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LITHOGENETIC ASPECTS OF OIL AND GAS SYSTEMS FORMATION IN THE VOLYNO-PODOLIA SILURIAN DEPOSITS

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Objective. To elucidate the dynamics of catagenetic processes that occurred in the Silurian sediments against the background of an oil and gas systems formation. **Method**. The method includes lithology-facies, mineralogical-petrographic, catagenetic, and litho-fluido-dynamic analyses. **Results**. The spatial-temporal development features of carbonate (bank-reefal facies), argillite (outer and inner shelf), and argillite-carbonate (transition facies) complexes located in the Silurian sediments (profile of boreholes: Lishchynska-1 – Peremyshlyany-1 – Baluchin-1 – Olesko-1) have been determined. The main post-sedimentary transformations of clayey compound rocks consistent in the formation of quartz, calcite, pyrite, as well in the formation of caverns and fractures, which in most cases are combined with thin channels forming a single system, have been studied. It has been established that during the Palaeozoic and Early Mesozoic, the regime of catagenesis of the Silurian sediments of the considered structures was identical. Its further differentiation caused by the individualization of various tectonic block development occurred. In the first catagenetic cycle, the Silurian deposits reached the temperature conditions of the main zone of gas formation. The hydrocarbon (HC) generation centre was located in the western part of the studied profile (the Lishynskaya area), and within the zone of hydrocarbon accumulation a number of lithogenetic reservoirs were localized, the formation of which took place at different catagenetic substages. The main phase of hydrocarbon accumulation is confined to the Late Cretaceous. At this time in the Lishchino-Peremyshlyanskaya area there was a knot of reservoirs pertaining to the heterogeneous morphology, genesis, and the time of their formation. The spatial superposition of these reservoirs and the presence of a multi-directional system of fractures led to the formation of a single fluid system. In the Palaeogene, the accumulated oil and gas accumulations were destroyed as a result of the regional fracture zone development. Hydrocarbon fluids migrated both laterally and vertically with their possible accumulation in structural or lithological traps in the Silurian and Devonian sediments. **Scientific novelty**. The novel periodization of the Silurian deposits catagenesis has been determined, and the difference in the regime of catagenesis which occurred in various tectonic structures has been established. **Practical relevance**. The hydrocarbon fluids migration stages and the history of conditions during the formation of the lithogenetic reservoirs have been determined, which allowed assessing specific aspects of the oil-and-gas potential of the Silurian and adjacent sedimentary complexes.

Key words: Silurian, Volyno-Podilia, lithological complexes, catagenesis, litho-fluido-dynamics, reservoir rock.

Introduction

The Silurian sediments, originally developed along the entire western slope of the East European Craton, are considered to be source rock for both conventional and unconventional hydrocarbon accumulations. The previous ones are associated with the zone of limestone bank-reefal formations, being potential cavernous-pore reservoirs; the latter are related with the depression, and predominantly filled with clays, with layers enriched with organic matter, constituting a shake gas/oil reservoir. These facial zones are characterized with practically submeridional strike and significant westward thickness increase [Kurovets et al., 2010; Naumko et al., 2017; Radkovets, Rauball, & Jaremchuk, 2017].

Lithological, mineralogical, and petrographic (including the content and degree of organic matter transformation) petro-physical features of the rocks located in this sedimentary strata have been previously studied in detail [Kurovets et al., 2010; Radkovets, Rauball, & Jaremchuk, 2017; Dryhant, 2000]. These results alongside with the general geological data allowed allocating a number of potential sites in respect of shale gas and/or oil [Krupskyi et al., 2013].

However, such structural and lithology-petrographical characteristics are determined based on the studies of individual core samples, i.e. based on point data and reflect only fragments of the general picture, which depend, first of all, on the efficiency of coring in particular boreholes. The porosity and permeability properties, the content of organic matter (OM), and the degree of its transformation are indicators characterising the present condition of rocks.

To provide a more valid and overall assessment of the Silurian complex oil and gas potential it is necessary to analyse it in the context of the hydrocarbon systems formation. With this in mind, it is essential to investigate the lithophysical structure of sediments (the distribution of reservoir units and seal), the location of the hydrocarbon kitchen, the spatial-temporal features of hydrocarbon fluid migration, as well as the projected sites of their accumulation.

This research presents the results of modelling of the Silurian lithological structure for the profiles of boreholes Lishchynska-1, Peremyshlyany-1, Baluchin-1, and Olesko-1. The results obtained allowed allocation of the reservoir and seal horizons, and the reconstruction of the history of catagenetic processes based on the fluid dynamics concept [Hryhorchuk, 2010] and localisation of the hydrocarbon kitchen, catagenetic reservoirs, as well as determination of the directions of hydrocarbon fluid migration at various stages of geological development in this part of the western slope of the East European Craton.

Objective

Based on the fluid dynamics concept of catagenesis the objectives are to establish the historical and genetic features of HC reservoir rocks and reservoir formations, the dynamics of their hydrocarbon generation, and their migration in the Volyno-Podilia Silurian deposits.

Methods

The lithological differentiation of boreholes was made by interpreting the results of wire log data (gamma ray logging). The identification of individual lithological complexes was carried out based on the respective classification of sediments along the borehole cross-sections. Thin sections were examined under a Carl Zeiss Jena polarizing microscope.

Since the development of lithofluid systems from the standpoint of the fluidodynamic concept of catagenesis is considered and for a better understanding of the material presented in this article we briefly present the main provisions and terms used. The fluidodynamic conception of catagenesis grounds the cyclic nature of catagenesis according to stages of tectonic regime, the features of which influence the rocks' alteration were mediated by fluidodynamic features. According to the well-known typification of fluid regimes [Kartsev, 1986], the infiltration and exfiltration stages were distinguished, the latter consisting of a passive and active sub-stage. Catagenesis cycles began with an infiltration or exfiltration passive substage (dominance of the downward tectonic movements) and ended with an exfiltration active substage (inversion movements). The performed catagenesis is based on modeling the burial history of the successions. At the passive substage, in the zones of intensive subsidence of low-permeable clay deposits, isolated systems were formed, and abnormally high reservoir pressures occurred. Due to the accumulation and impossibility of removing products of direct reactions, the processes of transformation of organic matter and clay minerals were inhibited (the phenomenon of conservation of lithogenesis), (Kudel'skij, 1982). At the same time high reserves of fluid, heat, and elastic energy accumulated, which are the driving forces of fluid migration including hydrocarbons. This migration occurred during the active sub-stage of catagenesis in regional sub-horizontal fracture zones of tectonophysical nature. On the paths of this migration, catagenetic type reservoirs are formed. The latter are areas of mineral dissolution of cement and rock carcass, shielded by zones of intense mineralogenesis.

