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The Importance of Tectonic Control in Delineation of CBM Production Sweet Spots in the Donets Basin (Ukraine)

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SUMMARY

The Donets Basin is a major coal-mining district in Ukraine. Coal mines in the Donets Basin are amongst the gassiest in the world. Most of the mines are operated within thrust-bounded domains with abundant occurrence of small-displacement strike-slip tectonic zones. Special attention needs to be given to analysis of local tectonic-and-structural regimes affecting coalbed methane producibility and resource assessments. Permeability patterns and, more specifically, lateral variations of methane content in coal beds are critically dependant upon present stress-state state and spatial distribution of local extension-compression domains. It has been observed that CBM production sweet spots, which tend to occur at relatively high permeability compartments, are typically structurally controlled by releasing bends or dilation traps located along strike-slip tectonic zones. The presence of fractured reservoir of pull-apart morphology in sandstones of Krasnolimanskaya mine is depicted on the basis of analysis of gravimetric and 3D seismic data

Introduction

The Donets Basin (Ukraine/Russia) has a centuries-long history of coal exploration and mining. Very thick Carboniferous sedimentary deposits, that included significant organic material, were accumulated repeatedly throughout 14 km thick Late Viséan-Serpukhovian-Pennsylvanian succession. These formations subsequently were buried and uplifted in such a way that economically important hydrocarbon (especially coal) resources formed at economically exploitable depths in the Earth. The Donets Basin (Donbas) contains one of the major coal fields in the world. Thermal maturation of concentrated in coal beds and dispersed in the Carboniferous host rocks organic matter has led to formation of an enormous methane resource. Most of the mines are operated within thrust-bounded domains with abundant occurrence of small-displacement strike-slip tectonic zones. Emissions of coal gas released by mining and related structurally induced underground hazards (coal-and-gas outbursts) are a major problem for safe and efficient coal exploitation in the basin. In the course of mining in the Donets Basin, about two billion cubic meters of methane gas a year are vented into the atmosphere, which could otherwise be captured and used to produce heat and electricity.

Methods

Interpretations and conclusions presented in this paper are based on information from reports provided by several research entities. The database of exploratory drilling, structural maps and geological sections combined with results of gravimetric, 2-D and 3-D seismic surveys for mine-scale sites were used to delineate tectonic framework for sites of particular significance for further exploration.

Results and discussion

The Carboniferous basin fill hosts 330 identified coal seams and layers to a depth of 1800 m. Total coal thickness in Carboniferous suites and lithological composition of suites are shown in Table 1.

Table 1. *Total coal thickness in Carboniferous formations and lithological composition of suites, based on results of deep parametric wells drilling.*

Suite	Suite thickness. m	Number of seams of fixed thickness and total coal seams thickness, m			Coefficient of coal occurrence, % for coal seams of thickness, m			Ash content
		>0.60	0.59–0.45	0.44–0.10	>0.60	0.59–0.45	0.44–0.10	A^d. %
Ocheretino well K-900 / *Total penetrated coal thickness 31 m*								
C_3^2	749	–	–	4 / 0.54	0.0	0.0	0.27	31.9
C_3^1	746	–	1 / 0.52	10 / 2.28	0.0	0.07	0.38	17.4
C_2^7	488	7 / 6.30	7 / 3.57	8 / 1.70	1.29	2.02	2.41	23.8
C_2^6	281	5 / 4.12	2 / 1.02	10 / 2.60	1.47	1.79	2.78	19.3
C_2^5	420	4 / 3.44	1 / 0.48	12 / 2.73	0.8	0.93	1.58	10.4
C_2^4	*Penetrated 175.6m*	–	1 / 0.46	7 / 1.80	0.0	0.26	1.00	21.7
Makeevka well Tsc-1027 / *Total penetrated coal thickness 39m*								
C_3^1	549	1 / 0.86	0.0	8 / 1.38	0.15	–	0.40	15.2
C_2^7	595	5 / 4.18	3 / 1.66	15 / 3.98	0.70	0.98	1.65	16.6
C_2^6	322	6 / 6.19	1 / 0.58	12 / 3.58	1.76	2.10	3.22	25.4
C_2^5	509	8 / 7.57	1 / 0.50	14 / 3.79	1.49	1.58	2.33	23.8
C_2^4	316	0 / 0	2 / 1.13	5 / 1.76	0	0.37	0.91	
C_2^3	*Penetrated 200m*	1 / 0.88	0 / 0	5 / 0.98	0.44	–	0.93	
Tchistyakovo well C-1379 / *Total penetrated coal thickness 31 m*								
C_2^5	656	9 / 8.29	5 / 2.77	13 / 3.27	1.26	1.67	2.19	27.5
C_2^4	362	1 / 0.93	0 / 0	11 / 2.99	0.26	0.26	1.08	30.8
C_2^3	672	6 / 6.28	1 / 0.50	17 / 4.32	0.92	1.01	1.63	27.5
C_2^2	*Penetrated 155m*	–	–	4 / 1.14	0	0	0.74	24.5

