# Lithological and geochemical characteristics of Triassic sediments from the central part of the South Barents depression (Arkticheskaya-1 well)

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## Abstract

The thickest section of the upper Triassic deposits in the South Barents depression is penetrated by the Arkticheskaya-1 well. Core samples from this well were analysed for lithology, palaeontology and geochemistry. Different environments of deposition were interpreted on the basis of these analyses. Continental and coastal facies dominate, but some short-term sea ingressions were also identified. The geochemical data include qualitative and quantitative characteristics of the organic matter and bitumen. Maturity-related changes are described, and the zone of optimum conditions for the generation of hydrocarbons is determined. Ladinian and Carnian deposits are found to be the major source of hydrocarbon-rich rocks: they are dominated by humic kerogens, and are of a maturity within the 3990–4515-m oil window. Triassic deposits of the Barents Sea region represent different depositional facies; consequently, a wide variety of lithologies are present. An integrated study of the sedimentary rocks provides information on the textural and mineral composition, organic geochemical parameters, the structural features and the fossil content to interpret their depositional environments, and their oil or gas potential.

In the Barents Sea region, Triassic deposits obtained through stratigraphic and explorative drilling on the continental shelf, as well as from natural exposures in the archipelagos of Svalbard and Arctic Russia, were studied. The findings of Russian geologists working on this material have been summarized by Gramberg et al. (1993) and Gramberg et al. (2004). Joint presentations by Russian and Norwegian scientists evaluating the Russian and Norwegian areas were published following the Norwegian Petroleum Society Conference in Tromsø in 1990 (Johansen et al. 1992; Leith et al. 1992; Mørk et al. 1992).

In the central part of the South Barents depression, the thickest succession (about 700 m thick) of Middle and Upper Triassic deposits (upper Ladinian, Carnian and Norian) was obtained in the exploration well Arkticheskaya-1, drilled by Arkticmorneftegazrazvedka in the 1980s to a total depth of 4524 m (Figs. 1, 2). The uppermost Upper Triassic sediments do not have palaeontological age control.

This article presents the lithological characteristics and results from laboratory analyses of the Triassic deposits in this well, which represent important data points in the eastern Barents Sea.

## Materials and methods

The Middle–Upper Triassic succession of Arkticheskaya-1 was characterized on the basis of eight cores covering about 10% of the total length of the Triassic section. More than 130 samples were analysed for petrography by examining thin sections, and calculating the total organic carbon (TOC) content, using Knopp's method, and clay fractions, analysed by X-ray diffraction (DRON-3, CuKα, 0.5° $min^{-1}$). Porosity was determined using the saturation method, and permeability was determined using a filtration test. Measurements of vitrinite reflectance were carried out by microspectrophotometry. About 25 samples were analysed for pyrolysis response with a Rock-Eval instrument (Integrated Geochemical

