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LITHOFACIES PECULIARITIES OF THE ORGANOGENIC STRUCTURES OF THE SECOND CARBONATE SEQUENCE OF THE EASTERN EDGE OF THE PERI-CASPIAN DEPRESSION OF THE ZHARKAMYS UPLIFT

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The Peri-Caspian Basin is the major oil and gas basin in Kazakhstan. It contains huge hydrocarbon reserves within pre-salt carbonate deposits.

Numerous oil and gas-condensate fields, associated with the pre-salt carbonate complexes had been discovered in the Eastern part of the Peri-Caspian Depression.

This work aims at the study of the second carbonate sequence (CS-II) of the Late Visean – Early Moskovian age of the Eastern edge of the Peri-Caspian Depression. The formation of the Eastern edge of the Peri-Caspian Depression took place in the zone of the junction of the East European craton and folded structures of the Urals. These conditions predetermined the complexity of the sedimentation processes, variety of lithological types of rocks, and the diagenesis processes with the formation of high heterogeneity of the reservoirs.

The CS-II will retain the leading role as the main reservoir of hydrocarbons and it has the further potential for oil exploration in the region for two to three decades. It is confirmed by the discovery of the large oil and gas-condensate fields in the CS-II, such as Zhanazhol, Urikhtau, Kozhasai, Alibekmola, etc.

Keywords: oil and gas content, second carbonate sequence (CT-II), the structure of biohermal rocks, diagenesis, Microcodium, prospects for the discovery of hydrocarbon clusters.

Introduction

The Peri-Caspian depression is one of the few depressions of the continental block, where a sedimentary cover of up to 20 km was formed during the Phanerozoic eon. The sediments of the second carbonate sequence (CS-II) accumulated in the edge areas of the Aktobe-Astrakhan uplift system of the Eastern edge of the Peri-Caspian depression, mainly in the shelf environment. The sedimentation of CS-II occurred from the Late Visean (the Venevian horizon) to the Early Moscovian age in the Eastern edge of the Peri-Caspian Depression in the Zharkamysky uplift. The research covers the complexes of lithofacies, biostratigraphic materials, obtained from the core, and sludge samples from the exploration wells of the Kozhasai, Urikhtau, Zhanazhol, and Alibekmola fields.

The biostratigraphic subdivision of the geological profile is based on the vertical distribution of the paleontological remains, which allows one to substantiate the age of the productive strata in detail. These studies are closely related to paleoecology, where the biotic material serves as an indicator of the marine basin regime, and the carbonate sediments with the typical marine fauna were formed in the littoral-sublittoral regime, with moderate wave energy, normal salinity, and sufficient water aeration. In some periods of sedimentation, there was an increase in water salinity as evidenced by individual nodular gypsum in the carbonates of the Steshevsky and Protvinian sediments of the Serpukhovian. A comprehensive study of the foraminifers and conodonts with the help of a microfacies analysis of the lithological composition allows one to reconstruct the ancient conditions of sedimentation, to reveal the regularities of the facies distribution over the section and area, to study the sedimentological features, reservoir properties and oil-and-gas content of the carbonate rocks in the region [1].

Geological development

At the end of the Visean age, with the weakening of tectonic movements in the neighboring continental areas, the replacement of the terrigenous sediments for the carbonate ones occurred. At the Zharkamyssky uplift, carbonates of the second sequence occur on the leveled surface of the terrigenous sediments. The carbonate rocks of the Mikhailovsky-Venevian period are practically devoid of terrigenous adulteration and have traces of sedimentation in shallow-sea environments. Only in the Alibekmola field area, the accumulation of the carbonate sediments was occasionally interrupted by the terrigenous sedimentation.

In the second carbonate sequence, a variety of shallow-shelf, lagoonal, slope, and shoal facies formed in the environment of the edge area of the carbonate shelf and its flanks with relevant cyclic boundaries (Fig. 1). A wide range of microfacies is represented by peloid and cartoid, oolitic algal-fine-foraminiferal grainstones, foraminiferal-crinoid packstones, bioclastic microbial-algal boudstones, rudstone-bufflestones, peloid-bioclastic packstones, and rare mudstones.

