Stratigraphic distribution of hydrocarbon accumulations and charging history of reservoirs based on thermal evolution of petroleum source rocks within the southern border area of the Dnieper-Donets Basin

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Stratygraficzna charakterystyka akumulacji weglowodorowych oraz historia napełniania pułapek złożowych na podstawie ewolucji termicznej skał macierzystych w obrębie południowej granicy basenu dnieprowsko-donieckiego. Prz. Geol., 65: 516–525.

A b s t r a k t. Kompleksowe badania systemu naftowego dostarczają prognoz i danych wejściowych do oceny ryzyka w celu ewaluacji nierozpoznanych wierceniami złóż w basenie dnieprowsko-donieckim (BDD), związanych ze strukturami solnymi lub występujących na znacznych głębokościach (5–7 km). Badania systemu naftowego dla zrozumienia mechanizmu i historii napełniania pułapek oraz geochronologii zdarzeń (czynnik czasu) wymagało zintegrowanych badań elementów systemu naftowego: występowania złóż ropy i gazu oraz ich wstępnych zasobów, rozprzestrzenienia skał macierzystych, ich właściwości oraz dojrzałości termicznej. Jednowymiarowe modelowanie historii pogrzebania dla otworów wiertniczych z BDD, skorelowane z danymi na temat refleksyjności witrynitu, dało informacje na temat rozkładu strumienia cieplnego w czasie jego ewolucji. Dwuwymiarowe modele systemu naftowego pozwoliły poznać wiek procesów generowania węglowodorów, typy migracji i historię napełniania znanych pułapek, jak również dostarczyły prognoz na temat złóż nierozpoznanych wierceniami. Generacja węglowodorów z każdego źródła następowała w krótkich okresach czasu z powodu szybkiego tempa pogrążania. Możliwość zachowania się złóż była zależna od wzrostu wysadów oraz migracji struktur solnych. Głębokie i bardzo głębokie pułapki w przyosiowej części basenu, które nie zostały naruszone wskutek wzrastających wysadów solnych w permie, są wypełnione złożami gazu po dzień dzisiejszy. Natomiast pułapki związane z wysadami solnymi w obrębie przyosiowych stref basenu były wypełniane węglowodorami tylko w osadach nie starszych niż śrokowokarbońskie, ponieważ starsze skały macierzyste wyczerpały już swój potencjał węglowodorowy do tego czasu.

Słowa kluczowe: basen dnieprowsko-doniecki, ryft, rów tektoniczny, skały macierzyste, system naftowy, geneza i dojrzałość termiczna, generacja i akumulacja węglowodorów, macerały

A b s t r a c t. In order to evaluate undrilled prospects in the Dnieper-Donets Basin (DDB) associated with salt domes or significant depth (over 5–7 km), a comprehensive study of petroleum system used to provide accurate forecasts and inputs for risk assessment. This paper is devoted to petroleum system studyof DDB aimed to understand charging mechanisms, charging history and geochronology of events (timing factor). Such analysis requires an interrelated study of all petroleum system elements: distribution of oil and gas accumulations and its initial reserves, distribution of source rocks, their properties and thermal maturity. 1D burial history modelling of well sections correlated with vitrinite reflectance values gave a heat flow trend during the basin evolution. 2D basin-scale petroleum system models provided understanding of hydrocarbons generation timing, types of migration, charging history of known accumulations, and forecasts on undrilled prospects. Hydrocarbons generation from each source occurred in short terms because of rapid burial rate. Preservation of accumulations was dependent on the rise of salt domes and migration of salt structures. Deep and ultra-deep traps within the paraxial part of the basin, which were not affected by rising salt domes in the Permian, preserve gas accumulations until nowadays. Meanwhile, domes-associated traps in paraxial basin areas were charged with hydrocarbons just in sediments not older than Mid-Carboniferous, as older sources already depleted their potential before that moment.

Keywords: *Dnieper-Donets Basin, rift, graben, source rocks, petroleum system, thermal maturity, burial history, hydrocarbons generation and accumulation, macerals*

Dnieper-Donets Basin (DDB) is 65–120 km wide and 400 km long in the northwest-southeast direction. It is a rift graben with a proved petroleum system that covers 99,000 km^2 in Eastern Ukraine (Fig. 1). The basin is bounded by the Voronezh High of the East European Craton to the northeast and by the Ukrainian Shield to the southwest. The rift extends southeastward, from the border with the Pripyat Basin, to its north-western border with the Donbas Foldbelt (Stovba, 2008; Gladun, 2012; Pryvalov et al., 2012). The crystalline basement deepens southeastward, from 5–10 km in the northwestern part of the basin, to 15–17 km in the southeastern part, and up to 20 km in the Donbas Foldbelt (Fig. 2). The boundary faults of the rift are inclined at 40–50°, locally up to 75–80°, the maximum amplitude of the boundary faults is up to a thousand metres.

Proper evaluation of undrilled prospects requires risks assessment especially for deep and ultra-deep objects, thus petroleum system modelling can provide a highly-informative support for such issue. Besides, 1D/2D models and simulations results are a basis for further development of a large-scale 3D model of the southern border zone of the Dnieper-Donets Basin.

METHODS

Stratigraphic distribution of oil and gas accumulations, initial recoverable reserves of discovered accumulations, and oil-to-gas ratios for each productive horizon were analyzed using comprehensive data from Atlas of Oil and Gas Fields of Ukraine (Ivanyuta et al., 1998). Burial history and

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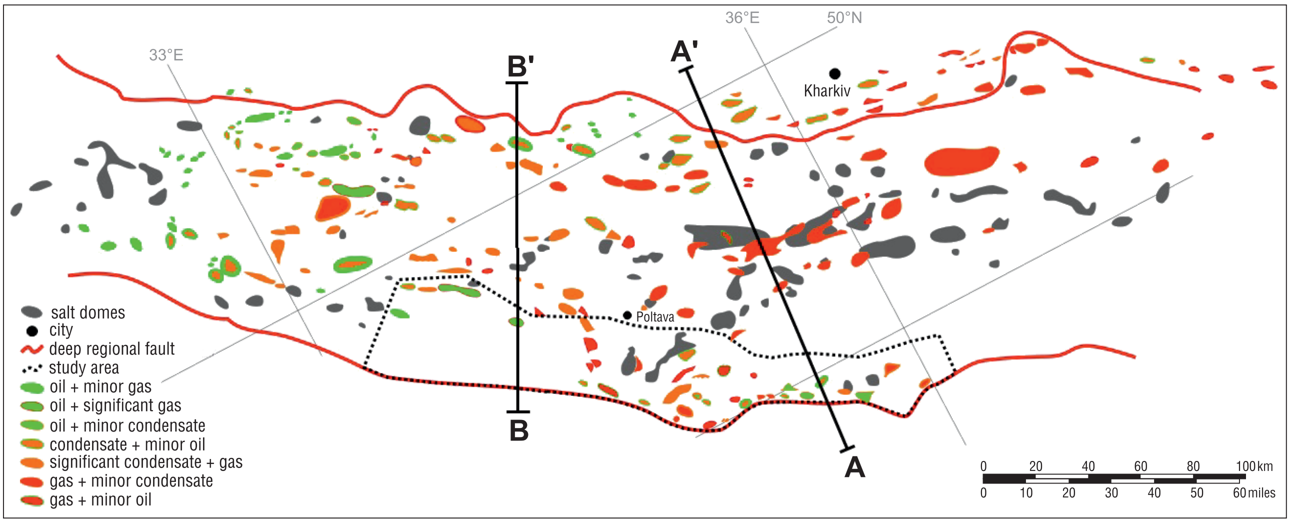

