Secondary Reservoirs of the Bazhenov and Abalak Formations and the Structure of the Pore Space*

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Abstract

Bazhenov Formation of the West Siberian basin is the largest unconventional oil resource play in Russia. Resource concentration of the Bazhenov formation is estimated as 13 million barrels/mi^2 (EIA/ARI, May 2013). However, until now there are a lot of dry wells, and it is not yet well understood what are the causes for variations in productivity. Bazhenov Formation combines conventional and unconventional oil accumulations. Exploration of unconventional oil accumulations in North America (e.g., Bakken) show the necessity to conduct a complex analysis of core data, organic matter and generation potential and distribution, rock composition, and petrophysical properties in the search for oil reservoirs, and the pore structure, in the Bazhenov Formation.

This work presents integrated core analysis, well logging, and production tests of both highly productive wells and dry holes in order to identify oil reservoirs with different pore structure and genesis. The study area encompasses several oil fields on the western slope of Surgut swell, Salym megalithic bank and eastern slope of Krasnoleninsk swell.

Whole cores from a total of 17 wells were analyzed; core recovery was more than 80%. A total of 1500 core plugs were analyzed: thin sections, carbonate metering, XRD, XRF and Rock-Eval analysis, porosity and permeability measurements. The reservoirs were identified only in six of 17 wells with oil – production rate more 10 tons per day. A 90-reservoir sample was used for more specific studies: x-ray macro-tomography and micro-tomography, SEM.

Reservoir rocks were identified in the following lithotypes: silicates with radiolarian structure, carbonate silicates, and platy, shaly silicates of the Bazhenov Formation, limestones and dolomites of the «KS» bed confined to top of Abalak Formation or bottom of the Bazhenov Formation.

Carbonates of the «KS» bed contain movable oil only in fractures and vugs that can be tens of centimeters wide and several tens of centimeters long. Purely fractured and vuggy type of reservoirs was not identified in Bazhenov rocks studied.

Carbonate silicates and silicates have average porosity of 8.6%, permeability of 4.4 mD, and pore size up to 100-250 micrometers. Platy, shaly silicates have average porosity of 5.8%, permeability of 0.46 mD, and pore size up to 2.5-2.5 micrometers and commonly less. The largest pores are associated with those resulting from solution of skeletons of radiolarians. Smaller pores exist between individual quartz crystals/grains or quartz and dolomite or calcite aggregates. The system of the smallest pores is kerogen porosity. Kerogen porosity appears only at the end of the oil window in both carbonate silicates and in platy, shaly silicates. The ratio of pore types in reservoirs can vary according to the mineral composition of reservoir rocks and the source-rock maturation level. Pyrite is the main mineral that occludes the pore volume and degrades porosity and permeability in the Bazhenov Formation.

Introduction

Bazhenov formation of the West Siberian basin is the largest unconventional oil resource play in Russia. Resource concentration of the Bazhenov formation is estimated as 13 million barrels /mi^2 (EIA/ARI, May 2013). Nowdays oil production from the Bazhenov formation rocks is carried out from several dozen fields of West Siberia.

Bazhenov Formation is present in an area, of more than 1 million km^2, in the central part of the West Siberian oil- and gas-bearing basin (WS) and is 10 to 60m thick (average 30 m). Deposits are deeper from southern parts of WS to the northern part. For the larger part of WS overburden thickness varies from 2.5 to 3 km. Geological age of the Bazhenov Formation is latter part of early Tithonian and early part of early Berriasian (Figure 1). Almost everywhere in WS, the Bazhenov is underlain by littoral and marine sediments of the Abalak and Geogriev formations and is overlain by sandy-argillaceous clinoform sediments. Accumulations of marine sediments within Bazhenov correspond to the conditions of maximal transgression of the sea during Late Jurassic- Early Cretaceous.

The lithology of the Bazhenov depends on the ratio of biogenic and terrigenous components. Biogenic components are silica from organic skeletons and shells (content ranges from 7 to 85%), algal kerogen (content ranges from 2 to 60%) and carbonates (content varies from 2 to 20%). Concentration of pyrite is 1 to 5% (with an average value of 2.5%). Terrigenous components are represented by clayey minerals (2 to 27%). Carbonates may be the product of chemical replacement in the relation to the primary biogenic siliceous rocks. In some cases the content of chemogenic carbonates is as much as 90%. Schematic diagram of the internal structure, lithotypes distribution, mineral composition, organic-matter content, and pore systems of the Bazhenov and Abalak formations are illustrated in Figure 2.

There are numerous models pertaining to the development and distribution patterns of Bazhenov and Abalak formations (J_0) reservoirs (e.g., Belkin et al., 1983; Karnyushina, 2003; Lopatin and Yemets, 1987; Sonich, 1985), and most disagree for a number of reasons. For instance, the abnormal physical properties, including overpressure, mineralogy and brittleness, coupled with the overall thin (average 20 meters) gross interval of the Bazhenov Formation, restrict the application of seismic and well-log attributes essential for reservoir recognition. Additionally, whole core recovery in the Bazhenov is commonly poor and core analysis due to the brittle nature of the material is challenging. The main difficulty in studying the reservoir properties of the Bazhenov Formation is the composition and structure of the pore space, which is considered unusual for terrigenous reservoirs.

In general, existing models of the Bazhenov reservoirs can be divided conditionally into three groups. The first group represents the transformation of organic matter and resulting oil generation as the main reservoir-forming mechanism. The transformations result in fissile, fractured reservoirs. The models of the second group are based on the theory that the key processes are diagenetic, such as differential compaction of sediments, alternation of laminae of different mineral compositions and secondary mineral generation. The changes result in reservoirs with fractured and fractured-vuggy-pore types, common in siliceous and carbonate radiolarites. The third group includes models of fractured-vuggy reservoirs in the J_0 bed of the Bazhenov and Abalak formations, formed by normal- and high-temperature hydrothermal fluids.

In general, the majority of researchers agree that reservoir intervals within the Bazhenov and Abalak formations are formed from secondary processes, and fractures of different orders of magnitude related to structural timing are common. Based on a review of available literature, numerous contradictions and inconsistencies exist regarding the genesis of the Bazhenov Formation pore space, which is the main focus of this research.

Study Objective and Available Data

The study area is located near the axis of the Frolov Mega-depression, in the areas of the Krasnoleninsky arch and Salym mega-swell. The depth of the Bazhenov and Abalak formations in the study area ranges from 2600 to 3000 meters.

The study is based on results of core analysis, well logging and production tests of both highly productive wells and dry holes that had penetrated the Bazhenov Formation and host rocks of the Abalak Formation that underlie the Neocomian sequence. The wells were drilled within Sredne-Nazymsky, Rogozhnikovsky, Malobalyksky, Salym, Prirazlomnoye, Priobsky, Pravdinsky, Ai-Pimsky, Yavinlorsky, and Sakhalin fields, where the Bazhenov Formation is the main oil source and pay section with high-oil flow rates (Figure 3). Whole cores from a total of 17 wells were analyzed, core recovery was more than 80%. A total of 100 core plugs were analyzed, and a 90-sample subset was used for more detailed studies.

Methodology and Interpretation Principles

In the present study, a reservoir is assumed to be a rock that allows an oil inflow from a bed into the wellbore without acid treatments, hydraulic fracturing, or thermal treatments of the well and the near-wellbore zone. An effective reservoir also requires the presence of connected pore space filled with movable oil. An integrated analysis was made based on whole core material, permeability and porosity, and geochemical characteristics of organic matter to identify reservoirs in the Bazhenov and Abalak intervals.

The large amount of organic matter in the Bazhenov Formation makes it difficult to determine porosity in core samples. The use of alcohol-benzene mixture or chloroform leads to extraction of both free oil and the soluble part of organic matter, and therefore measurements of porosity after the extraction with organic solvent overestimate the porosity and permeability of the rock. We compared different methods of determining the pore space in Bazhenov rocks and demonstrated that it is best to make measurements using naphtha saturation of non-extracted samples (Khamidullin et al., 2012). Porosity values discussed in this article utilized this approach.

The presence of movable oil was determined based on Rock-Eval 6 pyrolysis parameters that included an elevated content of free hydrocarbons (S1, mgHC/g of rock), S1/S2 ratio, and high productivity indices PI (e.g., Belkin et al., 1983; Lopatin and Yemets, 1987). Reservoirs were defined based on a porosity cut-off of 4%, an absolute gas permeability of 0.01 mD, and the presence of movable oil based on Rock-Eval S1 values.

The structure of the pore space in identified reservoirs was studied using standard petrographic methods, x-ray macro-tomography and micro-tomography, and scanning electronic microscopy (SEM). The material composition of reservoir rocks was determined based on x-ray fluorescence analysis data combined with the results of x-ray phase analysis, carbonate metering, and Rock-Eval 6 pyrolysis.

The application of multiple methods was utilized because unlike traditional reservoirs, the Bazhenov rocks can contain pores, fractures, and vugs differing in size by several orders of magnitude that exist in the different rock lithotypes. The priority was to detect reservoir rock lithotypes and to test them with a minimum impact on the samples. The next step was to study the relationship of pore types in the rock and the role in the formation of reservoir properties.

Macro-tomography and calculation of the volume of the pore space are applicable to natural macro-fractures and vugs whose size and length are comparable to the size of a whole core. The major advantage of this method is the possibility of estimating quantitatively the volume of pores including not only vugs and fractures visible to the eye but also those distributed throughout the selected part of the whole core.