Area of study. The research area is located in the south-western part of the Eastern European Platform, the Volyn-Podilsky margin belonging to the zone of transition of the old platform to the Alpine Carpathian orogen. The Silurian deposits on it are represented by a stratigraphically continuous layer, which, in the form of a monoclinal with sloping layers to the west and southwest, floats the edge of the platform in the territory from the Baltic to the Black Seas. Within Ukraine it is distributed in the western (Volyn) and southwestern (Podillya) slopes of the Ukrainian shield, in the Lviv and in the south-eastern part of the Carpathian depressions, forming together with the Lower Devonian a single structural complex. For the Silurian sequence, an almost submeridional strike of facial zones and a significant westward increase in the thickness of geological units is characteristic. The minimum thickness of the sequence (340–385 m) is observed in the eastern part of the region and along the south-eastern boundary of the Lviv depression, where carbonate sediments predominate in cross-sections; its maximum values (989–1102 m) are fixed in the Pre-Carpathian zone and the central part of the Lviv depression, where only argillites are spread [Dryhant, 2000].

Results
Lithological characteristics

Following the lithological interpretation of the boreholes' wire log data (radioactive logging), the lithological sections of the Silurian sediments were accomplished for the boreholes Lishchynska-1, Peremyshlyany-1, Baluchin-1, Olesko-1 (see Table 1 and Fig. 1).

Table 1

Lithological composition of the Silurian in the Lishchynska-1, Peremyshlyany-1, Baluchin-1, and Olesko-1 **borehole sections**

Boreholes	lithologic composition (%)		
	Argillite	Marl	Limestone
Lishchynska-1	65	30	5
Peremyshlyany-1	58	39	13
Baluchin-1	34	34	32
Olesko-1	43	29	28

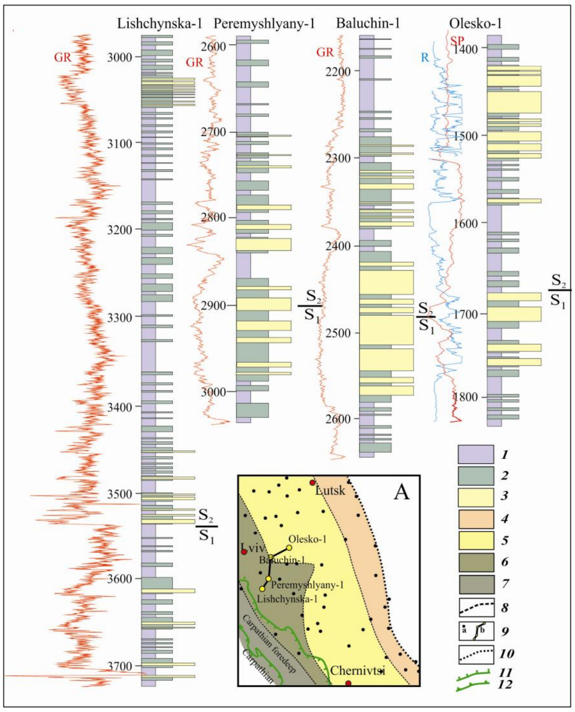

Fig. 1. Lithological sections of the Silurian sediments. Location of the studied boreholes (A)

1 – argillites, 2 – marls, 3 – limestones; facial zones (according to [Radkovets, 2015]) with changes in authors: 4 – internal shelf, 5 – barrier zone and front slope, 6 – external shelf, 7 – mesopelagic zone; 8 – eastern border of the Silurian sediments spreading; 9 – boreholes (a), studied boreholes (b); 10 – boundaries of facial zones; 11 – Stebnyk overthrust; 12 – Carpathian overthrus.t

The section of the Lishchynska-1 borehole is characterised by the domination of argillite (4–35 m) and marl (1–10 m) lithology with sporadic limestone layers (up to 3 m) (Table 1, see Fig. 1). In the eastern direction, a remarkable change in the sequence lithological structure is observed. For instance, the section of the Peremyshlyany-1 borehole can be considered as a transitional one: the content of limestones and marls increased there, while the role of clayey rocks decreased. At the same time, the thickness of intervals of the latter one does not exceed 18–20 m; however, the thickness of marl (up to 25–30 m) and limestone (up to 14 m) sequences increased. Their thickness is up to 35–40 m in cross-sections of the Baluchin-1 and Olesko-1 boreholes. Wherein if in the first case limestone formations are concentrated close to the Upper and Lower Silurian boundaries, then in the second case they are developed in the upper parts of the Upper and Lower Silurian, which indicates a certain migration of facial zones with time (see Fig. 2).

Based on the interpretation of lithological sections, a model of the Silurian deposit's lithological structure along the profile was designed through the above boreholes (Fig. 2). Three main lithological complexes were identified.

The characteristic feature of the carbonate complex is its 60–70 % content of carbonate rocks. The argillite complex is characterized by – similar content of clayey rocks, while the argillite-carbonate complex differs in terms of its relative content of limestone, marl and argillite, and their comparatively thin and frequent interstratification. The carbonate lithological complex is interpreted as a bank-reefal facies, the limestone lithological complex – as a unit of external (in the western part of the profile) or internal shelf (in its eastern part), and the argillite-carbonate complex is a zone of facial transitions which also includes formations of biogenic bodies destruction.

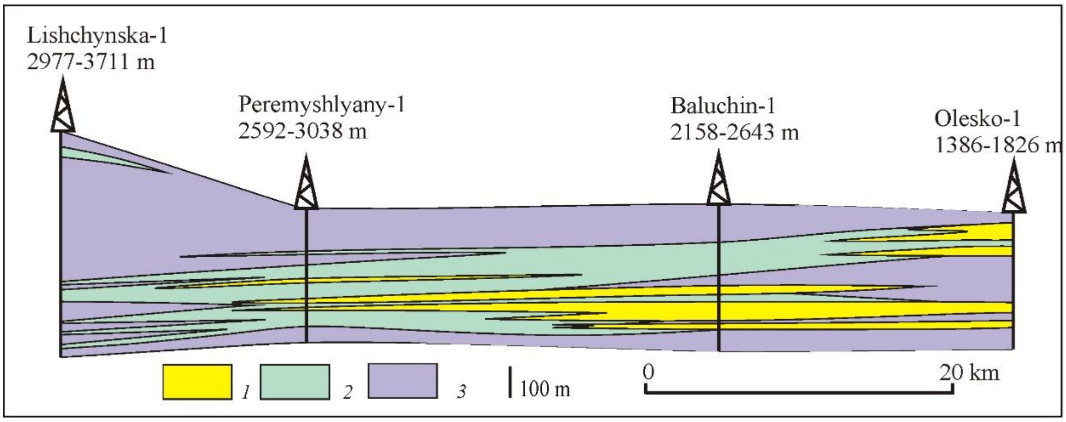

Fig. 2. Schematic cross-section illustrating lithological structure of the Silurian complex. Lithological complexes: 1 – carbonate, 2 – argillite-carbonate, 3 – argillite

In the terms of reservoir characteristics [Hryhorchuk, 2010; Hnidets et al., 2013] the first complex is characterised by the prevalence of porous reservoirs, the second one is a seal or under certain conditions – a fractured reservoir for the unconventional hydrocarbon (HC) accumulations, and the third one is fractured.