Fig. 1. Discovered oil and gas fields, salt domes, and study area in the Dnieper-Donets Basin (author's map, modified from Gladun, 2012). AA' – Guty–Gupalivka cross-section, BB' – Sagaidak–Lebedyn cross-section

Ryc. 1. Odkryte złoża ropy naftowej i gazu, wysady solne oraz zbadany obszar basenu dnieprowsko-donieckiego (własne opracowanie, wg Gladuna, 2012, zmienione). AA' – przekrój Guty–Gupalivka, BB' – przekrój Sagaidak–Lebedyn

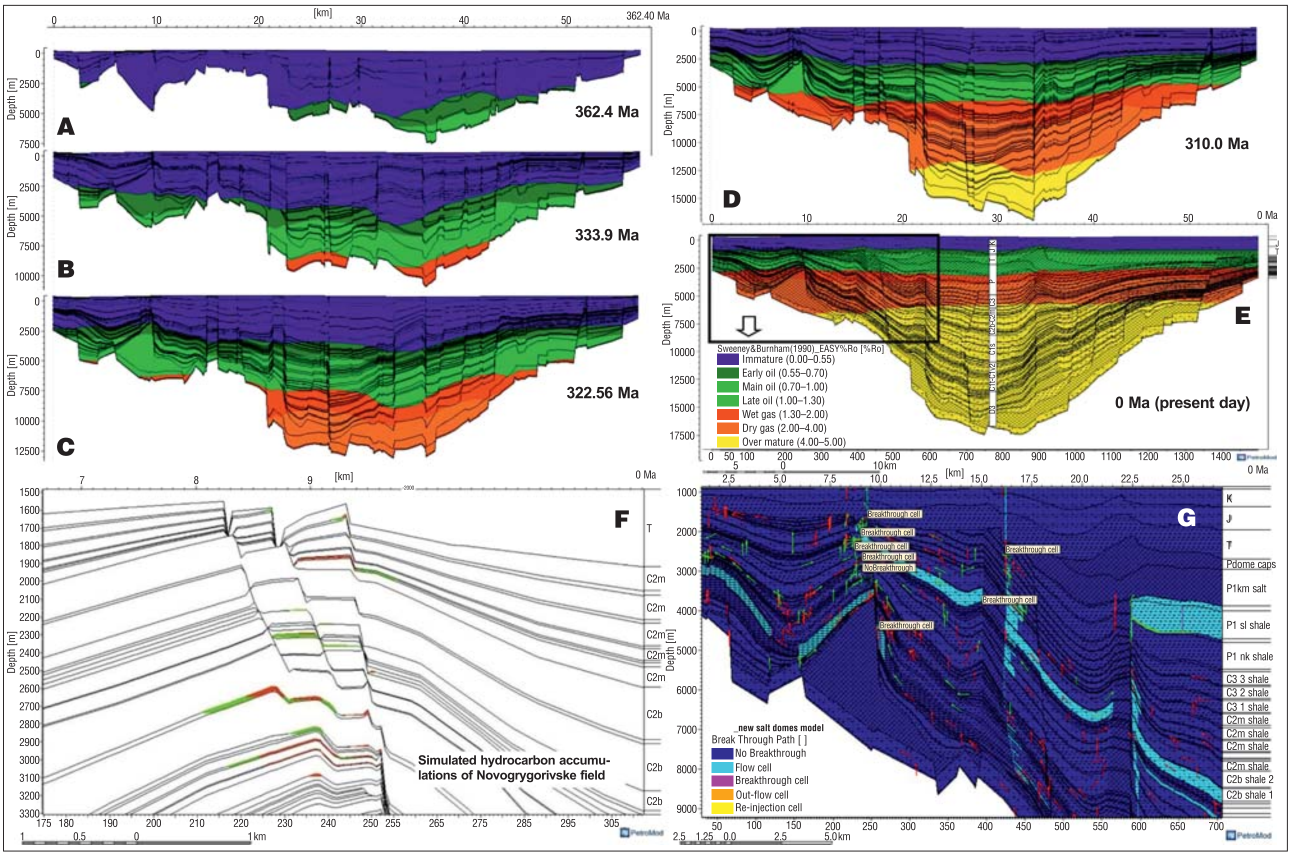

Fig. 2. Simulation visualization of 2D petroleum system modelling along the regional Sagaidak–Lebedyn cross-section. Upper cross-sections **A**–**E** – show certain moments of development of the Dnieper-Donets basin with thermal maturity windows indicated; **F** – simulated accumulations of the Novogrygoryvske field; **G** – visualization of migration vectors, major migration pathways and breakthrough areas

Ryc. 2. Wizualizacja symulacji 2D modelowania nafto-gazowego systemu wzdłuż regionalnego profilu Sagaidak–Lebedyn. Górne przekroje poprzeczne **A**–**E** przedstawiają pewien moment rozwoju basenu dnieprowsko-donieckiego ze wskazanymi oknami dojrzałości termicznej; **F** – symulowane akumulacje pola Novogrygoryvskiego; **G** – wizualizacja wektorów migracyjnych, główne szlaki migracji i obszary przełomowe

thermal maturity modeling (1D) for 53 well sections correlated with vitrinite reflectance values helped to identify a heat flow trend during the rift and post-rift stages of basin development. A kerogen-oil chemical math-model was used (Sweeney and Burnham, 1990). Two basin-scale 2D models were developed along the regional cross-section Sagaidak–Lebedyn (86 km) and Guty–Gupalivka (62 km). Each of 2D models consists of 150 horizons, which are a downscaling reproduction of real detailed characteristics of basin lithology. The 2D modelling provided geochronology of petroleum system events and an understanding of migration, charging, accumulation, pools destruction, leakage and pools preservation.

Microscopic images were taken at the laboratory of Petroleum Geology Dept. in Taras Shevchenko National University of Kyiv using a Micros Austria MC-300 polarizing optical microscope.

TECTONICS AND HALOKINESIS

The sedimentary cover consists of four tectonic-stratigraphic large-scale sequences comprising: Late Devonian rifting, which is overlain by a Carboniferous-Early Permian post-rift depression and a younger post-rift platform. Halokinesis have accompanied 2 tectonic events – first in the Late Devonian, and second in the Early Permian (Pryvalov et al., 2012). High sedimentation rate in the Carboniferous led to dipping and overlapping of salt domes by other sediments (Fig. 2). There are two separate Upper Devonian salt and Lower Permian salt formations (Stovba, 2008). Salt domes had significant influence on the petroleum system of DDB due to numerous salt domes (Figs 1, 2). Structural evolution of the extensive rift basin was controlled by vertical movements of basement blocks and by halokinesis (Khomenko, 1986; Stovba, 2008; Gladun, 2012). Growth of numerous salt domes led to the formation of extended anticlines and arched uplifts within the paraxial deep part of the basin and led to the creation of numerous faults, that became migration pathways for hundreds of hydrocarbon accumulations (Maluk, 1984; Stovba, 2008).