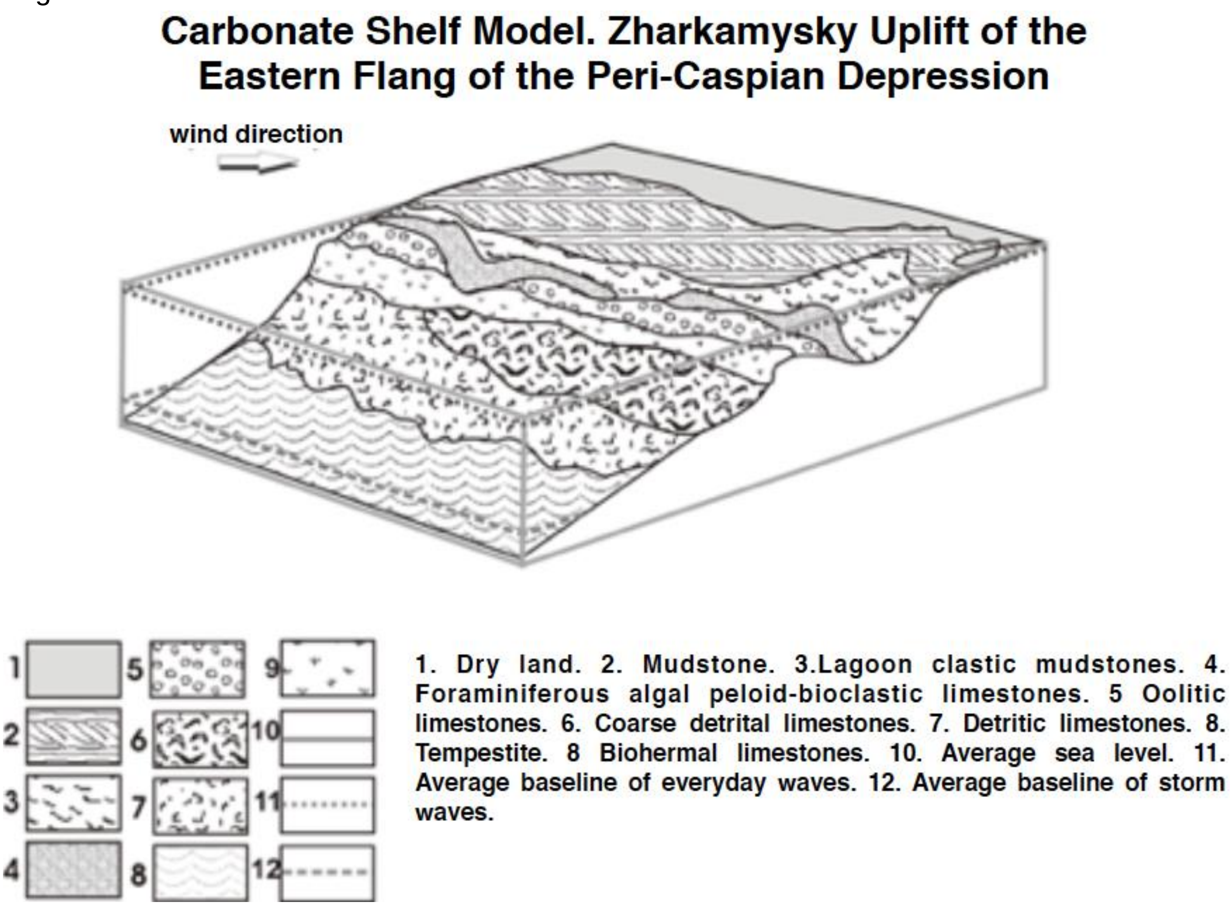


Figure 1. Diagram of carbonate formation

The main components of microfacies are algae of diverse species composition as *Praedonezella, Shartymophycus, Ungdarella, Calcifolium, Konincopora, Donezella, Berezella, Girvanella, Dasycladaciae*, bioclasts of crinoids, mosses, brachiopods, foraminifers, ostracods, and conditionally inorganic components - peloids, pellets, oolites, oncoids, intraclasts and cartoids [2].

The formation of the CS-II organogenic structures on the Eastern edge of the Peri-Caspian Depression begins at the Venevian age and continues during the Serpukhovian, Bashkirian, and Early Moscovian ages with the intensive growth of algal carbonates.

The framework of the second carbonate sequence consists of red algae of the Visean-Serpukhovian age [3].

The *Venevian sediments*, up to 85 m thick, are characterized by complexes of foraminifers of the Eostaffella tenebrosa subzone, and conodonts of the Locheriea mononodosa and L.nodosa zones. Lithologically, they are represented by dolomites, dolomitized packstones with abundant foraminifers, bioclasts of brachiopods, and crinoids with abundant pleiomorphic clots (~50%), and rare pyrite crystals (the Alibekmola field). In the core of well No. 6 of the Bashenkol area (the interval of 4675-4686 m), ooid grainstones with good roundness and consistent particle size are described. Microfacies of bioclastic, oncoid algal grainstones were determined in well P-3 of the Kozhasai field with the formed elements of foraminifera shells, brachiopods, echinoderms, and detritus of the Konikopora algae, fossilized and cemented by sparite.

The Serpukhovian Stage (up to 270 m thick) has been divided into two substages and four horizons: Tarussky, Steshevsky, Protvinian, and Zapaltyubinsky by the foraminifera zones of *Pseudoendothyra globosa - Janischewskina delicata-Eoladicus donbasicus* (the early Serpukhovian substage) and *Eostaffellina paraprotvae*, *Monotaxinoides transitorius-Eosigmalina explicate* (the Late Serpukhovian substage). The *Lochriea ziegleri* zone was distinguished by successive conodont assemblages, in the Lower Serpukhovian Substage, and the *Gnathodus bilineatus bollandensis* zone was distinguished in the Upper Serpukhovian Substage.

The Tarussky horizon is represented by algal-foraminiferous wax stones, packstones, and grainstones with an abundant presence of “spheres”– single-chambered foraminifera and calcispheres, and bioclasts of echinoderms, ostracods, brachiopods in sparite cement (the Kozhasai field, well No. 3, int. 3873-3938 m). Their formation took place in the upper part of the littoral of the semi-enclosed basin and lagoons under the calm hydrodynamic conditions. Similar microfacies are widespread in the area of the Alibekmola, Zhanazhol and Kuantai fields. In the Bashenkol area, the reef bufflstones were formed in the Tarusian age by abundant *Praedonezella in situ* and marine micropelloid cement in the interalgal space (well No. 6, int. 4510-4630 m).

in the younger stratigraphic levels of *the* Steshevsky horizon (int. 4510-4460 m), the textures of large bioclasts of mosses, echinoderms, and foraminifera (framestones) dominate. Mosses become the main elements of the reef facies, completely displacing algae. The fragments of mosses and inorganic grains of "lace-form" with a pseudo-micritic border are inlaid with fibrous cement (Fig. 2). The formation of carbonates of the *Steshevsky* horizon occurred in the conditions of the open sea shelf with the increased hydrodynamic activity of the sea.