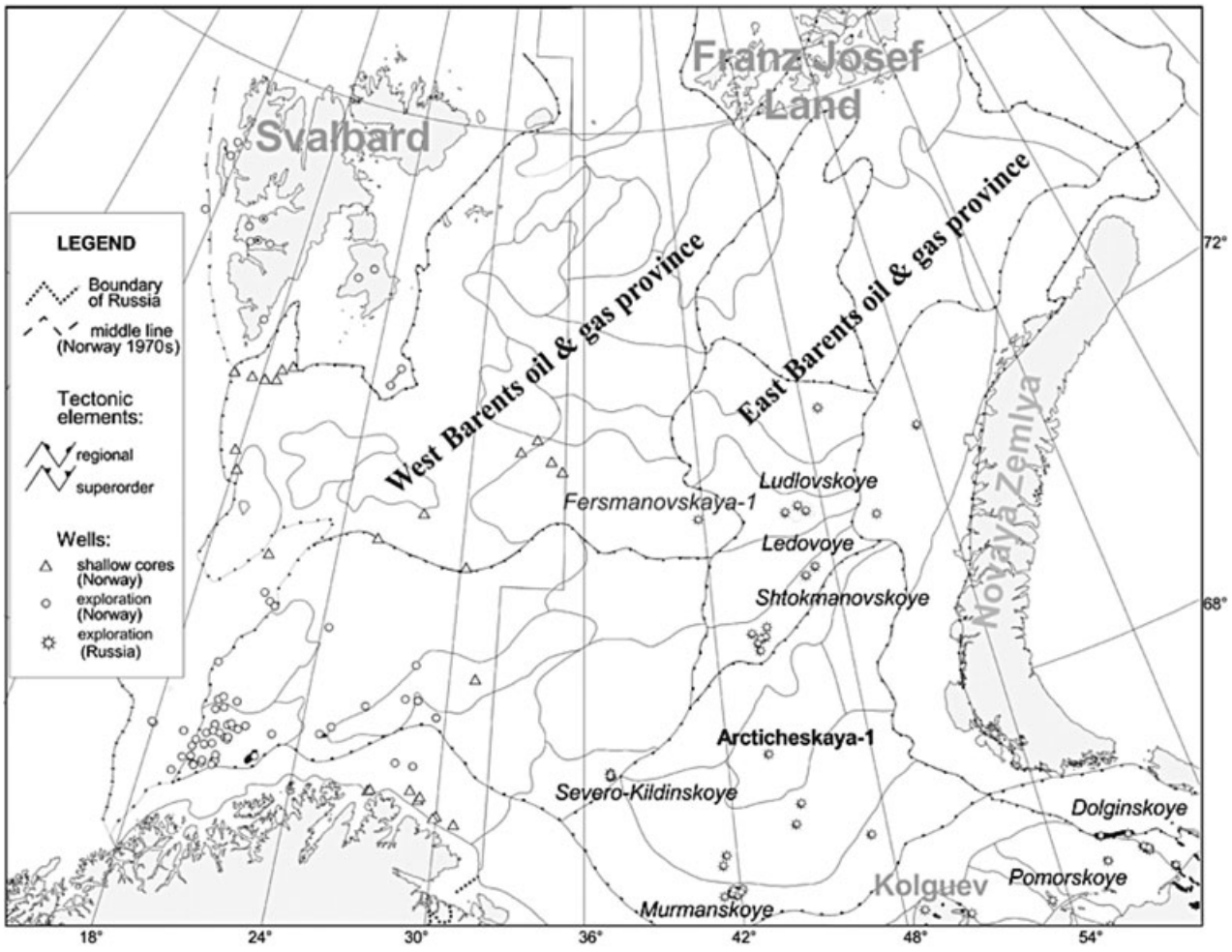


**Fig. 1** Simplified geological map of the Barents Sea region showing the locations of Arkticheskaya-1 and other wells.

Interpretation Ltd., Bideford, Devon, UK). About 30 samples were subjected to the Soxhlet method of solvent extraction, using chloroform, and the chemical and group composition was studied for bituminoids using gas chromatography–mass spectrometry. Analytical data were obtained in the laboratories at the All-Russia Research Institute for Geology and Mineral Resources of the World Ocean.

## Characterization of lithology and organic matter: results and discussion

### Ladinian

Ladinian deposits from the two core intervals 4505–4515 and 4488–4500 m are represented by shales, siltstones, and clayey siltstones and sandstones. In the lower Ladinian part, fine-grained sandstones with high concentrations of mainly detrital chlorite (Fig. 3a) pass into lenticular-laminated grey and brown argillaceous siltstone.

The clastic fractions are composed of quartz, rock debris, feldspars, muscovite, chlorite and coaly plant fragments. In the clay, cement chlorite (35%), illite (30%), kaolinite (23%) and illite/montmorillonite mixed layers (10%) predominate. Permeability is low, but the permeability perpendicular to the bedding (1.44 mD) is one order higher than the permeability measured along the bedding (0.13 mD). This is probably explained by the presence of microcracks.

The overlying section is dominated by brown, horizontally laminated coaly shales, clayey siltstones and argillaceous–silty sandstones. In the claystone, illite (37%) and kaolinite (29%) predominate, the average chlorite concentration is 26% and mixed-layer clay minerals contribute 12%. Diffuse bitumens are also present. The porosity of shales and argillaceous siltstones ranges from 5.2 to 6.9%.

