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Coalbed methane in the Donets Basin

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Abstract

В статье обобщены результаты исследований в области структурной геологии и тектонотермальной истории развития Донбасса применительно к вопросам генерации и локализации угольного метана. С помощью геоинформационных технологий проанализированы базы данных по газоносности горных пород и газообильности горных выработок, выделены структурные типы характерных ловушек углеводородов в зависимости от пространственно-временных вариаций параметров реконструированных палеотермальных режимов. С помощью метода термолитической газовой хроматографии изучены нетегазогенерационные свойства углей и вмещающих пород карбона Донбасса. Максимумы скоплений метана приурочены к площадям: 1) умеренных амплитуд инверсионных движений и высоких уровней доинверсионного теплового потока; 2) аномально высоких постинверсионных тепловых потоков, в том числе, в пределах трещиноватых коллекторов в донных частях синклиналей; 3) развития цветковых структур, развивающихся в зонах сдвиговых дислокаций.

In the course of the past century, the Donets Basin (Donbas) has been in the focus of geological interest mostly of an enormously high potential of its coal Carboniferous deposits and also because of its proximate adjacency with the Dnieper-Donets Depression, one of the most mature oil and gas provinces of Ukraine. In recent years a significant wave of new interest to geology of the Donets Basin has arisen dramatically from results of independent estimations obtained by several investigating entities about an impressive coalbed methane resource potential of coal-bearing measures in a range of 12–27 trillion m^3. Almost the all coal fields of the Donets Basin excluding most eastern regions are characterised by high coal bed methane content (from 8–10 to 25–37 m^3/t). In spite of serious diminishing of annual coal production methane emissions into atmosphere occurring from operating mines and sites of closed mines in the Donets Basin are still in range of 2 billion m^3 of methane per year. The commercial benefits of coal bed methane extraction from the prospective sites of the basin are unquestionable and this is evidenced by the successful installation of pilot local drainage or "degasification" systems at some of the gassiest underground mines.

Geologic setting and Basin structure

Both basins, the Donbas and the Dnieper-Donets Basin (DDB), are adjoining segments of large Late Devonian Pripyat-Dnieper-Donets-Karpinsky (PDDK) rift system located at the southern part of the Eastern European Craton (Fig. 1).

The eastern boundary of the of the Dnieper River Basin straddles an approximately 900 km long Mariupol-Kursk lineament, which underlies the transition between the Dnieper-Donets Basin and the Donets Basin of the PDDK rift. Within the domain of the rift, the Moho is vertically displaced by about 5 km across it, from ca. -35 km in the Dnieper-Donets segment in the west to ca. -40…45 km in the Donbas to the east [1]. The prominent axial Moho high of the Dnieper-Donets Basin is not observed in the Donbas segment, which stands out from all segments of PDD rift by its up to 20–24 km sedimentary column and its prominent inversion at the area of the Donets Fold-and-Thrust belt (DF).

The structure of the DF which is the inverted part of the Donbas Basin, is dominated by WNW-ESE trending linear folds in the central part of the basin (Fig. 1). The reflection data of DOBRE profile (Fig. 2) showed that the inversion of the Donbas Foldbelt occurred at the crustal scale as a mega–pop-up, which involved a major synthetic detachment fault through the entire crust and an associated antithetic detachment fault [2, 3]. Major thrusts occur along the northern margin of the basin in the limits of a zone of the Northern SSW-dipping deep fault, which is rooted into the Moho. The Southern margin of the basin is represented by a set of adjoining horst – graben structures within a zone of the Southern NNE-dipping deep fault. Minor folds [4], reversed faults with significant and even dominating strike-slip displacement components, rotated fault blocks [5] occur between zones of marginal deep faults and central zones of linear folds.

