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Sedimentary diagenesis and pore characteristics for the reservoir evaluation of Domanik formations (Semiluksk and Mendymsk) in the central part of Volga-Ural petroleum province

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ABSTRACT

The Upper Devonian Semiluksk (Domanik) and Mendymsk carbonate successions have been identified as the most promising unconventional oil and gas deposits in Russia's Volga-Ural petroleum province. Three lithofacies were identified: limestones, organic matter-rich siliceous carbonate, and dolomitic limestones/dolomite. Their sediments are thought to have accumulated in the relatively deep-sea shelf depositional environment. According to X-ray analysis, calcite is the most common mineral phase in the limestones. The siliceous carbonate rocks' major mineral phases were identified to be quartz, followed by calcite. The rocks have relatively poor reservoir qualities, with porosity ranging from 0.1 to 5% and permeability ranging from 0.01 to 10 mD. Petrographic examination of thin sections reveals four major types of pores: 1. interparticle pores, which are abundant in all of the examined lithofacies; 2. intercrystalline pores formed between dolomite crystals and the very fine components of the siliceous carbonate rocks. 3. vugs as a result of leaching, and 4. fracture as a result of tectonic and/or diagenetic events. Plotting the obtained data from the petrographically examined thin sections on the ternary pore plot diagram resulted in the identification of six pore facies and their related diagenetic patterns. Pore facies 1 depicts the pores that formed during the depositional process. Pore facies 4 displays moldic pores. The vugs are represented by pore facies 6. Pore facies 2 is a mixture between pore facies 1 and pore facies 4. Pore facies 3 is a mixture between pore facies 1 and pore facies 6. Pore facies 5 is a mixture between pore facies 4 and pore facies 6. Comparing the petrographic results and the identified pore facies show that pore facies 6 have touching pores and they played the most important role in improving the reservoir quality. The pore facies 4 which have separate pores have the most influence in the reduction of the reservoir quality. The diagenetic origin secondary pores are the most pores identified in the studied carbonate section. This reflects the strong modification of the pores by the diagenetic overprinting. The massive dissolution that forms the touching vugs, and the dolomitization process are the most diagenetic processes that affect the pore system within the studied rocks.

1. Introduction

While conventional reservoirs' hydrocarbon resources are depleting, most governments are focusing their attention on unconventional oil resources, which have large reserves and production potential (Alekseenko, 2011; Galimov and Kamaleeva 2015; Jia et al., 2016; Kiseleva et al., 2017). The current study focuses on the Upper Devonian Semiluksk (Domanik) and Mendymsk sediments in one of the Volga-Ural petroleum province's supergiant Romashkino oil fields (Fig. 1a and Fig. 1b). For more than a quarter-century, the Volga-Ural petroleum province supplied more than half of the Soviet Union's oil production; West Siberia only recently (1978) surpassed it (Morozov et al., 2021).

Semiluksk (Domanik) and Mendymsk formations are part of the Upper Devonian Frasnian stage (Fig. 1c and d), their sediments provide an important unconventional oil resource in the Volga-Ural basin. Lithologically, these sediments are characterised by successions of carbonates and siliceous carbonate rocks abundant in organic materials (Fig. 1d). They are distinguished by their ability to

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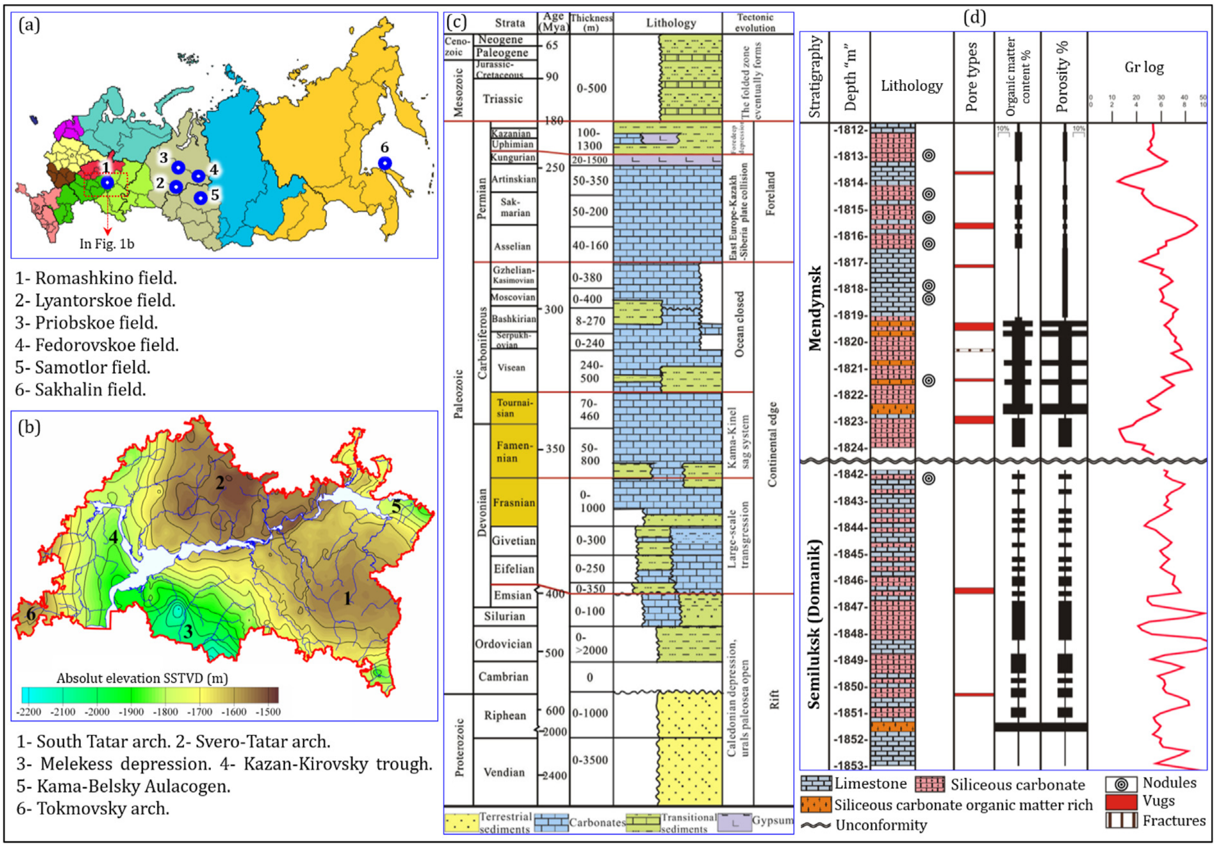

Fig. 1. Location and stratigraphic column of the studied area. (a) A map of Russia that shows the locations of some of the largest oil resources (blue spots with numbers 1–6) (Galimov and Kamaleeva, 2015). (b) Tectonic map of Romashkino oil field, indicating the main tectonic units (numbered from 1 to 6) (Cherepovitsyn et al., 2018). (c) The Volga-Ural petroleum province's stratigraphic column (Liang et al., 2019). (d) A lithology column of the Semiluksk (Domanik) and Mendymsk formations in the studied area.

produce hydrocarbons from their source strata as well as concentrate them in layers that serve as reservoirs (Morozov et al., 2021). These sediments have low porosity and permeability as well.

The relationship with the Middle Frasnian Domanik Formation is the source of the origin of the etymology of the terms “Domanik” and “Domanikity.” However, the Domanik Formation has been renamed the “Semiluksk Formation” to distinguish it from the 380 million-year-old “Domanik facies,” which was initially identified by Alexander Keyserling in 1843 near the southern Timan Ridge and called after the river Domanik. Later, N.M. Strakhov designated this unit's lithofacies as “Domanik facies” (Strakhov, 1939; Aliev et al., 1978; Parfenova et al., 1989; Abrams et al., 1999). Generally, “Domanikity” (or “Domanikitovye sediments”) refers to the rocks of the Semiluksk Formation (Middle Frasnian, D_3fr_2sm), while younger but similar bituminous and siliceous–clay–carbonate shales from Upper Frasnian–Lower Tournaisian are referred to as “Domanikoid-type” lithofacies/sediments (“Domanikoidy” or “Domanikoidnye”) (Astafiev and Alipova, 2002; Kiseleva et al., 2017). Based on similar sediment types and mineral contents, sediments previously labeled as “Domanikoidy” are now also considered to be Domanik facies from Upper Devonian (Upper Frasnian, D_3fr_3) to Lower Carboniferous (Tournaisian, C_1t) in the Volga-Ural and Timan-Pechora petroleum provinces (Abrams et al., 1999; Kiryukhina et al., 2013; Stupakova et al., 2017; Liang et al., 2019, 2020).

Several studies on the Semiluksk (Domanik) and Mendymsk formations have been published (Galimov and Kamaleeva 2015; Kiseleva et al., 2017; Vakhin et al., 2017; Liang et al., 2019, 2020; Morozov et al., 2021), with the majority of them focusing on geochemical characteristics and reservoir development strategies. However, few studies on lithofacies patterns and pore types have been carried out. As a result, it is critical to identify in detail the lithofacies patterns, pore types, and pore facies and elucidate them with the content of organic matter and oil saturation as part of an effort to understand the controls of diagenetic performance on petrophysical characterization and reservoir quality.

The following objectives were met using petrographical, petrophysical, and thermal analyses: (1) identify and describe the commonly encountered lithofacies; (2) mineralogical and petrophysical characterizations of the studied sediments; (3) interpret the depositional environments; (4) identify pore types and their origin; (5) ternary porosity plot to identify the common pore facies; (6) evaluate the relationship between the encountered lithofacies and content of the organic matter; and (7) evaluate the relationship between the encountered lithofacies and content of the organic matter.

The findings will help in understanding the effects of diagenetic processes on the development, alteration, and/or destruction of pore systems, and therefore in evaluating the reservoir characterizations of the Semiluksk (Domanik) and Mendymsk sediments over the studied area.

2. Geologic settings

The study area is located in the northern half of the Romashkino oil field in the East European Platform's Volga-Ural petroleum province (Russia). The study area is confined to the South Tatar arch in terms of regional tectonics (Galimov and Kamaleeva 2015). The sedimentary cover is made up of Devonian, Carboniferous, Permian, and Quaternary layers and stands on top of the crystalline basement's eroded surface (Fig. 1c).

Many oil-bearing formations have been identified in the Devonian sediments; some of them (Semiluksk (Domanik) and Mendymsk)) are of industrial interest because commercial oil flows were obtained during testing; however, the oil-bearing capacity of the Semiluksk (Domanik) Formation is characterised by a wider spatial distribution than the Mendymsk Formation (Liang et al., 2019).