X-ray macro-tomography is ineffective when studying smaller pores. The morphology of porous samples smaller than 1 mm can be identified and studied in color-enhanced petrographic thin sections; however, samples with a high level of bituminous components will make the analysis challenging. Some pores can be identified and studied only by means of a scanning electronic microscope, but neither method allows the acquisition of information pertaining to the position of pores in the rock relative to each other. Porous rock samples were then studied using an x-ray micro-tomographic imager that allowed the reconstruction of the internal structure of rocks, without disturbing their integrity to an accuracy of one micrometer. This method is critical for identifying natural fractures that were not generated by the drill bit or during core plug extraction.

The sub-micromorphology of small fragments of the geological monoliths was also studied under a scanning electron microscope.. Samples were examined in secondary electron mode at an accelerating voltage of 15 kV. Elemental analysis was performed by energy dispersive spectroscopy (EDS). Study of inner structure of the samples was done by X-ray micro-tomography system SkyScan-1172. Scanning of all samples were done with equal parameters of the system (current - 100 mkA, voltage - 100 kV, frame averaging - 15, rotation step - 0.3 g, filter - Al+Cu 0.5 mm) that allow us to provide further comparison of the results obtained on different samples.

Bazhenov and Abalak Reservoir Rocks

Reservoirs were found in several rock lithotypes of the Bazhenov Formation. In general, these were indistinctly laminated, low-clay silicates and carbonate silicates of biogenic origin (e.g., Balushkina et al., 2013; Karnyushina, 2003). Radiolaria sourced from biogenic silica and the radiolarian structure could be identified in the carbonate silicates lithotypes (Figure 4).

The composition of reservoir rocks depends on the ratio of biogenic silica, calcite, and / or dolomite and, to a lesser degree, kerogen and shaly minerals. The porosity and permeability values, mineral composition, and Rock-Eval 6 pyrolysis parameters of silicates and carbonate silicates are shown in Table 1. The total thickness of siliceous and carbonate-siliceous rocks in the subsurface can reach 10 meters, while the total thickness of reservoirs within the gross interval commonly does not exceed 2 meters.

Fissile or platy, shaly silicates sometimes have elevated porosity and permeability, as well as corresponding geochemical parameters of organic matter. These rocks are often called the Bazhenov "matrix", which compose about 70- 80% of the total thickness (Figure 3). Porosity and permeability of these rocks increase only in the event of high source-rock maturity corresponding to the end of the oil window, when the oil-generation potential of the rocks is almost completely exhausted. In the high-maturity rocks, the mean value of the hydrogen index (HI) is180 mgHC/g TOC and the T_{max} is $450^{o}C$ (Table 2). This high maturity stage is found in three wells in the study area. The formation overpressure factor in these wells can be as high as 1.8, and the characteristic feature of the rock is high man-made fracturing with chaotic fractures, generated by drilling and acquisition of whole cores. Sometimes fractures develop only on the surface of a core column and do not penetrate deeply into the core sample (Figure 5). Because the oil-generation processes have already been completed in these rocks, the associated high stress state can hinder the processes of primary migration. The porosity and permeability and the mineral composition of platy reservoir rocks in the Bazhenov matrix are shown in Table 2.

