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Assessment of the influence of lithofacies conditions on the distribution of organic carbon in the Upper Devonian "Domanik" deposits of the Timan-Pechora Province

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Abstract. The study of high-carbon formations was instigated both by the decreasing raw material base of oil as a result of its extraction, and by the progress in development of low-permeability shale strata, primarily in the USA, Australia, and China. The most valuable formations occur in traditional hydrocarbon production areas – the West Siberian, Volga-Ural and Timan-Pechora, North Pre-Caucasian and Lena-Tunguska oil and gas provinces. Specific features of the Late Devonian-Early Carboniferous high-carbon formation occurring in the eastern marginal part of the East European Platform are: heterogeneous section due to intense progradation of the carbonate platform from west to east; succession of lithofacies environments that determined the unevenness of the primary accumulation and secondary distribution of organic matter (OM); possible migration or preservation in the source strata during the subsidence stages of the moving parts of bitumides, which determined the prospects for oil and gas potential. The distribution pattern of the present OM content was investigated depending on lithofacies conditions and lithological composition of rocks in the "Domanik type" Upper Devonian-Tournaisian deposits in the Timan-Pechora Province (TPP), its transformation degree to bring it to the initial content of organic carbon and further estimation of the share of stored "mobile oil" in oil and gas source formation. The study was based on the analysis of the data set on organic carbon content in core samples and natural exposures in the Ukhta Region in the Domanik-Tournaisian part of the section including more than 5,000 determinations presented in reports and publications of VNIGRI and VNIGNI and supplemented by pyrolytic and bituminological analyses associated with the results of microtomographic, macro- and lithological studies and descriptions of thin sections made at the Saint Petersburg Mining University. For each tectonic zone of the TPP within the investigated high-carbon intervals, the content of total volumes of organic carbon was determined. The data obtained allow estimating the residual mass of mobile bitumoids in a low-permeability matrix of the high-carbon formation.

***Keywords*:** Domanik type deposits; facies; formation; organic matter; sedimentary basin; lithological type; hydrocarbons; oil; gas

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Introduction. Advances in technologies for developing hydrocarbons (HC) from unconventional (low-pore and low-permeability) reservoirs raised the interest to the study of high-carbon shale formations widespread in Russia [1, 2]. The most significant of them are in the West Siberian oil and gas province (OGP) – the Bazhenov Formation (upper part of the Jurassic – lower part of the Cretaceous), Timan-Pechora and Volga-Ural – Domanik (Upper Devonian – Lower Carboniferous), North Pre-Caucasian – Khadum Formation (Oligocene Maikop Series) and Lena-Tunguska – Kuonam Formation (Lower-Middle Cambrian) (Fig.1).

Bazhenov Formation in Western Siberia is the most adequately studied formation in Russia. Ranking second in importance is a complex of sediments including the Domanik (Semilukskii) Horizon and its younger facies analogues (up to and including the Tournaisian stage of the Carboniferous), widespread within the Volga-Ural and Timan-Pechora sedimentary basins [3-5].

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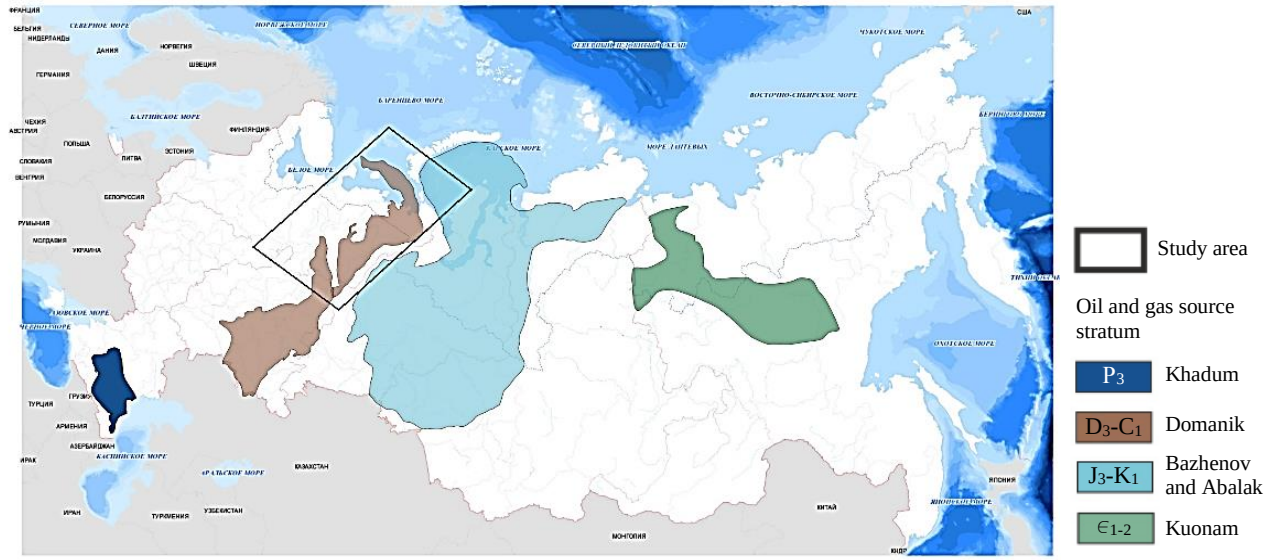


Fig.1.Distribution of the main high-carbon shale formations in Russia

Characteristic features of the Domanik Formation [3, 6, 7]:

• high values of organic matter (OM) (in some layers, C_{org} reaches 25 % for the Middle and Upper Frasnian, 5-8 % for the Lower Famennian, and 3-5 % for the Upper Famennian-Tournaisian;

• the degree of catagenesis ranges from proto- to apocatagenesis depending on location of a particular area and the history of the sedimentary basin subsidence.

The extraction of HC raw materials from the shale-type reservoirs, despite being widespread, is essentially not carried out in Russia [8, 9]. All most frequently discussed examples of the development of both "Bazhenov" and "Domanik" most often do not directly refer to clayey, siliceous-carbonate-clayey reservoirs of low quality, but are the development of deposits that are stratigraphically coeval with the "Domanik type" deposits (in the terminology of S.G.Neruchev) or individual interlayers represented by carbonate (radiolarite) or siliceous-carbonate facies of predominantly organogenic origin. The areas of fractured reservoirs forming due to certain reasons are also developed [9, 10].

Formulation of the problem. The residual potential of the high-carbon formation is determined by the initial concentration of OM in the rock and its catagenetic maturity [7, 10]. The emergence of effective reservoirs in rocks is associated both with sedimentation, diagenesis, and subsequent epigenesis including that determining the emergence of a void space formed by the OM proper [11, 12], which determines the necessity to conduct geochemical studies in assessing the resources and reserves. Among the main tasks, the solution of which makes it possible to assess the HC potential of the high-carbon strata, is the OM distribution over the area and in the section, determination of its transformation degree and the void space occupied by the mobile HC [9, 10, 13]. A considerable number of studies were devoted to the current distribution of the OM with averaging of data from laboratory studies of individual samples for the entire strata or with reference to the most significant level in the Timan-Pechora Province (TPP) – the Domanik Horizon as well as the assessment of its catagenesis [14-16]. At the same time, no due attention was paid to a detailed analysis of the distribution of these indicators, considering the lithofacies features and lithological types of the section, since the dominant approach in compiling the sketch maps and maps was the averaging of the obtained laboratory values of C_{org} content to the thickness of the high-carbon part of the section. This significantly distorted the total indicators considering the uneven content in the section, as evidenced by the detailed correlation of geochemical indicators and a purely subjective point associated with taking the most OM enriched rock varieties for the analysis.

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The most representative studies for modelling the HC hydrocarbon potential can be the studies aiming at detailed correlation of data of OM geochemical studies (distribution of organic carbon in the section and on area, assessment of the OM transformation degree) depending on lithofacies characteristics [7, 17] with determination of the association of zones with elevated OM concentration with certain lithotypes of rocks identified within the Middle Frasnian-Tournaisian part of the section of the Timan-Pechora sedimentary basin (TPSB).

