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Research Article

Facies and Sedimentary Environments in the Middle Devonian Basin of Novaya Zemlya

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Abstract

The present study is devoted to the sedimentology and paleogeography of the Middle Devonian of the Novaya Zemlya archipelago. It is based on long-term field observations and laboratory study of sedimentary rocks. Special attention is paid to the characteristics of sediment accumulation in the conditions of the submarine slope and base-of-slope. The archipelago of Novaya Zemlya is a folded belt in Russian Arctic. It is composed mostly of Paleozoic sedimentary rocks. Devonian deposits are predominant among them. Beginning from the end of the Early Devonian, two structural-facial zones are recognized here: Barents and Kara named according to the seas bounding them. The interaction between these zones controlled the facies distribution till the beginning of the Permian. Main controls on depositional patterns in both areas were provided by relative sea level fluctuations. The Barents zone is characterized by shallow marine, mostly carbonate deposits and is considered to be a shelf. The Kara zone is built of fine organic rich sediments interpreted as hemipelagites. Sediment gravity flow deposits are also common. Turbidites, exotic blocks (olistoliths) have been recognized among the middle Devonian deposits. Olistoliths consist of shallow-water bioclastic Lower Devonian limestones originating probably from nearby steep shelf break. Different-scale sliding occurred in many places, in one of locations specific “roulette” structures have been found. The relative sea level highstand caused widespread deposition of black shales in the Eifelian. In the Givetian, the paleogeographic situation of the Eifelian time preserved. Deep marine conditions expanded over the Novaya Zemlya except its north-east end. The presence of slides and sediment gravity flows implies significant slope steepness and seismic instability of the basin floor. During the Givetian, tectonic movements became more vigorous causing formation of a series of faults which were conduits for basaltic magma. At the end of the Givetian, the relative sea level fall accompanied by block tectonic movements occurred. As the result of these the upper part of the Devonian deposits in the central part of the South Island was exposed and eroded.

Keywords

Novaya Zemlya, Middle Devonian, Sedimentary Basin, Turbidites, Olistoliths, Slides

1. Introduction

The archipelago of Novaya Zemlya is situated in the Russian Arctic between the Barents and Kara seas.

The bottom of both seas as well as neighboring Timan-Pechora and North West Siberia regions are well known oil-and-gas prone basins (Figure 1).

The territory of the archipelago is a part of the Pai-Khoi-Novaya Zemlya folded system. It is built of Upper Proterozoic to Lower Mesozoic rocks (Figure 2). The Permian and Devonian

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rocks are most widespread among them. The latter are very diverse and have been deposited in a wide spectrum of sedimentary environments. Lithological properties and facies distribution are the main controls on the reservoirs and sources of hydrocarbons. That is why the structure, composition and sedimentary history of Devonian rocks have been thoroughly studied in Novaya Zemlya during the last decades. New data obtained by the author and his colleagues in 2004-2006 and in 2016 [5, 6, 13] in combination with the previous data made it possible to refine the model of the Novaya Zemlya sedimentary basin in the Middle Devonian.