Petrographic characteristics

The Silurian organogenic limestones have been studied in detail in several works [Dryhant, 2000; Radkovets, 2015]. These rocks are present at various stratigraphic levels and are represented mainly by biomorphic limestones composed of coral remains, stromatopora, algae, and crinoids cemented with the carbonate-clayey matter [Dryhant, 2000]. The reservoir parameters of the carbonate rocks are primarily defined by sedimentation factors, as well as considering specific post-diagenetic processes. Organogenic limestones are occasionally dolomitised in an intense way forming secondary dolomites, which contain a significant amount of caverns, making it a high-grade reservoir rock [Dryhant, 2000]. In the intervals, where various lithological types interbed, mainly fractured reservoirs are formed, according to [Yusupova, Abukova, & Abramova, 2005], due to the uneven compaction of different lithological bodies during catagenetic transfomations.

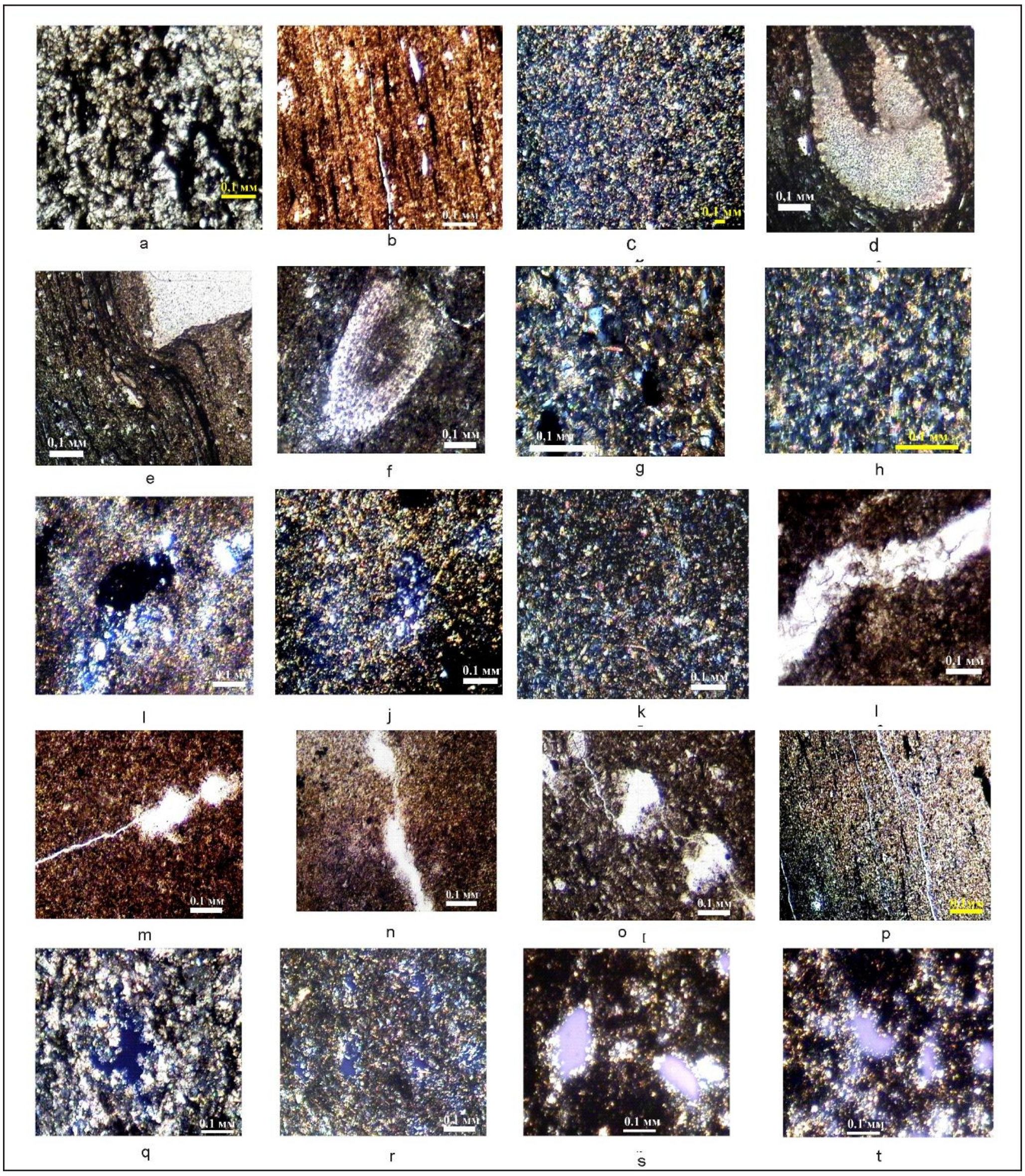

Fig. 3. Structural and mineralogical features of rocks (borehole Lishchynska-1)

The structural and mineralogical features of the rocks from borehole Lishchynska-1 in figure3: a – clayey bituminous limestone (int. 3500–3501 m, nick. II); b –laminated calcareous argillite (int. 3551–3556 m, nick. II); c– silicified pyritic marl (int. 3551–3556 m, nick. X); d – large fragments of crinoids in silt-clay limestone (int. 3250–3256 m, nick. II); e– fragment of a crinoid in laminated silty limy argillite (int. 3300–3306 m, nick. II); f – fragment of a crinoid with traces of dissolution in clayey limestone (int. 3651–3656 m, nick. X); g – organogenic-detrital silt-clayey limestone with pyrite (int. 3651–3656 m, nick. X); h – autogenic quartz-carbonate aggregates in argillite (int. 3002–3004 m, nick. X); i – a spot of autogenic quartz in marl (black is pyrite) (int. 3050–3056 m, nick X); j– a spot of autogenic quartz in pyritic marl (int. 3551 – 3556 m, nick. X); k– disseminated silicification in clayey limestone (int. 3651–3656 m, nick. X); l– calcite vein in clayey limestone, (int. 3651–3656 m, nick II); m– microfracture with cavities in argillite (int. 3002–3004 m, nick II); n– cavernous zone in marl (int. 3050–3056 m, nick. II); – microfracture with cavities in limy silty argillite (int. 3200–3205 m, nick. II); p – banded microfractures in limy argillite (int. 3300–3306 m, nick. II); q – cavern in clayey bituminous limestone (int. 3500–3501 m, nick. II); r– caverns in silicified clayey organogenic-detrital limestone (int. 3651–3656 m, nick. II), s,t – caverns, partially filled with quartz in marl, with a cellular microtexture (int. 3600–3603 m, nick. X)

The potential productivity of the above types of reservoirs can be explained by the dynamics of a lithofluid system development during the catagenesis. The energy of such a system is primarily determined by the rocks and OM transformations within the depression zone clayey layers, which to some extent are OM enriched [Radkovets, 2015]. These units dominate in the Lishchynska-1 borehole section and are predominantly composed of argillites and marls with the subordinate limestone's (see Fig. 3).