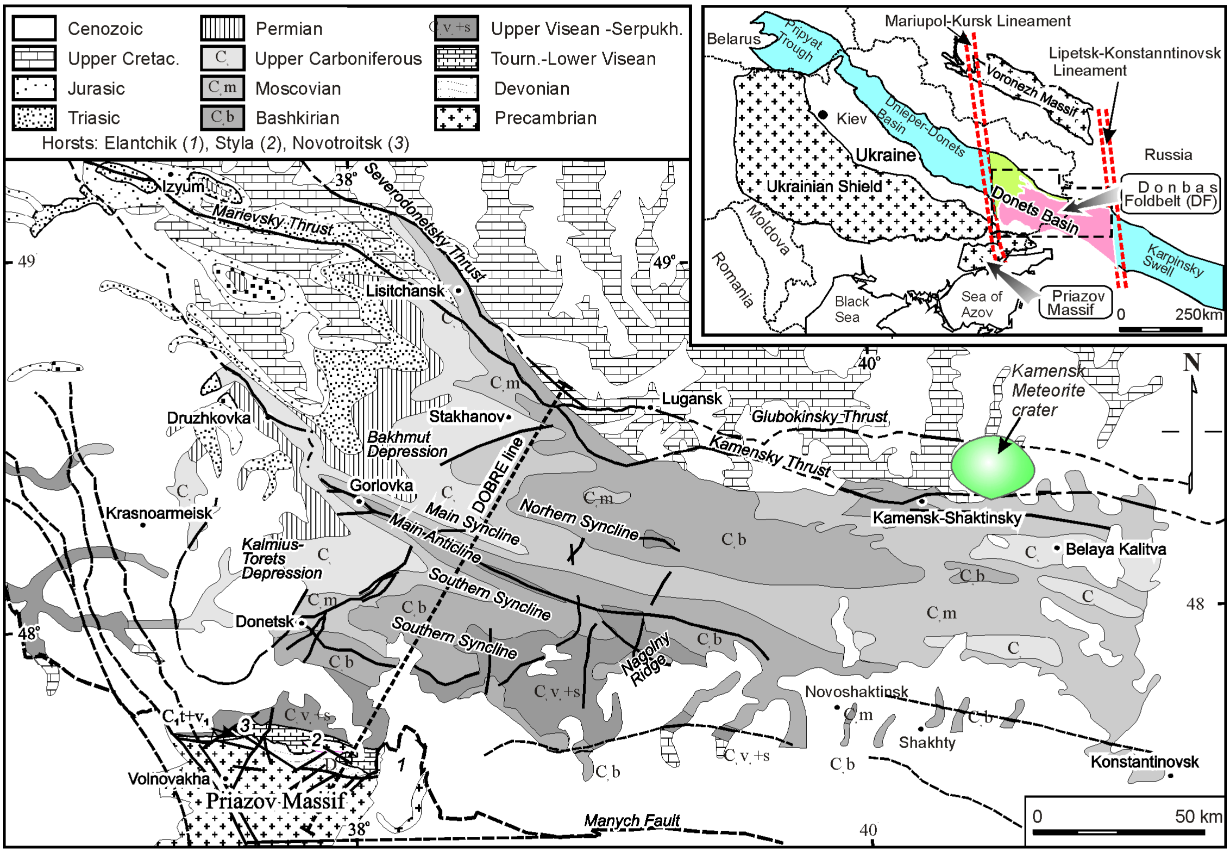

Fig. 1. Structural setting and geological sketch map of the Donets Basin.

According to *Privalov et al.* [6], 90 to 98 % of the 1.5–2.9 km displacement on reactivated thrusts along the northern basin margin, between Lugansk and Kamensk Shakhtinsky, occurred during Permian time. Late Triassic to early Jurassic and late Cretaceous compressional activities locally affected the north-western sector *B4* (Izyum – Lugansk) [4, 6], south-eastern margins of the DF [7, 8], and the south-western rim of the Kalmius-Torets Depression [7, 8].

The significant tectonic element of intrabasional architecture is WNW-ESE trending principal displacement zone (PDZ) consisting of a set of dextrally *en echelon* arranged deep basement faults with oversteps superimposed on depressions (pull-aparts) in the basement [7, 9]. During post-rift stage strike-slip pulses within PDZ affected local depositional environments in the vicinity of pull-aparts and influenced on depositional and inversion trends across the entire basin. The most prominent deep fault within PDZ is expressed in Palaeozoic strata as the Main Anticline, which is the largest and most pervasive fold with steeply dipping limbs, complicated by faults developed at its hinge, in which dextral movement has been recognised.

