 fauna, which occurs in the Buregi Beds and in the lowermost Snezha Beds. Both sculptured *Knoxites*, *Knoxella*, *Mennerella*, *Kloedenellitina*, *Milanovskya*, smooth-shelled *Bairdia*, *Mossolovella*, *Acratia*, and *Bairdiocypris* are common. The OI 4 also contains the palaeocopids: *Buregia*, *Kozlowskiella*, and *Neodrepanella*. The eridocopid *Cryptophyllus* and some platycopids (e.g. *Cavellina*) are scarce (Zaspelova 1952, 1959; Egorov 1950, 1953; Zhuravlev et al. 1997). The presence of *Neodrepanella parva* Zaspelova, 1952, *Acratia mayselae* Egorov, 1953, and *Mossolovella philippovae* in the fauna allows correlating of the Buregi Beds with the upper part of the Semiluki Horizon of the CDF.

Conclusions

The changes of the Late Devonian brachiopod and ostracod associations of the EEP shelves were controlled mainly by sea-level fluctuations. Within the Early–Middle Frasnian interval there are two levels at the Main Devonian Field, characterized by mass occurrence and diversification of the shelly benthos, coinciding with the Sargaievo (Pskov–Chudovo; IIB/c) and Svinord (IIC) transgressive pulses (see also Sokiran 2002).

The significant brachiopod and ostracod turnover marked by changes of dominant taxa, disappearance and appearance of some groups during the E–MF interval, followed by increasing abundance during the Porkhov–Svinord interval,

i.e., early part of *Palmatolepis punctata* Zone, coincides with the positive $\delta^{13}\text{C}$ anomaly (Fig. 5), a signature of global perturbation (Yans et al. in press). In this biogeochemical context, it is important to note that Tikhomirov (1995) indicated higher biological productivity of the marine basins at the Middle Frasnian time, as recorded by abundant and diversified benthos. The latter opinion is also supported by an increase in abundance and diversity of the nektonic biota, represented by conodonts. The increased value of average epithelial cell size in conodonts, possibly reflecting increase in metabolic rate, can be considered as circumstantial proof of the high nutrient and primary production levels (see also Zhuravlev 2001a, b), commonly assumed for the ^{13}C enrichment episodes (e.g., Piszarska et al. 2006; Yans et al. in press). Interestingly, according to the results of Pérez-Huerta and Sheldon (2006), spiriferids and other spire-bearing groups are successful brachiopods in high-nutrient settings because of their lophophore capacity to generate strong in-halant unidirectional currents in limited areas around the shell.

Occurrence of conodonts in the E–MF interval of the MDF was probably controlled mainly by facies changes, not by conodont evolution. Most of conodont species here seem to be immigrants from the central parts of the EEP Basin and western part of the Uralian Basin, where they display their maximal stratigraphic ranges (Fig. 7; Ziegler et al. 2000). Favorable environmental conditions during the transgressive episodes are indicated by increase in conodont diversity and abundance, and appearance of endemics. Regressions probably eliminated suitable niches for most of the conodonts and only the obsolete conodont associations remained.

Significant changes in benthic and nektic biota near the E–MF boundary in the MDF Basin were probably caused by regional ecological crisis and subsequent habitat recovery controlled by sea-level rises that improved circulation in this extremely shallow-marine basin. Therefore, similar biotic turnover, as a rule, is not observed in the more open shelf domains (see summary in Yans et al. in press), where the sea-level changes affect the biota to a lesser degree. However basins that underwent tension tectonic subsidence, exemplified by Domanik depressions in the Timan–Pechora Basin, demonstrate considerable biotic impoverishment caused by the spread of hypoxic conditions (Domanik crisis of Kuzmin et al. 1997).