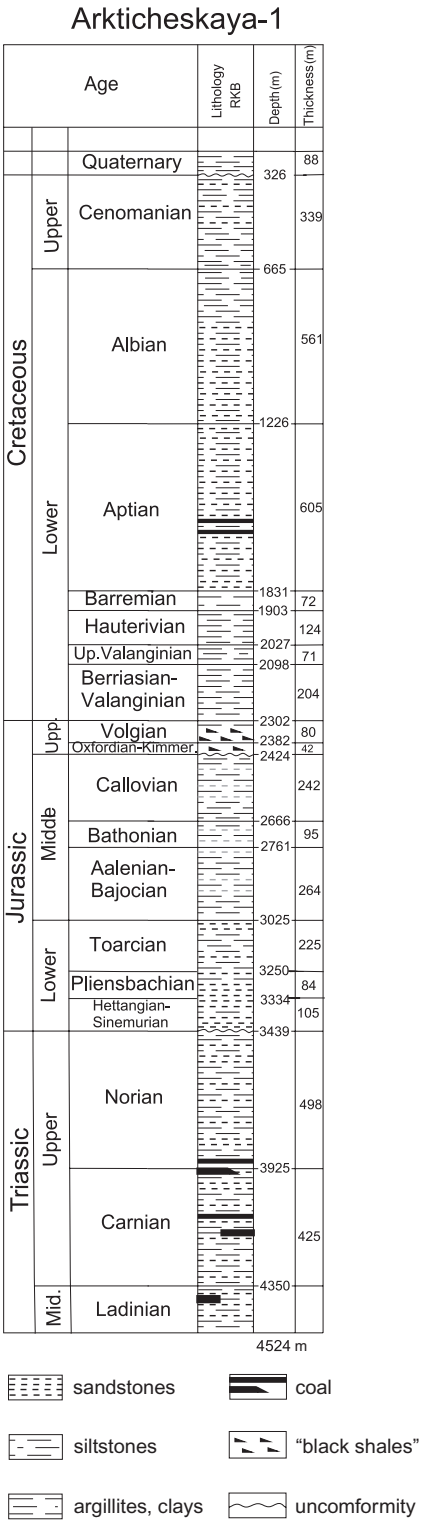


**Fig. 2** Lithostratigraphic column of the Arkticheskaya-1 well.

The average TOC content of Ladinian argillaceous rocks from the interval 4505–4515 m is 0.76%, and chloroform bitumen (ChB) yields are 0.01–0.03% of the rock weight. The bituminological factor $\beta$, i.e., the weight of chloroform extract expressed as a percentage of the weight of the TOC, is more than 60%, which indicates that the bitumen is migrated. Rock-Eval pyrolysis $S_1$ (the content of oil) varies from 0.06 to 0.23 mg hydrocarbon (HC) per gram of rock; $S_2$ (the oil potential of organic matter) ranges from 0.12 to 0.86 mg HC per gram of rock; the oil production index ($OPI = S_1/[S_1 + S_2]$) is on average 0.24; *HI* (hydrogen index), the parameter of kerogen quality, varies from 51 to 70 mg HC per gram of TOC; $T_{max}$ values range from 466 to 470°C; vitrinite reflectances ($R_o$) values are typically on the order of 0.97–1.0%.

From a depth of 4500 m, the Ladinian sediments are characterized by increasingly calcareous shales, siltstones and silt–sandstones. Dark-brown, horizontally laminated calcareous sandy–argillaceous siltstones, with microfractures along the bedding, and with porosities of up to 20% occur. The clay fractions have average compositions of 33% chlorite, 31% illite, 26% kaolinite and 9% mixed-layer clay minerals.

At a depth of 4488 m, spherulitic sideritized concretions are observed. These presumably represent recrystallized *Microcodium* (Maslov 1973) fossils, saturated by primary bitumen (Fig. 3b). The clay phase of this layer is characterized by high quantities of kaolinite (up to 40%) and mixed-layer phases (up to 15%).