In the Volga-Ural petroleum province, the Semiluksk (Domanik) source rocks are known as "Domanik deposits." They are quite extensive, forming a large and long southern strip west of the Urals (Liang et al., 2020). Domanik deposits are predominantly siliceous carbonate, with a high percentage of organic material and depths ranging from 1500 to 1800 m, according to recent studies. These deposits have been regarded as the parent rocks of the region's oil fields since the 1920^s (Morozov et al., 2021).

Sediments of the Semiluksk (Domanik) and Mendymsk formations are distinguished by their lateral and vertical distribution patterns, carbonate and siliceous carbonate mineral composition, and organic matter enrichment. They evolved in low-energy depositional environments with high levels of transgression (Kiseleva et al., 2016; Liang et al., 2019). Hydrocarbon accumulations are often restricted to the fracturing zones within these rocks, which usually have low porosity and permeability. Furthermore, the saturation of these rocks with organic matter hinders hydrocarbon desorption and migration because the insoluble fraction of kerogen acts as a molecular mesh, retaining them within the kerogen (Liang et al., 2020; Morozov et al., 2021).

3. Material and methods

To meet the study's aims, core samples were collected from the Semiluksk (Domanik) and Mendymsk formations in the Volga-Ural petroleum province. The optical microscopic investigation was performed on approximately 100 thin sections taken from the cores of the sediment penetrating by 8 wells. The thin sections were microscopically examined using an optical polarisation microscope and the transmitted light of an Axio Imager (Carl Zeiss, Germany). The microscope was equipped with a camera. Alizarin Red solution was not injected into thin sections. Prior to producing the thin sections, the core pieces were photographed to illustrate the texture of the rocks.

The overall porosity and percentage of each pore type in the thin sections were determined using the point-counting method (Chayes, 1949). To assess the porosity and permeability, the core plugs were subjected to routine petrophysical measurements using the standard procedures. The scanning electron microscopy (SEM) technique was used on 15 samples to determine the structure of the pore space. Lithofacies analysis, macroscopic and microscopic petrographic examinations, as well as review of the literature regarding the researched area, were utilised to interpret the depositional settings of the studied sediments. The mineralogy characterizations of the rocks were defined using X-ray diffraction investigations on 15 samples. Thermal investigations were performed concurrently to analyse the thermophysical properties of the sediments samples to determine two curves: the differential calorimetry curve (DSC) and the thermogravimetric curve (TG) (Ma et al., 2017). The experiment was carried out on a NETZSCH STA 499F3 apparatus. The firing interval was set between 30 and 1000 °C, with a heating step of 10° per minute. This mode is best suited for producing high-quality results. The samples were ground into powder before firing to maximise their specific surface area.

The depositional lithofacies were classified using the criteria of Dunham (1962), and Folk (1959; 1962). Pore system classifications have been done using Philip and Lloyd (1970) classification, Lucia (1983; 1995; 2007), and Lønøy (2006) classification.

Kopaska-Merkel and Mann (1993) ternary porosity plot was utilised to investigate the distribution and frequency of the pore types, as well as to determine the pore facies of the studied rocks. Comparing and integrating the obtained data from lithofacies analysis, microscopic examination of the thin sections, and literature on this issue (Kopaska-Merkel and Mann, 1991; Cathy et al., 2010; Chehrazi et al., 2011; Yousef et al., 2019; Ibrahem et al., 2020; Yousef et al., 2021) allowed us to clarify the links between the pore types, pore facies, and their impact on reservoir characterization, as well as to determine the diagenetic processes that influenced the pore development and reservoir quality.

4. Results

4.1. Mineralogical and petrophysical characterizations

Sediments of the Semiluksk (Domanik) and Mendymsk formations are dominated by successions of carbonates and siliceous carbonate rocks, as shown by the lithofacies classification. The carbonate layers are dominated by limestone; however, when dolomitization occurs, dolomite takes over as the dominant phase. According to the results of the X-ray study (Table 1), calcite is the most common mineral phase in the limestones, with secondary dolomite, quartz, and pyrites being minor components.

The siliceous carbonate rocks' major mineral phases were identified to be quartz (chalcedony), followed by calcite. Minor constituents include muscovite, albite, and microcline, as well as authigenic pyrite and secondary dolomite (Table 1). The siliceous carbonate rocks have the most quartz of any of the analyzed lithofacies. The majority of quartz grains are grey-blue in colour or non-luminescent (Table 1).

According to Götze and Zimmerle (2000) classification of quartz luminescent colour, quartz grains with non- or faintly luminescent colour are of authigenic origin. As a result, the great majority of the quartz grains in the siliceous carbonate rocks of Semiluksk (Domanik) and Mendymsk formations are authigenic. Clay minerals are essentially non-existent, except allogenic albite grains and muscovite flakes, which can be found as impurities at a concentration of 1–2%.

Organic matter is abundant in the siliceous carbonate rocks, with total organic matter (TOC) values ranging from 2 to 35% (Fadeeva et al., 2016; Morozov et al., 2021). They are evenly distributed, giving the rocks the dark grey to black appearances. The organic matters are concentrated at varied intervals in lenses with a thickness of up to 1.0 mm, resulting in a banded texture. The dolomites are the most common mineral phase in the dolomite/dolomitic limestone (up to 82%), (Table 1); other minerals such as calcite, quartz, and pyrite are usually minor components.

The petrophysical features of the samples from Semiluksk (Domanik) and Mendymsk formations revealed that both carbonate and siliceous carbonate rocks have relatively poor reservoir qualities, with porosity ranging from 0.1 to 5% and permeability ranging from 0.01 to 10 mD (Fig. 2a). The enhanced porosity (from 5 to 10%) and permeability (from 10 to 569 mD) values correspond to the oil-saturated limestone layers that have experienced leaching processes, as well as the associated cavernous, dolomitization, and/or microfractures.

Fig. 2 depicts a cross plot of porosity and permeability values from Semiluksk (Domanik) and Mendymsk formation sediments. At first glance, it appears that there is no relationship between the correlated parameters; nevertheless, if the samples are subdivided by physical properties, three areas of points may be determined,

Table 1
Mineral compositions of the Semiluksk (Domanik) and Mendymsk formations samples.

Mineral/rock	Quartz	Calcite	Dolomite	Pyrite	Muscovite	Microcline	Albite	Total
Limestone	1.0	92.7	5.7	0.5	0.0	0.0	0.0	100.0
	2.1	94.5	1.9	1.5	0.0	0.0	0.0	100.0
	2.0	89.8	7.3	0.9	0.0	0.0	0.0	100.0
Siliceous carbonate	81.8	13.2	3.6	1.4	0.0	0.0	0.0	100.0
	69.6	17.3	5.3	2.4	2.1	1.4	2.0	100.0
	72.7	15.8	4.1	3.2	1.8	0.9	1.5	100.0
Dolomitic limestone and dolomitic	3.8	52.6	42.6	1.0	0.0	0.0	0.0	100.0
	7.5	4.9	86.2	1.4	0.0	0.0	0.0	100.0
	3.1	13.3	82.3	1.3	0.0	0.0	0.0	100.0

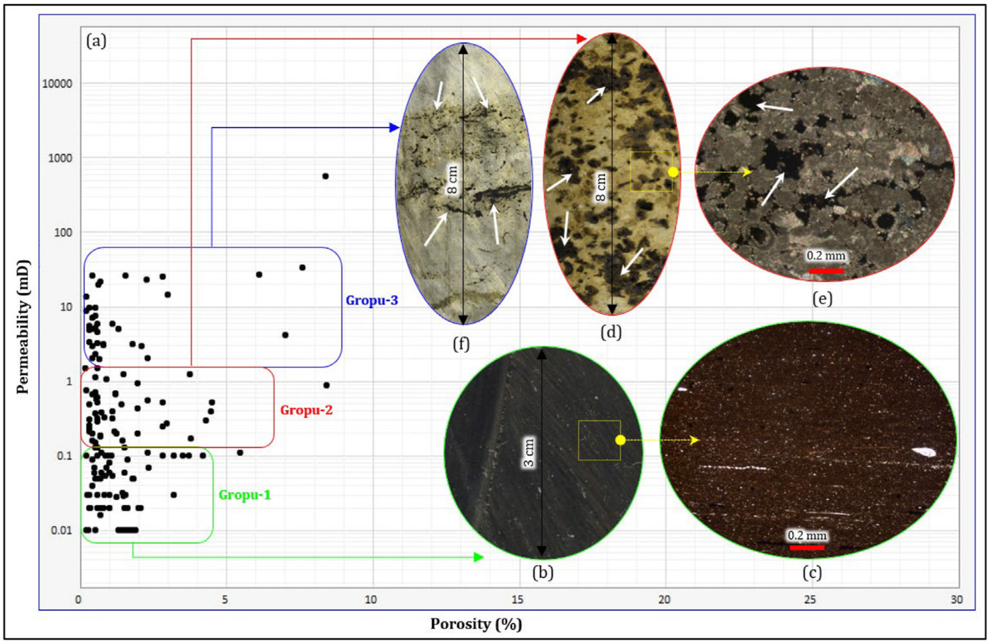

Fig. 2. (a) Cross plot of porosity and permeability of Semiluksk (Domanik) and Mendymsk formation samples. (b). The texture of the siliceous carbonate rocks is depicted in a representative core photograph. (c) Representative optical photomicrography of the siliceous carbonate rocks' microporosity. (d, f) Oil-saturated limestones with vugs (indicated by white arrows) are depicted in representative core photographs. (e) Representative optical photomicrography showing dissolution porosity (indicated by white arrows).

which are then united into three groups (Fig. 2a); The first group's values reflect the primary porosity and permeability of carbonates and siliceous carbonate rocks, which are visibly low (Fig. 2b and c). The second group's values represent the secondary porosity caused by the non-selective dissolution processes in the matrix, rock components, and/or cement (Fig. 2d and e). The third group's values reflect an increase in porosity and permeability values caused by the selective dissolution and microfracture processes (Fig. 2f).

4.2. *Lithofacies*

The macroscopic and optical-microscopic investigations of the studied cored intervals from the Upper Devonian Semiluksk (Domanik) and Mendymsk formations revealed three major lithofacies: (1) limestone; (2) siliceous carbonate; and (3) dolomitic limestones/dolomite. Each of the distinct lithofacies is explained below. The carbonate and siliceous carbonate are present in all of the investigated wells, whereas the dolomites have an uneven distribution; they may be present in some but not all of the wells.

4.2.1. *Limestone*

Limestone is abundant and well-developed in the investigated Semiluksk (Domanik) and Mendymsk sediments. They form interlayers that range in thickness from a few centimetres to 0.5 m and are interbedded with the siliceous carbonate rocks (Fig. 3a). The limestones have a light grey appearance and a horizontally layered structure due to the presence of the grey to black siliceous carbonate and/or the uneven layered distribution of the organic materials (Fig. 3a), in some cases, the fabric of the limestone deforms due to the limestones' local dolomitization (Fig. 3b). The inclusions of (up to 1.5 cm) of Ammonite shell fragments, the initial cavities of which are inlaid with brushes of calcite, give the limestones sometimes the patchy texture (Fig. 3c). Along with contacts with the siliceous carbonate rocks, the relatively thin limestone layers frequently brecciate (Fig. 3d), which is possibly created by breaking of the lithified lime mud and subsequent burial of the calcareous fragments in the viscous siliceous carbonate sediments (Lucia, 2007).