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References

- Abushik, A.F., Gusseva, E.A., Ivanova, V.A., Kanygin, A.V., Kashevarova, N.P. [Kaševarova, N.P.], Melnikova, L.M., Molostovskaya, I.I. [Molostovskaâ, I.I.], Neustrueva, I.Yu. [Neustrueva, I.Û.], Sidaravichene, N.V. [Sidaravičene, N.V.], Stepanajtys, N.E., and Tschigova, V.A. [Čižova, V.A.] 1990. *Praktičeskoe rukovodstvo po mikrofaune SSSR. Tom 4. Ostrakody paleozoâ*. 356 pp. Nedra, Leningrad.
- Alekseev, A.S., Kononova, L.I., and Nikishin, A.M. 1996. The Devonian and Carboniferous of the Moscow Syncline (Russian Platform): stratigraphy and sea-level changes. *Tectonophysics* 268: 149–168.
- Aristov, V.A. 1988. *Devonskie konodonty Central'nogo Devonskogo Polâ (Russkaâ Platforma)*. 120 pp. Nauka, Moskva.
- Bandel, K. and Becker, G. 1975. Ostracoden aus paläozoischen pelagischen Kalken der Karnischen Alpen (Silurium bis Unterkarbon). *Senckenbergiana lethaea* 56: 1–83.
- Becker, R.T., House, M.R., and Kirchgasser, W.T. 1993. Devonian goniatite biostratigraphy and timing of facies movements in the Frasnian of the Canning Basin, Western Australia. *Geological Society Special Publication (London)* 70: 293–321.
- Brand, U. 2004. Carbon, oxygen and strontium isotopes in Paleozoic carbonate components: an evaluation of original seawater-chemistry proxies. *Chemical Geology* 204: 23–44.
- Buch, L. von 1840. Beiträge zur Bestimmung der Gebirgsformationen Russlands. In: C.J.B. Karsten and H. von Dechen (eds.), *Archiv für Mineralogie, Geognosie, Bergbau und Hüttenkunde* 15 (1): 3–128.
- Dorofeeva, L.A., Sokiran, E.V., and Malkowski, K. 2002. Devonian environmental reconstructions and stratigraphical correlations by stable isotopes and geochemical data of brachiopod shells from the Russian Platform. In: N.P. Yushkin, V.S. Tsyganko, and P. Männik (eds.), *Geology of the Devonian System*, 156. Geoprint, Syktyvkar.
- Druce, E. 1973. Upper Paleozoic and Triassic conodont distribution and recognition of biofacies. *Conodont Paleozoology. Geological Society of America Special Paper* 141: 191–237.
- Egorov, V.G. 1950. *Ostrakody franskogo ârusa Russkoj platformy – 1: Kloedenellidae*. 175 pp. Gostoptehizdat, Moskva.
- Egorov, V.G. 1953. *Ostrakody franskogo ârusa Russkoj platformy – 2: Bairdiidae, Hollinidae, Kirkbyidae*. 133 pp. Gostoptehizdat, Moskva.
- Eichwald, E. 1841. About fossil fauna and flora contained in the Old Red Sandstone and Rock limestone [in Russian]. *Gornyj Žurnal* 1: 27–53.
- Evdokimova, I. 2002. Changes in benthic ostracode associations across the Sargaev-Semiluki boundary beds (Frasnian) in the Main Devonian Field. In: J. Satkūnas and J. Lazauskienė (eds.), *The Fifth Baltic Stratigraphical Conference “Basin Stratigraphy—Modern Methods and Problems”, September 22–27, Vilnius, Lithuania: Extended Abstracts*, 35–37. Vilnius.
- Evdokimova, I. 2006. Benthic ostracods from the Early–Middle Frasnian transition strata in the North–West of the East European Platform, Russia. *Acta Palaeontologica Polonica* 51: 773–788.
- Hecker, R.F. [Gekker, R.F.] 1933. Carbonate rocks of Devonian deposits [in Russian]. In: E.P. Bruns and S.G. Višnâkov (eds.), *Karbonatnye porody Leningradskoj oblasti, Severnogo kraâ i Karel'skoj ASSR, Vypusk 2*, 16–43. Gosudarstvennoe naučno-tehničeskoe gorno-geologo-neftânoe izdatel'stvo, Leningrad.
- Hecker, R.F. [Gekker, R.F.] 1941. Deposits, fauna and flora of the Main Devonian Field [in Russian]. In: A.A. Borisâk and R.F. Hecker (eds.), *Fauna Glavnogo Devonskogo Polâ, 1*, 17–70. Paleontologičeskij Institut AN SSSR, Moskva.
- Hecker, R.F. [Gekker, R.F.] 1954. Comparison of sections of eastern and western parts of the Main Devonian Field and main features of ecology of its fauna and flora [in Russian]. *Izvestiâ Akademii Nauk SSSR. Seriâ Geologičeskaâ* 4: 75–100.
- Hecker, R.F. [Gekker, R.F.] 1983. Taphonomic and ecological features of the fauna and flora of the Main Devonian Field [in Russian]. *Trudy Paleontologičeskogo Instituta* 190: 1–144.
- Helmersen, H. 1840. On geognostic composition of the part of European Russia bordered by the Il'men and Seliger lakes from the east and by the

