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From Siliciclastics to Carbonates and Black shales: Deciphering Sedimentary Continuity and Discontinuity in the Devonian Landscapes of the Volga-Ural Petroleum Province

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Analyses of the three predominant types of sedimentation – siliciclastic, carbonate and black shale – revealed their discontinuity/continuity across various facies environments within the Middle and Late Devonian of the central part of the Volga-Urals petroleum province. These environments include condensed and non-condensed depressions, slopes of depressions and shallow water settings located on tectonic arches or local biohermal uplifts.

The regional zonation of conodonts, correlated with the International Chronostratigraphic Chart, confirms the general stratigraphic completeness of the Middle-Upper Devonian geological record in this area. Meanwhile, sedimentation exhibited a discontinuous pattern, which enables to speak about the so-called "discontinuous continuity". In particular, the sedimentation of organic-rich black shales, traditionally considered as oil-source rocks, lasted more than 29 million years, from the Late Eifelian up to the Devonian-Carboniferous boundary. The longest hiatus (ca. 2.5 Ma) in the accumulation of black shales (as well as carbonates) took place at the end of the Givetian. Notably, this interval contains the most productive siliciclastic reservoirs.

During the Early Eifelian to Early Frasnian (ca. 17 Ma), siliciclastic sediments demonstrate the highest accumulation rates and the maximum discontinuity caused by short marine transgressive episodes. Simultaneously, the most complete sequences were deposited in the depressions where carbonate and black shale sediments accumulated. During the Famennian (ca. 12 Ma), siliciclastic sedimentation completely ceased, leading to the stable accumulation of carbonate sediments on the slopes of depressions and in shallow waters; the deposition of organic-rich black shales continued in the deep axial settings of the troughs. Our results highlight the complexity of the spatial relationship between various coexisting sedimentation types and the incompleteness of the geological record in different environments.

Keywords: Volga-Ural petroleum province, Devonian, black shales, carbonates, siliciclastic, sedimentation, rate, environments

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1. Introduction

The Devonian succession of the central part of the Volga-Ural petroleum province (Fig. 1), situated at depths of 1500–2000 m, consists of three predominant types of marine sediments: siliciclastic, carbonate, and black shale. The siliciclastic and carbonate sediments, recognised as oil and gas bearing, contain over 900 oil plays (Muslimov, 2008). Black shales are commonly considered as oil source rocks due to their significant content of sapropelic organic matter (Strakhov, 1938; Stupakova et al., 2015, 2017; Liang et al., 2020; Kabanov et al., 2023a,b).

Detailed lithological and biostratigraphic analyses of the Devonian strata of the central part of the Volga-Ural province were completed by the end of the 20th century. The outcomes of these studies have been generalised in regional stratigraphic schemes (Decision of the Interdepartmental Regional Stratigraphic Meeting…, 1990; Resolutions of the Interdepartmental Stratigraphic Committee…, 2008; Fortunatova et al., 2018) and are summarised in specialised publications (Menning et al., 2006; Zonal stratigraphy…, 2006).

Recent studies have concentrated on examining the sedimentological and facies characteristics of Devonian sediments to develop detailed sedimentation models. These models have been developed separately for siliciclastic

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sediments (Fortunatova et al., 2013; Loscheva et al., 2017; Silantiev et al., 2022), carbonate sediments (Fortunatova et al., 2016; Yousef et al., 2023), and black shales (Stupakova et al., 2015, 2017; Liang et al., 2020). In most cases, the authors examine only a certain stratigraphic interval of interest, not always using new stratigraphic schemes and data.

This study compares the regional Devonian conodont zonation of the Volga-Ural province (Aristov, 1988; Ovnatanova, Kononova, 2008; Nazarova, Kononova, 2015, 2020) with the standard conodont zones (Ziegler, 1962, 1969, 1971; Ziegler, Sandberg, 1984; 1990; Sandberg, Ziegler, 1996) and the global conodont zonation outlined in the modern Geological Time Scale (Becker et al., 2020). This comparative analysis clarifies the overall continuity of the Devonian succession in the central part of the Volga-Ural province and helps determine the duration of regional stratigraphic subdivisions (Regional Stages) in terms of absolute age.

We further analysed three predominant types of sedimentation observed in various settings of study area during the Devonian period (Aliev et al., 1978; Gubareva, 2003; Fortunatova et al., 2018): (1) condensed and non-condensed depressions, (2) slopes of depressions, and (3) shallow water environments situated within tectonic arches or local biohermal uplifts. Using the chronostratigraphic framework and available data on the rates of modern and ancient sediment accumulation, we demonstrate the duration of sediment deposition of different types in various settings of the basin. As expected, the completeness of the sedimentary record increases in the transition from shallow to deep-water environments, while the number of discontinuities in the stratigraphic succession is maximal in shallow-water settings. Evidently, these patterns are crucial for well log correlation and geological modelling.

Therefore, this study aims to ascertain the completeness of the Devonian sedimentary sequences within diverse marine environments in the central region of the Volga-Ural province. The research involved (1) analysis of current biostratigraphic and chronostratigraphic data; (2) examination of the three predominant types of sedimentation in the study area during the Devonian.

2. Geological settings

In the central region of the Volga-Ural petroleum province, the Devonian succession is stratified into three series: Lower, Middle, and Upper, encompassing a total thickness of 500–1500 m. The Lower Devonian (Emsian) exhibits a local distribution, in contrast to the Middle and Upper Devonian formations, which cover the whole area (Aliev et al., 1978; Gubareva, 2003; Muslimov, 2008).

The Devonian sediment accumulation occurred in an equatorial marine basin located on the passive margin of the East European Platform. This passive margin constituted a wide (500–1000 km in cross-section) continental shelf, gently dipping towards the continental slope's bend and exchanging water with the Ural Palaeoocean (Fig. 1). The complicated geomorphology of the basin floor facilitated sometimes subsequent but more often simultaneous accumulation of siliciclastic, carbonate, and organic-rich black shale sediments.

During the Late Devonian (Frasnian), some island arcs of the Ural Palaeoocean accreted to the eastern margin of Laurussia, leading to a decrease of the ocean size. This collision between the island arcs and the continental margin resulted in the fracturing of the East European Platform's basement, giving rise to a complex network of broad basinal low-plains and narrow depressions across the shelf. This network, now known as the Kama-Kinel trough system, had a major influence on the architecture of the basin (Fig. 2). The basinal low-plains and depressions separated areas of shallow-water environments from each other. The gentle and steep slopes of depressions were conducive to the formation of biohermal reef-like carbonates.

In the central part of the Volga-Ural petroleum province, the Devonian strata form the basal layers of the sedimentary cover, lying unconformably atop either the Riphean-Vendian rocks of the avlacogens or the platform's crystalline basement. The oldest strata of the Devonian succession, distributed in the east and southwest of the province, consist of variegated sandstones, mudstones, and siltstones, with occasional interbeds of dolomites and limestones.

The Eifelian sequence, developed in depressions or basinal low-plains, features alternating layers of carbonate and black shale sediments, with an overall thickness ranging from 130 to 175 m. The carbonate strata consist of dark grey and black, clayey, bituminous limestones, enriched with fossils such as corals, ostracods, brachiopods, tentaculitids, and bivalves. The accompanying black shale layers encompass clayey shales, mudstones, and calcareous mudstones. On the depression slopes, the Eifelian deposits are characterized by intercalated siliciclastic, carbonate, and black shale sediments, with a reduced total thickness of 50 to 125 m. In the shallow water settings of tectonic arches, the Eifelian deposits are sporadically distributed and exclusively siliciclastic, comprising sandy-clayey rocks with abundant charred plant remains, and exhibit a thickness of 2 to 45 m.

The Givetian deposits, formed within depressions or basinal low-plains, are predominantly composed of dark coloured carbonate-clayey rocks, namely limestones and mudstones, with a total thickness reaching up to 1000 m. The upper part of the Stage, the Pashyian and the lower part of the Timanian, consists mainly of siliciclastic sediments, specifically siltstones and silty mudstones, interspersed with occasional limestone interbeds. The limestones contain ostracods, brachiopods and crinoids, with a less frequent presence of corals and trilobites.

On the slopes of depressions, the Givetian deposits, up to 350 m thick, are composed of siliciclastic sediments with intervals of black shales, sandstones, siltstones, and mudstones enriched with siderite, pyrite, charred plant detritus, and spores (Fig. 3). Carbonate interbeds contain crinoids, brachiopods, and ostracods. In shallow water environments, where the total thickness does not exceed 170 m, the Givetian also consists of siliciclastic sediments, including sandstones with interlayers of siltstones and mudstones. The mudstone interbeds contain lingulid brachiopods, scolecodonts, fish scales, and plant detritus.

The Frasnian deposits are widespread in the studied area. The lower part of the sequence (upper Timanian) is composed of interbedded siliciclastic and carbonate rocks, while the overlying part of the sequence is composed of carbonate and black shale sediments.

In both condensed and non-condensed depressions, the Frasnian succession initiates with upper Timanian carbonate rocks, which are overlaid by black shales. The latter consist

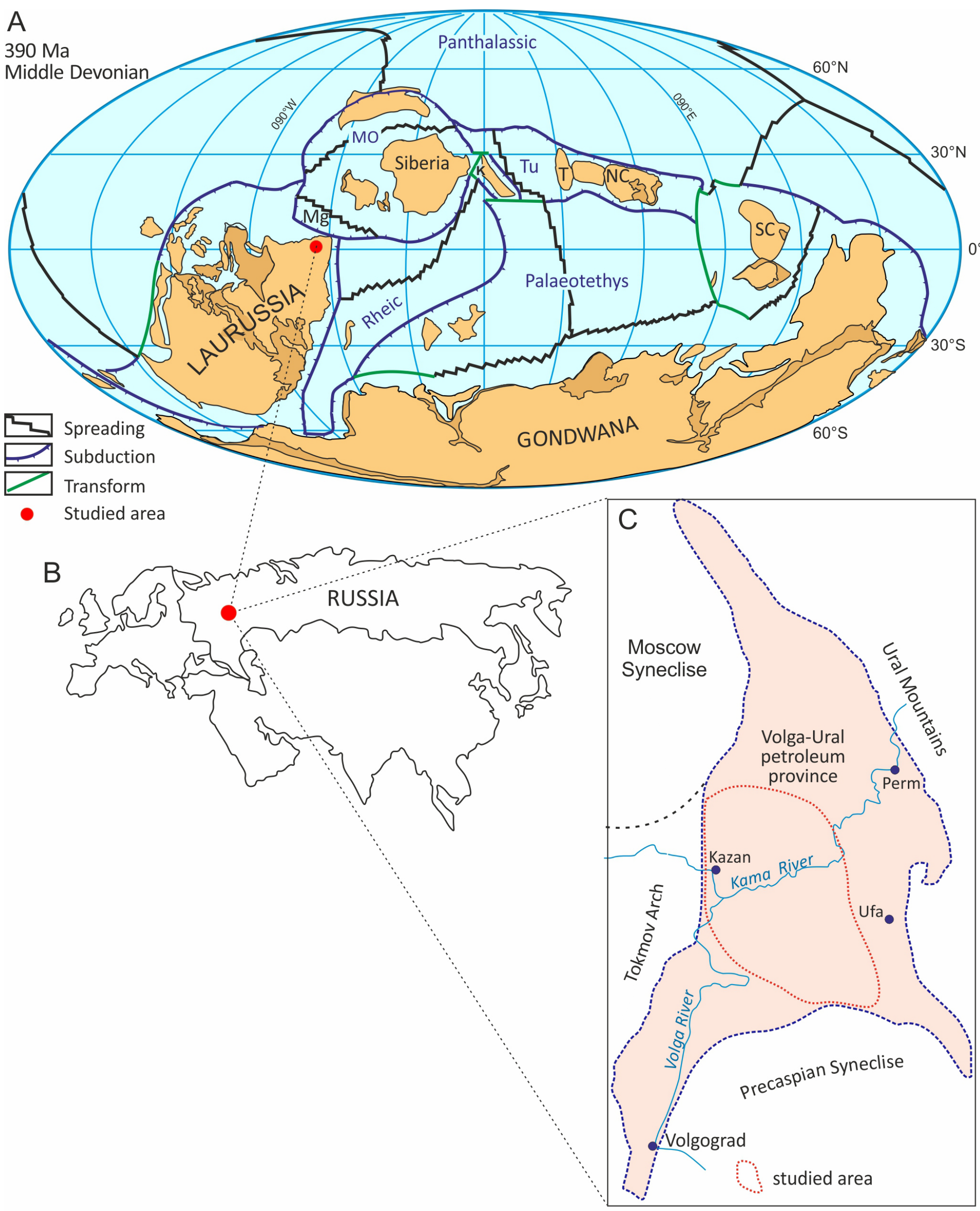

Fig. 1. The Middle Devonian palaeogeography and location of the studied area: (A) palaeogeographic map simplified from Golonka (2002), Torsvik and Cocks (2017), Scotese (http://www.scotese.com/earth.htm) and Blakey (https://deeptimemaps.com) (B) Overview map, (C) location of the studied area within the Volga-Ural petroleum province; terranes and continents on palaeogeographic map: NC, North China; SC, South China; T, Tarim. Oceans and Island Arcs: Mo, Mongol-Okhotsk Ocean; Mg, Magnitogorsk Island Arc; Tu, Turkestan Ocean

of bituminous or clay-siliceous carbonate shales with cherty interbeds, exhibiting a relict radiolarian structure. In non-condensed depressions, the thickness reaches up to 250 m, whereas in the condensed depressions of the southeast of the province it increases to 1100 m. The fossils include sponge spicules, tentaculitids, lingulid brachiopods, *Buchiola* bivalves, and algal fragments. Additionally, the rocks feature sapropelite interlayers with an organic carbon content of up to 30% (Fortunatova et al., 2018).

