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Facies Differentiation of Mineral and Organic Matters under Coastal-Marine Sedimentation Conditions

M. A. Tugarova

St. Petersburg State University, Universitetskaya nab. 7/9, St. Petersburg, 198904 Russia

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Abstract—Coastal-marine sedimentation conditions in the Pechora River delta, Korovinskaya Bay, and intertidal zone of the Pechora Sea are characterized by diverse physicochemical processes that define the differentiation of mineral and organic components of sediments. On the basis of a complex study of abundant observation data, lithostructural and geochemical (including organic-geochemical) features of sediments in different facies circumstances of a common lateral series are considered. Synchronous changes in mineral and organic components are also taken into account. Informative numerical indices characterizing sediments of different facies conditions and lithodynamic–geochemical regimes of their formation are defined. Major factors of sedimentation and early diagenesis are distinguished.

Each facies type of sediments is considered a product of sedimentary-diagenetic differentiation of polycomponent substance in certain hydrodynamic and geochemical conditions. These processes are dramatically manifested under deltaic coastal-marine complex conditions that serves as a natural lithodynamic and geochemical barrier.

Sedimentogenesis and early diagenesis are stages of the formation of the initial composition of sediment. They reflect different physicochemical conditions of sedimentation and strongly affect the subsequent stages of sedimentary matter transformation.

This work mainly deals with coastal-marine sediments in the northern European part of Russia, including inundated northern areas of the Malaya Zemlya tundra and the adjacent coastal shoal zone (Fig. 1). The study area is characterized by the following series of facies conditions: continental–alluvial, lacustrine (large lacustrine basins, small tundra, and frequently swamped basins); coastal-marine–deltaic (lacustrine–swamp basins, abandoned lakes and channels, sediment runoff channels–deltaic channels, and prodeltas); estuarine (accumulative and abrasion); and open tidal shoals (beach and coastal-storm bars facies). The continuous facies series allows us to trace specific features of the mechanical and biogeochemical differentiation of sedimentary material and the initial stage of sediment diagenesis. The term "facies" is used after Krasheninnikov "…as a complex of deposits differing in composition and physicogeographic conditions of formation from adjacent deposits of the same stratigraphic range" (Krasheninnikov *et al*., 1988, p. 3).

Sediments are considered a common system of mineral and organic components situated in different phase conditions (solid, liquid, and gaseous) with correlated processes of material differentiation.

The aim of this work was to consider lithostructural, geochemical, and organic-geochemical features of sediments from different facies conditions of the common lateral series taking into consideration synchronous changes of mineral and organic components, define the informative set of numerical indices characterizing separate facies conditions and their lithodynamic–geochemical regimes, and distinguish the major factors of sedimentation and early diagenesis.

MATERIALS AND METHODS

A vast factual material was obtained with the author's participation in the course of multipurpose large-scale geochemical survey carried out by the All-Russia Research Geological Exploration Institute (VNIGRI) in water reservoirs and channels of the Pechora River delta, Korovinskaya Bay, Kolokolkova Bay, and intertidal flat of the Pechora Sea. The studied areas are favorable for the investigation of a wide range of sedimentation environments (temporary channels, creeks, Pechora River (the principal water pathway of this region), its delta with specific facies, and Pechora Sea). More than 1300 samples were taken and analyzed. Analytical methods developed by workers of VNIGNI (Astaf'ev *et al*., 1989) for the study of mineral and organic matters included the following procedures: standard grain-size distribution analysis, including the use of a GS-1 hydraulic sedimentometer (*Metodicheskie…*, 1989), petrographic analysis, mineralogical analysis with the determination of light and heavy fractions, X-ray phase analysis, determination of valence forms of iron, measurement of C_{org}, bituminological analysis with separation of bitumen groups, gas chromatography, and determination of sulfate-reducing microorganisms. Analyses were carried out in laborato-

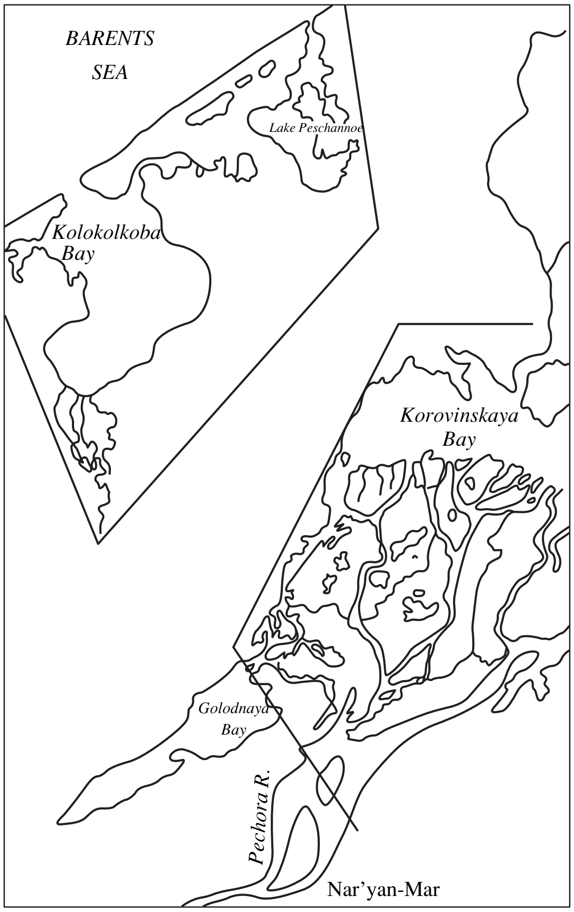

Fig. 1. Location of the studied areas. Scale 1 : 1000000.

ries of VNIGNI and SPbGU (St.-Petersburg State University).

