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Paleoкarst, hydrothermal karst and karst reservoirs of the Franian reefs of the Rybkinsky group

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Abstract. More than 20 isolated reefs of the Rybkinsky group were discovered in 2015-2018 in the eastern part of the Rubezhinsky Trough, west of the Sol-Iletsky Arch (Orenburg region; southern part of Volga-Ural Oil and Gas Province), thanks to the use of seismic surveys 3D and exploration drilling. The interval of the stratigraphic distribution of the reefs encompasses Domanikian, Rechitskian and Voronezhian Horizons (=Regional Stages) of the Franian Stage of Upper Devonian. The reefs are cased and overlapped by carbonate-terrigene-clay deposits of the Kolganian Formation that form the seal. High-amplitude oil fields (up to 150 m high) are related to the bodies of reefs. Reefs developed under conditions of significant changes in sea level caused by both eustatic fluctuations and regional tectonics.

Actual data on features of surface and deep karst in different reefs of the Rybkinsky group are given. Three karst epochs are allocated: 1) late Domanikian; 2) late Rechitskian; 3) late Voronezhian. Evidences of the post-franian hydrothermal karst in the reefs are presented. Reservoirs formed as a result of karst are characterized by high complexity of pore space.

Reef reservoirs have a scale permeability effect that is necessary to consider in hydrocarbon reserve calculations.

Keywords: reefs, karst, hydrothermal karst, Franian, reef facies, karst reservoirs, Volga-Ural oil and gas province

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Introduction

According to the definition of G.A. Maximovich (1963), «karst is process of chemical and partly mechanical influence of underground and surface off-channel waters on soluble and permeable rocks». Due to karst, voids of various shape and size are formed in the carbonate massif. The ancient karst (or paleokarst) played an important role in the formation of reservoir in carbonate oil and gas complexes of different ages. Franian isolated reefs of the Rybkinsky group, which are located in the south part of the Volga-Ural oil and gas province, within the territory of the Orenburg region, are one example of the mentioned value of the paleokarst. This paper provides new information on the manifestations of karst in these peculiar carbonate reservoirs. The article is a logical continuation of the review publication about the Rybkinsky reefs (Vilesov et al., 2019a).

It should be noted that for the devonian sedimentary basins of Australia and Canada, where franian and famenian reefs are widespread, numerous factual data on ancient karst have been published (for example: Chow & Wendte, 2011; Playford, 2002; George & Powell, 1997; etc.). At the same time, this important part of the geology of devonian reefs remains a white spot for the Volga-Ural oil and gas province to date.

The first isolated franian reef of the Rybkinsky group with a high-amplitude oil pool (West-Rybkinsky reef) was discovered accidentally in 1990 during prospecting and exploration drilling on the terrigenous sandstone reservoirs of the Middle Devonian. Targeted searches led to the discovery nearby of another organic buildup with a oil pool – the North-Zhokhovsky reef (Nikitin et al., 2011). Reserves of opened oil pools were put on balance as part of the Rybkinskoye Oil Field. According to biostratigraphic studies, it was found that the formation of Rybkinsky reefs occurred in the Rechitsky and Voronezh time of the late Franian. Reefs overlap the upper franian – lower famenian carbonate-terrigenous-clay Colganian Formation. In 2012-2013 on the territory of the Volostnovsky licensed area, that includes the reefs of the Rybkinskoye Oil Field, «Orenburgneft» oil

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company performed high-resolution three-dimensional (3D) seismic exploration. As a result, about 30 franian isolated basin reefs (similar to ones of the Rybkinsky Oil Field) were discovered and prepared for drilling (Nikitin et al., 2017, 2018). The height of the reefs varies from 180 to 220 m, diameter – from 0.6 to 1.5 km.

Drilling of reefs was carried out in 2015-2018. New oil pools are open both in reef reservoirs and in the famenian and tournesian carbonate deposits, covering the reefs.

Material

Within the Volostnovsky license area more than 20 productive isolated franian reefs (including ones of the Rybkinskoye Oil Field) have been opened by drilling already (Fig. 1). Core predominantly good quality with diameter 100 and 110 mm was taken from the reef path of section during well drilling. Franian reef at the Volostnovsky license area are characterized by the core unevenly, since the coring was performed mainly from the oil saturated upper part of the section or at separated intervals. Significant coring is made to individual reefs. In particular, continuous coring for more than 100 m was performed on Novozhokhovsky Reef (Shakirov et al., 2019). In total, studies of the core of reef facies were carried out on 19 carbonate buildup.

As a result of the sedimentological analysis of the core, the reconstruction of the history of the Rybkinsky group reefs was carried out, the facies reef zones were characterized, the groups of organisms building the reef and their distribution within reefs were established, the diagenesis off reef rocks was reconstructed (Vilesov et al., 2019a). In the reef section different scale cycles are highlighted and horizons of the subaeral exposure are established. The history of the development of Rybkinsky reefs was compared with the eustatic curve developed by a team of specialists from Moscow University for the Russian Plate (Alekseev et al., 1996). In the reef history were identified three stages, coinciding with three stages of regional sea level fluctuations – Domanikian, Rechitskian and Voronezhian. It has been established that the epochs of paleokarst are associated with the completion of each stage and periods of low sea level.

Tectonics of the Sol-Iletsky Arch had a significant impact on sea level changes during the late Devonian (Nikitin et al., 2013; Vilesov et al., 2019b).

Stratigraphic and tectonic position of the Rybkinsky reef group

The stratigraphic interval of Rybkinsky reefs corresponds to the Domanikian, Rechitskian and Voronezhian horizons (=Regional Stage) of the Franian Stage of the Upper Devonian (Vilesov et al., 2019a). In 2015, a section of the Rybkinsky reefs was allocated to the Rybkinskian formation (Fortunatova et al., 2015). In 2017 the Rybkinskian formation was introduced into the unified subregional stratigraphic scheme of the Upper Devonian of the Volga-Ural subregion (Unified subregional stratigraphic scheme…, 2018). The Rybkinskian formation is underlain by the thin limestone units of the Sargaevian formation. It is covered by carbonate-terrigenous-clay deposits of the Colganian formation and replaced by that to the lateral. The clay rocks of the Lower Famenian, which form a seal over franian deposits edging the Sol-Iletsky arch, are also part of the Colganian formation.

In tectonic terms, the area of the Rybkinsky reef group is located in the joint zone of the Rubezhinsky Trough, Sol-Iletsky Arch and Pavlovskaya Saddle (Nikitin et al., 2011). The reefs of the Rybkinskoye Oil Field together with the Zhokhovsky reef are located on the Devonian tectonic flexure, oriented according to the sedimentation bench of the late franian carbonate platform in the northwestern part of the Volostnovsky license area (Fig. 1). Most of the reefs located between flexure and sedimentation bench form subparallel lines. It is possible that these reefs are also controlled by low-amplitude tectonic breaks.

Paleogeographic position of the Rybkinsky reef group

The area of distribution of Rybkinsky reefs in paleogeographic terms is confined to the northeastern shelf edge of the paleocontinent Laurussia (Fig. 2). As can be seen on the palinspathic map of C.Scotese (2014), this part of the continental shelf in franian time was in the equatorial zone of the northern hemisphere. Other palinspathic reconstructions give a similar paleogeographic position (for example: Orenburg tectonic…, 2013; Golonka, 2002; and others).

The equatorial climatic zone is characterized by high temperatures, heavy rainfall, and high humidity. All these factors are favorable for the intensive development of karst in carbonate deposits brought to the conditions of the subaeral exposure (Moor, 2001; Wilson, 2012).