Argillites are characterized by both pelitic and siltpelitic structure, a massive or thin-laminated texture (see Fig. 3 b). The latter resulted from the uneven distribution of clastic fragments and elongated clusters of black organic matter. The silt material content (mainly quartz grains) varies from 1–2 to 8–12%, and its dimensions are 0.01–0.03 mm on average. Frequent small finely scattered (up to 0.04 mm) grains of carbonate minerals, thin (up to 0.01–0.02 mm) pyrite impregnations forming sporadic concretion sized up to 0.2 mm are observed. The pyrite content is 5–6%.

Fragments (up to 0.5x1.9 mm) of crinoids (see Fig. 3 c,d) occur in thin-laminated silty (up to 7 % of quartz grains) argillite (int. 3300–3306 m). These skeletal fossils are somehow stratifically "flown around" which is due to the post-sedimentation compaction of rocks.

Carbonate rocks are represented with marls and clayey or silty-clayey limestones. The latter often contain crinoid fossils (see Fig. 3 д), which reveal individual traces of the post-sedimentation dissolution.

Limestones are chiefly clayey and marked with a thin-laminated texture (int. 3250–3256 m). Lamination is caused by the development of elongated (0.01–0.02x0.1–0.25 mm) clusters of black OM and lenses (up to 0.08x0.3 mm) of carbonate material against the background of the more clayey mass.

In the thin-section lower part (see Fig. 3 f) clayey-silt limestone is present. Its characteristic feature is the increased content of terrigenous material (up to 25–27%) represented with quartz grains (0.01–0.03 mm) and muskovite laths.

Limestone from the interval of 3500–3501 m (see Fig. 3 a) differs in its fine crystalline structure and significant (up to 8–12%) development of black bitumens.

Post-sedimentation transformations of rocks located within Lishchynska-1 borehole are mainly associated with the developement of authigenous quartz and calcite found both in clayey and carbonate rocks (see Fig. 3 c, h, i, j, l,). In the interval of 3551–3556 m silicified marl is identified. It is characterized with finely-diffused silica (an approximate content is up to 15–20%). The latter forms (see Figure 3 t) sporadic forms sized up to 0.1x0.3 mm and composed of fine quartz crystals (0.003–0.006 mm). Sometimes, authigenous quartz is accompanied with pyrite (Fig. 3 i).

In argillite (int. 3002–3004 m) we detected a concretion (3x7 mm) composed of authigenous quartz and calcite (see Fig. 3 h). In the interval of 3350–3358 m an area (up to 0.4x0.5 mm) of fine (0.01–0.03 mm) calcite crystals are developed.

The presence of palm-like grains of authigenous quartz, silicified skeletons of foraminifera shells, cells of which are filled with crystals of calcite, is also mentioned in [Kurovets et al., 2010]. Moreover, rocks bear traces of their ancient decompaction. Thus, in the interval of 2755–2804 m the rocks are divided with a considerable number of sub-vertical fractures (up to 3–5 mm) filled with calcite. Winding calcite veins up to 0.1 mm thick are observed (see Fig. 3 l).

In addition, various cavities are observed in the studied rocks, i.e. caverns, cavernous zones, microfractures (see Fig. 3 m–t), found in argillites and in marls and limestones. The dimensions of caverns are 0.1x0.1 mm on average, and sometimes they are up to 0.1x0.4–0.5 mm. In most cases, caverns are joined by thin channels, forming a single system. In argillites (see Fig. 3 p), 0.02–0.03 mm wide thin layer-wise fractures are developed. Similar microfractures are described in the interval of 2804–3020 m [Kurovets et al.2010].

Burial and thermal history

According to the methodological approach by [Hryhorchuk, 2010], the post-diagenetic evolution of the Silurian complex was analysed with use of the of the burial history modelling applied to each of the analyzed borehole sections (Fig. 4).

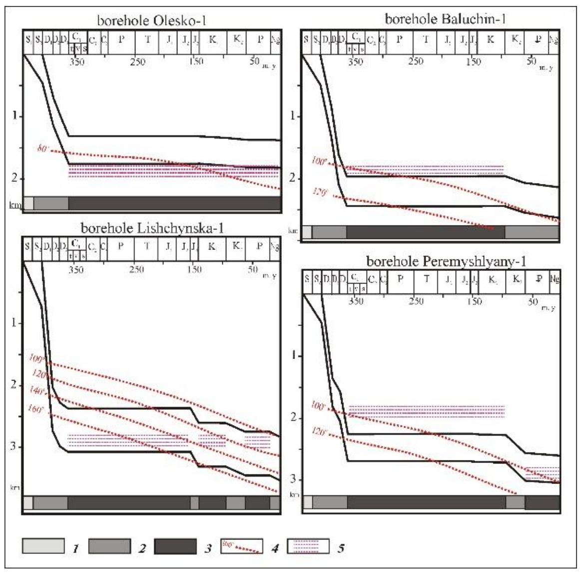

Fig. 4. Burial and thermal history of the Silurian complex

Stages of catagenesis: 1 – infiltration; exfiltration: 2 – passive substage, 3 – active substage; 4 – paleotemperatures, 5 – regional fracture zones

The obtained results show that during the Palaeozoic and Early Mesozoic, the catagenetic regime of Silurian deposits within all considered areas was identical: by the end of the Devonian, the passive substage of the exfiltration catagenesis occured, later its active phase began. The further regime of catagenesis within these areas was different, which led to an uneven number of cycles, stages, and substages of catagenesis. However, a tendency of their westward quantity increase is observed.

In Lishchynska-1 borehole, according to the fluidodynamic conception of catagenesis [Hryhorchuk, 2010], three cycles of latter are manifested, Peremyshlyany-1 – two cycles, Baluchin-1 – two cycles (second one incomplete), Olesko-1 – one cycle. The boreholes are located in various tectonic blocks [Kurovets et al., 2010]. Thus, the above features can indicate some difference in the tectonic regime of their development during the Mesozoic-Cenozoic time. The dynamics of post-diagenetic processes within these areas somehow reflect this fact, what we describe below.