- Chudskoe Lake from the west [in Russian]. *Gornyj žurnal* 2 (5): 196–212.
- Ivanov, A., Zhuravlev, A., Stinkulins, G., Evdokimova, I., Dronov, A., Sokiran, E., Shishlov, S., Broushkin, A., and Myshkina, N. 2005. *Devonian Sections of North-West of East European Platform. Guidebook*. 66 pp. St. Petersburg University Press, St. Petersburg.
- Johnson, J.G. 1990. Lower and Middle Devonian brachiopod-dominated communities of Nevada, and their position in a biofacies-province-realm model. *Journal of Paleontology* 64: 902–941.
- Johnson, J.G., Klapper, G., and Sandberg, C.A. 1985. Devonian eustatic fluctuations in Euroamerica. *Geological Society of America Bulletin* 96: 567–587.
- Klapper, G. 1997. Graphic correlation of Frasnian (Upper Devonian) sequences in Montagne Noire, France, and western Canada. *Geological Society of America, Special Papers* 321: 113–129.
- Klapper, G. and Lane, R. 1985. Upper Devonian (Frasnian) conodonts of the *Polygnathus* biofacies, N.W.T., Canada. *Journal of Paleontology* 59: 904–951.
- Kuzmin, A.V., Yatskov, S.V., Orlov, A.N., and Ivanov, A.O. 1997. “Domanic Crisis” in the evolution of fauna of the Frasnian marine basin in the South Timan. *Paleontological Journal* 31 (3): 251–258.
- Murchison, R. I., Verneuil, E. de, and Keyserling, A. 1845. *Geologie de la Russie d’Europe et des Montagnes de l’Oural. Paleontologie* 2. 512 pp. John Murray, London.
- Nalivkin, D. V. 1941. Brachiopods of the Main Devonian Field [in Russian]. In: A.A. Borisák and R.F. Gekker (eds.), *Fauna Glavnogo Devonskogo Polâ, 1*, 139–221. Paleontologičeskij Institut AN SSSR, Moskva.
- Nikishin, A.M., Ziegler, P.A., Stephenson, R.A., Cloetingh, S., Furne, A.V., Fokin, P.A., Ershov, A.V., Bolotov, S.N., Korotaev, M.V., Alekseev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., Bembinova, E.Y., and Shalimov, I.V. 1996. Late Precambrian to Triassic history of the East European Craton—dynamics of sedimentary basin evolution. *Tectonophysics* 268: 23–63.
- Pérez-Huerta, A. and Sheldon, N.D., 2006. Pennsylvanian sea level cycles, nutrient availability and brachiopod paleoecology. *Palaeogeography, Palaeoclimatology, Palaeoecology* 230: 264–279.
- Pisarzowska A., Sobstel, M., and Racki, G. 2006. Conodont-based event stratigraphy of the Early–Middle Frasnian transition on the South Polish carbonate shelf. *Acta Palaeontologica Polonica* 51: 609–646.
- Racki, G. 1993. Evolution of the bank to reef complex in the Devonian of the Holy Cross Mountains. *Acta Palaeontologica Polonica* 37: 87–182.
- Rzhonsnitskaya, M.A. 2000. Devonian stage boundaries on the East European (Russian) Platform. *Courier Forschungsinstitut Senckenberg* 225: 227–237.
- Sokiran, E.V. 2002. Frasnian–Famennian extinction and recovery of rhynchonellid brachiopods from the East European Platform. *Acta Palaeontologica Polonica* 47: 339–354.
- Sokiran, E.V. 2006. Early–Middle Frasnian cyrtospiriferid brachiopods from the East European Platform. *Acta Palaeontologica Polonica* 51: 759–772.