The third lithological rock type where reservoirs were identified are carbonates (limestones, dolomites or mixed limestone-dolomitic rocks) of the Correlation Layer bed confined to the base of the Bazhenov Formation or the top of the Abalak Formation (Figure 6). The layer «KS» was identified originally by wireline-log corelation at the top of the Abalak Formation, hence the abbreviated designation of "Correlation Layer" or «KS» (Belkin et al., 1983). The CL abbreviation is used here, but because the CL carbonate bed is time transgressive, the CL beds can occur both in the Bazhenov and Abalak part of the section. In some wells, there may be up to five CL layers, or the layer may be absent. The CL layers are carbonate bacterial formations with a brecciated structure composed of different sizes and shapes, and are commonly vuggy. Portions of the formation matrix are limestones or dolomites, and the limestone matrix has a spherolitic, lumpy, or stromatolitic microstructure. The dolomites or dolomitic limestones have a fine-grained or detrital microstructure. The microstructure of carbonate rocks in the CL bed can be distinguished from the Bazhenov limestones and dolomites, as these have a radiolarian microstructure. The CL rocks acquired the brecciated structure due to widespread fractures and associated dissolution vugs, with common calcite mineralization that acts as cement. The size of the vugs and fractures can be several centimeters wide and several tens of centimeters long. The reservoirs in the CL bed differ from the Bazhenov reservoir rocks in that their oil saturation is confined only to vugs and fractures (Figure 6). Oil saturation of matrix rocks in the CL layer is low in dolomites and is absent in limestones; their porosity and permeability being below the limit of analytical detection. Processes of impregnation of the matrix by hydrocarbons directed from the edges of fractures or vugs were noted in some core samples. The uniformity and intensity of the impregnation is controlled by the structure and composition of matrix rocks and by the extent of oil saturation of the fractures and vugs.
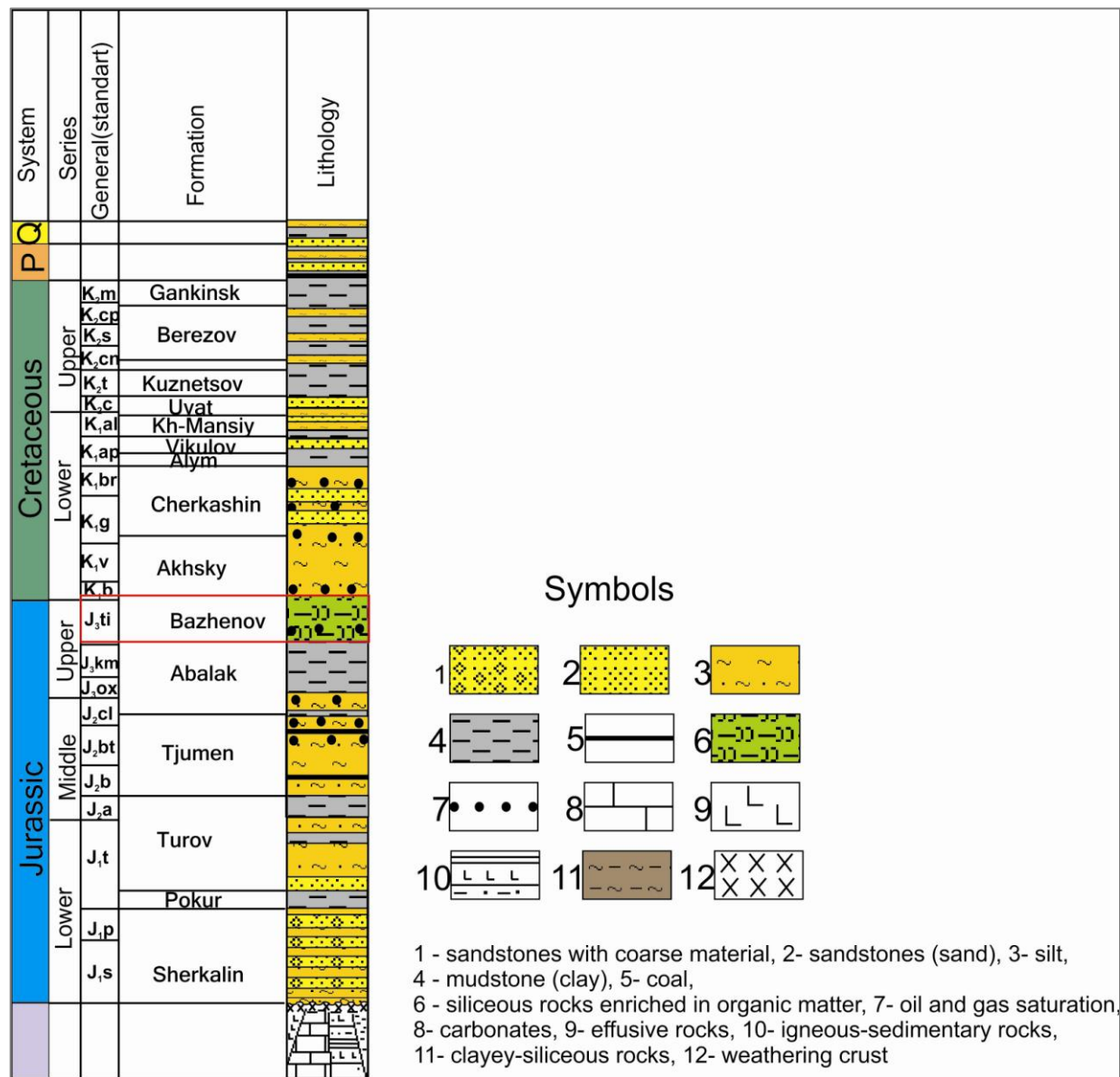
Figure 1. Typical lithostratigraphic section of the central part of the West Siberian Plate (modified from Kontorovich et al., 2009).
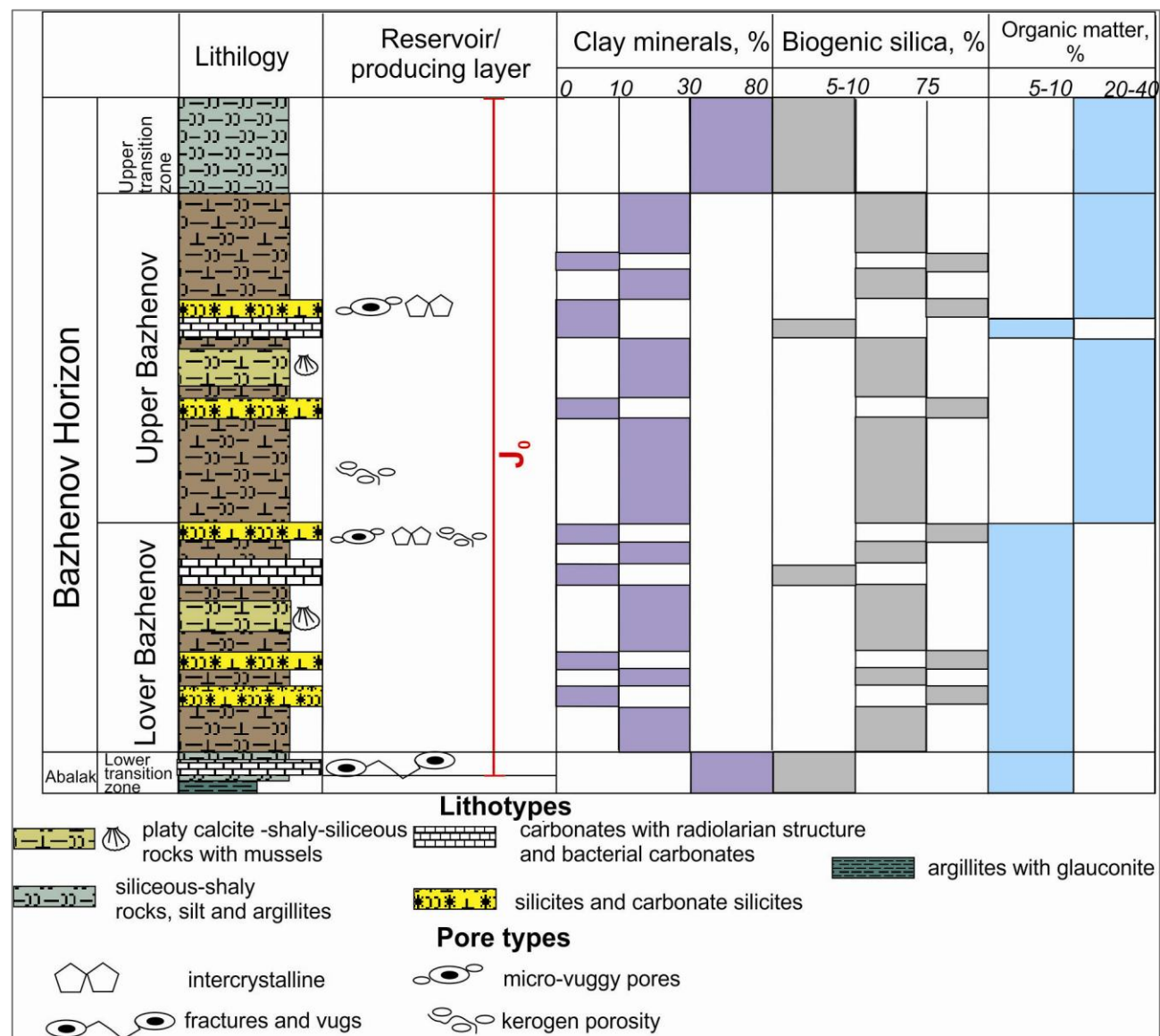
Figure 2. Schematic diagram of the internal structure, mineral composition, organic-matter content, and pore systems of the Bazhenov and Abalak formations.
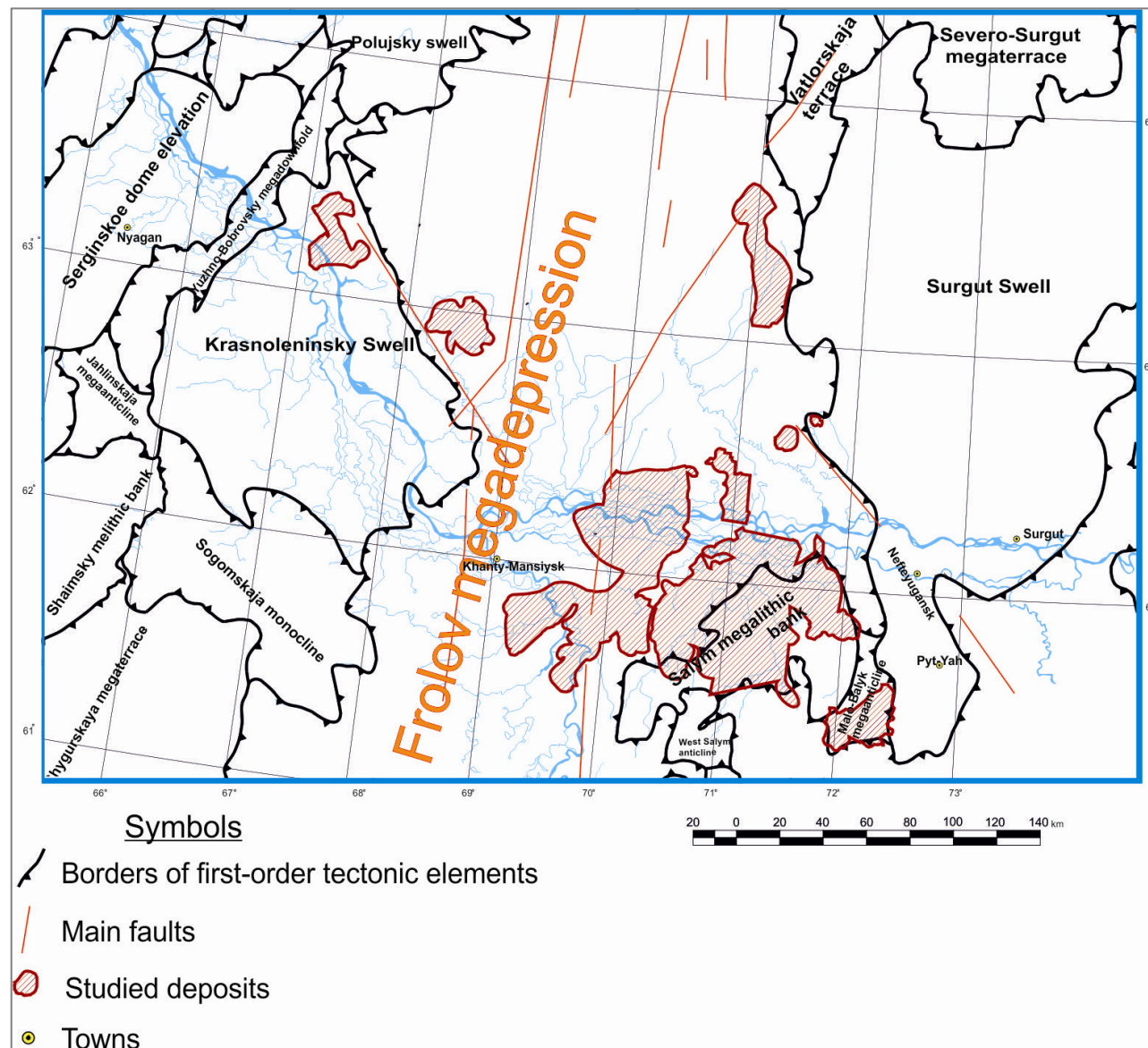
Figure 3. Deposits under study shown on a part of the tectonic map of the central part of the West Siberian Plate (modified from Shpilman et al., 1998, Afanasiev et al., 2011).
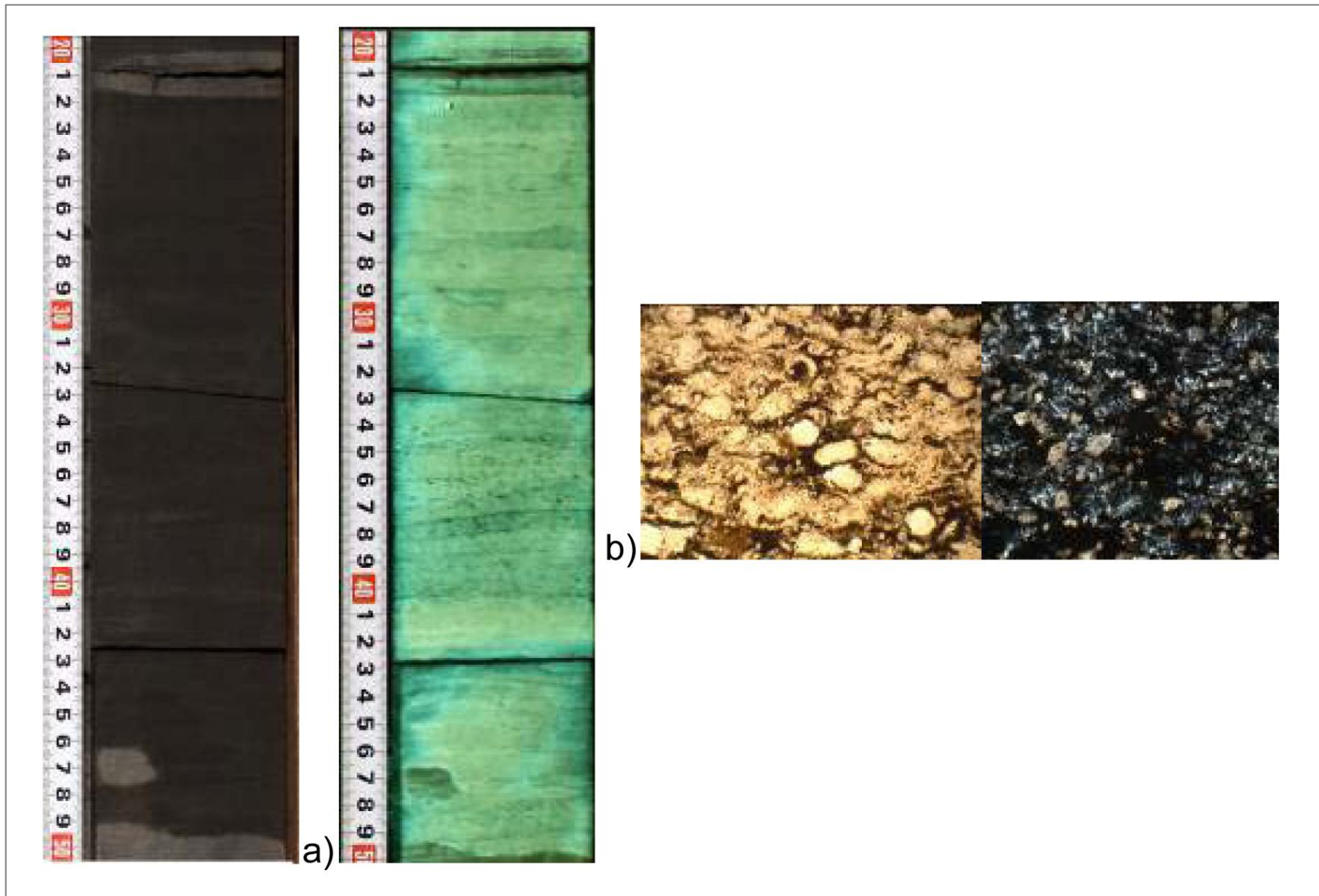
Figure. 4. Left: core photo of oil-saturated dolomitized silicate in daylight and in UV light, Right: Radiolarian structure in a petrographic thin section, parallel and crossed nicols.