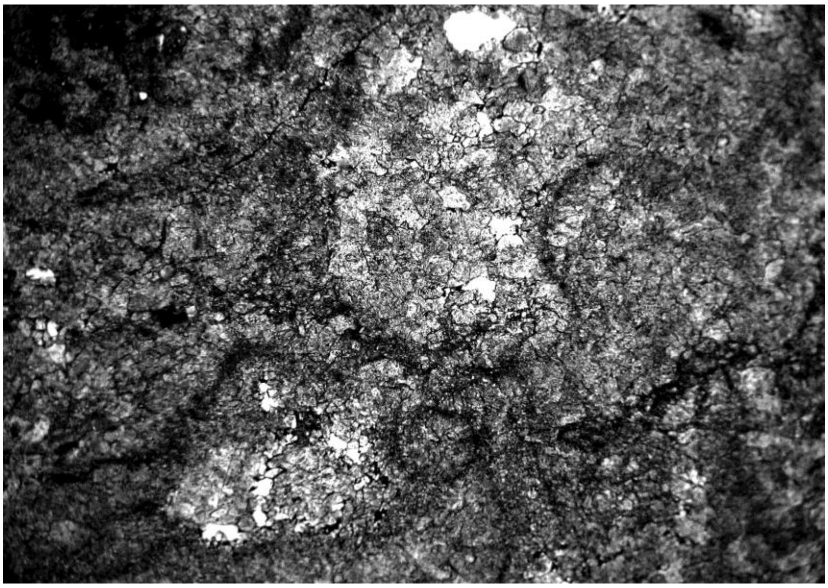


Figure 2. Lace-form thin section of the Tortkol field, well No.8, int. 3493-3501 m, 40x

In the *Protvinian horizon,* brachiopod crinoid and crinoid-foraminiferous algal packstones, ore stones, and bufflstones with clastic packstones and oolitic and oncolytic grainstones are widespread. The Early Protvinian sediments are composed of algal, biohermal facies, while the oncoidal-olitic grainstones occupy the upper part of the Serpukhovian sediments.

The *Bashkirian Stage* (up to 350 m thick) in the area under consideration is represented by the sediments of the lower substage. There foraminiferous zones of *Plectostaffella bogdanovkensis* are identified (the Voznesensky horizon is widespread locally), as well as *Semistaffella variabilis* (the Krasnopolyansk horizon), *Pseudostaffella antiqua* (the North Keltmen horizon), *Pseudostaffella praegorsky – R. stafellaeformis* (the Kama horizon) and zones of conodonts *Declinognathodus noduliferus, Idiognathoides sinuatus, Idiognathodus sinuosus.*

In the sediments of the *Krasnopolyansk horizon* (up to 130 m thick), lumpy peloid, detrital oolitic, clotty lumpy, and oncolitic varieties of grainstones and dolomites are distinguished. The biocenosis is represented by foraminifera, spheres, blue-green algae, gastropods. The deposition of the Krasnopolyansk sediments occurred against the background of the sea-level regression under the prevailing conditions of a shallow basin with limited seawater circulation.

The North Keltman part of the section (120-160 m thick) is represented by lumpy-peloid, lumpy-oolitic grainstones, bioclastic-algal packstones, and bufflstones. A significant part of the North Keltmen sediments is formed by algal limestones (bufflstones) composed of red algae (*Donezella*, more rarely *Ungdarella*) (Fig. 3).

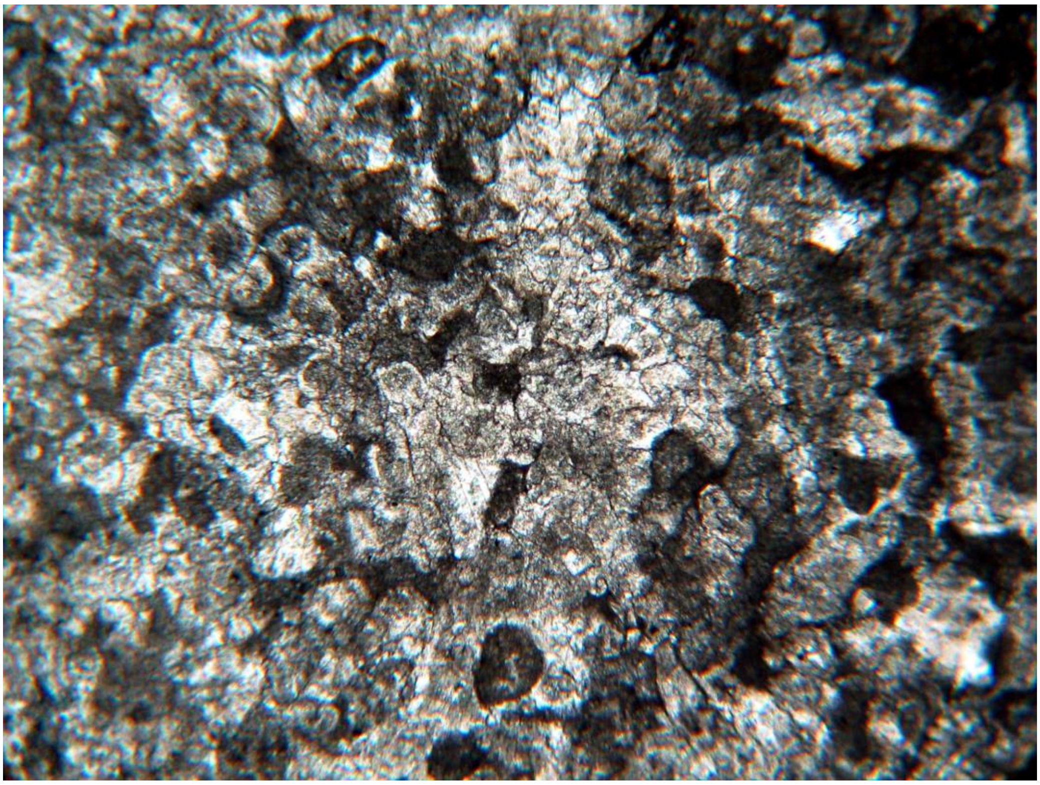


Figure 3. Thin section, 25x magnification, Donezella bufflstone, well U-2, int. 3958 m