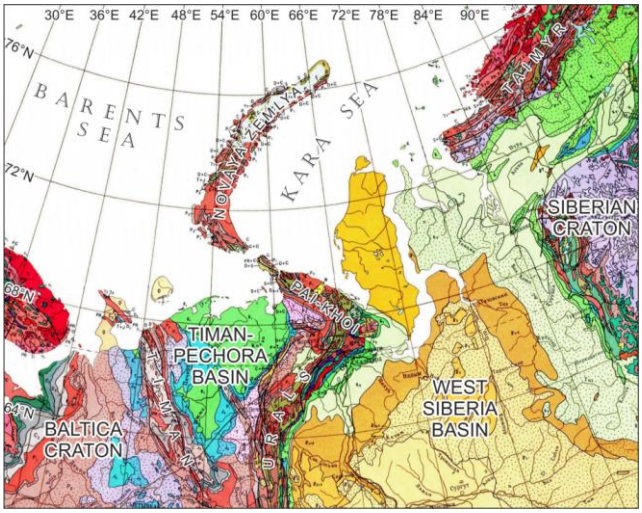

Figure 1. *General position of the Novaya Zemlya archipelago.*

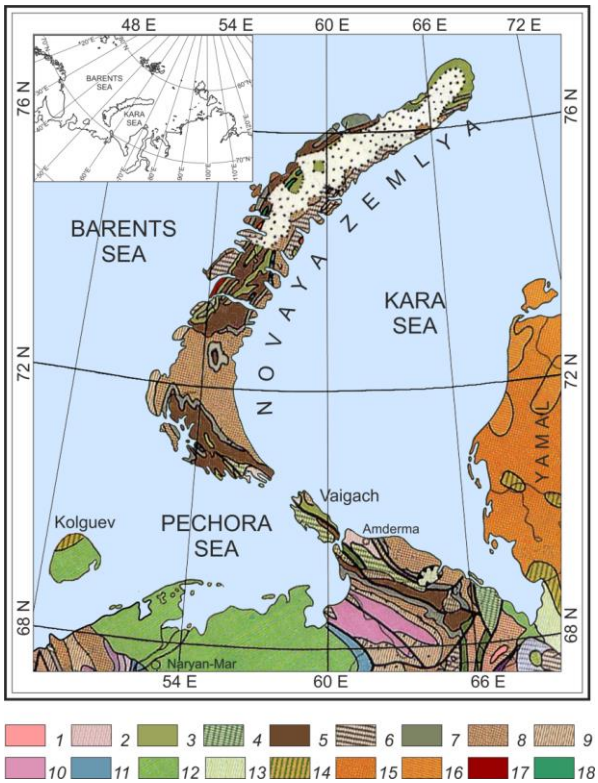

Figure 2. *Schematic geological map of Novaya Zemlya.*

Legend: *1* – Mesoproterozoic; *2* – Neoprotereozoic; *3* – Ordovician; *4* – Silurian;
5 – Devonian; *6* – Devonian- Carboniferous; *7* – Carboniferous; *8* – Lower Permian;
9 – Upper Permian; *10* – Triassic; *11* – Jurassic; *12* – Lower Cretaceous;
13 – Upper Cretaceous; *14* – Upper Cretaceous-Paleocene; *15* – Paleocene;
16 – Eocene; *17* – granites; *18* – dolerites

2. Geological Background

Two sedimentary areas are distinguished in Novaya Zemlya due to compositional, structural and paleoenvironmental peculiarities of the Devonian deposits: the Barents and Kara ones [2, 11]. Separation of the Novaya Zemlya sedimentary basin into these areas started in the Emsian. The Barents area is characterized by thick, predominantly carbonate deposits. These contain a diversity of benthic fossils. These strata are considered to be deposited in a shallow-water shelf environment. In contrary, the Kara area is distinguished by shales, cherts and micritic carbonates. These contain only scarce pelagic fossils. Benthic fossils are found here only in allochtonous deposits. The thickness of coeval strata is here several times less than in the Barents area. These deposits are suggested to form on a slope and basin floor.(Figure 3).

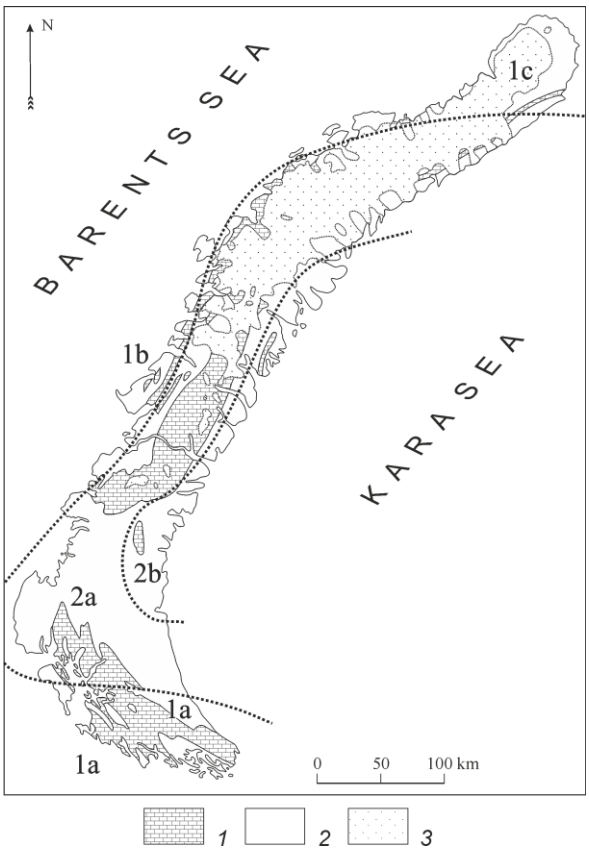

Figure 3. *Sedimentary areas: 1 – Barents (1a – south, 1b – central, 1c – north parts); 2 – Kara (2a – slope, 2b – basin). Legend: 1 – Devonian; 2 – Pre- and Postdevonian; 3 – glacier.*