Figure 5. Core photo in daylight and in thin section in parallel nicols. Man-made fractures can be seen on the surface of the core plug (Afanasiev et al., 2011).
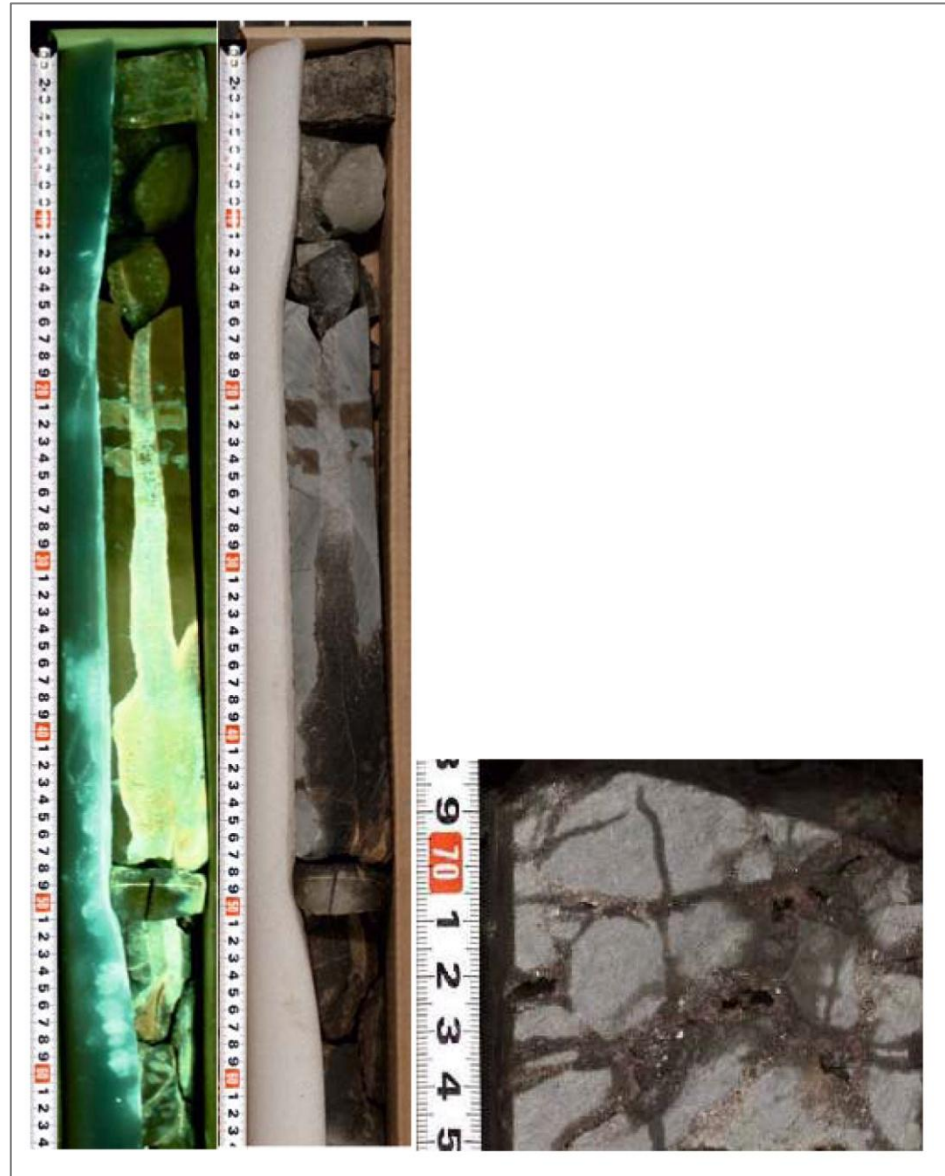
Figure 6. Core photos of unevenly oil-saturated reservoir rocks in the CL bed and detailed photo of fractured and vuggy limestones saturated with hydrocarbons.

No.	Mineral rock composition, wt. %							Porosity and permeability		Rock Eval 6 pyrolysis					
	Quartz	Albite	Calcite	Dolomite	Siderite	Pyrite	Clay minerals	K, mD	Φ_naphta, %	S1, mgHC/g of rock	S2, mgHC/g of rock	PI	T_{max}, ^{0}C	TOC, wt. %	HI
1	86.59	1.64	0.00	0.00	0.19	3.58	4.64	0.07	8.44	10.42	8.26	0.56	441	3.36	246
2	82.67	1.64	0.00	0.00	1.45	6.07	4.53	0.05	7.37	9.55	8.84	0.52	439	3.65	242
3	54.96	1.85	3.90	25.77	0.00	3.81	7.22	0.17	7.06	7.35	6.23	0.54	436	2.38	262
4	64.93	0.48	0.19	21.87	0.39	4.55	4.35	1.93	12.11	12.78	7.92	0.62	435	3.23	245
5	73.58	0.39	0.19	16.15	0.00	4.74	1.55	3	10.99	15.86	6.53	0.71	424	3.31	197
6	75.27	0.39	0.00	10.53	0.00	8.39	2.93	2.38	11.9	10.35	5.33	0.66	429	2.5	213
7	60.43	0.98	6.35	16.50	0.00	8.10	5.27	2.66	11.67	7.24	5.6	0.56	429	2.38	235
8	74.21	0.00	20.29	1.35	0.00	0.77	0.00	0.05	4.81	7.38	8.49	0.47	440	3.37	252
9	48.14	0.00	0.40	44.29	0.00	4.55	1.38	0.02	0.09	1.36	2.51	0.35	440	1.14	220
10	0.99	0.00	95.47	0.40	0.00	2.38	0.00	0.06	0.95	0.96	1.47	0.39	439	0.76	193
11	12.03	0.00	86.07	0.00	0.00	1.29	0.00	0.02	0.57	0.38	1.26	0.23	440	0.61	207
12	49.49	0.00	49.49	0.00	0.00	0.40	0.00	0.58	1.47	1.66	1.25	0.57	438	0.62	202
13	74.21	0.00	20.29	1.35	0.00	0.77	0.00	0.05	4.81	7.38	8.49	0.47	440	3.37	252

Table 1. Mineral composition, porosity, permeability, and Rock-Eval 6 parameters in siliceous and carbonate-siliceous reservoirs of the Bazhenov Formation.

No.	Mineral rock composition, wt. %							Porosity and permeability		Rock Eval 6 pyrolysis					
	Quartz	Albite	Calcite	Dolomite	Siderite	Pyrite	Clay minerals	K, mD	Φ_naphta, %	S1, mgHC/g of rock	S2, mgHC/g of rock	PI	T_{max}, ^{0}C	TOC, wt. %	HI
1								<0,01	7.12	8.82	15.15	0.37	444		215
2	70.44	3.55	3.10	0.00	0.00	3.10	11.01	<0,01	6.10	7.70	14.73	0.34	450	8.80	236
3	60.24	4.63	0.00	1.96	0.00	2.47	17.33	0.01	4.25	8.76	17.50	0.33	447	13.37	203
4	58.78	4.93	0.00	2.18	0.00	2.06	20.14	<0,01	4.56	9.45	15.81	0.37	450	11.90	220
5	67.04	3.50	1.28	0.00	0.00	3.42	15.29	<0,01	5.34	9.03	13.82	0.40	445	9.47	209
6	29.71	1.09	0.00	44.51	0.00	15.59	3.10	1.87	5.65	6.24	8.66	0.42	438	5.99	208
7	62.08	4.31	0.00	1.19	0.00	4.27	16.57	0.18	2.97	7.46	15.28	0.33	442	11.58	188
8	62.34	4.60	0.00	1.51	0.00	3.83	16.58	<0,01	3.64	7.24	16.45	0.31	450	11.14	212
9	55.58	4.46	1.96	8.37	0.00	4.77	14.08	<0,01	4.87	8.71	17.57	0.33	444	10.77	227
10	40.84	4.94	0.00	16.11	0.00	11.25	18.16	0.03	3.99	6.66	16.68	0.29	446	8.71	260
11	58.50	5.85	1.31	2.95	2.12	1.74	15.37	2.56	9.45	7.09	11.29	0.39	451	12.16	126
12	56.37	4.71	5.77	7.56	1.67	3.09	10.07	0.01	4.28	6.50	7.66	0.46	439	10.76	91
13	71.26	3.36	0.00	7.72	0.80	0.79	9.06	0.01	6.88	6.61	8.86	0.43	440	7.01	120
14	49.55	4.37	2.91	3.21	4.37	6.17	12.18	0.17	8.40	6.33	7.01	0.47	439	17.24	71
15	24.88	9.35	16.49	5.79	2.27	6.76	24.38	0.25	5.35	5.82	9.89	0.37	464.00	10.09	90

Table 2. Mineral composition, porosity, permeability, and Rock-Eval 6 parameters in platy, shaly-siliceous and kerogen-shaly-siliceous reservoirs of the Bazhenov Formation.