The *Kama horizon* (100-180 m) consists of bioclastic-lumpy, oolitic grainstones, bioclastic packstones, and bufflstones. In phytogenic limestones, the rock-forming species are purple algae (*Beresella, Dvinella*). The section alternates between facies of shallow shoals (oolitic, lumpy-oolitic, and algal) and the outer slope of the platform (bioclastic varieties). In the core of well A-28, in the interval of 3430-3435 m, it became possible to identify the *Microcodium* formations (Fig.4) and residual traces of fine-grained sparite cementation, which indicate a significant lowering of the sea level and subaerial exposure of the carbonate structure [4].

The Moscovian Stage. The sediments of the Moscovian Stage were formed in the transgressive phase of the sedimentary cycle. The rocks of the lower part of the Moscovian Stage, which are part of the second carbonate sequence, are characterized by the foraminiferal complexes of Aljutovella aljutovica (the Vereiskian substage), Priscoidea priscoidea, Moellerites praecolaniae - Fusulinella subpulchra (the Kashirian substage) zones, as well as conodont zones of Declinognathodus donetzianus (the Vereiskian substage), Neognathodus Bothrops, N. medadultimus (the Kashirian substage).

The Vereiskian substage with a thickness of 70-100 m consists of an alternation of carbonate and terrigenous rocks. Carbonate rocks are represented by organogenic, algal-foraminiferous, (bioclastic, interclastic grainstones), organogenic-clumpy-lumpy (bioclastic waxstones, bioclastic-peloid, grainstones, bioclastic-oolitic grainstones, bioclastic-algal boundstones) limestones. The section contains dolomitized limestones, partially silicified (bioclasts, rudstones, floutstones) with the fragments of clay-siliceous carbonate rocks. The main part of rock-forming particles consists of green algae (Berezella eracta), red algae (Donezella lutugini, Ungdarella uralica), crinoideans, brachiopods, ostracods, mosses, and foraminifera.

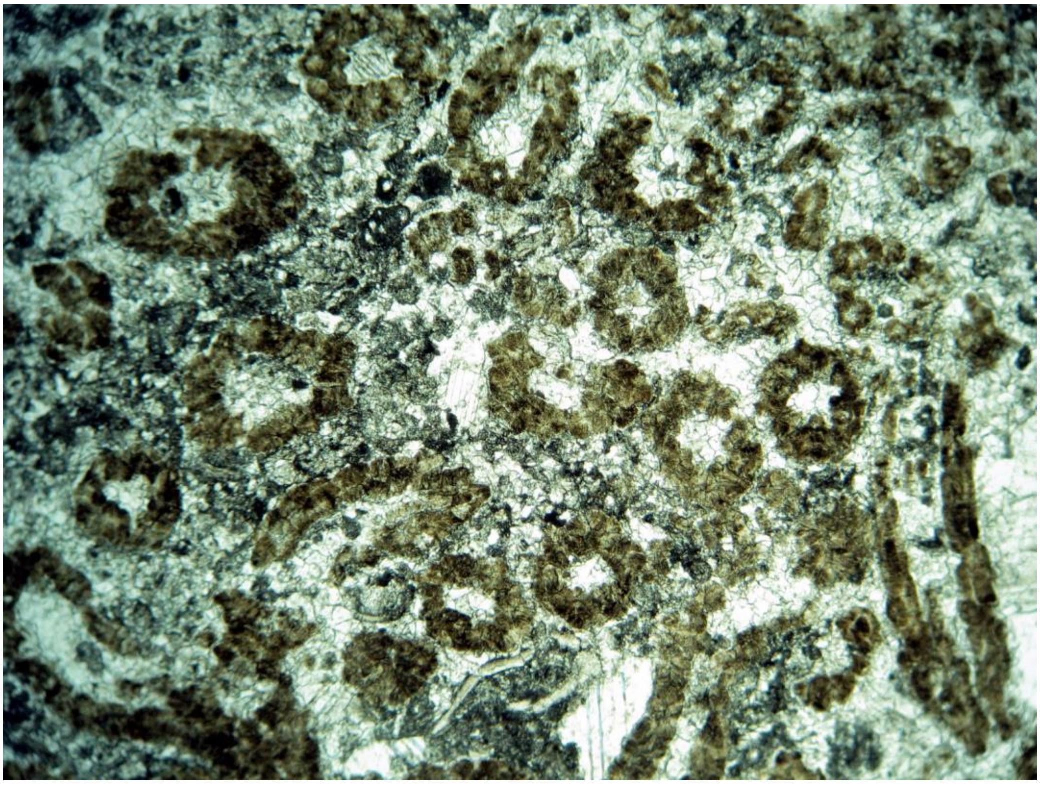


Figure 4. Thin section, 25x magnification Microcodium of well A-28, int. 3430-3435 m

The Kashirian substage (with a thickness of 200-275 m) is represented by detritus-organogenic (polydetritic algal bufflstones), lumpy-organogenic-oolitic (bioclast-peloid grainstone) limestones with interlayers of mudstones and dolomites. The paleobiota consists of fragments of algae (*Ungdarella, Berezella*), foraminifera, brachiopods, crinoids, and more rarely tabulatomorphic corals - *Multithecopora*.

The formation took place in the Vereiskian and Early Kashirian ages under the conditions of the heading slope of the carbonate platform and the inner part of the rim. The Late Kashirian period of sedimentation occurred during the further sea level rise and the spreading of shallow facies of the inner part of the platform with the reduced hydrodynamics of the aquatic environment.