On the slopes of depressions, the Frasnian succession primarily consists of carbonate sediments, including bioclastic limestones interspersed with marls, dolomites, and mudstones, hosting brachiopods and crinoids (with a total thickness of up to 650 m). In the middle part of the succession (Sargaevian), the slopes feature an intercalation of bioclastic carbonate sediments and black shales, characterised by dark coloured bituminous limestones, marls, mudstones, and shales. The bituminous rocks predominantly contain fauna typical of black shales, while the organogenic limestones are marked by stromatopores, ostracods, tentaculitids, and brachiopods. The upper part of the succession comprises light coloured organogenic and bioclastic limestones, enriched with corals, foraminifers, brachiopods, and ostracods.

Shallow-water sediments of the Frasnian, with a total thickness ranging from 60 to 300 m, are predominantly found outside the Kama-Kinel trough system and its slopes. These sediments are transgressively deposited over the underlying strata, characterized by a minimal thickness and often a mottled colouration, with an increased presence of sandy material in the lower part of the sequence. In shallow-water

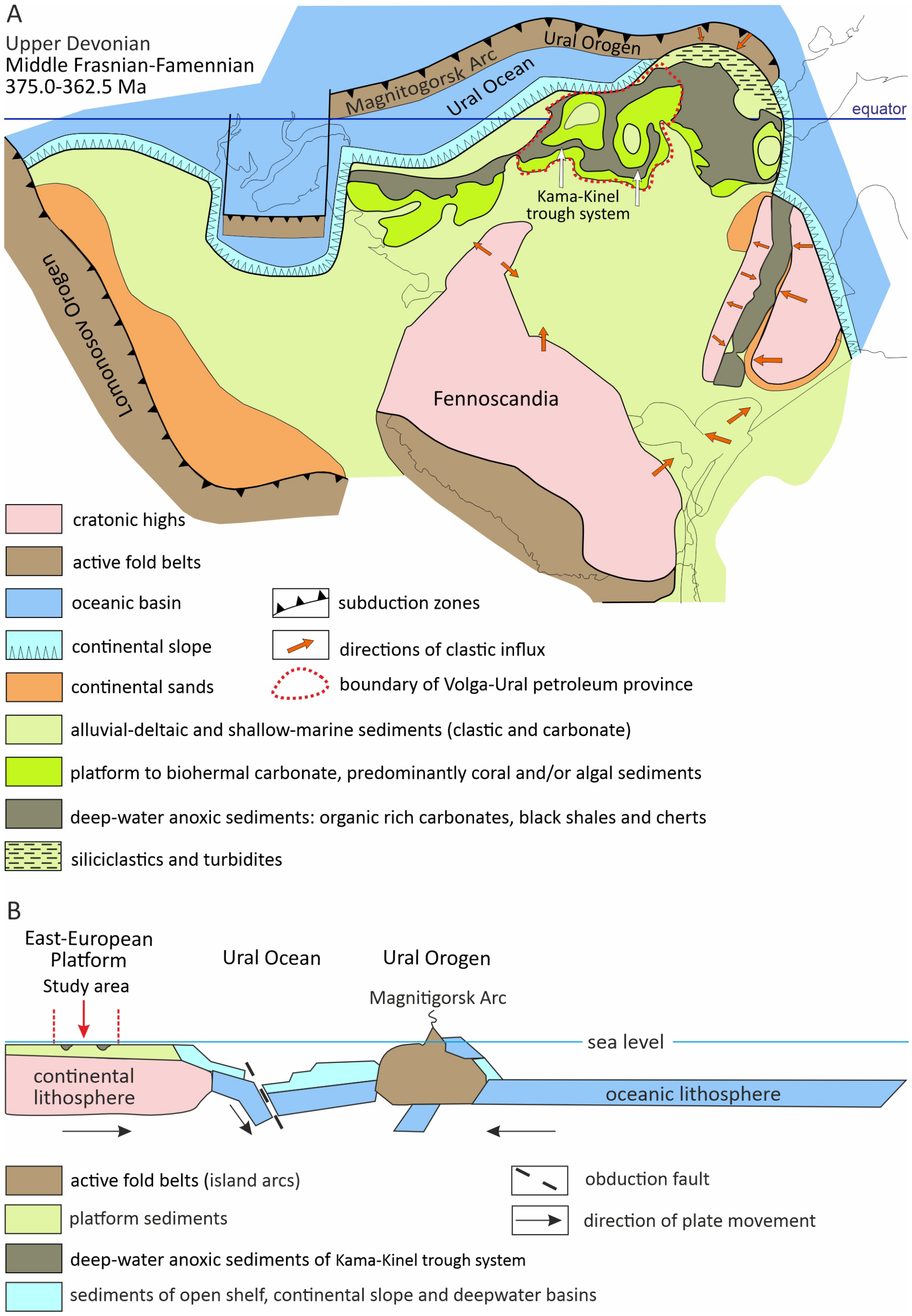

Fig. 2. Late Devonian palaeogeography of the passive margin of the East European Platform and the Ural Palaeoocean: (A) Middle Frasnian to Famennian palaeogeography (modified and simplified from Nikishin et al., 1996 and Kabanov et al., 2023a); (B) schematic profile (simplified from Puchkov, 2010)

settings, the upper half of the Frasnian sedimentary sequence is typically composed of limestones, which frequently undergo dolomitisation.

The Famennian deposits in non-condensed depressions, with a thickness of 50 to 70 m, comprise black shale sediments. These sediments include interlayers of dark grey and black, thinly laminated, bituminous, and silicified limestones, interspersed with marls and mudstones. Fossils include foraminifers, sponge spicules, ostracods, and brachiopods. On the depression slopes, where deposits reach a thickness of 200 to 500 m, carbonate sediments predominate. These sediments include clayey and organogenic limestones, occasionally with dark grey bituminous intervals and dolomite interlayers. The associated fauna is diverse, encompassing foraminifers, ostracods, serpulids (microconchids?), brachiopods, gastropods, bivalves, bryozoans, crinoids, and charred plant detritus. In the shallow water environments of tectonic arches, particularly the South Tatar Arch, Famennian sediments, which are of 200 to 350 m thick, are widespread. These sediments consist of grey to light-grey irregularly dolomitised, sometimes silicified, bioclastic limestones with thin clay interlayers and limestone breccia at the base.

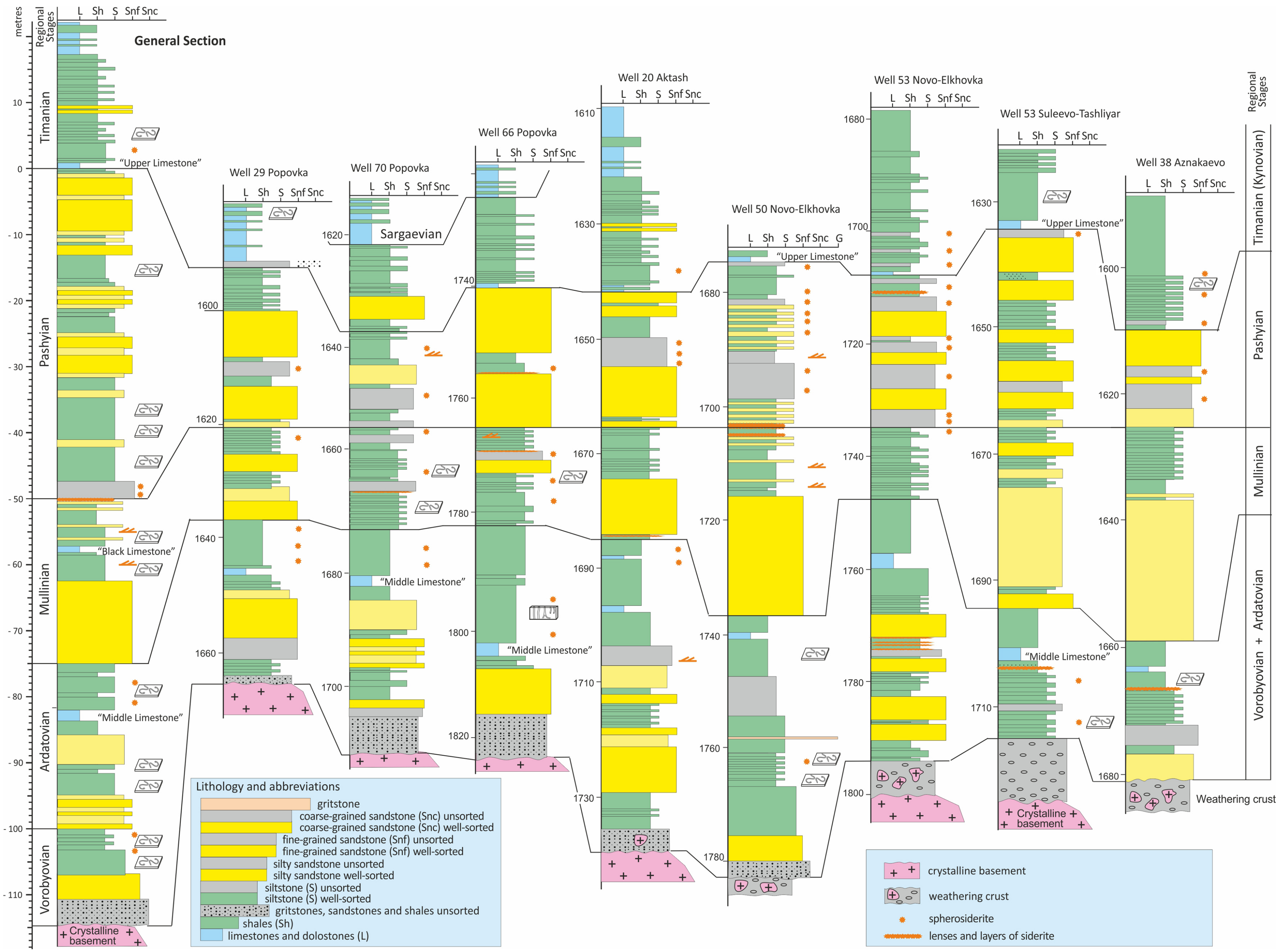

Fig. 3. Some sections of the Devonian siliciclastic strata of the South Tatar Arch, illustrating facies variability of stratigraphic units and alternation of sorted and unsorted rocks; it should be noted that the general section corresponds only in broad outline to the real well sections (modified from Silantiev et al., 2022)

3. Materials and Methods

The results and discussion in this paper are based on data from the study of sedimentological, faunistic, and ichnological characteristics of the Devonian sediments.

These sediments were accessed through more than 60 wells across various locations in the central part of the Volga-Ural province. The total thickness of the core intervals studied exceeds 600 m. Some of the findings, particularly on the siliciclastic interval of the Givetian, which include detailed well logs, rock descriptions, and ichnofossil illustrations have been published recently (Silantiev et al., 2022; Miftakhutdinova, 2023). In-depth analysis of the well cores was conducted directly at the core storage facility, where highly representative rock samples were selected for closer examination. These samples were polished and scanned to provide a detailed study of sedimentological and ichnological features. The collection of core samples is housed at the Geological Museum of Kazan Federal University, under collection number 44.

Sedimentological analysis aimed to reconstruct the environments in which the sediments were formed, utilising the sedimentological characteristics of the rocks and their variations across the section. Detailed examinations of the core layers, conducted at the core storage facility with precision up to 1 cm, covered lithology, colour, lamination patterns, sediment sorting, and the nature of rhythmic interbedding, including boundaries with adjacent layers. The assessment also focused on the burial and preservation of faunal remains, identification of biogenic structures disrupting rock laminations, and observation of any secondary changes in the rocks.

Ichnofacies analysis entailed the identification and taxonomic classification of trace fossils indicative of organism activity in the rocks, determining ichnotaxa combinations within assemblages, and categorising these ichnoassemblages into specific ichnofacies (Buatois, Mangano, 2011).