Considering specific features of the geological structure of the region, its hydrocarbon specialization, and the presence of local productive structures in the Pechora River delta, samples with background values of gas and bitumen contents were taken to characterize sedimentary-diagenetic processes.

RESULTS AND DISCUSSION

Landscape-dynamic typification of sedimentation conditions. Omitting the detail description of region topography, let us note the principal landscape-dynamic types of sedimentation conditions. The Kolokolkova Bay includes a series of alluvial and lagoon-marine terraces (height 8, 10–15, 20–25, 30–50, and >50 m) and coastal-marine lowland (laida). The terraced shore is cut by small rivers. The intertidal flat incorporates small river deltas affected by marine tides, mouths of bays with tidal deltas, beach zone, and tidal-storm bar. Landscape-dymanic forms of another study area (Pechora River delta) are shown in Fig. 2.

Grain-size composition and lithodynamics. Proceeding from the activity of the near-bottom hydrodynamic regime and specific features of lithodynamics, environments of the studied area can be divided into four categories: active environment (intertidal flat and abrasion surfaces of estuaries with total flow velocity of up to 200 cm/s), moderately active environment (rivers, large lakes, discharge channels of delta, and prodeltas with flow velocity of up to 10–50 cm/s), weakly active environment (accumulative zones of estuaries, abandoned and inactive lakes, deltaic channels, and others with flow velocity of less than 10 cm/s), and passive environment (lacustrine-swamp and swamp basins). Major lithological and geochemical parameters of sediments are given in Table 1.

Alluvial sediments vary in grain-size composition from mixed silty-clayey and sand-silty–clayey varieties to pebbly ones in axial parts of channels. Channel sediments are more homogeneous (sand, silty sand, clayey–silty sand, and sandy silt). The median size of sediment grains changes from 0.07 to 0.25 mm. The entropy measure, which reflects the grade of sediment sorting, varies from 0.20 (well-sorted) to 0.85 (unsorted) (average 0.61). The empirical grain-size distribution (EGD) of material is characterized by the predominant mode 0.1–0.125 mm (22–32% of sedimentary particles) and the second mode 0.008–0.01 mm (3–17%). The minimal grain content is noted for classes ranging from 0.01 to 0.08 mm. The principal portion of channel sediments was formed during the continuous deposition of suspended material from unidirectional flows. Sediments from floodplains are generally characterized by the trimodal EGD with modes in sandy and silty classes (0.16–0.20 mm, up to 25%; 0.063–0.08 mm, up to 20%; and 0.008–0.01 mm, up to 7%). Sediment classes 0.08–0.01 mm and 0.01–0.04 mm are subordinate. Such a distribution of terrigenous material reflects, first of all the diversity of factors forming floodplain sediments (temporary flows, flood river waters, and stagnant-type waters during flood recession). The sediments are differently enriched in terrigenous organic matter (OM) supplied from eroded river terraces and by plant detritus of floodplain soils. Based on the distribution by specific gravity, the plant detritus generally corresponds to grain-size classes of less than 0.05 mm.

Lacustrine sediments are represented by silt, sand, and clayey–silty sands. The median grain size ranges from 0.008 to 0.18 mm (average 0.10 mm). Sediments of large lacustrine basins consist of well- to moderately sorted sand and silty sand (entropy is 0.15–0.50). Mixed sediments of shallow peat bogs are poorly sorted (entropy 0.50–0.90). The typical EGD is stable (in form and mode position): weakly expressed mode 0.20–0.25 mm (2–14%), mode 0.01–0,125 mm (11–25%), and mode 0.04–0.05 mm (5–23%). The increase of terrigenous plant detritus up to 15% does not change the EGD pattern, but increases the content of classes less than 0.063 mm. In general, lacustrine sediments formed under the influence of subdued wave action, and their

