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Distribution of thermogenic methane in Carboniferous coal seams of the Donets Basin (Ukraine): "Applications to exploitation of methane and forecast of mining hazards"

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ABSTRACT

The main purpose of this contribution is to estimate methane production and to define its migration paths and storage in the Donets Basin formations for exploitation of methane and forecast of mining hazards. In order to study methane migration and storage, maps of production calculated by 2D modelling, adsorption capacity of methane in coal, and present-day methane contents were constructed for an altitude of −300 m (close to 500 m depth) in this basin. The results show that three principal factors influenced the methane migration and accumulation in Donets Basin: 1) faults that acted as migration pathways, 2) a replacement of thermogenic methane by endogenic CO_2 in the central and SE parts, and 3) the occurrence of magmatic events in some areas in this basin. Finally, in Donbas, the areas with the highest methane potential and the maximum risk of outburst are not the areas with anthracite that produce the highest volume of methane, but areas with volatile bituminous coals where an impermeable cover preserved the accumulated gas until the Cenozoic and where dextral shear belts facilitated its migration.

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1. Introduction

Coal is known as a source of hydrocarbons (HCs), especially methane, and it can also play the role of reservoir rock, where coal is able to store an important quantity of generated hydrocarbons (Béhar et al., 1995; Hunt, 1996). The generation of thermogenic gas in coal basins takes place beginning at high-volatile bituminous stage (~0.6% R_r). However, vitrinite reflectance (R_r) values need to be between 0.8% and 1.0% before large volumes of thermogenic gas can be generated (Scott, 2002). Beyond this R_r, the methane generation potential decreases with increasing rank of the coal. Experimental results indicate that the yield of methane is very low at a R_r of 3.5% (Friberg et al., 2000). Therefore the cumulative methane generation curve significantly increases between about 1.0% R_r and 3% R_r (Higgs, 1986). Methane, carbon dioxide, and water are the most important products of the devolatilization process (Rice, 1993). In absence of coal mining and drilling operations, the generation and entrapment of methane in coal seams are affected by several factors such as coalification level, the capacity of coal to adsorb generated methane, related with coal type and the microporosity in this coal, geological structures of compressional and extensional origin, erosional processes and endogenic CO_2. As a consequence, the knowledge of the volume of methane generated from coal seams during natural coalification is almost impossible.

Several ways have been proposed to overcome the restrictions of the above mentioned factors in predicting the volume of methane generated from coals. The first models have been established from mass balance calculations based on changes in elemental composition with coal rank (Jüntgen and Karweil, 1966; Jüntgen and Klein, 1975). Depending on several parameters, such as maceral compositions and initial coal rank, the estimated methane yield ranged from 100–300 m^3/ton of coal (Jüntgen and Karweil, 1966; Stach et al., 1982; Ermakov and Skorobogatov, 1984; Meissner, 1984; Levine, 1987; Krooss et al., 1995; Clayton, 1998; Flores, 1998). The second way used laboratory pyrolysis methods to determine the coal capacity to HCs generation, especially the methane because it is the major HCs component generated there. There is a limited amount of data on the generation of gas from Carboniferous coals during heating experiments. Different pyrolysis systems, such as open (Krooss et al., 1995; Friberg et al., 2000; Cramer, 2004), anhydrous closed (Higgs, 1986),

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hydrous (Kotarba and Lewan, 2004), MSSV (Schenk and Horsfield, 1998), and confined (Piedad-Sánchez et al., 2005) have been used to estimate the gas-generating potential of Carboniferous coals. Two Carboniferous coals from the Donets Basin in the Ukraine (Alsaab et al., 2007b) were pyrolysed in a confined pyrolysis system, covering a maturity range from 1.07 to 2.78%R_r. Methane was quantified and its evolution with coal rank was reported by Alsaab et al. (2008a). Significant differences in methane generation are observed among the afore-mentioned approaches, with yields increasing in the following order: hydrous pyrolysis < open pyrolysis < closed pyrolysis < elemental-composition models. Such an evolution is mainly attributed to pyrolysis conditions and reacting medium (Krooss et al., 1995; Kotarba and Lewan, 2004). The lower estimates of methane amounts made from heating experiments relative to mass balance approaches may be more realistic. However, the ability of a pyrolysis system to predict the quantities of thermogenic methane should not be based only on the amounts yielded during artificial maturation compared to those existing in thermogenic coalbed gas. For example, Thielemann et al. (2000, 2004) reported that 99% of the thermogenic methane escaped during geological history within the Ruhr Basin.