At present, ~200 gas deposits have been discovered in the Dnieper-Donets Basin with proved reserves in order of 60 trillion m^3. However, the giant Shebelinka gas field and very promising West-Shebelinka node of gas accumulations, which have been traditionally positioned within the frame of the DDB, according mentioned above model of structural setting, are almost entirely located within the Donets Basin. Lower Visean deep seated black anoxic shales and carbonates are considered as principal source-rocks intervals for the Dnieper-Donets hydrocarbon system formation, however, the role of the Carboniferous coals as source rocks is still uncertain [10].

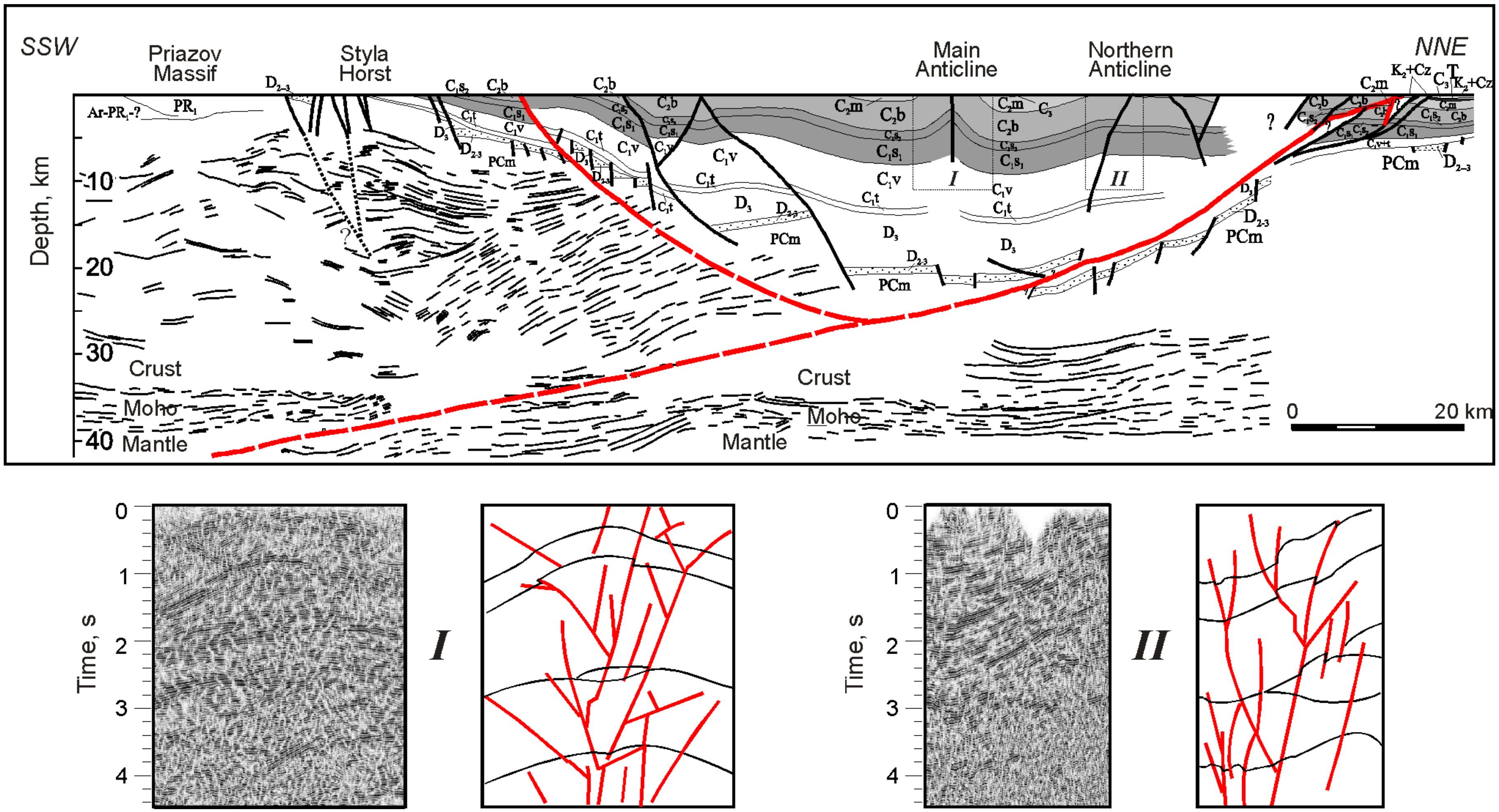

Fig. 2. Geological cross-section along DOBRE seismic profile after [2, 3]. Flower type structures [9] depicted from fragment of DOBRE reflection records are shown on the insets I and II.