In the section of the second carbonate sequence, the subaerial exposure surfaces were identified, which mark the boundaries of cyclites III and IV and allowed one to trace the history of the eustatic sea level fluctuations Fig. 5). The sediments of the second carbonate sequence with the stratigraphic discordance are overlain by Late-Moscovian terrigenous rocks [5].

The main facies of biohermal structures

The Late Visean-Serpukhovian algal mounds consist of the following facies zones:

1) The base of the mounds is composed of bioclastic rudstones with abundant skeletal particles of echinoderms and a small amount of algal detritus, ooid-oncoid bioclastic grainstones, and secondary dolomites. The sedimentation of carbonates occurred under the conditions of lagoons common in the Late Visean age in the Eastern Caspian Sea region;

2) In the inner part of the mounds, with the onset of the Early Serpukhovian transgression, there were conditions for the formation of bindstones with bioclasts and

micritic groundmass and microbial-spongy structures. Also, chartimophicus and pre-target bufflstones, mossy framestones, spongiostomes were developed. The developed fiber cement in the intergranular space binds the bioclasts together. Such marine (syndepositional) cementation of algae and mosses contributed to the preservation of primary porosity in the reefogenic facies, which were formed during the high sea level in the Early Serpukhovian Stage [6];

3) The upper part of the mounds consists of bioclastic packstones, ungdarella, and calcifolium bufflstones with bioclasts of mosses and isometric fine-grained sparite cement. Their formation occurred in the conditions of fluctuation of the sea level in the middle of the Serpukhovian age;

4) During the Late Serpukhovian Regression, ooid and ooid-oncolite grainstones, more rarely bioclast algal packstones, and rudstones of the mound crest facies developed in the shallow water conditions.

Diagenesis of rocks

The carbonate rocks of the second sequence accumulated in different parts of the shallow shelf and had unequal primary porosity. Under the conditions of weak hydrodynamics, colloidal mudstones and micro-grained layered dolomites were formed. Intergranular sedimentary pores, formed as a result of hardening of the lime are hardly detectable in the thin sections under the microscope (their size is 0.001-0.01 mm and their content is negligible). They are limited by the faces of calcite or dolomite crystals; their shape is angular, polygonal, irregular, often with dust-like clusters. As a rule, the rocks with only such pores, without sufficiently developed fracturing are non-collectors.

The mobile hydrodynamic environment contributed to the accumulation of organogenic (bioclastic) limestones (calcareous sands, in some areas - biohermal limestones) with high primary interfragmentary and intraformational porosity.

The post-sedimentation processes were multidirectional and had different intensities; the primary pore space was virtually nonexistent but served as the basis for the secondary inherited porosity arising from leaching.

The leaching processes in the carbonate rocks occurred under the influence of the reservoir fluids and, due to the freshwater diagenesis, surface waters. Leaching occurred repeatedly and with varying degrees of intensity. The subaerial exposure resulted in the formation of pores and caverns of various shapes with microgranular isometric calcite at the cavity edges, often with the appearance of brown micritic mass as a product of rock calcretization. The leaching processes often proceeded selectively along the inter- and intra-formational primary pores in biomorphic, peloid-bioclastic, organogenic-detritic, and oolitic limestones. In some other cases, leaching proceeded together with the recrystallization and dolomitization processes. During leaching, a wide variety of forms of void space are formed: irregular, lenticular, rounded, multidirectional, paw-shaped, ellipsoidal, in rare cases repeating the shape of the dissolved aggregate. The sizes of pores and caverns vary widely from 0.05 to 10.0 mm or more. Voids up to 1 mm refer to pores, that of more than 1 mm to caverns. The leached zones form spotted, scattered, and chained areas in the rock. The pores are connected by microcracks of 3-5 - 20-30 microns wide, sometimes through channels of 0.01 - 0.1 mm wide.