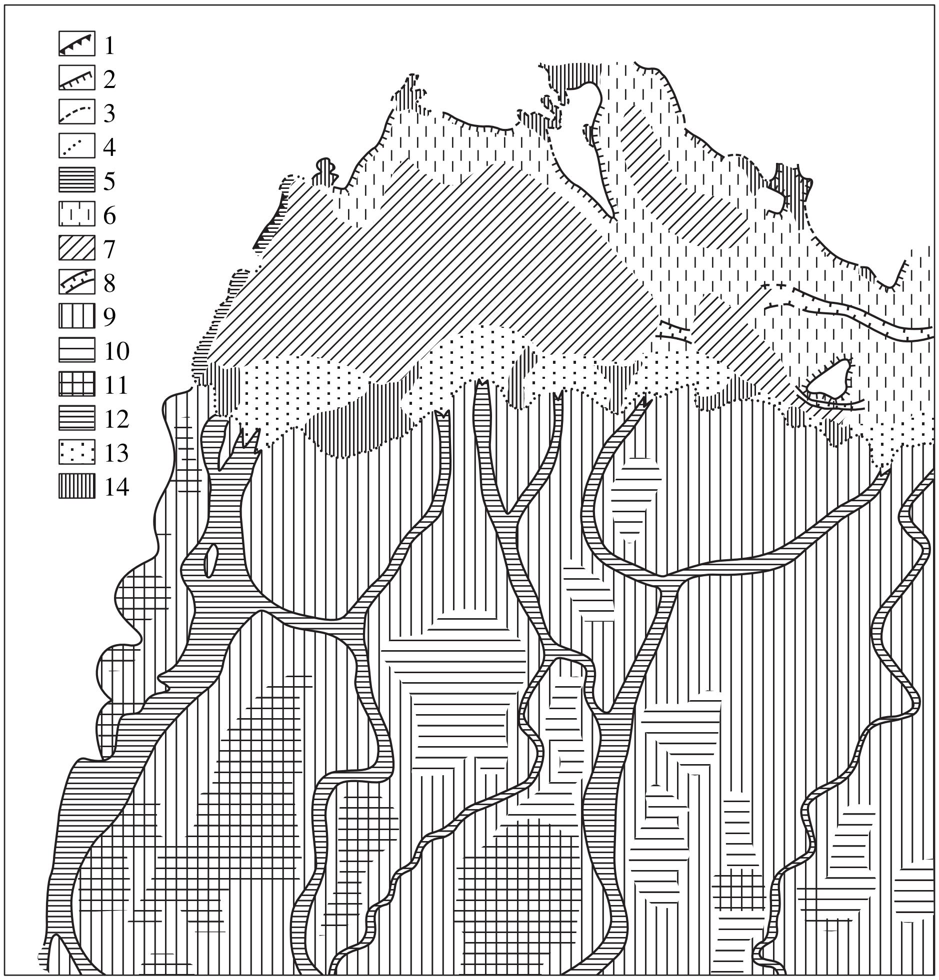

Fig. 2. Scheme of landscape-dynamic forms of the Pechora River delta and Korovinskaya Bay.

Lagoon forms and shores: (1) Abrasion of glaciomarine boulder-containing loam, (2) abrasion of sandy sediments of coastal-marine plain, (3) ingressive lacustrine, (4) accumulative deltaic; bay bottom surfaces: (5) abrasion surface of glaciomarine deposits, (6) abrasion surfaces on lagoonal–deluvial sediments, (7) accumulative surfaces of lagoonal and alluvial deposits, depth 2.5–5.0 m or more, (8) discharge channels; delta (balanced areas): (9) surfaces with abandoned and inactive channels, lakes, and swamps, (10) large lacustrine-swamp basins, (11) lacustrine-swamp basins with water level not exceeding the normal level of channels; unbalanced areas: (12) main channels of sediment runoff, (13) prodeltas, (14) inlet basins.

reworking rate did not exceed the terrigenous supply rate. Sand and silt of deep lakes, where the grain-size distribution of sediments is controlled by waterdepth and wave action, are an exception.

The *Pechora River delta area* is characterized by a significant differentiation of sedimentation conditions within the coastal-marine lowland. Sediments of lacustrine-swamp and inactive reservoirs inherit the general EGD pattern. They are marked by the predominance of classes of lesser size and general increase in dispersity of terrigenous matter. Sediments of lacustrine-swamp basins with low water level have a bimodal or weakly expressed trimodal EGD pattern. The presence of the mode in grain-size classes < 0.04 mm is dictated by both the fine-dispersed mineral and organic terrigenous substances. Median grain size of sediments of passive deltaic basins varies from 0.002 to 0.09 mm (average 0.03 mm). The sediments are poorly sorted. The average value of entropy measure is 0.80 for lacustrine-swamp basins and 0.57 for sediments of inactive lakes and channels.

The EGD values for sediments of runoff channels are similar to those for channel and floodplain sediments. The median grain size varies from 0.008 mm for sediments of quiet zones of channels and floodplain areas to 0.13 mm for channel sediments. The grade of sorting within a wide range (entropy measure) varies from 0.10 in well-sorted channel sediments to 0.92 in poorly sorted floodplain deposits. Judging from the grain-size composition of sediments, unidirectional transportation in suspension is the predominant process in these reservoirs. The transportation is accompanied by settling of particles in the near-bottom layer without their stirring-up and removal of fine silt and clay material.

Table 1. Lithological and geochemical parameters of sediments of different sedimentation environments