LITHOLOGICAL OVERVIEW

The section consists of Upper Devonian (Fransian, Famenian), Mississippian (Tournaisian, Visean, Serpukhovian) and Pennsylvanian (Bashkirian, Moscovian) subsections. The majority of fine-grained siltstones and sandstones with numerous coal beds represent the Pennsylvanian section. The Bashkirian carbonate platform (Fig. 3, B-10-b-10) is well recognized in most basin areas and is composed of dominant limestone and dolomite facies with minor marls and carbonate shale (Fedorishin and Gardener, 2011; Prokopiv et al., 2015; Vakarchuk, 2015). The central and SE part of the southern border zone of DDB had favourable environmental conditions for carbonate sedimentation during the Early Visean and subsequent Tournaisian and part of the Late Devonian (Upper Famennian formations Ozero-Khovanska D3fm3oz-ch) had formed a continuous carbonate platform with a thickness up to 1300 m (Khomenko, 1986; Vakarchuk, 2003). Favourable climate and environmental conditions for carbonate sedimentation occurred in Late Devonian (Fransian) and Early Carboniferous (Tournaisian–Early Visean) times; warm climate, plenty of marine biota and periodic anoxic conditions supported the deposition of several significant organic-rich formations within the Dnieper-Donets rift and in the Donbas subbasin (Khomenko, 1986; Vakarchuk, 2003, 2015; Machulina, 2008; Ogar, 2012). The Tournaisian section also includes sandstone horizons brought by paleorivers, that flowed into the paleobasin from the SW. In the NW

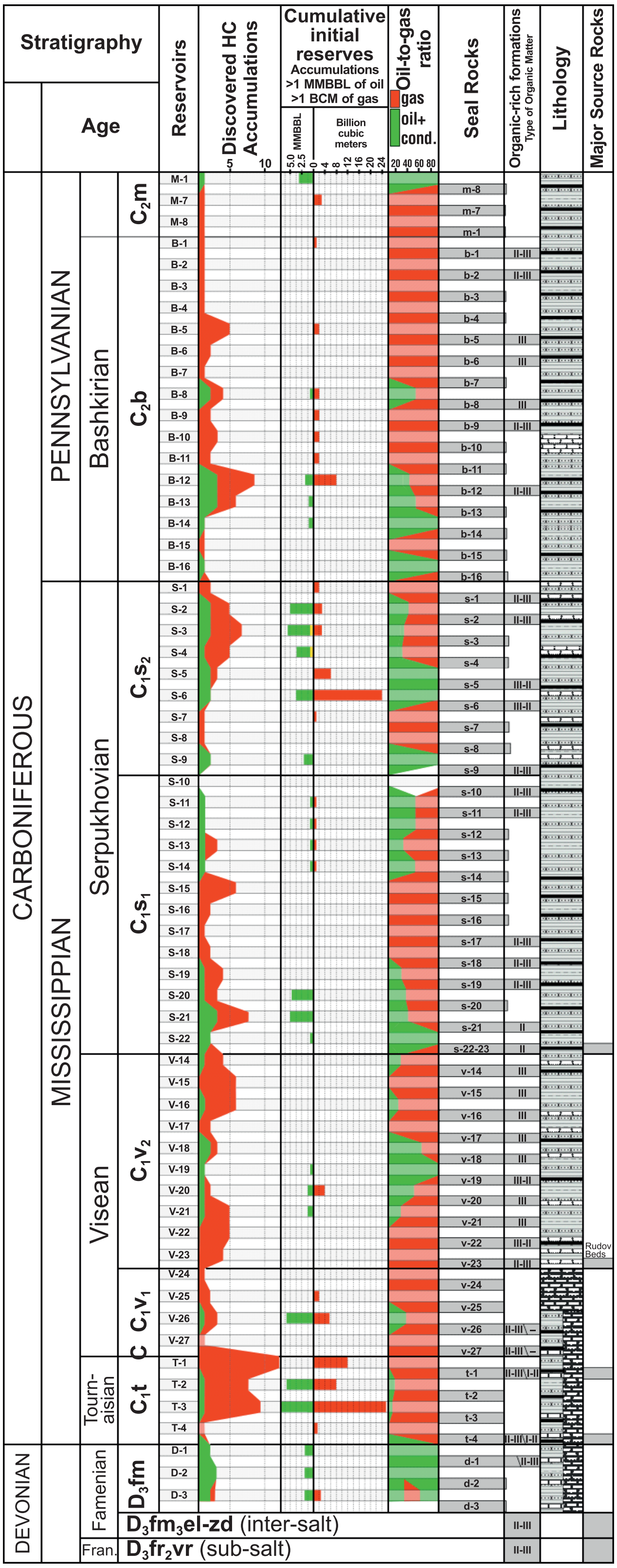

Fig. 3. Results of current study: stratigraphic distribution of discovered oil and gas accumulations and organic-rich horizons along the southern border of the Dnieper-Donets Basin. Cumulative initial recoverable reserves and types of kerogen in studied transgressive sequences are prasented

Ryc. 3. Stratygraficzny podział odkrytych złóż i horyzontów ropy naftowej i gazu oraz formacji bogatych w materię organiczną wzdłuż południowej granicy BDD. Ilustracja zawiera stratygraficzny podział skumulowanych wydobywalnych zasobów i rodzaje materii organicznej w badanych sekwencjach transgresywnych part of the southern border of DDB, a major carbonate formation covers only the Lower Visean (V-24-v-25). Underlying horizons V-26-V-27 and the Tournaisian section in the NW is represented by alteration of argillaceous clastic facies interbedded with thin carbonate beds and thin coal beds (Machulina, 2008; Karpenko, 2015).

OIL AND GAS RESOURCES AND RESERVES

Initial recoverable reserves of DDB were about 1.6 bn bbl of liquids and 59 TCF of natural gas (gas-to-oil ratio 86%) in about 250 oil and gas fields (Gladun, 2012; Fig. 1). The largest gas-condensate field Shebelynske (25.4 Tcf of gas) contained the third part (32.8%) of initial gas reserves, and it is actually increased to 86%. Upper Carboniferous sediments contain 45 deposits associated with 26.4% of hydrocarbons reserves. The Mississippian section holds 165 deposits associated with 5% of total hydrocarbons reserves, and the Pennsylvanian section, which is the main hydrocarbon producer, counts 415 deposits associated with 35.8% of total hydrocarbon reserves of the basin. Serpukhovian strata comprise 67 deposits, Upper Visean strata – 198, Lower Visean strata – 92, Tournaisian strata – 21, and Precambrian basement – 35 deposits. Devonian hydrocarbon deposits were identified just in 8 fields (Gladun, 2012). According to a previous assessment, undiscovered conventional hydrocarbon resources of the Dnieper-Donets Basin are about 16.5 bn boe (2250 Mtoe). The basin holds around 139 undrilled prospects and leads (Gladun, 2012). The proportion of undiscovered prospective resources up to 3 km depth is 17%, between 3- and 4 km – 22%, between 4- and 5 km – 19%, and in the range of 5–7 km – 42%.