Isolated basin reefs of the Leduk Formation of Western Canada (Atchley et al., 2006; Switzer et al., 1994; and other) are similar age analogues of Rybkinsky reefs. They were also formed in the equatorial zone, only on the western shelf margin of Laurussia.

Facial structure of Rybkinsky reefs

During sedimentological analysis of core of Rybkinsky reefs facial complexes of the reef core and reef slope, as well as zones of karst and hydrothermal karst manifestations, were identified (Vilesov et al., 2019a). Signs of ancient karst (paleokarst) and hydrothermal karst cross the rocks of the facial complexes of the reef core and reef slope.

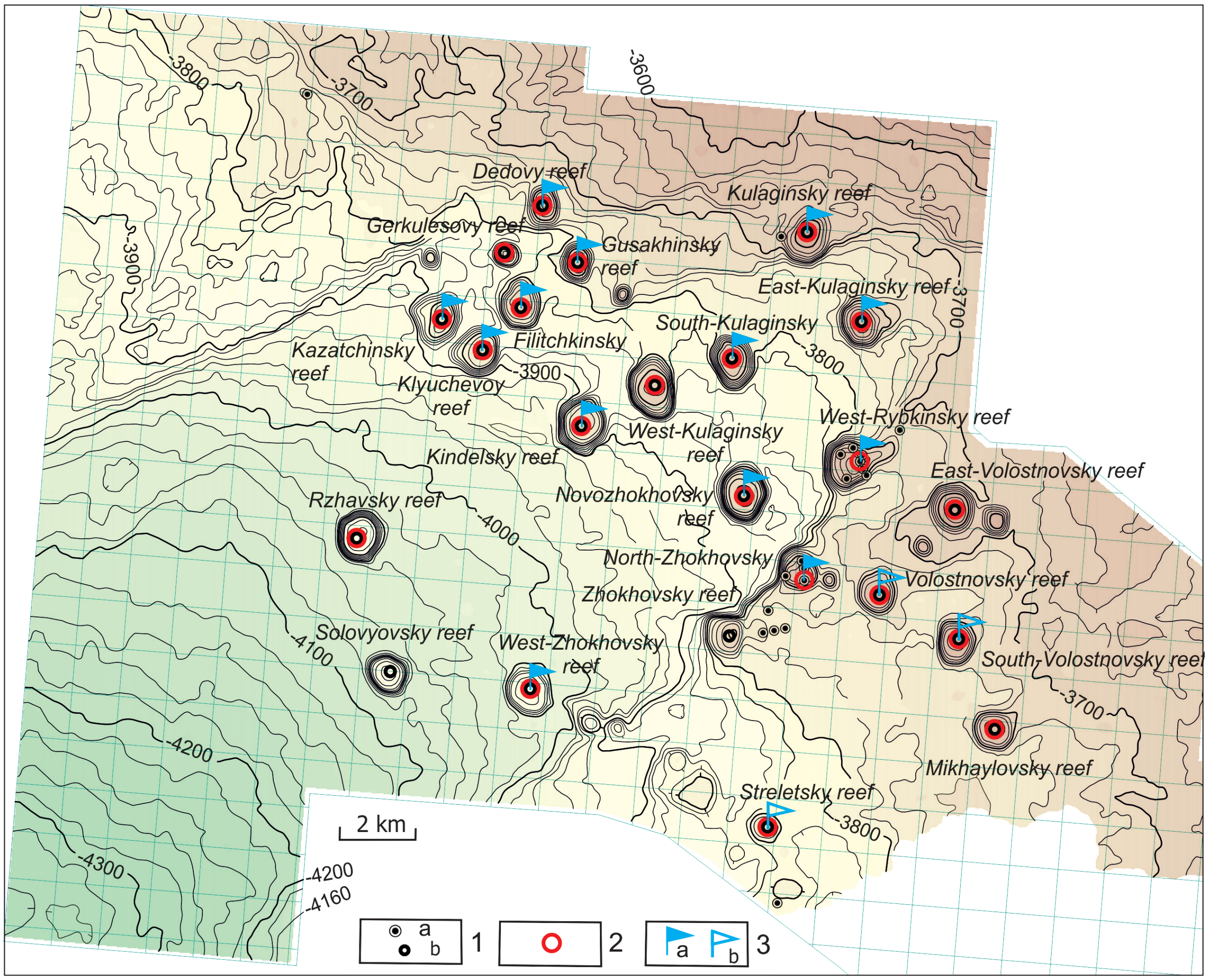

Fig. 1. Rybkinsky group of franian reefs: structural map on the surface of the Voronezhian regional stage (Nikitin et al., 2017). 1a – old wells, 1b – wells drilled in 2015-2018; 2 – reefs with signs of surface karst and deep karst in the core; 3 – reefs with signs of hydrothermal karst in the core (a – intense, b – weak)

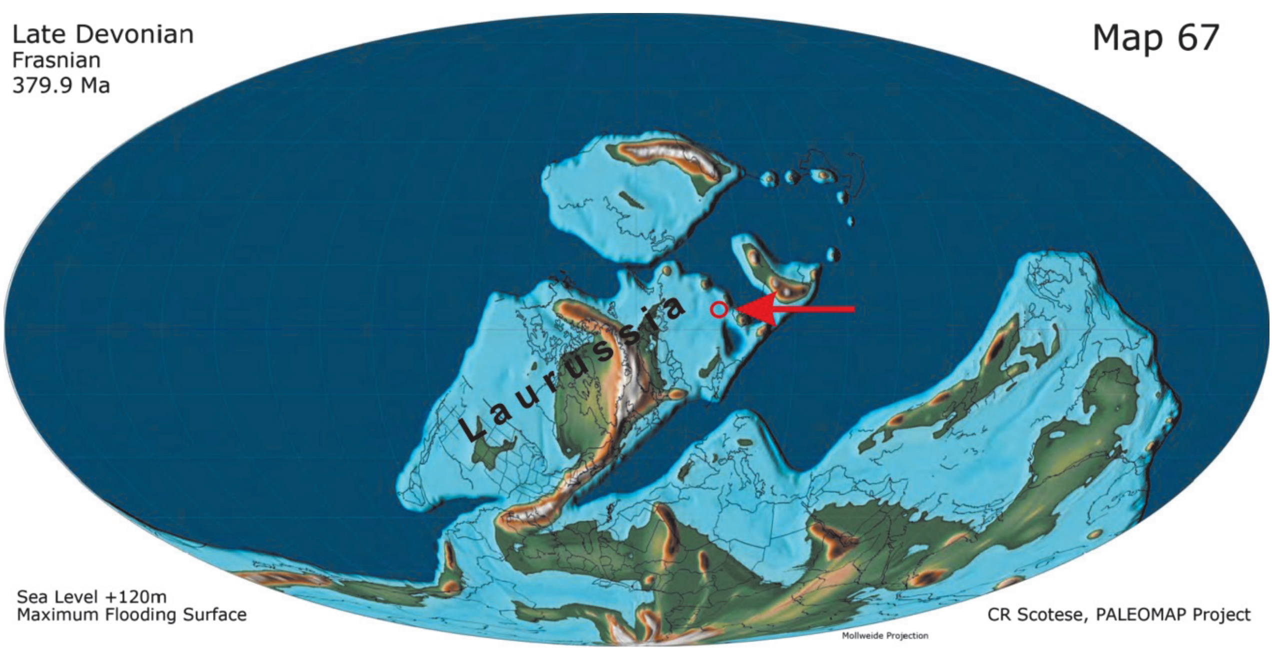

Fig. 2. Paleogeographic map of the franian time of the Devonian period on a palinspatic basis (Scotese, 2014). The area of the Rybkinsky reef group is shown by a red circle and arrow

According to lithological features, the following facies are distinguished ***in the facial complex of the reef core***: 1) the ridge zone of the reef; 2) the back-reef zone; 3) reef shallow subtidal zone; 4) up-reef tidal flat; 5) reef lagoon. Massive, tabular and combined skeletons of stromatoporoids, forming a strong framework resistant to wave influence, are characteristic for rocks of the ridge zone of the reef. Large stromatoporoids with a combined mushroom-like skeleton and abundant microbial fouling are most typical for limestones of the back-reef zone. Numerous thick-branched stromatoporoids are found in the limestone of reef shallow subtidal zone; various skeletal grains are distributed among their skeletons. The rocks of the up-reef tidal flat are represented by different-grained limestones with a texture from grainstone to rudstone. The facies of the reef lagoon are characterized by mad limestones with dispersed bioclastic material.