Main controls on depositional patterns in both areas were provided by relative sea level fluctuations. Relative sea level highstands correspond to periods of low sedimentation rates in the deep-water environments [6, 12, 13]. Sediment gravity flows were confined to rare low-density turbidity currents. Stagnant conditions favoured organic matter preservation. Relative sea level lowstands, in contrary, caused higher sedimentation rates, increased sediment gravity flows activity and better water aeration.

In the Middle Devonian, shallow marine conditions remained only in the extreme south and north-east of the archipelago whereas the most part of the archipelago was occupied by deeper water basin and slope environments. Deep-water facies are represented by hemipelagites and sparse turbidites. Types of rocks, sedimentary environments and depositional processes are considered here.

2.1. Stratigraphy

The Middle Devonian shallow-water deposits are represented by the Rozinskaya, Kabaninskaya and Chernogubskaya formations (Figure 4).

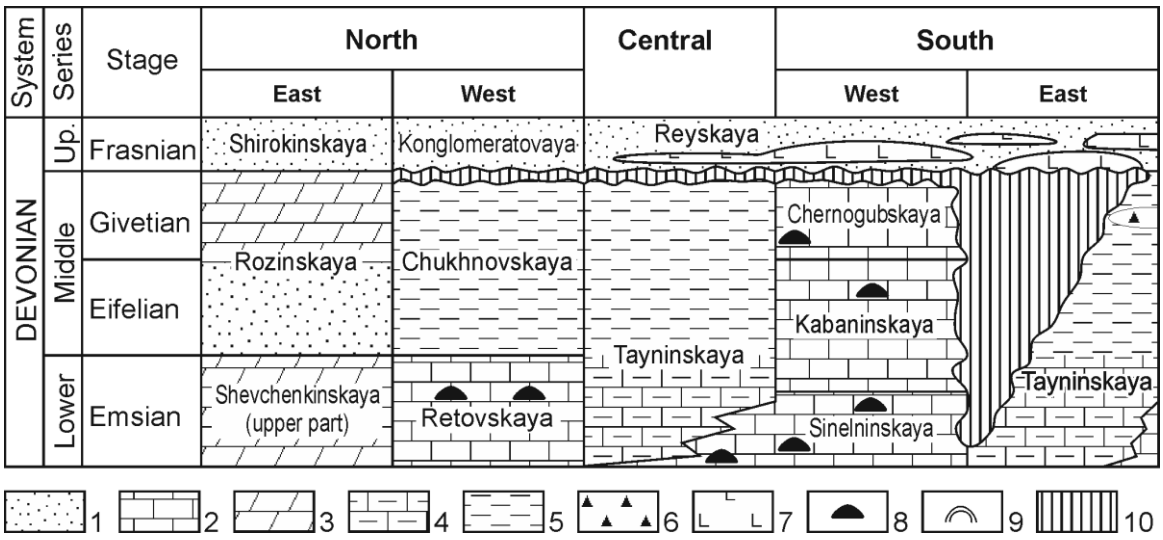

Figure 4. *Stratigraphy of the uppermost Lower Devonian to the lowermost Upper Devonian (Guo et al., 2010). 1 – coarse siliciclastics; 2 – shallow marine limestones; 3 – dolostones; 4 – deep water limestones; 5 – black shales; 6 – cherts; 7 – basalts; 8 – carbonate buildups; 9 – stromatolites; 10 – non deposition/erosion.*

