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GEODYNAMIC ASPECTS OF HYDROCARBON DEPOSIT FORMATION IN CARBONATE COMPLEX OF LOWER CARBON OF THE DNIEPER-DONETS BASIN AND PECULIARITY OF THEIR FORECASTING AND INDUSTRIAL DEVELOPMENT

The purpose of the research is to analyze the impact of the region's geodynamics on the formation of hydrocarbon reservoirs in the carbonate Lower Visean-Tournaisian stratum. The paper is focused on the substantiation of hydrocarbon traps within the Machukhy-Tyshchenky area of the southern zone of the Dnieper-Donets basin, as well as oil and gas exploratory drilling and new effective methods of stimulating gas inflows to boreholes. Methodology. The study applies the stratigraphic, lithological, tectonic, paleotectonic methods of studying geology and oil potential, as well as the method of geological analogies. Results. Gas-bearing carbonate rocks of the Early Visean-Tournaisian age in the Machuhy-Tyshchenky area have been studied. A comparison with other oil and gas regions has shown that they are the domes of carbonate platforms (Waulsortian facies). Three echelons of bioherm limestones have been identified within the the area. The research helped to describe the stages of their formation and determine the dependence of reservoir properties of limestones on their biofacial types. The role of tectonic fracture in the formation of reservoir rocks is shown. As a rule, tectonic fractures are cemented by calcite under the action of formation waters. An assumption is made about the formation of microfractures in dense limestones due to the action of plumectonic. It consists in the intrusion of high-energy fluids from the depths of the earth, the natural fluid fracturing of rocks and the formation of non-anticlinal hydrocarbon accumulations in them. Probable places of fluid breakthrough may be zones of deep faults: the Ingulets-Kryvorizhzhya-Krupetsk fault zone crosses Machuhy-Tyshchenky area. Filling microfractures with hydrocarbons prevents their cementation. The paper gives examples of microfracturing in the cores of boreholes and establishes reduced core from microfracture intervals. To identify microfracturing intervals in carbonate rocks, it is proposed to use information on the reduction of core, as well as the speed drilling of rocks. The study suggests using multistage hydrofracturing and acid hydrofracturing in order to stabilize and increase gas influxes from carbonate reservoirs to the boreholes. Such technology should provide the connection between the borehole and oil-saturated reservoirs. Probable factors of negative impact on the environment during hydrofracturing have been identified. Originality. Adiabatic microfracturing of dense lithotypes of rocks is possible at considerable depths, in addition to tectonic fracturing. It is due to natural fluid fracturing of sedimentary strata by hydrocarbon gases. This gives hope for the discovery of new types of hydrocarbon deposits that are not associated with anticline traps. Practical significance. Geophysical surveys and the location of six boreholes are recommended in order to search for hydrocarbon deposits in the Machuhy-Tyshchenky area. The study suggests effective methods for increasing gas influxes to boreholes from low-permeability carbonate rocks.

Key words: geodynamics; plume tectonics; microfracturing; carbonate reservoir; sedimentation; unconventional hydrocarbon deposits.

Introduction

The fund of promising anticline objects in the Dnieper-Donets basin is practically exhausted. Therefore, recently much attention has been given to the justification of non-anticline traps of oil and gas [Lazaruk, 2006; Benko et al., 2013; Vysochansky, 2015]. In this aspect, the prospects for the discovery of new hydrocarbon deposits in the Dnieper-Donets basin are associated with insufficiently studied carbonate rocks of the Early Visean and Tournaisian ages [Lukin and Korzhnev, 1999; Lukin et al., 2007]. Areas with proven commercial oil and gas-bearing are of the greatest interest. They are confined mainly to the Rudenky-Proletarka oil and gas zone which is located in the southern part of the region. The layers of fractured-cavernous-porous limestones are reservoirs for hydrocarbon deposits. Undoubtedly, the problem of hydrocarbon exploration in carbonate reservoirs is a paleogeographic one. It consists in the reconstruction of sedimentation conditions and mapping of carbonate organogenic formations. Another important factor in the formation of emptiness in carbonates is their fracture due to tectonic movements of the earth's crust. Tectonic fractures contribute to the leaching of rocks and increase their porosity. However, in addition to tectonic fractures at great depths, fractures of other genesis are formed. They are associated with plumec-tonic – the intrusion of deep fluids into the upper layers of the lithosphere and the natural fracturing of layers [Mayevsky et al., 2014]. From the above positions, we consider the prospects of oil and gas carbonate stratum of the Early Visean and Tournaisian ages of the southern near-edge zone of the Dnieper-Donets basin.

Purpose

The purpose of the researches is to analyze the impact of the region's geodynamics on the formation of hydrocarbon reservoirs in the carbonate Lower Visean-Tournaisian stratum. The study also aims at substantiation of hydrocarbon traps within the Machuhy-Tyshchenky area of the southern near-edge zone of the Dnieper-Donets basin, as well as of oil and gas exploratory drilling and new effective methods of stimulating gas inflows to wells.

Methodology

The methodology of the investigation consisted in the integrated analysis of data on the geological structure and gas content of the Machukhy-Tyshchenky area. It also included research of the sedimentary environments of Lower Visean-Tournaisian carbonate deposits, as well as study of factors in the formation of reservoir empty space and filling them with hydrocarbons. We used the following methods of studying geology and gas content: stratigraphic, lithological, tectonic, paleotectonic. We conducted a comparative analysis of the structure and gas content of the Machukhy-Tyshchenky area with similar regions. Data on executed works and the newest methods for hydrocarbon influx stimulation are given in this paper.

Results

General characteristics of perspective area

Hydrocarbon deposits associated with carbonate formations are known in the Dnieper-Donets basin. They are confined mainly to the Rudenky-Proletarka oil and gas-bearing area, located in the southern near-edge zone of the region. The Machukhy, Rudenky, Gnativka, Novomykolaivka, Ryasky, Bagate deposits have been discovered here [Arsiriy et al., 1999]. They extend along the southern marginal break in the southeastern part of the Dnieper-Donets basin. Gas-condensate deposits are connected with limestones of the productive horizons V-24–V-25 of the Lower Visean substage and T-1–T-4 of the Tournaisian stage. They are mostly massive-formational, sometimes formational.

In the extreme south-eastern part of the Rudenky-Proletarka oil and gas-bearing area, perspectives may be connected with the large Bagate-Orilka-Zatyshne mega atoll, which O. Yu. Lukin and co-authors consider as the only area of oil and gas accumulation [Lukin et al., 2005]. They have identified 17 local formations, which are associated with significant perspectives for the discovery of new oil and gas deposits. The Bagate gas-condensate field is an example of the commercial productivity of carbonate deposits within the Bagate-Orilka-Zatyshne mega atoll.

Further east from the mega atoll to the border with Donbass, similar favorable conditions for carbonate sedimentogenesis are predicted. According to the results of the seismolithostratigraphic method on some regional seismic profiles (Metchebylove-Brygadyrivka, Blyznuky-Pivnitchna Golubivka) anomalous areas have been identified. According to their morphogenetic features they are attributed to organogenic structures [Vysochansky, 2015].

Thus, prospective areas for the search for hydrocarbon deposits in the carbonate strata of the Early Carboniferous age extend from the border of the Dnieper-Donets basin with the folded Donbass in the south east to the Machukhy gas-condensate field in the north west. In our opinion, the prospective carbonate objects continue further north-west of the Machukhy field within the Machukhy-Tyshchenky monocline and further to the Radchenky and Mali Sorochyntsi fields. There are all geological prerequisites for this. Small influxes of gas during drilling from Lower Visean-Tournaisian organogenic carbonate deposits were recorded in boreholes 2 Shkurupii, 1 Slavky, 1 Tyshchenky, 58 Radchenky, 410 Mali Sorochyntsi.