Research methodology. To obtain the parameters for assessing the HC resources of "residual oil", geological field work and laboratory studies were conducted making it possible to significantly clarify and supplement the data on the occurrence, distribution in the section, lithotypes, geochemistry of OM, porosity and permeability of the Domanik deposits and their equivalents within the sedimentary basin. Such clarification can have a significant impact on the assessment of own potential of high-carbon Domanik Formation, as it will provide an idea of the extent of HC generation and a possibility of preserving their non-migrating part generated by the oil and gas source HC strata.

The most effective basis for balance estimations is the use of dependencies obtained by S.G.Neruchev, E.A.Rogozina and T.K.Bazhenova when developing the balance method of oil and gas formation [3, 7]. The main trend of research is to refine the maps of lithofacies zonality and thickness of the Domanik-Tournaisian complex [18-20], the distribution of OM concentrations and the assessment of catagenesis [3, 5, 16] with resolving the problem of identifying the geochemical and lithological heterogeneities of the section for distinguishing the main types of organic carbon distribution in representative sections.

The work methodology comprised a series of successive procedures including clarification of the features of geological structure of the section intervals of high-carbon strata in the Upper Devonian (Middle Frasnian-Famennian) and the Tournaisian (Carboniferous) classified as the main oil and gas producers in the two provinces – the Volga-Ural and the Timan-Pechora taking into account their geochemical and petrophysical features. These successive steps included:

• identification of characteristic features for assigning to high-carbon deposits of the "Domanik type" based on geophysical surveys of wells;

• determination of the stratigraphic occurrence interval of sediments primarily enriched in OM and attributed to the "Domanik type" (according to section descriptions, characteristic features, and the study of thin sections);

• determination of the occurrence area of each of the identified stratigraphic units classified as "Domanik type" deposits;

• determination of lithological composition (microscopic and petrographic studies of thin sections) and lithological typification of "Domanik type" deposits;

• assessment of geochemical features (laboratory study of bitumoid extracts and pyrolytic studies of core samples), OM distribution and transformation degree in high-carbon "Domanik type" deposits, association with various lithological types and zones differing in the facies conditions of formation;

• assessment of petrophysical (porosity) parameters of the distinguished lithotypes in "Domanik type" deposits;

• identification of typical geochemical sections for all facies zones and stratigraphic intervals of "Domanik type" deposits occurrence;

• compilation of maps of modern concentration of organic carbon and catagenetic maturity of OM based on bituminological and pyrolytic studies.

Actual data. As the basis of the study to solve the problems of identifying the geochemical and lithological inhomogeneities of the section, identifying the main types of the section and the distribution of organic carbon, the maps of lithofacies zonality and thickness of the Domanik-Tournaisian complex [18-20], OM concentrations and the degree of catagenesis were used [3, 14], field geophysical data from wells that penetrated the above deposits in the TPSB (more than 350 wells) with

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reference to the main identified lithotypes in the interval of the Domanik-Tournaisian deposits (separately for the Domanik, Upper Frasnian-Lower Famennian and Famennian-Tournaisian parts of the section). To get an idea of the main types of the section, natural exposures, and to clarify the OM distribution by lithotype and section, the geological field work was conducted in the Ukhta Region (Komi Republic) with sampling (300 pcs.). Sections of more than 30 wells that penetrated the Upper Frasnian-Famennian-Tournaisian deposits at depths from 2,500 to 4,300 m were studied with the selection of core samples (from 10 wells – more than 200 samples), macro- and microscopic studies of samples and thin sections were performed at the Department of Oil and Gas Geology at Saint Petersburg Mining University (more than 400). The correlation of deep drilling materials and seismic exploration work was accomplished for three reference areas with identification of characteristic units of different facies zones in the studied part of the section (in the central Izhma-Pechora Depression, southern Denisovskii Trough, and the Khoreiver Depression). The above materials provided by E.I.Grokhotov, Al.Av.Otmas, O.M.Prishchepa were obtained as part of research on the state budget themes for the study of the Upper Devonian reefogenic units in the TPP in 2016-2017.

To clarify the geochemical indicators, state-of-the-art laboratory geochemical studies of high-carbon Middle Frasnian-Tournaisian strata were carried out (pyrolysis using Rock-Eval technology, determination of vitrinite reflectivity) on 100 samples from rock exposures in the vicinity of Ukhta [5, 21] and on 210 core samples (collection of O.M.Prishchepa, A.V.Kuranov, E.I.Grokhotov) in the laboratories of INGG SB RAS, Novosibirsk, Moscow State University and VNIGNI (with the assistance of A.E.Kontorovich, T.K.Bazhenova, M.V.Dakhnova).

At the Saint Petersburg Mining University, the lithological study and the description of thin sections (400) were accomplished to determine the mineralogical composition and structural and textural features as well as geochemical (pyrolytic according to the Rock-Eval method) studies of 310 samples, bituminological (chromatographic) studies of bitumoid extracts (70 extracts), microtomographic studies of core (120 primary undestroyed samples, 70 secondary undestroyed samples after extraction).

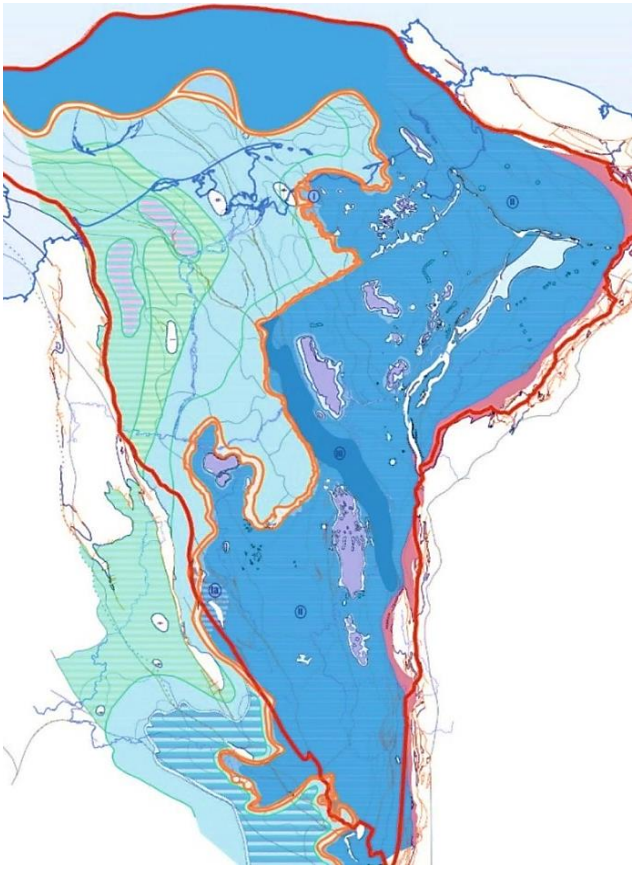
The data set on the content of organic carbon within the Domanik-Tournaisian part of the section amounted to over 5,000 determinations compiled into the database of the content of organic (non-carbonate) carbon in the TPP [22]. The basis of the data set were the results of laboratory studies accumulated from 1970 to 2016 including over 4,000 determinations of organic carbon and bituminological indicators presented in VNIGRI and VNIGNI reports and summarized in papers [3, 7].

Occurrence and facies composition of Upper Devonian-Lower Carboniferous deposits. The main tectonic event that determined the accumulation of the high-carbon formation was the subsidence of the basin that started in the Late Devonian within the Timan-Pechora OGP [23, 24]. The rock complex enriched in OM (assigned to “Domanik type” deposits or Domanikoids) is represented by deposits from the Domanik Horizon of the Middle Frasnian (the upper series of the Devonian system) to the Lower Tournaisian (the lower series of the Carboniferous system) [5, 18, 25]. A characteristic feature of the complex is facies variability caused by a succession of sedimentation environments under conditions of uncompensated subsidence of the sedimentary basin. An abrupt facies variability and thickness changes are recorded confirming the roughness of the basin floor (grabens and ledges) during sedimentation. This pattern is emphasized when tracing the age of reef formation at the shelf margin, which is successively rejuvenated from west to east in the basin [25, 26]. The Precambrian margin of the East European Craton [19, 27, 28] is considered as the western limit of the Domanik-Tournaisian carbonate platform forming on shallow shelf.