Rozinskaya Formation is known from the northeastern Novaya Zemlya. Its complete section has been reported from the river Shirokaya [9]. The lower part of the formation, 130 m thick, consists of small-to-coarse-grained quartz sandstones, intercalated with mudstones, siltstones and granule conglomerates. The thickness of sandstone beds is 1 to 3 m, in some cases up to 6 m. Cross stratification, ripples and bioturbation are common. The granule conglomerates form beds up to 1 m thick. They often contain bioclasts and mudstone pebbles. *Tabulata* coral colonies are met throughout the unit. In the upper half of the unit, brachiopod limestone seams, up to 20 cm thick, are included into the mudstone beds. The rocks of this unit are suggested to be deposited in storm-dominated shoreface to shallow marine environments. It is presumed that this part of the Rozinskaya Formation is of the Eifelian age [9]. The upper part of the formation, 430 m thick, is represented mostly by coral limestones (biostromes?) interbedded with dolostones. Both rock varieties occur in beds 0,2 to 1,0 m thick. The uppermost 30 meters of this unit consist of fine crystalline limestones with intercalations of shelly brachiopod limestones. The sedimentary environment for this unit is suggested to be a flat carbonate bank below the fair weather wave basis. The geological age of the upper part of the Rozinskaya Formation is assumed to be the Givetian.

Kabaninskaya Formation crops out in a relatively small area in the south of Novaya Zemlya. Its section has been described from the Kabaniy peninsula [3, 4]. The predominant rocks here are dark organic-rich wackestones and packstones containing carbonate buildups up to several tens of meters thick [8]. This formation corresponds to the Eifelian [3, 4].

Chernogubskaya Formation possesses even smaller territory than the Kabaninskaya Formation and crops out in the neighborhood of the Chernaya Guba bay in the south of Novaya Zemlya. The section of these deposits has been described by Miloradovich [7]. The rock types of this formation are very similar to those of the previous one. The geological age of this formation is the Givetian [3, 4]. It is obvious that the sedimentary environments for both formations were shallow marine and remote from sources of siliciclastics.

The contemporary deep marine units are the Upper Taininskaya and Chukhnovskaya formations (Figure 4).

Tayninskaya Formation is the most widespread middle Devonian unit in Novaya Zemlya. It has been described by Burskiy et al. (1981) from the surroundings of Taynaya Bay in the south Novaya Zemlya and later traced throughout the central part of the archipelago. Its lower part consists mostly of black lime mudstones and is of Lower Devonian age [2, 4]. Upper Tayninskaya Formation is of Middle Devonian age [2, 4] and consists of black shales with some proportion of sandstone beds in its upper part.

Chukhnovskaya Formation has been described from the Russian Harbour in the north of Novaya Zemlya [1]. It consists also of black shales and is considered to be of middle Devonian age. Both the Upper Tayninskaya and Chuknovskaya formations contain deposits which are interpreted as products of sediment gravity flows. The latter are considered here.

2.2. Sedimentology

Black shales (mudrocks) constituting the Upper Tayninskaya Formation are black argillaceous rocks almost non-transparent in thin sections, but with relatively low TOC content (2-5%). They consist of illite with admixture of chlorite and sericite. Quartz silt is also present both in microseams and dispersed throughout the rock. They are thinly laminated with no evidences of bioturbation. Rare intercalations of micritic limestones contain only fossils of planktonic and nektonic organisms (mainly tentaculites and conodonts). Towards the eastern side of the archipelago, black chert (phtanite) intercalations appear. These rocks are interpreted as hemipelagites. Gravity displaced sediments include slides, slumps, debrites and turbidites.

Slides of different scale are common. Evidences of sliding or, probably, of sediment creep appear mostly in form of minor folds and microfaults (Figure 5). Larger scale deformation include very complicated disharmonic folds (Figure 6) and, in some cases, irregular sandstone bodies (Figure 7).



Figure 5. *Minor slide-related deformations in black shales of the Tayninskaya Formation. The ruler is 25 cm long.*



Figure 6. *A fragment of a large slide in black shales and sandstones of the Tayninskaya Formation (the person in front is geologist Dmitry Kotel'nikov).*



Figure 7. *Irregular sandstone body incorporated into black shales of the Tayninskaya Formation. Note the abrupt termination of the body.*

Very unusual structures related to sliding have been met in the Tayninskaya Formation near the Mityushikha Bay in the North Island. Laminated lime mudstones are convolute into specific "roulettes" several centimeters to tens of centimeters in diameter (Figure 8). These are interpreted as a result of friction between the slide body and underlying strata.