Peculiarities of sedimentation of Lower Visean-Tournaisian organogenic carbonates

Productive carbonate structures of the lower Carboniferous of the Dnieper-Donets basin belong to specific formations known in geological history as the domes of carbonate platforms [Wilson, 1975]. The rocks that make them up are called Walsort facies after a village in the Dinant basin in Belgium. They are massive pelitomorphic limestones that contain scattered fragments of crinoids, bryozoans and form a peculiar lens and domes. These are ubiquitous facies of the Visean-Tournaisian sedimentation, which are widespread in the northern hemisphere. Domes and massive limestone coverings of the same age were studied in detail in Western Europe: in Pembroke, Derbyshire, and the Pennines in England and Ireland; they are also found in central France. In North America, in the same age, similar structures were studied in Montana [Cotter, 1965], Oklahoma [Harbaugh, 1957; McKenna, 1979; Pray, 1958], Arkansas [Troell, 1962]; they are also known in Texas, Alberta, the Sacramento Mountains in New Mexico.

Walsortian domes and lenses are mostly shallow facies. They are composed of pelitomorphic and poorly sorted organogenic-fragmentary limestones. Walsortian facies were deposited mainly in a relatively calm tectonic regime, without active inflow of clay material, in warm shallow seas, below the base of the waves. In some cases, those geological bodies formed the foundation on which ecological reefs later emerged. They are most common in lagoons and shallow basins. Dome-like formations were formed due to the aggregation (accretion) of carbonate sediment somewhere in the seabed. Subsequently, they grew to the basis of the action of waves at a stable sea level or its slow rise. The content of limestone in the domes is higher than in the surrounding rocks. The shape of the domes varies from elongated flat lenses to low conical formations. Their usual sizes are from one to several kilometers in diameter. Carbonate domes have different dislocations, but generally are located approximately linearly, surrounding depressions and bays. Elongated domes acquire their shape, apparently under the influence of coastal currents. Chains of such domes are parallel to the shoreline and form multi-row groups (echelons). Their axes are mostly oriented parallel to the ancient coastlines.

In [Lazaruk and Kreidenkov, 2000] we present a detailed scheme of formation of Walsortian facies of the Dnieper-Donets basin on the example of Lower Visean carbonate deposits of Ozeryany-Khortytsia-Bilousivka mega atoll located in the northwestern part of the region. Initially, carbonate micrite precipitates fell from seawater in small uplifts or in places where the depth of the shelf changed. Among them were small brachiopods, pelecypods, algae, and foraminifera. Later, carcass-forming organisms settled on the tops and slopes of micrite domes: reticulate bryozoans, colonies of horvanel, blue-green algae, crinoids [Machulina, 1996], which fastened and held carbonate silt. The growth of the domes continued until the basis of the action of waves and thus organogenic-detrital limestones were formed. Limestones with the greatest thickness are located not in the apical parts of the domes, but on their slopes on the open sea. As a result of the further growth of the domes above sea level, the rocks were destroyed by waves and plumes of bioclastic limestones were formed around the domes.

Influence of geodynamic factors on the formation of empty space in carbonate rocks

Limestones of different biofacial types have different reservoir properties. Carbonate rocks have primary (sedimentation) porosity. In addition, a significant role belongs to the capacity formed as a result of epigenetic processes. The micrite core with the lowest sedimentation porosity is usually almost unchanged by secondary processes, so the porosity of limestone composes several percent. Organogenic-fragment carbonate facies with a larger primary capacity are more recrystallized and dolomitized, as a result their porosity is 4–5 %. The plumes limestones are the most modified in the process of epigenesis; their porosity reaches 5–7 % and even more.

The intensity of epigenetic transformations of carbonate rocks is significantly influenced by their fracturing. Tectonophysical modeling of the stress state of rocks is used to predict fractured oil and gas reservoirs. Its basics are established in the fundamental work of M. V. Gzovsky [Gzovsky, 1975]. This researcher determined the tectonophysical criteria for the formation of tectonic fracture systems according to the analysis of the rock stress state in different structural situations. These criteria are based on the laws of rock destruction mechanics and are associated with volumetric tectonophysical deformations of rock massifs. Their state is characterized by the relationship of the axes of normal and tangential stresses, due to which the systems of fractures of breaking and chipping are formed. Circulation of formation waters through these fractures can lead to diametrically opposite results. In some cases, it is leaching the matrix of limestone rocks with increasing porosity. In others – mineralization of fractures by carbonate, quartz, sulfide and polymineral ores, that is, cementation of fractures and, accordingly, reducing the rock porosity. The course of the leaching-crystallization process depends on many factors: the chemical composition of water, salt concentration, water velocity, thermodynamic conditions, etc.

Tectonophysical reconstructions are quite effecttive for modeling fractures associated with tectonic deformation of rock massifs [Bartashchuk and Suyarko, 2021; Gonchar, 2019]. However, with increasing depths of more than 5 km, a network of fractures appears in the rocks, which differ signifycantly from tectonic fractures in morphology, lack of mineralization, scale and spatial distribution. In addition, at considerable depths, tectonophysical criteria cannot explain the nature of such phenomena as supercollectors with extremely high permeability due to the system of open subhorizontal fractures, and “sweet spots” (dilatancy cushions in black shale strata and central basin deposits) [Lukin, 2009]. Therefore, in recent years, the theory of plumectonics and related specific fracturing of rocks has become widespread [Lukin, 2000; Lukin, 2004; Lukin, 2014; Lebid, 2016]. O. Yu. Lukin calls such fractures as adiabatic [Lukin, 2009]. In his opinion, the geological section is not only an association of rocks, but also a complex fluid-rock system, which, in addition to the background rock pressure, is also characterized by seismotectonic impulses and phenomena of natural fluid fracturing. During an earthquake at the front of the shock wave in the sedimentary rocks there are impulses of electric fields due to imbalance of the electric double layer in the capillaries. This initiates various electrokinetic phenomena, in particular electroosmosis. The result is breakthroughs of deep high-pressure fluids into the rocks of the sedimentary cover. Probable places of fluid breakthrough may be zones of deep faults. The Ingulets-Kryvorizhzhya-Krupetsk fault zone crosses Machuhy-Tyshchenky area [Starostenko et al., 2017]. It was formed in the Riphean and continues to be formed today, reflected in the relief of the region [Palienko, 1992].

O. Yu. Lukin [Lukin, 2009] considers that the interrelated seismotectonic and fluid-dynamic factors caused by plumtectonics play a leading role in the formation of adiabatic fractures. Fracturing is localized in the deep parts of oil and gas-bearing sedimentary basins. The rocks in them are hydrophobized due to the filling of hydrocarbons. This can be, for example, in the transformation of oil shale into black shale or as a result of direct influence to rocks of anhydrous deep fluid, which consists of hydrocarbon gas and its condensation products. A characteristic feature of hydrophobized rocks is a specific microfracturing, which differs significantly from tectonic and lithogenetic fracturing. A characteristic feature of hydrophobized rocks is a specific microcracking, which differs significantly from tectonic and lithogenetic fracture. It is especially pronounced in hydrocarbopelite rocks: domanikoids, bazhenites, black shales, cryptocrystalline limestones. They have microfracturing due to the injection of hydrocarbons into the hydrophobized microporous rock. Abnormally high formation pressures are an indicator of such injection. The filling of rocks with hydrocarbon fluids and the absence of chemically active formation waters promote to the preservation of capacitive-filtration properties of rocks.

Therefore, we can assume that in the study area carbonate rocks of the Early Visean-Tournaisian age are subject to adiabatic fracturing due to the injection of deep hydrocarbons. Evidence of this process is the numerous gas deposits in sufficiently dense rocks, formation pressures of which are much higher than hydrostatic ones For example, pressure measured instrumentally at a depth of 5208 m in the borehole 500 Machukhy was 94.9 MPa. At relatively low porosity, the fracturing of carbonates provides their high permeability. Therefore, the initial flow rates of gas boreholes range from 100 to 200 thousand m^3/day, reaching 400 thousand m^3/day at the Rudenky field and even more than 1 million m^3/day at the Machukhy field.