Ichnofabric analysis was utilised to assess bioturbation intensity – quantifying the disruption in the rock's primary lamination due to living organisms' activity on the sediment. This reworking intensity was evaluated using a qualitative Ichnofabric Index scale, as devised by M. Droser and D. Bottjer (1986).

Biofacies analysis involved estimating the relative oxygen content and hydrodynamic conditions, based on the interplay between fossils and their surrounding rocks. This approach integrated findings from sedimentological, paleontological, ichnofacial, and ichnofabric analyses to offer a comprehensive environmental interpretation.

The assessment of oxygen levels in palaeoenvironments utilised a range of indicators, including the nature of textures and ichnotextures (highlighting the intensity of bioturbation), the presence of biota (especially groups differing in their resistance to oxygen reduction), and, when available, specific geochemical criteria such as the ratio of organic carbon to sulphur, sulphur isotopes, and trace element concentrations (Flugel, 2010).

The evaluation of oxygen levels in organic-rich black shale sediments was conducted using the oxygen-restricted biofacies (ORB) determination method, as outlined by Wignall, Hallam (1991), Wignall (1994), and Flugel (2010). This method relies on assessing the abundance of fossil species, lamination, and ichnofabric in the rocks, offering insights into the sedimentary environment's oxygenation.

The interpretation of hydrodynamic conditions was based on an analysis of lithological, sedimentological, and palaeontological characteristics, including the identification of lithotypes of rocks, examination of lamination patterns, evaluation sediment sorting, understanding the burial nature of benthic fauna, studying ichnofossil assemblages, and determining the character and intensity of bioturbation.

Biostratigraphic and biofacial analyses of the fossils were conducted based on data presented in comprehensive publications (Aliev et al., 1978; Gubareva, 2003; Fortunatova et al., 2018 and others). These data were correlated with regional conodont zones of the Volga-Ural province, established for different facies settings (Aristov, 1988; Ovnatanova and Kononova, 2008; Nazarova and Kononova, 2015, 2020), representing the most reliable stratigraphic framework for the Devonian of studied area. Regional conodont zones were compared with standard (Ziegler, 1962, 1969, 1971; Ziegler, Sandberg, 1984; 1990; Sandberg, Ziegler, 1996) and global conodont zones (Becker et al., 2020). This comparison served as the basis for correlating the Regional stages of the Volga-Ural province with the contemporary Chronostratigraphic Chart.

The sedimentation rates were assessed by adopting the minimal accumulation rates observed in contemporary environments for both siliciclastic and carbonate sedimentation processes. The rate of siliciclastic sedimentation was set at 0.2 mm/year, corresponding to the minimal rate identified in the Gulf of Maine along the North American Atlantic coastline (Kukal, 1971). With such a rate and assuming continuous sedimentation, a minimum of 200 m of sediment would accumulate over one million years. The rate of carbonate sedimentation was determined to be 0.03 mm/year, reflecting the minimal rate of carbonate mud accumulation recorded in the modern Gulf of Mexico and Caribbean Sea (Emiliani, 1966). At this rate, approximately 30 m of sediment would accumulate over one million years with ongoing sedimentation. For organic-rich black shale sediments, the rate was set at 0.1 mm/year (or 10 cm/1000 years), aligning with the rate for modern sapropelic sediment accumulation in the Black Sea, as determined using ^{14}C radioisotope datings (Staffers et al., 1978). At this rate, 100 m of sediment would accumulate over one million years, excluding sediment compaction effects.

The assessment of the sediment compaction ratio was conducted based on an analysis of literary and empirical data. The compaction ratio for siliciclastic and carbonate sediments, which can reach values of 1:2 (Shinn, Robbin, 1983; Croizé et al., 2013), was not considered in this work. Quantitative data on the compaction of ancient organic-rich sediments have not yet to be found. Most studies indicate significant compaction ratio (at least 1:4) (Littke and Zieger, 2020).

Observations on the compaction of modern organic-rich sediments indicate that compaction occurs very rapidly (within the first 100–500 years after deposition) and under minimal pressures from overlying sediments (3–10 m); compaction intensifies with an increase in organic matter content. For instance, organic-rich sediments (≥ 5% organic matter) in the Mississippi Delta, situated at depths of around 10 metres, have already experienced a fourfold compaction

(Keogh et al., 2021). The compaction ratio calculated for modern sapropelic sediments in the Black Sea is 1:6 (i.e., 1 m of primary sediment compacts to a 16.7 cm layer) (Staffers et al., 1978). It is noteworthy that these findings pertain to modern sediments that have not undergone diagenesis, a process that would further increase the degree of compaction in rocks.

The data on the compaction ratio of peat, an organic sediment from continental settings, exhibit a wide range of values. During the transformation of peat into coal, the compaction ratio can vary from 1:3 to 1:60 (Winston, 1986), indicating that the thickness of the primary sediment, composed of organic matter and water, can be reduced by 3 to 60 times. In the latter case, only a 1.67 cm thick coal seam would be preserved from 1 m of primary peat. For this article, we adopt a compaction ratio of 1:10 for organic-rich black shale sediments, meaning that for every metre of primary sediment, an average of 10 cm of rock remains in geological record.

4. Results

4.1. Regional conodont zonation as evidence of stratigraphic completeness of the Devonian succession

The stratigraphic completeness of the Devonian succession in the central part of the Volga-Urals petroleum province is substantiated by the continuous conodont zonation traced from the *kockelianus* Zone of the Eifelian to the Devonian-Carboniferous boundary (Fig. 4).

The Eifelian and Givetian conodont zonation is most comprehensively developed in the Voronezh Anteclise, located in the south-western part of the East European Platform. The initial conodont zonal schemes (Aristov, 1985) and the taxonomic composition of the conodont assemblages have been significantly refined in recent years (Kononova, Kim, 2005; Nazarova, Kononova, 2016, 2020). These updated schemes are applied to the central part of the Volga-Ural petroleum province (Fig. 3), where Eifelian deposits are unevenly distributed and infrequently penetrated by wells. According to conodont zonation, the Mosolovian and Chernoyarian regional stages correspond to the interval of the *kockelianus*, *eiflius*, and *ensensis* Zones of the Global Scale, which matches the upper part of the Eifelian (Fig. 3). The Vorobyovian and Ardatovian regional stages are correlated with the *hemiansatus*, *timorensis*, *rhenanus-varcus* Zones of the Global Scale, indicative of the lower and middle parts of the Givetian. The Mullinian, Pashyian and lower Timanian regional stages, predominantly represented by siliciclastic sediments, poses a challenge for correlation with the Global Scale due to the absence of representative conodont assemblages. The duration of this interval is estimated at approximately 3 Ma and can be correlated with the interval of conodont zonation from the *ansatus* Zone to the *dengleri* Zone, representing the upper Givetian in the International Chronostratigraphic Chart (Becker et al., 2020).

The Frasnian conodont zonation of the Volga-Ural petroleum province was elaborated separately for shallow-water and open, deeper-water settings (Khalymbadzha, Chernysheva, 1969a,b; Khalymbadzha, 1982, 2001; Ovnatanova, Kononova, 2008) (Fig. 3). Conodont assemblages include species used in modern global zonation (Becker et al., 2020), which makes the comparison more reliable. Notably, species like *Ancyrodella pristina* Khalymbadzha and Chernysheva, 1970, pivotal for identifying the lowest Frasnian global zone, was originally established in the central part of the Volga-Ural province (Khalymbadzha, Chernysheva, 1970).

The Famennian zonation within the province aligns with Standard conodont zonation (Ziegler, Sandberg, 1984, 1990) and continues to be applied both in the central areas of the Volga-Ural province and in North-Eastern European Russia (Ovnatanova et al., 2017).

In summary, almost all conodont zones (or their analogues) from the Standard (Ziegler, 1962a, 1969, 1971; Ziegler, Sandberg, 1984, 1990) and Global conodont zonations (Becker et al., 2020) have been identified in the Devonian of the central part of the Volga-Ural province. Correlation of Regional Stages with conodont zonation, and the latter with the International Chronostratigraphic Chart, enables estimate of the duration and sediment accumulation rate of distinct stratigraphic units in different depositional environments.

4.2. Main sedimentation types and their distribution patterns

In the central part of the Volga-Ural province, the Devonian sequences display considerable variation in sediment composition, faunal assemblages, thickness, and completeness. Based on these features, three predominant sedimentary types can be identified: siliciclastic, carbonate, and black shale. The first two types have contributed to the deposition of carbonate and siliciclastic reservoirs. The third type, which is characterised by a high content of organic matter, is traditionally considered as a source rock.

Siliciclastic sediments are distributed from the Middle Devonian (Emsian) to the Early Frasnian and are represented by well-sorted sandstones and siltstones interbedded with thin layers of limestones as well as with intervals of unsorted siliciclastic rocks (Figs. 3, 5–7). The thicknesses range from the first hundreds of metres in depressions (and basinal low-plains) to the first tens of metres in uplifted areas of the seabed (including tectonic arches) representing shallow water environments. Marine fossils are rare; meanwhile, a diverse assemblage of ichnofossils including *Chondrites, Spirophyton, Scolicia, Planolites, Palaeophycus, Zoophycos* and *Skolithos* indicates the marine origin of these sediments (Silantiev et al., 2022; Miftakhutdinova, 2023). The Paschyian Regional Stage represents the time during which siliciclastic sedimentation completely covered the entire studied area, displacing all other types of sedimentation.

Sections predominantly composed of siliciclastic rocks are characterised by a rather sharp and rapid transition between rock types: laminated rocks alternate with bioturbated ones, there is interbedding of rocks with varying grain sizes and sorting, and there is a notable variability in the assemblages of faunal remains and ichnofossils. The light colour of the siliciclastic rocks makes it easy to identify and assess changes in their biosedimentological features. An analysis of these combined features allows for the determination of environmental conditions and the evaluation of relative fluctuations in hydrodynamics, as well as oxygenation of the sediment and the bottom water layer. The biosedimentological characteristics of the siliciclastic rocks indicate their accumulation in environments with significantly fluctuating hydrodynamic conditions and oxygen content.

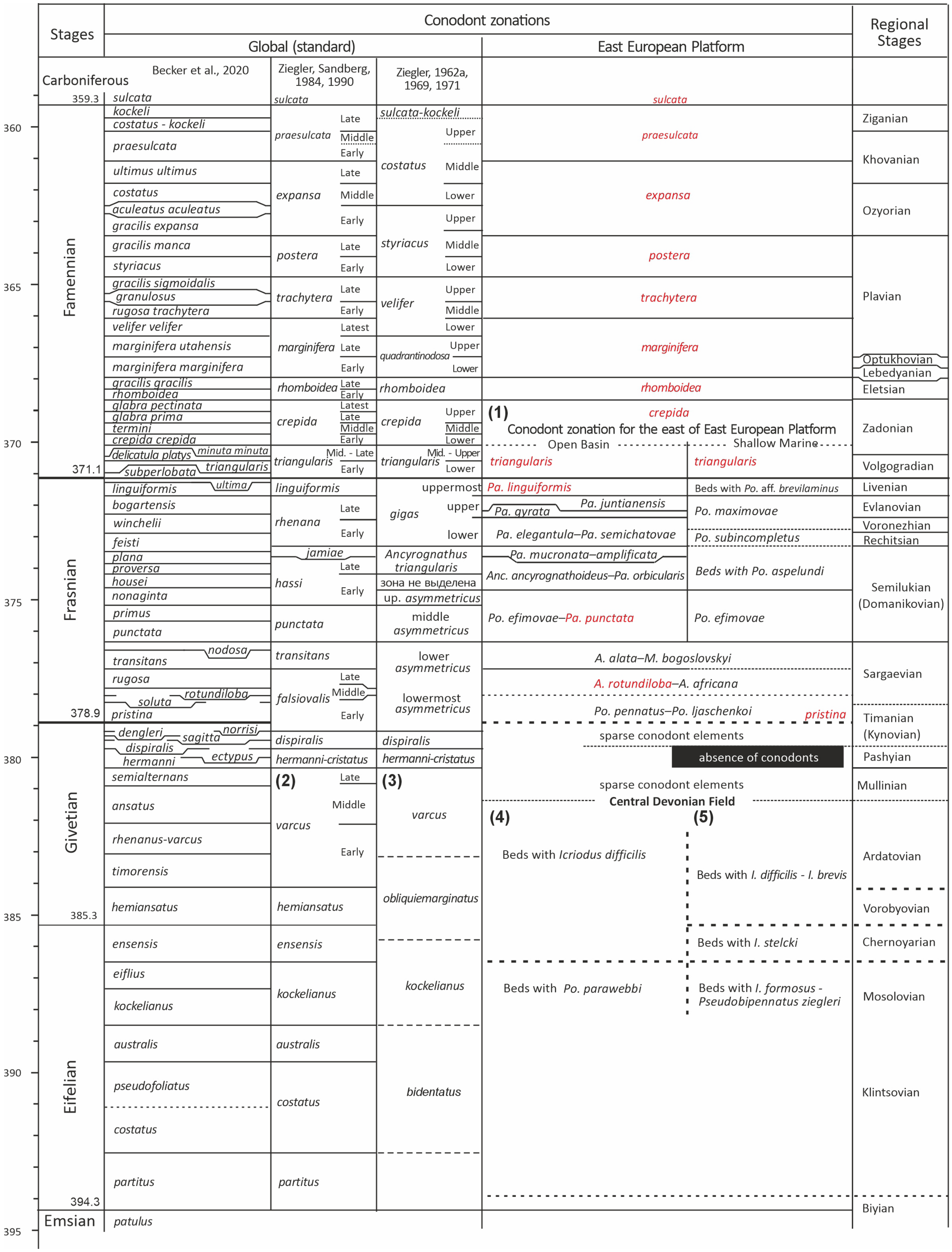

Fig. 4. Middle and Late Devonian conodont zonations: Global, Standard or classical, and regional for the east of the East European Platform. Conodont zonations, denoted with numbers (1) to (5), have been compiled from following sources: (1) Ovnatanova, Kononova, 2008; (2) Sandberg, Ziegler, 1996; (3) Wittekindt, 1966; Bultynck, 1975; (4) Aristov, 1988; (5) Nazarova, Kononova, 2016, 2020. Regional Stages are given according to (Decision of the Interdepartmental Regional Stratigraphic Meeting…, 1990; Fortunatova et al., 2018); red font indicates global or standard conodont zones traceable in the central part of the Volga-Ural petroleum province