The average TOC content for Ladinian argillaceous rocks from this interval is 0.73%, and ChB accounts for 0.04–0.07% of the rock weight; Rock-Eval $S_1$ is on average 0.14 mg HC per gram of rock, $S_2$ ranges from 0.31 up to 0.47 mg HC per gram of rock, the OPI is on average 0.25, *HI* varies from 55 to 70 mg HC per gram of TOC, $T_{max}$ ranges from 459 to 466°C and a single $R_o$ value of 0.97% was obtained.

The Ladinian rocks in both intervals are mainly of clastic nearshore type, with a strong terrestrial input and some admixture of alga matter. According to the classification of source rocks (Tissot & Welte 1978; Peters 1986), they have a poor initial potential for the generation of liquid hydrocarbons, and their maturity is at the base of the oil window.

## Carnian

Carnian deposits are cored in the intervals 4213.4–4224.4, 4082–4096, 4037–4047, 4001–4013 and 3946–3951 m.

At a depth of 4224–4217 m, the fine-grained quartz–graywacke sandstones, rich in red to black bituminous coaly plant remains, are interbedded with calcareous

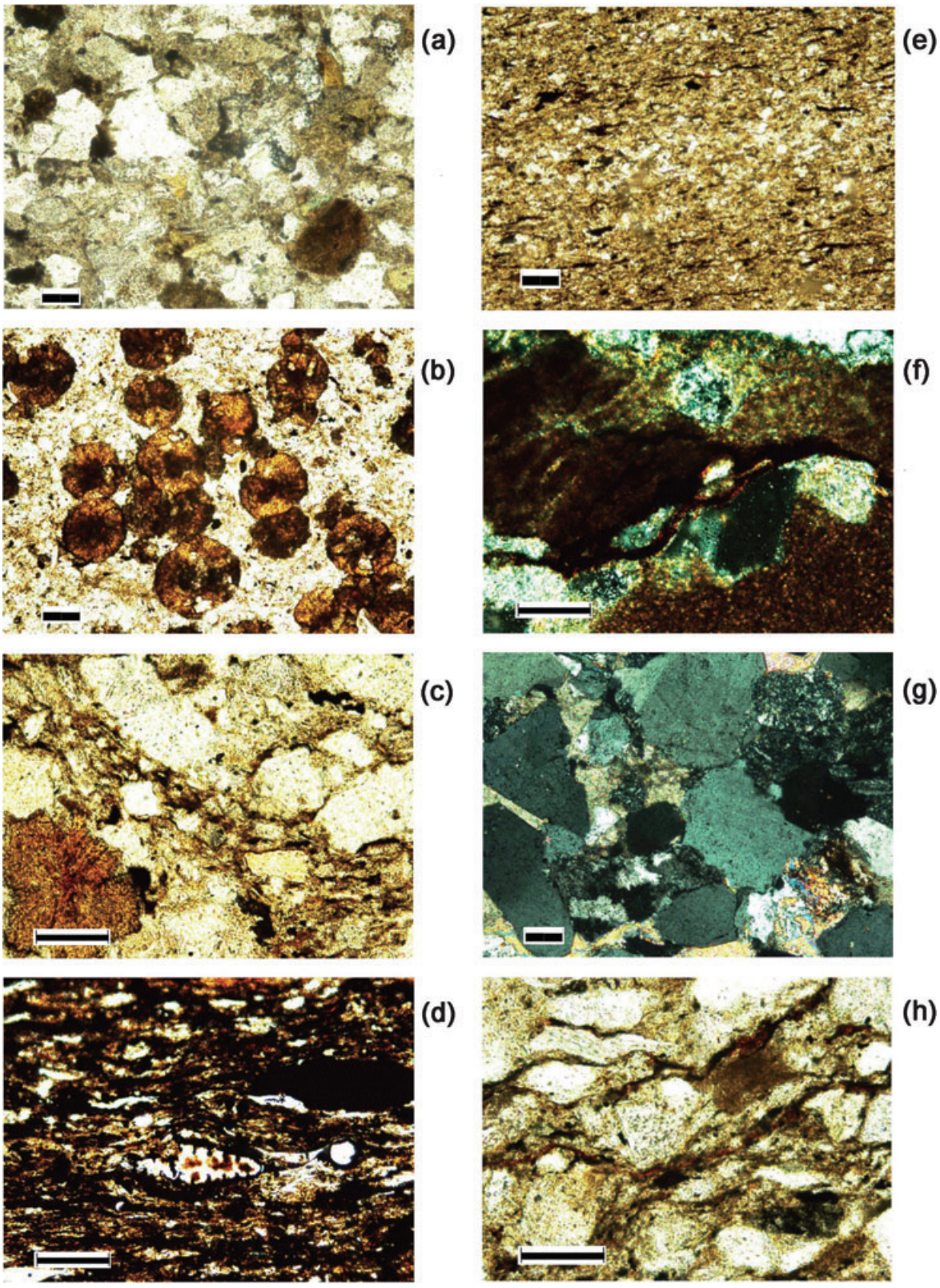
(a)
(e)
(b)
(f)
(c)
(g)
(d)
(h)