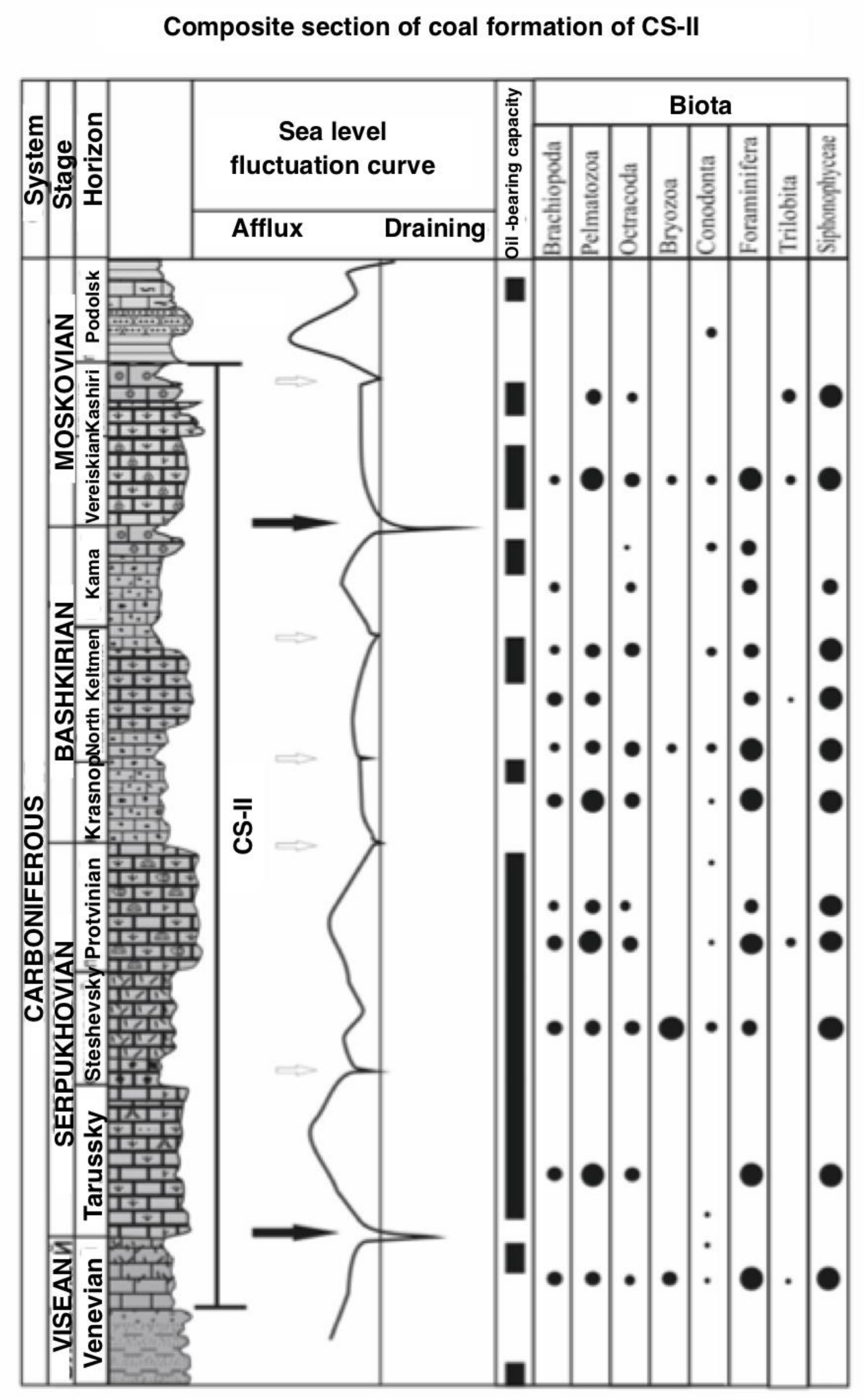
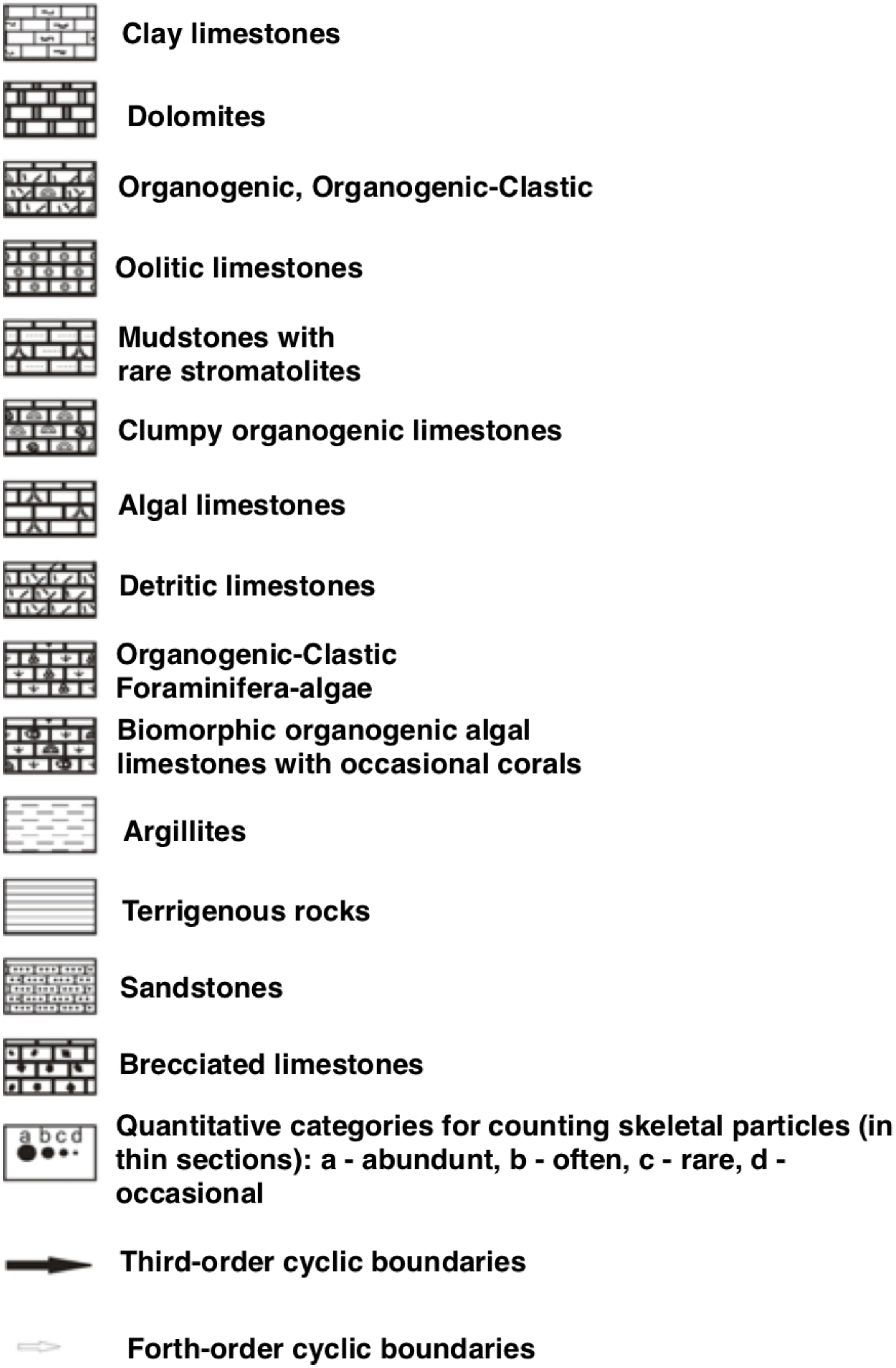