Parameters	Facies conditions									
	Active		Moderately active				Weakly active			Passive
	Marine tidal	Abrasion estuarine	Lacustrine	Alluvial	Deltaic channels	Prodeltaic	Accumulative estuarine	Small tundra lakes	Abandoned lakes and channels	Lacustrine-swamp
Median size, *Md*, mm	$\frac{0.2}{0.1\text{–}0.23}$	$\frac{0.14}{0.1\text{–}0.16}$	$\frac{0.096}{0.008\text{–}0.18}$	$\frac{0.12}{0.07\text{–}0.25}$	$\frac{0.06}{0.008\text{–}0.13}$	$\frac{0.05}{0.006\text{–}0.11}$	$\frac{0.04}{0.009\text{–}0.08}$	$\frac{0.03}{0.002\text{–}0.06}$	$\frac{0.03}{0.005\text{–}0.05}$	$\frac{0.03}{0.002\text{–}0.09}$
Entropy measure	$\frac{0.17}{0.15\text{–}0.20}$	$\frac{0.18}{0.10\text{–}0.55}$	$\frac{0.75}{0.15\text{–}0.90}$	$\frac{0.61}{0.20\text{–}0.85}$	$\frac{0.51}{0.10\text{–}0.92}$	$\frac{0.37}{0.12\text{–}0.90}$	$\frac{0.48}{0.10\text{–}0.78}$	$\frac{0.76}{0.10\text{–}0.90}$	$\frac{0.57}{0.18\text{–}0.92}$	$\frac{0.80}{0.10\text{–}0.92}$
EGD type	unimodal		bi- and trimodal							
Coefficient of general maturity	0.90	0.83	0.71	0.79	0.80	0.83	0.74	0.67	0.67	0.62
Content, % Fe_{tot}	$\frac{0.28}{0.24\text{–}0.35}$	$\frac{0.9}{0.71\text{–}2.57}$	$\frac{2.1}{0.20\text{–}2.96}$	$\frac{0.12}{0.45\text{–}2.12}$	$\frac{2.02}{1.01\text{–}6.14}$	$\frac{1.22}{0.78\text{–}2.96}$	$\frac{2.7}{0.80\text{–}4.20}$	$\frac{0.98}{0.20\text{–}2.96}$	$\frac{2.6}{1.0\text{–}8.99}$	$\frac{3.27}{1.23\text{–}5.75}$
Fe^{2+}	$\frac{0.05}{0.0\text{–}0.08}$	$\frac{0.24}{0.11\text{–}0.97}$	$\frac{1.18}{0.0\text{–}1.84}$	$\frac{0.4}{0.11\text{–}1.28}$	$\frac{0.62}{0.18\text{–}4.22}$	$\frac{0.38}{0.0\text{–}0.96}$	$\frac{0.82}{0.08\text{–}1.28}$	$\frac{0.41}{0.0\text{–}1.84}$	$\frac{1.02}{0.2\text{–}4.22}$	$\frac{1.51}{0.22\text{–}5.46}$
Fe^{3+}	$\frac{0.07}{0.06\text{–}0.08}$	$\frac{0.27}{0.12\text{–}1.11}$	$\frac{0.55}{0.0\text{–}0.89}$	$\frac{0.32}{0.06\text{–}0.62}$	$\frac{0.63}{0.32\text{–}1.32}$	$\frac{0.42}{0.0\text{–}1.02}$	$\frac{1.07}{0.42\text{–}2.0}$	$\frac{0.12}{0.0\text{–}0.49}$	$\frac{0.72}{0.20\text{–}4.10}$	$\frac{0.85}{0.17\text{–}1.95}$
Fe_{sulf}	n.d.	$\frac{0}{0.0\text{–}0.008}$	$\frac{0.012}{0.0\text{–}0.14}$	$\frac{0.005}{0.0\text{–}0.014}$	$\frac{0.004}{0.0\text{–}0.4}$	$\frac{0.005}{0.0\text{–}0.04}$	$\frac{0.016}{0.0\text{–}0.08}$	$\frac{0.09}{0.0\text{–}0.54}$	$\frac{0.004}{0.0\text{–}0.04}$	$\frac{0.019}{0.0\text{–}0.08}$
Clastic iron	$\frac{0.15}{0.10\text{–}0.22}$	$\frac{0.39}{0.23\text{–}1.04}$	$\frac{0.36}{0.0\text{–}1.00}$	$\frac{0.39}{0.09\text{–}0.63}$	$\frac{0.77}{0.34\text{–}1.34}$	$\frac{0.78}{0.47\text{–}1.07}$	$\frac{0.81}{0.39\text{–}1.28}$	$\frac{0.36}{0.0\text{–}1.0}$	$\frac{0.79}{0.5\text{–}0.9}$	$\frac{0.88}{0.36\text{–}1.59}$
Fe^{2+}/Fe^{3+}	0.77	0.89	2.1	1.25	0.98	0.9	0.77	1.4	3.4	1.8
Recent C_{org}, %	$\frac{0.2}{0.11\text{–}0.25}$	$\frac{0.34}{0.15\text{–}1.25}$	$\frac{0.87}{0.01\text{–}3.44}$	$\frac{0.71}{0.02\text{–}3.12}$	$\frac{0.86}{0.26\text{–}2.34}$	$\frac{0.5}{0.12\text{–}1.05}$	$\frac{1.14}{0.18\text{–}1.67}$	$\frac{1.37}{0.3\text{–}6.44}$	$\frac{1.53}{0.49\text{–}3.76}$	$\frac{1.8}{0.30\text{–}14.94}$
Total diagenetic expense of C_{org}, %	$\frac{0.003}{0\text{–}0.005}$	$\frac{0.013}{0.01\text{–}0.052}$	$\frac{0.04}{0.01\text{–}0.10}$	$\frac{0.026}{0.01\text{–}0.07}$	$\frac{0.037}{0.01\text{–}0.23}$	$\frac{0.025}{0.01\text{–}0.06}$	$\frac{0.057}{0.01\text{–}0.20}$	$\frac{0.049}{0.01\text{–}0.30}$	$\frac{0.058}{0.01\text{–}0.55}$	$\frac{0.097}{0.01\text{–}0.32}$
Coefficient of diagenetic loss	1.7	3.4	4.2	3.5	4.1	4.8	4.8	4.1	3.6	5.3
CBA, % of sediment	$\frac{0.002}{0.00\text{–}0.01}$	$\frac{0.006}{0.005\text{–}0.015}$	$\frac{0.019}{0.005\text{–}0.024}$	$\frac{0.01}{0.006\text{–}0.026}$	$\frac{0.012}{0.008\text{–}0.024}$	$\frac{0.014}{0.012\text{–}0.026}$	$\frac{0.19}{0.006\text{–}0.026}$	$\frac{0.0018}{0.007\text{–}0.024}$	$\frac{0.018}{0.008\text{–}0.024}$	$\frac{0.022}{0.005\text{–}0.021}$
CBA/C_{org}, %	1.2	1.6	1.4	1.5	1.4	2.0	1.7	1.5	1.4	1.3

Note: Numerator designates average value, denominator is shows variation range. (n.d.) Not detected.