CBM accumulations were formed in the Donets Basin during a number of different phases:

- the first phase of formation of primary pre-inversion methane deposits took place in the Carboniferous - Early Permian. This occurred during the Carboniferous and Early Permian burial before the Permian uplift and resulted from an intensive gas-generating process due to suitable thermic conditions and to the richness in the organic matter of Carboniferous formations, and that was combined with sedimentation. Coaly clastics and coal seams could have sourced the gas also at deep levels of the basin *(Alsaab et al, 2008; Alsaab et al, 2009)*. The isotopic composition of carbon $\delta^{13}C$ plotted vs. dryness of the gas from CBM deposits of the Donbas *(Privalov et al., 2004),* conventional gas deposits of the Northern margin of the Donbas and Shebelinka gas field in the Dnieper-Donets Basin *(Antsiferov et al., 2004)* clearly indicates the thermogenic origin of the methane. According results of artificial maturation of coal samples (Sepukhovian seam c_2^{10}, mine Yuzhno-Donbaskaya #3, R_o = 0.73 %; Moscovian seam l_1, Dimitrova mine in Krasnoarmeisk region, R_o = 0.62 %) thermal generation of gas from humic coal beds begins at 0.7% R_o. Large amounts of methane (up to 81 mg/g coal) are formed at high temperatures by cracking of previously formed heavier hydrocarbons and by desalkylation from the coal matrix. Peak methane generation may occur at levels of thermal maturity between 2.5–2.8% R_o *(Privalov et al., 2006)*. In terms of coal rank, the coal in the Donets Basin ranges from lignite to bituminous and anthracite. The rank of the coals is controlled mainly by temperatures attained during deep Early Permian burial *(Sachsenhofer et al., 2002)*. Anomalously high coalification, including spatially restricted natural coking or graphitization volumes, is observed in close vicinity (several meters) to magmatic gabbro - monzonite-syenitic sills and stocks of Permian age (~275 Ma) south-west of Donetsk. The amount of heat was not high enough to switch regional heat flow. The relationship between Ukrainian coal rank scale and international coal rank is shown at the Figure 1.
- the second phase occurred in the Carboniferous formations during the Late Permian inversion, when a major part of the Donets basin has been strongly uplifted and deformed during the latest phases of Hercynian orogeny. This contributed to intensive redistribution of gases in the sedimentary rocks and to the escape of the major part of gas deposits. Also, post-Permian (presumably Early Cretaceous) inversion episode is proved in the Donbas by fission track basin modeling and low-temperature thermometry *(Danisik et al., 2010)*. In the area of the Donbas Foldbelt, the amplitude of ascending vertical movements, that were characteristic for inversion, ranged from 4 to 11 km;
- the third phase of post-inversion methane generation related with thermal effects of post-inversion Late Permian-Triassic andesitic magmatic intrusions (~250 Ma) of regional importance. This heating event had overprinted the Permian maturity patterns and significantly distorted them in some domains.
- the forth phase of new coalbed methane short-track migration pulses and enhanced a role of multifold and multistage trapping within fractured and sealed secondary reservoirs during Cimmerian and Alpine tectonic events resulted in multiple fault reactivations, de-planation of already deformed strata surfaces, formation of linear and subconcentric shallow dextral shear belts in the sedimentary cover (Figure 2, *a*).

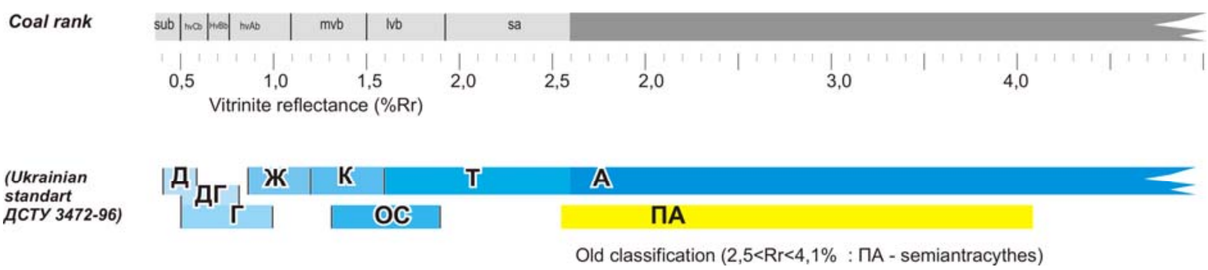

Figure 1*: Relationship between Ukrainian coal rank scale and international coal rank classification.*