Paleotemperature reconstructions are an important element in historical and catagenetic studies. They are essential both for reconstruction of hydrocarbon generation, and for determining the spatial-time localization of the so-called carbonate minerals “instability window” (80–120 ^{o}C) [Minskij, 1972; Dixon, Summers, & Surdam, 1989], which contributed to the formation of reservoir rocks through leaching processes.

Paleotemperatures specified in the models of sediments historical burial were determined based on the modern parameter values [Krupskyi et al., 2013] (Fig.4) and considerations [Belokon', 2005; Leonov & Volozha, 2004] testifying that at the early stage of development of such basins the temperatures exceeded the modern values by 1.4–1.5 times. Besides, we have taken into account the data [Ivanova, 2016] indicating that the paleogeothermal gradient during the Paleozoic was approximately 7.5^{o} C per 100 m.

The reconstruction paleotemperature values in our model are well correlated with the results of other studies [Środon, 2013; Schito et. al., 2018], which have shown that maximum paleotemperatures in the near-bottom part of the Silurian deposits reached 200 C.

Evolution of lithofluid systems

The lithofluid system, according to [Sokolov, 2002) is a well-ordered set of interacting and mutual influencing solid, liquid, and gas components of the lithosphere, linked by a common history of development. Aiming to reconstruct the Silurian deposits catagenetic processes we have performed a coceptual modelling per the considered section in Fig. 5, 6. Since the main source of the lithofluid energy were clayey depression units prevailing in the westward sections, we have designed the retrospective models for two catagenetic cycles clearly manifested within the area of boreholes Lishchynska-1 and Peremyshlyany-1.

The passive substage of exfiltration catagenesis had lasted until the end of the Late Devonian. At that time, the Silurian deposits reached temperature conditions of the main gas generation phase [Radkovets, Kosakowski, Rauball, Zakrzewski, 2018]. Consequently, it is possible that hydrocarbons then accumulated in different traps (in this particular case only catagenetic reservoirs are considered).

However, at the passive substage the large-scale migration of hydrocarbons was impossible since no effective fluid carriers were present [Hryhorchuk, 2010], which led to the preservation of lithogenetic processes ([Kudel'skij, 1982]). The latter was maximally manifested only within the Lishchynska- Peremyshlyany area (see Fig. 5). In its section prevail mainly clayey sediments enriched to some extent with the organic matter [Radkovets, Rauball, & Jaremchuk, 2017].

Under the above conditions, the diffusive processes prevailed [Hryhorchuk, 2010]. As a result of the defluidisation of clayey units and the OM transformation, the abnormally high reservoir pressures generated and “layers-reactors” (the term by [Sidorova, Safronova, Burova, 1991]) appeared, which accumulated substantial reserves of fluid dynamic energy.

In the eastern direction, following changes in the sequence lithological structure, no lithogenetic conservation processes occurred due to the formation of more permeable carbonate and argillite-carbonate units, which promoted a certain emigration of fluids. Such processes were activate in the areas of lithological substitutions (facial transitions), which differed by inhomogeneous lithological structure (interstratification of argillites, limestones and marls). Here the uneven compaction of various lithological bodies resulted in the formation of multidirectional lithogenetic fractures, which facilitated the migration of fluids. These fluids were enriched with aggressive agents (primarily OM transformation products), which triggered leaching; recrystallization and dolomitization of carbonate rocks. As a result, catagenetic reservoirs formed in these areas [Hryhorchuk & Senkovskyi, 2013], which differed by their complex structure: blocks of porous and micro-fractured rocks divided by more thick fracture zones. At the end of the passive substage of exfiltration catagenesis (the Late Devonian), based on the lateral variations of the Silurian sediments lithological structure, we predict the presence of three main reservoirs of this type (see Fig. 5). With regard to HCs accumulation, an R-1 reservoir drive is the most important. This can be explained by two factors. Firstly, it has the most volume due to more pronounced facial substitutions which occurred within this area. Secondly, it is located in close proximity to the (HC source zone). Fluids, including hydrocarbon, periodically arrived from their generation zones into this reservoir when the fluid energy became accumulated. This, on the one hand, contributed to some energy relaxation in the conservation zone; on the other hand, it caused gradually accumulation of hydrocarbons in the R-1 reservoir.