Due to karst, the different-age parts of the reef core are connected into a integrated hydrodynamic system. Limestones in the reef core zone are chemically pure. The appearance of impurities (for example, clay minerals, quartz) is due to their injection through the karst voids system.

The facial complex of the reef slope is divided into two facies: the upper part of the reef slope and the lower part of the reef slope.

The facies of the upper part of the reef slope are divided into the following subfacies: 1) biogerms of the upper part of the slope; 2) granular deposits of the reef apron of the upper part of the slope; 3) carbonate debrites of the upper part of the slope; 4) ladge syndepositional fracture of reef margin – neptunian dyke.

Biogermal rocks of the upper part of the reef slope are characterized by lamellar and leaf-shaped forms of frame-forming organisms – stromatoporoids, corals, and hydroids.

Granular deposits of reef apron are represented by different-grained limestones with the texture of rudstone, grainstone, packstone, floatstone. Carbonate grains are diverse: lithoclasts, bioclasts, cortoids, peloids. Skeleton fragments of echinoderms and thick-branching stromatoporoids dominate among other bioclast grains. Granular deposits of the reef apron reach a maximum length and thickness in the rear (leeward) part of the reefs and can form a significant part of the reef complex (Vilesov et al., 2019a).

Carbonate debrites of the upper part of the slope are represented by breccias and conglomerates with a different-grained carbonate matrix. The size of the debris varies from small rubble to blocks in the first tens of centimeters. The most typical texture of debris are stromatoporoid and coral boundstone. The texture of the matrix containing the debris varies from wackestone to different-grained rudstone.

In the matrix of debrites crinoid fragments predominate among other bioclasts. In some cases, the distribution of debris in the bed sequence is gradational: large debris at the bottom, small debris at the top, and contact with the underlying bed is erosive.

Neptunian dyke subfacies of the reef slope has been diagnosed in several reef buildings. The visible length of dykes in the core reaches 1.5 m. The walls of the dykes are relatively even, inclined, formed by the bedrocks of the reef slope. The sediments filling the dykes differ sharply in structure from the containing bedrock subjected to break. Different-grained limestones from packstones to rudstones and limestone breccias are distinguished in dyke filling. In some cases, one can observe distinct vertical zonality in the filling of dykes, which is expressed in the form of a noticeable enlargement of grains from top to bottom or a change of texture from granular to breccia. Significant signs of karst can be traced along neptunian dykes.

The rocks of the upper reef slope, like the rocks of the facial complex of the reef core, are characterized by chemical purity.

The facies of the lower part of the reef slope are represented by detrital clay limestones to varying degrees dolomitic, with an uneven admixture of insoluble sediment (clay mineral, quartz and feldspar grains from silt to thin sand dimension, pyrite). Clay limestones can pass into marls with interlayers of calcareous claystones. The predominant texture of limestones is a different-grained floatstone. The clay-carbonate matrix of floatstones is unevenly dolomitic; various bioclasts and carbonate lithoclasts are included in it.

Karst of Rybkinsky reefs

According to the main dissolution agent, *meteoric water karst* and *thermal water karst* (hydrothermal karst) were identified in reef rocks. In the first case, the dissolution of carbonate rocks occurred due to filtration into reef arrays of atmospheric precipitation. In the second case, hot deep waters enriched with a specific complex of dissolved chemical elements affected reef rocks.

In relation to the terrestrial paleo-surface, meteoric water karst can be divided into surface and deep karst. Surface karst (or epikarst) is manifested at exposure surfaces of reefs and is represented by such characteristic morphological karst forms as ponors and karren. Deep karst (or subsurface karst) crosses a significant interval of the reef section. It was formed in the zone of vertical percolating of fresh waters, as well as along the surface of the fresh water mirror and below it, up to the zone of mixing with sea pore waters. Caves are the most significant morphological forms of the deep karst.

Surface karst

Attributes of surface karst (Fig. 3) was observed at or beneath subaerial exposure unconformities. In Rybkinsky reef sections three such levels have been identified: 1) top of the Domanikian regional stage; 2); top of the Rechitskian regional stage; 3) top of the Voronezhian regional stage (Table 1).

Features of surface karst are most fully represented on well core in the upper part of the Voronezhian regional stage. Limestones from this stratigraphic interval were coring on twelve reefs. In all cases, sharp lithological contact can be observed in the core: gray and dark-gray clay silt-sandstones of subtidal with small brachiopods and trace fossil Zoophycos lay on eroded light-gray limestones of the reef complex (Fig. 3a, b, e). In the western part of the area, silt-sandstones are replaced by dark-gray clay-silt limestones with a texture of bioclastic floatstone. Skeletons of thin-branched rugosa and stromatoporoids, shell of brachiopods, echinoderm detritus are unevenly distributed in the microcrystalline calcite matrix of floatstones.

Morphological varieties of surface karst are represented by karren and ponors. *Karren* are furrows on the surface of reef limestones (Fig. 3b), *ponors* are small funnels or tubular recesses on it (Fig. 3a, e). Ponors are filled with terrigenous-clay material (Fig. 3a). A breccia-like detachment of the bedrock can be observed along their walls. The visible width of ponors can reach 5-6 cm, depth – 0.5-1.5 m.

The facts about surface karst features of different stratigraphic levels and different reefs recorded on the well core are given in Table 1.