Areas of high-energy fluids from great depths are characterized by elevated subsoil temperatures. According to research I. M. Kurovets and co-authors [Kurovets et al., 2019] the rocks of sedimentary cover of Machukhy-Tyshchenky area are in the zone of temperature anomaly.

Another indication of adiabatic fractures is the specificity of their manifestation when breaking the cores of boreholes. Cores from fractured intervals break very easily. A light smite of a hammer is able to reveal a network of microfractures of different directions (Fig. 1). Some cores are destroyed by smite into small fragments (Fig. 2). On the other hand, the cores of unfractured clay-carbonate rocks are very dense and strong, they are difficult to break with a hammer. Such cores are destroyed by the most clay layers along the sedimentation planes that are approximately perpendicular to the axes of the cores.

Fig. 1. Adiabatic fractures of limestones from borehole 1 Machukhy, interval 5197–5214 m, the yield of core is 25 %.

Fig. 2. Adiabatic fractures of limestones from borehole 2 Machukhy, interval 5247–5262 m, the yield of core is 17 %.

Note that the yield of the core from the fractured intervals is significantly less than from the intervals without fractures. For example, twelve limestone cores were obtained from the Lower Visean-Tournaisian deposits in borehole 479 Novodykanka from a depth of 4507–4684 m. The lengths of the cores ranged from 21 % to 95 % of the lengths of the drilled intervals. From fractured rocks, where core yield is minimal, mainly rock fragments were obtained, and from dense limestones, where core yield is maximum, the length of rock columns sometimes exceeds a half meter (Fig. 3). From the productive limestones of the Tournaisian stage (horizons T-1, T-2) of the Machukhy deposit, the yield of core is even lower and for different boreholes ranges from 2 % to 41 %.

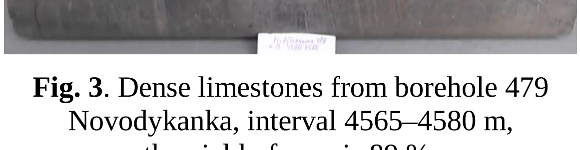

Fig. 3. Dense limestones from borehole 479 Novodykanka, interval 4565–4580 m, the yield of core is 89 %.

Thus, two types of fractures of the Lower Visean-Tournaisian carbonates can be established. The first type is represented by tectonic fracturing. The width of the fractures varies from fractions of a millimeter to several centimeters. They are usually filled with calcite. The second type is characterized by microfracturing with a dense network of adiabatic fractures. Their width is hundreds and even thousands of particles per millimeter. It is diagnosed by the characteristic appearance of the core when hammered. Microfractures are open, at depth they are filled with hydrocarbon fluids and are able to filter them. Mapping microfractured zones is possible by geophysical surveys using the method of vertical electrical sounding.

These are "multi-transient" (from English "transient" – fast-flowing, fleeting) electromagnetic technologies. They make it possible to perform "logging from the earth's surface", providing spatial modeling of rock bodies with different electrical resistance [Anderson et al., 2008]. C. Anderson and co-authors show the great possibilities of using this technology to search for traditional oil and gas fields. However, its efficiency can be high enough to detect deposits of the central basin type, as well as in fractured reservoirs, given their connection with anhydrous hydrophobized zones of the lithosphere. Moreover, the data presented in [Anderson et al., 2008] indicate the possibility of mapping rock bodies of different formation rank with different gas saturation by the method of "multi-transient EM technology". Thus, the data of electrical methods for spatial mapping of rocks with high resistances acquire direct search value.

S. K. Singh with co-authors [Singh et al., 2008] demonstrated the possibility of mapping high-fracture zones of carbonate reservoirs for five Kuwaiti deposits using seismic studies of high-separate ability. The authors call such zones corridors of fractures. They are used in practice for design of borehole locations with high oil influxes.

Despite the long history of studying carbonate reservoir rocks and related oil and gas deposits, there are still problems with identifying fractured intervals of productive sections. Modern methods of geophysical research of boreholes do not allow unambiguous and reliable identifying fractured intervals in the carbonate stratum. Therefore, to identify such intervals, we propose to use information about the amount yield of core. In addition, the speed of drilling fractured limestone is greater than that of dense types of carbonates. Therefore, mechanical logging data, which reflect the drilling speed of rocks, should be used to determine promising oil and gas intervals in a set of methods of geophysical research of boreholes.

Structure of carbonate reservoirs according to paleotectonic reconstructions and their gas content

In 2016, specialists of the Technological Center for Processing and Interpretation of Geophysical Materials of the State Geophysical Enterprise "Ukrgeofizika" (V. V. Naprasnova, Z. Y. Voytsytsky, V. M. Kochkur et al.) performed research on the thematic revision of seismic materials and geophysical research of boreholes of Western Machukhy area. Based on the results of these studies, the following maps were constructed: a structural map of the top of the Lower Visean-Tournaisian carbonate deposits, a map of the thicknesses of these deposits and a map of the thicknesses of the Upper Visean substage which overlaps the carbonate deposits.

The Western Machukhy area stretches northwest from the Machu field in a strip 20 km long and 12 km wide. In general, it is a monoclinal, inclined at an angle of 15–17°. On the top of the Lower Visean deposits it is immersed in the northeastern direction to the axis of the Dnieper-Donets basin from the absolute marks -3300 m to -6000 m (Fig. 4). Monocline is divided into separate tectonic blocks by faults with amplitudes of 25–50 m. Within the monocline there are several structural noses: Chkalivka, Novodykanka, North Novodykanka, East Tsyganske, Brateshky, Shkurupii, Zhytnyky, Rodnikove.

The map of the thicknesses of the Lower Visean-Tournaisian deposits of the Western Machukhy area shows the accumulative carbonate structures (Fig. 5). They are significantly differentiated, their thickness in the study area varies two and a half times: from 350 m on the Brateshky structural nose to 850 m on the Zhytnyky and Rodnikove structural noses. The zone with the largest thicknesses of organogenic carbonates, over 700 m, extends in a strip along the monocline from northwest to southeast in the central part of the area. Within this strip there are local increases in the thicknesses of the Lower Visean-Tournaisian deposits up to 750 m on the North Novodykanka and East Tsyganske structure, more than 850 m – on Zhytnyky, Rodnikove structures and even more than 900 m beyond the northwestern border of the Western Machukhy area. In the northeastern direction, that is in the direction of regional immersion of the strata to the axial part of the Dnieper-Donets basin, the thickness of the Lower Visean-Tournaisian sediments decreases to 500 m. This may indicate a zone of relatively deep-water decompensation with carbonate-clay sedimentation in the Early Visean-Tournaisian time. This area was later compensated by terrigenous sediments of the Upper Visean substage: Fig. 6 shows a significant increase of thicknesses of the substage from 400 m in the central part of the Western Machukhy area to 950 m in the northeastern part of the area.

The structure of carbonate is more complicated than the map of the thicknesses of the Lower Visean-Tournaisian deposits shows. According to the time section 38/46/90 (Fig. 7) it is possible to predict two echelons of organogenic structures: Rodnikove and Zhytnyky. This coincides with the interpretation of the authors of the report on the thematic revision of seismic materials. They identified two echelons of organogenic structures (Fig. 4). In the first of them there is the Rodnikove structure. The carbonates of the Early Visean-Tournaisian ages were discovered here by borehole 3 Rodnikove. It is located northeast of the zone of increased thicknesses of the Lower Visean-Tournaisian carbonates (Fig. 5).The tests of Lower Visean carbonates from the interval 5820–5637 m resulted in receiving non-commercial gas influxe with a flow rate 0.24 thousand m^3/day. From the upper part of the Tournaisian stage in the interval 5927–5920 m only gas manifestations are noted.