Pore Types, Nomenclature, and Distribution

All pores identified in the reservoirs can be divided into two groups - mineral and organic. The group of mineral pores includes fractures and vugs of the CL bed and micro-vugs and pores in the shaly carbonate-siliceous lithotype of the Bazhenov Formation.

Mineral Pore Types

The size of fractures and vugs of the CL bed can be tens of centimeters wide and several tens of centimeters long. Due to the size of the features, macro-tomography using a full-size core was utilized to characterize the distribution of pore space in the fractures and vugs within the «KS» bed. A stereographic analysis of such pore systems illustrates that that practically all vugs are connected to the exterior surface of the core and have minimal communication.

Based on macro-tomography, vuggy porosity was calculated for individual intact parts of the whole core. The calculations demonstrate that the porosity in these intervals varies from 5% to 8% according to the chosen zone and integrity of the whole core sample; the maximum vuggy-fractured porosity in the CL bed can be up to 10%. However, as mentioned above, the connectivity of individual elements of macro-porosity is quite low, suggesting low permeability and low overall porosity.

The bulk of the pore space in the shaly carbonate-siliceous lithotype of the Bazhenov Formation is associated with pores resulting from solution of skeletons of radiolaria that were subsequently partially or completely dolomitized. The pores are generally roundish and tower-like and are described as micro-vuggy porosity; their diameter can reach 100 micrometers and length 250 micrometers (Figure 7).

There are a large number of smaller pores in the siliceous rock type in addition to the radiolaria solution micro-vugs. The siliceous porous rock is composed of quartz microcrystals, and the pores exist between individual crystals or crystal accumulations. The silicified areas with inter-crystalline pores delineate in general larger solution pores (Figure 8) or skeletons of radiolaria that have been replaced by carbonates (Figure 9).
The positions of intercrystalline and micro-vuggy pores relative to each other were studied by means of x-ray micro-tomography. Various tints of gray on the density x-ray section (Figure 10) show the distribution of density in a reservoir rock sample. The low-porosity regions have white colors on the x-ray slices, whereas the porous regions are characterized by dark gray to black tints. The solution pores or micro-vugs have a round or oval shape; their diameter is commonly 0.1 mm, and the pores are connected through small canals, or intercrystalline pores in the mineral matrix of the rock. This reservoir type tends to be void of fractures.

The degree of carbonate replacement is one of major factors that control the porosity and permeability of reservoirs. For instance, it can be seen from Table 1 that the lowest porosity and permeability are in secondary apo-radiolarite limestones that are more than 75% composed of calcite. This rock type is also distinguished by a low TOC which does not exceed 1 wt. %. The residual generation potential of apo-radiolarite limestones is generally low, not exceeding 1.5 mg HC/g of rock. Porosity and permeability are also impaired where the content of dolomite is more than 50% (Table 1).

Pyrite is another component that affects porosity and permeability. Occupying the pore volume, pyrite will lower the porosity and permeability of rocks, with the composition of the rock matrix being equal. The impact of pyritization on pore space volume was modeled and evaluated using x-ray micro-tomography techniques. Samples A and B with porosities of 7.83% and 15.17%, and permeabilities of <0.1 mD and 50 mD, respectively, are shown as an example (Figure 11). For sample B, the presence of 1% pyrite in the rock reduced the porosity from 16% to 15%. Conversely in sample A, the presence of 8% pyrite in the rock reduced porosity from 15% to 7% (Figure 11).

Organic Pore Types

The second group of Bazhenov Formation pores types is associated with the organic material in the rock. Such pores were identified in many high-TOC analogs of the Bazhenov Formation and are referred to as "kerogen porosity" or "organic porosity" (e.g., Curtis et al., 2010; Loucks et al., 2009).

Figure 12 illustrates circular pores confined to the areas composed of kerogen. Photomicrographs of a reservoir rock sample surface (Figure 12) illustrate results of a x-ray fluorescence surface scan that resulted in the distribution of carbon, silicon and sulfur. See table and histogram in Figure 12c/d for the average concentration and distribution of concentrations of basic elements in this portion of the sample. The set of elements for mapping was dictated by the rock composition as silicon reflects the distribution of biogenic silica and, being a shale component, also shows the presence of shaly minerals in the rock. Sulfur provides information about pyrite. The negligibly low concentrations of calcium illustrate that carbon is not part of carbonate minerals.

The pore size does not exceed 1 micrometer, which is comparable to the size of oil hydrocarbon molecules (the length of C—C bonds in saturated hydrocarbons is ~0.154 nm and of C—H bonds is ~0,109 nm (Sidorovich, 1989). In the regions where the pores are connected, the composite pore system is larger than 2 micrometers (Figure 13). These characteristics allow the organic porosity of the Bazhenov Formation to be characterized as a part of total porosity system that is filled with gas and oil.

A key challenge with this analysis is the limitation of the micro-tomographic instrument. For instance, it is impossible to identify pores inside kerogen by means of x-ray micro-tomography due to the limited resolution, and due to the close density characteristics of oil and kerogen. Nevertheless, the micro-tomography approach allows insight regarding the pore distribution and connectivity (in areas of the rock where kerogen is present) and the relationship to the mineral matrix.

Two types of pores can be identified based on x-ray micro-tomographic slices that include tower-like pores and round and flat, lens-like pores (Figure 14). The former are pores related to the dissolution of radiolarian skeletons, and the latter are related to kerogen ("organic") porosity. The organic porosity, similar to the intercrystalline porosity in the siliceous rock type, plays an important role in fluid-flow processes.

The properties of reservoirs with kerogen porosity as well as those with solution porosity can deteriorate owing to bacterial processing of organic matter and emplacement of pyrite in the pore space.

Conclusions

Reservoir rocks were identified in the Bazhenov and Abalak formations by an integrated analysis of whole core data, petrophysical data, and geochemical parameters of organic matter in the following lithotypes: dolomitized silicates, platy, shaly silicates, and carbonates of the CL (Correlation Layer) bed. All reservoirs are secondary and have a complex network of pore space. The Bazhenov reservoirs are characterized as a pore and pore micro-vuggy type that was generated resulting from the transformation of the mineral (biogenic silica) and organic (kerogen) parts of the rock.

Mineral-related porosity includes solution micro-vugs and intercrystalline pores, whereas the organic porosity is contained within the organic matter, and is generated from transformed kerogen. Solution pores can be quite large, whereas the kerogen-related pores are small (micron to nano). The ratio of pore types can vary according to the mineral composition of reservoir rocks and the source-rock maturation level.

The main contribution to the total capacity in carbonate silicates at the beginning and in the middle of the oil window is made by solution pores, and the intercrystalline porosity creates permeability. Reservoirs were not identified in the platy, shaly silicate lithotype at the beginning and middle of the oil-window maturity level.

Kerogen porosity appears at the end of the oil window and at the beginning of the gas window, both in carbonate silicates and in platy, shaly silicates. Similar to intercrystalline porosity, when kerogen porosity is formed, the permeability of the Bazhenov Formation can increase. Pyrite is the main mineral that occludes the pore volume and degrades porosity and permeability.