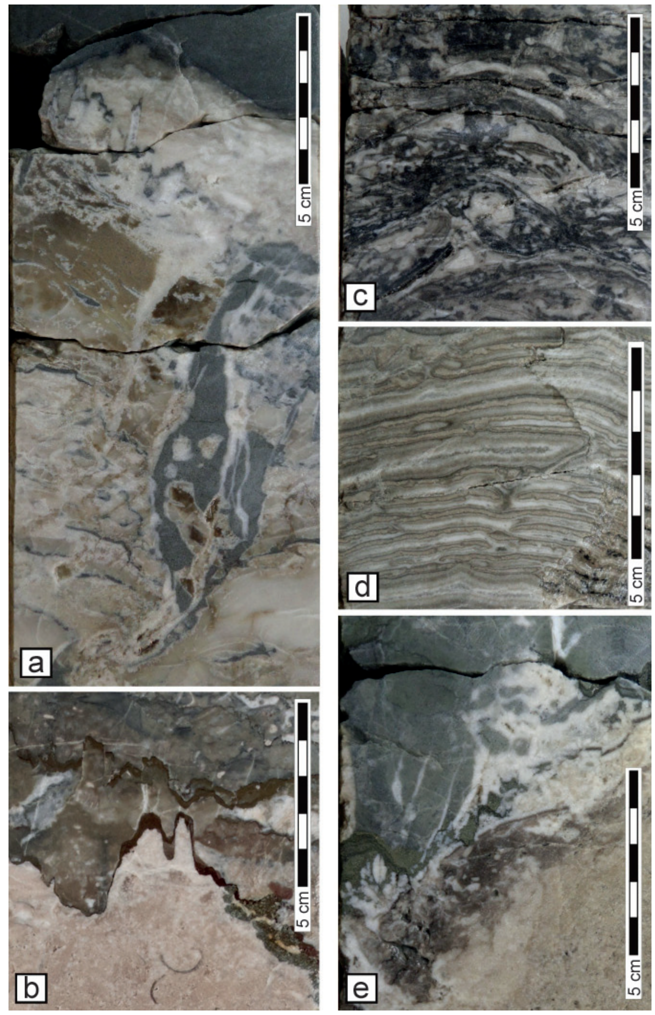

Fig. 3. Features of epikarst in the reefs of the Volostnovsky license area: a – narrow funnel-shaped ponor at the top of voronezhian reef limestones (Novozhokhovsky reef); b – karren on the surface of reef limestones of the Voronezhian regional stage (Gusakhinsky reef); c – limestones of the palaeosol (top of the Rechitskian regional stage, Streletsky reef); d – microbial tuff limestones of the karst-water unloading zone (Streletsky reef); e – large funnel-shaped ponor at the top of voronezhian reef limestones (East-Kulaginsky reef).

Deep karst

Deep karst was diagnosed in the well core for 22 reefs. According to the available material, various forms of subsurface karst for the Rechitskian and Voronezhian intervals are identified (Table 2; Fig. 4). In particular, caves were identified in the well core, which are characteristic morphological varieties of deep karst. Systems of small karst cavities and karst fracture are associated with caves. Deep karst forms and features are located significantly lower than installed surfaces of subaeral exposure.

The width of *кarst caves* significantly exceeds the diameter of the core, their height varies from 0.1 to 4.0-7.5 m. The largest paleokarst caves were found in the core of the East-Volostnovsky, Kindelsky and East-Kulaginsky reefs (Table 2). These caves are filled with sandy, silt-clay and clay dolomite, in which angular blocks of reef bedrocks are found. Natural localization of coarse angular fragments of the collapse breccia to the lower part of caves is observed. Clay and terrigenous material at the stages of sea level falling and sea level lowstand (LST) in significant volumes was carried by rivers from Sol-Iletsk island to Rubezhinsky Trough. At the stages of sea level rise, these precipitation was redistributed by wave processes and through systems of vertical karst voids fell into cavities formed by deep karst. The increased content of terrigenous and clay material in the filling of karst voids is most characteristic of the Voronezhian part of the reefs.

Intervals of caves in wells are diagnosed by the gamma-ray log (GR) based on increased natural radiation.

Karst cavities reach a width of 5-10 cm. They are quite common in reef section, have different shapes and, as a rule, are accompanied by fractures. Systems of cavities associated with fractures can be often observed. Cavities can be filled with clay dolomite,

Reef	Top of the Voronezhian regional stage	Top of the Rechitskian regional stage	Top of the Domanikian regional stage
Rybkinsky	terrigenous sediments lie with erosion on frame limestone	-	-
Novozhokhovsky	karren and ponors, filled with clay silt-sand material	karren fracture, wedging down and filled with clay dolomite	-
Volostnovsky	-	-	limestone breccia
Kulaginsky	small karren corroded with stylolites	dolomite breccia	-
South-Volostnovsky	gentle karren	-	-
Mikhaylovsky	coarce clast limestone breccia	-	-
South-Kulaginsky	small karren, brecciated limestone	coarce clast carbonate breccia	coarce clast carbonate breccia
East-Kulaginsky	funnel-shaped ponor, passing down into a large karst cavity filled with dolomite breccia and sand-silt dolomite	-	-
Kazatchinsky	terrigenous sediments lie with erosion on frame limestone	-	-
Klyutchevoy	small karren, almost vertical fractures with carbonate-clay filling	small karren	-
Rzhavsky	terrigenous sediments lie with erosion on frame limestone	-	-
West-Zhokhovsky	-	coarce clast carbonate breccia	-
Gusakhinsky	deep karren (до 5 sm)	-	-
Gerkulesovy	small karren	-	-
Streletsky	-	carbonate palaeosol with rhizoliths, microbial tuffs of karst water unloading zone	-

Table 1. Features of surface karst and subaeral exposure surfaces of franian reefs of the Rybkinsky group diagnosed on the well core

clay-silt sandstone, carbonate rubble in clay-dolomite and silt-sand-dolomite matrix. The walls of the cavities are uneven, corroded; at contacts with the bedrock, large-toothed and large-amplitude stylolitization is often developed. Slit-like karst cavities with a width from 2-5 mm to 3-6 cm are quite common in well sections.

Karst fractures have a variable width and shape. They are filled with carbonate rubble, clay dolomite, clay silt-stone. Systems of elongated vugs, karst cavities are often developed along karst fractures.

A specific group of karst fractures, coupled with a system of almost vertical neptunian dykes, has been identified in the slope zone of reefs. Such fractures developed along the contacts of the reef bedrock and the various granular filling of dykes.

Within reefs, karst zones form areas of increased permeability, since almost always voids, even with dense filling, are accompanied by systems of open fractures and microfractures. Later hydrothermal karst textures intersects often the systems of paleokarst fractures and cavities (Fig. 4a), complicating significantly the pore space of reservoir and increasing its capacity. In cases of intense properties of hydrothermal dolomitization, signs of the preceding deep karst cannot be diagnosed practically.

The formation of the secondary dolomite zone according to the model of mixing meteoric and sea pore waters is an important result of the development of deep karst. This conclusion was made based on the results of the study of the West-Rybkinsky and North-Zhokhovsky reefs (Vilesov et al., 2013). The interval of secondary different-crystal dolomites with increased porosity and permeability is located 60-70 m below the top of the Voronezhian part of the reefs. The thickness of the dolomite units varies from 10-12 to 15-18 m. The pore space in the dolomites of the mixing zone is represented by numerous intercrystalline pores, molds (by dissolved fossils) and wugs (leaching caverns).

Hydrothermal karst of Rybkinsky reefs

Hydrothermal karst (or hydrothermokarst) refers to the process of leaching rocks with heated solutions with the formation and subsequent filling of cavities (Maksimovich, 1969; Dublyansky, 1985; etc.). In carbonate rocks, hydrothermal karst can be accompanied by intense dolomite metasomatosis. One of the models