Most of methane in coal beds is sorbed onto microporous surfaces of coal beds and dispersed coaly matter in rock massive. The significant methane resource is expected as result of conventional trapping related with gas migration and permeability contrasts of tectonic and lithological origin. Much attention has been recently given to exploration using coal rank analysis and burial history reconstruction *(e.g. Panova et al., 2005)*. Much more attention needs to be given to analysis of local tectonic-and-structural regimes affecting CBM producibility and resource assessments. Permeability patterns and, more specifically, lateral variations of methane content in coal beds are critically dependant upon present stress-state state and spatial distribution of local extension-compression domains. It has been observed *(Panova and Privalov, 2003)* that CBM production sweet spots, which tend to occur at relatively high permeability compartments, are typically structurally controlled by releasing bends or dilation traps located along strike-slip tectonic zones.

Figure 1, *b* demonstrates results of fractal treatment of gravimetric data *(Bulat et al., 2007)* based on transformation of *Saxov and Nygaard (1954)* in the area of the Ukrainian Donbas.

The depicted basement fault pattern (Figure 1, *c*) advocates: (1) prominent structural control of distribution of conventional gas deposits in dome-type and fault-breached structures within Donbas margins; (2) presence to north from Lugansk a set of dextral shear belts, that can facilitate gas migration; (3) presence in Krasnormeisk monocline area of dextral strike-slip zone containing row of CBM production sweet spots (relatively high permeability compartments) within severe domains of local extension.