In most of the large tectonic zones of the basin characterized by uncompensated downwarping (ancient rift structures of basins and troughs), conditions favourable for the accumulation of high-carbon formations persisted for a long time. In these structures, the thickness of the formation also sometimes reached or exceeded 200 m. The thickness of the high-carbon part was to 60-80 m. On the

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shelf slopes, where the Domanikoids formed during the Middle-Late Frasnian and Famennian, the thickness of the strata can reach 100 m or more, the thickness of high-carbon layers is up to 30 m [15, 29]. Early Frasnian time is characterized by an extensive occurrence of clayey and carbonate silts forming in an open shelf sea basin with the absence of clastic sediments [14, 30]. In Late Frasnian time, the Timan-Pechora Basin developed from the maximum transgression in Domanik time – the beginning of regression in the Late Frasnian to the maximum regression by the end of the Tournaisian [31, 32], which can be recorded by a successive analysis of sections from the Middle Frasnian to the Tournaisian. Formation of the Domanik deposits proper is associated with an active transgression of the sea basin from the Paleo-Urals to the adjacent platform areas. In the mid-Frasnian, zones of relatively deepwater shelf emerged in the south of the Pechora-Kolva aulacogen, Khoreiver Depression and Varandei-Adzva structural zone associated with an open sea basin in the territory of the Ural-Pripaikhoi Paleobasin (Fig.2) [14, 31, 33].



Depositional environment	Facies zones	
Closed and semi-closed water bodies (lagoons, bays and estuaries)	Zone with mixed sedimentation and increased salinity	
Coastal-tidal (littoral)	With terrigenous (clastic) sedimentation	
Shallow shelf	Coastal shelf strip with bioclasts, oolites, carbonate breccias	
	Back-reef plain, back-reef shelf	
	Barrier reef massifs (barrier reef buildups and their shelves)	
Moderate deepwater-shelf	Clay-siliceous-carbonate (Domanikoid)	
	Banks, atolls, reefs	
	Intra-atoll lagoon with dolomites and evaporites	
	Intra-atoll lagoonal organogenic structures	
	Terrigenous, including prodelta	
	Clay-carbonate	
Deep sea-shelf	With clay-carbonate accumulation	
Sediment-free zone		

Facies conditions within moderate deep-water basin with uncompensated clay-siliceous-bituminous-carbonate sedimentation

I Domanik facies of the Domanik Horizon at a depth to 100 m occurring along barrier reefs

Ia Domanik facies of the Domanik Horizon at a depth to 100 m in the zone of partial compensation of developing troughs

II Domanik facies of the Domanik Horizon at a depth to 100 m

III Domanik facies of the Domanik Horizon in partially compensated troughs at depths to 100 m

Timan-Pechora Province

Coast

Fig.2. Lithofacies of the Domanik-Sirachoiskii horizons (Middle and Upper Frasnian) of the Upper Devonian of the Timan-Pechora sedimentary basin

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The sea basin first covered all the depressions inherited from the earlier aulacogenic development stage of the region, and by the beginning of Middle Frasnian (Domanik) time of the Late Devonian, an uncompensated sedimentation regime set in over most of the Timan-Pechora Basin (Fig.3, 4) [14]. The emplaced clayey and clay-siliceous deposits of Domanik were synchronous with the reef shelf deposits of the carbonate platform. They are represented by thin-layered dark-coloured siliceous mudstones, limestones and marls with calcareous, siliceous, phosphate and pyrite nodules, which occur in reference sections of the Izhma-Pechora Depression and the Pechora-Kolva aulacogen (Fig.4). The lithological composition of rocks in the Domanik deposits is highly diverse. These are limestones (Pteropoda with abundant goniatites; polydetritic; fine-grained with radiolarians; siliceous), siliceous marls and mudstones, silicites [34]. One of characteristics of the material composition of the Domanik Formation is a high proportion of silica. This feature is also typical for many sections of the Volga-Ural sedimentary basin, which, according to S.V.Maksimova [34], T.K.Bazhenova et al. [3], T.A.Kiryukhina et al. [35], can result from the supply of sedimentary material from the East Ural Basin. Up the section from the Domanik, the overlying horizons comprise section intervals with interlayers of high-carbon varieties; however, they have a local occurrence determined by the facies environments in the marginal part of the carbonate platform.

The occurrence depth of the Domanik, according to different points of view, is 100-200 m (rarely 400 m) under conditions of low sedimentation rates and a high sea level [7, 36, 37]. Modern studies indicate possible shallower formation depths of Domanik deposits [6, 38]. The eastward monoclinal tilt of the ramp towards the paleoocean that existed in the place of the Urals led to advancement of the western margin of the shelf with a successive eastward sea regression, and the area filled with deep sea mudstone strata reduced significantly [19, 39]. Even within the same exploration area wells often penetrated both a purely carbonate (reef) type of section as well as clastic aprons, back-reef facies and filling strata.