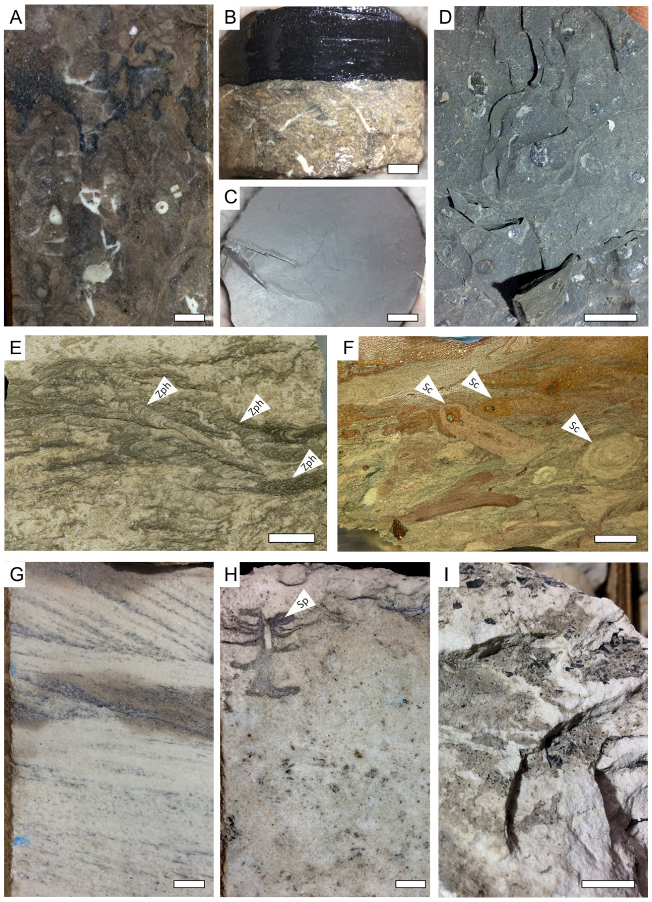

*Fig. 5. Middle Devonian (Givetian) siliciclastic and carbonate rocks of Vorobyovian and Ardatovian regional stages: A) Microbial algal limestone with crinoid bioclasts and stylolitic sutures; "Middle Limestone" geophysical marker; well 116**, Suleyevo, 1736 m, Ardatovian; B) Erosional contact between black shale with high organic matter content and bioclastic limestone; "Middle Limestone" geophysical marker; well 116**, Suleyevo, 1737 m, Ardatovian; C) Flat and smooth bedding plane of thinly layered black shale with high content of organic matter; well 116**, Suleyevo, 1738 m, Ardatovian; D) Uneven bedding plane of siltstone with scattering of small shells of lingulids; well 327**, Minnibayevo, 1860 m, Ardatovian; E) Bioturbated siltstone with Zoophycos (Zph) traces; well 194**, Pavlovo, 1792 m, Vorobyovian; F) Entirely bioturbated siltstone containing superimposed horizontal Scolicia (Sc) traces with menisciform filling; red colours of the rock are caused by sideritisation; well 23**, Sabanchi, 1815 m, Ardatovian; G) Contact of sandstones with inclined and subhorizontal laminations, emphasised by thin dark layers of charred plant detritus; well 194**, Pavlovo, 1799 m, Vorobyovian; H) Fully bioturbated sandstone with superimposed Spirophyton (Sp) traces and dispersed plant detritus; well 194**, Pavlovo, 1802 m, Vorobyovian; I) Bedding plane of sandstone with thin lenses and inclusions of charred plant detritus; well 79**, Tashliar, 1910.1 m, Vorobyovian. The scale bar on all photos is 1 cm*

For example, sandstones were deposited under the most active hydrodynamics and high oxygenation, while clay-rich rocks accumulated under the least active hydrodynamic conditions; this is evidenced by the grain size and the presence of free-living and burrowing benthos. An example of one of the wells that penetrated a succession of siliciclastic rocks, along with the interpretation of sedimentation conditions, is shown in Fig. 8.

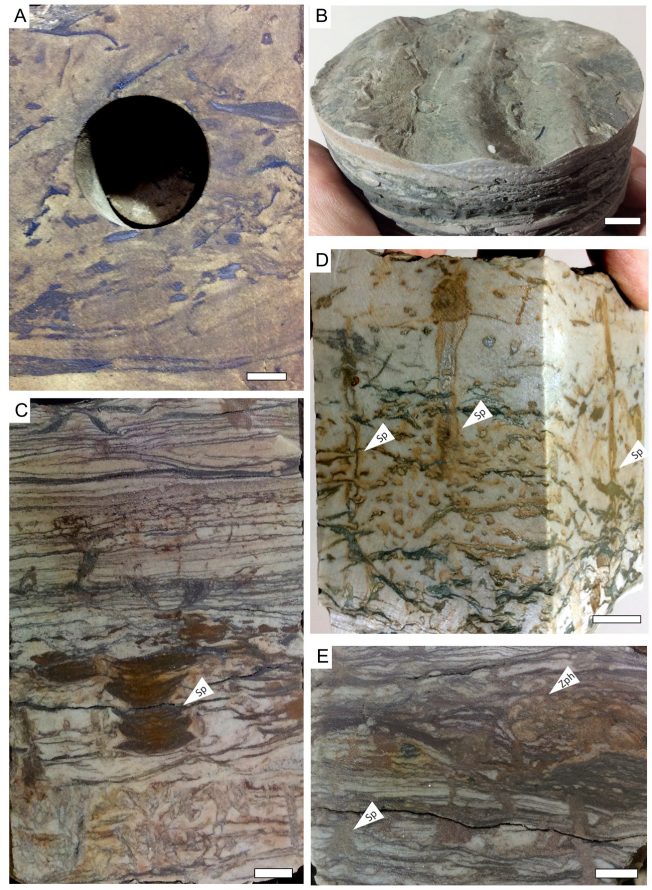

*Fig. 6. Middle and Upper Devonian siliciclastic rocks of the Mullinian, Pashyian and Timanian regional stages: A) Oil-bearing sandstone strongly bioturbated; well 220**, Sarmanovo, 1672 m, Pashyian; B) Greenish-grey mudstone overlapping sandstone; the bedding plane contains ripple marks, as well as vertical and horizontal traces; well 23**, Novo-Yelkhovo, 1673.5 m; Frasnian; lower Timanian; C) Bioturbated siltstone with vertical cross-sections of Spirophyton (Sp) traces, and siderite inclusions; bioturbation decreases in the upper part of the sample; well 23**, Novo-Yelkhovo, 1693 m, Givetian, Pashyian; D) Bioturbated siltstone with vertical cross-sections of Spirophyton (Sp) traces highlighted by sideritisation; well 136**, Karmala, 1805 m, Givetian, Mullinian; E) Bioturbated siltstone with vertical cross-sections of Zoophycos (Zph) and Spirophyton (Sp) traces highlighted by sideritisation; well 136**, Karmala, 1804 m, Givetian, Mullinian. The scale bar on all photos is 1 cm*

Carbonate shallow-water oxic sediments include isolated carbonate buildups (reefs, banks and broader platforms) and off-reef carbonate and mud covers. Isolated carbonate buildups (up to 600 m thick) consist of biogenic limestones, oolitic, microbial, containing a relatively rich assemblage of fossils: calcareous algae, foraminifers, stromatopores, corals, crinoids, and conodonts. Sediments of this type were formed predominantly along the slopes of intrashelf trough net of the Kama-Kinel trough system (Fig. 2A). Off-reef carbonate and mud covers are composed of bioturbated limestones and mudstones with a diverse benthic fauna and moderate sediment thickness. In some cases, stratigraphic incompleteness and breaks in sedimentation are observed.

The Eifelian and Givetian accumulation of carbonate sediments occurred predominantly in depressions, on

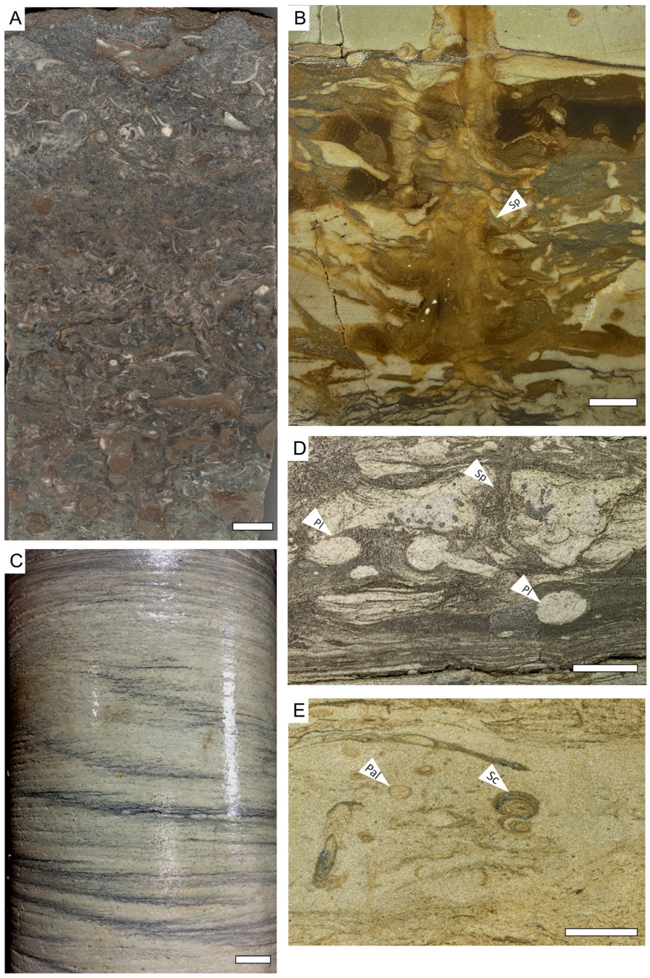

*Fig. 7. Middle and Upper Devonian siliciclastic and carbonate rocks of Pashyian (Givetian) and Timanian (Frasnian) regional stages: A) Bioturbated limestone with bioclasts of brachiopod shells and crinoid fragments; processes of pyritisation and sideritisation are recorded; "Upper Limestone" geophysical marker; well 232p, Novo-Yelkhovo, 1677 m; the basement of the Timanian; B) Bioturbated siltstone with vertical cross-sections of Spirophyton (Sp) traces highlighted by yellow-brown secondary siderite; well 201**, Glazovo, 1717 m, Pashyian; C) Fine-grained sandstone with inclined lenticular layering highlighted by layers of charred plant detritus; well 23**, Novo-Yelkhovo, 1696 m, Pashyian; D) Bioturbated fine-grained sandstone with traces of Spirophyton (Sp) and Planolites (Pl); in the lower part – thin wavy lamination with weak bioturbation (30% of recycling). Upwards, the degree of bioturbation increases to full reworking; well 9**, Muslyumovo, 1683 m, Pashyian; E) Fully bioturbated fine-graned sandstone with superimposed horizontal traces of Palaeophycos (Pal) and Scolicia (Sc); well 220**, Sarmanovo, 1669 m; Pashyian. The scale bar on all photos is 1 cm*

their slopes, and in basinal low-plains, where this type of sedimentation frequently coincided with the accumulation of deep-water organic rich black shales. This is recorded in the geological succession by the alternation of carbonate and black shale facies. At the end of the Givetian (Pashyian Regional Stage), carbonate sedimentation in the studied area completely terminated. Steady accumulation of carbonate sediments was recovered and stabilised in the studied area in the early Frasnian and continued until the global regression in the Early Visean (Silantiev et al., 2023). Transgression in the Early Frasnian (Timanian Regional stage) for the first time extended carbonate sedimentation to shallow water environments located on tectonic arches (Fig. 9).