Reef	Voronezhian regional stage	Rechitskian regional stage	Domanikian regional stage
West-Rybkinsky	karst fractures	-	-
North-Zhokhovsky	karst fractures with systems of small cavities filled with clay dolomite	-	-
Rybkinsky	inclined karst fractures with systems of cavities partially filled with terrigenous-clay material	-	-
Novozhokhovsky	inclined fractures of various widths; a system of fractures and various cavities, filled with silt-clay and carbonate-clay material, carbonate rubble	small karst cavities filled with carbonate rubble in clay-carbonate matrix	-
East-Volostnovsky	karst cave 17 m from the surface; height more than 5 m; cave filling – dolomite rubble and dolomite breccia, silt-clay-dolomite material	-	-
Volostnovsky	inclined fractures of various widths filled with silt-clay and carbonate-clay material	almost vertical and inclined fractures of various widths, filled with silt-clay, clay-dolomite material and carbonate rubble	inclined tortuous fractures of various widths filled with silt-clay-dolomite material
Kulaginsky	diverse in width inclined fractures with dolomite and dolomite-clay filling; cavities with clay filling; subhorizontal cave up to 30-50 cm high with layered dolomite filling and angular carbonate fragments	almost horizontal and inclined cavities up to 30 cm high with carbonate breccia in clay and dolomite-clay matrix	-
South-Volostnovsky	diverse almost vertical and inclined fractures, small cavities with sand-silt-clay, dolomite-clay and calcite filling; rare almost horizontal cavities with carbonate breccia	-	-
Mikhaylovsky	inclined fractures with dolomite-clay and sand-silt-clay filling; inclined cavities filling with carbonate block and rubble in dolomite-clay matrix	caves up to 2 m high, filled with dolomite breccia; extended inclined karst slot-like cavities along neptunian dykes with carbonate rubble filling	-
West- Kulaginsky	inclined karst fractures with clay-dolomite filling	-	-
South-Kulaginsky	almost vertical tortuous fractures with crystalline calcite and dolomite filling; almost horizontal and inclined cavities with dolomite breccias; single cavities filled with anhydrite	-	-
East-Kulaginsky	karst caves from 2.0 to 3.5 m (or more) high, filled with different block dolomite breccia	cave up to 0.5 m high, filled with dolomite breccia with dolomite-clay matrix	-
Kindelsky	a system of karst caves from 1 to 8 m high, filled with dolomite breccias, dolomite conglomerates, lithoclastic floatstone and dolomadstone	-	-
Kazatchinsky	inclined karst fractures with systems of small cavities filled with dolomite-clay material	-	-
Klyuchevoy	inclined and almost vertical fractures with variable width filled with different crystalline dolomite	-	-
Rzhavsky	vertical karst fractures with systems of small cavities	-	-
Filichkinsky	rare isometric cavities with clay-dolomite filling	-	-

Table 2. Features of deep karst diagnosed on the well core of franian Rybkinsky reefs

West-Zhokhovsky	complex system of almost vertical fractures and fracture cavities	a system of numerous almost vertical fractures, cavities and caves (from 0.5 to 1.5 m high). Filling - clay and clay-dolomite material. In large cavities and caves - broken fragments of reef bedrock	-
Gusakhinsky	small karst cavities and fractures filled with carbonate crushed stone, dolomite and anhydrite	-	-
Dedovy	large karst cavities filled with carbonate breccia and clay dolomite	a system of cavities filled with clay dolomite	-
Gerkulesovy	small karst cavities filled with clay dolomite	-	-
Streletsky	karst cavities up to 12 cm high with clay-dolomite filling	-	-

Table 2. Continuation. Features of deep karst diagnosed on the well core of franian Rybkinsky reefs

for the formation of secondary diagenetic dolomites is called hydrothermal (Warren, 2000).

Secondary dolomites of Rybkinsky reefs formed as a result of hydrothermal karst are unevenly found in section and area (Table 3; Fig. 1, 5). Signs of hydrothermal metasomatosis in individual reefs are recorded in intervals with a continuous vertical length of more than 30 m (for example, in the upper part of the South-Kulaginsky and West-Rybkinsky reefs). In other reefs, signs of hydrothermal exposure occur at frequent intervals of variable thickness (from 1-2 to 6-12 m) throughout the reef section. In the third group of reefs, hydrothermal karst is found in rare and small areas, or not diagnosed at all in the core. It should be noted that the signs of hydrothermal karst are installed in the core only from Voronezhian and Rechitskian intervals of reef sections (Table 3).

Rocks formed as a result of hydrothermal karst are represented by multicrystalline dolomites with characteristic features: saddle-shaped crystals, zebroid and spotted color, the development of crystalline veins, complex fracture systems with coarse crystal inlays, uneven development of the ore iron sulfide (in the form of crystalline veins and pyrite inclusions). The primary texture of reef rocks subjected to hydrothermal metasomatosis is often not preserved practically.

The hydrothermal nature of secondary dolomites is confidently diagnosed according to the results of laboratory geochemical studies by the method of X-ray fluorescence analysis: in coarse crystalline secondary dolomites of Rybkinsky reefs the content of manganese and iron is increased (Fig. 6a, b), that is typical for dolomites of the hydrothermal model (Warren, 2000). Strontium content in dolomites is reduced compared to slightly modified limestones (Fig. 6c).

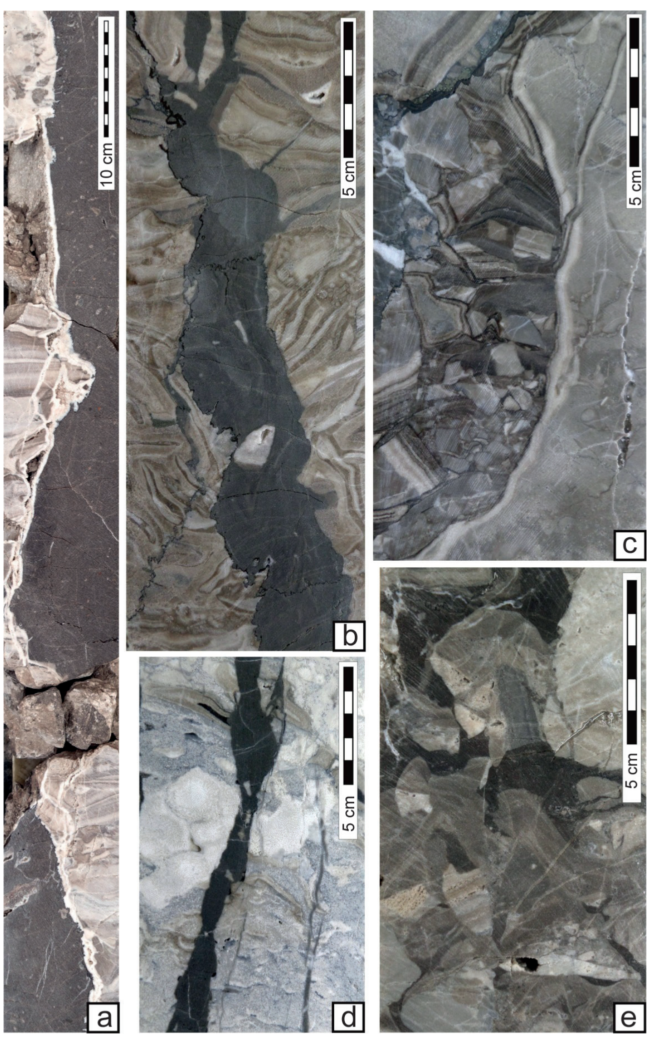

Fig. 4. Deep karst in the reefs of the Rybkinsky group: a - a cave filled with dark-gray clay microcrystalline dolomite; along the walls of frame limestones are the veins of hydrothermal dolomite (Kindelsky Reef, Voronezhian regional stage); b – inclined slit-like karst cavity in frame stromatoporoid limestone filled with clay dolomite (Volostnovsky reef, Rechitskian regional stage); c – karst cavity filled with carbonate rubble (Kulaginsky reef, Voronezhian regional stage); d - slit-like karst fracture in bioherm limestone of reef slope with clay-dolomite filling (West-Zhokhovsky reef); e – limestone collapse breccia of the bottom part of the karst cave (Kindelsky reef, Voronezhian regional stage)