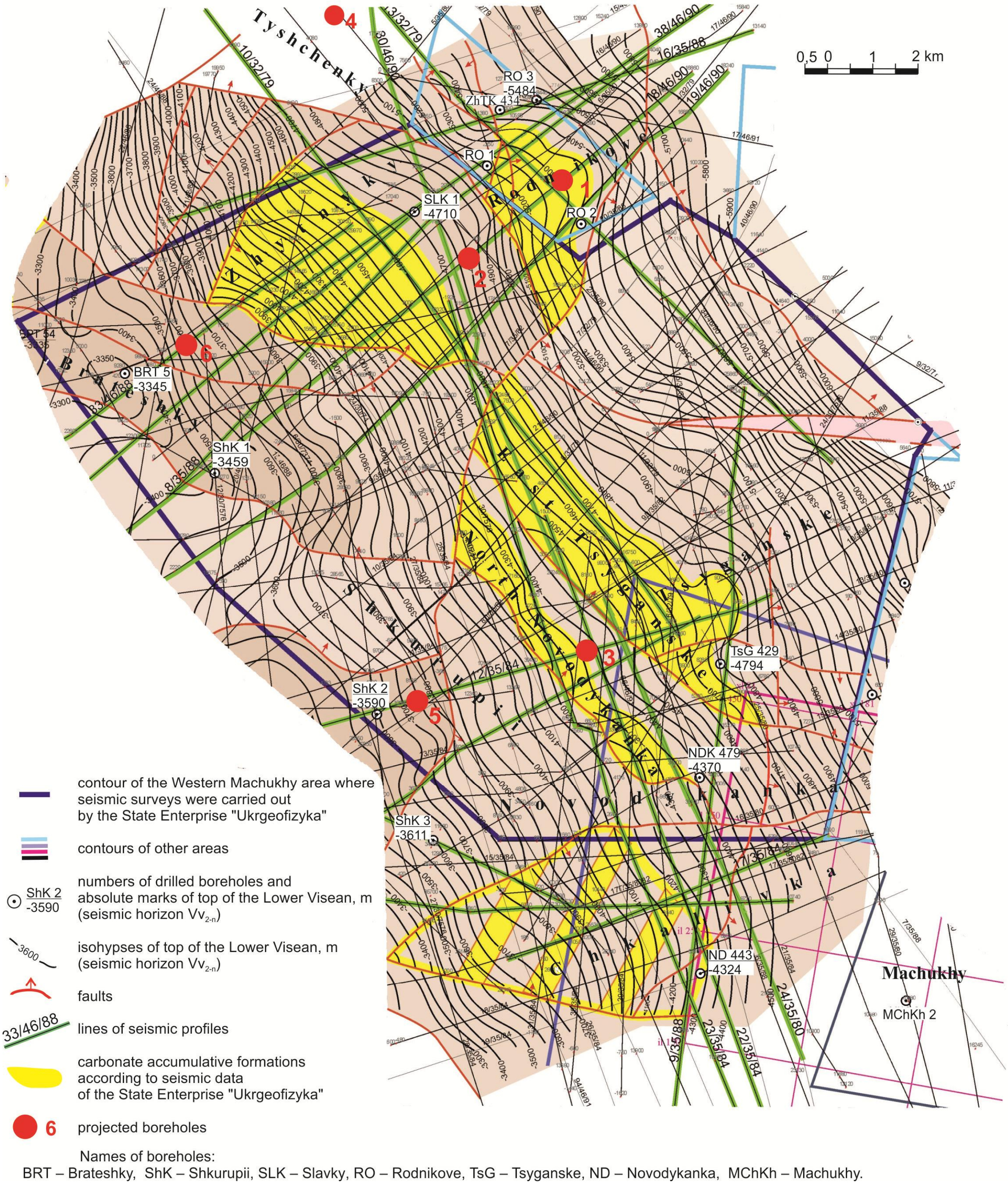

Fig. 4. Structural map of the top of the Lower Visean substage of the Western Machukhy area according to the data of the State Geophysical Enterprise "Ukrgeofizyka" [V. V. Naprasnova, Z. Y. Voytsytsky, V. M. Kochkur et al., 2016].

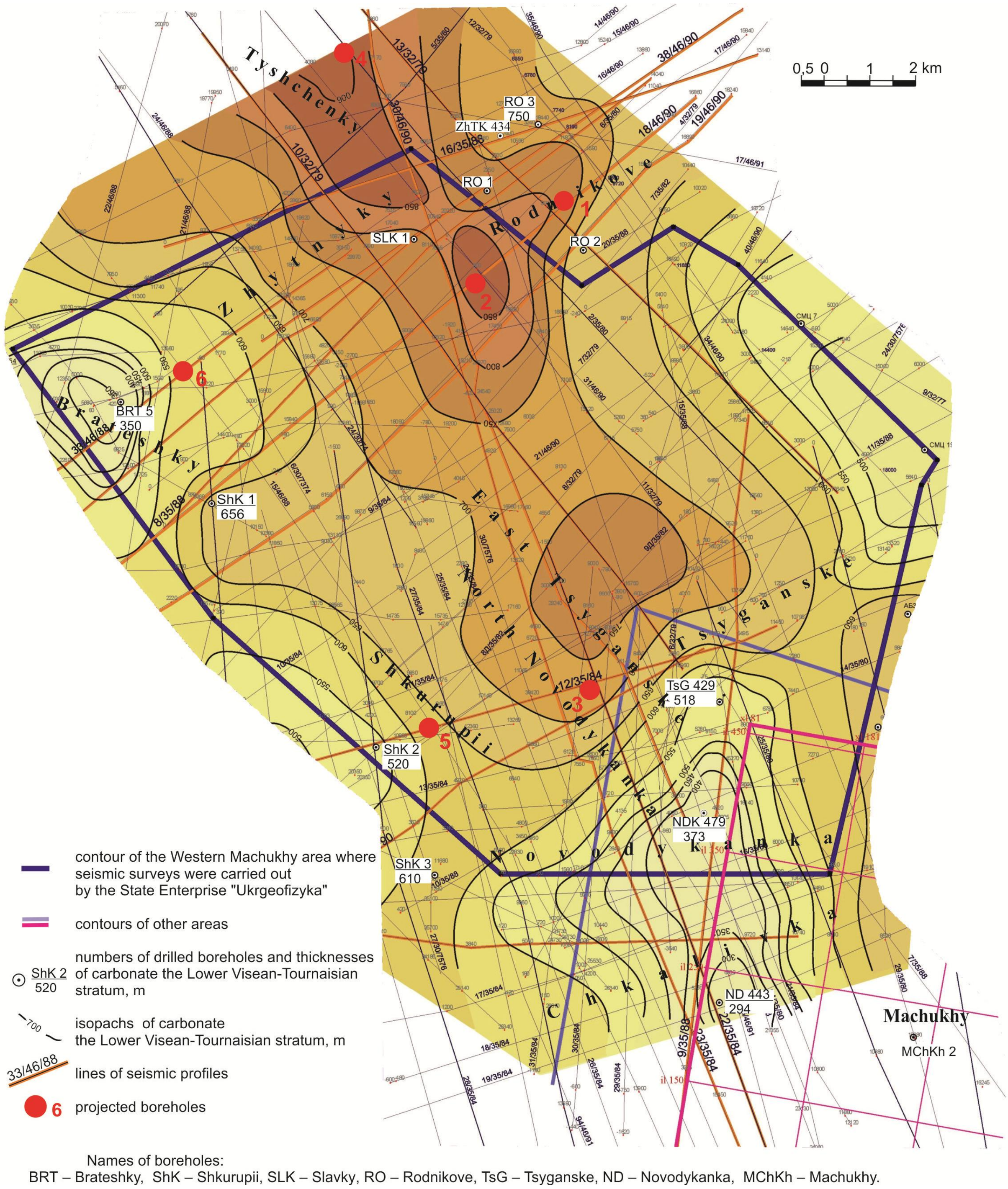

Fig. 5. Map of thicknesses of deposits of the Lower Visean substage and the Tournaisian stage of the Western Machukhy area according to the data of the State Geophysical Enterprise "Ukrgeofizyka" [V. V. Naprasnova, Z. Y. Voytsytsky, V. M. Kochkur et al., 2016].