According to the thin section's optical microscopic examinations, the limestone texture is granular, entirely consisting of tightly adjoining granular calcite grains with an average size of 0.05–0.1 mm (Fig. 3e and f, and Fig. 3g), the grains are primarily xenomorphic and isometric in shape. Under an optical microscope, there is no visible porosity in the granular limestones. Only at some intervals (Fig. 3b and c), the rocks become more vuggy due to the dolomitizations and/or dissolution processes. Oil effusions can be seen in interform caverns as middle as 2.0 cm in diameter (Fig. 3b).

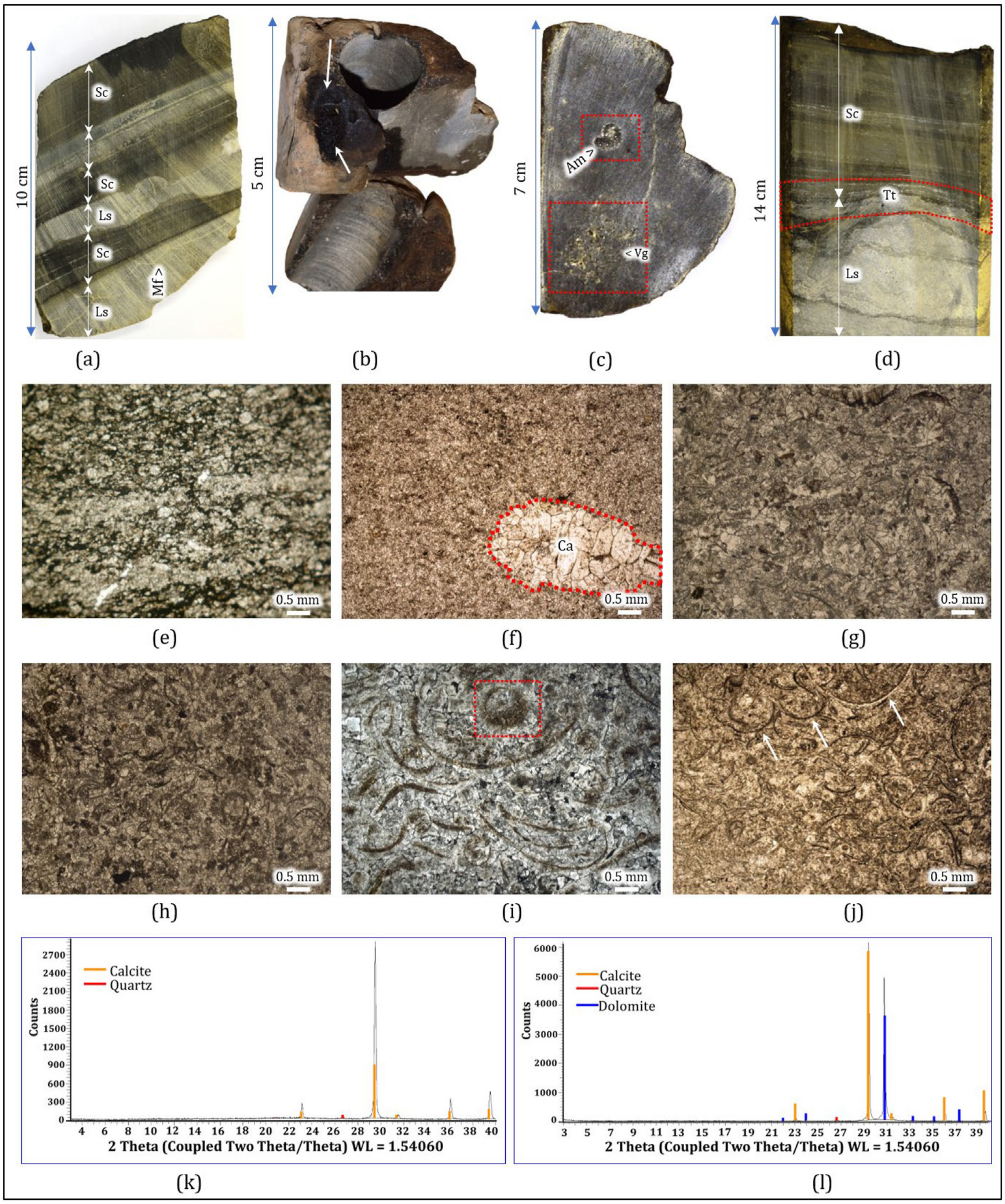

Fig. 3. Representative core photographs showing. (a) Interlayering of limestone (Ls) and siliceous carbonate rocks (Sc). (b) Oil-saturated dolomitized limestone (oil saturation is indicated by the white arrows). (c) Limestone containing fragments of Ammonite shells (Am) and vugs (Vg). (d) A brecciated/turbidity (Tt) thin layer of limestone (Ls) at the contact with siliceous carbonate rocks (Sc). Representative optical photomicrographs showing; (e) Highly recrystallized fine-grained limestone. (f) Fine-grained limestone with inclusions of secondary calcite (Ca). (g, h) Granular recrystallized limestone. (i) Recrystallized limestone with Ostracoda fragments (indicated by the red square). (j) Recrystallized limestone with Brachiopod fragments (indicated by white arrows). (k, l) XRD sample analysis charts from the Semiluksk (Domanik) and Mendymsk limestones.

The limestones include 65–70% of organic remnants fragments at some intervals and are hence classified as organogenic limestones (Lucia, 2007), (Fig. 3h, I and j). The organic remains are in the form of reasonably big clots up to 0.25 mm in diameter or sinuous layers up to 0.5 mm in thickness (Fig. 3i and j). They are mostly represented by Radiolarian fragments, Foraminifera shells, bioclastic Ostracoda (Fig. 3i), and Brachiopoda (Fig. 3j).

The organic remains are characterized by poor and medium degrees of preservation due to the granulation and recrystallization processes of the limestones (Lucia, 1995), their biomasses are filled with very fine-fine-medium-grained calcite crystals. The shells of the remnant's fragments are cemented with calcite cement. The porosity of the organogenic limestones, according to the microscopic examinations, does not exceed 5%. The intergranular pores and capillary pores form sinuous, short-length organic matter-filled channels (Fig. 3i). In the siliceous carbonate rocks intervals, the calcite grains are substantially replaced by the very fine to fine chalcedony/quartz aggregates or crystals.

4.2.2. Siliceous carbonate

The siliceous carbonate rocks in sediments of the Semiluksk (Domanik) and Mendymsk formations are easily distinguished by their dark grey to black colours and are characterized by their dense composition and horizontal stratification, which can also be referred to as “bands” (Fig. 4a).

The banding appears to be caused by the rapid deposition of the fine-grained clastics with diverse compositional features, organic content, grain size variation, and horizontal bioturbation (Bathurst, 1975; Tucker and Wright, 1990).

Due to the unequal distribution of the organic materials, these rocks have dark and light colour gradients. The distribution of light to grey calcareous/limestone concretions and/or interlayers results in the lenticular structure of these rocks (Fig. 4b). At the contacts with the limestone, milky-white veins of authigenic calcite can be noticed. Some strata of siliceous carbonate rocks are fragile and split by microfractures up to 10 cm long. Some are open, others are closed by authigenic calcite veins up to 5.0 mm thick (Fig. 4d).

Petrographic (optical-microscopic) examinations (Fig. 4e and f, Fig. 4g, and Fig. 4h) revealed that siliceous carbonate rocks had a very fine-grained structure, with organic content concentrated in the intergranular area, giving the rock a black colour. The siliceous carbonate rocks' matrix contains up to 25% inclusions of organic leftovers. Radiolarites, shell valves of Brachiopoda and Ostracoda, Tentaculites pieces, and calcified Algal are all represented. Elongated organic remnants have a typical spatial orientation based on the rock bedding. In addition to organic remains, the siliceous carbonate rocks contain lenticular-veinlets of authigenic pyrite in separate strata.

4.2.3. Dolomite

Dolomites and/or dolomitic limestones have a dark grey to black colour, a homogenous and patchy texture due to scattering of the primary limestone and the uneven distribution of organic matter/oil saturation (Fig. 5a, Fig. 5b and c).

Dolomitization and leaching processes have increased the caves saturated with hydrocarbons/oil, giving the rock dark colours (Fig. 5c). According to the optical-microscopic petrographic investigations (Fig. 5d, e and f), dolomites have a homogeneous texture consisting primarily of densely abutting medium to coarse-grained dolomite crystals ranging in size from 0.1 to 0.5 mm, and the crystals are mostly xenomorphic and isometric in shape, according to optical-microscopic petrographic investigations (Fig. 5d, e, and Fig. 5f). Organic materials produce distributed inclusions in the dolomite crystals' intergranular pores, channels, vugs, and/or microfracture (Fig. 5d, e and f). Dolomite includes 5–10% poorly preserved organic residues that are difficult to identify (Radiolarites and Brachiopods?) (Fig. 5e and f).

4.3. Sedimentary environments

Based on the lithofacies analysis and rock texture, as well as interpretations from the literature (Galimov and Kamaleeva, 2015; Liang et al., 2019, 2020; Morozov et al., 2021), it is believed that the accumulation area of the Semiluksk (Domanik) and Mendymsk sediments in the studied area of the Volga-Ural basin was a passive continental margin of a relatively deep-sea shelf (Fig. 6).