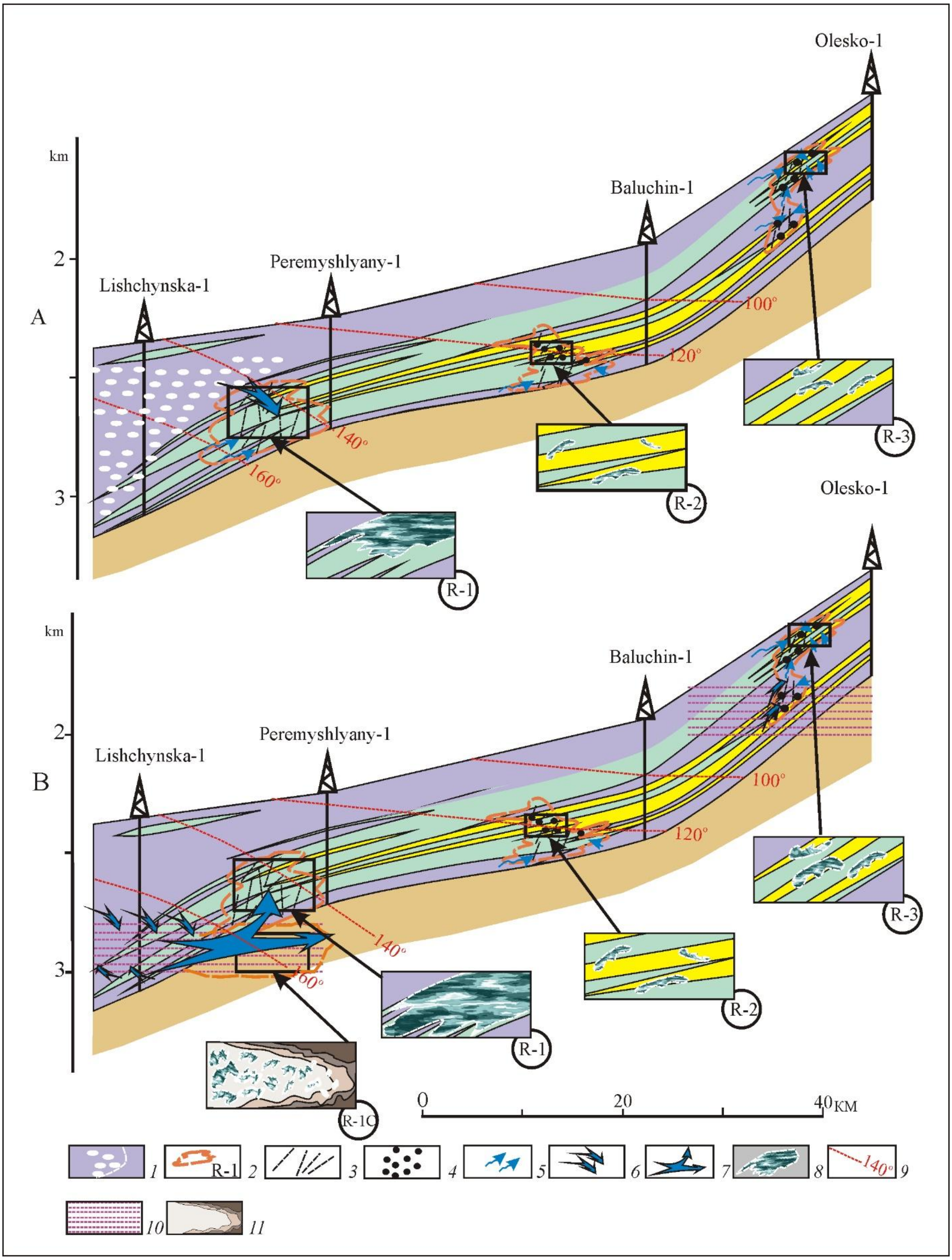

Fig. 5. Model of the hydrocarbon reservoirs development in the first cycle of catagenesis
1 – the area of lithogenetic processes conservation; 2 – reservoirs; 3 – fractures; 4 – reservoir rocks within the zone of decarbonatization; fluid migration: 5 – scattered; 6 – aggregated; 7 – avalanched; 8 – hydrocarbons; 9 – paleotemperatures; 10 – regional fractured zones; 11 – zones of mineral compaction

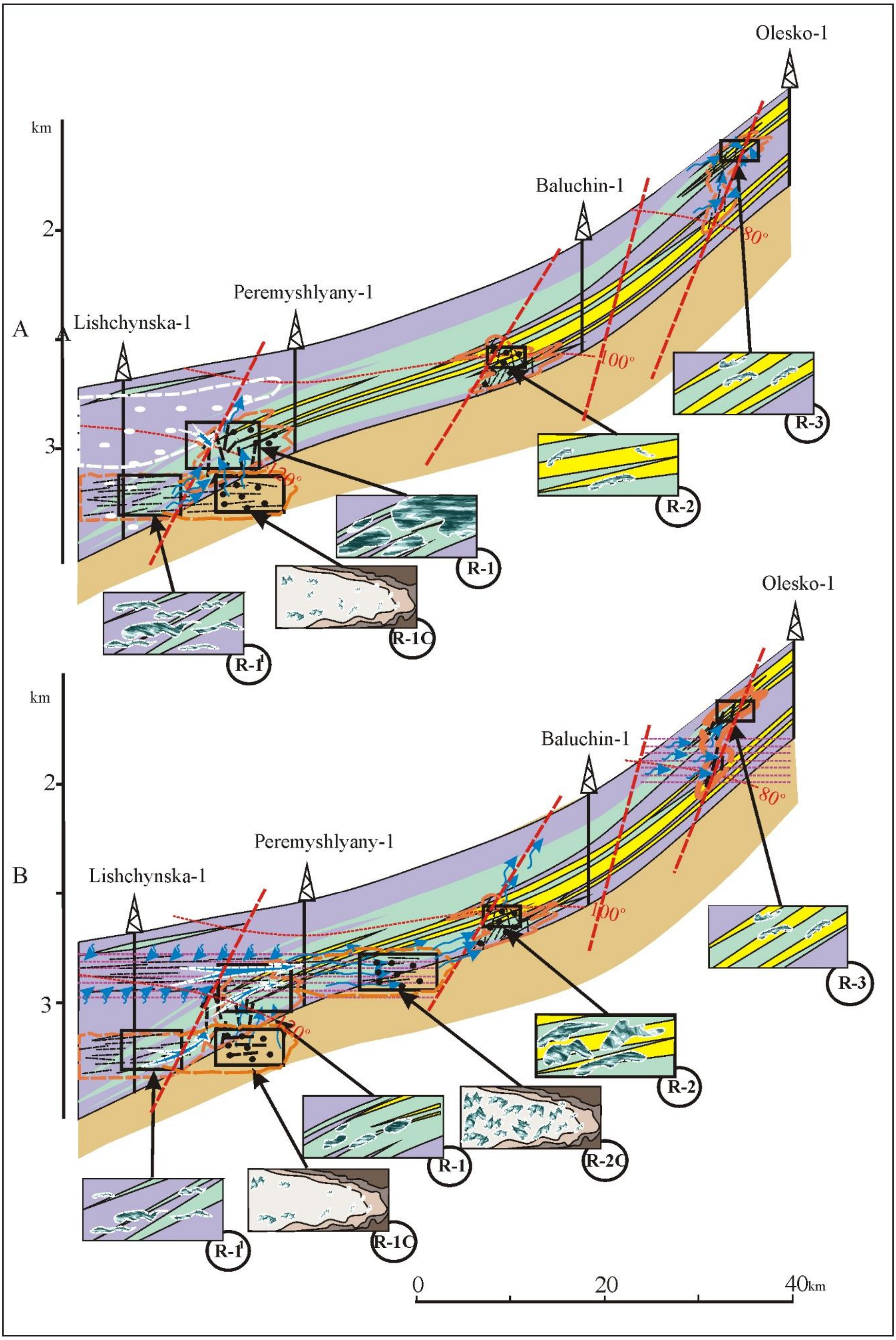

Fig. 6. Model of the hydrocarbon reservoirs development in the second cycle of catagenesis

Two other reservoirs (R-2 and R-3) are characterized by their smaller sizes (volumes) and are located farther from the main hydrocarbon fluid generation zone (east part of the profile). Taking into consideration the location of these reservoirs and the maximum temperature range of 80–120 ^{0}C , calcite dissolution occurred in carbonate rocks, as well pores and caverns were formed. The latter could partially be filled with hydrocarbons from adjacent marl-clayey source rock.