In shallow water environments, carbonate sedimentation was often interrupted, resulting in the erosion of already accumulated sediments (Fig. 10). In particular, calculations for the Frasnian indicate that carbonate sediments deposited in shallow water environments represent approximately less than 60% of the duration of this time interval, while most of the geological time corresponds to discontinuities in sedimentation (for details see part 4.3). The Famennian is characterised by the most stable carbonate sedimentation, distributed both on the slopes of depressions (Fig. 11) and in shallow water environments of tectonic arches (Fig. 12).

Black shale sediments, believed to have originated in photic-zone euxinic conditions (Kabanov et al., 2023a, b), consist of dark-coloured carbonate-clay or siliceous-clay-carbonate rocks with a high organic matter content (Fig. 13). When these sediments have a considerable thickness (several hundred metres), they are usually interpreted as having been accumulated in non-condensed (compensated) depressions. In contrast, when the thickness is relatively minimal (several tens of metres), they are thought to have been deposited in condensed (uncompensated) depressions.

Black shale sediments are characterised by a low diversity of benthic fauna, represented by few species of bivalves, and both inarticulated and articulated brachiopods. In contrast, the diversity of planktonic and nektonic organisms is increasing. The plankton is represented by numerous radiolarians, Entomozoacean ostracods, a rare pteropods, and tentaculitids (predominantly dacryoconarids), while the remains of actively swimming nektonic organisms are represented by polychaete annelids (scolecodonts), cephalopods, conodonts, and fish. Microbial bioherms are represented by lens-like non-layered forms, as well by stratiform, hemispherical and columnar-dome stromatolites of small size (first centimetres) (Fig. 13, A–D).

The organic-rich black shales comprise several lithological types, which are difficult to distinguish from each other due to their external similarities. These different rock types represent a mixture of fine-grained, dark-coloured organic, clayer and siliciclastic material that appears thinly bedded in cross section. Detailed analysis supports N.M. Strakhov's (1939) assertion that these rocks actually lack true lamination (i.e. the rocks lack layers in the strict sense). Instead, the thinly laminated appearance is caused by the compact arrangement of minute lenses of organic and clayey (clay-silt) material. In some cases, organic-rich black shales contain thin (0.5–10.0 cm) lenses and interlayers of lighter (yellowish-grey) carbonate material, occasionally with elevated P_2O_5 content. To assess oxygen variation in these organic-rich black shales, we used the oxygen-restricted biofacies (ORB) method, which assesses the sedimentary fabric alongside the presence and diversity of nektonic and benthic fossils in the rocks.

The compositional, sedimentological, and structural features of the black shales suggest that these sediments accumulated at very low rates in a calm, low-energy setting. The biosedimentological characteristics of the black shales indicate anoxic and dysoxic conditions. These organic-rich black shales show no signs of bioturbation, and fossils are exceptionally rare, small, and exhibit low diversity,

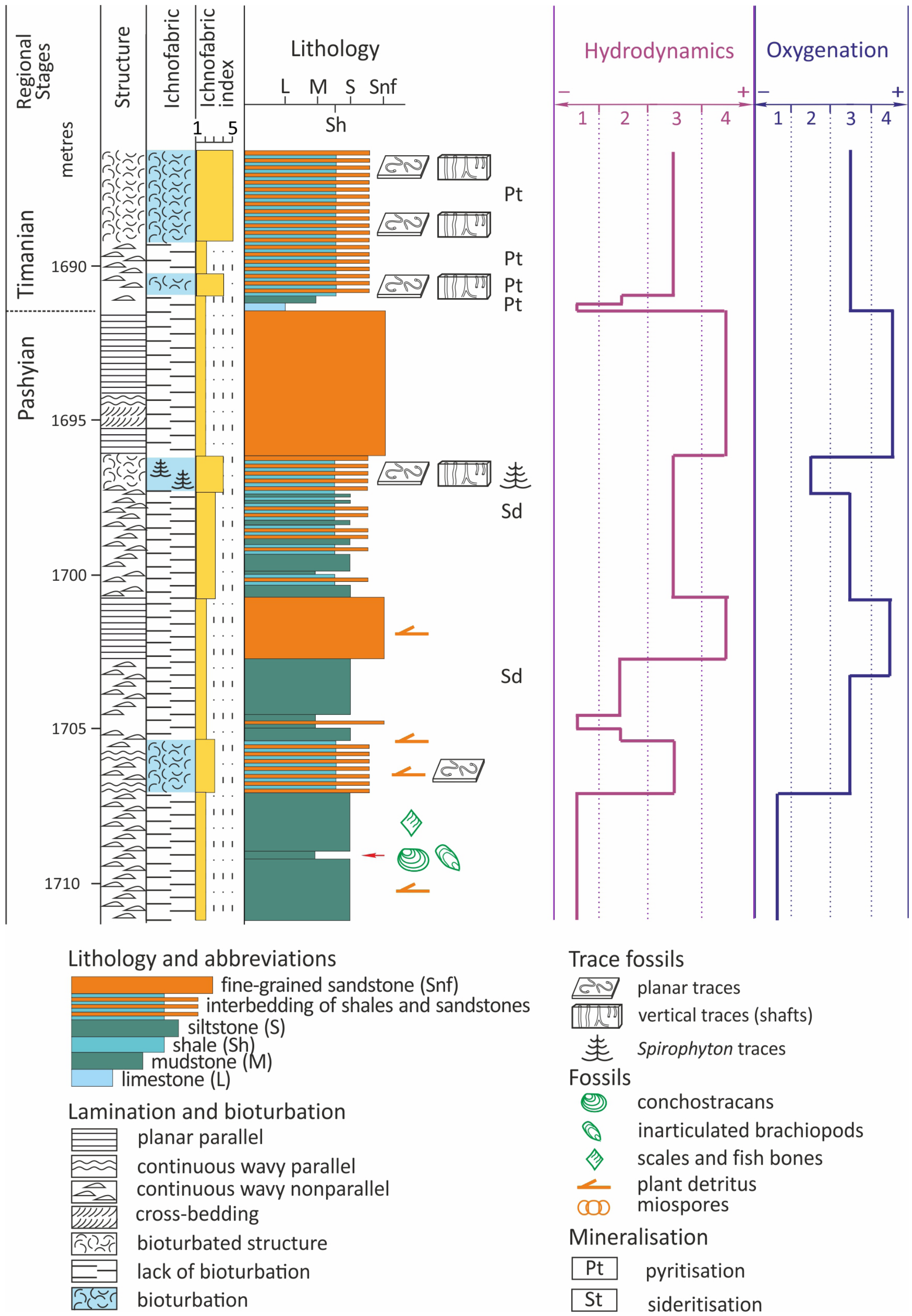

Fig. 8. Representation of lithological, sedimentological and ichnological features in the core of the studied wells and interpretation of these features in terms of hydrodynamics and oxygenation

indicating harsh conditions for life. The lighter (yellowish-grey) carbonate lenses and layers are microbial in origin and completely devoid of organic remains. The very rare layers of bioclastic, bioturbated limestones probably formed under more favourable oxic conditions, which supported a diverse and abundant fauna. An example of a black shale sedimentary succession and an interpretation of the sedimentary settings is shown in Fig. 14.

The sedimentation of black shales began in the central part of the Volga-Ural province in the late Eifelian. Sediments of this type were accumulated predominantly in depressions or basinal low-plains and, as mentioned above, were adjacent to bioclastic carbonate sediments. At the end of the Givetian (Pashyian Regional Stage) black shale sedimentation, as well as carbonate sedimentation, completely ceased in the studied area.

Reactivation of black shale sedimentation commenced in the Early Frasnian. From this period, the steady accumulation of black shales enveloped the axial zones of the Kama-Kinel trough system, persisting almost without interruption until the onset of the Carboniferous (Mississippian, Tournaisian). The most widespread and well-known black shales were accumulated during the Middle Frasnian (Semilukian). In the literature by Russian geologists, the Middle Frasnian black shales are referred to as “Domanic sediments” or “Domanic

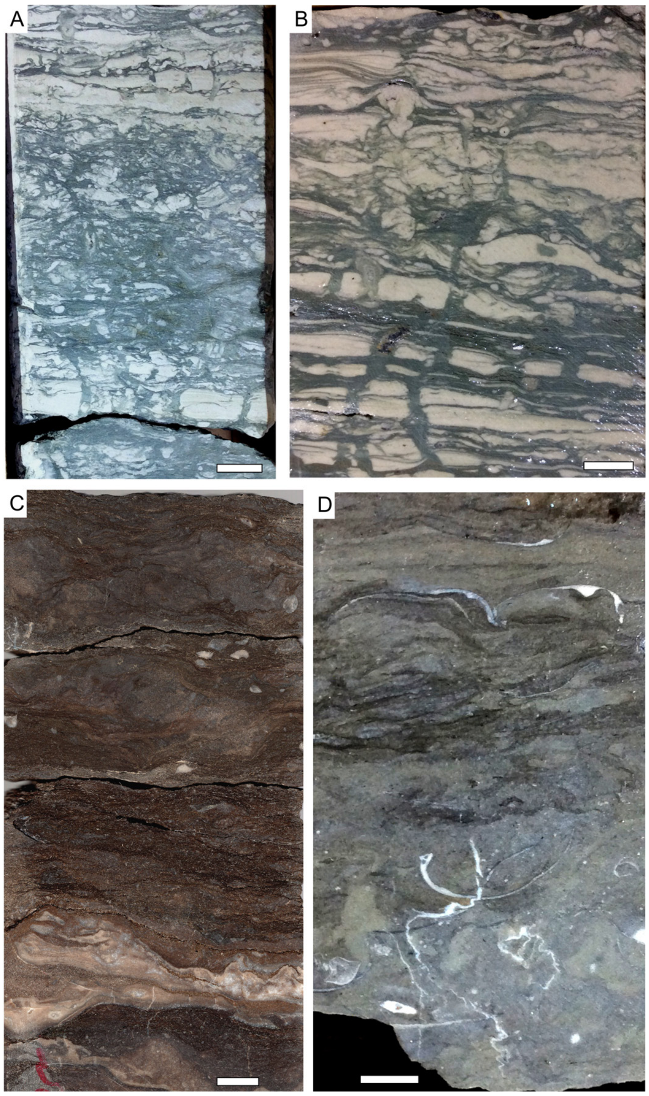

Fig. 9. Lower Frasnian marls and limestones, the lower part of Timanian regional stage: A) Interlayering of grey fine-grained sandstone and greenish-grey siltstone; bioturbation is estimated at 90–100%; well 220[**], Sarmanovo, 1661 m; B) Interlayer of grey and light grey siltstone, with 80–90% bioturbation, well 220[**], Sarmanovo, 1660 m; C) Bioclast-microbial bioturbated limestone with secondary mineralisation; "Upper Limestone" geophysical marker; well 403[**], Tumutuk, 1646 m; the basement of the Timanian; D) Bioturbated siltstone with interlayers of clayey material and bioclasts of brachiopod shells; well 329[**], Berezovo, 1727 m; the basement of the Timanian. The scale bar on all photos is 1 cm

facies", names derived from the Domanic Formation and Domanic River of Pechora Basin (Strakhov, 1939). The Middle Devonian-Mississippian organic-rich black shales located above and below the Middle Frasnian are designated as "domanikites" (5–25% organic matter) or "domanikoids" (< 5% organic matter). The relationship between the main types of Devonian sediments (siliciclastic, carbonate and black shale) and the predominant environment types within the central part of the Volga-Ural province is shown in Fig. 15. The probable rates and duration of sedimentation of each type are discussed below.