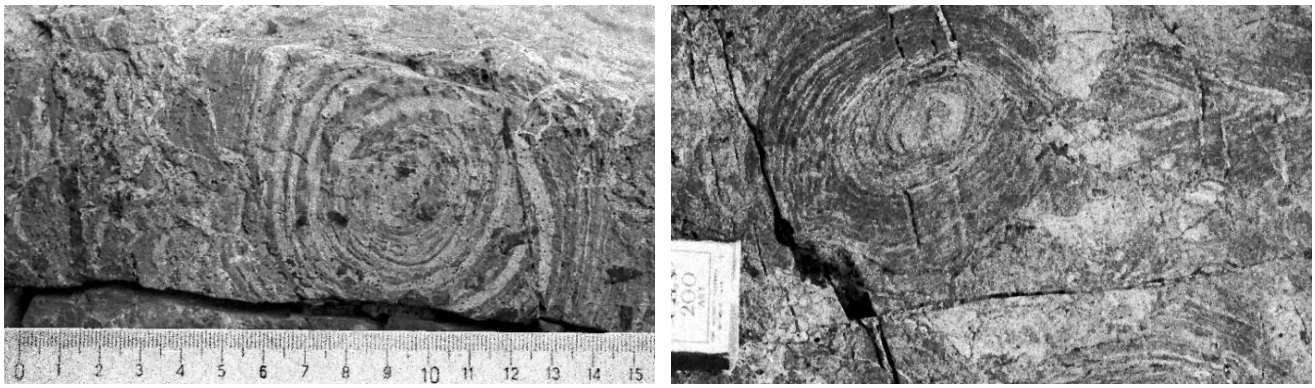

Figure 8. *Slide "roulettes". The ruler is in centimeters, the match box is 4 centimeters wide.*

Turbidites are met in the upper part of the Upper Tayninskaya Formation in the neighborhood of the Taynaya Guba bay. These are pure quartz sandstones (not greywackes) coarse- to fine-grained, graded or massive, turning into parallel stratified to the top. They occur in beds 10 centimeters to 3 meters thick. Many beds contain intraclasts (soft clasts) of mudstones (Figure 9). The quartz grains are well rounded and sorted. The heavy fraction is represented by a zircon complex (up to 35.4% of well-rounded zircon) [10]. The maturity of the sediment suggests that its source were ancient sedimentary rocks eroded in a calm tectonic setting (probably within the Baltica craton).

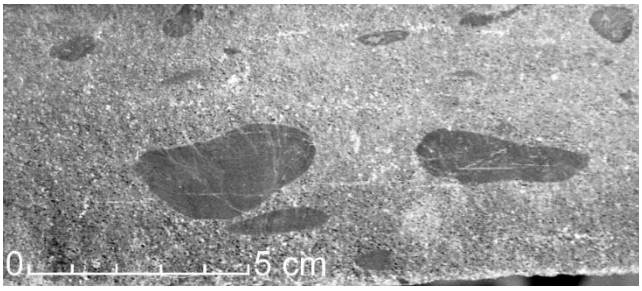

Figure 9. *Mudstone intraclasts at the bottom of a turbidite graded sandstone bed.*

On the bed tops, some current marks are met (shadow marks, stream marks) (Figure 10) which are interpreted as the spurs of the vanishing turbidite current.

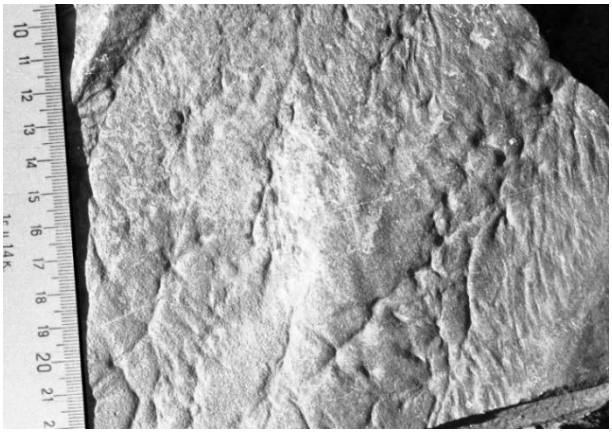

Figure 10. *Current marks on the top of a turbidite sandstone. The ruler is in centimeters.*

The bottoms of beds exhibit flute, groove and load casts (Figures 11, 12) of different scale.