Prodelta of the Korovinskaya Bay basin. Within a small shallow area of the prodelta, one can find different types of sediments ranging from sand to clayey–silty sand, sand silt, and clayey-silty sediments. Their distribution is controlled by bottom topography and proximity to mouths of sediment runoff channels. The median grain size varies from 0.006 to 0.11 mm (average 0.05 mm) and the sediments are well-sorted (the entropy measure averages 0.37). Terrigenous material is accumulated as a result of the settling of suspension during a relatively continuous supply of clastic matter. Accumulation of organic matter is mainly related to the deposition of organic particles suspended and dissolved in water.

Within *estuaries* (Kolokolkova and Korovinskaya bays), the distribution and accumulation of sediments are controlled by bathymetry of water areas, activity of waves, and depth of wave agitation. One can distinguish two contrast (abrasive and accumulative) environments. Sediments of alongshore abrasion facies (depth up to 2.5 m) are represented by well-sorted sands with the mean median grain size of 0.14 mm. The EGD value of such sediments reflects an active hydrodynamic regime of sedimentation. Sandy sediments account for up to 90% of the terrigeneous material.

Fine-dispersed sediments (mainly sandy–clayey and clay silt) with mean median grain size of 0.04 mm, actively accumulate in estuarine sedimentation areas at depths greater than 2.5 m. Up to 85% of clastic material (grain size less than 0.05 mm) is characterized by the major distribution mode in class 0.008–0.001 mm and subordinate mode in class 0.005–0.0063 mm.

Sands of coastal-storm bars and beaches are typical sediments of *tidal marine shoals*. Silt fractions are subordinate in them and clay-sized particles are completely absent. The median grain size of sandy sediments in beaches and coastal-marine bars varies from 0.19 to 0.21 mm (average 0.20 mm). The sands are well-sorted (the entropy measure is 0.18 for beach sands and 0.16 for sediments of coastal-storm bars) and characterized by slight dispersion of sorting coefficient. The EGD value of sediments of tidal shoals reflects the intensive wave-surf reworking of clastic material with predominant settling of medium- and fine-grained sandy fractions.

The structural maturity of sedimentary material defined by mechanical differentiation is closely related to the mineral maturity of sediments.

Mineral composition of sediments. The lithodynamics of sedimentation environment governs not only structural features of deposits but also their component composition.

Sandy–silty fractions of sediments in the studied area are characterized by increase of mineral material maturity (increase of quartz content and relative decrease of feldspars and rock fragments) from continental basins with moderately active lithodynamic regime to active coastal-marine basins.

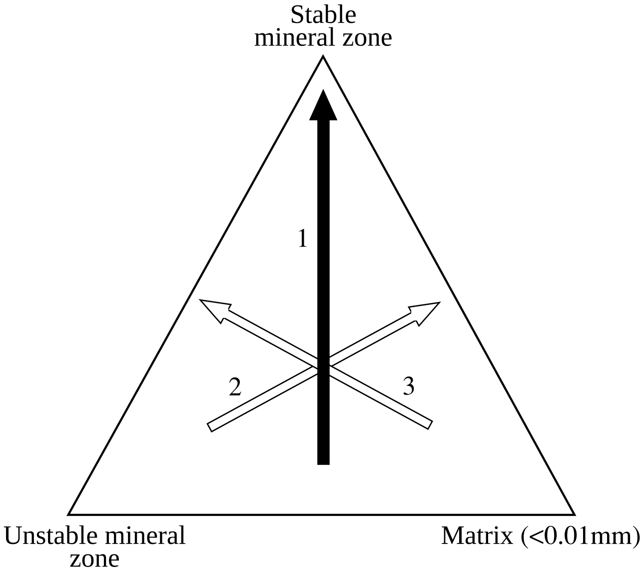

Fig. 3. Sediment composition vs. structural and mineral maturity. Arrows indicate increase of (1) general, (2) structural, (3) mineral maturity.

Average quartz concentrations range from 56.2% in lithodynamically low-active facies of abandoned lakes and deltaic channels to 79% in the most active facies of intertidal flats. Relatively low quartz contents (57%, on the average) are recorded in deposits of accumulative zones of the Korovinskaya Bay. This is likely to be related to decrease of grain size in these facies. In sediments of moderately active environment, the quartz content varies from 60 to 68%.

The scheme of Selley (1981) was used to estimate the general maturity of mineral composition (Fig. 3). Average coefficients of structural maturity (ratio of the content of grains to the total content of grains and matrix) and mineral maturity (ratio of the content of stable grains to the total content of stable and unstable grains) were calculated for sediments from each facies. The arithmetic mean value of these indices was recognized as the total maturity of the sediment.

Thus, we obtained the following series of sediments in accordance with the increasing rate of maturity (Table 1): lacustrine-swamp (0.62) ⟶ abandoned lakes and channels (0.67) ⟶ lacustrine (0.71) ⟶ accumulative estuaries (0.74) ⟶ alluvial (0.79) ⟶ deltaic channels of sediment discharge (0.80) ⟶ prodeltas and abrasion estuaries (0.83) ⟶ beaches and coastal-storm bars (0.90). Values of structural and mineralogical maturity vary for facies of prodeltas and abrasion estuaries although coefficient of the general maturity is similar. Abrasion sediments are characterized by a higher structural maturity, whereas prodeltaic sediments show a higher mineral maturity.

When studying heavy minerals from sand-silt fractions, special attention was paid to minerals that can actively respond to changes in redox conditions. The content of chlorides, siderite, iron sulfides, and occasionally iron oxides is relatively low in sand-silt fractions. Their contents slightly change in deposits of different sedimentation environments and do not correlate with analytic data on contents of the labile and clastic iron in the same samples. Thus, the coarse-grained material sharply differs from fine silty (0.01–0.005 mm) and pelitic (<0.005 mm) fractions.