Coal seams in the Donets Basin are typically thin, but have a wide lateral distribution. The post-Early Visean Carboniferous Donbas fill hosts more than 130 seams (each with a thickness over 0.45 m). Most coal reserves are accumulated in seams 0.6 to 1.0 m thick. However, about 36% of coal reserves were identified in 12 seams more than 1.0 m thick. Owning unique concentration of resource base in order of 52 Gt for workable coal seams [11], and, more specifically, tremendous mass of dispersed predominately terrigeneous organic matter, which is considered to be at ~900 Gt [12], appropriate P-T conditions during burial history for gas generation, almost the all coal fields of the Donets Basin excluding most eastern super-anthracite regions are characterised by high coalbed methane content.

The average methane contents in coal seams of different ranks are in range of: 5–7 m^3/t (sb), 7–9 m^3/t (hvb), 9–15 m^3/t (mvb), 15–17 m^3/t (lvb), 14–16 m^3/t (sa), 17–20 m^3/t (low ranked anthracites), 0.5–1 m^3/t (anthracites and super-anthracites). Numerous seams have significantly higher gas content (up to 25–37 m^3/t), presenting a high potential for coal mine methane projects.

The primary focus of this article is on delineating prospective areas with promising coal gas resource potential in the Donbas from results of investigations in the following areas: (1) hydrocarbon-generation potential of coals and clastic rocks from *Rock-Eval* experiments; (2) compiling database on gas regimes of underground coal mines; (3) analysis of structural types of entrapments with special emphasis on results of burial and thermal history reconstructions.

Methods

For estimations of hydrocarbon generation potential of coals and clastic rocks from coal-bearing measures of the Donbas the Rock Eval pyrolysis was performed in duplicate using a *RockEval 2+* instrument. The amount of latent hydrocarbons released from kerogen during gradual heating (S2) was normalised to TOC to give the hydrogen index (HI = S2/TOC). For compilation of database on gas regime (CH_4 and CO_2 content in coal seams *in situ* and per tonne of extracted coal mass), structural patterns of gas entrapments there have been used comprehensive information from published sources [12–14] and unpublished reports provided by the industry. The analysis of parametric information on the burial and heat flow histories of the Donbas was based on the results of 1-D and 2-D numerical models using vitrinite reflectance data [15–17] and zircon-apatite fission track data [18–19].

Results and Discussion

The isotopic composition of carbon $\delta^{13}C$ plotted vs. dryness of the gas from CBM deposits of the Donbas [20], conventional gas deposits of the Northern margin of the Donbas and Shebelinka gas field [14] clearly indicates the thermogenic origin of the methane.

Low-rank coals in the Donbas are restricted to the western part of the Basin surrounding the Bakhmut and the Kalmius-Torets Depressions and northern basin margin [21]. High-rank coals (anthracites) are typical for the eastern part. Variations of methane content in coal beds and host clastic rocks in the Donbas reflect a consequence of events from kerogen to gas generation, migration and formation of reservoirs and local entrapments [22].

Results of *Rock-Eval* experiments (Fig. 3) have shown that the effective hydrogen index HI for coal seams is quite enough to serve as effective gas and oil prone source rocks. The concentration of dispersed organic matter is different in different lithologies (0.5 to 6 % for mudstones; 0.5 to 16 % for siltstones), however, for deltaic siltstones, lacustrine and marine mudstones HI values are in range of 50–200 mgHC/gTOC.

This suggests that some facial intervals from low-permeable clastic host rocks have significant gas generation potential [23]. The methane is released during the mining process when the coal seam is fractured. However, coal extraction tends to lead to the escape into mining works of more methane than was originally trapped within the mined coal seam itself. This is because of the impact of additional methane source from fractured surrounding strata containing gas generated from clastic gas-prone rocks.