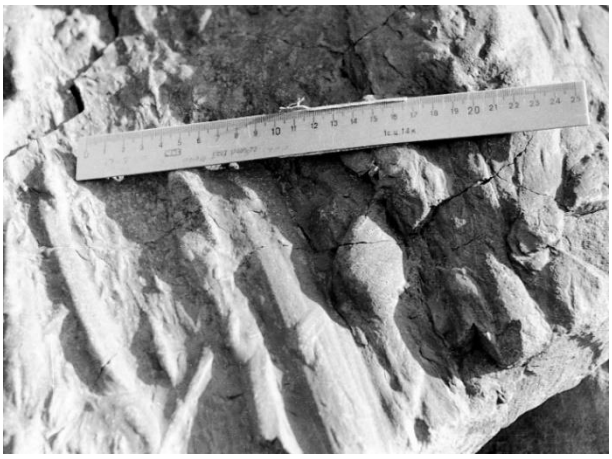

Figure 11. *Flute and load casts on the bottom of a turbiditie bed. The ruler is 25 cm long.*



Figure 12. *Large groove casts on the bottom of a turbidite. White are calcite veinlets. The outcrop height is about 2 m.*



Figure 13. *A large block (olistolith) of bioclastic limestone, incorporated into black shales of the Chukhnovskaya Formation, Russian Harbor. The outcrop height is about 10 meters.*

The size of these marks is suggested to be related to the velocity and erosional capacity of the turbidity current, thus, some of the currents were very rapid and, consequently, evolve on a relatively steep slope.

Even more drastic gravity driven mass movements occurred in the central and northern parts of Novaya Zemlya. For example, large olistoliths of shallow-water limestones with brachiopod fossils have been found in the Russian Harbor Bay (Figure 13).

The dimensions of the largest of them are 20/20/10 meters [1].

3. Facies Interpretation and Paleogeography

In the Middle Devonian, the accelerated subsidence of the central and eastern parts of the Novaya Zemlya paleobasin, started in the Emsian, continued. Shallow water carbonate shelf environments remained only in the extreme south and north of the archipelago (Figure 14).

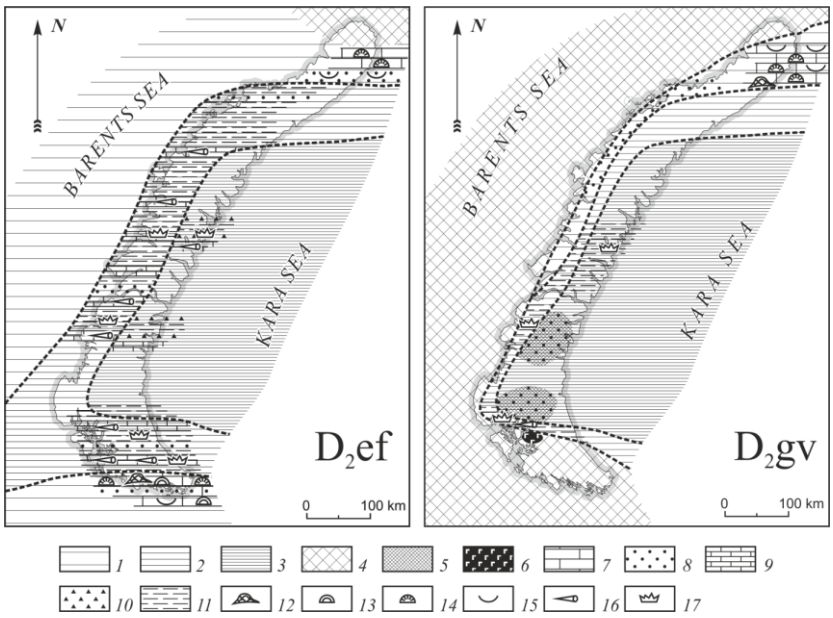

Figure 14. *Paleogeographic maps of the Middle Devonian Novaya Zemlya basin.*

Legend: *1—5* – environments. *1* – shallow marine shelf; *2* – slope; *3* – deep water basin; *4* – continental (non-deposition or erosion); *5* – submarine fan. *6—12* – lithologies: *6* – basalts and tuffs; *7* – shallow marine carbonates; *8* – siliciclastics; *9* – deep marine limestones; *10* – cherts; *11* – mudstones; *12* – reefs. *13—17* – fossils: *13* – stromatoporoids; *14* – corals; *15* – shelly fauna (mollusks, brachiopods); *16* – dacryoconarids; *17* – conodonts