4.3. Rate and duration of sediment accumulation

The Chronostratigraphic Chart of the Middle and Upper Devonian, which includes global, standard, and regional

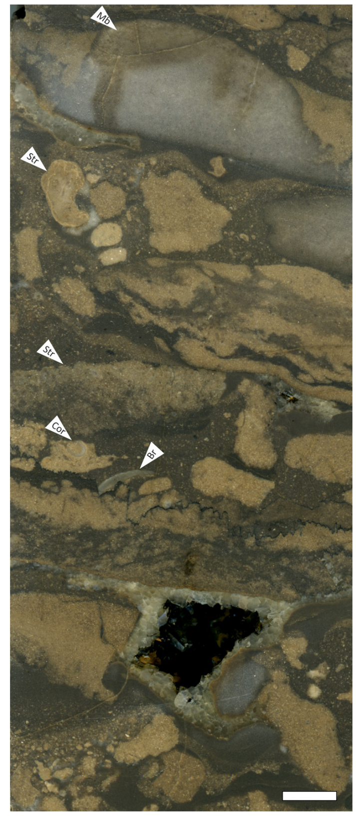

Fig. 10. Bioclast-microbial limestone; microbial structures and their fragments, coloured grey and light yellow-brown, are located in the darker micritic mass; light yellow-brown microbial structures are mainly represented by fragments of different sizes (0.2-5.0 cm) with irregular edges and appear to be the most susceptible to destruction; grey microbial bioherms (Mb) have lenticular and rounded shape and appear to be more resistant to destruction; fragments of stomatoporates (Str), corals (Cor), brachiopods (Br) are occurred; well 4482, Novo-Yelkhovo, 1562 m, upper Frasnian. The scale bar is 1 cm

conodont zonations (Fig. 3), estimates that the Devonian strata deposited in the central part of the Volga-Ural region accumulated over a period of 35 million years, from the Late Emsian to the Late Famennian.

The sedimentation rates and compaction ratios used in this paper are explained earlier in Section 3, Materials and Methods. The siliciclastic sedimentation rate is assumed to be 0.2 mm/yr (1 Ma = 200 m of sediment), the carbonate sedimentation rate is assumed to be 0.03 mm/yr (1 Ma = 30 m of sediment), and the accumulation rate of organic-rich black shales is assumed to be 0.1 mm/yr (1 Ma = 100 m of sediment). The compaction ratio of 1:10 (i.e. 1 m of primary sediment compacted to 10 cm of rock) was only considered for organic-rich black shale sediments.

Figure 15, specifically its "Main types of environments" column, shows the duration of accumulation of different sediment types (siliciclastic, carbonate, black shale) in various sedimentary environments for each regional stage. The duration of accumulation is expressed through the vertical size of the symbols corresponding to each sediment type. The vertical size is calculated based on actual sediment thickness and assumed accumulation rates.

Below is an example of this column for organic rich black shale sediments that accumulated in non-condensed depressions during the Semilukian regional stage (Middle

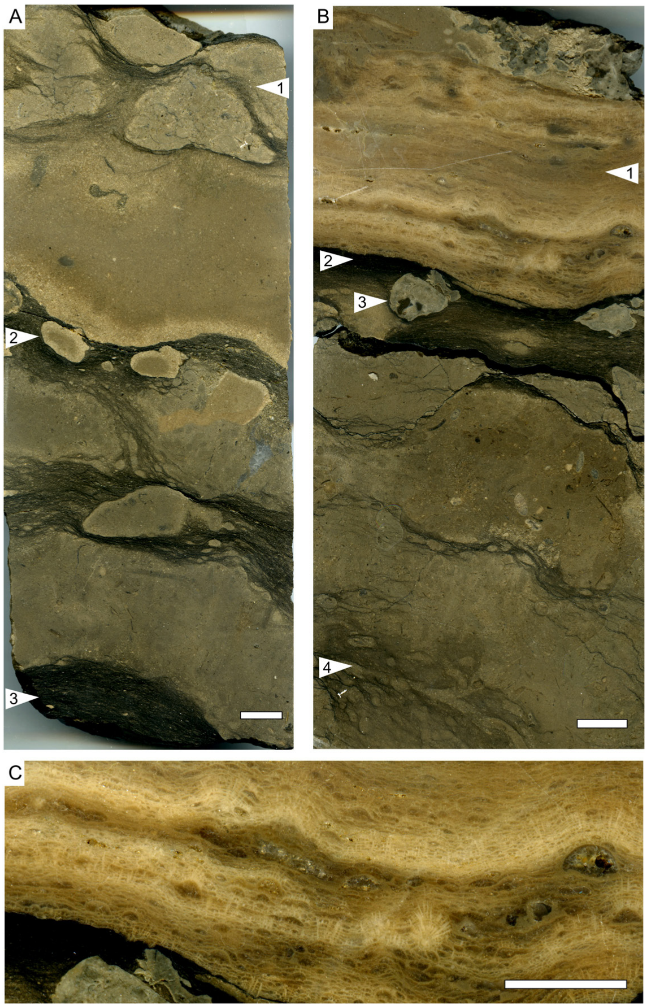

*Fig. 11. Limestones of the Upper Famennian (Zavolzhian regional superstage) interbedded with thin interbeds of organic-rich black shales: A) Microbial-stromatoporoid limestone with thin interbeds of black shales; interstices of deformed organic-rich black shales are observed between the carbonate nodules (1); deformation and compression of black shale layers probably formed as a result of post-sedimentation compaction; small microbial structures (2) are located in black shale interbeds (3); well 304**, Alkeevo, 1355 m; B, C) Microbial-stromatoporoid limestone; (B) Stromatoporoid framestone (1) coloured in brighter yellow-brown shades are located in the upper part of the sample; a thin layer of black shales (2) separates microbial (3) and stromatoporoid structures; large microbial structures are complicated by bioturbation and traces (4); (C) Stromatoporoid framestone (same sample; the fragment with magnification); well 304**, Alkeevskaya, 1355 m. The scale bar on all photos is 1 cm*

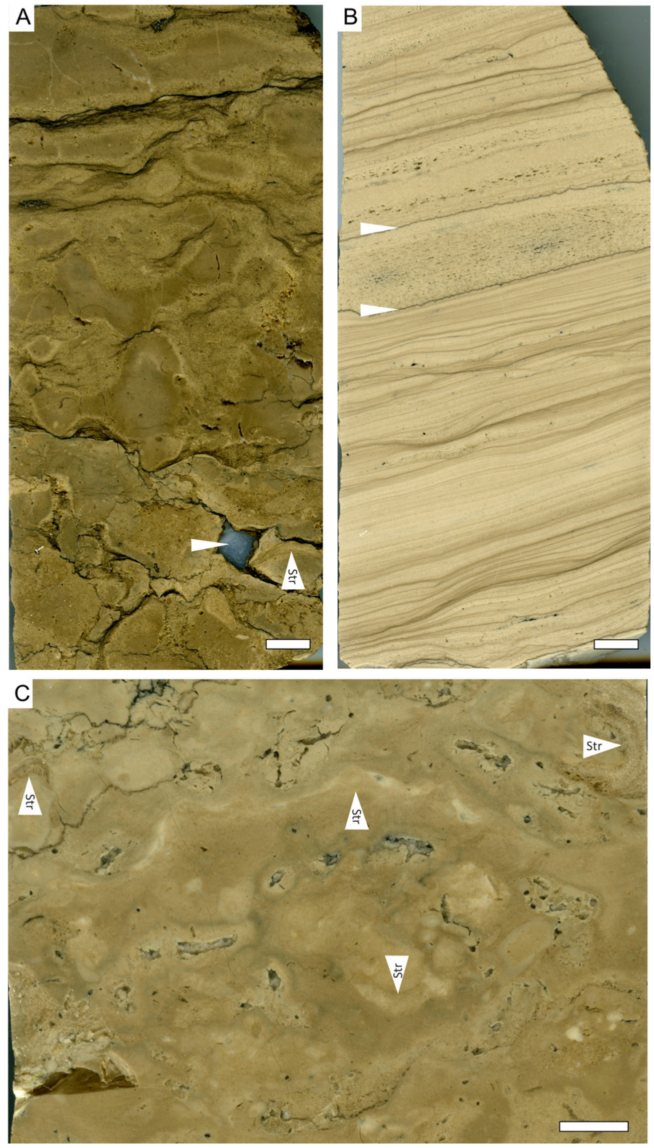

*Fig. 12. Limestones of the Upper Famennian, Zavolzhian regional superstage: A) Microbial-stromatoporoid (Str) limestone with anhydrite jointing (white arrow); lumpy-nodular structure of limestone probably formed as a result of post-sedimentation compaction; well 304**, Alkeevo; 1372 m; B) Sandstone-like limestone with horizontal lamination and stylolitic sutures (white arrows); well 304**, Alkeevo; 1354 m ; C) Microbial-stromatoporoid limestone; stromatoporoid structures (Str) are oriented in different directions, probably due to post-sedimentation compaction; borehole 42**, Sulinskaya, 1609 m. The scale bar on all photos is 1 cm*

Frasnian) (Fig. 15). The Semilukian in these sections averages 30 m. The compaction ratio of 1:10, which we adopted for black shales, increases this value by 10 times, i.e. up to 300 m of primary sapropelic sediment. The estimated duration for the accumulation of 300 metres of primary sapropelic sediment at an assumed rate of 0.1 mm/year (1 million years = 100 m) is 3 million years. Therefore, the vertical size of the icon in the column 'Main Types of Environments' indicating the accumulation of 30 m of Semilukian black shales (already compacted) corresponds to 3 Ma on the Chronostratigraphic Chart. Therefore, it appears that during the 3 Ma of the Semilukian regional stage, there was a continuous accumulation of Semilukian black shales in non-condensed depressions in the studied area.

Below we present a summary of our analysis regarding the duration of sediment accumulation across various sediment types.

The siliciclastic sediments, which have the highest accumulation rate, are characterised by the maximum discontinuity and irregularity in the chronostratigraphic record (Fig. 4). Despite of the total duration of siliciclastic sedimentation in the studied area of 16 Ma, the duration of accumulation of individual intervals (or geological bodies) of siliciclastic sediments varies from 100 Ka in shallow

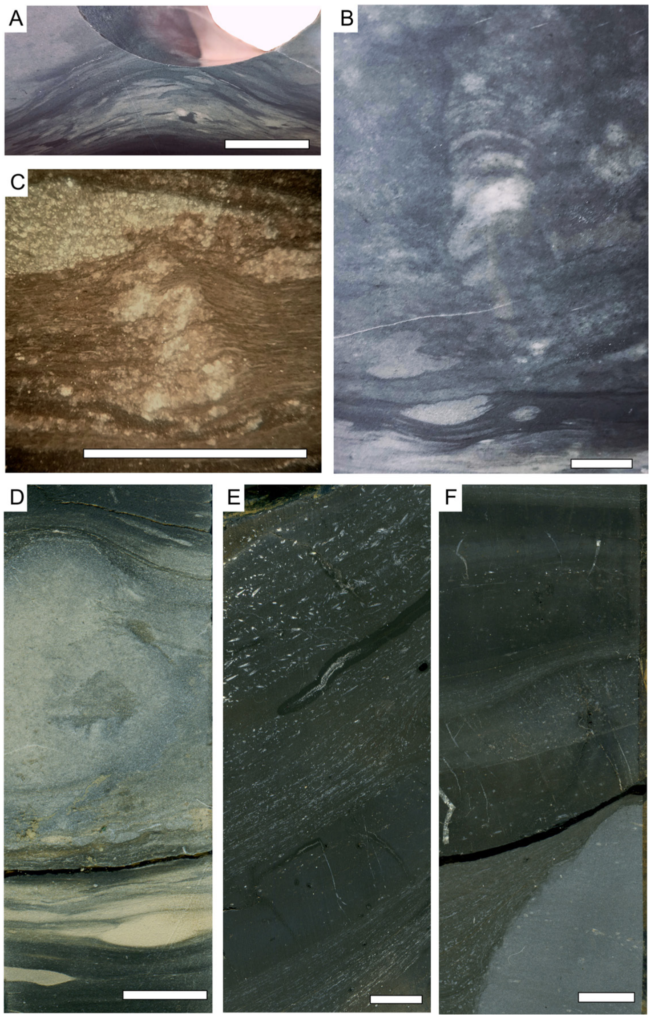

Fig. 13. *Organic-rich black shale and carbonate microbial bioherms: A, B) Stromatolite structures in microbial limestone; A) stratified stromatolite in the vertical section of the core; B) columnar-dome stromatolite (the same sample; outer surface of the core); well 14**, Pervomayskoye, 1478 m, uppermost layers of the upper Famennian, Zavolzhian; C) A columnar carbonate bioherm in thinly layered organic-rich black shale; a zigzag bend, probably caused by post-sedimentation compression, is notable; in the upper part of the image there is a pyrite concretion; well 19**, Bondyuga, 1391 m, uppermost layers of the Famennian, Zavolzhian; D) Microbial structures of different shapes and sizes in the vertical section of the core; well 14**, Pervomayskoye, 1479 m, uppermost layers of the Famennian, Zavolzhian; E) Carbonate-siliceous rock with high content of organic matter; an accumulation of tentaculitid shells in different orientation is noticed in the upper part of the sample; well 44**, Novo-Yelkhovo; 1643 m, Middle Frasnian, Semilukian; F) organic-rich carbonate-siliceous rock enclosing a microbial limestone bioherm in the lower part; well 4482, Novo-Yelkhovo; 1672 m, Lower Frasnian, Sargaevian. The scale bar on all photos is 1 cm*