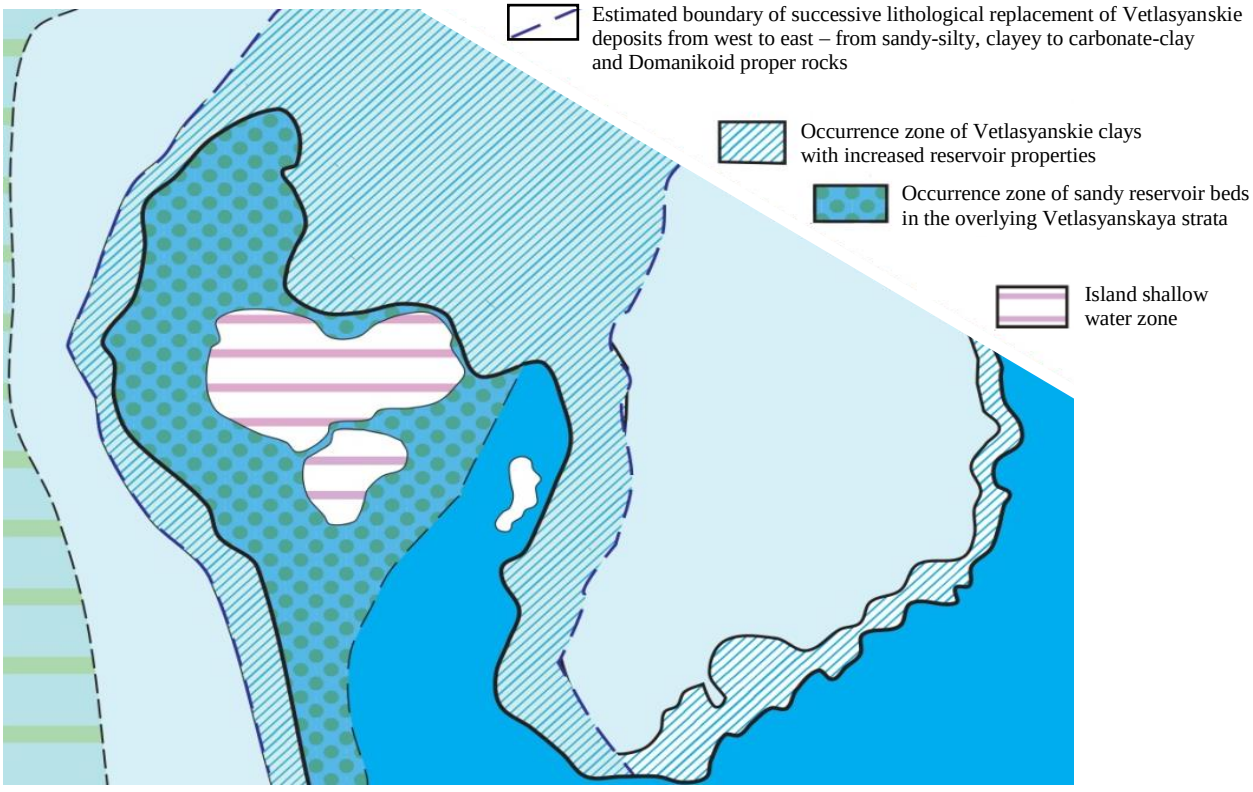
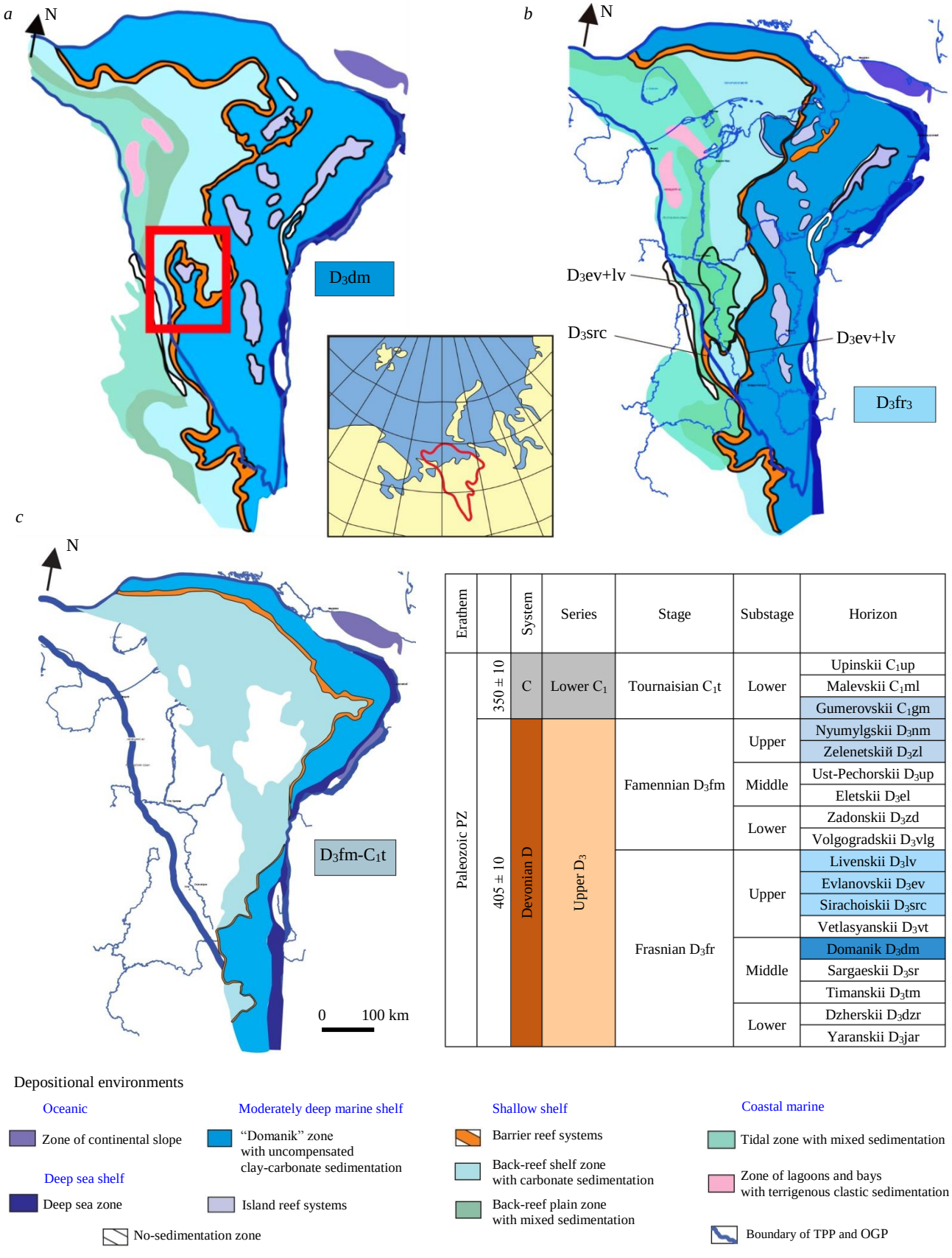


Fig.3. Lithofacies model of the Domanik-Vetlasyanskii horizons (Middle and Upper Frasnian) of the Upper Devonian in the central Izhma-Pechora Depression ([19, 23] with clarifications)

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Erathem		System	Series	Stage	Substage	Horizon
Paleozoic PZ	350 ± 10	C	Lower C_1	Tournaisian C_1t	Lower	Upinskii C_1up
						Malevskii C_1ml
						Gumerovskii C_1gm
	405 ± 10	Devonian D	Upper D_3	Famennian D_3fm	Upper	Nyumylgskii D_3nm
						Zelenetskiй D_3zl
					Middle	Ust-Pechorskii D_3up
						Eletskii D_3el
					Lower	Zadonskii D_3zd
						Volgogradskii D_3vlg
				Frasnian D_3fr	Upper	Livenskii D_3lv
						Evlanovskii D_3ev
						Sirachoiskii D_3src
						Vetlasyanskii D_3vt
					Middle	Domanik D_3dm
						Sargaeskii D_3sr
						Timanskii D_3tm
					Lower	Dzherskii D_3dzr
						Yaranskii D_3jar

Fug.4. Lithofacies of the Domanik Horizon (*a*), Upper Frasnian and Upper Famennian (*b*), Lower Tournaisian (*c*) of the Timan-Pechora sedimentary basin (occurrence of the zone of uncompensated downwarping with accumulation of clay-carbonate OM-enriched "Domanik type" deposits [16, 19, 20]. Red rectangle shows the study area

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Distribution of high-bituminous deposits. High-carbon formation within the TPSB is most often limited from below by the base of depression deposits of the Domanik Horizon. The top of the high-carbon formation is drawn, as a rule, along the base of the overlying carbonate or clayey rocks for each corresponding interval [3]. Above the Domanik deposits along the section, the Upper Frasnian-Lower Famennian and Tournaisian deposits are widespread to varying degrees enriched in dispersed OM with thicknesses reaching 500 m [7, 40], which is significantly greater than that of the Domanik. It was ascertained that in one part of the TPSB the high-carbon strata formed only in the Middle Frasnian; in the other one, in the Middle-Late Frasnian-Early Famennian; in the limited eastern part – in the Middle Frasnian-Early Tournaisian (Fig.4). The thickness of the strata varies from 10-20 to 140-150 m. Thicker sections (to 140 and even to 300 m) accumulated in the conditions of a carbonate platform on the sea shelf, and in the larger carbonate part of the complex section; oil source rocks are often characterized by a low content of organic carbon or its complete absence. In the north-west of the sedimentary basin lying on land and adjacent waters, there is an area without Domanik type deposits (see Fig.3, 4). In the sections of wells in the northern Izhma-Pechora Depression, the Malozemelskaya-Kolguev Monocline and in exposures of Northern Timan, the Domanik-Tournaisian complex is represented by terrigenous strata of alternating siltstones, mudstones and clays with rare interlayers of coarser-grained rocks. In the wells to the east and north, interlayers of marl and carbonates appear, and lithofacies of transition zones to the shallow-marine shelf are also recorded (Fig.4).

Features of the influence of paleoanoxic events on the OM accumulation in carbonaceous marine sediments were recorded [41, 42]. Arylcarotinoid derivatives found in bitumoids of the Domanik deposits in the Pechora Basin point to anoxia of the photic layer of paleobasin waters. Dissolved hydrogen sulphide interacts with lipids and carbohydrates of the source OM forming a wide range of soluble and high-molecular sulphur compounds. The structure of kerogen in the Domanik deposits is saturated with sulphur-bound lipid fragments [6, 11, 43]. The Domanik Horizon was most widespread in the sedimentary basin in the pre-Late Frasnian [15, 23, 40]. Later, the occurrence area of Domanik type deposits narrowed – its outer boundary coincided with the occurrence boundary of the most ancient filling stratum – the Vetlasyanskaya Formation. In Famennian, bituminous shales continued to form in marginal parts of the sedimentary basin in the east. Their occurrence area was controlled by marginal slopes of the Late Famennian barrier reef systems (see Fig.3). Overlying deposits of relatively deep-water facies, the equivalents of Domanik, were well studied in both shallow and deep wells. Among the most important conclusions is a much lower C_{org} content in rock, if the entire section is considered, which is discussed in many papers [35, 44, 45].