THERMAL MATURITY AND OVERPRESSURE

Hydrocarbon generation process continued throughout all subsequent deepening of the rift basin. Whereas the predominant part of the Devonian, Tournaisian and Lower Visean source rocks are overmature (*Ro* >4.0%) within the paraxial part of Central and SE DDB deeper than 6 km (Fig. 2), and less mature in the NW part of DDB (Fig. 4). Several thermal maturity maps cut at depths 3, 4 and 5 km were published as part of a comprehensive study of shale gas in DDB (Mykhailov et al., 2014a, b). Thermal evolution of source rocks was modelled using over 50 well sections within the southern part of the rift (Figs 5, 6, 7) and several wells in the paraxial part of DDB. Over 50 developed 1D models provided certainty about history of heat flow within the basin. Also, analyzed previous investigations corresponds the resulted paleo-heatflow values: high heat flow during syn-rift Late Devonian age, relatively high heat flow until mid-Permian and flat decrease of heat flow during Mesozoic and Cenozoic times (Mitsch et al., 2015). During several tens of years, Ivanova was studying vitrinite reflectance (VR) of polished sections (2700 VR values) represented mainly by coal and carbonaceous lithofacies of the Donetsk coal basin and DDB, and published a catalog with a comprehensive study of thermal maturity and geothermal gradients (Ivanova, 2012). This VR database

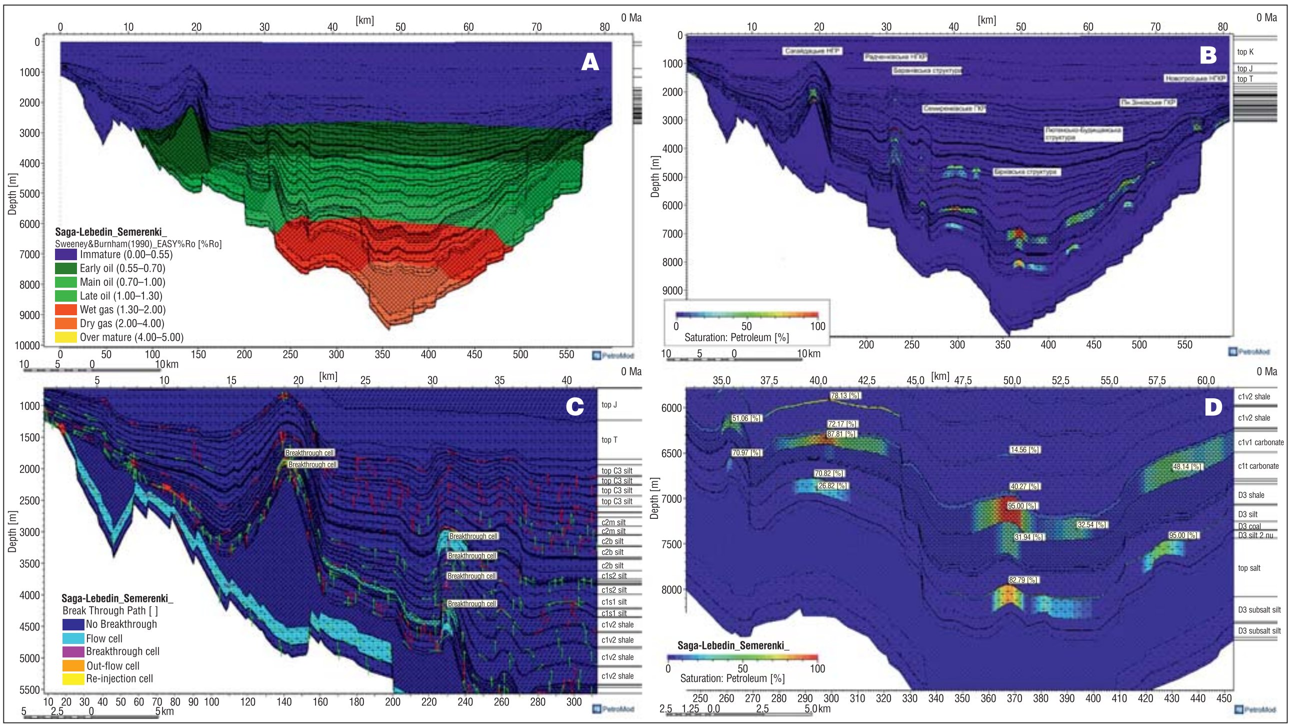

Fig. 4. Visualization of 2D petroleum system modelling along the regional Guty–Gupalivka cross-section. **A** – thermal maturity windows; **B** – forecasted accumulations correspond to discovered oil and gas fields and highlight deep undrilled prospects; **C** – visualization of migration vectors, major migration pathways and breakthrough areas; **D** – estimated gas saturation at forecasted undiscovered gas accumulations at 6500–8000 m depth

Ryc. 4. Wizualizacja symulacji 2D modelowania systemu naftowo-gazowego wzdłuż regionalnego przekroju Guty-Gupalivka. **A** – okna dojrzałości termicznej; **B** – prognozowane akumulacje odpowiadają odkrytym polom naftowym i gazowym oraz głębokim nierozpoznanym wierceniami złożom; **C** – wizualizacja wektorów migracyjnych, główne szlaki migracji i obszary przełomowe; **D** – prognozowane gromadzenie gazu (nieotwarte) na głębokości 6500–8000 m