The relative sea level highstand caused widespread deposition of black shales in the Eifelian. In the southernmost part of the archipelago, there occurred accumulation of carbonate, mainly bioclastic, sediments containing skeletal remains of stromatoporoids, corals, brachiopods, bivalves, gastropods, etc. Biogenic buildups continued to grow, and bioclastic sediments accumulated in inter-reef depressions. The supply of silt- and sand-sized siliciclastc material increased, which probably had a depressing effect on the development of communities of reef-building organisms: the size and number of biogenic buildups decreased in comparison with that in the Emsian. Bioherms do not exceed 1.5 m in thickness.

To the north, the deeper water conditions occurred. Black organic-rich carbonate-clayey muds deposited here. Fossils of benthic organisms are absent, only pseudoplanctonic (tentakulites) and nektonic (conodonts) fauna remains are met. This suggests anoxic bottom water conditions. Futher to the north, in the northern part of the South island, non-carbonate organic-rich clayey muds accumulated. Turbidite currents and slides occurred periodically. Analogous conditions existed along the Barents sea side of the North island. The water depth increased towards the Kara sea side where the mudrocks were partly replaced by black siliceous sediments.

In the Givetian, the paleogeographic situation of the Eifelian time preserved. In the south, in those places where deposits of this age have been preserved from erosion (near the Karskie Vorota Strait), they are mainly represented by biogenic and bioclastic formations. Carbonate buildups are represented by fairly large brachiopod-algae and algae-stromatopore-coral biogerms (from a few meters to the first tens of meters in thickness). The inter-reef depressions were filled with bioclastic material and clay-carbonate muds with an admixture of quartz silt, containing a rich and diverse complex of fossils predominantly brachiopods.

In the central part of the South Island black carbonate-free clays were deposited. Apparently, these sediments accumulated at considerable depths, on the underwater slope, probably below the depth of the carbonate compensation. The high content of organic matter and finely dispersed pyrite suggests the existence of reducing conditions in the bottom and pore waters. The presence of slides and sediment gravity flows implies significant slope steepness and seismic instability of the basin floor. During the Givetian, tectonic movements became more vigorous causing formation of a series of faults which were conduits for basaltic magma. It is supposed that for a short time there existed small volcanic apparatuses of the central type, the eruptions of which had explosive character [14].

Deep marine conditions expanded over the rest of Novaya Zemlya except its north-east end. In the vicinity of the Ice Bay and Shirokaya River shallow marine carbonate-sliciclastic sediments were deposited.

At the end of the Givetian, the relative sea level fall accompanied by block tectonic movements occurred. As the result of these the upper part of the Devonian deposits in the central part of the South Island was exposed and eroded.

4. Conclusions

At the end of the Early Devonian, the previously existed more or less uniform shallow marine Novaya Zemlya basin started to separate into two structural-facial zones. The central and eastern parts of the modern archipelago undergone accelerated subsidence. During the Middle Devonian, the difference between these zones increased that led to formation of deep-water slope and base-of-slope environments. Hemipelagites and gravity induced mass flow sediments deposited here. The latter include siliciclastic turbidites, exotic blocks and slides. Some unusual features related to the slides have been recognized. They are represented, in part, by amusing “roulettes” originated from the friction zone between the slide body and the underlying strata. Hemipelagites are black organic rich claystones intercalated with mictritic limestones containing fossils of pelagic and nektonic organisms. These rocks are replaced by black cherts (phtanites) towards the Kara sea side.

Paleogeographic situation evolved from the vast epeiric sea in the Early Devonian to the transition between shelf and slope-base- of slope in the Middle Devonian. Shallow marine conditions remained only in the extreme south and north-east of the modern archipelago. The pre-rifting elevation of the south part of the basin in the end of Givetian caused erosion of the upper part of the deposits. Tectonic movements were accompanied by minor volcanic eruptions of explosive type.

Abbreviations

TOC Total Organic Carbon

Acknowledgments

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Author Contributions

Roman Schekoldin: Conceptualization, Data curation, Formal Analysis, Methodology, Visualization

Conflicts of Interest

The author declares no conflicts of interest.

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