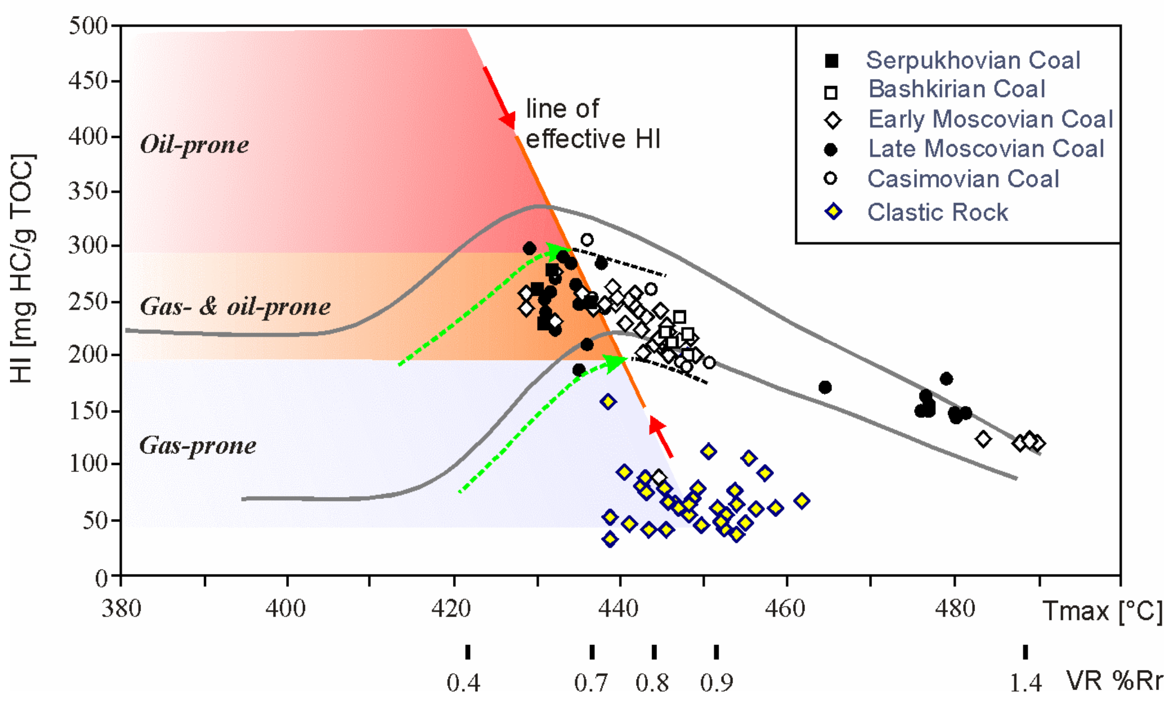

Fig. 3. Results of Rock-Eval experiments for determination of hydrocarbon generation potential for coal seam and clastic rocks of the Donets Basin [23].

The obtained thermal history modeling results showed (Fig. 4, A) that along the Main anticline during maximal burial the heat flow was in range of 64–66 mW/m² and even >70 mW/m² (in area of pull-apart *PA4*). This suggests an activity of this structure even during post-rift sedimentation stage, which can be recognized also from analysis of regional deference in burial history. According the results of modeling the Main anticline between pull-aparts *PA3* and *MA1* has been partially formed as synsedimentary antiform, because of the local minimum of thickness of Middle-Late Carboniferous (from suite G (C_2^2) to suite P (C_3^3)) and Early Permian rocks (Fig. 4, B).

In the region gravitated to pull-apart PA3 we revealed the abnormal post-inversion heat flow < 150 mW/m², which could be responsible to hot aqueous solutions and formation of epigenetic mercury-antimony deposits within this area. Taking into account, that to the west from pull-apart *PA3* coals were lower in rank and had not attained enough thermal maturity during pre-inversion stage, this anomaly may have induced the generation of large amounts of thermogenic coalbed methane with its further trapping into the Druzhkovka-Konstantinovka (DK) anticline, wherein numerous prospective high-permeability and fractured reservoirs are present.