Reef	Voronezhian regional stage	Rechitskian regional stage
West-Rybkinsky	coarce crystalline dolomites with saddle-like crystals	-
North-Zhokhovsky	spotted dolomitization zones with large dolomite crystals; extended inclined fractures inlaid with saddle crystalline dolomite and pyrite	-
Rybkinsky	numerous inclined fractures with inlays of coarse crystal saddle dolomite	-
Novozhokhovsky	beds of multicrystalline dolomites with thickness from 1-2 to 5-6 m distributed unevenly along the section; saddle-like crystals; uneven incrustation by pyrite	frequent units of different crystalline dolomites with a thickness of 0.5 to 3.0 m and with saddle-like crystals; uneven pyritization, including as crystalline veins
Volostnovsky	rare saddle crystals of dolomite along the walls of vugs	-
Kulaginsky	crystalline veins of saddle dolomite with pyrite	various crystalline veins of saddle dolomite with pyrite; units of secondary multicrystalline dolomites up to 1.5 m thick
South-Volostnovsky	rare saddle crystals of dolomite along the walls of vugs	-
South-Kulaginsky	intensive dolomitization along the section; units of multicrystalline dolomites with a thickness of 6 to 11 m; saddle dolomite forms various crystalline veins and inlays fractures; uneven pyritization, including as crystalline veins	saddle dolomite is developed in the form of crystalline veins and incrustations along fractures; pyrite meets with him
East-Kulaginsky	intensive dolomitization in the upper part of the reef, units of multicrystalline dolomites up to 4 m thick; saddle dolomite is represented in the form various crystalline veins, it inlays extended fractures; uneven pyritization across dolomites	-
Kindelsky	intensive dolomitization; units of multicrystalline dolomites from 2 to 4 m thick; saddle dolomite is represented in the form crystalline veins, it inlays fractures; pyritization is unevenly distributed among dolomites	-
Kazatchinsky	white coarse crystal saddle dolomite forms crystalline veins along karst fractures	-
Klyuchevoy	intensive dolomitization throughout the sections in the form of crystalline veins of saddle dolomite, inlays on fractures and vugs; uneven pyritization, including in the form of pyrite veins	-
Filitchkinsky	intensive dolomitization throughout the sections; units of multicrystalline dolomites from 2 to 7 m thick; saddle dolomite is represented in the form crystalline veins; it, together with pyrite, is distributed among extended fractures	-
West-Zhokhovsky	units of multicrystalline dolomites up to 6 m thick; saddle dolomite is represented in the form crystalline veins; together with pyrite, it is distributed to various directed fractures	units of multicrystalline dolomites reach a thickness of up to 1 m; saddle dolomite forms crystalline veins and inlays multi-directional fractures
Gusakhinsky	units of multicrystalline dolomites from 0.3 to 1.2 m thick; saddle dolomite forms crystalline veins and inlays fractures and vugs; there are usually veins of ore pyrite along the section	-
Dedovy	intensive dolomitization along the section with units dolomites with zebra-structures; saddle dolomite forms extended tortuous crystalline veins, inlays fractures	uneven dolomitization along the section; white saddle dolomite forms tortuous crystalline veins
Streletsky	rare fractures with inlays of coarse crystal saddle dolomite and pyrite	-

Table 3. Features of hydrothermal karst diagnosed on the well core of Rybkinsky reefs

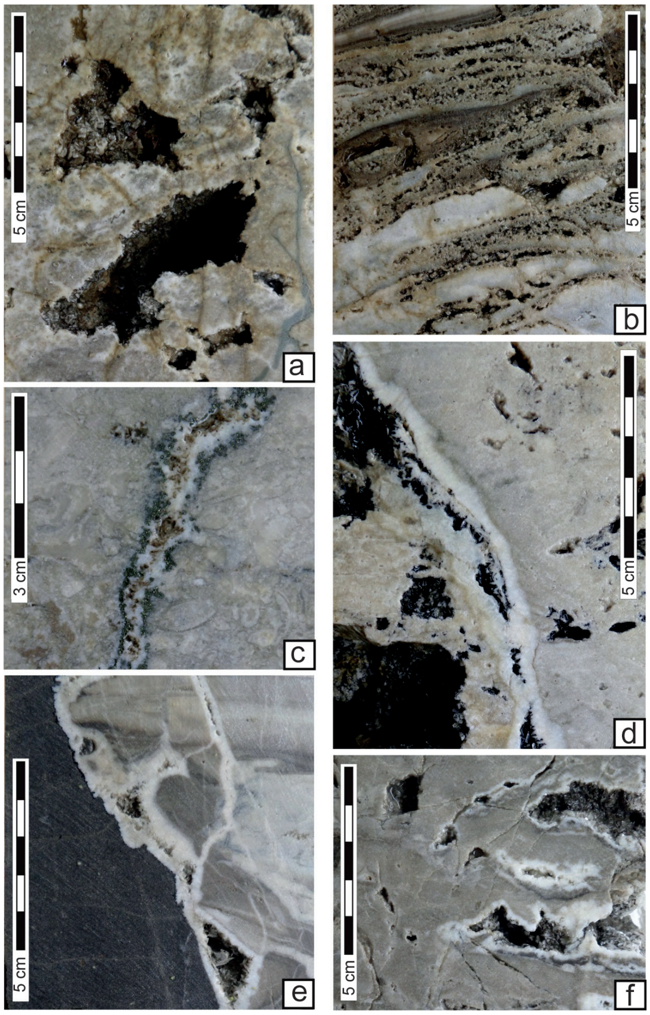

Fig. 5. Hydrothermal karst on Novozhokhovsky (a, b, c), South-Kulaginsky (d), Kindelsky (e) and West-Zhokhovsky (f) reefs: a – zebra-structures of secondary large-crystal dolomite with a system of vugs, cavities and microfractures; b – secondary multicrystalline hydrothermal dolomite with relics of stromatoporoid skeletons; c – crystalline dolomite vein with a chain of vugs and a pyrite fringe; d – secondary dolomite with large cavities and vugs, with coarse-crystal saddle dolomite; e – crystalline vein of large-crystal hydrothermal dolomite along the walls of the karst cave; f – zebra-structures of hydrothermal dolomite with a system of cavities, vugs and fractures.