- Sorokin, V.S. 1978. *Etapy razvitiâ severo-zapada Russkoj platformy vo franskom veke*. 268 pp. Zinatne, Riga.
- Tikhomirov S.V. [Tihomirov S.V.] 1995. *Etapy osadkonakopleniâ devona Russkoj platformy i obščie voprosy razvitiâ i stroeniâ stratisfery*. 445 pp. Nedra, Moskva.
- Venyukov, P.N. [Venûkov, P.N.] 1884. Deposits of the Devonian System of European Russia [in Russian]. *Trudy Sankt-Peterburgskogo obščestva estestvoispytatelej* 15: 1–302.
- Venyukov, P.N. [Venûkov, P.N.] 1886. *Fauna devonskoj sistemy severo-zapadnoj i centralnoj evropejskoj Rossii*. 129 pp. Tipografiâ V. Demakova, Sankt-Peterburg.
- Verbitsky, V.R. [Verbickij, V.R.], Zhuravlev, A.V. [Žuravlev, A.V.], and Nenashev, Yu.P. [Nenašev, Ū.P.] 1999. Diachrony of the boundaries of the local stratigraphical subdivisions—Middle Frasnian deposits of west of the Russian part of Main Devonian Field as example [in Russian]. In: A.H. Kagarmanov (ed.), *Istoričeskaâ geologiâ v sisteme geologičeskogo obrazovaniâ*, 125–131. Gornyj Institut, Sankt-Peterburg.
- Yans, J., Corfield, R.M., Racki, G., and Préat, A. (in press). Evidence for perturbation of the carbon cycle in the Middle Frasnian *punctata* Zone (Late Devonian). *Geological Magazine*.
- Zaspelova, V.S. 1952. Ostracoda of the family Drepanellidae from Upper Devonian deposits of the Russian Platform [in Russian]. *Trudy Vsesoûznogo nefitânogo naučno-issledovatel’skogo geologo-razvedočnogo instituta (VNIGRI), Mikrofauna SSSR 5, Novaâ seriâ* 60: 157–216.
- Zaspelova, V.S. 1959. Ostracoda and their value for the stratigraphy of the Devonian of the north-western regions of the Russian Platform [in Russian]. *Trudy Vsesoûznogo nefitânogo naučno-issledovatel’skogo geologo-razvedočnogo instituta (VNIGRI), Mikrofauna SSSR 10, Novaâ seriâ* 136: 5–131.
- Zhuravlev, A.V. 1999. Conodonts of the *Polygnathus pollocki* Druce group (Upper Devonian, Lower Frasnian) from the East European Platform. *Proceedings of the Estonian Academy of Sciences, Geology* 48: 35–47.
- Zhuravlev, A.V. 2001a. Variation in outline and distribution of epithelial cell imprints on the surface of polygnathacean conodont elements. *Lethaia* 34: 136–142.
- Zhuravlev, A.V. [Žuravlev, A.V.] 2001b. *Gistologiâ i mikroskulptura pozdnepaleozojskih konodontovyh elementov*. 94 pp. NPF Geoservis Plûs, Sankt Peterburg.
- Zhuravlev, A.V., Evdokimova, I.O., and Sokiran, E.V. 1997. New data on conodonts, brachiopods and ostracodes from the stratotypes of the Ilmen and Buregi beds (Frasnian, Main Devonian Field). *Proceedings of the Estonian Academy of Sciences, Geology* 46 (4): 169–186.
- Ziegler, W. and Sandberg, C.A. 2001. Utility of palmatolepids and icriodontids in recognizing Upper Devonian series, stage, and possible substage boundaries. *Courier Forschungsinstitut Senckenberg* 225: 335–347.
- Ziegler, W., Ovnatanova, N., and Kononova, L. 2000. Devonian polygnathids from the Frasnian of the Rheinisches Schiefergebirge, Germany, and the Russian Platform. *Senckenbergiana lethaea* 80: 593–645.