In each of the above stratigraphic intervals of the "Domanikoid" part of the formation (according to the classification of T.K.Bazhenova [46]), isolated intervals with a higher content of organic carbon were found. The highest values were recorded for the Tournaisian deposits of the Dzhebol'skaya step – to 4.9 %. Average C_{org} content in clays and mudstones in the filling strata was 0.34 % for 22 samples, which in general differs slightly from the content in the deep sea Famennian sediments.

Identification of lithological rock types from well cores. Macro- and microscopic studies of the core from the Upper Devonian deposits allowed identifying the lithological rock types, the formation of which reflects the paleohydrodynamic sedimentation conditions of facies environments. The main criteria that made it possible to combine rocks into lithological types are the material composition, structural and textural features as well as secondary transformations [21, 47]. Examples of the identified lithological rock types are shown in Fig.5.

Systematization of lithological rock types into genetic groups of deposits. In order to get an idea about the facies environments of sediment accumulation which determine the possibility of OM accumulation and concentration, 11 lithological rock types were characterized which were combined into lithological genetic groups of deposits (6 groups) according to the classification developed for the reef and the associated sediments (according to the materials of V.D.Ilyin and N.K.Fortunatova with supplements by V.I.Bogatsky [15, 20, 30]).

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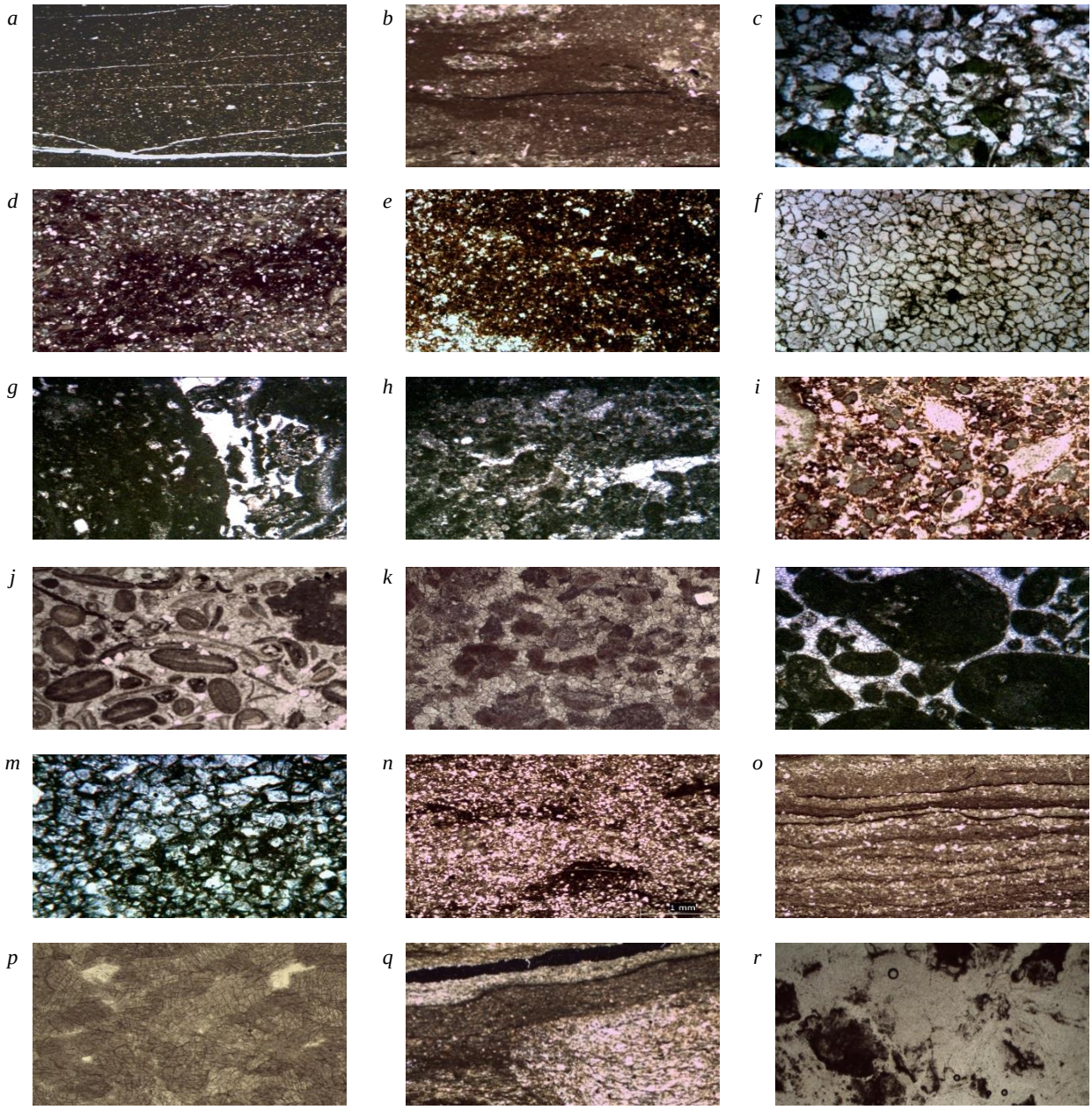


Fig.5. Examples of the main identified lithological rock types in the Domanik-Tournaisian part of the section in the Timan-Pechora sedimentary basin

a – mudstone with terrigenous material (to 5-7 %), intensely fractured (Severo-Komandirshorskaya-2 well, D_3dm); *b* – marl with lenses enriched in terrigenous material (Dvoinikovaya-1 well, D_3el); *c* – coarse-grained siltstone. Clastic part of rock is represented by quartz grains. Clay-carbonate cement (Srednekharyaginskaya-144 well, D_3ev+lv); *d* – fine-grained siltstone, clay-carbonate, intensely ferruginized (Severo-Komandirshorskaya-13 well, D_3ev+lv); *e* – fine-grained siltstone with clay-carbonate cement (to 15-20 %), with zones of intense carbonatization, slightly fractured (outcrop N 8 D_3dm); *f* – fine-grained sandstone fine-grained with carbonate, clay-carbonate cement, dense in places, quartzite-like, porous in places (Severo-Komandirshorskaya-2 well, D_3nm); *g* – algal limestone with stromatolite structure (Severo-Komandirshorskaya-13 well, D_3ev+lv); *h* – clotted-lumpy limestone, algal, with scattered spherical algae (Komandirshorskaya-2 well, D_3src); *i* – clotted-lumpy limestone with rare and large organogenic detritus, with an admixture of terrigenous material, unevenly ferruginized (Moroshkinskaya-31 well, D_3ev+lv); *j* – organogenic limestone, granular (oolitized) with calcite cement and an admixture of terrigenous material (Dvoynikovaya-1 well, D_3vg+zd); *k* – fine-to-coarse-grained limestone, recrystallized, irregularly spotty-dolomitized with clotted-lumpy formations, irregularly sulphated through the pores (1 %) (Severo-Salyukinskaya-1 well, D_3vt+ src+ ev+ lv); *l* – lumpy-clastic limestone (lithoclastic) with organic remains, dolomitized, with calcite cement (Severo-Komandirshorskaya-2 well, D_3zd); *m* – carbonate-clay rock, dolomitized (to 45 %), with abundant dolomite grains and a layer-wise admixture of quartz grains. Granular structure (Severo-Komandirshorskaya-13 well, D_3ev+lv); *n* – terrigenous-carbonate rock with isolated clayey segregations, uniformly ferruginized (Moroshkinskaya-31 well, D_3zd); *o* – pelitomorphic limestone with numerous clay veinlets pigmented with iron hydroxides (Moroshkinskaya-31 well, D_3ev+lv); *p* – medium-grained dolomite, in places to coarse-grained, clayey ~10-12 %, with large pyrite segregations ~2-3 %. The structure is granular, mosaic (Srednekharyaginskaya-144 well, D_3ev+lv); *q* – anhydrite-dolomite rock, clayey, lens-shaped-layered (Severo-Komandirshorskaya-13 well, D_3ev+lv); *r* – fibrous anhydrite with residual fragments of pelitomorphic clay-carbonate rock (Moroshkinskaya-31 well, D_3ev+lv)