Figure 5. Composite section of CS-II

LEGEND


Clay limestones
Dolomites
Organogenic, Organogenic-Clastic
Oolitic limestones
Mudstones with rare stromatolites
Clumpy organogenic limestones
Algal limestones
Detritic limestones
Organogenic-Clastic Foraminifera-algae
Biomorphic organogenic algal limestones with occasional corals
Argillites
Terrigenous rocks
Sandstones
Brecciated limestones
a b c d
Quantitative categories for counting skeletal particles (in thin sections): a - abundunt, b - often, c - rare, d - occasional
Third-order cyclic boundaries
Forth-order cyclic boundaries

The leaching processes in mudstones, detritic, and other dense limestone varieties proceed along with the fractures with the formation of slit-shaped caverns. The leaching processes under the influence of the formation waters occurred mainly in the horizontal direction, as indicated by the horizontally oriented, outlines of elongated slit-shaped caverns and pores, parallel to the stratification, and increased core permeability values in the horizontal direction.

The reduction of the rock void space occurred under the effect of the secondary mineral formation processes. The filling of the void space was due to the processes of neomorphic transformation of calcium carbonate, dolomitization, and silicification.

The recrystallization processes occurred in all rock lithotypes. The cement and organogenic residues were recrystallized to varying degrees from small spotted, vein-like areas to the almost complete neomorphic transformation of the primary rock structure. Recrystallization is often associated with the appearance of small intercrystalline pores of polygonal angular shape. The pore sizes rarely exceed 0.05 mm. The pores are connected by intercrystalline channels with a width of one micron.

The dolomitization processes in the studied rock formation of the Zharkamyssky uplift affected in varying degrees almost all lithotypes of limestone. The dolomite crystals occur as individual rhombohedrons in the cement or rock allochems, forming aggregates of grains of tightly adjoining fine- and medium-grained crystals. Dolomitization contributed to the formation of voids in the limestone. The formation of secondary porosity occurred in the process of dolomitization accompanied by the dissolution of carbonate material by slightly mineralized solutions. Structurally and morphologically, the pores of dolomitization have a polyhedral shape; the pore sizes correspond to the size of newly formed dolomite crystals (0.05-0.25 mm). The pores are connected by intercrystalline channels with a width of one micron.

The isolation of carbonate minerals occurs as small (0.01-0.1 mm) polyhedral calcite crystals and hypidotopic dolomite crystals covering the cavity walls, or larger (0.1-0.8 mm, sometimes up to 1-2 mm), filling the entire pore space or part thereof. There are areas of poikilitic inclusion of dolomite rock with large crystals (1-5 mm) of calcite; rhombohedron of dolomite (0.05-0.25 mm) form inclusions in calcite crystals. The neomorphic processes of calcite transformation were intensive in limestones and dolomites of the second carbonate sequence, reaching 10-12% of the rock volume.

Silicification in carbonate rocks occurred with the formation of microinclusions of quartz, silicon aggregates, and chalcedony spots. Crustified siliceous cement of quartz and chalcedony can rarely be observed, forming crusts of crustification on the rock fragments without filling the free pore space. Silicification in the rocks of the carbonate complex was mainly in dolomites, with silicification ranging from 2-3% to 8% of the rock (Fig. 6).

The main factors of lithogenesis controlling the formation of the reservoir properties of rocks are the conditions, environment, and features of sedimentation, which may have been favorable or unfavorable for the primary porosity formation. These conditions are greatly enhanced by the processes of post-sedimentation transformation – leaching, recrystallization, dolomitization, etc. The evolution of the sediments in lithogenesis determines the presence and absence of pores, as well as their geometry in the carbonate rocks. Recrystallization with the formation of a dense crystal packing leads to the filling of the entire pore space with neomorphic calcite; the pores in the rock are practically absent. The diagenetic recrystallization by the unsaturated solutions, proceeding with the dissolution of the rock carbonate matter and the formation of enlarged calcite crystals, leads to the formation of intergranular pores. The disseminated dolomitization does not affect an increase in the void space, only during diagenetic dolomitization by the slightly mineralized solutions the intergranular pores are formed.