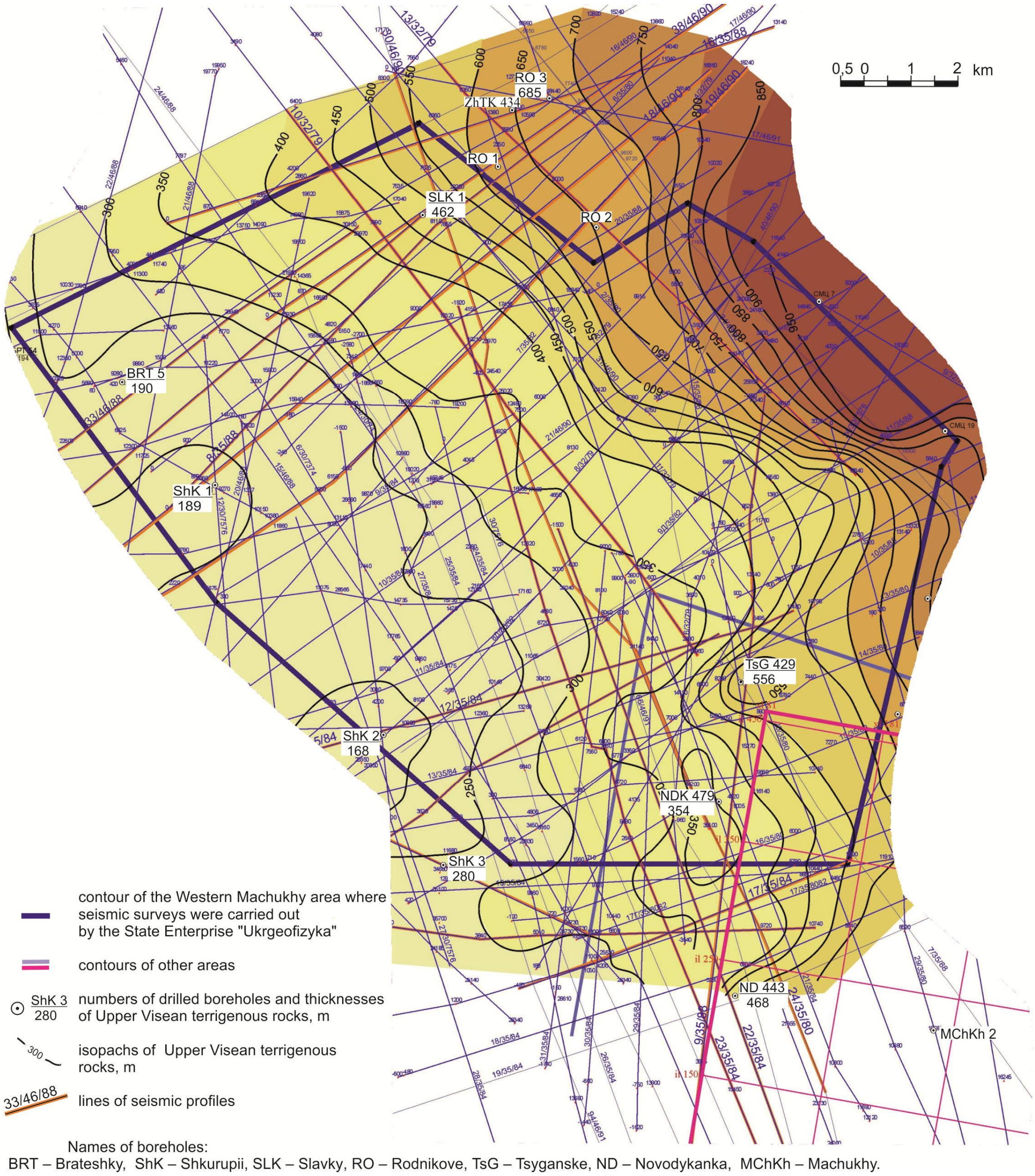

Fig. 6. Map of thicknesses of deposits of the Upper Visean substage of the Western Machukhy area according to the data of the State Geophysical Enterprise "Ukrgeofizyka" [V. V. Naprasnova, Z. Y. Voytsytsky, V. M. Kochkur et al., 2016].

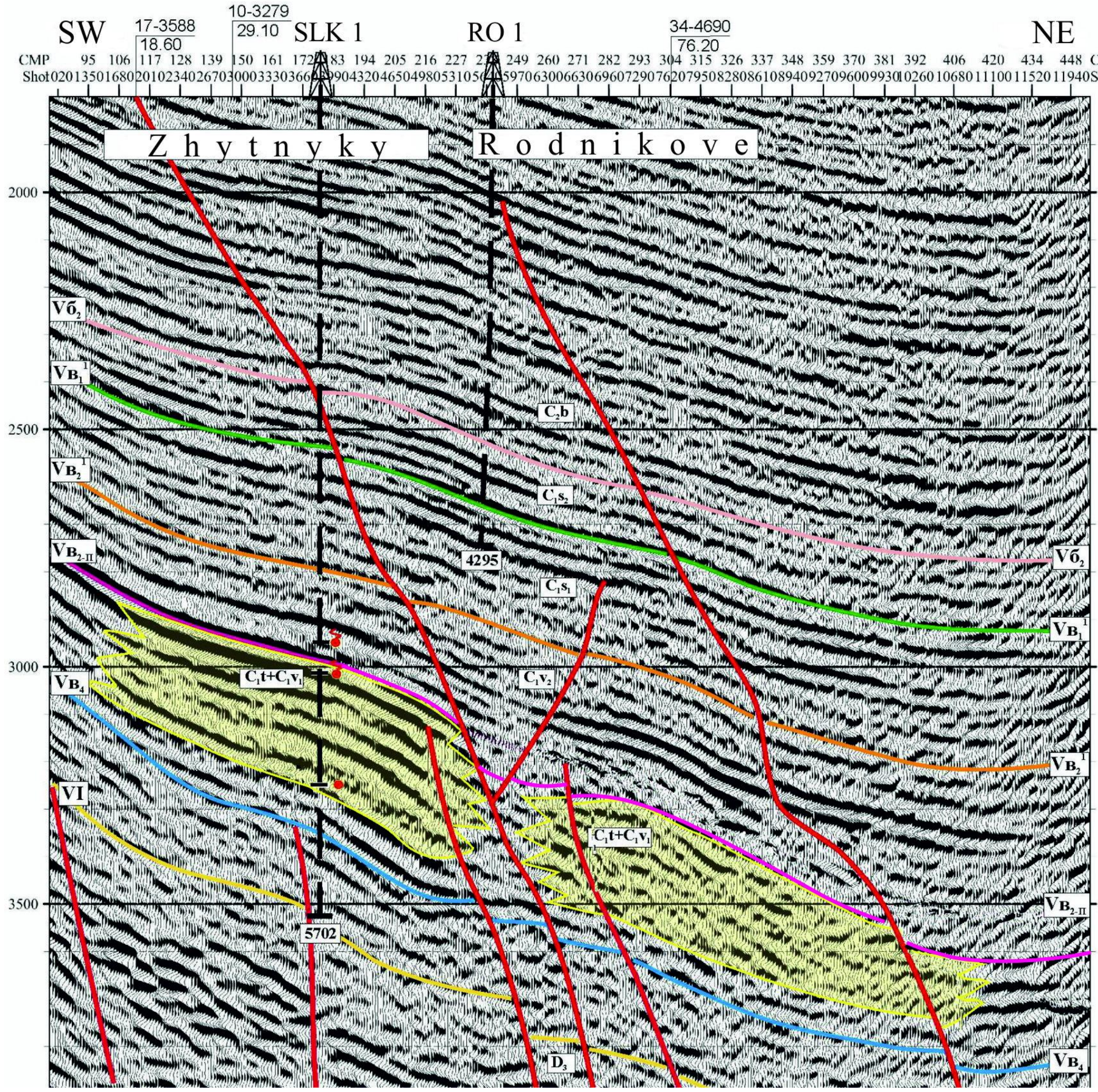

Fig. 7. Fragment of the time section 38/46/90 across Rodnikove and Zhytnyky structures of the State Geophysical Enterprise “Ukrgeofizyka”:

SLK 1 – borehole 1 Slavky, RO 1 – borehole 1 Rodnikove, VI – seismic horizon in the upper part of the Famennian stage, $Vв_4$ – seismic horizon in the base of the Tournaisian stage, $Vв_{2-п}$ – seismic horizon in the top of the Lower Visean substage, $Vв_2^1$ – seismic horizon in the top of the Upper Visean substage, $Vв_1^1$ – seismic horizon in the top of the Lower Serpuchovian substage, $Vб_2$ – seismic horizon in the base of the Bashkirian stage. Probable biogerms are marked in yellow.