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According to predominance of the main rock type in the section as well as considering the carbonate content determined by laboratory studies, all the analytical results were grouped into six enlarged rock types (mudstones, limestones, marls, siltstones, silicites, and sapropelites) in the section interval from the Middle Frasnian (Upper Devonian) to the Tournaisian (Lower Carboniferous). These types (lithotypes) are characterized by major differences in the content of organic carbon according to laboratory determinations, even within single or border lithofacies zones. The results of C_{org} distribution in the lithological stratigraphic units for all age intervals of "Domanik" deposits: Middle Frasnian (Domanik Horizon D_3dm_1, D_3dm_2, D_3dm and undivided D_3dm+src); Upper Frasnian; Lower Famennian (Evlanovskii-Livenskii and Zadonskii horizons); Famennian (Middle and Upper Famennian) and Lower Carboniferous (Tournaisian) – also showed major differences in concentration.

Type sedimentation environments of the Upper Devonian reefogenic deposits were distinguished within the investigated reference areas in the TPOGP.

The shelf subformation, described in detail in the work of T.D.Shibina [30] comprised genetic groups of coastal-marine sediments, open and closed shelf sediments, which determines the diversity and the greatest number of rock lithotypes.

Coastal-marine (littoral) sediments with carbonate complexes occurring therein comprise the deposits of tidal plains, coastal lagoons [20, 44], coral reefs, and terrigenous coastal-marine deposits – beach sediments, embankments, underwater bars as well as terrigenous coastal lagoons The rocks contain numerous fragments of coastal rocks. They surround the continental and island coasts and cover the floor of coastal seas. Away from the coast, the size of clastic grains of sediments decreases and, at a great distance from the coast, the sediments are grading into carbonate or terrigenous silt [30, 48].

Lithologically, coastal-marine deposits are represented by clay-silty micrograined limestones cemented by clay-carbonate material, sometimes dolomitic, less frequently, gypsum. Layers of gypsum (anhydrite), dolomites, alternating limestones and dolomites, pelitomorphic, breccia-like were found. Traces of burrowing organisms and stromatolites occur in rocks. The coastal-marine facies is widespread in the northwestern TPSB.

Open shelf sediments. This group includes the deposits of shallow shelf plains, bars, and deep shelf (lower shelf) deposits. Traces of erosion, large ripple marks, bottom and tidal currents are often recorded in rocks. In depression-like deposits of the deep part of the open shelf, the rocks contain thin, pelitomorphic carbonate and clayey material [18, 23, 30].

Closed shelf. The specific feature of this facies is an elevated or low water salinity due to isolation of this zone from the open shelf and fencing-off from deep sea areas by barrier reef systems. The deposits are characterized by lumpy-clumpy, pelitomorphic limestones, often algal with lumps of blue-green algae and oncolites.

Reef subformation comprises the deposits of genetic groups: reef (reef proper) and interreef (deposits of interreef channels and others forming within wide barrier reef systems). It comprises deposits of the following genetic types: bioherm, interbioherm, apron (deposits of rear and leading reef aprons) and lagoonal (interreef lagoonal). These types are closely spatially related to each other and form geological bodies of different extent and structures [25].

Bioherm deposits are organogenic structures created by plant and animal colonial organisms growing on top of each other. The rocks consist of a framework and a filler, have a bioherm structure and a massive texture. The bioherm facies is a seafloor facies [30].

Interbioherm deposits are part of bioherm massifs. The composition of interbioherm deposits directly depends on the composition of the surrounding bioherm structures. They are often close in composition to the interreef deposits (deposits of interreef channels, tidal channels), in the section of

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which, similar to interbioherm deposits, the ratio of detrital sludge, pelitomorphic limestones and widespread large and small detritus, whole shell fauna is recorded.

Apron sediments (rear and leading aprons). Rocks classified as rear apron facies are destruction products of organogenic structures that were subjected to wave action. Organogenic clastic material accumulated in the back-reef area. Distinctive features of the rear aprons were bioclastic (clastic) rock structures, good sorting and roundness of rocks, and the composition of fragments proper reflects that of the destroyed organogenic structure.

Lagoonal sediments (of intrareef lagoons). According to the description by T.D.Shibina [30], they are represented by "carbonates and evaporites forming in internal parts of reef structures that are ring-shaped or have a more complex shape in plan. The accumulation of sediments in intrareef lagoons is characterized by shallow sedimentation depths, complete or partial isolation of lagoons (connection with the basin occurs through the straits or reef voids), which leads to an increase in basin salinity entailing the development of sulphates."

The depression subformation comprises moderate deep-water facies, underwater uplift facies, and deep sea environments ("domanikites") [20, 23, 30].

Moderate deep-water facies. They formed in a depression zone, where structures of a negative type occur – depressions and their slopes, which are an accumulation area of thin clayey and carbonate material. Sediments accumulated outside the turbulence zone, in calmer hydrodynamic conditions. Clayey, clay-carbonate rocks formed there [30].

Deep-water facies ("*domanikites*"). Domanik type rocks form in areas with uncompensated sedimentation. Their occurrence areas are often confined to the deep sea shelf. A distinctive feature of domanikites is their high content of sapropel-type OM (C_{org} 3-15 %). Domanikites consist of up to 70 % of carbonate material (calcite, dolomite), clayey matter and silica.

In most cases, low-permeability reservoir rocks with porosity below 1-2 % and permeability less than 0.001 D should be classified as "domanikites", and the open fractures allow considering them in certain cases as fracture-type reservoir rocks with filtration paths along open fractures.

Subformation of the filling strata is the strata of smoothing and filling with sediments of a relatively deep sea part of the emerging reef systems due to regressive or the beginning of transgressive development trend of the sea basin [30].

In certain periods, each younger facies reefogenic zone shifted towards the open sea with gradual filling by sediments of relatively deep sea marginal-bioherm (apron, interbioherm) formation (see Fig.2, 4). Sedimentation occurred on inclined relief towards the advance of the sea basin with formation of accumulative terraces (filling strata). At the border of the shallow-water part of the shelf and a relatively deep-water part of the depression, new reefogenic bodies of different morphologies and different stratigraphic ranges form on accumulative terraces. Filling strata are the lower sedimentation part of the depression. In reef systems, they correspond to formation of the base of bio- and lithoclastic limestones, while in the shelf lagoon the terrigenous-carbonate sediments form simultaneously.

The highest concentration of OM in the Domanik Formation was recorded in mud shales, clay-siliceous limestones with the finest interlayers of sapropelites in the zone of low OM transformation corresponding to the stages of protocatagenesis (PC_2-PC_3). C_{org} content in them reached 15-25 %, in sapropelites it exceeded 30 % [14]. In the lower part of the Domanik Horizon (D_3dm_1), the average C_{org} content was 6.5 % (52 samples); in the upper part (D_3dm_2) – 10.2 % (56 samples) and in the undivided part of the Domanik Horizon – 4.64 % (287 samples), on average for D_3dm – 5.68 % (397 samples) which is much lower than, for example, the average contents within the southern TPP used for estimations [46].