Many researchers (Kolchugin et al., 2018; Liang et al., 2019; Khayuzkin et al., 2020; Eskin et al., 2020; Morozov et al., 2021) believe that the accumulation of dark grey to black siliceous carbonate rocks over the Volga-Ural basin occurred during tectonic and volcanic activation of the basin, as evidenced by the noted

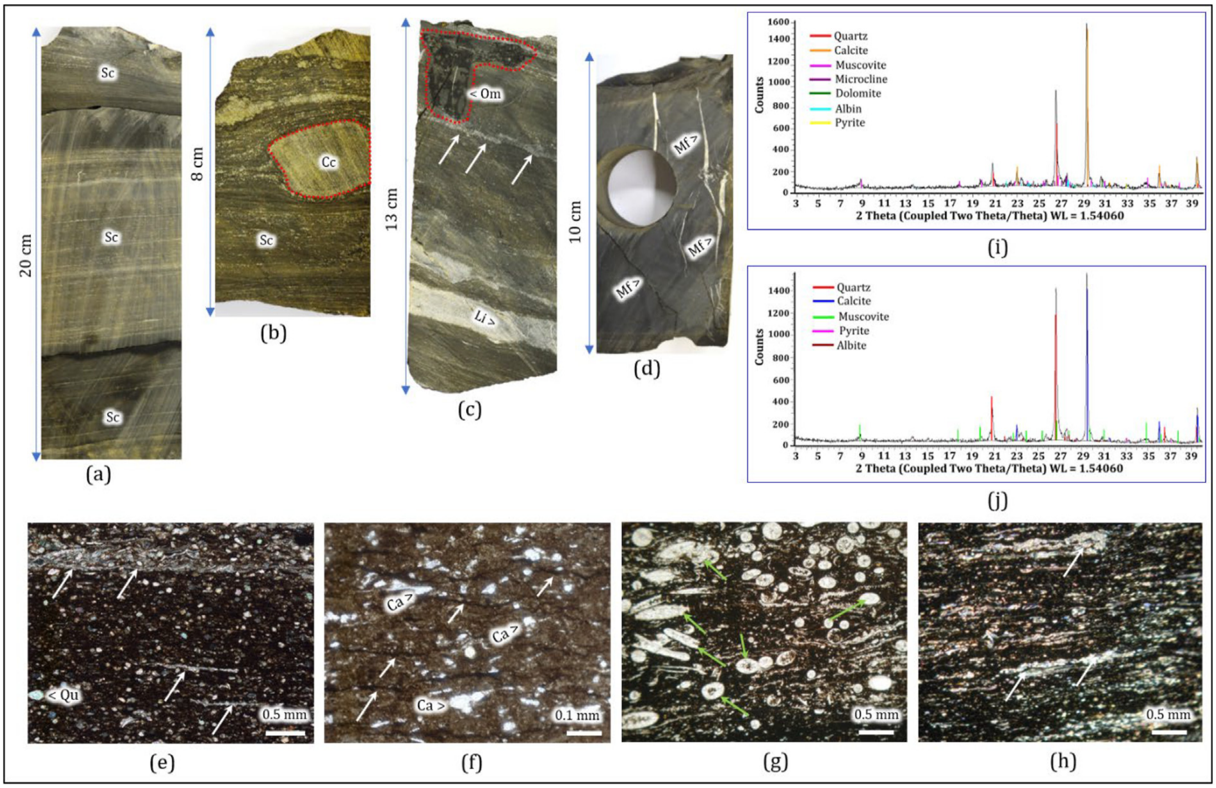

Fig. 4. Representative core photographs showing; (a) Horizontally stratified siliceous carbonate rocks (Sc). (b) Calcareous/limestone concretions (Cc) in the siliceous carbonate rocks (Sc). (c) Limestone interlayers (Li) and milky-white veins of calcite (indicated by white arrows) within the enriched organic matter (Om) siliceous carbonate rocks. (d) Sub-vertical open and calcite cemented microfractures (Mf) in the siliceous carbonate rocks. Representative optical photomicrographs showing; (e) Calcite lenses (indicated by white arrows) in the very fine-grained organic-rich siliceous carbonate matrix. (f) Secondary calcite (Ca) in the very fine-grained siliceous carbonate matrix, channels organic-rich are noted within the matrix (indicated by white arrows). (g) Very fine-grained enriched in organic matter siliceous carbonate contains inclusions of crushed Brachiopoda shells (indicated by green arrows). (h) Very fine-grained siliceous carbonate enriched in organic matter, frequent alternation with calcite lenses (indicated by white arrows). (i, j) XRD sample analysis charts from the Semiluksk (Domanik) and Mendymsk siliceous carbonate rocks.

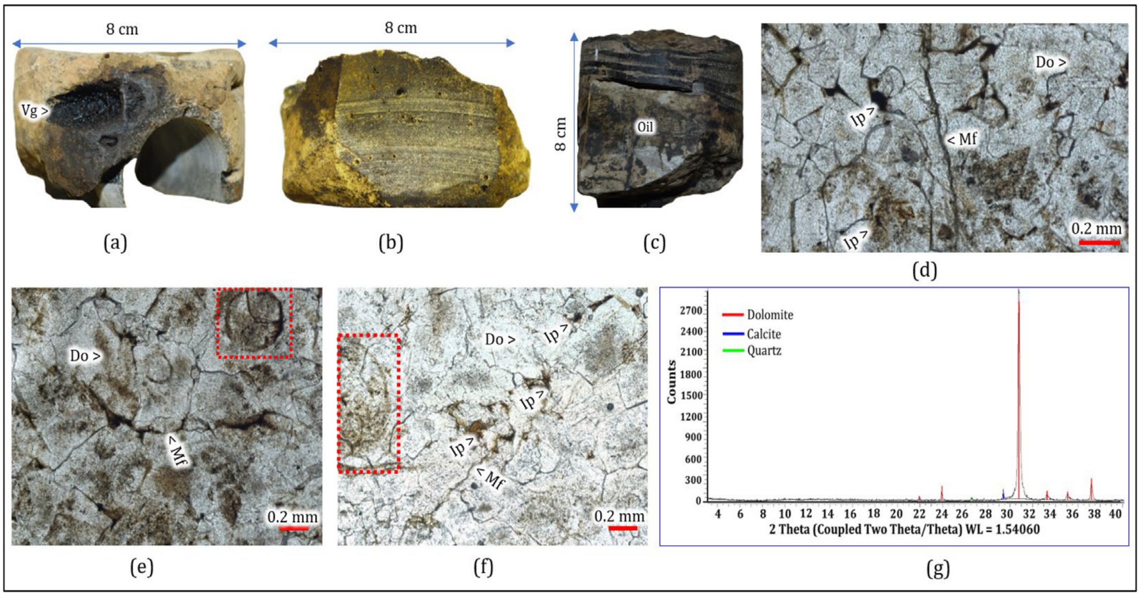

Fig. 5. Representative core photographs showing; (a) Large dimension oil-saturated vugs (Vg) within the dolomitic limestone. (b) Small to medium dimensions vugs within the dolomitic limestone. (c) Fully oil-saturated dolomitic limestone. Representative optical photomicrographs showing; (d, e, f) Medium to coarse grain dolomite crystals (Do), distributed inclusions of organic matter within the intergranular pores (Ip), microfractures (Mf), and/or the channels porosity. Preserved organic residues (indicated by the red square). (g) XRD sample analysis charts from the Semiluksk (Domanik) and Mendymsk dolomitic limestone/dolomite rocks.

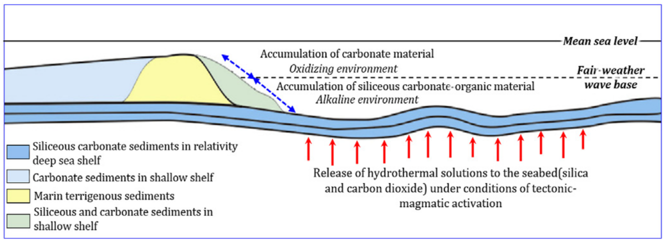

Fig. 6. Depositional model of the Semiluksk (Domanik) and Mendymsk formations in the studied area from the Volga-Ural petroleum province (after Liang et al., 2020).

volcanic rocks strata in the lower section of the Frasnian stage, which testify to the region's tectonic activation during the Frasnian (Kolchugin et al., 2018). In general, the Frasnian stage is distinguished by the highest volcanic activity, which is thought to be the primary reason for the ingress of enormous volumes of silica into sedimentary basins.

The development of the Semiluksk (Domanik) and Mendymsk sediments coincides with the development of the intense tectonic activity, and the high biological productivity is due to the appearance of abnormally temperature fields caused by hydrothermal fluids along the tectonic fluid-conducting pathways, and thus the nutrient salts. The latter is also shown by the relationship between the formation of siliceous organisms with the periods of volcanic activation, as well as the influx of huge quantities of silica with hydrothermal solutions. This also suppressed biogenic carbonate sedimentation because of an increase in carbon dioxide, which also reached the sedimentation basin in considerable quantities. Simultaneously, the increased content of carbon dioxide, methane, iron, and other volcanic activity products causes a boom of biological life, followed by a quick mass extinction, which causes the formation of strata enriched in the organic matter (Khayuzkin et al., 2020). The changes in the hydro-chemical composition of the basin, specifically an increase in the proportion of CO2 and SiO2, can cause the formation of relatively shallow radiolarian siliceous carbonate sediments, resulting in an explosion in the development of silicon organisms and suppression of organisms that build their skeleton from calcium carbonate. Thus, the tectonic and accompanying volcanic regime, which had become active by that time, played a key influence in the sedimentation conditions of the Semiluksk (Domanik) and Mendymsk layers. This expressed itself as a periodic pulsating flow of volcanic eruption products into the sea basin, resulting in a surge of biological activity and the subsequent burial of vast quantities of organic matter (Khayuzkin et al., 2020).

In this regard, cyclicity is quite clearly shown in the sediment structure of the Semiluksk (Domanik) and Mendymsk formations, where siliceous rocks with a high organic content are interspersed with siliceous carbonate and carbonate rocks with significantly less scattered organic matter. The existence of the thin-layered, horizontally-layered texture in siliceous carbonate rocks suggests stagnant sluggish sedimentation processes under conditions of low medium hydrodynamics (below the wave action), as well as a declining sedimentation environment. Whereas carbonate deposits formed in an oxidising environment with mixing of water masses above the wave action's base (Fig. 6). The recurrent shallowing of the basin and the influence of wave and storm activity on the appearance of the produced sediments are related to the overlap of thin-layered siliceous carbonate rocks by carbonate ones with breccia textures (Tucker and Wright, 1990).

4.4. Pore types and origin

Carbonate reservoirs are distinguished by multiple porous systems and heterogeneous in most cases, resulting in petrophysical heterogeneity (Lucia, 2007). As a result, the types of pores, their proportions, and distribution patterns have a considerable influence on the production and stimulation characteristics of carbonate reservoirs.

According to petrographic observations and Lucia (1995; 2007) pore classification, four major pore types were observed within the studied cored intervals from the Semiluksk (Domanik) and Mendymsk formations, which are as follows: (1) interparticle pore, (2) intercrystalline pore, (3) vugs, and (4) fracture. The sections that follow summarise the features of each pore type.

4.4.1. Interparticle pore

The void spaces preserved between the carbonate grains, organic materials, and/or authigenic minerals are identified as interparticle pores (Lucia, 1995). The carbonate lithofacies of the Semiluksk (Domanik) and Mendymsk formations have a higher frequency of interparticle pores than the siliceous carbonate. They are typically dispersed and poorly connected. They observed in a variety of sizes ranging from 10 to 100 μm (Fig. 7a, Fig. 7b, c, Fig. 7d, e and f). In the examined thin section, two classes of interparticle pores were identified based on pore sizes: interparticle micropores and interparticle patchy mesopores. The interparticle micropores can be seen in the siliceous carbonate (Fig. 7a upper part), they are characterised by small pore sizes of several up to a maximum of 20 μm, the pore distribution is usually connected with the rocks texture and uniform throughout the rock, including the matrix (Fig. 7b and c).