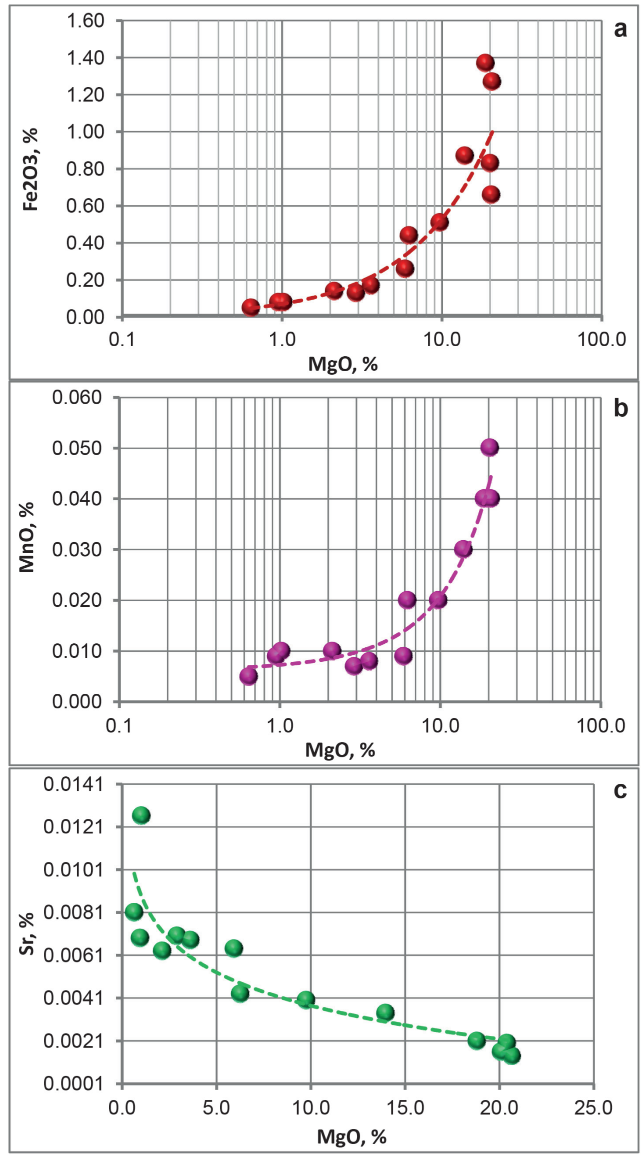

Fig. 6. Connection of individual chemical elements content with the intensity of hydrothermal dolomitization (using the example of rocks of the West-Zhokhovsky reef): a – Iron; b – Manganese; c – Strontium

Hydrothermal karst developed most strongly along the primary permeable rocks of the paleokarst zones. Therefore, combining two different forms of diagenetic changes is quite usual. The features of hydrothermal karst are especially characteristic of reefs located within linear zones. For example, hydrothermokarst is recorded at the core of all wells in the linear zone of Klyuchevoy reef – Filitchkinsky reef – Gusakhinsky reefs (Fig. 1). He was diagnosed in the linear zone of the Kindelsky reef – West-Kulaginsky reef – South-Kulaginsky reef. Hydrothermal karst is not fixed within separate reefs located outside pronounced linear zones (for example, in the Mikhailovsky and Gerkulesovy reefs). At the same time, it was very intensively formed in the section of the Novo-Zhokhovsky reef, which is located in the linear zone of another direction: Gusakhinsky reef – West-Kulaginsky reef – Novozhokhovsky reef – North-Zhokhovsky reef (Fig. 1).

Limestones of the franian reefs within the Volostnovsky license area underwent hydrothermal diagenesis in post-franian times, much later than the sedimentation stage. The replacement of limestones with secondary dolomites was caused by the rise and filtration into reef massifs of hot deep waters enriched with magnesium and iron ions.

Rocks subjected to hydrothermal diagenesis are characterized by the development of a system of the most diverse voids (intercrystalline pores, vugs, fractures, cavities) and, accordingly, the most complex structure of the pore space. Hydrothermal voids, unlike paleokarst ones, that usually filled with products of destruction of bedrocks and introduced material (clay dolomite, clay silt-sandstones, etc.), remained largely empty. Their walls are unevenly inlaid with coarse crystalline dolomite, pyrite and more later in crystallization time sulfates. However, fully filled hydrothermal cavities are much less common than paleokarst ones.

Reef rocks that have experienced hydrothermal metasomatosis are almost always complex highly productive fracture-vug and fracture-vug-pore reservoirs. The thickness of the units of secondary highly porous dolomites in the reef section can reach 15-30 m, and in some cases 50-60 m.

Karstic epochs in the development of Rybkinsky reefs

In the history of the formation of Rybkinsky reefs, three epochs of surface and deep karst (hypergenesis) can be distinguished. They are associated with periods of significant falls in sea level, caused both by eustatic fluctuations and the influence of inversion tectonic processes in the Sol-Iletsky Arch area.

The first epoch of paleokarst (Later Domanikian). At the end of Domanikian time, as a result of a significant decrease in sea level (Alekseev et al., 1996), Rybkinsky reefs underwent weathering and karst. Carbonate breccia horizons are observed at this level in the core. Mosaic carbonate platforms framing the Sol-Iletsky island from the north were also subjected to Late Domanikian karst and weathering (Vilesov et al., 2019b).

The second paleokarst epoch (Late Rechitskian) is associated with a significant regional falling of sea level at the end of the Rechitskian time. It was mainly caused by tectonic processes in the Sol-Iletsky Arch zone (against the background of a global eustatic rise). In the reefs of the Rybkinsky group, a second level of paleokarst is formed with a various karst fractures, cavities and caves. The karst water unloading zone with characteristic tuff-like microbialites was identified in the well core of the Streletsky Reef (Fig. 3d).

The third paleokarst epoch (Late Voronezhian) is associated with a significant global falling of sea level at the end of Voronezhian time (Alekseev et al., 1996; Johnson et al., 1985). Numerous and various signs of the late Voronezhian karst are revealed in reef sections: karst relief of the reef surface with karren and ponors, systems of karst cavities and caves with collapse breccia, karst fractures, vug zones. Intensive supply of terrigenous-clay material and its introduction by karst voids into reef buildings is characteristic of the third stage. An important feature of the third karst epoch is the formation of secondary dolomitization zones in reef reservoirs according to the mixing model (Vilesov et al., 2013).

Late Voronezhian and Late Rechitskian karst epochs are comparable to each other in the scale of karst manifestations. An important difference between them is the more significant presence of clay-terrigenous impurities in the filling of karst voids of Late Voronezhian karst.

Formation of the Rybkinsky reefs did not resume after the Late Voronezhian karst epoch. Layered subtidal carbonate-terrigenous-clay sediments deposited on reefs at the stage of Evlanovian transgression. Siliciclastic sediment, which was discharge from Sol-Iletsky island, played the role of an important limiting factor for the development of highly organized groups of frame builders. It is possible also that the Late Franian crisis in marine ecosystems was an equally important reason for the cessation of reef formation (Copper, 2002).

The development of hydrothermal karst in the reefs of the Rybkinsky group falls on the post-franian time. It is possible that it is associated with the intense block movements of the Sol-Iletsky Arch at the turn of the Franian and Famenian centuries. Taking into account the fact that there are no signs of hydrothermal karst at the well core higher in the section (in famenian and tournesian limestones), this time limit of hydrothermal activation is most likely.

Karst reservoirs of Rybkinsky reefs

Thus, complex karst reservoirs of Rybkinky reefs were formed as a result of three stages of hypergenesis, as well as the later period of hydrothermal karst. Various secondary voids, such as vugs, fracture, cavities and caves, were formed during periods of development of surface and deep karst (hypergenesis stages) as a result of atmospheric water filtration through carbonate reef massifs. Large paleokarst voids (caves and cavities) were filled with products of destruction of reef bedrocks, as well as clay-terrigenous sediments discharged from Sol-Iletsk land. Hydrothermal karst processes developed in reef massifs following karst permeable zones. Unlike large karst voids, hydrothermokarst cavities were only partially filled with newly formed minerals

Karst reservoirs of Rybkinsky reefs are characterized by a complex structure of pore space. Voids are presented by all variety – pores, vugs, fractures, cavities, caves. The high complexity of the pore space of karst reef reservoirs can be observed especially clearly from images obtained by X-ray computed tomography on an entire core column (Fig. 7).