Composition of pelitic fraction. The content of fine-dispersed material in sediments is governed by lithodynamic features of sedimentation basins. The maximal content of pelitic fraction is recorded in sediments of abandoned lakes and deltaic channels (up to 40%) and accumulative zones of the Korovinskaya Bay (up to 45%). Associations of clay minerals in different sediment facies within the studied areas show a variable distribution pattern. Hydromica and kaolinite predominate in fluvial, lacustrine, and accumulative estuarine sediments. Kaolinite and Mg–Fe-chlorite prevail in sediments of lacustrine-swamp basins. With increase of the chlorite content, siderite also appears in the clay fraction. In sediments of stagnant sedimentation regime (marsh and lacustrine-swamp basins of the Pechora delta), pyrite accounts for up to 6% of clayey–silty fraction. Maximal contents of smectites and mixed-layer minerals of the illite–smectite type are noted in sediments from the deltaic channel estuary (up to 35–48%). This probably reflects the influence of more alkaline marine waters on the trend of clay matter transformation. According to Suzdal’skii *et al*. (1997), pH of the near-bottom water layer in the delta estuary changes from 0.7 to 8.0. The decreased of smectites in sediments of accumulative environments of the Korovinskaya Bay seems to be related to their transit in the form of fine-dispersed suspended material through the bay water area.

Diffractograms of clay fractions of sediments characterized by high C_{org} contents, sometimes show a halo with minimum at 3.5 Å, which is typical of aromatic structures (Korchagina and Chetverikova, 1976). Normally, these samples are simultaneously enriched in sorption-capable clay minerals (smectites along with mixed-layer phases of illite–smectite and chlorite–smectite types containing expanding interlayers up to 35%). One can suggest that such sediments include organomineral complexes as a result of the introduction of OM molecules into the structure of expanding mineral phases. Their thin sections reveal dispersed (morphologically indiscernible) OM, which imparts dark colors to clay minerals.

Distribution of C_{org} and Fe. Average contents of C_{org} and various forms of Fe in different sediment facies are given in Table 1. Lithodynamically active environments are characterized by sediments with low sorption capacity, low C_{org} content (average 0.14–0.34%), low concentration of labile Fe forms (average 0.12–0.51%), and complete absence of Fe_{sulf}.

Sediments of moderately active environments are marked by the following average contents (%): C_{org} 0.50–0.86, Fe_{tot} 1.0–2.0, Fe^{2+} 0.38–0.62, and Fe_{sulf} concentration 0–0.04.

Sediments of lithodynamically passive environments are marked by the maximal accumulation of OM and the following average contents (%): C_{org} 1.14–1.78 (maximum 15), labile Fe > 1.7, Fe^{2+} 0.85–1.07, and Fe_{sulf} up to 0.08.

Regular change of the Fe^{2+}/Fe^{3+} ratio in sediments testifies to the variation of geochemical conditions from oxidizing to weakly reducing and reducing ones with decrease in the activity of hydro- and lithodynamic processes. In the lithodynamically active environment, oxidizing conditions are developed over more than 70% of the bottom area. Reducing environment of different grades predominate in lithodynamically passive facies of lacustrine-swamp basins of the Pechora River delta.

Sulfate-reducing bacteria. The distribution of sulfate-reducing bacteria (primarily, *Disulfovibrio desulfuricans*) is a criterion allowing us to estimate geochemical environment of sedimentation and intensity of reduction processes. Sulfate-reducing microorganisms are virtually absent under highly dynamic and well aerated conditions. The microorganism content does not exceed 100 cells/g of sediment. The most diverse distribution pattern is observed in the subaeral deltaic facies, where the content of sulfate-reducing bacteria varies from 100 to 10000 cells/g of sediment. The maximum concentration of microorganisms was revealed in sediments with high contents of sorption-active particles, OM, and biochemical gases, i.e., in passive sedimentation environment with reducing geochemistry.

Facies differentiation of organic matter in sediments. Organic matter and mineral particles are transported to continental basins as a result of denudation and involved in the common lithogenetic process according to the common regularities of mechanical and chemical differentiation.

The content, composition, distribution, and common regularities of OM differentiation are defined by natural biocoenosis, specific features of lithodynamic processes and geochemical conditions of bottom sediments governing the degree of initial OM conservation, i.e., facies specifics of sedimentation and early diagenesis.

Diminution of detrital OM fragments during the transportation from provenances to accumulation areas is the principle trend. The detrital OM actively participates in the formation of sediment structure. Modeling of precipitation with the use of hydraulic sedimentometers showed that the second EGD mode is formed in fine-grained sand, silt or pelite classes (depending on grain size) as a result of enrichment in detrital OM.

Organic detritus is subordinate or absent in sediments of lithodynamically active environment. Organic matter is mostly confined to fine-grained sand and silt classes in deposits of moderately active and poorly active reservoirs and clay matrix in sediments of passive environments.

Sediments of sedimentation environments discussed above (deltaic, coastal-marine, shelf facies, and so on) mainly contain the allochthonous terrestrial OM or type III OM (according to after Danyushevskaya *et al.*, 1990). This is defined by the proximity of main sources of OM (denudated soil and vegetation layer of watersheds. Low temperatures of the subarctic belt are responsible for the low productivity of hydrobionts and, as a consequence, relatively low content of autochthonous OM in coastal-marine and continental sedimentation environments.