The interparticle patchy mesopores class is defined by pore sizes ranging from 20 to 50 μm, and also their patchy distribution within the rocks (Fig. 7a, lower portion), (Fig. 7d and e). The majority of the interparticle pores identified in the examined carbonate samples belong to this type. Furthermore, because of their patchy distribution in the rock matrix, they have heterogeneous effects on petrophysical properties (Lucia, 1983).

The interparticle pores are mostly of depositional origin, but some are of diagenetic origin and are formed by the selective solution of the matrix and/or the cement between the rock components. As a result of compaction during the deep burial diagenesis, the majority of interparticle pores collapse and decrease in abundance (Lønøy, 2006). The morphologies and size distribution of the interparticle pores authigenic minerals differ from those of the grain interparticle pores. They range from minor to well-preserved and connected. Some of the grain and/or authigenic interparticle

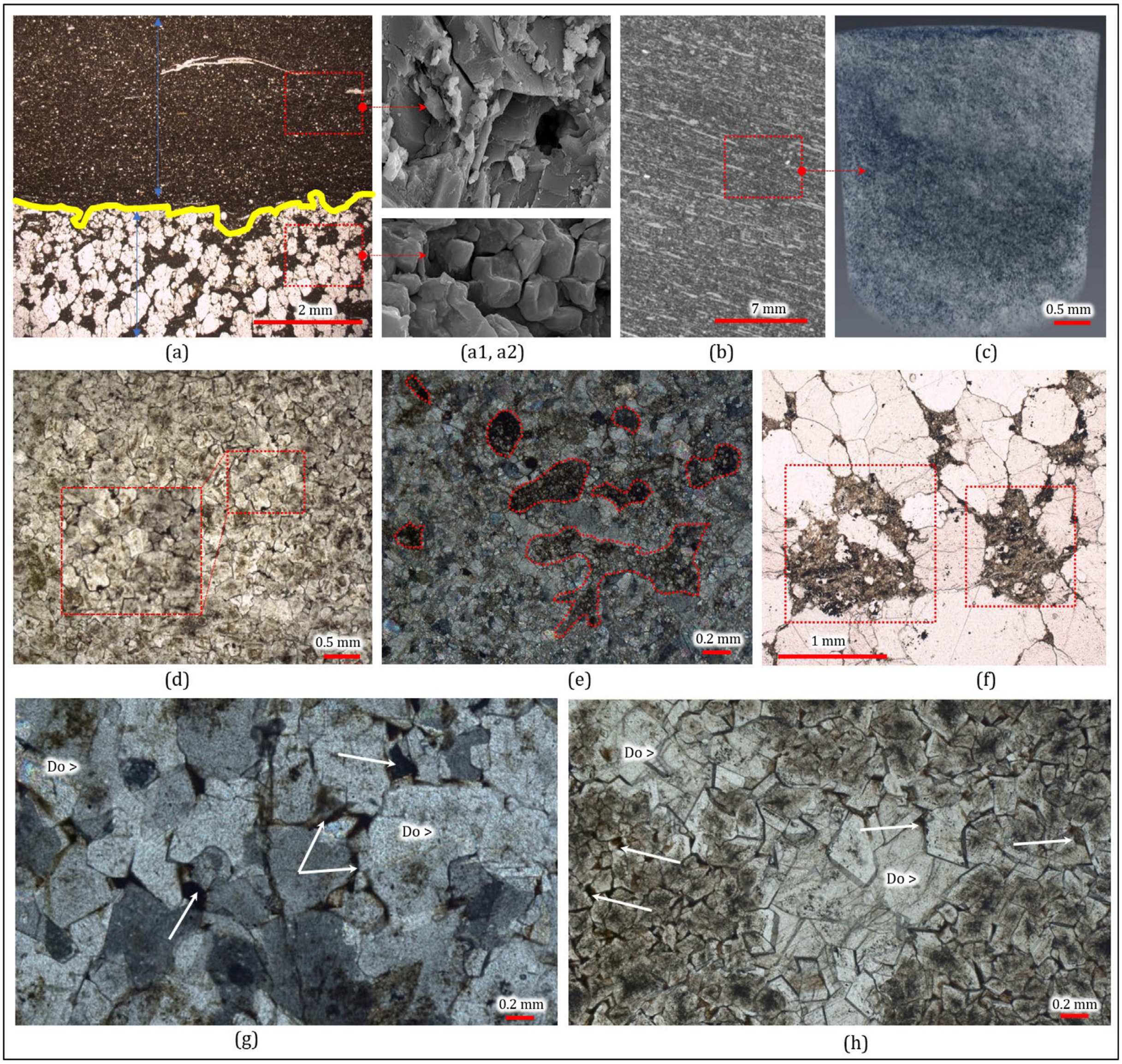

Fig. 7. Representative optical photomicrographs showing; (a) The upper section show uniform interparticle micropores within the siliceous carbonate, the lower section show uniform interparticle patchy mesopores within the carbonate (a1, a2 represented photomicrographs of the specified pores taken using a scanning electron microscope SEM). (b) Representative core photomicrography showing the texture of the siliceous. (c) Representative photomicrography using X-ray tomography showing the structure of the interparticle micropores within the siliceous carbonate. (d, e) Interparticle patchy mesopores within the crystallized limestones (indicated by the red squares). (f) Intercrystalline patchy mesopores between the limestones components (indicated by the red square). (g) Intercrystalline patchy mesopores between the dolomite crystals (Do) (indicated by white arrows). (h) Intercrystalline patchy micropores between the dolomite crystals (Do) (indicated by the white arrows).

pores are blocked by organic debris and/or authigenic minerals, primarily calcite.

4.4.2. Intercrystalline pore

The term “intercrystalline pore” refers to the pores between crystals, which might be of primary or secondary origin and are generally formed of dissolution features. This form of the pores can be found in all lithofacies; however, it is more common in the dolomitic limestones and/or dolomite (Fig. 7f, g and h). According to Lønøy (2006) classification, there are two types of intercrystalline pore: intercrystalline patchy micropores and intercrystalline patchy mesopores. The pore diameters of intercrystalline patchy mesopores range from 20 to 70 μm. (Fig. 7f and g). This type of intercrystalline pore is typically encountered between anhedral and subhedral planer dolomite crystals in dolomitic carbonate lithofacies (Fig. 7g). These pore formations are caused by the fabric damaging dolomitization of the matrix. Pore diameters in the intercrystalline patchy micropores range from 10 to 20 μm. (Fig. 7h). They are most noticeable in the examined thin sections between dolomite crystals. The distribution of these pores is related to the patchy cementation and, less frequently, the crystal organisation (Lønøy, 2006).

4.4.3. Vugs

Vugs refers to the pore spaces that exist in particles and/or crystals that are larger than the particles or crystals (Lucia, 1995; Lønøy, 2006). Vugs are presented in all the examined lithofacies (Fig. 8) at random or according to the bedding, and it is found mostly in oil-saturated limestones and dolomitic limestones, with less development in siliceous carbonates. They appear along the intergranular pores, microfracture, and/or the weaker zones. They can be completely or partially empty, or filled with secondary minerals and/or hydrocarbons. The vugs are classified according to the Lucia (1995) classification as separate vugs and touching vugs as shown below.

4.4.3.1. Separate vugs. According to the Lucia (1995) classification, the separate vugs are represented by; separate vugs, moldic pore, and intraparticle pore.

Separate vugs are referred to as solution pores and is often fabric-selective in origin (Lucia, 1995). They are most common in the limestone (Fig. 8a) of the examined section and have a low frequency in the siliceous carbonates. Because of the lack of connecting throats, the presence of these pore types in rocks increased the total porosity but did not influence the effective porosity and/or the permeability.

Moldic pore contains the non-fabric selective pores that dissolve separately (Lucia, 1995). Moldic pores are classified (Lucia, 1995) as moldic micropores (with a diameter less than 20 μm) developed in the mud-supported carbonate lithofacies (Fig. 8b) and the moldic macropores (with a diameter greater than 20 μm) that developed in the siliceous carbonate lithofacies (Fig. 8c).

Intraparticle pore refers to the pores that their distribution is typically fauna dependant (Fig. 8d). They are often fabric-specific in origin (Lucia, 1995). They appeared mostly as intra-fossil pores within cells of benthic foraminifers such as Miliolid and Borealis in the examined sediments section; pore sizes are typically less than 0.5 mm, and the inner pore walls are partially or totally filled with secondary calcite.

4.4.3.2. Touching vugs. According to the Lucia (1995) classification, the touching vugs are represented by; touching vugs, cavernous and channel pores as shown below.

Touching vugs refers to pores that are often non-fabric selective in origin and generated by the massive dissolution of the matrix and/or the components of the rocks, (Fig. 8e). In the studied samples, the observed vuggy touching pores occurred in a variety of the carbonate and dolomitized lithofacies, with sizes ranging from small to medium (in the term of micrometre scale). Massive dissolution resulted in the creation of relatively wide pore spaces that were unaffected by the rock fabric. Identification of touching vugs is critical in reservoir rocks because they have a large influence on reservoir flow characteristics by creating additional paths that contribute to the movement of fluids through the reservoir rocks (Lucia, 1995; Lønøy, 2006).

Cavernous pores are identified as a non-fabric selective pores and characterised by dissolving cavities ranging in size from less than 2 mm to 1.0 cm, sometimes with huge voids (mesopores) (Lucia, 1995; Lønøy, 2006). The varied sizes and forms of these pores are relatively common in the limestone lithofacies (Fig. 8f and g), less developed in the siliceous carbonate rocks. Caverns have a non-isometric shape, are saturated with hydrocarbons/oil, have a slit-like shape, and in certain cases, their walls are coated with secondary calcite (Fig. 8d indicated by the yellow rectangle). Cavernous pores are created as a result of the chemical dissolution of the calcite limestones, as well as dolomitization processes that remove the dissolved components, this explains why they are so common in the limestone and dolomitized limestone lithofacies (Liu et al., 2017). Cavernous pores are very important in increasing the storage properties of the carbonate reservoir of the studied Semiluksk (Domanik) and Mendymsk formations, as their expansion and connectivity between them contribute to the containment of more hydrocarbons and fluid kinetics within the reservoir rocks, and thus increase the permeability. Cavernous pores also play a good role in increasing the capacitive properties of the reservoir in siliceous carbonate rocks, but their impact is limited in this regard due to their low frequency here.