The second echelon of carbonate structures was discovered by borehole 1 Slavky (Fig. 7). According to the forecast of the specialists of the State Enterprise "Ukrgeofizyka", this echelon from Slavky structure extends to the south east through the East Tsyganske and South Novodykanka structures to the Machukhy field (Fig. 4). In borehole 1 Slavky from the deposits of the Lower Visean substage in the interval 4875–5040 m received a gas influxe with a flow rate of 4.7 thousand m^3/day. Highly sparkling formation water was obtained from the sediments of the Tournaisian stage in the interval 5568–5639 m.

The Lower Visean-Tournaisian deposits in borehole 429 Tsyganske were not tested, because according to the geophysical study of the borehole, no promising objects have been identified in the section; the section is significantly clay.

In borehole 479 Novodykanka, the deposits of the Lower Visean substage in the production column were tested. No inflow of formation fluids was received from the interval 4525–4500 m. As in borehole 429 Tsyganske the section is significantly clay. The map of the distribution of carbonate thicknesses shows the minimum thicknesses in the area of the two mentioned boreholes (Fig. 5).

On the Machukhy field, located outside the southeastern border of the West Machukhy area, commercial gas influxes with a flow rate from 6.5 to 1667.2 thousand m^3/day (at different diaphragms) were obtained from carbonate deposits of the Tournaisian stage in boreholes 2, 3, 4, 51, 500 Machukhy and in several other production boreholes drilled by Private Joint-Stock Company "Naftogazvydobuvannia".

A third echelon of biogerms may extend along the southwestern border of the Western Machukhy area. It includes organogenic formations of the Lower Visean substage and the Tournaisian stage, located northwest of borehole 443 Novodykanka (Fig. 4). In the section of the borehole limestones contain a significant amount of clay material. According to the geophysical study, no promising objects have been identified in the borehole. However, gas-saturated limestones were established based on the results of the test of borehole 2 Shkurupii. From the intervals 3805–3925 m and 4060–4030 m received a short-term gas-water fountain: gas influx was 140 thousand m^3/day, water influx – 60 m^3/day. Obviously, the great depression on the carbonate led to the closure of the fractures and the influx of gas-water mixture stopped. Note that the third echelon of organogenic structures is not reflected in the thicknesses distribution of the Lower Visean-Tournaisian deposits (Fig. 5).

Location of projected exploratory boreholes

In view of the above, we can recommend the following locations for the placement of exploratory boreholes on the sediments of the Lower Visean-Tournaisian carbonate complex. Within the first echelon on Rodnikove structure, it is advisable to drill a borehole at picket 513 of seismic profile 18/46/90 (Fig. 8) on the northeastern wing of the biogerm, hoping to reveal plumes of bioclastic limestones.

In the strip of the second echelon of the biogerms on Zhytnyky structure, we recommend drilling the second exploratory borehole at picket 436 of seismic profile 18/46/90, where according to seismic data the zone of maximum carbonate thicknesses is forecasted (Fig. 5). For similar reasons, we propose to place the project borehole on the northeastern wing of the probable bioherm. We propose to place the third borehole on the northeastern slope of the North Novodykanka bioherm, which at the time section 12/35/84 will correspond to picket 329 (Fig. 9).

It is advisable to drill the fourth well on the northeastern wing of the most pronounced bioherm of the second echelon. The well will be located outside the northwestern border of the Western Machukhy area (Figs. 4, 5). Nearby is the Tyshchenky structural nose, on which the parametric borehole 455 Tyshchenky was drilled. The thickness of the discovered Lower Viseu carbonate deposits exceeds 200 m. Thus, bioherm structures can stretch in an intermittent strip along the monocline from the Machukhy gas field in the south east to the Tyschenky structure in the north west.

In the third echelon, the Shkurupii structure deserves attention, where in borehole 2 Shkurupii received gas influx from the Lower Visean-Tournaisian carbonate deposits. We recommend placing the fifth exploration borehole on picket 203 of time section 12/35/84 (Fig. 9). It is obvious that the strip of bioherms of the third echelon stretches along the monocline from Chkalivka to Brateshky structures. Therefore, another sixth borehole can be drilled at the picket 1782 of time section 33/46/88 (Fig. 10).

The locations of the proposed boreholes are approximate and should be adjusted based on the results of 3D seismic surveys, which we propose to conduct on the Machukhy-Tyshchenky area. The location of the proposed wells is approximate and should be adjusted based on the results of 3D seismic surveys, which we propose to conduct on the Machusko-Tyshchenkivska section. The latest seismic achievements should be used for geological interpretation of the obtained materials. For example, the application of the shear wave method allows detailing the internal structure of carbonate formations [Davis, 2022], and the methods proposed in [Anderson et al., 2008, Singh et al., 2008] – to map carbonate zones with maximum fracturing.