Analytical data support the predominance of humid OM in all of the studied samples. Its share in the total OM content slightly decreases when passing from continental sediments to marine ones (decrease of carbon preference index (CPI) of *n*-alkanes, relative increase of the CO_2/CH_4 ratio, and others). As shown above, the bulk C_{org} content in the sediments is closely related to lithodynamic conditions in the sedimentation basin and decreases from dynamically passive to active environments. Moreover, variations of C_{org} concentration are lower in more homogeneous sediments of the same facies. The calculated average diagenetic C_{org} consumption varies from 0.003% in beach sediments to 0.097% in lacustrine-swamp sediments. The coefficient of diagenetic loss, i.e., (total diagenetic C_{org} consumption/initial C_{org} content) × 100%, successively changes from 2.5 in sediments of lithodynamically active zones to 5.3 in passively accumulated varieties. Comparison of average C_{org} values in sediments of certain grain-size types with the background C_{org} value showed that the scatter of values for sands, silts, and clays within a single facies environment frequently turns out to be insignificant, although their average content appreciably varies in different facies.

Thus, organic matter is differentiated simultaneously with the differentiation of terrigenous material. The grain-size composition of sediments is related to a definite morphological type of OM and its quantitative and qualitative parameters.

Distribution of chloroform bitumens in sediments. The determination of chloroform bitumen (CBA) content and study of its group composition make it possible to obtain information on the genetic type of initial OM and the degree of transformation at the stage of early diagenesis.

The CBA content in sediments of the studied facies varies from $n \times 10^{-4}$ to $n \times 10^{-1}\%$. The CBA distribution directly correlates with the C_{org} content in sediments. The background concentration changes from $n \times 10^{-3}$ to $n \times 10^{-2}\%$. The maximal average value is observed in sediments of lacustrine-swamp basins (0.022%), lacustrine and accumulative estuaries (0.019%), and abandoned deltaic channels (0.018%). Similar values are registered in sediments of prodelta (0.014%), deltaic channels of sediment discharge (0.012%), and alluvial deposits (0.010%). Minimal values are observed in abrasion sediments of estuaries (0.006%) and intertidal flat (0.002%). The CBA/C_{org} ratio is low (1.0–2.6%), which is typical of sediments at the early diagenetic stage, but variations of this parameter testifies to changes in the intensity of OM transformation in sediments of different facies environments. The CBA/C_{org} ratio, which reflects the maturity of initial OM, is highest in sediments of prodelta (1.0–2.6%) and accumulative estuaties (1.7%), but successively falls in the following series: abrasion estuaries (1.6%), alluvial zones (1.5%), lakes and abandoned deltaic channels (1.4%), lacustrine–wamp basins (1.3%), shelf (1.1%), and coastal-marine bar and beach (1.0%).

It is interesting that generally high CBA/C_{org} values (>1.3%) are typical of sediments with the high coefficient of diagenetic loss (>3.4%). Direct correlation between these parameters is absent, because the relative accumulation of bitumens is governed by both diagenetic loss of C_{org} and genetic type of the accumulated OM (abundance of initial lipids). Hydrobionts, which are the main suppliers of lipids, seem to be involved in the formation of OM of estuaries. Therefore, the CBA/C_{org} ratio is additionally increased in sediments of the prodelta and estuaries.

In sediments of different environments, the CBA distribution and group composition depends on lithodynamic activity of water basins. The oil fraction is maximal in bitumen composition is typical of shelf and estuarine sediments (up to 68%) and minimal in coastal abrasion and fluvial deposits (7–8%). When passing from active abrasion to passive accumulative conditions, the sediments are enriched in C_{org} (from 0.41 to 1.32%), CBA (from 0.006 to 0.020%), oil fraction (from 0.0005 to 0.0038%), tar-asphaltene fraction (from 0.0056 to 0.0169%), and the total HC content (from 0.0005 to 0.0036%).

The maximal methane–naphthene HC content (0.0045%) is recorded in sediments of estuarine accumulative conditions (Korovinskaya Bay). Their composition is dominated by the methane–naphthene fraction of *n*-alkanes (C_{17}–C_{40} up to 94%). The specific distribution of *n*-alkanes (relative predominance of high-molecular odd homologues C_{25}–C_{29} and high carbon preference index of *n*-alkanes ranging from 2.0 to 5.9) reflect the dominant role of plant OM and its weak diagenetic transformation.

Pristane and phytane dominate in the composition of isoprenoids. The pristine/phytane ratio varies from 0.5 to 1.4 and reaches the minimum (0.5) in lacustrine-swamp sediments of the Pechora River delta. The ratio is governed by both genetic features of OM and redox conditions.

Chrizene, alkilchrizene, and perilene prevail, but phenantrene and its derivates are subordinate in the polyaromatic oil fraction of the sediments not polluted by

Table 2. Averaged contents of bituminological parameters and variation ranges in different grain-size types of sediments and facies conditions

Sediment type	C_{org}, %	CBA, % of sediment	HC content, %	
			in sediments	in CBA
Sand	0.55 0.14–0.91	0.009 0.002–0.020	0.002 0.000–0.0038	15
Silt	0.77 0.42–0.97	0.016 0.009–0.021	0.0021 0.0011–0.0028	12
Clay	1.12 0.62–1.68	0.019 0.013–0.022	0.0023 0.0018–0.0026	12
	Variation range of average values in different facies conditions			
	0.14–1.78	0.002–0.022	0.0005–0.0036	9–19

Note: Numerator designates average values, denominator shows variation range.