At the end of the Devonian, a long-term and active substage of exfiltration catagenesis began (see Fig. 5). Then, regional fracture zones were formed at two hypsometric levels. In the Silurian deposits the first one manifested itself within the Olesko-1 borehole area, the second one (deeper) – within the Lishchynska-1 borehole area. Due to a significant dilatancy effect [Dmitrievskij, Beljankin, & Karakin, 2007], the high-energy hydrocarbon fluids were pumped into the Lishchynska-1 borehole from the surrounding rock mass having been accumulated at the passive substage of catagenesis within the lithogenetic conservation zone. Some portion of these fluids arrived in the P-1 reservoir replenishing its reserves, while the remainder migrated into Ordovician and Cambrian bottom set deposits where they apparently formed a catagenetic reservoir (leaching rocks shielded with zones of intence mineralogenesis [Hryhorchuk, 2010]). These reservoirs were a temporary accumulation for the HC, which in the course of the onward geological history could emigrate both horizontally and vertically. Certain traces of the such reservoir existence can serve as a gas fountain (int 3475-3545 m) in the Peremyshlyany-1 borehole [non-traditional sources…, 2013].

Long time span (over 200 Ma) duration of the active substage of catagenesis (see Fig. 5) does not exclude the possibility of the manifestation of several catagenetic cycles. This is justified by the results of burial history processes modelling applied to the Peremyshlyany-1 borehole [Radkovets, Kosakowski, Rauball, & Zakrzewski, 2018]. However, we believe that the depth of the fracture zone did not significantly change and covered the lower part of the Silurian, where organic matter had already exhausted the generation potential by the end of the first cycle.

The lithofluidal features of the R-2 reservoir,compared to the previous substage of catagenesis, have remained unchanged. Instead, the R-3 reservoir fell under the influence of the second regional fracture zone, which led to the activation of fluid dynamics including their probable migration from the upper sediments of the Lower Devonian. Taking into account temperature conditions, these fluids promoted, first of all, leaching and recrystallization of calcite as well as the formation of dolomite. All this improved the filtration and reservoir properties of rocks by creating pores and caverns. Previously accumulated HCs underwent redistribution within the reservoir.

The further burial history and, accordingly, the regime of Silurian deposits catagenesis in the studied boreholes were somewhat different (see Fig. 4).

It should be noted that in the area of the Lishchinskaya-1 borehole another cycle of catagenesis (late Jurassic - Early Cretaceous) was revealed. Despite some decrease in temperature, its result was probably the entry into the reservoirs P-1 and P-1K having certain portions of HC.

The last catagenetic cycle began in the Late Cretaceous. It is more or less distinctive in all studied sites (apart from the Olesko-1 borehole). The passive substage of exfiltration catagenesis occurred during the Late Cretaceous, and its active phase began in the Palaeogene. During the passive substage, the most diverse and broad-scale processes took place in the Lishchino-Peremyshlyanskaya area, where in the upper part of the Silurian sequence a lithogenetic process conservation zone was formed (see Fig. 6). Along its periphery there existed two previously originated reservoirs (R-1, R-1C) and later the $P-1^1$ reservoir appeared. The decreased tectonic tension stress within a fracture (fluids transit) zone occurred at the previous stage (lower part of the Silurian sediments) and promoted its formation. At the same time, the residual porosity has remained within its limits but the permeability of fractures was reduced. Pre-generated hydrocarbon fluids took the form of individual lenses and inclusions in fractured rocks (marls, argillites).

Thus, a knot of reservoirs of heterogeneous morphology and genesis existed in this area and moreover they formed during different times. The spatial superposition of these reservoirs and the presence of a multi-directional system of fractures resulted in the formation of a single fluid system during the indicated substage. Fluids migrated mainly to the R-1 reservoir causing its maximum filling with hydrocarbons. They were preserved owing to the fact that the reservoir became blocked with over 200 m of thick clayey sediments. Consequently, during the passive sub stage of the second catagenetic cycle the HCs mainly accumulated within the Lishchino-Peremyshlyanskaya area.

The lithofluid features in the R-2 and R-3 reservoirs did not significantly change at the above substage. It should be noted that the fluid migration started to be activated following fault development (their location is shown according to [Kurovets, 2010]. At the first stage the leaching processes and rock reservoir properties improvement continued, in the second case the pores and caverns were filled with calcite (at temperature less than 80 ^{o}C).

During the active substage, which began in the Palaeogene, the largest lithofluidal processes re-manifested within the Lishchino-Peremyshlyanskaya area. First of all, this was associated with the formation of a regional fracture zone, which drained the conservation area, contributing to the hydrocarbons' migration. To some extent, they could move up along the fault.

The R-1 reservoir content was destroyed by the fracture zone that affected most of its extent.

Following this, hydrocarbons kept in their generation zone and accumulated in the R-1 reservoir, migrated eastward into the catagenetic reservoir (R-2C) encompassing the Late Silurian deposits and lying below the Cambrian and Ordovician formations. This reservoir was temporary. Hydrocarbons could gradually migrate laterally into the adjacent R-2 reservoir and vertically along the fault into the Lower Devonian and Upper Silurian layers.

Consequently, in general, it can be stated that during the geological history hydrocarbon fluids generated by the OM of the Silurian sediments were scattered due to their discrete lateral and vertical migration.

Scientific novelty

The Silurian deposits have been thoroughly dismembered with respect to their lithological structure, and the lithological complexes per Lishchynska-1 – Peremyshlyany-1 – Baluchin-1 – Olesko-1 boreholes have been specified for the first time. The first-ever periodization of the Silurian sediments' catagenesis has been determined. In has been shown that during the Palaeozoic and Early Mesozoic, the catagenetic regime in the considered structures was identical. The subsequent catagenetic history was diverse and was affected by the developmental dynamics of individual tectonic blocks.

Practical relevance

The stages of generation and migration of hydrocarbon fluids, and the history of lithogenetic reservoir formation has been determined in the study area. This allowed assessing the potential oil and gas bearing capacity of the Silurian and the adjacent sedimentary complexes.

Conclusions

1. In the analysed sections of the Silurian complex we have identified carbonate, argillite, and argillite-carbonate lithologies. The first one is interpreted as a bank-reefal facies, the second one – as the external (in the west profile part) or inner shelf (in its east part), the third one is a zone of facial substitutions. In the reservoir rock aspect, the first complex is characterized by the dominance of pore reservoir rocks, the second one is a cap rock, or, under certain conditions, a reservoir for unconventional HC accumulations, and the third is fractured.

2. Post-depositional transformations of the rocks of the clay lithological complex consisted in the formation of authigenous quartz, calcite and pyrite developed in argillites, marls and limestones. The traces of decompaction have been detected in all type of rocks, namely various cavities, i.e. caverns, cavernous zones, microfractures, which in most cases are joined by thin channels, forming a single system.