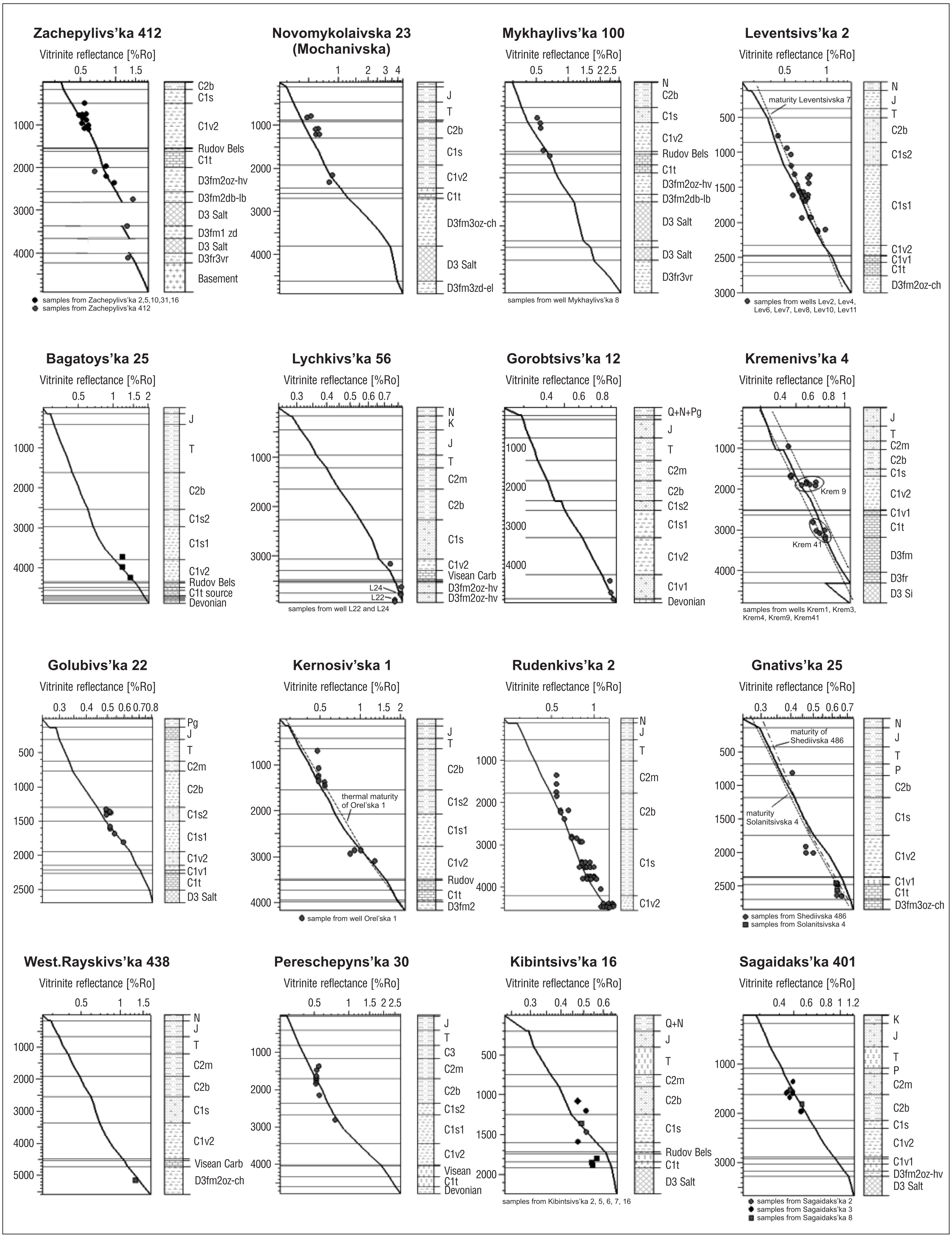

Fig. 5. Burial history and thermal maturity based on 16 boreholes along the southern border of the Dnieper-Donets Basin. Vitrinite reflectance values prove models of thermal evolution of source rocks within the southern border of DDB. All vertical scales are in metres, all horizontal scales are in percent. VR values were used from Ivanova's catalog (Ivanova, 2012)

Ryc. 5. Geneza i dojrzałość termiczna oparta na danych z 16 otworów wiertniczych wzdłuż południowej granicy BDD. Modele wartości odbicia witrynitu potwierdzające termiczną ewolucję skał w strefie południowej granicy BDD. Osie pionowe w metrach, osie poziome w procentach. Wartości VR zostały wykorzystane z katalogu Iwanowej (Ivanova, 2012)

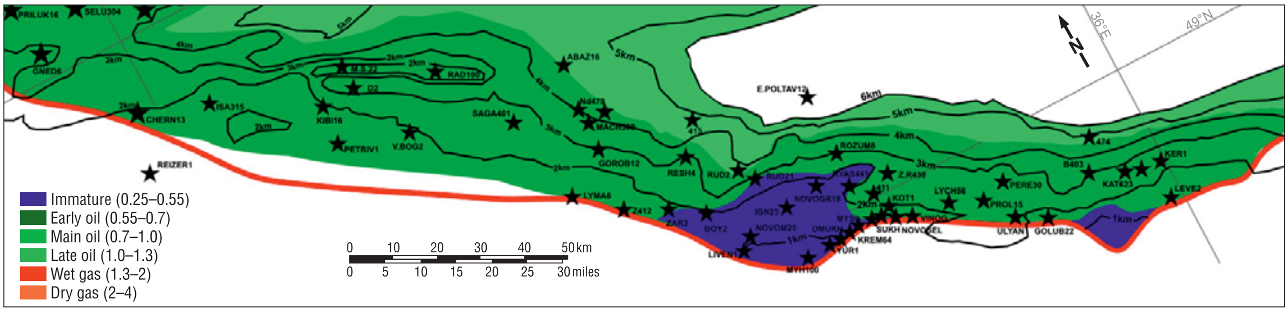

Fig. 6. Thermal maturity map of the top surface of the Upper Serpukhovian within the southern border of the Dnieper-Donets Basin. Data sets from starred boreholes were used for 1D modelling in the current study

Ryc. 6. Mapa dojrzałośći termicznej powierzchni przekroju serpuchowa górnego w obrębie południowej granicy ZDD. Zastosowano zestawy danych z oznaczonych otworów

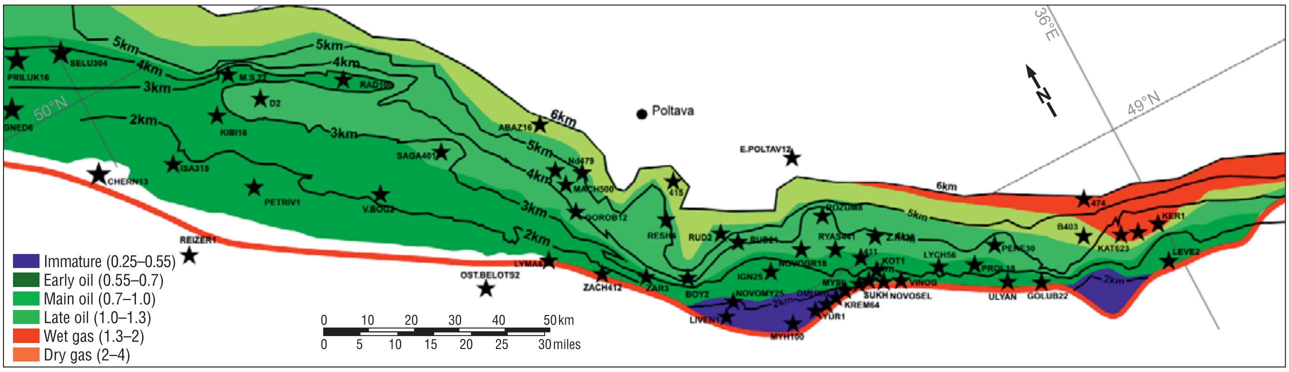

Fig. 7. Thermal maturity map of the top surface of the Lower Visean within the southern border of the Dnieper-Donets Basin. Data sets from starred boreholes were used for 1D modelling in the current study

Ryc. 7. Mapa dojrzałośći termicznej powierzchni przekroju wizenu dolnego wzdłuż południowej granicy BDD. Zastosowano zestawy danych z oznaczonych otworów

provided a basis for calibrating 1D/2D models. Overpressure in DDB is caused foremost by hydrocarbon generation and rapid sedimentation rates during the Carboniferous period. The formation overpressure ratio vary 1.12–1.95 and can reach 19,000 psi (130 MPa). Overpressured lithological reservoirs are typical for the Lower Visean–Tournaisian Carbonate Platform (Fig. 3).

1D/2D modelling. Quite short terms of hydrocarbon generation from each source formation are explained by the rapid sedimentation rate throughout the Late Devonian and especially the Carboniferous (Fig. 2). Upward movements of large-scale tectonic blocks during the Devonian rifting together with increased tectonic activity in the beggining of the post-rift phase formed deep structuers associated with C1v2-C1t-D stratigraphic units within the NW part of DDB. Looking at the 2D model of the Sagaidak–Lebedyn line (Fig. 2), it is quite certain that Devonian + Tournaisian + Lower Visean source rockswere buried to 10–15 km by the end of the Carboniferous. Temperature at 8–9 km in Late Carboniferous rocks corresponded to the overmature zone, so it is obvious that the period of gas and/or oil generation was relatively short. Serpukhovian and Upper Visean sources generated HCs most intensely during the Late Permian and less intensely during all subsequent periods of the basin development. According to the same 2D model (Fig. 2) there should not be any HC accumulations in sediments older then mid-Carboniferous (C1s2-C1v2-C1v1-C1t-D3) within the deep, axial part of the Dnieper-Donets Basin. This assertion is confirmed by 2D modelling results and the absence of commercial HCs discoveries in sediments older that mid-Carboniferous within the deep paraxial part of central and SE DDB. The 2D model (Fig. 2) proves that all accumulations within the axial part of DDB, formed before the Permian holokinesis, were destroyed by rising domes, and the traps formed later by salt domes were charged with hydrocarbons just in C2m and C2b or hydrocarbons migrated into the traps in younger sediments. Another conclusion was done while watching simulation results of the Guty–Gupalivka 2D model (Fig. 4): deep and ultra-deep traps in the central paraxial part of NW DDB, which were not affected by salt domes rise in the Permian, have preserved gas accumulations until the present.