The reservoirs of the Bazhenov Formation or of the Bazhenov and Abalak sequence are confined to the Correlation Layer (CL) bed and are of the fractured-vuggy type. Movable oil is contained only in fractures and vugs that generally do not communicate with each other in the wells studied, despite the considerable size of the pore space.
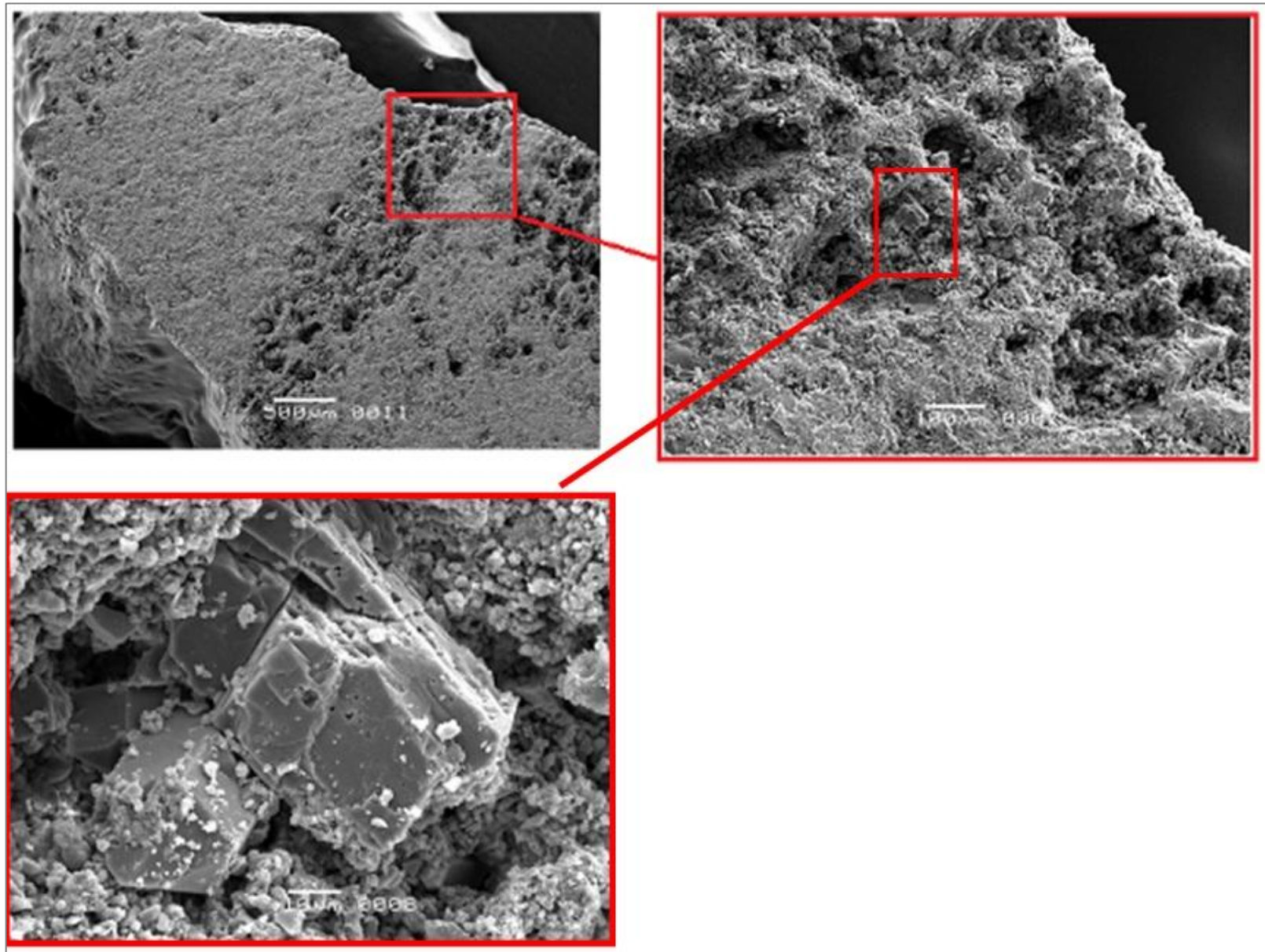
Figure 7. Scanning electron microscope (SEM) image of solution pores related to the dissolution of siliceous radiolarian skeletons and dolomite crystals.
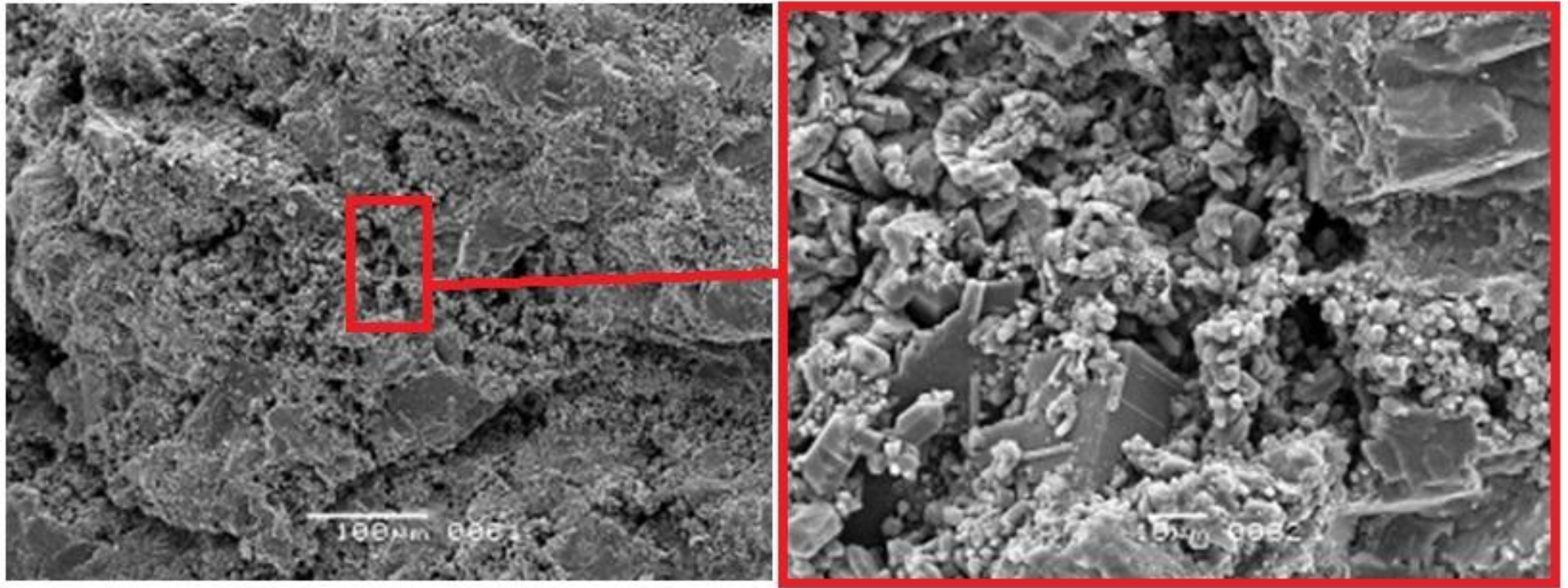
Figure 8. SEM photo of intercrystalline pores that delineate larger solution pores.
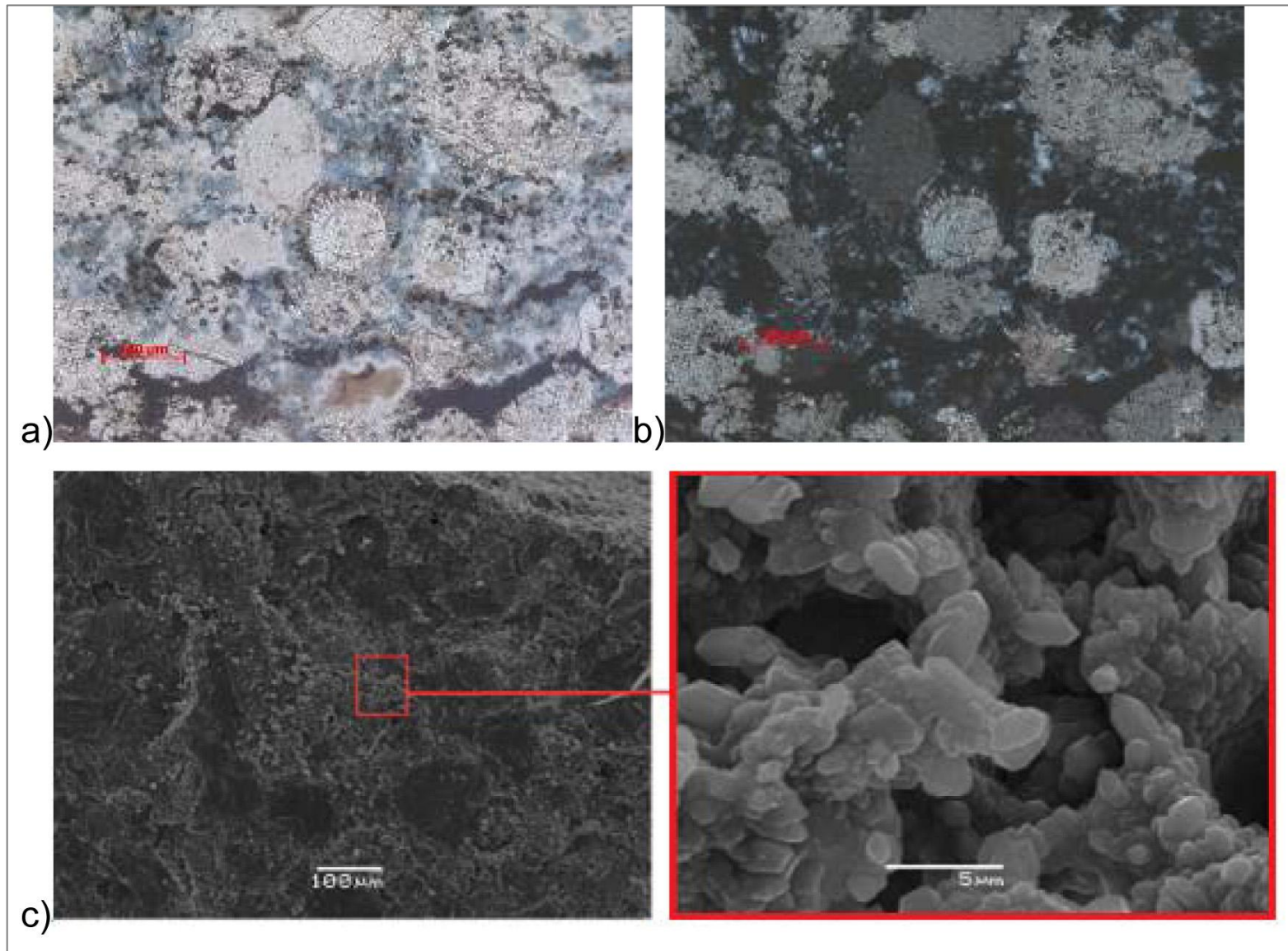