**Fig. 3** Photographs of thin sections. Scale bars are 0.1 mm. (a) Quartz–graywacke fine-grained sandstone with detrital muscovite, chlorite and coaly fragments. Depth from top of core: 4505 + 2.2 m, nicols II. (b) Microcodium in the silty shale. Depth from top of core: 4488 + 1.8 m, nicols II. (c) Quartz–graywacke fine- to medium-grained sandstone with coaly fragments, Microcodium and primary bitumens diffused in microcracks. Depth from top of core: 4216 + 3.1 m, nicols II. (d) Dark brown-black horizontally laminated shales with the thin-lenticular siliceous spots resembling recrystallized microfossil fragments. Depth from top of core: 4216 + 1.1 m, nicols II. (e) Silty shale with a lot of coaly fragments. Depth from top of core: 4082 + 3.8 m, nicols II. (f) Medium-grained sandstone with calcareous fragments containing bitumens. Depth from top of core: 4001 + 4.3 m, nicols X. (g) Quartz–graywacke medium-grained sandstone. Depth from top of core: 3946 + 0.5 m, nicols X. (h) Fine- to medium-grained quartz–graywacke sandstone with detrital mica and authigenic calcareous cement (5–7%). Depth from top of core: 3828 + 1.1 m, nicols II.

clayey siltstones, coaly sandy–silt claystones and coal shales. The carbonates are present mainly as fragments of micritic limestones and as spherulitic sideritized fossils (*Microcodium*), similar to that occuring in the Ladinian layer at 4489.8 m (Fig. 3c). In the micropores of calcareous micrite, diffuse primary bitumens are widely distributed.

At a depth of 4217 m there are dark-brown/black horizontally laminated shales with thin lenticular siliceous spots resembling recrystallized alga fragments (Fig. 3d).

In these shales, mixed-layer clay minerals account for > (up to) 5% of the composition, and the kaolinite content varies up to 40% of the composition. The average composition of the clay fraction is 35% illite, 28% chlorite, 33% kaolinite and 4% of mixed-layer clay minerals, with up to 20% montmorillonite layers in the mixed-layer clay minerals.

In the sediments of this horizon numerous fragments of ostracods, foraminifers and fragments of pelecypods are present. Jakovleva (unpubl. data [1989]) reports foraminifers in various systematic compositions (*Lituolidae*, *Ataxophragmiidae* and *Nodosariidae*) with both agglutinated and calcareous walls. The fossils are strongly deformed and recrystallized. Among the secretory foraminifers, *Astacolus minita* (Bornemann) is typical for the layers with Carnian microfauna of the Nordvik area, in East Siberia. Presence of these foraminifers supports marine depositional environments for the sediments. Kolesnikov (unpubl. data [1989]) reports mollusc shells indicating a low-salt (12–15 ‰) environment, possibly a restricted basin gradually transformed to open sea.