Systems of oriented fractures (Fig. 7a, h), cavities connected by fractures (Fig. 7b, c, e), areas with multiple vugs (Fig. 7d, g), the directed systems of the touch-vug channels (Fig. 7f), a system of vugs connected by a porous matrix (Fig. 7i) can be diagnosed on tomographic sections. In fact, due to the presence of large voids and fractures, the well core from the intervals of karst reservoirs cannot be studied by standard methods in the petrophysical laboratory. Standard size samples (small core plug 30 mm/1 inch in diameter) may be made in

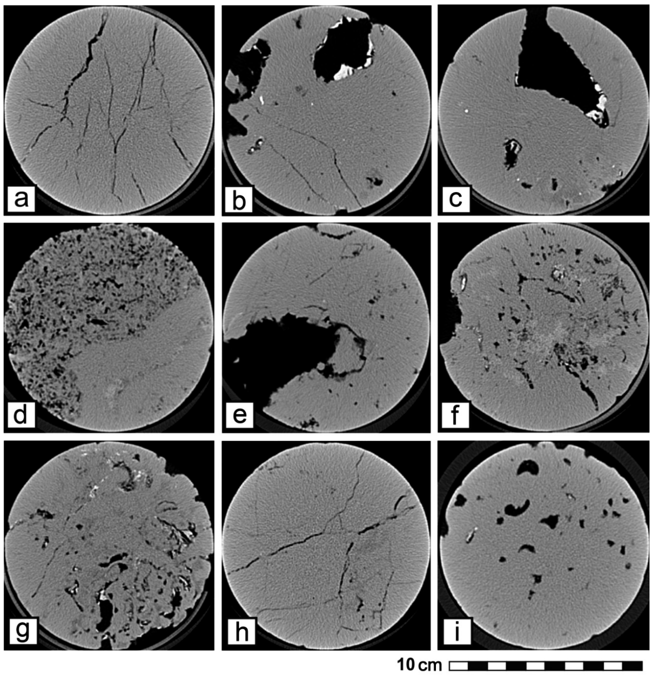

Fig. 7. Visualized images of the pore space of the karst reservoirs of Rybkinsky reefs obtained on the core column using X-ray computed tomography: a-c – Kindelsky reef, d-e – Novozhokhovsky reef, f-g – South-Kulaginsky reef, h – South-Volostnovsky reef, i – West-Kulaginsky Reef. Dark – pore space, light – dense part of rock. Explains to the images in the text. Tomograph operator – Kuznetsov E.G. (Core Research Center TNNC)

areas of porous or moderately cavernous rocks, but they do not characterize rocks with extended conductive fractures or a system of large vugs and cavities. The transition to the study of porosity and permeability of karst reservoirs according to the method of full-diameter core samples (with diameter 100 mm) to some extent allows us to solve this problem, since larger pores are involved in the research.

When studying the filtration properties of complex reservoirs of Rybkinsky reefs on small core plugs (that is, standart samples) and full-diameter samples, the "scale effect" is clearly manifested. It is a noticeable difference between standard and full-size samples in permeability. In Russia this direction of laboratory core analysis of carbonate reservoirs began to actively develop during the transition to the study of borehole core with a diameter of 100 or more millimeters, coring using the latest core-saving technologies (Mikhailov, Gurbatova, 2011; Gurbatova et al., 2011; Gurbatova, Mikhailov, 2011). Analysis of full-size core makes it possible to characterize not only pore channels of rock (available for study on standard samples of 1-inch diameter), but also filtering pores of larger size (fractures, cavern channel systems). As a result, at similar porosity values, the permeability of full-diameter samples can be one to two orders of magnitude higher than that of standard samples (Fig. 8). Taking into account the "*scale effect*" when working with complex reef reservoirs allows you to correctly estimate reserves (Nemirovitch et al., 2016; Shakirov et al., 2019).

However, the most accurate filtration characteristics of karst reservoirs can be obtained only when analyzing hydrodynamic studies of wells. Oil inflows from 190 to 380 m^3/day obtained by testing the karst intervals of Rybkinsky reefs (Vilesov et al., 2019a) indicate a significant role in the fluids filtration of cavern channels and fractures with high permeability. The results of laboratory core analysis using only small core plugs do not explain such production property of oil reservoirs.

Conclusions

Various attributes of surface and deep paleokarst as well as hydrothermal karst were diagnosed in the franian isolated reefs of the Rybkinsky group as a result of laboratory sedimentological studies of the borehole core.

The three epochs of the paleokarst, the Late Domanikian, Late Rechitskian and Late Voronezhian, are distinguished in the history of the formation of

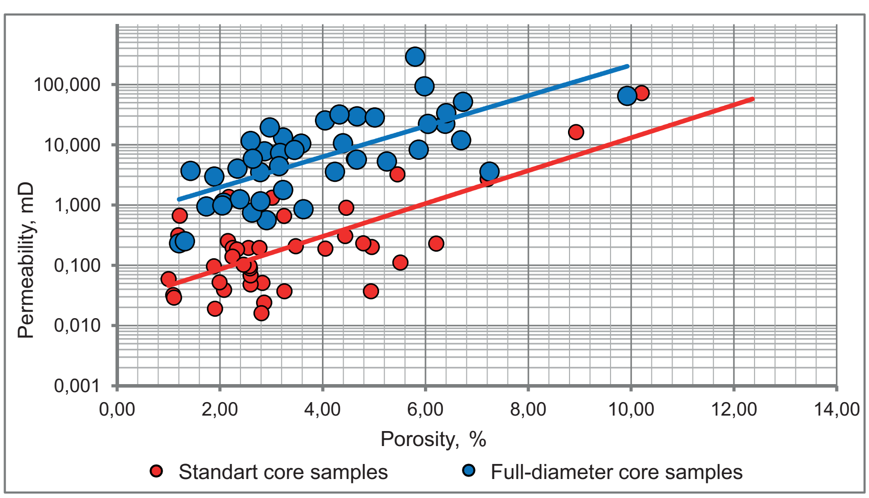

Fig. 8. Porosity-permeability cross plot for core samples of standart and full-diameter sizes (according to the results of laboratory core analysis of karst reservoirs of the South-Kulaginsky reef)

Rybkinsky reefs. Signs of surface and subsurface karst are established for each of them.

Carbonate breccias are assigned to the signs of surface karst in the upper part of the Domanikian regional stage. Karst at this level was caused by a regional decrease of sea level.

The late Rechitskian karst epoch was caused by significant inversion tectonic processes in the Sol-Iletsky Arch and its neighboring blocks against the background of global sea level rise. Surface karst is expressed by limestone breccias and carren, deep karst – by caves, fractures and cavities. Caves and cavities are filled mainly with carbonate and clay-carbonate sediment.

The Late Voronezhian paleokarst was caused by a significant eustatic falling of sea level and positive movements of the tectonic blocks of the Sol-Iletsky Arch. Ponors, carren and carbonate breccias are the results of surface karst. Deep karst formed such structures as caves, fractures, cavities. Filling karst voids at this stratigraphic level is the most diverse in terms of material composition that is represented by carbonate breccias, terrigenous-clay and clay-carbonate material.

The stages of the Late Rechitskian and Late Voronezhian karst are comparable in scale. Significant development of deep karst attributes is characteristic of each of these time lines.

Rybkinsky reefs were exposed to hydrothermal karst possibly at the turn of Late Franian – early Famenian ages. Hydrothermal karst developed mainly along permeable zones formed earlier by deep karst. An important result of hydrothermal karst is secondary high-porous hydrothermal dolomites.

Signs of the hydrothermal karst are distributed unevenly in area. They are developed most intensively along some linear zones, apparently associated with low-amplitude tectonic faults.

Reservoirs in the body of Rybkinsky reefs were formed as a result of a complex diagenetic history in which paleokarst (hypergenesis) and hydrothermal karst played leading roles.

The complex structure of the pore space is characteristic for the karst reservoirs of Rybkinsky reefs. Voids are presented here by all morphological types – pores, vugs, fractures, cavities, caves.

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