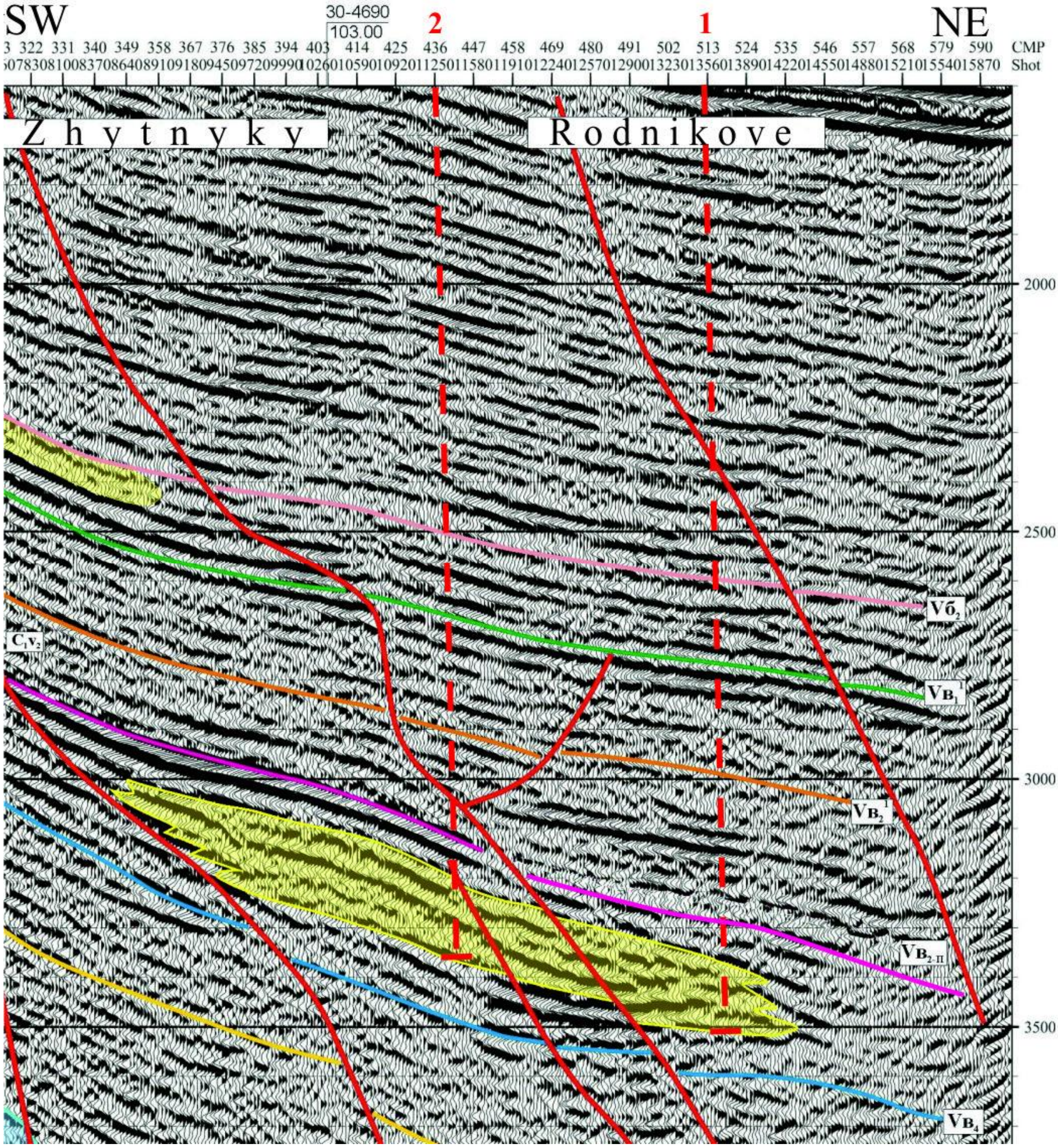

Fig. 8. Fragment of the time section 18/46/90 across Rodnikove and Zhytnyky structures of the State Geophysical Enterprise “Ukrgeofizyka”. Symbols see Fig. 7.

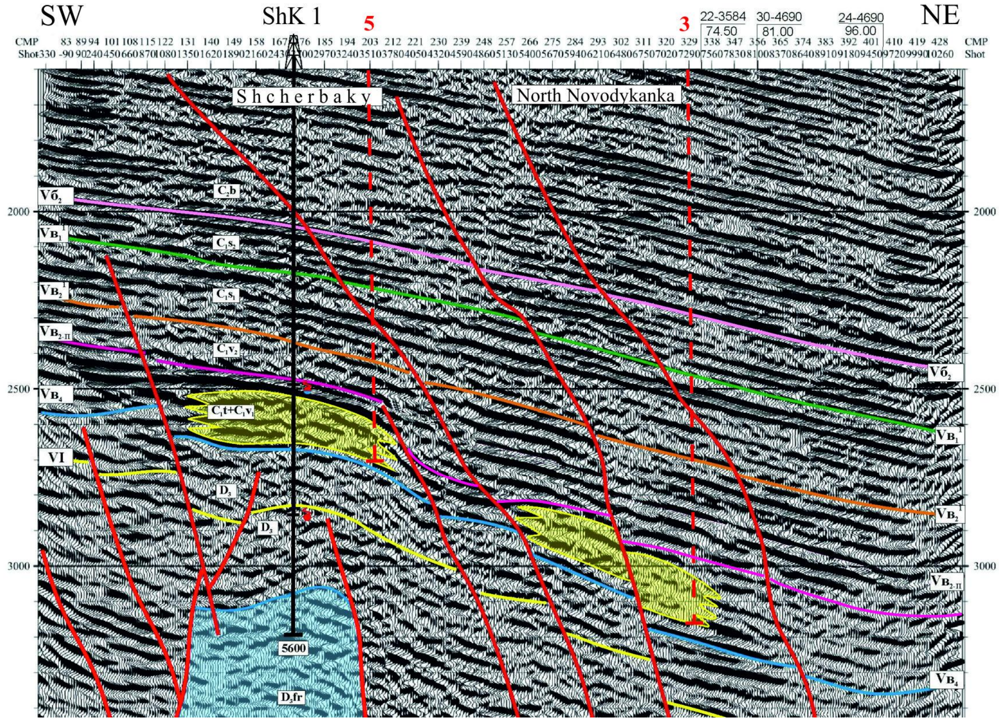

Fig. 9. Fragment of the time section 12/35/84 across North Novodykanka and Shcherbaky structures of the State Geophysical Enterprise “Ukrgeofizyka”. ShK – borehole 1 Shkurupii. Symbols see Fig. 7.

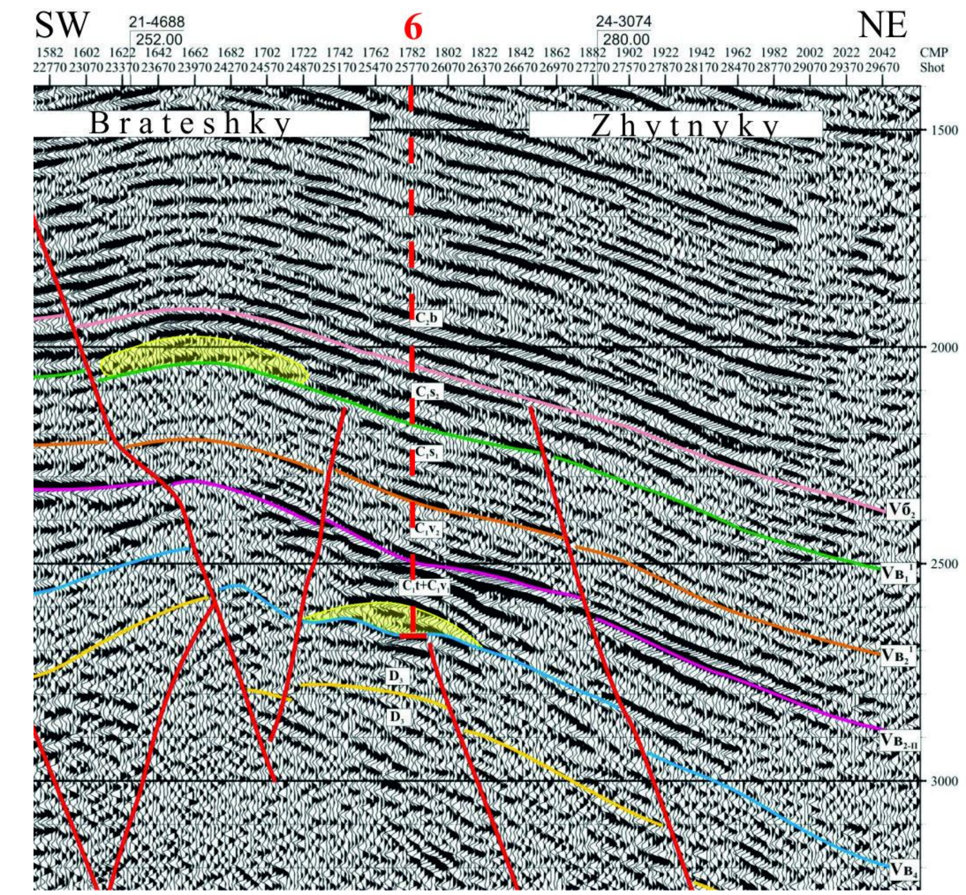

Fig. 10. Fragment of the time section 33/46/88 across Zhytnyky and Brateshky structures of the State Geophysical Enterprise “Ukrgeofizyka”. Symbols see Fig. 7.

Methods of increasing gas influxes from carbonate rocks

Commercial development of oil-gas potential of the Lower Visean-Tournaisian carbonate reservoirs requires the employment of the complex of geological and technological methods. First of all, in the mentioned deposits it is necessary to localize zones of spatial distribution of rocks with the highest content of limestones in which the processes of the secondary porosity formation mostly occur. For this, it is necessary to create sedimentary models of carbonate deposits, using paleontological studies, paleotectonic constructions as well as data of seismic survey and geophysical investigation of the boreholes. It is also important to determine carbonate fracturing zones on the basis of core study, tectonic modeling and parametric analysis of the seismic survey materials. Such a complex of geological-geophysical investigation should enable us to predict spatial distribution of carbonate reservoir rocks and to distinguish the targets for exploration drilling.

In technological terms, it is possible to use hydraulic fracturing to improve the hydrodynamic connection between the void space of the reservoir and the boreholes.