The TOC contents for this interval reach 4% (average 1.94%), and the chloroform bitumen yield gives a value of up to 0.27% of the rock weight (average 0.14%). In the bitumen composition, the $C_{15}$+ saturated hydrocarbon fraction (up to 50%) and heavy aromatic hydrocarbons (33–37%) prevail (Sorokov & Krasnova 1993). The bituminological factor $\beta$ is about 7–15%, and sharp increases are recorded at shallower depths (4082–4096 m), where $\beta$ reaches 50%, indicating the migration of hydrocarbons. A single Rock-Eval analysis at 4216 + 1.1 m gave an $S_1$ value of 0.42 mg HC per gram of rock, an $S_2$ value of 1.51 mg HC per gram of rock, an *OPI* of 0.24, an *HI* of 232 mg HC per gram of TOC and a $T_{max}$ value of 450°C. The kerogen belongs to type II. The single $R_o$ value is 0.8%. The shales of this horizon are characterized by increased levels of vanadium (up to $2 \times 10^{-2}$%).

The sediments of this interval belong to nearshore shale facies, with intermediate source rock potential and maturity within the oil window.

Interbedded sandstones, siltstones and shales occur between 4082 and 4096 m in a slightly coarsening upward succession. The composition of rocks includes fragments of micritic limestones, muscovite, chlorite and coaly plant fragments (Fig. 3e). The compositions of clay fractions of all lithotypes are very similar, on average 46.5% illite, 29.5% chlorite, 15% kaolinite and 9% mixed-layer clay minerals, with up to 25% expandable interlayers. The porosity of the sandstones is 2.5%. The TOC contents in this interval reach 2%, and the chloroform bitumen yields are up to 0.16% of the rock weight. Unfortunately, there are no Rock-Eval and vitrinite reflectance data from this interval.

The deposits from the interval 4037–4047 m are characterized by a gradual change upwards from calcareous clayey siltstones, silty argillites with criss-cross and subhorizontal laminations, to fine-grained sandstones with horizontal and gentle wave-like laminations. The porosity in the sandstones does not exceed 3.5%, and the permeability is low (0.38 mD). The compositions of clay fractions of all lithotypes of the interval are rather similar, and are on average 49.5% illite, 25% chlorite, 14% kaolinite and 11.5% mixed-layer clay minerals, with up to 25% expandable layers.

The average content of organic carbon is 0.15% (typical values range from 0.13 to 0.17%) in sandstones, and 1.40% (0.56–1.66 %) in argillites. In the argillites, $S_1$ ranges from 0.26 to 0.54 mg HC per gram of rock (average 0.45 mg HC per gram of rock), $S_2$ ranges from 0.97 to 2.59 mg HC per gram of rock (average 1.64 mg HC per gram of rock), *OPI* ranges from 0.17 to 0.21 (average 0.19), *HI* ranges from 96 to 201 mg HC per gram of TOC (average 144 mg HC per gram of TOC) and $T_{max}$ varies in a narrow interval of 444–446°C. The typical $R_o$ is 0.8%.

The facies varies in type from clastic coastal to nearshore shale, and in accordance with the lithotypes, the source potential changes from poor to fair.

The interval 4001–4013 m is characterized by a prevalence of fine- to medium-grained sandstones with modal sizes of 0.15–0.30 mm, and separate layers of siltstones and clayey siltstones. The clastic fractions contain up to 50% quartz, and there are a lot of micritic limestone fragments with diffused primary bitumens. In samples with high carbonate contents debituminization of calcareous fragments, with clearly expressed expulsion of bitumens from these fragments into the microcracks, is noted (Fig. 3f).

The total content of calcite in fragments and cement reaches 50%. An increase in grain size corresponds with a slight increase of porosity: up to 6–7%. The average composition of the clay fractions is 42% illite, 38% chlorite, 10% kaolinite and 10% mixed-layer phases, with up to 20% montmorillonite layers in the mixed-layer clay minerals.