Carboniferous coals are recognised to be the sources of thermogenic coalbed methane (CBM) in numerous basins (Kotarba, 1988; Rice, 1993; Krooss et al., 1995; Freudenberg et al., 1996; Juch, 1996; Fails, 1996; Murray, 1996; Bodden and Ehrlich, 1998; Schenk and Dieckmann, 2004; Privalov et al., 2004b). Methane normally dominates the seam gases but other gases may also be present (hydrocarbons gas, CO_2, N_2 etc). The amount of methane stored in coal seams can be up to 25 m^3/ton of coal (Lunarzewski, 1998).

The third way concerns the integrated petroleum systems modelling that use kinetic models established on the basis of pyrolysis experiences allow to predict the generation of gas, migration pathways, and accumulation in a sedimentary basin. An independent approach, based on numerical modelling using field data (Alsaab et al., 2008b), was used to construct a methane generation map in this paper. Maps of adsorption capacity and present-day methane contents were added to better understand the migration and accumulation of methane. Finally, applications to exploitation of methane and forecast of mining hazards were proposed in Donets Basin.

2. Geological settings and timing of coalbed methane formations

The Donets Basin, named Donbas by Ukrainian geologists (Fig. 1) is located in the south-eastern part of Ukraine, extending into the territory of Russia. Geologically, the Donets Basin represents a large bending flexure that covers an area of approximately 60,000 km^2 (Triplett et al., 2001; Sachsenhofer et al., 2003). Donbas is located between the Dnieper-Donets Depression Basin and the buried Karpinsky Ridge within the limits of a continuous Devonian rift system that developed along the margin of the East-European Craton (Chekunov, 1976; Chekunov et al., 1992; Stovba et al., 1996). Among the set of rift structures the Donets Basin is the most anomalous segment: it stands out by its up to 24 km sedimentary column with prominent inversion (Stovba et al., 1996).

This basin is one of the major late Paleozoic coal basins in the world with proven reserves in the order of 60 Gt. The stratigraphy of Donbas was described by Sachsenhofer et al. (2003). The coal-bearing strata consist of cyclic successions of marine, continental and transitional facies. An elementary sequence (20 to 40 m thick; Sachsenhofer et al., 2003; Izart et al., 2006) is composed of fluvial sandstone (10 m thick, 10% porosity), coal seam (1–2 m thick), marine limestone (1 m thick) and claystone (10 m thick) and deltaic siltstone (10 m thick). The thickness of the Carboniferous coal measured in the Donets Basin increases from the basin margins towards the basin centre and in a south-eastern direction. Maximum Carboniferous thickness is about 14 km. Total coal thickness in Carboniferous formations is about 60 m. There are over 330 identified coal seams to a depth of 1800 m. However, only a hundred seams are considered mineable due to either thin nature or depth constraints (Privalov et al., 1998).

CBM deposits were formed in the Donets Basin during two different phases (Triplett et al., 2001; Alsaab et al., 2008b):

i) the first phase of formation of primary vertical gas deposits was completed in the Upper Palaeozoic. This occurred before the Permian uplift and resulted from an intensive gas-generating process due to suitable thermic conditions and to the richness in OM of Carboniferous formations, and that was combined with massive sedimentation during Carboniferous,
ii) the second phase occurred in Carboniferous formations at the time when the geologic bending flexure was developed, during the Late Permian inversion. Given the complex nature of inversion and exposure of the coal-bearing strata, the process of gas migration prevailed over the process of its generation during this phase. This contributed to intensive redistribution of gases in the sedimentary rocks and to the escape of the major part of gas deposits. As a result, the initial gas deposits were transformed into the vertical and horizontal gas zones that encountered today.

The Permian uplift in the Donets Basin ranged from 2 km at western part to 11 km at eastern part. These movements caused surface exposure and erosion of coal beds that had been deposited in all zones of the initial vertical gas zoning. At the same time, gas of the uppermost part of the geological section escaped into the atmosphere and a gas-weathering zone was formed within this part (Triplett et al., 2001; Privalov et al., 2004a,b).

3. Methodology

By using PetroMod software version 09 SP3, IES GmbH, Germany on six cross sections (Fig. 1), a 2D modelling of burial and paleotemperatures of Donbas was done by Alsaab et al. (2007a, 2008b). The section 1 will be used in this paper to show calibration and define zones of maturity and recent gas migration. The methane generation at 500 m was calculated by this 2D modelling. Adsorption data came from 58 coal samples from Krivitskaya et al. (1985). The present-day methane contents in coals (m^3/ton of coal) came from 100 data points from Antsiferov et al. (2004) who measured the methane content in cores by the desorption canister method (Diamond and Schatzel, 1998). The present-day methane contents in coal mines (m^3/ton of mined coal) estimated considering the volume and composition of the ventilation stream in the mine, and the average tons of mined coal (tons/hour), came from 101 data points from Brizhanyev and Panov (1990) and Triplett et al. (2001). By using Surfer software, version 07 (Kriging algorithms) as well as calculated and published data, isolines maps at 500 m depth of vitrinite reflectance distribution, methane production, adsorption and present-day contents were generated in order to analyse the methane distribution in the Donets Basin.