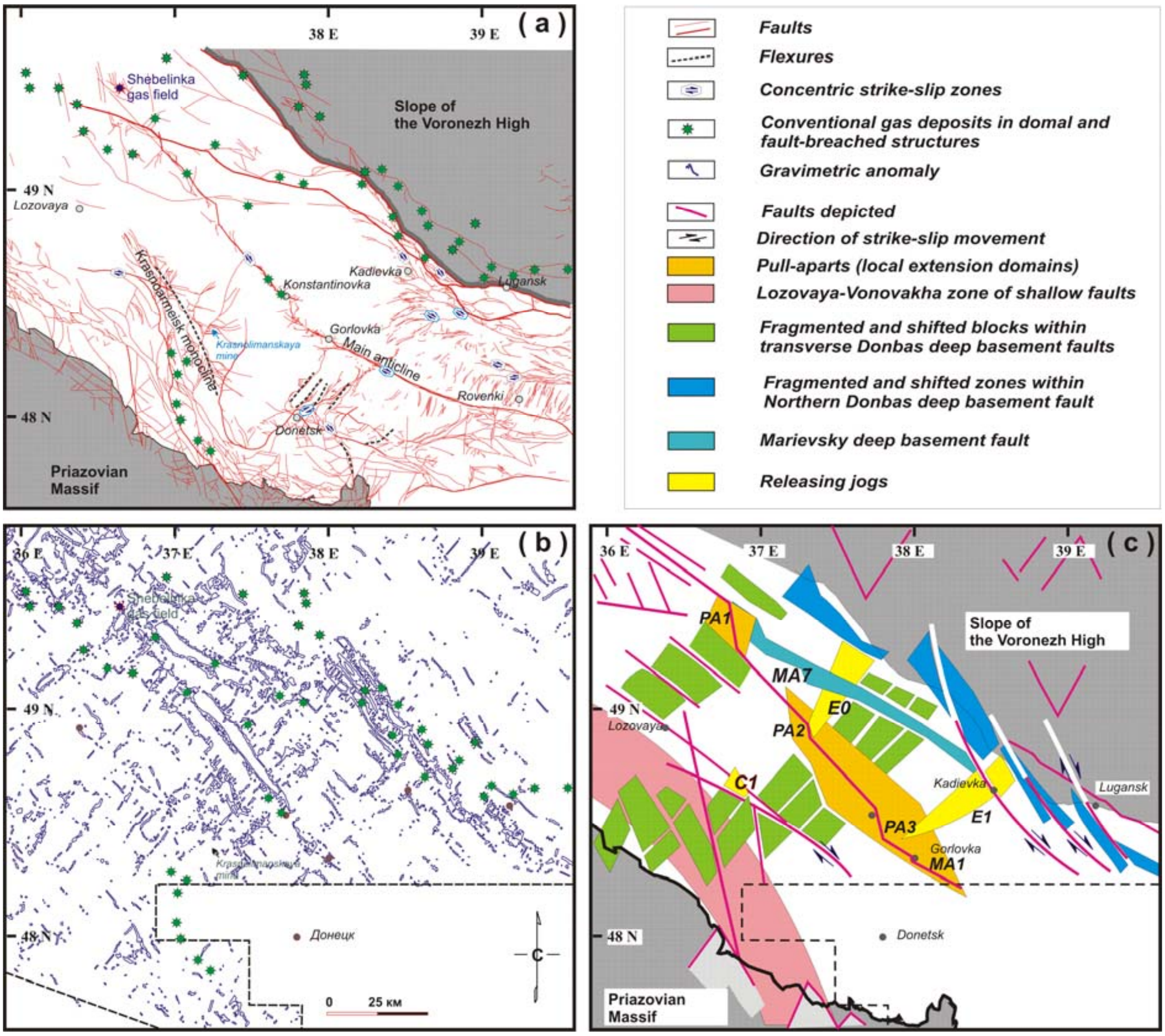

***Figure 2**: a- Tectonic map of the western part of the Donbas; b- results of fractal treatment of gravimetric data; c - depicted deep basement patterns. The location of C1 sector with releasing environment due to block rotation and tectonic escape is shown.*

The presence of fractured reservoir of pull-apart morphology in sandstones here can be proved by results of 3D seismic exploration techniques. Figure 3 shows location of faults and horizontal slice of

3D seismic cube within Krasnolimanskaya mine with characteristic geometry of released jog between junction of two regional “normal faults” (in fact, these are dextral shears). The Krasnolimanskaya mine is one of the most dangerous coal mines in the basin due to naturally high levels of methane, relatively high permeability of coal-bearing strata and significant risk of coal dust explosion hazards. Here within the Krasnolimanskaya mine gas accumulations are coincided with sandstones horizons l_7Sl_6, l_6Sl_5, l_5Sl_4, l_4Sl_3, l_2Sk_7, k_7Sk_5: open porosity of these is varying from 10.58 to 4.68%, permeability is in range 0,06 –0,69 mD. Free bitumen showings are recorded within horizons m_8Sm_9, M_5Sm_5, $m_4^1Sm_3$, $l_8Sl_8^1$, $l_4^1\ Sl_5$, L_7Sl_7, k_8Sl_1, $k_9Sk_7^5$, $k_7^2Sk_9$, $k_7^1Sl_7^2$ (mainly in region of Glubokoyarsky fault). Maximal gas content is documented as 14.0, 14.0, 20.1, 27.8, 24.3, 26.6, 24.1, 25.4 m^3/t^{daf} within seams m_6^2, m_4^2, l_7, l_5, l_4, l_3, k_7, k_5 at following depths 338, 429, 406, 467, 538, 632, 634, 980 m (or altitudes below sea level -182, -242, -420, -288, -453, -447, -819, -1005 m). It has been observed here that the most intensive methane emissions during underground mining coal seams are typically related with zones of active recent migration of hydrocarbons from deeply seated dilatational traps.

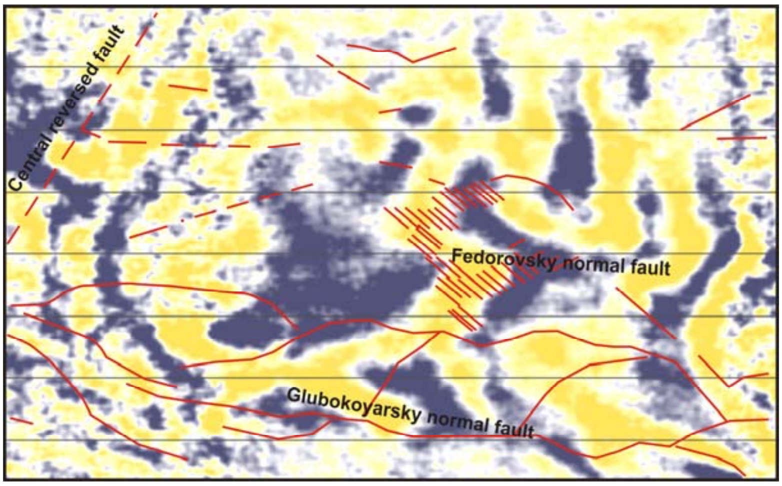

Figure 3: *Horizontal section of 3D seismic cube within Krasnolimanskaya mine in Krasnoarmeisk monocline region.*

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