Figure 9. SEM photos of a) intercrystalline pores around totally dolomitized skeletons of radiolarian; b) colored petrographic thin sections; c) photo of a fractured surface.
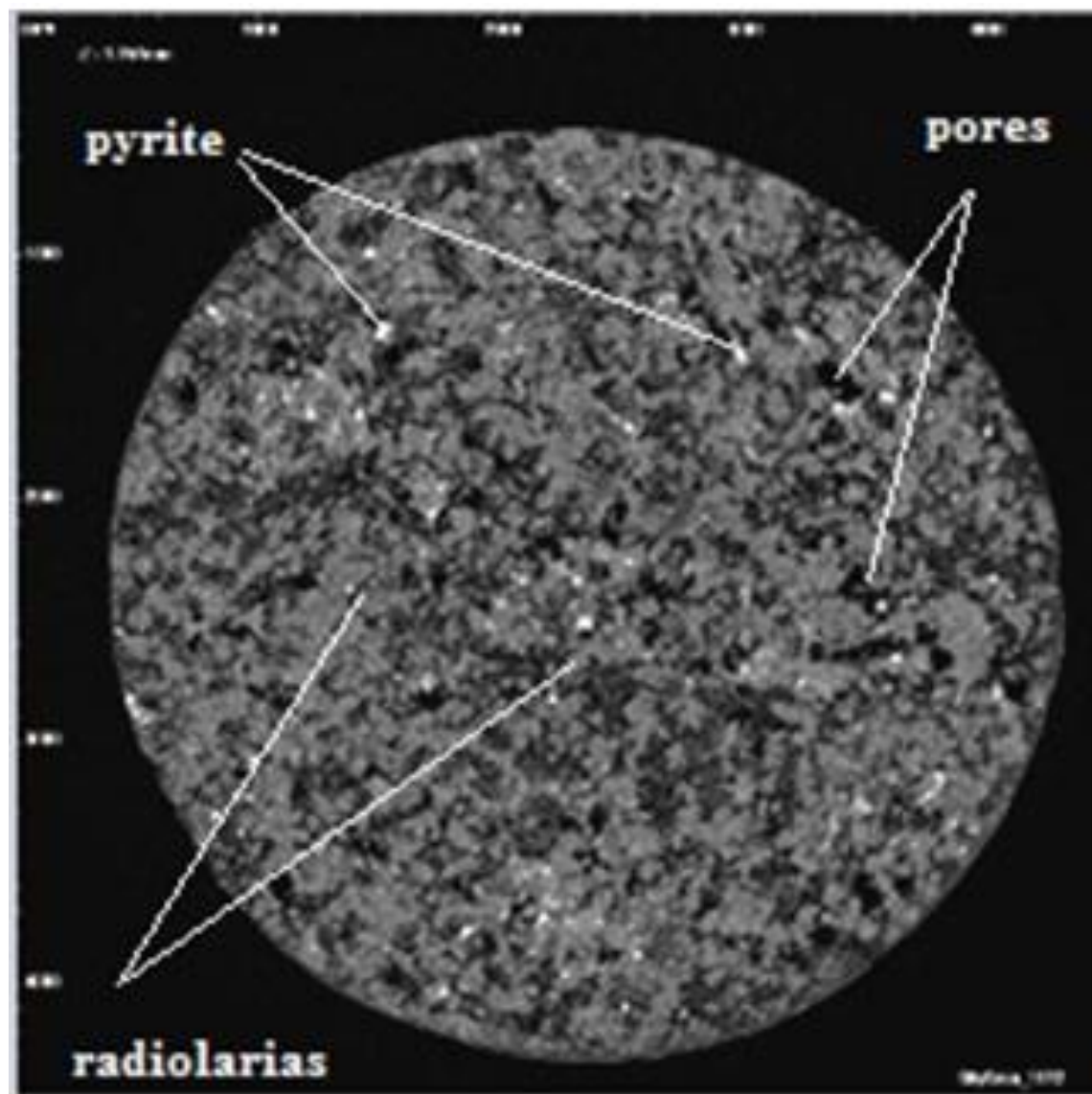
Figure 10. Density x-ray section of a reservoir sample with porosity of 12.4% and permeability of 2.94 mD.
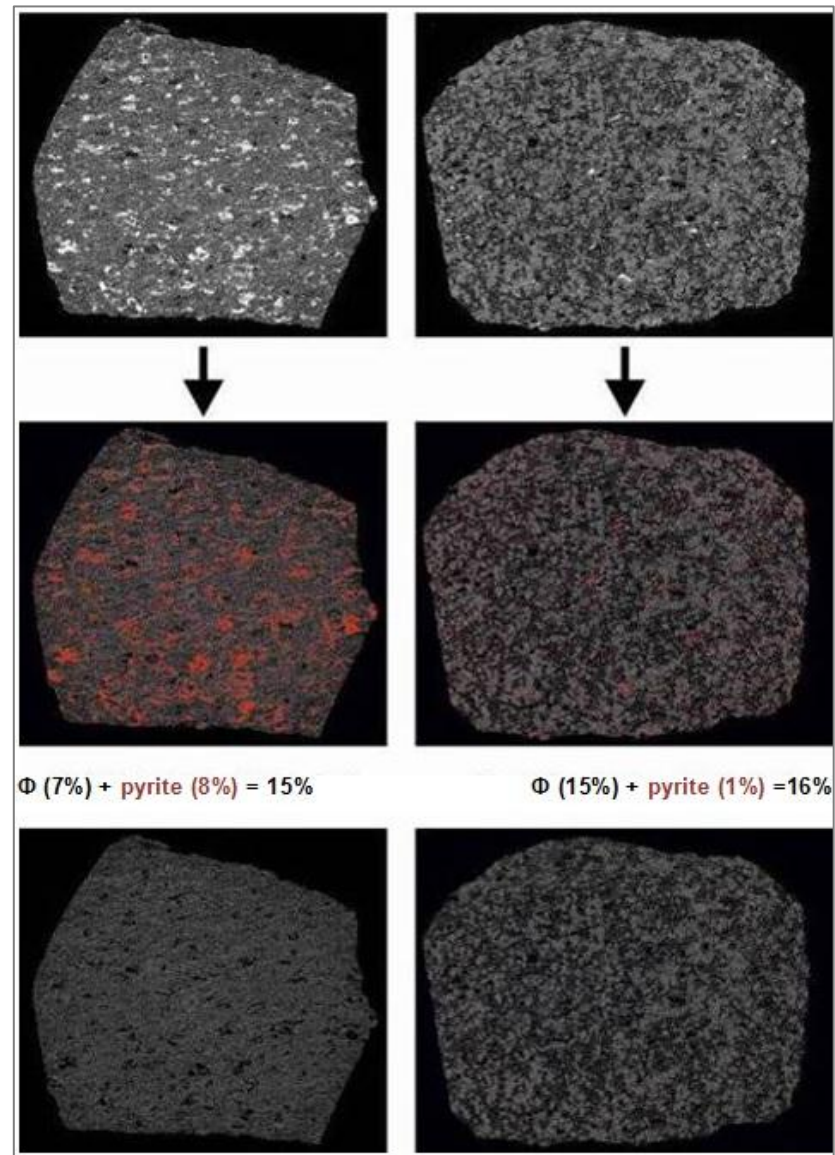
Figure 11. Core plug x-ray micro-tomography photos illustrating the impact of authigenic pyrite on porosity and permeability properties of samples A (left) and B (right) with micro-vuggy and intercrystalline mineral porosity.
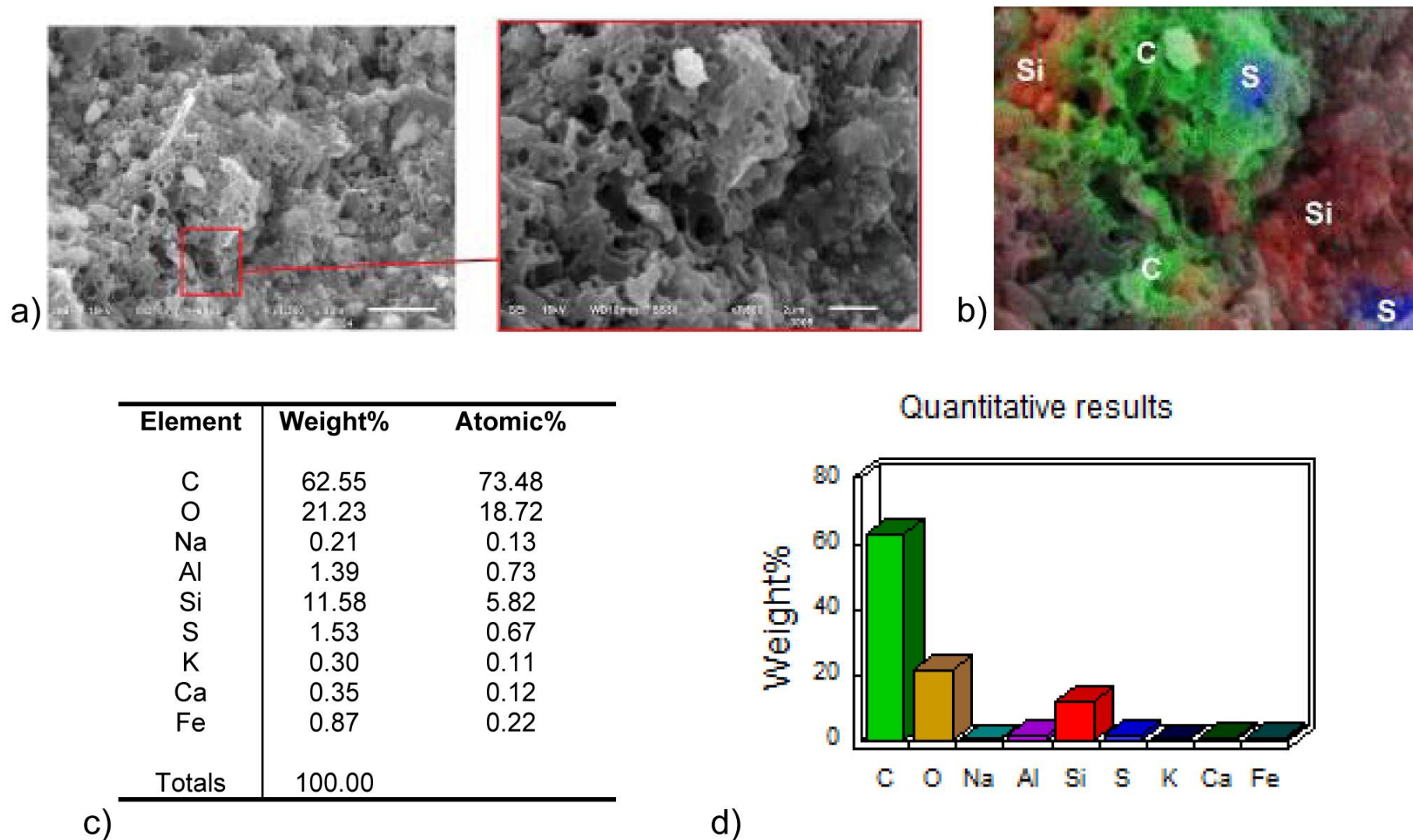
Element	Weight%	Atomic%
C	62.55	73.48
O	21.23	18.72
Na	0.21	0.13
Al	1.39	0.73
Si	11.58	5.82
S	1.53	0.67
K	0.30	0.11
Ca	0.35	0.12
Fe	0.87	0.22
Totals	100.00	