PETROLEUM SOURCE ROCKS

Recent study (publication pending) identified and characterized Carboniferous and Devonian organic-rich formations within the southern border zone of DDB. The study included 240 thin-sections/polished samples (Karpenko, 2016), estimated TOC (total organic carbon) using well logs in 53 well sections (method of Karpenko et al., 2014), core descriptions, and results of previous comprehensive geochemical studies (Sachsenhofer et al., 2010; Misch et al., 2015; Vakarchuk, 2015). The analysis identified organic-rich formations and, with aid of fundamental knowledge of van Krevelen (1993), the following major source rocks have been recognized:

– sub-salt formation (Devonian, Upper Frasnian, Voronezh Formation – D3fr2vr) is formed by black bituminous

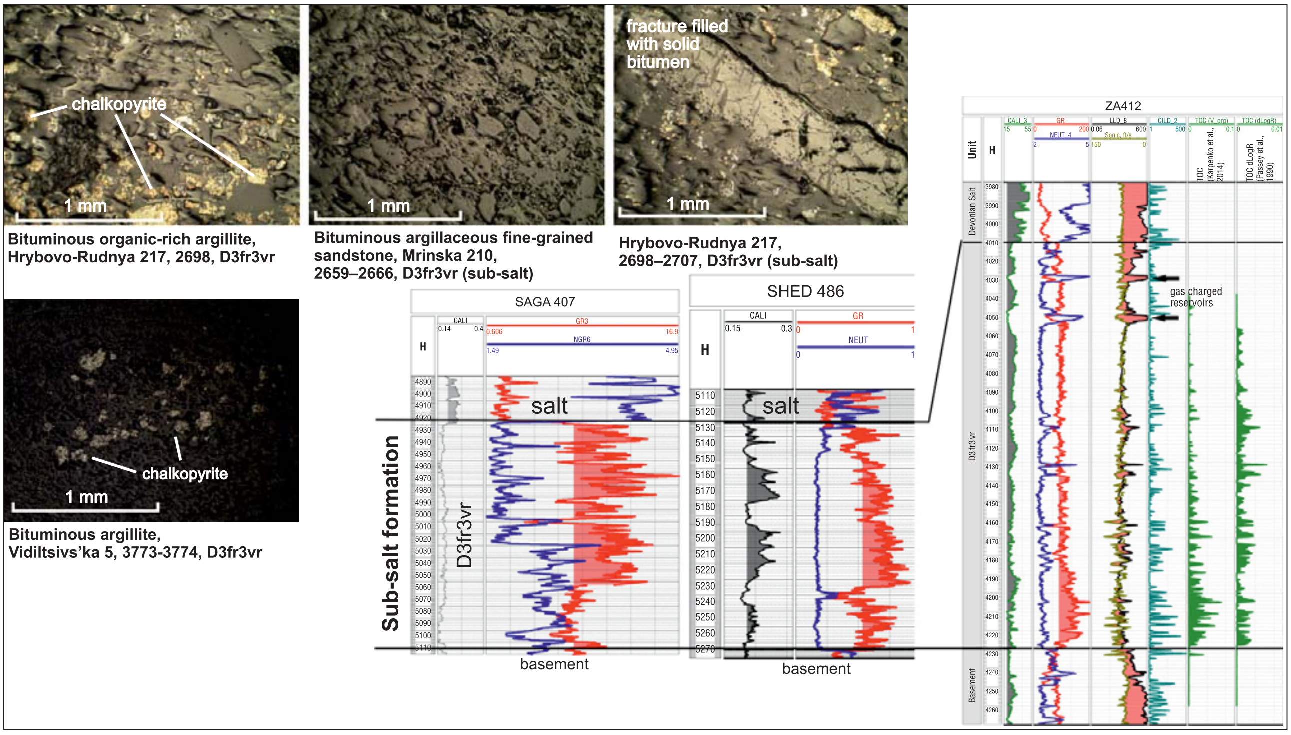

Fig. 8. Well logs and estimated TOC content (green log on the right) of the Devonian sub-salt formation (D3fr3vr) within southern border of the Dnieper-Donets Basin. Microscopic images of organic-rich samples (on the left) of the Devonian sub-salt formation within the NW part of DDB

Ryc. 8. Dane z odwiertów i wyznaczony skład TOC (zielona kolumna po prawej stronie) z formacji podsolnych dewonu (D3fr3vr) wzdłuż południowej granicy BDD. Mikrofotografie – przykłady bogatych w materię organiczną skał (po lewej stronie) formacji podsolnych dewonu w NW części BDD

sandstones, black marls, clay-rich limestone, and dolomites with bituminous argillites, and contain significant amounts of II–III type kerogen (Fig. 8);

– sulphate-carbonate-argillite formation (D3fm2mk) overlying the upper salt unit has organic-rich argillaceous-carbonate lithofacies with uncertain generating potential (Khomenko, 1986);

– intra-salt section Devonian, Lower Famenian, Zadon-Elets Formation (D3fm1zd-el) composed of highly-bituminous argillaceous shaly siltstones and sandstones with terrestrial and marine organic matter (OM), numerous fractures filled with bitumen and oil. Numerous oil and gas shows, sub-commercial flows, and oil saturated core samples indicate the presence of source rocks in the inter-salt section (Khomenko, 1986);

– supra-salt section (Devonian, mid-Famenian formations, Lebedyansko-Dankovski – D3fm3dn-lb), the clastic and carbonate lithofacies includes black limestone beds, with black vitrinite-rich argillites and coals of unknown geochemical properties. Numerous oil and gas shows were detected during well tests, and Lychkivske field has oil-gascondensate accumulations in the D3fm3dn-lb section, so it is obvious that there are source rocks;

– supra-salt section (Devonian, Upper Famenian formations, Ozersko-Khovanski – D3fm1oz-hv) consisting of the overlying carbonate formation and the underlying terrigenous shale formation, which was formed in the sub-continental conditions and is enriched by OM of terrestrial origin. Overlying carbonates contain marine black limestones in the open marine paleo-environment area with high generating potential (Khomenko, 1986);

– Carboniferous, Tournaisian horizons (t-3-t-5) in the central part of study area include two 5–8-m thick beds with TOC over 10% with marine oil-prone OM, in adjacent areas they are interbedded with organic-lean beds with a total thickness up to 80 m (Fig. 3). According to recently published research, the TOC content in carbonates of the Tournaisian section in the depression zone is 2.2%. The section contains terrestrial OM (III type kerogen) and sapropel-humic (II–III type kerogen). Clay-rich lithofacies have the average TOC content of 5.2% with a sapropelic type of OM (I type kerogen) (Vakarchuk, 2015);