Table 3. Chemical composition of gaseous phase in sediments

Sedimentation environment	Gas content	Chemical composition of gases, cm^3/dm^3			CO_2/CH_4
		CO_2	N_2	CH_4	
Intertidal flat	12 (12.0) 5.0–19.0	1.5 (0.9) 0.2–4.0	10.4 (10.3)	0.01 (0.02) 0.004–0.06	140.0 (50.0) 3.3–575
Abrasion zones of the Korovinskaya Bay	29.0 (16.0) 5.0–72.0	10.6 (8.8) 2.5–25.6		0.6 (0.4) 0.02–5.9	18.5 (7.5) 0.07–109.0
Large lakes	95.0 (67.0) 15.0–370.0	48.0 (31.0) 0.7–239.0	33.0 (27.0)	13.7 (4.0) 0.01–76.2	67.5 (10.0) 0.3–470
Medium and small lakes	95.0 (79.0) 27.0–260.0	31.0 (19.0) 3.4–106.0	33.0 (29.0)	31.4 (20.0) 7.0–117.0	1.0 (0.9) 0.3–3.5
Alluvial (lower reaches and estuaries)	86.0 (84.0) 30.0–130.0	30.0 (18.0) 4.4–84.0		14.4 (16.8) 0.13–30.0	27.6 (1.4) 0.5–220.0
Main sediment runoff channels of delta	63.0 (65.0) 15.0–125.0	28.0 (23.0) 0.8–88.0	24.0 (24.0)	12.6 (8.7) 0.2–59.0	12.7 (2.3) 0.5–176.0
Prodelta	61.0 (54.0) 7.0–184.0	1.8 (1.5) 0.08–5.7		13.7 (6.7) 0.01–96.0	32.1 (5.0) 0.13–147.0
Accumulative zones of the Korovinskaya Bay	50.0 (34.0) 7.0–164.0	1.5 (0.9) 0.2–4.0		7.2 (3.6) 0.5–34.6	6.1 (2.6) 0.3–35.4
Abandoned and inactive lakes and channels	112.0 (90.0) 34.0–295.0	65.0 (50.0) 10.0–242.0	23.0 (21.0)	20.2 (21.5) 0.5–46.0	10.7 (2.9) 0.3–128.0
Lacustrine-swamp basins	119.0 (117.0) 47.0–226.0	65.7 (48.5) 15.0–166.0	29.0 (19.0)	24.4 (23.0) 0.8–45.0	6.2 (2.0) 0.3–24.0

Note: Numerator designates average and median (in parenthesis) values, denominator show variation range. Sediments with natural humidity were analyzed.

technogenic naphtides. The presence of bens(*a*)pirene and some other polyaromatic hydrocarbons is detected in some cases.

Data on the CBA content group composition, and HC component in sediments testify to the crucial role of facies in the CBA distribution. Lithodynamically active environment is unfavorable for the accumulation and preservation of OM in general, and its HC component, in particular, because of the low sorption capacity of sediments, practically complete absence of organic detritus, and active gas exchange that provides oxidation regime in the surface sediment layer.

Other facies zones are favorable for the accumulation of OM (including hydrocarbons) to a variable extent. The presence of the sorption-capable silty–clayey matrix and dispersed OM, as well as the predominance of neutral–reducing geochemical environment provide OM accumulation during at the early diagenesis.

Backgroung contents of organic matter and its separate components were determined for both different sedimentation conditions and different grain-size types of sediments. Table 2 shows variation ranges and averaged background values of C_{org}, CBA, HC fractions in the sediment and CBA.

It is seen that variations of the average content in different grain-size types are minimal, but the differentiation of OM and its separate components is significant for each group of similar (in grain-size composition) sediments. At the same time, scatter of the values for different grain-size types of continental and coastal-marine sediments is often insignificant, although the average values are considerably different in various facies zones. These data one more testify to the dominant role of facies factor in the OM distribution.

Gaseous phase in sediments. Processes of early diagenetic transformation of OM lead to the formation of a wide spectrum of biochemical gases. Concentrations of hydrocarbon gases, nitrogen, and carbon dioxide and the total gas content are shown in Table 3. The average content of gaseous phase and concentration of its separate components are controlled by conditions of sedimentation, degree of sediment dispersion, and OM content in the sediments. Maximal concentrations of gases are recorded in organic-rich sediments of the passive lacustrine-swamp environment of the Pechora River delta. Sediments of the active dynamic environment of intertidal flats and abrasion facies of the Korovinskaya Bay are characterized by minimal concentrations of all gaseous components.

CONCLUSIONS

(1) Sediments of separate facies differ in lithostructural and geochemical parameters. Their formation is mainly governed by processes of mechanical and chemical differentiation.

(2) Distribution of mineral and organic substances and processes of their early genetic transformation are interrelated.

(3) Each facies type of sediments is characterized by specific composition and physiogeographic formation condition. This is reflected in the assemblage of informative numerical criteria.

(4) Lithodynamically active conditions are unfavorable for the accumulation and preservation of OM, in general, and its hydrocarbon constituents, in particular. Other facies conditions (accumulation of sorption-capable fine-dispersed fractions with syngenetic OM, and the predominance of neutral–reducing geochemical conditions and so on) are generally favorable for the accumulation of hydrocarbons and their preservation at the stage of early diagenesis.

Facies differentiation and early diagenetic transformation of polycomponent sedimentary material discussed in this work demonstrate the multiple-factor evolution of lithogenesis. These issue are crucial for the lithology, geochemistry, and petroleum geology, estimation of ore and oil potentials of sediments, scales of recent gas formation, and accomplishing ecological tasks.

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