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Average C_{org} content for 92 samples from the Upper Frasnian was only 0.36 %; for the Upper Frasnian – Lower Famennian boundary deposits 0.32 % (89 samples + 71 samples): 22 marl and clay samples from the Eletskii, Zadonskii and Evlanovskii-Livenskii deposits – 0.27 %, 35 marl and mudstone samples from wells in the Lower Famennian part of the section – 0.43 %, 70 marl and mudstone samples from the Upper Famennian part of the section – 0.15 %, and 136 mudstone and marl samples from the Tournaisian relatively deep sea sediments – 0.76 %.

Studies of samples from natural exposures in the Ukhta Region and wells with occurrence depth of the Frasnian-Famennian deposits within 200-400 m determined [15, 40] a possibility of identifying groups with different lithologies and C_{org} content, which allowed refining the maps of its distribution. The lowest C_{org} contents are characteristic mainly of carbonate and siliceous rocks (to 6-8 %), but they have a high generation potential (Table 1) compared to clayey varieties. In the central and eastern parts of the sedimentary basin, C_{org}-enriched domanikites often alternate with less enriched interlayers (1-4 %) which are represented by more carbonate rocks. Organic carbon in the latter most often did not exceed tenths of a percent. Individual interlayers of C_{org}-enriched rocks are recorded in the lower part of the Famennian. However, C_{org} content in them is also not high and does not exceed 3-4 %, and in the upper predominantly carbonate part of the section it decreases to tenths of a percent. When assessing the HC potential of the entire section from wells with the complex occurrence depth more than 2 km, it should be stated that actually only two or three, rarely four interlayers can be distinguished with relatively high C_{org} values with thicknesses of the first meters, which does not allow extending the obtained analytical values (concentrations) to the entire Domanik-Tournaisian complex. Despite the fact that the interlayers of high-carbon carbonate-siliceous and clayey rocks occur in almost all the studied sections, the average OM concentration per rock is much lower than it is assumed in most estimations using the volumetric genetic method for the TPSB [3, 25, 43].

Table 1

Results of pyrolytic study of the Domanik and Domanik deposits from natural exposures of TPSB

Age	Lithology	S1, mg HC/g of rock	T_{max}, °C	Total content of organic carbon TOC, %	S1/TOC, g/kg
D_3vt	Clay, marl, marlstone	0.02	418	0.3	6.7
D_3f_2(dm)	Calcareous dark mudstone	10.19	417	14.18	1.3
D_3f_2(dm)	Mudstone	9.39	419	13.22	7.0
D_3f_2(dm)	Marl	7.26	420	10.75	67.5
D_3f_2(dm)	Limestone and marlstone	3.81	420	6.82	55.9
D_3f_2(sr)	Clay	0.14	426	1.53	9.1
$D_3f_2dm_1$	Marlstone, calcareous mudstone	7.44	420	1.64	70.1
D_3f_2-f_3	Average for five exposures (excluding pure limestones)	6.22	419.97	9.35	66.5

A clear relationship between C_{org} content and rock carbonate content was recorded (Fig.6). Rocks with low content of carbonate material are characterized by the highest C_{org} content (10-15 %), and in some samples to 20-30 %. Lithotypes of limestones and marlstones, on the contrary, are characterized by a low content of C_{org} (from tenths to a few percent) and low values of the S1 index. At the same time, the most clayey replacement strata are characterized by an almost complete absence of non-carbonate carbon.

Based on results of the previous works [3, 5, 49] it was ascertained that samples of the Domanik deposits from exposures contained type II OM and were at the beginning of the "oil window" (T_{max} = 409-424 °C). Current research proved the catagenesis values that are close to those indicated – T_{max} = 411-423 °C, with average values of 420 °C. The conclusions obtained in this study and article [44] on the correlation between the OM content and lithological types of rocks (based on

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wells with shallow depth of Domanik occurrence) fully coincide. The lowest C_{org} content is predominantly found in carbonate rocks and siltstones. Their C_{org} content rarely exceeds 1 %. In this case, a slight increase in HI is recorded at lower T_{max} values, which may indicate the presence of already displaced HC in these intervals.

The main pattern identified is as follows. The most significant within the identified OM-enriched section intervals and facies zones is an interval of the Domanik Horizon with an area of relatively deep sea sedimentation in the PC_3-MC_1 catagenesis zone over 12,000 km^2 with a thickness of the lower part 10-16 m and C_{org} concentration 10-15 %, the upper part with a thickness of 12-15 m and C_{org} concentration 8-12 %. Catagenesis zone MC_2 covers an area of about 20,000 km^2 characterized by a total thickness of the section to 15-20 m (high-carbon part) with C_{org} concentration 3-5 %. The catagenesis zone MC_3 has an area of about 35,000 km^2 with an average thickness to 20 m and C_{org} concentration 4.5 % (Fig.7). The second in importance interval is the Upper Frasnian divided into two subtypes based on the association with a particular catagenesis zone: predominantly clay and shale varieties occurring in the MC_2 catagenesis zone with an area of about 25,000 km^2 and an average thickness of the section 12-20 m and C_{org} content 3 %, and in the MC_3 catagenesis zone with an area of about 40,000 km^2 and an average thickness of 20 m and an average C_{org} concentration 1.5 %. The least significant of the three considered intervals of the high-carbon formation section, but important for the eastern regions of the sedimentary basin (Pre-Ural Trough and the southeastern Izhma-Pechora Depression) is the Famennian and lower part of the Tournaisian composed predominantly of clayey and carbonate-clay varieties and also divided into two areas in the catagenesis zone MC_2 (occurrence area 15,000 km^2) with an average thickness from 20 to 30 m and C_{org} content 1-2 %, and in the catagenesis zone MC_3 with an area of about 60,000 km^2 and thickness of the high-carbon part of the section to 30 m and C_{org} content 0.5-1.0 %.

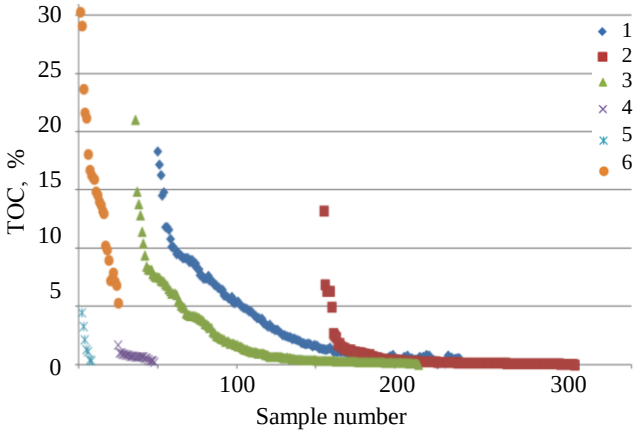


Fig.6. Distribution of non-carbonate carbon content D_3fr_2-D_3fm_2 in the Timan-Pechora Province by lithological rock types

1 – mudstone; 2 – limestone; 3 – marl; 4 – siltstone; 5 – silicite; 6 – sapropelite

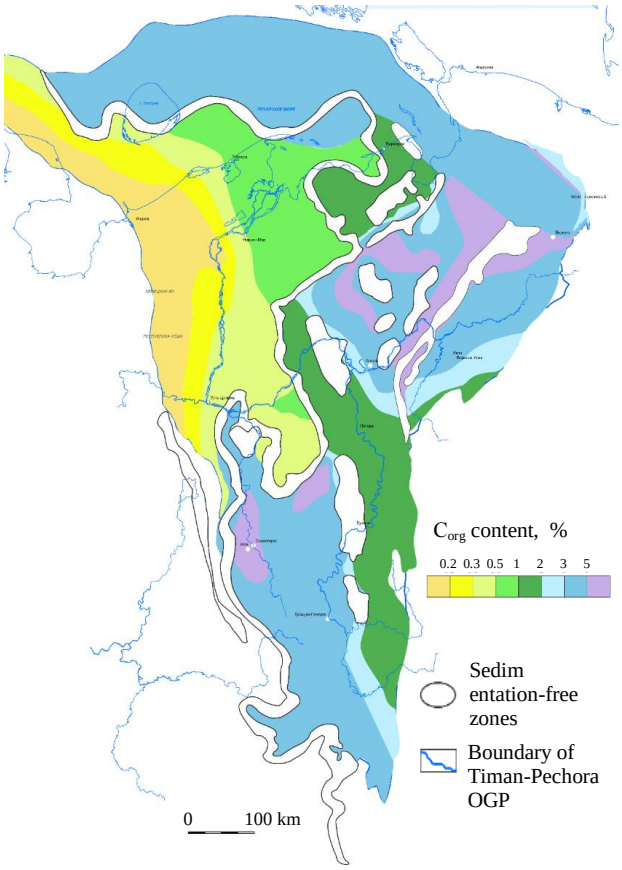


Fig.7. Average density of C_{org} within the Timan-Pechora oil-and-gas province for the Middle Frasnian (Domanik) deposits (after [3])