– lower Visean horizons (v-26-v-27) below the carbonate platform (v-24-25) within the far NW of the study area contain black organic-rich argillites and black marls thinly interbedded with sapropelic coals (I–II–III type kerogen) (Karpenko, 2015);

– Rudov Beds formation (v-23) has a very limited distribution within the study area, but in the SE part of the area (Kernosivka area, Bagatoiske field area) its thickness increases to 30–35 m and contains up to 10% of TOC and II–III type kerogen (Figs 3 and 9). This area is the most promising for further exploration and pilot drilling for shale gas;

– majority of upper Visean transgressive sequences (v-14-v-21) have 1.5–2.5% TOC content with predominant terrestrial humic OM (III type kerogen), horizon v-22 has TOC 1.0–4.2% with (III type kerogen). Organic matter in horizons v-15-v-16 contain high content of liptinite macerals and pore space are filled with exudatinite (II type kerogen);

– most of Serpukhovian horizons include thin, from 0.2–1.0 mm to 0.1–0.5 m, vitrinite coal beds (III type kero-

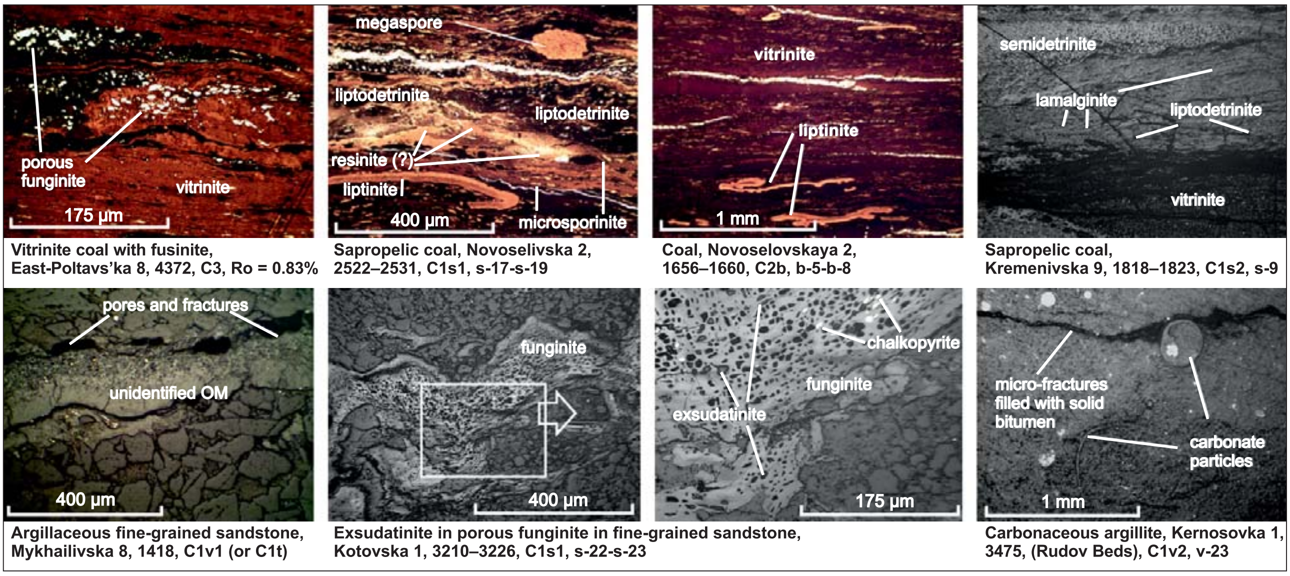

Fig. 9. Micro-images of organic-rich facies and coal of Carboniferous age within the southern border of the Dnieper-Donets Basin
Ryc. 9. Mikrofotografie facji bogatych bogatych w materię organiczną i węgla z karbonu południowej granicy BDD

gen), but several coal beds contain liptinite, liptodetrinite, micro- and macrosporinite (II type kerogen; Fig. 9). Lowest Serpukhovian horizons (s-22-s-23) contain high concentration of funginite with 20–25% of pores filled by exsudatinite (Fig. 9). These organic-rich horizons might be the same, as were described in previous studies within the NW part of the basin and included organic-rich shale with up to 5% of TOC and HI up to 290 mgHC g-1 TOC (Sachsenhofer et al., 2010);

– Mississippian (Bashkirian, Moscovian) section is composed of organic-lean fine-grained siltstones and sandstones including numerous vitrinite coal beds (III type kerogen). Coal horizons in b-7-b-10 contain liptinite and resinite (II type kerogen) and a significant share of porous funginite or fusinite filled with exudatinite which is an indicator of nearby oil generating source (Fig. 9).

According to a recently accomplished study, the most significant source rocks were identified is the sub-salt formation (D3fr2vr), in the Devonian inter-salt section, in Tournaisian carbonates. They are rarely distributed in the Rudov Beds (v-23) and in all upper Visean shale horizons, Serpukhovian coals and Mid/Upper Carboniferous coals (Fig. 3).

STRATIGRAPHIC DISTRIBUTION OF DISCOVERED HYDROCARBON ACCUMULATIONS

The distribution of discovered HCs accumulations (Fig. 3) with corresponding initial recoverable reserves, oil-to-gas ratio of each horizon, and analyzed oil density and compositions allows to conclude that:

– just a few accumulations discovered in the Moscovian section were apparently filled by vertical oil and gas leakage through the imperfect shallow seals (see breakthrough points in Figs 2 and 4);

– most accumulations and initial recoverable reserves in the Bashkirian section are associated with horizons B-12-B-13 under the impermeable Bashkirian carbonate platform (B-10-b-10). Reservoirs in B-12 horizon were charged with light oil and liquids-rich gas. Other two highly productive horizons are B-5 and B-8, mostly gas-charged or with equal oil-to-gas ratio;

– most of upper Serpukhovian accumulations and reserves are associated with horizons S-2, S-3 and S-4 (Fig. 3). Oil-to-gas ratio is approximately equal, but the major share of initial reserves is specific of light oil and condensate;

– lower Serpukhovian accumulations are associated with horizons S-15 and S-19-20-21, with the highest concentration of discovered accumulations in S-21. The most significant oil discoveries were made in horizons S-20-21, but the number of small gas accumulations dominates throughout all C1s1 horizons. Oil accumulations discovered in S-20-S-21 contain very light oil with condensate (low density up to 686 g/cm^3);

– upper Visean section has high concentration of gas accumulations in all horizons. The absolute majority of C1v2 are "dry gas-filled" or condensate-lean accumulations. Oil accumulations were identified in V-16 and V-19 (in two "single-reservoir" fields). Other few oil accumulations in V-19, V-20 and V-23 were discovered in the far NW part of the southern border zone of DDB.

– lower Visean carbonate section includes very rare discoveries, just in combination with Tournaisian reef build-up structures;

– Tournaisian section has the highest concentration of wet-gas accumulations and the highest initial gas reserves. The only oil field (Ignativske oilfield) discovered in C1t + C1v1 units contains the highest initial oil reserves within the study area;

– Devonian section has two discovered liquids-rich gas fields, numerous oil and gas shows, and sub-commercial flow rates.