In the most uplifted domains de-methanisation of anthracites took a place, and sorption niche was re-occupied by CO_2 [22]. On the tectonic map the position of coal mines with different levels of methane and carbon dioxide content is shown (Fig. 5). Some seams during underground coal mining demonstrate more than 100 m³ CH_4 per ton of mined coal.

According our interpretation of seismic images of DOBRE profile there have been inferred [9] very typical for the restraining stepovers images of positive flower-palm tree structures (Fig. 2, insets I and II) in the central part of the Basin. Strike-slip deformations are recognised across the entire basin. Small displacement faults which caused dramatic obstacles for safe and efficient underground coal-mining have been traditionally interpreted in the Donbas as normal and/or reversed faults. However, most of them are concentrated within strike-slip zones with clear patterns of Riedel (R_1 and R_2), Y and P shears [4, 9].

To delineate prospective sites we have to take into account that a major part of the Donbas (Donets Fold-and-Thrust Belt) has been uplifted and deformed with prominent NNE-SSW shortening grain during the latest phases of Hercynian orogeny. Cimmerian and Alpine tectonic events resulted in multiple fault reactivations, deplanation of already deformed strata surfaces, formation of linear and subconcentric shallow dextral shear belts in the sedimentary cover [8, 9]. These processes provoked new coalbed methane short-track migration pulses and enhanced a role of multifold and multistage trapping within fractured and sealed secondary reservoirs. The significant methane resource is also expected as result of conventional trapping related with gas migration and permeability contrasts of tectonic and lithological origin (e. g. fractured and sealed sandstones in domal structures). The deposits in cupola-like structures related with dextral strike slip-zones along the northern marginal fault of the Donbas host conventional gas reserves of 240 billion m^3. Of particular significance to further exploration and development potential are sites of methane accumulations, which position is exemplified in Fig. 5.