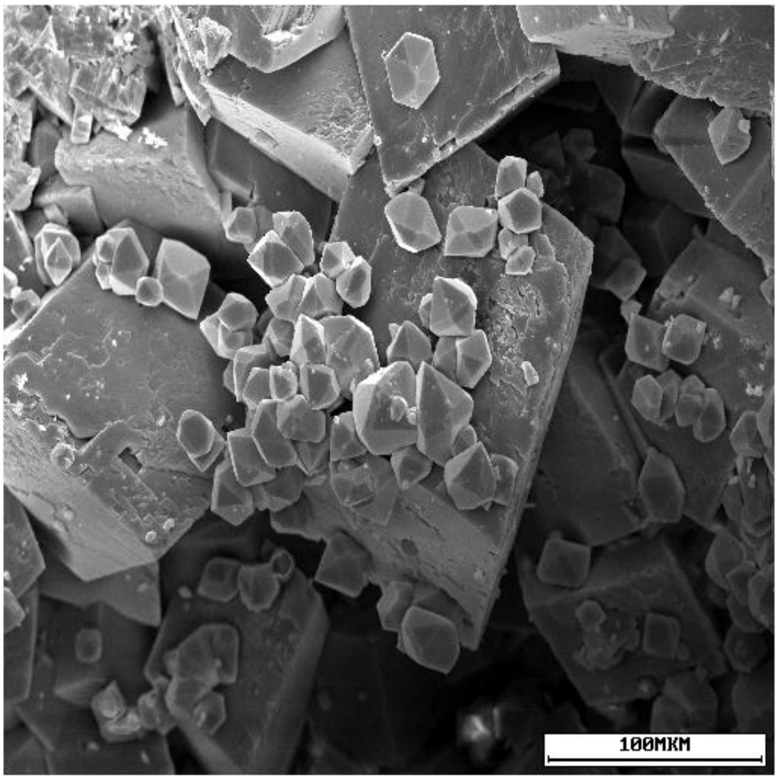


Figure 6. Quartz crystals on the dolomite crystals from well A-61 at 3424 m, Middle Carboniferous, Lower Moscovian Substage (C_2m_1) (JEOL T-100 scanning electron microscope)

Prospects for the discovery of hydrocarbon clusters

The prospects of the second carbonate sequence are formed by a favorable combination of the availability of reservoirs, traps, local and regional fluid seals, the presence of high-bituminous, fine-grained depression sediments of the slope root of the Zharkamys uplift.

Large clusters of oil and gas can be identified based on the analysis of the distribution area, capacity, and quality of the regional and zonal natural reservoirs, including the reservoir rocks and rocks with the sealing properties. The geochemical criteria of an oil-and-gas bearing capacity include the development of zones of an increased capacity of the Devonian and Early Carboniferous carbonate-terrigenous sediments. Thus, the maximum thickness of the Zharkamyssky uplift sediments between the bottom of the Late Visean carbonate sediments and the foundation reaches 5-5.5 km. The Kungurian halogen sequence is the main regional overlying seal of the subsalt Paleozoic reservoir rocks, which ensures reliable closure of the subsurface. In the studied area, the zonal overlying seal is composed of clay members developed in the Late Moscovian sediments.

The oil-bearing content of the Venevian sediments in the east of the Peri-Caspian depression.

The highly productive carbonate reservoirs of the Serpukhovian stage of the Kozhasai, Alibekmola, and Urikhtau fields are represented by algal bioherms of the rim part and oolitic sandstones of the inner platform. The further prospects of the Serpukhovian deposits may be associated with organogenic structures - biogerms and algal mounds of the complex composition in the environment of the outer lagoon and the foreset shelf slope.

The Devonian and Lower Carboniferous-terrigenous rocks, which lie between the bottom of the Late Visean carbonate sediments and the foundation, should be considered as oil and gas generating rocks. The maximum capacity of the sedimentary cover in the area of the Zharkamyssky uplift reaches 5-5.5 km [7].

The new oil and gas clusters, especially favorable in terms of the prospects for discovering, are carbonate formations, which formed in the marginal part of the shelf. This is the largest reservoir of oil and gas overlain by the Upper Moscovian terrigenous sediments. It was there that the massive hydrocarbon sediments were discovered at the Zhanazhol, Urikhtau, Sinelnikovskoye, Alibekmola, and other fields.

The objects for the further oil-prospecting works can be the Visean-Bashkirian, Lower Moscovian carbonate sequences, which form the anticlinal swell-like uplifts at the edge of the carbonate platform. In this zone of the paleo shelf margin, high-capacity organogenic structures are developed with the transgressive eastward displacement as they rejuvenate. The undiscovered potential resources here are associated with the structures grouped into the swell-like uplifts with the known Zhanazhol, Sinelnikovskoye, and Alibekmola fields. At the same time, the shelf carbonate systems, developed in close genetic connection with the deltaic sediments, which determined the formation of the intercarbonate terrigenous sequence serving as the fluid seals for the CS-II.

The main objects at the new stage of oil prospecting in the region should be the carbonate rocks of the Visean-Bashkirian and Early Moscovian stage, which form the anticlinal swell-like uplifts at the edge of the carbonate platform. Here, organogenic structures with high-capacity reservoirs are present at the edge of the paleo shelf, whose development zones migrate eastward as they rejuvenate. Large hydrocarbon clusters may be discovered on the structures close to swell-like uplifts as the continuation of the known Alibekmola, Zhanazhol, and Sinelnikovskoye fields. Here, carbonates of the shelf genesis are interspersed with the deltaic formations, i.e. horizons of the terrigenous sediments serving as fluid seals.

The stratigraphic intervals of an oil and gas bearing capacity can be extended by the Devonian sediments. According to the results of drilling of well U-5 of the Urikhtau field, the gas occurrences in the Frasian sediments of the Late Devonian were revealed.

Conclusion

Sedimentation of the second carbonate sequence during the Early-Middle Carboniferous was affected by tectonic movements and sea-level fluctuations within the Zharkamys uplift. The formation of the organogenic structures occurred on the margin of the carbonate shelf framing the slopes of the Zharkamyssky uplift along with the development of algal bioherms. In the inner part of the shelf, oolitic and limestone-sandy facies were widespread, and on the positive landforms there were conditions for the clusters of algal strata of ~1 m thick during the periods of regression, which were replaced by the calcareous sands of shoals. During the periods of basin deepening, the sediments of biohermal (algal, crinoid-bryozoan) mounds of small thickness were formed at the shelf edge and the foreset shelf slope.

The biostratigraphic, sedimentological studies, and test results for the second carbonate sequence of the Eastern Peri-Caspian Depression revealed that the positive results of prospecting for hydrocarbons are associated with:

1) large algal interlayers of the shelf edge of the Zharkamys uplift;

2) algal mounds and swells of the inner part of the shelf;

3) offshore bars and dunes of the inner part of the shelf.

The research carried out in the article allows one to identify the patterns of distribution of the high-capacity oil and gas reservoirs in the region.

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