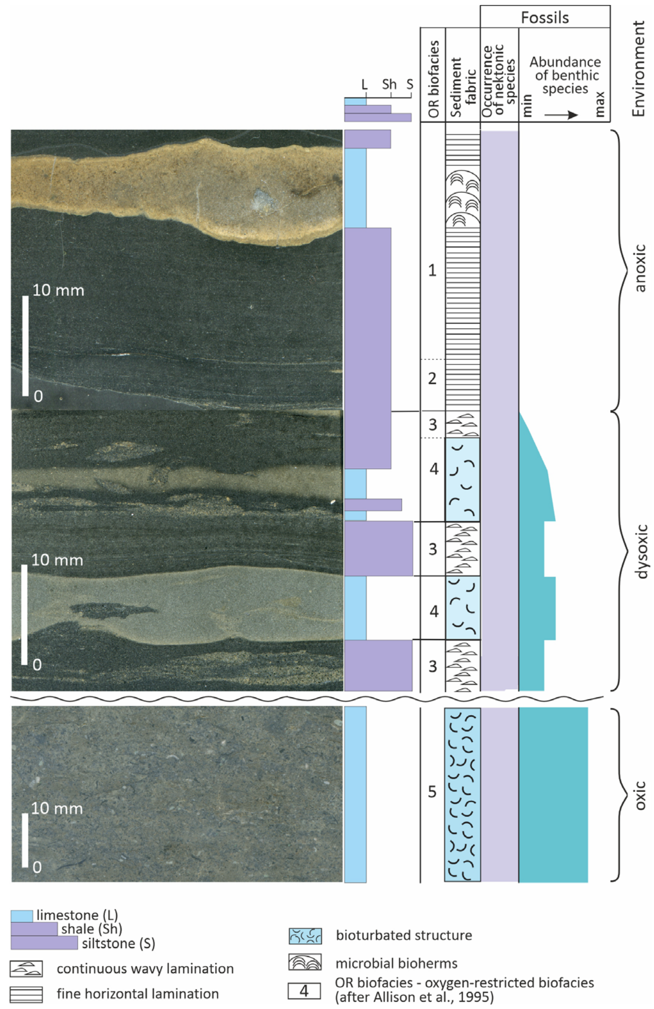

Fig. 14. *Example of lithological, sedimentological, ichnological and biofacial features in black shale cores of studied wells and interpretation of these features in terms of oxygen restricted biofacies (ORB) and oxic–dysoxic–anoxic environments (according to Flugel, 2010)*

water environments to 1 Ma in depressions. In all cases, both in shallow water and in depressions, the accumulations of siliciclastic sediments appear to be discrete events separated from each other by discontinuities. In the works of many researchers, the origin of siliciclastic sediments was associated with continental alluvial processes (Danilova, 2008; Loscheva et al., 2017). Meanwhile, recent studies (Silantiev et al., 2022; Miftakhutdinova, 2023) have confirmed the marine origin of these sediments and linked them to transgressive episodes of the Devonian marine basin.

Carbonate sedimentation in the studied area extended over approximately 36 million years, from the Late Emsian to the Late Famennian. Before the Frasnian, periods of carbonate sedimentation were relatively brief, not exceeding 1 Ma, and were often interrupted by shorter episodes (200–300 Ka) of organic-rich black shale accumulation. A notable shift to prolonged and stable carbonate sedimentation commenced in the Early Frasnian, initially affecting the slopes of depressions for up to 5 Ma. Subsequently, this sedimentation process expanded into the shallow water environments of tectonic arcs, lasting for up to 12 Ma during the Famennian.

Black shales accumulated in the studied area for about 29 Ma – from the Late Eifelian (Mosolovian Regional Stage) until the end of the Famennian (Fig. 15). During the Eifelian and Givetian, the accumulation of black shales represented short (200–300 Ka) episodes alternating with episodes of carbonate sedimentation, and was confined to depressions, their slopes, and basinal low-plains (see e.g., Mosolovian).

During the Late Eifelian, Givetian and Early Frasnian, the accumulation of certain black shale intervals correlates well with the Devonian global anoxic events (Gradstein et al., 2020). For example, the accumulation of Chernoyarian black shales correlates with the Late Eifelian Kacak event, the accumulation of Mullinian black shales can be linked to the Givetian Taghanic event, and a short episode of black shale accumulation in the Timanian (Early Frasnian) is associated with the Frasnes event (Fig. 15). The last two episodes of black shale accumulation are noteworthy for two reasons: (1) they are recorded not only in depressions, but also on their slopes, in shallower settings; (2) intervals of black shale accumulation are spatially closer to siliciclastic sediments rather than carbonate ones, as observed in the Eifelian and Upper Devonian. It should be noted that the above observations require further confirmation based on the biostratigraphy and radioisotopic dating. In the Middle-Late Frasnian and Famennian, such comparisons are obscured.

Prolonged and stable sedimentation of black shales has been observed since the Early Frasnian, with the formation of the Kama-Kinel trough system. Since that time, the sedimentation of black shales has occupied the deepest (axial) settings of depressions and no longer formed frequent alternations with carbonate sedimentation, which has spread to the slopes of depressions and shallow-water environments.

4.4. Accumulation of sediments in different environments

During the Middle and Late Devonian, the central part of the Volga-Ural province included three predominant types of environments: (1) non-condensed depressions, (2) slopes of depressions, and (3) shallow waters of tectonic arches. These environments were filled with various types of sediments at different intervals throughout the Devonian history.

Condensed and non-condensed depressions contain the most complete sequences of sediments. In the Eifelian, these sequences are represented by alternating carbonate and black shale sediments; in the Givetian, thick layers of siliciclastic rocks were added to them. In the Late Devonian, and more specifically from the beginning of the Middle Frasnian, these deep-water environments were occupied by the accumulation of organic-rich black shale sediments. Some regional hiatuses recorded in the sequences of depressions correspond well to global regressive events, particularly at the Eifelian-Givetian boundary, in the Late Givetian (at the base of the Mullinian), and at the Frasnian-Famennian boundary (Fig. 15).

Slopes of depressions throughout the Eifelian and Givetian represented environments in which sediments of all three main types were accumulated: siliciclastic, carbonate and black shale. On the one hand, this may indicate the complex geomorphological surface of the slopes, and on the other hand, it may indicate the conventional nature of the designation of this type of settings (indirect confirmation of the latter assumption is provided by the close values of thicknesses of slope and shallow facies). Only since the Frasnian, the slopes of depressions have become well separated from other environments, which is emphasised by the predominance of carbonate sedimentation.

Shallow waters of tectonic arches are distinguished from other environments by the maximum incompleteness of the geological record. During the Middle Devonian, these environments were the scene of short-term (100 Ka) transgressive episodes of siliciclastic sedimentation (Fig. 4). It should be noted, that in Fig. 15, each stratigraphic subdivision (Regional Stage) corresponds to only one episode of siliciclastic accumulation; however, in reality, there may be multiple such episodes. Secondly, the position of these episodes on the chronostratigraphic scale is shown only conditionally. At present, we lack the tools to solve these problems: to determine the number of episodes of siliciclastic sediment accumulation and their precise ages. Therefore, all correlations involving siliciclastic intervals of the succession are approximate.

5. Discussion

Fortunatova et al. (2016, 2018) considered the Upper Devonian sequences of the Volga-Urals petroleum province and provided a regional conodont zonation for the Frasnian and Famennian according to Ovnatanova and Kononova (2008), comparing it with the standard conodont zonation according to Gradstein (2004). We have used this comparison in this paper, extending the zonation to the Middle Devonian and adding a modern chronostratigraphic framework (Becker et al., 2020), which enables to estimate the duration of conodont zones and regional stages.

The designation of three predominant types of environments in the Middle-Late Devonian basin of the central part of the Volga-Ural Province: (1) condensed and non-condensed depressions, (2) slopes of depressions, and (3) shallow waters of tectonic arches (Aliev et al., 1978; Mkrtchyan, 1980) is supported by most contemporary researchers (Gatovsky et al., 2015; Fortunatova et al., 2016, 2018; Liang et al. 2015, 2020; Stupakova et al., 2015, 2017; Kabanov, Jiang, 2020; Kabanov et al., 2023a, b).

Many of the cited works consider essentially the Upper Devonian, i.e. the interval of the territory's evolution when the Kama-Kinel trough system was already formed, which intensified the difference in sedimentary settings (Fig. 2). In this regard, most of the researches (Fortunatova et al., 2016, 2018; Liang et al. 2015, 2020; Stupakova et al., 2015, 2017; Kabanov, Jiang, 2020; Kabanov et al., 2023a, b) limit the time of black shale sedimentation to the interval from the Middle Frasnian of the Late Devonian to the Tournaisian of the Early Carboniferous (Mississippian). In this paper, we point out that these sediments, which are considered as source rocks, were formed in the studied area in both the Late and Middle Devonian. Particularly, in the Middle Devonian, they were accumulated for at least 8 Ma and could have been deposited both in the axial zones of the depressions and on their slopes (Fig. 15).

Gorozhanina et al. (2019) suggest that the present narrow configuration of depressions in the Kama-Kinel trough system bounding the uplifted areas of tectonic arches appeared after the accumulation of the Devonian sediments and is related to tectonic (and neotectonic) movements. These authors consider the Late Devonian sedimentary setting as an extensive basinal low-plain with gentle shelf including shallow settings (about 20–50 m deep), deep settings (50–100 m deep), and depression settings (100–150 m deep). Our Middle Devonian data generally support this view, indicating that the accumulation of the main different types of sediments at that time occurred in approximately the same (or close) settings of the basin (see, e.g., Mosolovian, Vorobyovian, Mullinian, Fig. 15).

Below we briefly discuss some contradictions in the views on the accumulation settings of the Devonian black

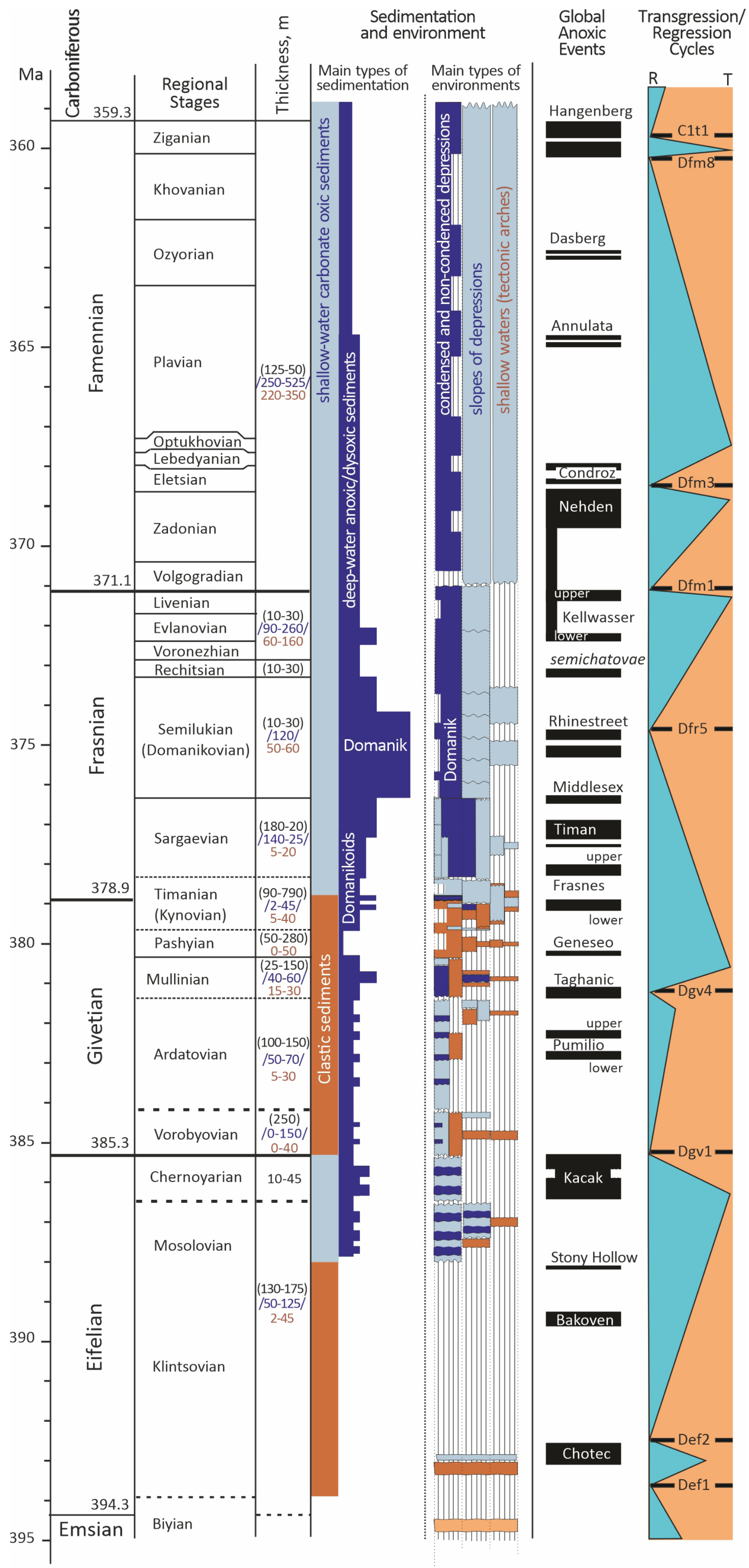

Fig. 15. Main types of Devonian sedimentation (siliciclastic, carbonate and black shale) and duration of sediment accumulation in the predominant environments of the Volga-Ural petroleum province, compared with global sequence of events and sea level history (highlighting major transgression/regression cycles). The data on sedimentation are updated from Kabanov, Jiang, 2020; Kabanov et al., 2023 a, b; while the global events and sea level history compiled from Becker et al., 2020. The width of the columns signifies the relative areal distribution of the sediments, the white breaks indicate the hiatuses in sedimentation. Thickness indications: black font in parentheses – condensed and uncondensed depressions; blue font in oblique brackets – slopes of depressions; brown font – shallow waters