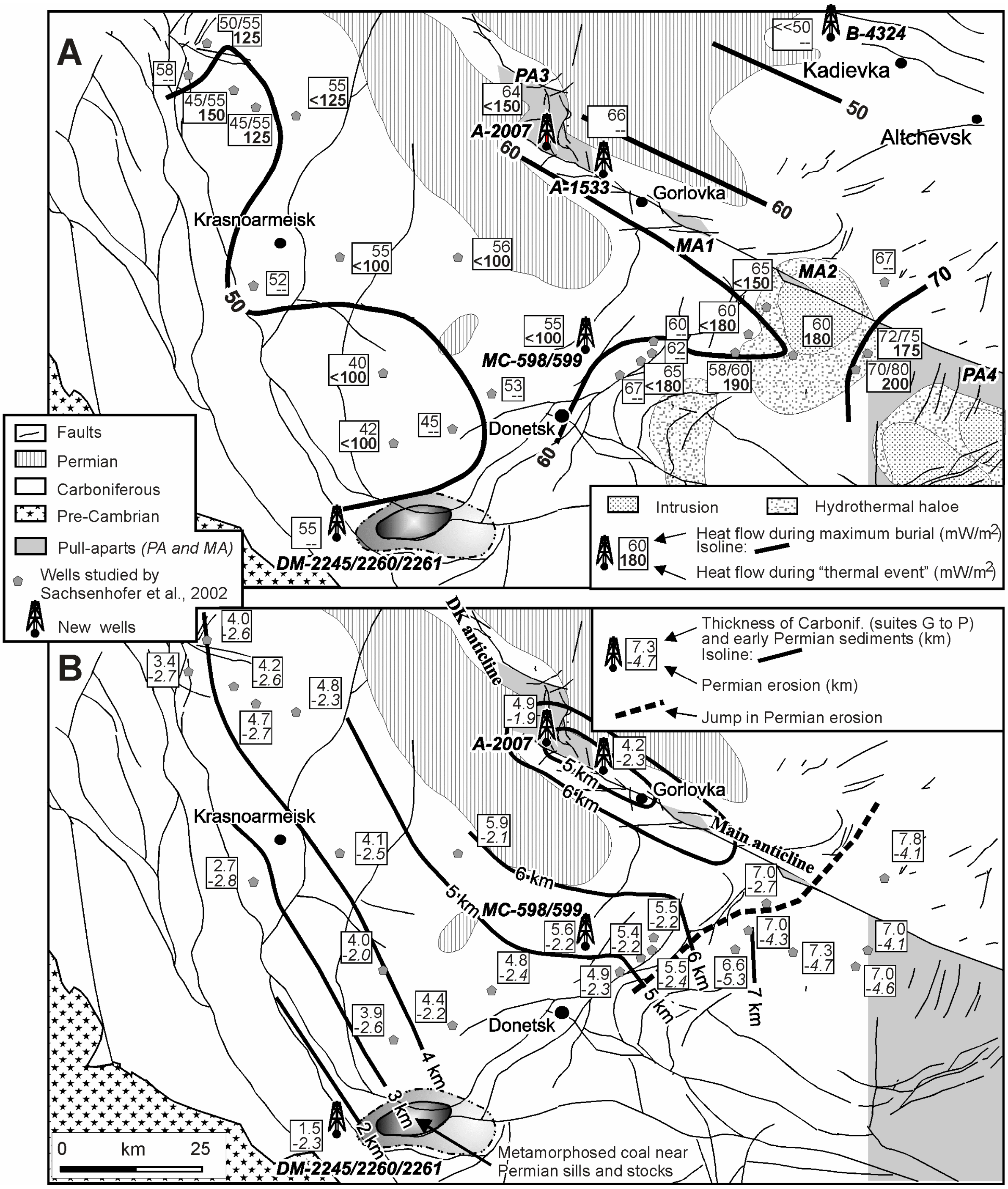

Fig. 4. Results from 1-D models [17]: A) heat flow distribution during maximum burial; B) map showing thickness of Middle/Upper Carboniferous interval from suite G (C_2^2) to suite P (C_3^3) and Early Permian rocks. The thickness of rocks removed during Permian erosion is also indicated (negative numbers).