Channel pores are formed as a result of the occurrence and development of dissolution processes along some microfractures and/or of some elongated fossil remnants, and it is differentiated by its channel-like shapes (Lucia, 1995; Lønøy, 2006). The channels pores are well developed in the limestone with a high proportion of fossilised residues, where the process of dissolution of these residues leads to the formation of channels that may be filled with organic matter (see Fig. 2i) or, in certain conditions with diagenetic minerals. Furthermore, channel pores are common in the siliceous carbonate and dolomites, where matrix dissolution results in the formation of channels that are typically filled with organic debris or secondary minerals (Fig. 8h and i). This class of pores is formed as a result of the dissolution along the contacts between the dolomite crystals (see Fig. 4e and d). The channel pores come in a wide range of sizes and forms, ranging from a few microns to a few millimetres in some situations. Furthermore, large degrees of tortuosity increase the length of the filtration routes, complicating fluid exchange within the reservoir rocks (Zhou et al., 2020). Channel pores was grated during diagenesis in the siliceous carbonate rocks and did not alter further. As a result, organic matter has a pretty homogeneous distribution in these rocks. The investigated interval's limestones have two types of channel pores: primary and secondary, with the secondary having the biggest pores (Yang. and Dong., 2017). The primary channel pores were generated during the diagenesis of rocks and did not undergo any further changes (Lucia, 1995). They are distinguished by a uniform distribution of the rock's volume, relatively consistent size, and uniform filling with organic content. Secondary channel pores were produced during the secondary recrystallization of the carbonate rocks (Lønøy, 2006).

4.4.4. Fracture

The fracture within the section of the Semiluksk (Domanik) and Mendymsk formations is slightly developed. Some of them cut

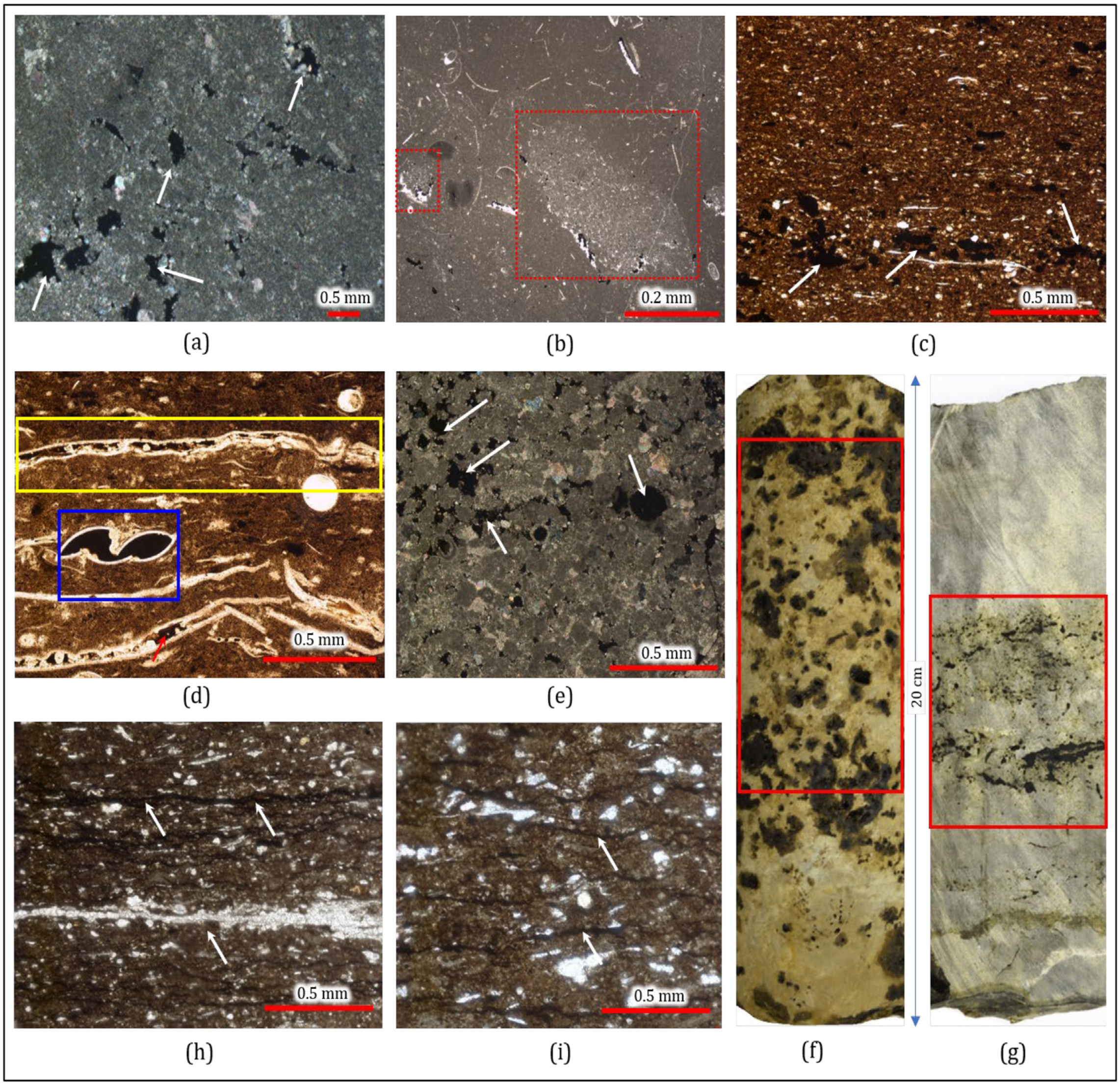

Fig. 8. Representative optical photomicrographs showing; (a) Separate vugs within the limestone (indicated by white arrows). (b) Moldic micropores developed in the limestone (indicated by red squares). (c) Moldic macropores developed in the siliceous carbonate (indicated by white arrows). (d) Fauna dependent intraparticle pores developed in the limestone (indicated by the blue square). (e) Touching vugs created by the dissolution within the limestone (indicated by white arrows). (h, i) Channel porosity developed in the siliceous carbonate rocks (indicated by white arrows). Representative core photographs showing; (f, g) Cavernous pores oil-saturated developed within the limestone (indicated by red squares).

through the carbonate rocks (Fig. 9a), whereas others cut through the siliceous carbonates (Fig. 9b). In many cases, the fracture interacts with the channel pores and/or the touching vugs, forming a similar porosity amongst these types and making it impossible to ascribe the resulting pore type to any of the previously stated categories.

In the investigated section of the Semiluksk (Domanik) and Mendymsk formations, there is an uncertain trend to increase fracture density by increasing the amount of siliceous in the carbonate rocks.

According to the genetic characteristics, there are two primary systems of fractures: tectonic fractures and diagenetic fractures. The lumpy and rough morphology of their walls without indications of sliding and rubbing indicates tectonic fractures; additionally, they are characterised mostly by sub-vertical strike and straightness (Qi et al., 2018; Martyushev. and Alexey, 2021). That is, no longitudinal displacements of the walls occur; only transverse expansion occurs. In some layers, single fractures cleave the rocks (Fig. 9b), while in others, fractures create systems of two to four parallel faults (Fig. 9c).

The apparent length of the tectonic fractures ranges from 1.5 cm to 10 cm, while the opening amplitude ranges from 0.05 to 0.25 mm. Fracture morphology is typically straightforward in highly homogeneous rocks (Fig. 9d). It is more complex in rocks with a well-defined layered texture, due to the presence of horizontal branches spreading from the main fracture channel and intruding along the boundaries of several lithotypes of rocks (Fig. 9e). The tectonic fractures in oil-saturated limestones are complicated by leaching caverns that are connected with them (Fig. 9f). The cavities of the fractures also bear traces of dissolution in the form of slit-like broadenings. Some tectonic fractures are unfilled (Fig. 9b), oil-saturated (Fig. 9d and f), or partially or totally filled with secondary calcite (Fig. 9g), and as a result do not participate in modern fluid movement processes inside reservoir rocks. More recent fractures are distinguished by various degrees of openness, with constrictions alternating with blow-ups. Because

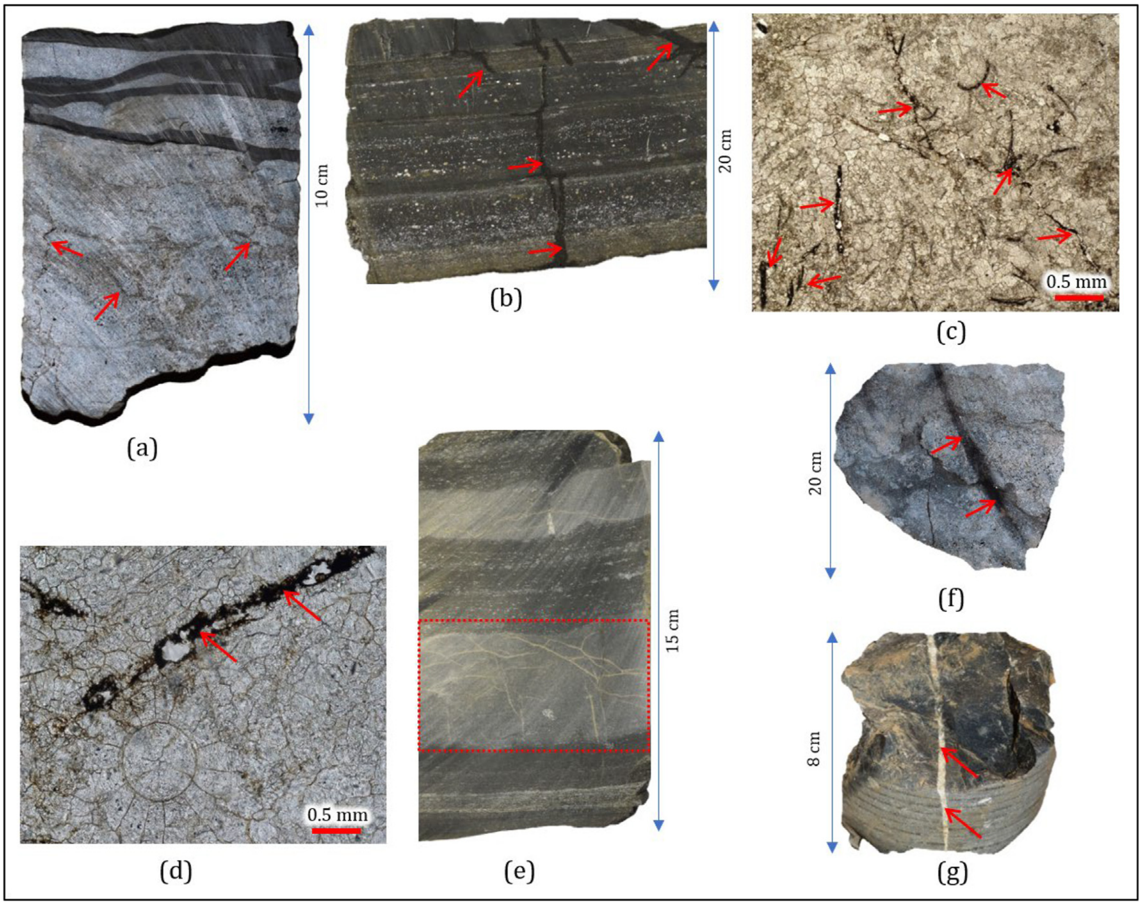

Fig. 9. Representative core photographs showing; (a) Microfractures developed in the carbonate rocks (indicated by white arrows). (b) Microfractures developed in the siliceous carbonate rocks (indicated by red arrows). Representative optical photomicrographs showing; (c, d) Microfractures in carbonate rocks filled with hydrocarbons (indicated by red arrows). Representative core photographs showing; (e) Microfractures filled with secondary calcite developed in the siliceous carbonate rocks (indicated by red squares). (f) Microfractures free of secondary mineralization and filled with hydrocarbons (indicated by red arrows). (g) Microfractures filled with secondary calcite (indicated by red arrows).

they include oil, some of them are likely engaged in the migration of water-oil fluids (Qi et al., 2018).