shale sediments. For example, Stupakova et al. (2015, 2017; Karpushin, Stupakova et al., 2022) suggest that the accumulation of the Devonian organic-rich black shale sediments took place in relatively deep-water environments (100–300 m depth) predominantly under normal (oxic) gas regime conditions. The absence of sulphide contamination of bottom waters is justified by these authors by the wide distribution of sessile benthic invertebrates (bivalves, articulated brachiopods) and nektonic cephalopods (goniatites) sensitive to oxygen deficiency. Simultaneously, the same authors point out that geochemical data indicate periodic episodes of hydrogen sulphide contamination, as derivatives of isorenieratene, a biomarker of sulphide contamination of the photic layer, were found in a number of samples (Stupakova et al., 2017).

A similar opinion is expressed in a recent study by Liang et al. (2020), which defines the depositional environment of black shales as "the basin with normal salinity, normal oxygen regime and a depth of about 100 m..." (Liang et al., 2020, p. 8). Interestingly, in a previous paper by the same first author (Liang et al., 2015, p. 54), the Devonian organic-rich sediment accumulation setting was associated with a stagnant hydrodynamic regime and hydrogen sulphide contamination of bottom waters.

Many authors attribute the formation of sediments enriched in organic matter to the maximum level of basin flooding; and the formation of carbonate sediments, on the contrary, to basin regression (Stupakova et al., 2017; Chupakhina et al., 2022; Karpushin et al., 2022; Zavyalova et al., 2023).

Gatovsky et al. (2015) considering Middle Frasnian organic rich black shales noted that these sediments are oversaturated with organic matter, and this circumstance could be the reason for the complete absence of the oxidative zone of diagenesis and the development of benthic anoxic conditions. The authors attribute the accumulation of organic rich sediments to the periods of high planktonic bioproductivity, which resulted in the accumulation of thin interlayers of horizontally laminated sapropelic muds. Note that Wignall (1994) discusses the absence of true horizontal lamination in organic-rich sediments in detail. In turn, we note that the thickness of the primary Devonian sapropelic sediments could exceed hundreds of metres. The thickness of the first few tens of metres now documented in the geological record is the result of compaction of the primary sediment and an average tenfold reduction in its thickness.

In this paper, we accept the viewpoint of P. Kabanov et al. (Kabanov, Jiang, 2020; Kabanov et al., 2023a, b), who attributed the origin of organic-rich sediments to photic-zone euxinic conditions in the Devonian "greenhouse" shelf seas. Kabanov et al (2023a, b) hypothesised that variations in the concentration of hydrogen sulphide in the water column significantly impacted the facies structure of carbonate platforms and inter-platform anoxic troughs (Kabanov et al., 2023a). They identified slowed water circulation, euxinic upwelling, and increased eutrophication from rising river runoff as the main factors forming the stratified water column with a fluctuating chemocline (oxic-anoxic water layer boundary).

Photic zone euxinia means that the water in the photic zone (the upper layer of the basin where light sufficient for photosynthesis penetrates) is oxygen-deficient or completely oxygen-free, but at the same time saturated with hydrogen sulphide (H_2S). Under normal conditions, the photic zone is oxygenated (~5 to ~14 mg/l depending on temperature, salinity and pressure) due to the photosynthetic activity of phytoplankton, which use sunlight to produce oxygen. However, under euxinic conditions, even in this illuminated zone, anoxic (oxygen-deficient or oxygen-free) conditions prevail, resulting in the accumulation of hydrogen sulphide. This situation may result from an excessive input of organic matter, consuming substantial oxygen during accumulation, or from slowed water circulation, preventing oxygen influx from other water layers. Euxinic conditions in the photic zone seriously affect the ecosystem, as most photosynthetic organisms and many other marine animals cannot survive in anoxic and hydrogen sulphide conditions. Such conditions transform the structure of the marine ecosystem, resulting in diminished biodiversity and altered food chains. Evidently, these are the alterations observed in Devonian organic-rich black shales.

Kabanov et al. (2023a, b) emphasised that the extensive zones of minimal oxygen content in the Devonian 'greenhouse' ocean supported stratification (layering) of the water column of shelf seas, i.e. conditions in which heavier, salty and oxygen-poor water remained at depth, whereas lighter and oxygen-rich water stayed at the surface; stratification prevented mixing of water layers and oxygen exchange. This circumstance explains the formation of thick anoxic (oxygen-poor) sediments in oceanographically open conditions, especially in the basin of the Volga-Ural, which was open to the Ural Palaeocean.

The shallowness of hydrogen sulphide episodes in the water column is confirmed by the wide distribution of Chlorobi biomarkers in Devonian organic-rich sediments (Kabanov et al., 2023a, b). Chlorobi biomarkers represent a group of photosynthetic bacteria that inhabit the photic zone but perform photosynthesis under anoxic (oxygen-free) conditions, using sulfide as an electron donor instead of water. The presence of Chlorobi biomarkers in the Devonian organic-rich sediments suggests that hydrogen sulphide episodes were not restricted to deep waters, but also occurred at relatively shallow depths.

The shallow water chemocline in the extended oxygen minimum zone fluctuated with high frequency and probably suppressed the spatial expansion of carbonate accumulation, thus controlling the distribution of shallow and deep water facies (Kabanov et al., 2023a, b). These frequent changes in conditions may have prevented the expansion of carbonate sediments such as reefs or bioherms, which normally form under more stable and predictable conditions. As a result, such variable conditions influenced the general architecture of the seafloor, forming characteristic alternations of uplifts and depressions.

In general, the hypothesis proposed by Kabanov et al. (2023a, b) aligns well with models of sapropel accumulation in modern environments, particularly in the Mediterranean Sea. These models include two processes: (1) reduced or absent ventilation of the deep water due to stratification of the water column, leading to anoxic conditions at the seafloor and consequently to preservation and accumulation of organic matter; (2) enhanced primary production due to increased nutrient availability in the surface water (Emeis et al., 2000a, 2000b; Rohling, 1994; Warning, Brumsack, 2000).

The Middle Devonian siliciclastic sediments of the central part of the Volga-Ural province attract the attention of many researchers due to their high oil and gas content (Muslimov, 2008; Danilova, 2008). There are opinions about the formation of these sediments in continental alluvial and deltaic environments (Danilova, 2008; Loscheva et al., 2017, etc.). The detailed reviews of the composition and origin of these sediments considered in recent publications have proved their marine nature (Fortunatova et al., 2013; Silantiev et al., 2022).

We adhere to the viewpoint (Silantiev et al., 2022; Miftakhutdinova, 2023) that clayey-siltstone beds were formed in the conditions of the *Cruziana* Ichnofacies, localised between the levels of weak and storm waves. Sandy packs could have been formed in the *Skolithos* Ichnofacies, represented, most often, by well-sorted sands that had been constantly moved and subjected to sudden erosion or re-deposition (Mikulash, Dronov, 2006; Bromley, 1996). Accumulation of siliciclastic sediments of both clay-siltstone and sandy types occurred during marine transgressions, whereas regression of the sea led to erosion and destruction of the already formed sediments.

Figure 15 highlights a hiatus in the accumulation of black shale and carbonate sediments in the Late Givetian (Pashyian and lower Timanian); precisely during the deposition of the best and most widespread siliciclastic reservoirs. This hiatus requires further study and clarification. Attention should be focused on the Pashyian mudstones, which represent a marker bed in the middle of the sequence (Danilova, 2008). Recent data (Silantiev et al., 2022) indicate that these mudstones contain remains of soft-bodied fauna, impressions of conodonts and internal moulds of myospores. This fossil assemblage and its preservation indicate unusual anoxic (< 0.2 ml/l O_2, normally no O_2) or dysoxic (1.0–0.2 ml/l O_2) conditions for the formation of these mudstones. Finds of soft tissues of lingulids favour dysoxic conditions. Lingulid burrows of reduced length (5–10 mm instead of 50–70 mm) were also found here (Miftakhutdinova, 2023), indicating that the primary sediment was compacted.

6. Conclusions

Examining the sediment accumulation across various environments leads to the following conclusions.

1. Depressions and basinal low-plains exhibited nearly continuous accumulation of organic-rich black shales, alternating with carbonate sediments in the Eifelian and Givetian. This accumulation of source rocks spanned from the end of the Eifelian (Mosolovian; 388 Ma) to the end of the Famennian (359.3 Ma), covering approximately 29 Ma.

2. Environments on the slopes of depressions often experienced discontinuities in sedimentation, particularly during the Givetian. Notably, in the Eifelian (Mosolovian), Givetian (Mullinian and lower Timanian), and Lower Frasnian (Sargaevian), these settings accumulated organic-rich black shales. This might be attributed to significant organic matter formation under photic-zone euxinic conditions in basins of varying depths.

3. Shallow water environments were marked by the thinnest sediment layers and the longest sedimentation hiatuses. These hiatuses likely represent periods of prolonged sorting of sandy and silty sediments, typical of the Middle Devonian siliciclastic reservoirs in the study area.

4. Since the beginning of the Famennian, the distinctions between the slopes of depressions and shallow water environments have diminished, indicating a restructuring of the basin floor outside the axial zones of the Kama-Kinel trough system.

5. The results imply that correlating Devonian sequences in the central part of the Volga-Ural petroleum province should consider the accumulation rates of various sediment types and the incompleteness of the geological record in different environments.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Терригенное, карбонатное и черносланцевое осадконакопление: прерывистая непрерывность осадочных процессов в девонских ландшафтах Волго-Уральской нефтяной провинции

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Аннотация. Анализ трех основных типов осадконакопления – терригенного, карбонатного и черносланцевого (доманикитного) – выявил особенности их прерывистости и/или непрерывности в различных фациальных обстановках среднего и позднего девона центральной части Волго-Уральской нефтяной провинции. Эти обстановки включают как прогибы и их склоны, так и мелководные участки, расположенные на тектонических сводах или локальных биогермовых возвышенностях. Региональная зональность конодонтов, коррелируемая с Международной хроностратиграфической шкалой, подтверждает общую стратиграфическую полноту геологической летописи среднего и верхнего девона в данном регионе. Однако осадконакопление имело прерывистый характер, что позволяет говорить о так называемой «прерывистой непрерывности». В частности, накопление черных сланцев с высоким содержанием органического вещества, традиционно рассматриваемых как нефтематеринские породы, продолжалось более 29 млн лет – с позднего эйфеля до границы девона и карбона. Наиболее длительный перерыв в осадконакоплении черных сланцев (а также карбонатных осадков), составляющий около 2,5 млн лет, произошел в конце живетского яруса. Примечательно, что этот интервал включает наиболее продуктивные терригенные коллектора. В период с раннего эйфеля до раннего франа (около 17 млн лет) терригенные отложения демонстрируют максимальные скорости накопления и наибольшую прерывистость, вызванную кратковременными эпизодами морских трансгрессий. Одновременно в прогибах формировались наиболее полные последовательности, представленные карбонатными и черносланцевыми осадками. В фамене (около 12 млн лет) терригенное осадконакопление полностью прекратилось, что привело к стабильному накоплению карбонатных осадков на склонах депрессий и в мелководных зонах; одновременно в глубоких осевых частях прогибов продолжалось осаждение осадков с высоким содержанием органического вещества. Результаты подчеркивают, что типы осадконакопления, существовавшие в разных ландшафтах девонского морского бассейна, характеризовались сложными пространственными взаимосвязями и различной полнотой геологической летописи.

Ключевые слова: Волго-Уральская нефтяная провинция, девон, черные сланцы, карбонатные осадки, терригенные осадки, скорость осадконакопления, обстановки

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