SUMMARY

1. The major type of HCs migration in the study area has sub-horizontal direction: from the deeper areas of the basin with mature source rocks. Hydrocarbons migra-

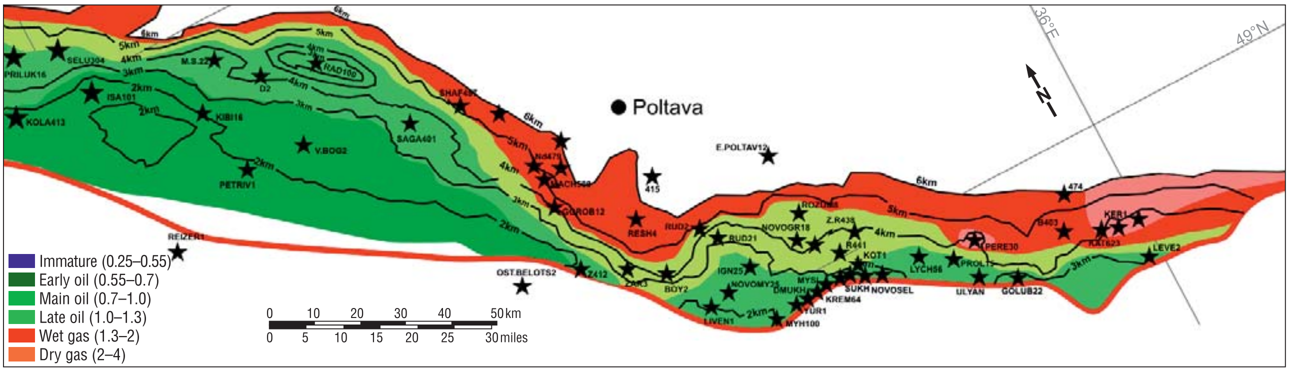

Fig. 10. Thermal maturity map top of the surface of the Devonian within the southern border of the Dnieper-Donets Basin. Data sets from starred boreholes were used for 1D modelling in the current study

Ryc. 10. Mapa dojrzałośći termicznej powierzchni przekroju Dewonu w południowej granicę BDD. W tym badaniu zastosowano dane z oznaczonych otworów

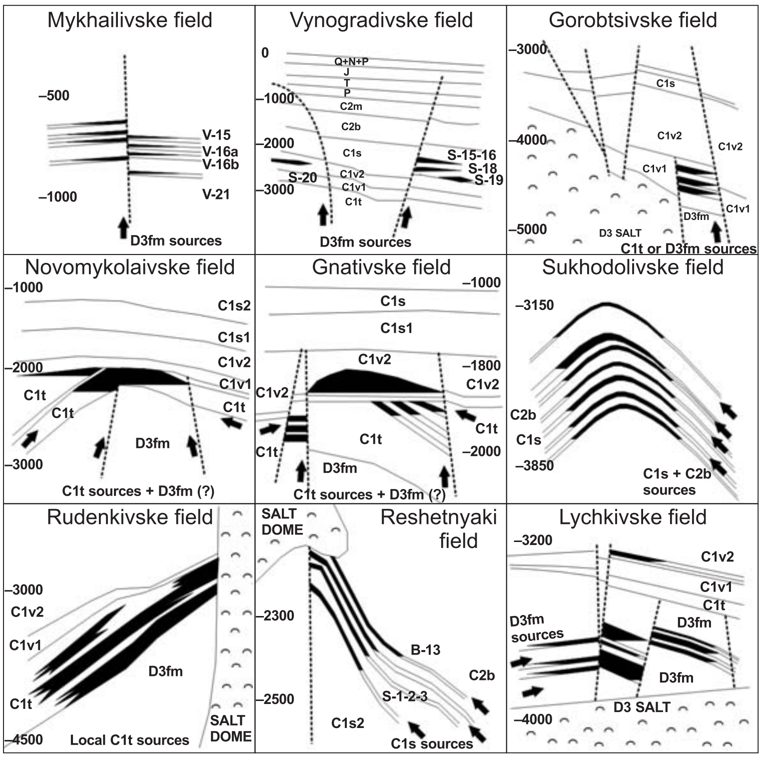

Fig. 11. Typical types of hydrocarbon accumulations within the southern border of the Dnieper-Donets Basin based on 2D modelling. Arrows illustrates migration pathways from hydrocarbon source rocks. Reservoir models from Atlas of Oil & Gas Field of Ukraine (Ivanyuta et al., 1998), modified by the autor

Ryc. 11. Typowe rodzaje akumulacji węglowodorów w złożach południowej granicy BDD (wnioski modelowania 2D). Strzałki przedstawiają drogi migracji ze źródeł generujących węglowodory. Zbiornikowe modele na podstawie Atlasu złóż gazu i ropy naftowej Ukrainy (Ivanyuta et al., 1998), zmienione przez autora

ted to faulted or anticline traps within the southern border of DDB (Figs 2, 4, 6, 7, 10 and 11).

2. Sub-vertical migration and leakage also significantly influenced a number of analyzed HC accumulations, especially sub-vertical migration from deep Devonian rock sources (Figs 2 and 4).

3. Mississippian source rocks are mostly immature (Figs 2, 4 and 6) within the southern border zone of DDB, so discovered accumulations (M-2-7-8) were filled via sub-vertical migration and leakage from mature Serpukhovian and upper Visean sources. Bashkirian horizons B-11-12 contain condensate and specific light oil, which might have originated from local Bashkirian rock sources or upper Serpukhovian sources, due to the fact that very similar light oil and condensate (similar components) were discovered in the upper and lower Serpukhovian reservoirs.

4. Upper Serpukhovian source rocks of the study area are in the oil window (Fig. 6), hence numerous oil accumulations were charged from local sources (Fig. 11). Upper and lower Serpukhovian source rocks are prone to generate liquids (condensate and light oil), so the upper and lower Serpukhovian HC accumulations seems to have originated in the same Serpukhovian sources. Gas migrated over long distances (15+ km) from the deep axial basin area (Figs 2 and 4).

5. Dry gas accumulations of Yurjivske, Dmuhailivske, Gupalivske, Musienkivske, Mykhailivske fields, located along the continuous Zachepylivka-Leventsi uplift, are associated with numerous deep sub-vertical faults (Fig. 11). They allow to presuming, that deep Devonian mature sources (Fig. 10) had major influence on its charging. Local upper Visean gas-prone source rocks are in the early stage of gas generation (Fig. 7), so it seems that they had an insignificant impact on accumulations in the Upper Visean.

6. Rudov Beds (v-23) are most likely a large gas-condensate reservoir (V-20-21) discovered at the Kremenivske field. In the NW part of study area, several oil accumulations have been identified in V-22-V-23 (Malosorochynske and Selukhivske fields) with the Rudov Beds most likely source.

7. Few Lower Visean HC accumulations were charged from Tournaisian sources (Fig. 11). Tournaisian carbonates underlie impermeable Lower Visean carbonates (V-24-v-25) which are a regional seal (Fig. 11). The majority of HC reservoirs in the Tournaisian Carbonate Platform are carbonates; clastic rocks are subordinate. Tournaisian carbonate source rocks had a very significant impact on the petroleum system in the study area. Tournaisian source rocks, which are in the main oil window to wet gas window (Fig. 11), charged the largest oil fields (Gnativske–Novogry-

gorivske–Novomykolaivske carbonate complex). 2D modelling identified that the underlying Devonian coal beds additionally influenced the Tournaisian accumulations. In deeper parts of the basin, Tournaisian source rocks produced gas-condensate that accumulated in carbonate reservoirs discovered in the largest gas fields, e.g. the Machukhske, Rudenkivske and Bagatoiske fields.

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