The diagenetic fractures are characterized by sub-horizontal strike and tortuosity of the fissure channel (Lønøy, 2006). The cavities of diagenetic fractures, as a rule, are tightly closed under the action of rock pressure. However, despite this, in some of them, the presence of films of the bituminous matter is noted. Possibly, they are products of hydrocarbons squeezed out from oil source rocks (Lucia, 1995).

5. Discussion

5.1. Ternary porosity plot

The various diagenetic processes to which carbonate rocks are subject have a considerable impact on the formation of porosity and the changes that occur to it. Understanding the types of pores and how they evolve leads to a better understanding and identification of the predominant diagenetic processes. Kopaska-Merkel and Mann (1993) ternary pore plot diagram (Fig. 10), was used in this work, which provides valuable information about the pore facies classification of the studied rocks and facilitates the identification of influential diagenetic processes, their distribution, trends, effects, and/or diagenetic products. The ternary pore plot diagram depicts the effects of dissolution processes, cementation, compaction, and dolomitization on the pore space system of the investigated carbonate rocks. The three vertices of the ternary diagram are represented by the three primary pore types. Point counts data obtained from petrography thin section examinations were used and plotted on the ternary pore plot diagram (Fig. 10).

The identified pore types in this study were divided into three major groups based on Kopaska-Merkel and Mann (1993) classification: (1) “Depositional Pores” or pores of sedimentary origin, which include the interparticle and intraparticle pores; (2) “Fabric Selective Pores”, which include the moldic and intercrystalline pores. (3) “Non-fabric Selective Pores” are those that include (vugs, cavernous, channel, and fracture, in addition to the intercrystalline pores caused by the fabric destructive dolomitization processes). The three apexes of the ternary pore plot diagram are used to place the primary pore types/groups, as shown in Fig. 10.

The major groupings of predefined pores represent the common types of pores in the examined thin section samples, and each one is introduced as a distinct “Pore Facies”. Pore facies analysis is a new generation of reservoir rock classification based on pore system properties (Kopaska-Merkel and Mann, 1993). The term “Pore Facies” refers to a certain rock unit that is distinguished by a specific proportion of the pore type/types. This facies has a particular form of the pore, which is differentiated by unique size and distribution and reflects specific features in the processes of passing porous fluids and hence reservoir qualities. Pore facies may comprise a single type of common pore or diversity of pores; in carbonate rocks, pore facies are defined by a diverse mixture of pores. The

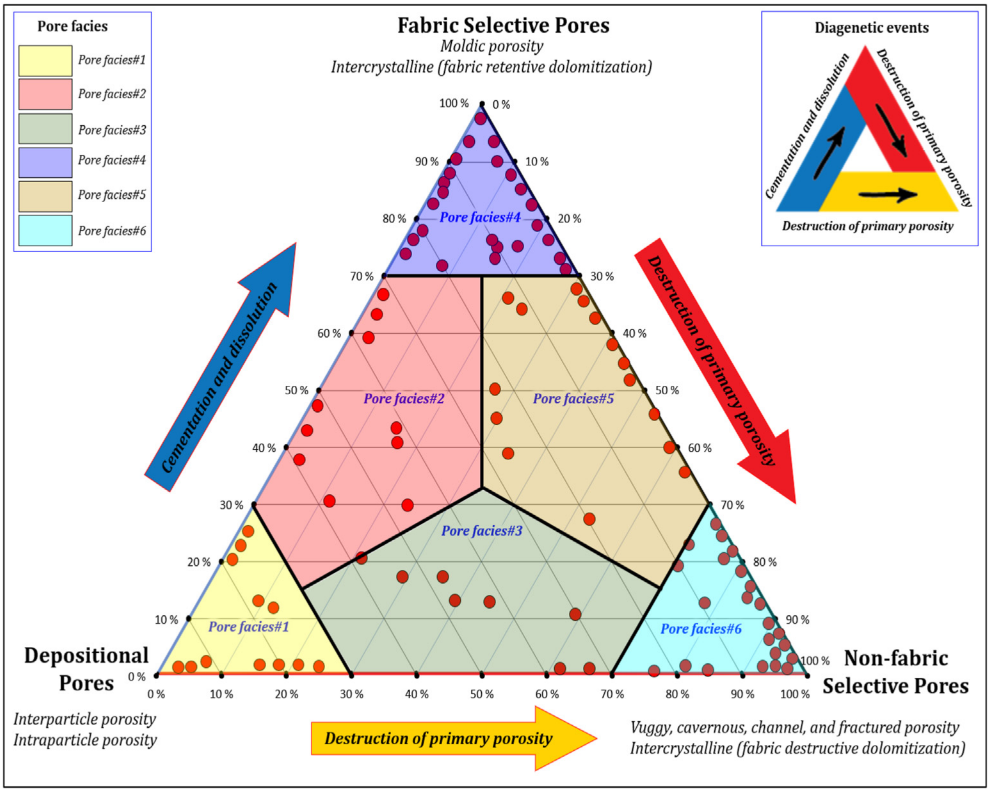

Fig. 10. Kopaska-Merkel and Mann (1993) ternary pore plot diagram for pore types and pore facies classification of the Semiluksk (Domanik) and Mendymsk formations sediments in the central part of Volga-Ural petroleum province. The variations in pore spaces reflect the diagenetic trends of the pore facies. The changes in pore types and quantities are influenced by diagenetic processes as dissolution, cementation, fracturing, and dolomitization. (The studied samples are denoted by red circles).

identified pore facies, their diagenetic and reservoir properties in the Semiluksk (Domanik) and Mendymsk formations sediments are as follows:

(1) *Pore facies 1*: This pore facies can account for up to 70% of the total volume and is commonly referred to as sedimentary pore facies since the pores are related to the depositional origin. The points indicating these pore facies are located near the vertex representing “Depositional Pores” on the ternary pore plot diagram (Fig. 10). The pores linked to this type of pore facies include interparticle and intraparticle pores, which are typically encountered in the carbonate rocks that have been less subjected to the diagenetic processes such as dissolution, dissolution, and dolomitization.

(2) Pore *facies 2*: Pores belonging to this pore facies account for 30–70% of the “Depositional Pores” and the “Fabric Selective Pores” (Fig. 10). This pore facies is represented by the points on the ternary pore plot diagram between the vertex representing “Depositional Pores” and the vertex indicating “Fabric Selective Pores”. As a result, this pore facies can be regarded a mixture of them, and its petrographical and petrophysical features are comparable to those of “Depositional Pores”/Pore facies 1 and “Fabric Selective Pores”/Pore facies 4 (Fig. 10).

(3) *Pore facies 3*: Pores belonging to this pore facies account for 30–70% of the “Depositional Pores” and “Non-fabric Selective Pores” (Fig. 10). Most of the pores in this pore facies have good interconnectivity with each other, hence they have better reservoir properties than the Pore facies 2 pores, which have generally poor reservoir properties. Pore facies 3 have a limited impact on reservoir quality since they are less common in the examined samples from Semiluksk (Domanik) and Mendymsk formations.

(4) *Pore facies 4*: This type of pore facies is known as “Fabric Selective Pores” because the represented points on the ternary pore plot diagram are near the vertex signifying “Fabric Selective Pores” (Fig. 10). This pore facies have more than 70% moldic and intercrystalline pores. Because the frequency of moldic pores in the analyzed samples is substantially higher than the frequency of intercrystalline pores, this pore facies is also known as moldic pore facies, and it is often created in the cemented carbonate rocks whose constituents have been partially or totally dissolving. Fabric selective intercrystalline pores have formed in the carbonate rocks with moldic pore facies as a result of partial and/or totally fabric selective dolomitization processes. The pores associated with this type of pore facies have relatively substantial dimensions from a petrophysical standpoint, but the widths of their throats are often modest, limiting effective communication between them. Because these pores are solely connected by intercrystalline pore space pathways, they do not contribute effectively to increasing reservoir quality due to their limited function in the development of reservoir rock permeability.

(5) *Pore facies 5*: Pores belonging to this pore facies account for 30–70% of the “Fabric Selective Pores” and “Non-Fabric Selective Pores” (Fig. 10). The majority of these pores has a diagenetic origin. On the ternary pore plot diagram, the points representing this pore facies are placed between the vertex representing “Fabric Selective Pores” and the vertex representing “Non-fabric Selective Pores.” As a result, this pore facies can be considered a mixture of them, and its

petrographical and petrophysical features are a combination of properties from the Pore facies 4 and the Pore facies 6 (Fig. 10).

(6) Pore facies 6: This pore facies is also known as “Non-fabric Selective Pores” because more than 70% of its representing points are positioned near the vertex representing the “Non-fabric Selective Pores” on the ternary Pore plot diagram (Fig. 10). The observed pores in this pore facies are the vugs, cavernous, fracture, and intercrystalline pores, with the vugs having the highest frequency, hence this type of pore facies can be named “vuggy pore facies.” The most prevalent pores in this pore facies are contacting vugs, which have formed as a result of several diagenetic processes such as dissolution, compaction, fracturing, and dolomitization. The variable pore geometry of these pore facies distinguishes them since they can be detected in a variety of forms and sizes depending on the extent to which the original rock was influenced by the diagenetic processes. The majority of the pores in this facies are characterized by their size (macropores) and large pore throat diameters. Some of the limestones were subjected to dolomitization processes, which resulted in the formation of intercrystalline pores among the dolomite crystals. The vuggy pore facies, also known as pore facies 6, is the most abundant in the examined carbonate section; it is found mostly in limestone, dolomite, and dolomitic limestone.

5.2. *The relationship between lithofacies and organic matter*

Petrographic studies have revealed that sediments of Semiluksk (Domanik) and Mendymsk formations are represented by interbedded limestones and siliceous carbonate rocks enriched in organic matter, with dolomitic limestone and/or dolomite also present in some intervals where dolomitization is the dominant process. Thermal analysis of the investigated rocks revealed considerable changes in organic matter content and composition. Organic matter is classified into two categories based on the results of thermal analysis and petrographical examinations: the syngenetic (autochthonous) organic matter and the epigenetic organic matter (allochthonous) (Morozov et al., 2021).