Figure 12. a) SEM photo a shaly siliceous rock type with porosity of 9.45% and the region chosen for scanning; b) the map of the distribution of silicon (red), carbon (green), and sulfur (blue) on the chosen sample region; c) average concentration of basic elements; d) the histogram of the distribution of average concentrations of basic elements.
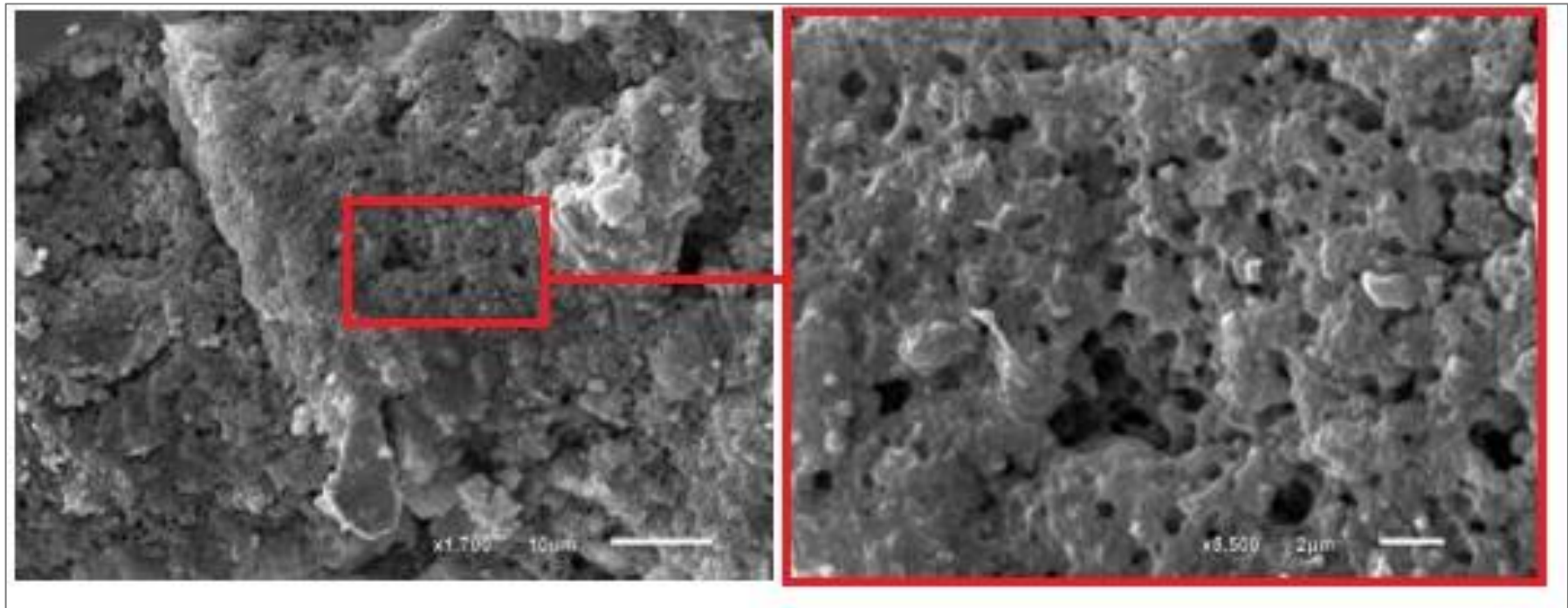
Figure 13. SEM photo illustrating that pore size increases in kerogen when the pores connect with each other.
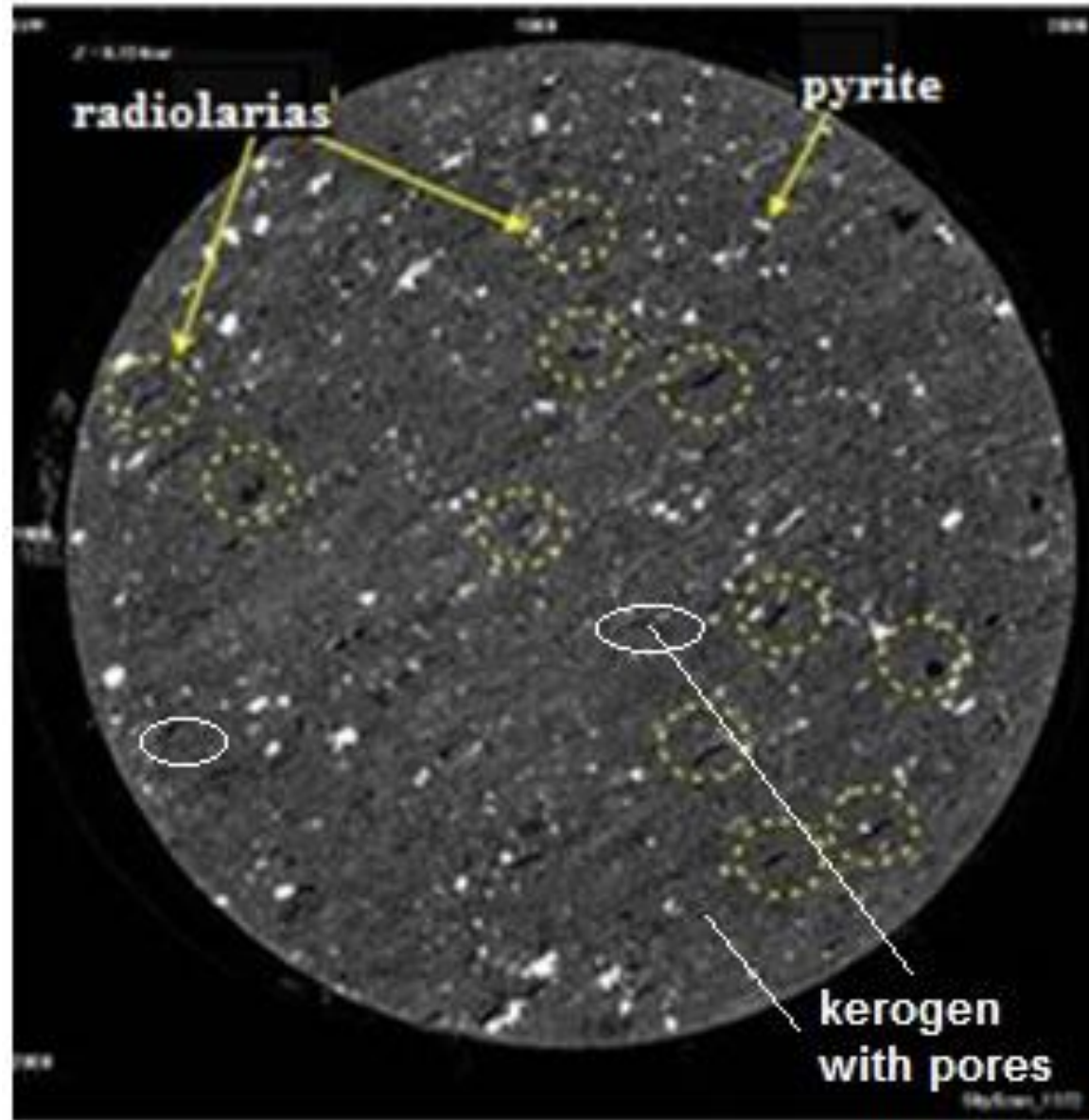
Figure 14. X-ray micro-tomographic image slice showing density of a sample of shaly-siliceous rock with porosity of 9.45% and permeability of 2.56 mD.

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