The TOC contents are 0.12% in the sandstones, 0.46% in the siltstones and up to 1.2% (average 0.86%) in the clayey siltstones. Chloroform bitumen contents are 0.01% of rock weight in sandstones, and increase to 0.10% in siltstones and clayey siltstones. Average values of Rock-Eval parameters from two samples of clayey siltstones are: $S_1 = 0.17$ mg HC per gram of rock; $S_2 = 0.76$ mg HC per gram of rock; $OPI = 0.16$; $HI = 154$ mg HC per gram of TOC; and $T_{max} = 441$°C. The $R_o$ is 0.73%.

The interval 3946–3951 m basically consists of siltstones and sandstones grading from fine- to medium-grained, from the bottom to the top. The clastic fractions contain more than 50% quartz, 15% K-feldspars and about 30% of fragments of mainly siliceous rocks (Fig. 3g).

The average composition of the clay fractions is characterized by a decreased content of kaolinite compared with the section below (<3%), and a prevalence of illite (51%). Chlorite accounts for 33% and mixed-layer clay minerals contribute 14%, containing up to 25% expandable layers.

Organic carbon was determined in one sandstone sample, and accounts for 0.14% TOC, whereas the content of bitumens is less than 0.01%. Pyrolysis was not carried out, and there are no vitrinite reflectance data.

The coastal facies of the last two intervals are characterized by a grain-size increase upwards, and a prevalence of sandstones with a low degree of sorting. The porosity of the sandstones at 4001–4013 m is somewhat higher for this section as compared with the underlying layers (6.4%), and the presence of migratory bitumen ($\beta$ varies from 10 up to 30%) corresponds with this.

### Norian

Norian clastic rocks (3828–3834 m) are predominantly represented by fine-grained to fine–medium-grained sandstones, argillaceous–silty sandstones and siltstones. The authigenic cement contains about 5–7% sparite (Fig. 3h), single grains of glauconite (up to 0.2 mm in size), globular microconcretional pyrite and fine-grained plant fragments.

The average mineral contents of the clay fraction are: 48% illite, 19% chlorite, 22% kaolinite and 11% illite–montmorillonite mixed-layer clay. The chlorite shows higher magnesium content than chlorite in the underlying interval. The TOC content attains 1.13% in siltstones and 0.32% in sandstones, and the chloroform bitumens yield is 0.06%. The Rock-Eval data from a single sample are: $S_1 = 0.11$ mg HC per gram of rock; $S_2 = 0.26$ mg HC per gram of rock; $OPI = 0.3$; $HI = 81$; and $T_{max} = 435$°C.

In the Norian nearshore sediments the average TOC contents for argillaceous rocks are 0.9% (of rock weight), but the source potential of these deposits is low, and their maturity is at the beginning of the oil window.

## Conclusions

The Triassic sediments of Arkticheskaya-1 are mainly formed in continental and coastal facies, as indicated by lithological and geochemical studies (composition, structure, microfossils, qualitative and quantitative indicators of organic substance). The most fine-grained rocks are present in the Ladinian and middle Carnian. In the lower Carnian section there are shales with marine microfossils. In the Ladinian sediments planktonic calcareous algae are present. Increased calcareous content in the rocks, caused by the presence of the smallest plankton and the presence of low-salt-tolerant and normal marine microfossils in separate Triassic layers, show that the formation of these sedimentary beds took place in conditions with short-term sea ingressions.

There is a successsion of morphological appearances of the primary bituminization: a gentle bituminization of coalified plant fragments, a diffuse bituminization in argillaceous and calcaerous rock matrix, and calcaerous micrite fragments that are transitory in the bituminization of microcracks.

The Upper Triassic sediments of this Arctic area are characterized by increased bituminization—the highest concentrations of organic carbon and chloroform bitumens were recorded in Carnian coaly shales.

According to pyrolysis response and vitrinite reflectance, the sedimentary rocks span the range of thermal maturity for oil generation and preservation.

The prevalence of organic matter in the form of kerogen types II and III indicates a mainly gas-yielding potential. The data presented here are consistent with those published previously (Gramberg et al. 1993; Šipilov

& Mursin 2001; Fedorovskij et al. 2005; Bjorøy et al. 2006).

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