The products of the diagenetic transformation of siliceous carbonate sediments enriched in organic matter during the lithification/diagenetic processes are classified as syngenetic. The epigenetic category includes organic matter/oil that migrates to the limestones and/or dolomites. According to the optical microscopic investigations, syngenetic organic matter is concentrated in siliceous carbonate rocks and is scattered between the granular bulk of the rock's extremely fine to fine components, which determine the dominating dark colour of these rocks. In traces, epigenetic organic matter has been found within the pore spaces of dolomitic limestones and dolomite thin interlayers. The content of epigenetic organic matter in the dense limestones is typically low, ranging from 0.5 to a maximum of 2.0%. Its presence is indicated by two low-amplitude exothermic peaks in the temperature ranges of 200–350 °C and 360–480 °C, according to thermograms (Fig. 11a).

Thermal degradation of organic components of sapropel derivatives happens in these temperature ranges. The thermogram shows the following loss of mass in the range of 650–780 °C. Thermal dissociation of calcite, which makes up the skeleton of the carbonate rock, happens at these temperatures, resulting in the creation of CaO and the release of CO2 (Wilson and Schieber, 2015). The overall weight loss is approximately 1.0%, indicating a negligible residual hydrocarbon concentration in the limestone rocks.

The proportion of epigenetic organic matter in the oil-saturated dolomites and/or dolomitic limestones ranges from 5 to 10%. Its existence is shown on thermograms by a lingering exothermic effect in the temperature range of 200–460 °C, induced by the processes of thermal degradation and oxidation of the various groups of hydrocarbons (Fig. 11b). The ensuing weight loss, accompanied by a strong endothermic effect on DSC, is linked to the thermal dissociation of dolomite (CaMg [CO3]2), which results in the creation of MgO and CaO as well as the release of CO2 (Lucia, 2007).

Organic matter content increases dramatically in the siliceous carbonate rocks enriched with organic matter and low calcite content, reaching up to 35%. In this scenario, three distinct exothermic peaks may be seen on the thermogram with temperatures ranging from 200 to 320 °C, 330–440 °C, and 460–520 °C. (Fig. 11c). According to thermal analysis, the three exothermic peaks can be attributed to both staged thermal annihilation of mobile organic materials and kerogen decomposition. Considering the sequence of thermo-oxidative hydrocarbon destruction, it may be assumed that the first stage is light hydrocarbons, the second stage is heavy hydrocarbons, and the third stage is kerogen decomposition. The data obtained from optical microscopic examinations confirm the substantial presence of organic components in siliceous carbonate rocks.

An experiment was carried out to eliminate the organic materials in order to evaluate the consistency of the obtained results. Pieces of siliceous carbonate rocks enriched with a known mass of organic materials were placed in a muffle furnace and held there for 12 h at $T = 600$ °C. The samples were then taken out of the oven and weighed again. Weight loss ranged from 28 to 40% in diverse samples. The samples were entirely cleared in this example without losing their form (Fig. 11d and e).

All clarified samples have significant hygroscopic characteristics, meaning they can absorb and retain up to 40% of their weight in water. The carbonates and siliceous carbonate rocks have a very high intergranular porosity that is totally filled with organic materials, according to the experimental data. The organic component's black hue makes it impossible to consistently establish the presence of void-pore space in rocks using an optical microscope. The complete clarity of the samples' full volume implies that the pore intergranular space of carbonate-siliceous-carbonaceous rocks has strong connectedness.

5.3. *Diagenesis and reservoir quality relationship*

In general, the exceptional petrophysical complexity of carbonate reservoirs can be attributed to the large range of pore types found in them (Lucia, 1995). The relative chemical instability of carbonate rocks, in addition to the evident influence of various diagenetic processes, is the fundamental cause for the great variety of pore forms. Indeed, diagenetic processes are the primary determinants of carbonate rock hydrocarbon productivity in Tatarstan region fields and throughout Russia (Kolchugin et al., 2018; Liang et al., 2020; Khayuzkin et al., 2020; Eskin et al., 2020; Morozov et al., 2021). Based on ternary porosity plot results (Fig. 10) and their association with results of the thin sections microscopic petrographic investigation, a trend defining the relationships between the different types of pore facies and the distinct diagenetic processes can be seen.

The pore facies 1 to which the interparticle pores belong is the least altered by the diagenetic processes to which the rock was exposed. The majority of the pores in this facies are primary pores of sedimentary origin, with a high frequency in siliceous carbonate rocks and a lesser frequency in limestone and/or dolomitic limestone rocks.

Pore facies 4 is distinguished by being one of the facies that has been subjected to the various diagenetic processes such as

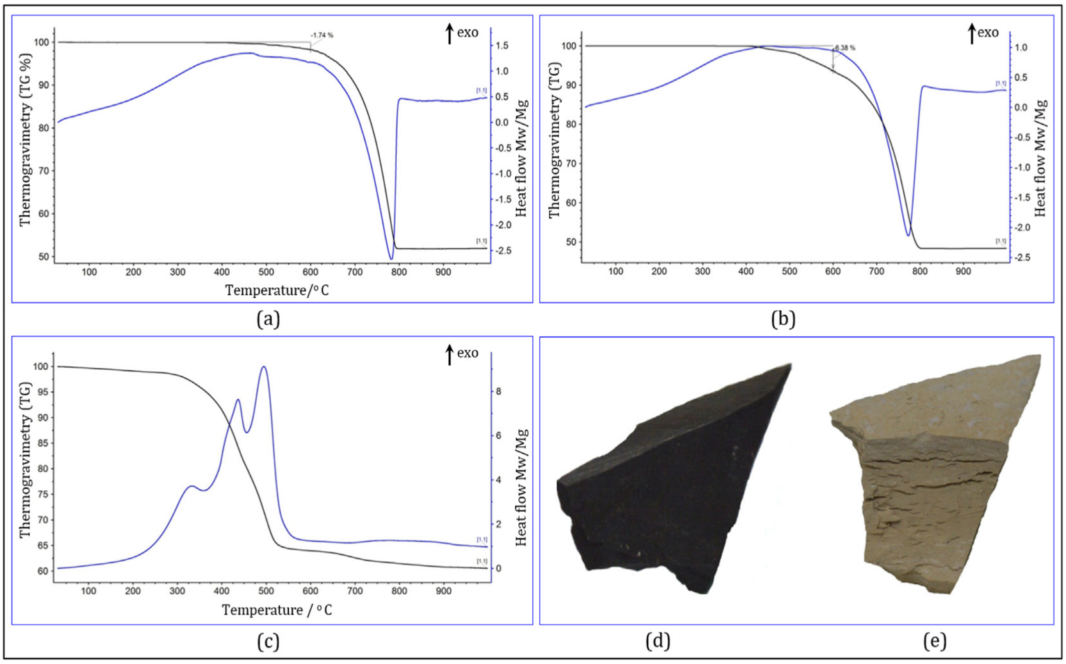

Fig. 11. Differential calorimetry curve (DSC) and thermogravimetric curve (TG) for samples from sediments of the Semiluksk (Domanik) and Mendymsk formations in the Volga-Ural oil and gas basin; (a) Poorly oil-saturated recrystallized dense limestone. (b) Poorly oil-saturated dolomitic limestone. (c) Oil-saturated siliceous carbonate rocks with a high content of organic matter. An experiment to eliminate the organic matter; (d) Photo of siliceous carbonate sample in its original form before firing. (e) Photo of siliceous carbonate sample after firing for 12 h at T = 600 °C.

dissolution, cementation, and fabric dolomitization; these processes were effective in the partial destruction of the rock fabric; as a result, the rock fabric is partially preserved in this pore facies.

By moving from pore facies 1 to pore facies 4, the effect of the different diagenetic processes (dissolution, cementation, and dolomitization) increased, resulting in the closure of many of the pore facies 2 pores due to cementation, which contributed to the closure of many pore throats, and as a result, reducing the reservoir properties of the pore facies 2 by reducing the effective conductivity between pores, and thus the permeability.

Pore facies 6 was also modified by the diagenetic processes, dissolution and dolomitization are the two diagenetic processes that effectively affected the rocks of the studied section, changing partially or completely the primary fabric. They also changed the porosity of the rocks by creating significant secondary porosity due to calcium sulphate dissolution during the various burial stages.

As shown in Fig. 10, the impact of the diagenetic processes increases with the transition from pore facies 4 to pore facies 6, where the processes of dissolution, dolomitization, and fracturing participated in the formation of the touching pores, and this contributed to improving reservoir quality by moving from pore facies 4 to pore facies 6, while with the transition from pore facies 4 to pore facies 6, the impact of the diagenetic processes decreases. Considering the relationship between facies and oil saturation, it is possible to conclude that the massive dissolution of limestone is the main dominant process that has contributed to improving reservoir quality, in addition to dolomitization and the accompanying diagenetic processes, which have also contributed relatively to improving reservoir properties in the dolomite intervals.

6. Conclusion

Three lithofacies were identified within the Upper Devonian Semiluksk (Domanik) and Mendymsk strata: limestones, organic matter-rich siliceous carbonate, and dolomitic limestones/dolomite. Their sediments are thought to have accumulated on the continental margin of a deep-sea shelf. According to X-ray study, calcite is the most common mineral phase in limestones. The siliceous carbonate rocks' major mineral phases were identified as quartz, followed by calcite. The rocks have relatively low reservoir characteristics, with porosity ranging from 0.1 to 5 percent and permeability ranging from 0.01 to 10 mD. Several primary and secondary pores have been identified in the carbonate successions of the upper Devonian Semiluksk (Domanik) and Mendymsk formations in the studied field of the Volga-Ural Basin based on petrographic data. The occurrence of vuggy, moldic, and intercrystalline pores was found to be more common than intraparticle and interparticle pores. Using the ternary pore plot schematic plot, six different pore facies with diverse diagenetic and reservoir features were discovered. Depositional pore facies 1, moldic pore facies 4, vuggy pore facies 6, pore facies 2 is a combination of pore facies 1 and 4, pore facies 3 is a combination of pore facies 1 and 6, and pore facies 5 is a combination of pore facies 4 and 6. The majority of the pores in the investigated carbonate section are secondary as a result of the rock's different diagenetic processes, which include selective and massive dissolution, fracturing, compaction, and dolomitization. Massive dissolution was the most important factor in the establishment of secondary porosity and the improvement of reservoir quality, particularly in the limestone strata. Pore facies 6, which has the highest percentage of vuggy pores, has significantly improved the reservoir's quality. Pore facies 4 played a limited role in improving reservoir quality.

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