The revealed distribution pattern of non-carbonate carbon content in the identified lithofacies zones, taking into account the results of subdivision of the Domanik-Tournaisian part of the section based on materials from the field geophysical surveys of wells, made it possible to significantly clarify the distribution sketch maps of organic carbon through the section and across the area of the Timan-

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Pechora Basin for the three most significant parts of the "Domanik" Formation – Domanik-Sirachoiskii, Upper Frasnian-Lower Famennian and Upper Famennian-Tournaisian (Fig.7) further used to assess the initial hydrocarbon potential of the formation according to catagenetic zoning based on balance equations proposed by S.G.Neruchev, E.A.Rogozina and T.K.Bazhenova [3, 7, 46]. To restore the initial mass of OM (by the beginning of mesocatagenesis – MC_1), the corresponding coefficient was applied, the use of which was proved for the Domanik type of OM in the works of S.G.Neruchev and A.E.Kontorovich [7, 10, 50]. This coefficient indicates how the mass of OM changed as a result of generation of volatile products (water, gases, liquid HC).

Estimations of the generation potential of the Domanik Formation (Timan-Pechora Basin without the aquatorial part – 310,000 km^2), taking into account the clarification of the distribution in section, on area and by lithological types of geochemical parameters of the section for the areas of completion of the main zones of oil and gas formation showed a total estimate of 203.4 billion t^3 (with oil potential estimated at 143.6 billion tons, gas potential at 59.8 trillion m^3, which generally does not contradict the relationship from estimates [40, 51]), the residual potential of hydrocarbons that did not migrate from the strata was estimated in this work at 98.2 billion tons of oil and 24.2 trillion m^3 of gas (Table 2).

Table 2

Assessment of initial potential of high-carbon Domanik Formation in the TPP

Main characteristics	Shale formation		Domanik southwestern, central, northwestern parts of the basin		Domanik (Upper Frasnian, Famennian and Tournaisian) central, northeastern and eastern parts of the basin		Total
	Geological age		Middle Frasnian		Upper Frasnian, Lower Famennian	Upper Famennian, Lower Tournaisian	
	Sedimentation		Marine (relatively deep sea)		Marine (relatively deep sea), marine shallow		
	Area with strata enriched in OM, thousand km^2		25.0 (Ukhta Region)	140.0 (central, eastern, and northeastern)	155.0	58.0	165.0
	Thickness, m	Interval/average	10-50/20	10-30/15	10-40/20	5-60/20	
		With a high content of C_{org} / average in clayey, carbonate-clay / siliceous-clay parts	10/5/5	8/5/2	8/12/5	5/15/5	
	Depth, m	Interval (to AK_2)	0-2,000	2,000-4,600	1,000-4,500	2,400-4,400	
		Average	1,200	3,200	2,800	3,200	
Reservoir properties	Formation pressure		Abnormally high	High	Normal	Normal	
	Average TOC (%) for the enriched part of the section / re-estimated before the start of catagenesis / number of C_{org} and C_{nonorg} samples		8.0/8.5/2,150	4.0/6.0/680	2.0/3.0/1,810	1.5/2.2/685	
	Thermal maturity according to vitrinite reflectivity, % Ro		6.5-8.0	8.0-12.0	7.5-12.0	7.8-11.0	
	Clay content		High	Average and low	Average and low	Low	
	Void space (porosity + fracturing), %		4	3	2.5	1.5	
Resources	Oil phase		Oil	Oil-condensate	Oil-condensate	Oil-condensate	
	Geological resources (generated), billion m^3		40.0	84	62	17.4	203.4
	Geological oil resources (generated), billion t		36.0	56.4	41.2	10.0	143.6
	Geological gas resources (generated), trillion m^3		4.0	27.6	20.8	7.4	59.8

Conclusion. Considering the accomplished research, the distribution of organic carbon both section-wise and on area in the Middle Frasnian-Tournaisian high-carbon formation was significantly refined. The most enriched intervals were identified in the Middle Frasnian, Upper Frasnian-Lower Famennian, and Upper Famennian-Tournaisian parts of the section. The lithofacies characteristics of deposits of the Domanik Horizon, Upper Frasnian-Lower Famennian, and Upper Famennian-

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Tournaisian in the zones of relatively deep-water part of the shelf characterized by the highest OM contents, and insular shallow waters with the lowest OM concentrations were determined more precisely.

Systematization of lithological rock types into genetic groups of deposits of the Middle Frasnian-Tournaisian complex was accomplished. Within the lithofacies zone, the highest OM contents were characteristic of the least catagenetically altered sapropelites, clays, marls and, conversely, the lowest ones – of the areas where the complex occurred at great depths (in zones of high catagenesis) represented by silicites, siltstones, limestones and dolomites.

It was ascertained that the distribution of average C_{org} content values obtained from individual samples for the entire high-carbon formation, without considering the lithological type, significantly distorted the assessment of the volume of non-carbonate carbon in the formation, since it depended not only on its content in a specific section interval, but also on the proportion in the section of lithological types with a high concentration of C_{org} (sapropelites, mudstones, marls). Thus, the re-estimation of C_{org} density for the Ukhta Region showed the current concentrations 2-4 times lower for 1 km^2 compared with the known estimates given in the works of T.K.Bazhenova et al. [3]; O.M.Prishchepa et al.; T.A.Kiryukhina et al. [5, 14]; N.K.Fortunatova et al. [15]. Over most of the area of the Pechora-Kolva and Khoreiver oil and gas regions, the residual densities of C_{org}, according to the studies conducted, on the contrary, were estimated much higher than in the earlier studies, despite a higher OM transformation degree compared to the Ukhta Region.

Total occurrence area of zones with elevated OM concentration in rocks of the Domanik-Tournaisian complex is only about 50 % of the entire area of the Province (excluding its aquatorial part), and the area of zones with high concentration of C_{org} (more than 5 %) with a large number of such values (over 25 % of samples) covers less than 12 % of the Province area. About 15 % of the area is in the range of average C_{org} values of 2-5 %.

The revealed distribution pattern of the current OM content allowed re-estimating its content at the beginning of catagenesis, and, taking into account the catagenetic zoning, to assess the initial potential of the high-carbon Domanik Formation in the TPP (the most significant clarification was obtained for the central Izhma-Pechora Depression, the southern part of the Denisovskii Trough and the northern Khoreiver Depression as well as the aquatorial extent of the Timan-Pechora Province in the Pechora Sea), which makes it possible to use these data for reducing the initial OM concentrations and estimating the residual mass of mobile bitumoids in the low-permeability matrix of the high-carbon formation.

Areas with the highest potential for further scientific and commercial studies of unconventional accumulations of ("shale") HC within the TPP forming due to the non-migrated part of the HC generated from the "Domanik" oil and gas source formation, are the areas associated with zones of high C_{org} concentration, mostly in the moderate deep-water basin with uncompensated predominantly clayey and clay-carbonate sedimentation. The optimal degree of OM transformation in such areas was assessed for stages MC_1-MC_2 (Middle-Upper Frasnian and Lower Famennian deposits within the southwestern Izhma-Pechora Depression and Upper Frasnian and Lower Famennian deposits in the eastern Khoreiver Depression).

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