3. Based on burial history modelling it was established that during the Palaeozoic and Early Mesozoic the catagenetic regime of the Silurian sediments in all considered structures was identical: the passive substage of exfiltration catagenesis lasted to the end of the Devonian, then the active one began. Further on regime at the studied sites was its diversity located in the various tectonic blocks, which during the Mesozoic-Cenozoic period their individual developmental dynamics were manifested.

4. In the first catagenetic cycle the HC generation centre was located in the west part of the profile (the Lishynskaya area), and within the zone of hydrocarbon accumulation a number of catagenetic reservoirs were localized, the formation of which took place at different catagenetic substages.

5. The main phase of the HC accumulation occurred during the passive substage of the second catagenetic cycle (the Late Cretaceous). At this time in the Lishchino-Peremyshlyanskaya area there was a knot of reservoirs pertaining to the heterogeneous structure, genesis, and time of formation. The spatial superposition of these reservoirs and the presence of a multi-directional system of fractures resulted in the formation of a single fluid system. HCs were preserved owing to the fact that the reservoir became sealed with over 200 m thick clayey deposits.

6. In the Palaeogene, the pre-accumulated HC deposits were destroyed since the reservoirs fell into the regional fracture zone. Hydrocarbon fluids migrated both laterally and vertically. In this respect, they could possibly be accumulated in structural or lithological traps located both in the Silurian and Devonian sediments.

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ЛІТОГЕНЕТИЧНІ АСПЕКТИ ФОРМУВАННЯ НАФТОГАЗОВИХ СИСТЕМ У ВІДКЛАДАХ СИЛУРУ ВОЛИНО-ПОДІЛЛЯ

Мета. З'ясувати динаміку процесів катагенезу відкладів силуру в контексті формування нафтогазових систем. **Методика**. Методика включає літолого-фаціальний, мінералого-петрографічний, історико-катагенетичний та літофлюїдодинамічний аналізи. **Результати**. З'ясовано просторово-вікові особливості розвитку у відкладах силуру (профіль св. Ліщинська-1 – Перемишляни-1 – Балучин-1 – Олесько-1) карбонатного (банко-рифова фація), аргілітового (зовнішній та внутрішній шельф) та аргіліто-карбонатного (перехідні фації) комплексів. Вивчені основні післяседиментаційні перетворення порід глинистого комплексу, які полягають в утворенні кварцу, кальциту, піриту, а також формуванні каверн та тріщин, які у більшості випадків сполучаються тонкими каналами, формуючи єдину систему. Встановлено, що протягом палеозою та раннього мезозою режим катагенезу силурійських відкладів розглянутих структур був адекватним. У подальшому відбулася його диференціація, що зумовлено індивідуалізацією розвитку різних тектонічних блоків. На першому циклі катагенезу відклади силуру досягли температурних умов головної зони газоутворення. Осередок генерації вуглеводнів був розташований у західній частині перетину (район Ліщинської площі), а в межах зони вуглеводненагромадження локалізована низка резервуарів літогенетичного типу, формування яких відбулося на різних підетапах катагенезу. Основна фаза акумуляції вуглеводнів приурочена до пізньої крейди. В цей час у Ліщинсько-Перемишлянській ділянці існував вузол резервуарів різної морфології, генезису та часу утворення. Просторова суперпозиція цих резервуарів та наявність різноспрямованої системи тріщин зумовили формування єдиної флюїдної системи. В палеогені акумульовані поклади вуглеводнів зруйновані внаслідок прояву регіональної зони розущільнення. Вуглеводневі флюїди мігрували як по латералі, так по вертикалі з можливим їх нагромадженням у структурних чи літологічних пастках і у відкладах силуру, і девону. **Наукова новизна.** Вперше визначена періодизація катагенезу силурійських відкладів, встановлена різниця режиму катагенезу на різних тектонічних структурах. **Практична значущість**. З’ясована стадійність міграції вуглеводневих флюїдів, історія формування резервуарів літогенетичної природи, що дозволило оцінити певні аспекти перспектив нафтогазоносності силурійського та суміжних осадових комплексів.

Ключові слова: силур, Волино-Поділля, літологічні комплекси, катагенез, літофлюїдодинаміка, резервуари вуглеводнів.

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ЛИТОГЕНЕТИЧЕСКИЕ АСПЕКТЫ ФОРМИРОВАНИЯ НЕФТЕГАЗОВЫХ СИСТЕМ В ОТЛОЖЕНИЯХ СИЛУРА ВОЛЫНО-ПОДОЛИИ

Цель. Выяснить динамику процессов катагенеза отложений силура в контексте формирования нефтегазовых систем. **Методика**. Методика включает литолого-фациальный, минералого-петрографический, историко-катагенетичний и литофлюидодинамический анализы. **Результаты.** Выяснены пространственно-возрастные особенности развития в отложениях силура (профиль скв. Лещинская-1 – Перемышляны-1 – Балучин-1 – Олесько-1) карбонатного (банко – рифовая фация), аргиллитового (внешний и внутренний шельф) и аргиллит-карбонатного (переходные фации) комплексов. Изучены основные постседиментационные преобразования пород глинистого комплекса, заключающиеся в образовании кварца, кальцита, пирита, а также формировании каверн и трещин, которые в большинстве случаев соединяются тонкими каналами, формируя единую систему. Установлено, что в течение палеозоя и раннего мезозоя режим катагенеза силурийских отложений рассмотренных структур был адекватным. В дальнейшем произошла его дифференциация, обусловленная индивидуализацией развития различных тектонических блоков. На первом цикле катагенеза отложения силура достигли температурных условий главной зоны газообразования. Очаг генерации углеводородов находился в западной части профиля (район Лещинской площади), а в пределах зоны аккумуляции углеводородов локализирован ряд резервуаров литогенетического типа, которые формировались на разных подэтапах катагенеза. Основная фаза их аккумуляции состоялась в позднем мелу. В это время в Лещинско-Перемышлянском участке существовал узел резервуаров разной морфологии, генезиса и времени образования. Пространственная суперпозиция этих резервуаров и существование разнонаправленной системы трещин обусловили формирование единой флюидной системы. В палеогене аккумулированные залежи углеводородов были разрушены в результате проявления региональной зоны разуплотнения. Углеводородные флюиды мигрировали как по латерали, так по вертикали с возможным их накоплением в структурных или литологических ловушках как в отложениях силура, так и девона. **Научная новизна.** Впервые определена периодизация катагенеза силурийских отложений, установлена разница режима катагенеза на разных тектонических структурах. **Практическая значимость.** Определена стадийность миграции углеводородных флюидов, история формирования резервуаров литогенетической природы, что позволило оценить некоторые аспекты перспектив нефтегазоносности силурийского и смежных осадочных комплексов.

Ключевые слова: силур, Волыно-Подолия, литологические комплексы, катагенез, литофлюидодинамика, резервуары углеводородов**.**

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