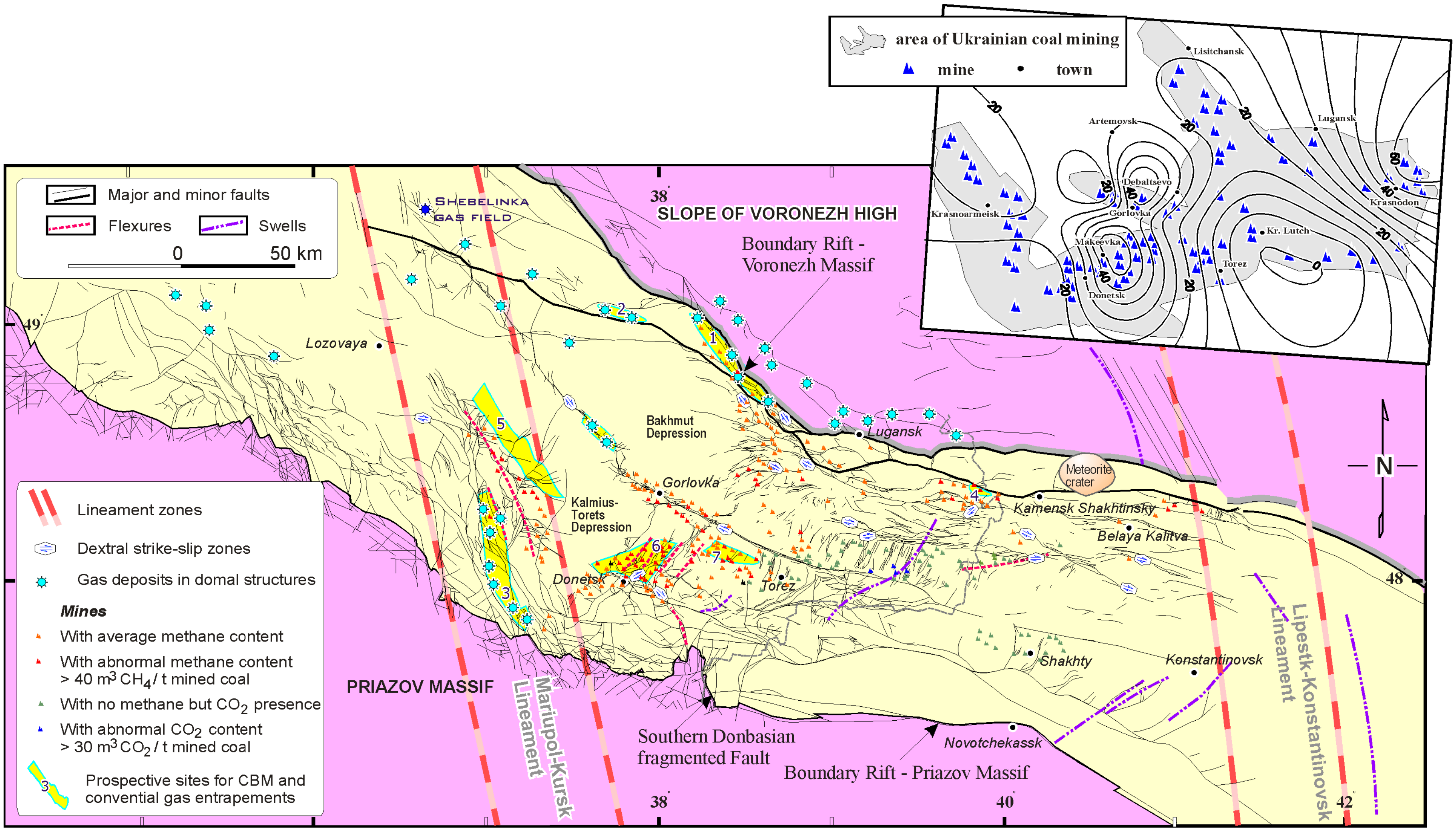

Fig. 5. Tectonic map of the Donets Basin. The position of mines with different gas regimes, gas deposits in domal structures and prospective sites for conventional gas and CBM accumulations is shown. On the inset map of real observed methane content in coal mines (m³/t of mined coal) at 1000m depth is shown

These are related with: a) the thermal effects of post-inversion Late Permian-Triassic magmatic intrusions, e. g. within prospective site #7, where methane accumulation is structurally gravitated to local extension zone in bottom part of syncline (Fig. 6) or site #5, where Carboniferous reservoirs are overlapped, like in Shebelinka, by impermeable Permian-Mesozoic cover; b) high levels of pre-inversion heat flow in moderately uplifted areas, e. g. site #6, wherein at the Zasyadko coal mine local drainage or degasification systems, for capturing gas of commercial quality have been successfully installed with steadily growing gas production.

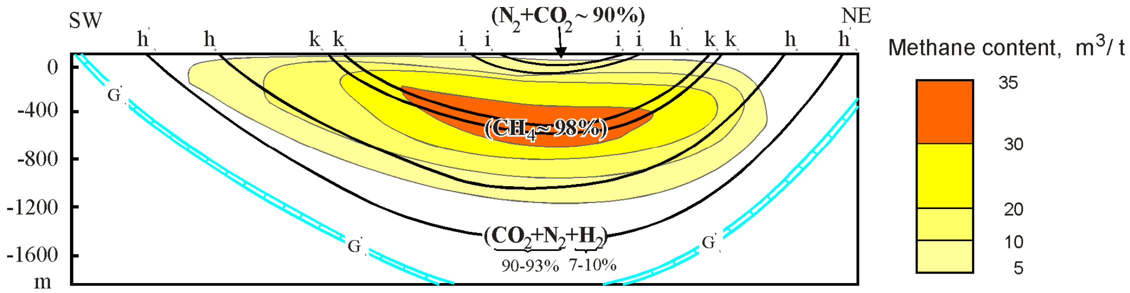

Fig. 6. Geological section demonstrating structural trap of methane in syncline located west of Torez [14].

Conclusion

Carboniferous coal-bearing measures of the Donbas have the best coal gas resource potential in areas: (1) of moderate uplift with high levels of pre-inversion "burial" heat flow; (2) post-of inversion thermal pulse occurrence; (3) wherein dextral shear belts facilitated gas migration and an impermeable Permian-Mesozoic cover provided a seal.

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