Oil industry experts of Belarus have reached considerable progress in the development of the carbonate reservoirs. Over the last years they succeeded in stabilization and even slight increase of hydrocarbon extraction using various methods of hydrofracturing low-permeable Devonian reservoirs at great depths – up to 6000 m [Voitekhin, 2021]. Carbonate reservoir rocks of Devonian of the Prypiat deep are similar to the Lower Visean-Tournaisian reservoirs of the Dnieper-Donets depression. The fulfillment of effective hydrofracturing needs the preliminary studies of geomechanical properties of rocks, in particular tension strain, through which the dominant fractures are formed. It will be rather difficult to obtain a considerable positive effect from a horizontal borehole using hydrofracturing. So, the completion of the well by horizontal track is necessary. Deviation from the vertical hole at the Belarusian fields is from 300 to 400 m, in some cases – up to 1200 m. In the carbonate beds the acid hydrofracturing with proppant is conducted. Moreover, the better results were obtained, using many-stage (clustered) hydrofracturing. For reservoirs with developed natural fracturing, the method of cyclic acid hydrofracturing has shown itself to be the best. It is based on the technology of PLUG & PERF that envisages fracture opening, acid leaching and fixing with proppant the net of fractures.

Cyclic acid hydrofracturing is successfully applied for the carbonate reservoirs of Belarus fields. Its share in the total number of hydrofracturrings comes to 80 percent. As an example, O. L. Voitekhin adduces the results of work at the 41602-borehole of Rechytsa field. The hydrofracturing of 40 intervals of carbonate reservoirs with porosity about 5 percent was conducted in the 1,200 m horizontal hole. As a fracturing fluid we used a specially created system with low viscosity (up to 1.2 g/cm^3), low friction factor, high dynamic load-carrying ability of proppant that ensured high pump consumption: 15 m^3 / minute. As a result, the oil yield is estimated to be 112 t/day from the 41602 – borehole of the Rechytsa field.

It would be feasible to use directed multistage hydrofracturings in fractured carbonate reservoirs of the Machukhy-Tyshchenky area of considerable thickness. Acid hydrofracturings might ensure connection with oil-saturated reservoirs and stable hydrocarbon filtration to the borehole. It is obvious that hydrofracturing should be conducted on the oil based drilling mud and with use of reagents that could ensure the existence of exposed fractures after their release from sand-bearers. It should be also reasonable to use chelate compounds that extend the acid effect on the reservoir layers.

During conducting hydrofracturing, the necessity of a great amount of water will arise. Chemical reagents, functioning of the large-gabarit equipment will create a considerable loading upon the environment [Lazaruk and Karabyn, 2020]. Aimed at multi-staged hydrofracturing of the beds in the 41602– borehole i Rechytsa field of the Prypiat deep, 15768 m^3 of water with addition of polyacrylamide polymers and other reagents were used during 17 days. That is why it is necessary to foresee utilization of technical waters and chemical reagents, nature protection and recreation measures in the process of hydrofracturing conduction and hydrocarbon production.

Originality

The study shows the possibility of fractured reservoir formation at great depths in the Lower Visean-Tournaisian carbonate complex of the southern near-edge zone of the Dnieper-Donets basin. This opens up new perspectives for the search of gas deposits at great depths.

Practical significance

Geophysical surveys and the location of six boreholes are recommended in order to search for hydrocarbon deposits in the Machukhy-Tyshchenky area.

Conclusions

1. In addition to tectonic fracturing, adiabatic microfracturing of dense lithotypes of rocks is possible at considerable depths. It is due to natural fluid fracturing of sedimentary strata by hydrocarbon gases. Gases come from the earth's interior due to the manifestations of plumectonic. Tectonic processes lead to degassing of the Earth and redistribution of matter and energy in the lithosphere. This gives hope for the discovery of new types of hydrocarbon deposits that are not associated with anticline traps.

2. To identify microfracturing intervals in carbonate rocks, it is proposed to use information on the reduction of core, as well as the speed drilling of rocks.

3. Three echelons of bioherm in the carbonate Lower Visean-Tournaisian stratum have been identified within the Machukhy-Tyshchenky area. The stages of their formation are shown. Bioherms are promising objects for the search of hydrocarbon accumulations.

4. Geophysical surveys and the location of six boreholes are recommended in order to search for hydrocarbon deposits within the Machukhy-Tyshchenky area.

5. Effective methods for increasing gas influxes to boreholes from low-permeability carbonate rocks are recommended in the paper.

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ГЕОДИНАМІЧНІ АСПЕКТИ ФОРМУВАННЯ РОДОВИЩ ВУГЛЕВОДНІВ У КАРБОНАТНИХ ВІДКЛАДАХ НИЖНЬОГО КАРБОНУ ДНІПРОВСЬКО-ДОНЕЦЬКОЇ ЗАПАДИНИ ТА ОСОБЛИВОСТІ ЇХ ПРОГНОЗУВАННЯ І ПРОМИСЛОВОГО ОСВОЄННЯ

Мета досліджень – аналіз впливу геодинаміки регіону на формування колекторів вуглеводнів у карбонатній нижньовізейсько-турнейській товщі, обґрунтування пасток вуглеводнів у межах Мачусько-Тищенківської ділянки південної прибортової зони Дніпровсько-Донецької западини, завдання пошукового буріння на нафту і газ і нових ефективних методів стимуляції припливів газу до свердловин. **Методика.** В роботі використано стратиграфічний, літологічний, тектонічний, палеотектонічний методи вивчення геології та нафтоносності, а також метод геологічних аналогій. **Результати.** Досліджено газоносні карбонатні породи ранньовізейсько-турнейського віку на Мачусько-Тищенківській ділянці. За результатами порівняння з іншими нафтогазоносними регіонами доведено, що вони є куполами карбонатних платформ (уолсортськими фаціями). В межах ділянки виділено три ешелони біогермних вапняків, показано етапи їхнього формування. Визначено залежність колекторських властивостей вапняків від їхніх біофаціальних типів. Показано роль тектонічної тріщинуватості у формуванні порід-колекторів. Зазвичай тектонічні тріщини зацементовані кальцитом внаслідок дії пластових вод. Висловлено припущення про формування мікротріщинуватості у щільних вапняках внаслідок плюмтектоніки. Воно полягає у вторгненні високоенергетичних флюїдів з глибин землі, природному флюїдорозриві порід і формуванні в них неантиклінальних вуглеводневих скупчень. Ймовірними місцями прориву флюїдів можуть бути зони глибинних розломів: Мачусько-Тищенківську ділянку перетинає Інгулецько-Криворізько-Крупецька шовна зона. Заповнення мікротріщин вуглеводнями запобігає їх цементуванню. Наведено приклади мікротріщинуватості в керні свердловин. Встановлено зменшений винос керна з мікротріщинуватих пластів. Для виділення у карбонатних товщах інтервалів з мікротріщинуватістю пропонується застосовувати інформацію про зменшення винесення керна, а також швидкості буріння порід. З метою стабілізації та збільшення припливів газу з карбонатних колекторів до свердловин запропоновано застосування скерованих багатоступеневих гідророзривів, а також кислотних гідророзривів, які забезпечать зв'язок свердловин з газонасиченими колекторами. Визначено ймовірні чинники негативного впливу на довкілля під час проведення гідророзривів. **Наукова новизна.** На значних глибинах крім тектонічної тріщинуватості можлива адіабатична мікротріщинуватість щільних літотипів порід, зумовлена природним флюїдоророзривом осадової товщі вуглеводневими газами. Це дає можливість відкриття вуглеводневих скупчень нового типу, які не пов'язані з антиклінальними пастками. **Практична значущість.** Рекомендовано геофізичні дослідження та розміщення шести свердловин з метою пошуків покладів вуглеводнів на Мачусько-Тищенківській ділянці. Рекомендовано застосовувати ефективні методи збільшення припливу газу до свердловин з низькопроникних карбонатних порід.

Ключові слова: геодинаміка; плюмтектоніка; мікротріщинуватість; карбонатний колектор; седиментація; нетрадиційні поклади вуглеводнів.

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