4. Results and discussion

4.1. Methane production and storage in the Donets Basin

The vitrinite reflectance map (Fig. 2) is based on 58 data of volatile matter content (Krivitskaya et al., 1985), transformed into vitrinite reflectance according to the chart of Levenshtein et al. (1991). This map shows low values (<1.2%R_r) in the Krasnoarmeisk, Lisitchansk and Lugansk areas, intermediate values (1.4–2.0%R_r) in the Donetsk-Makeevka and Krasnodon areas, and high values (>2.5%R_r) in the Torez and Krasniy Lutch areas. Such a coalification pattern could be explained by (1) an eastward increase in burial depth, (2) an eastward increase in heat flow, and (3) magmatic activity observed in the SE part (Sachsenhofer et al., 2002; Spiegel et al., 2004; Alsaab et al., 2008b). The vitrinite reflectance from 40 wells (Alsaab et al., 2008b) allowed us to model the paleothermicity in Donbas along six sections.

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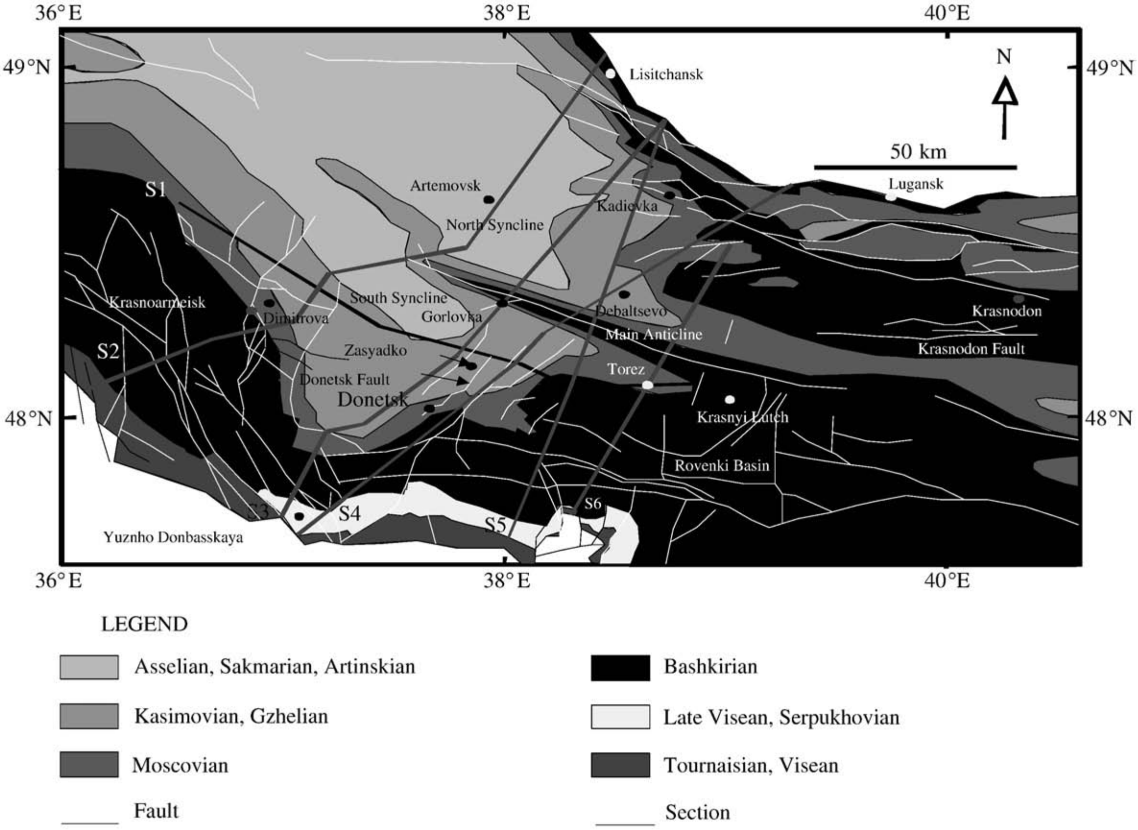

Fig. 1. Geological map of the Donets Basin (drawn after Makarov, 1990).

Fig. 3 represents the vitrinite reflectances along the section 1 obtained by the calibration between modelled and measured vitrinite reflectances in each well.

The map of the methane generation at 500 m was done on this basis of 2D modelling (Alsaab et al., 2008b). The kinetic model of methane generation from coal by Burnham (1989) was used in this

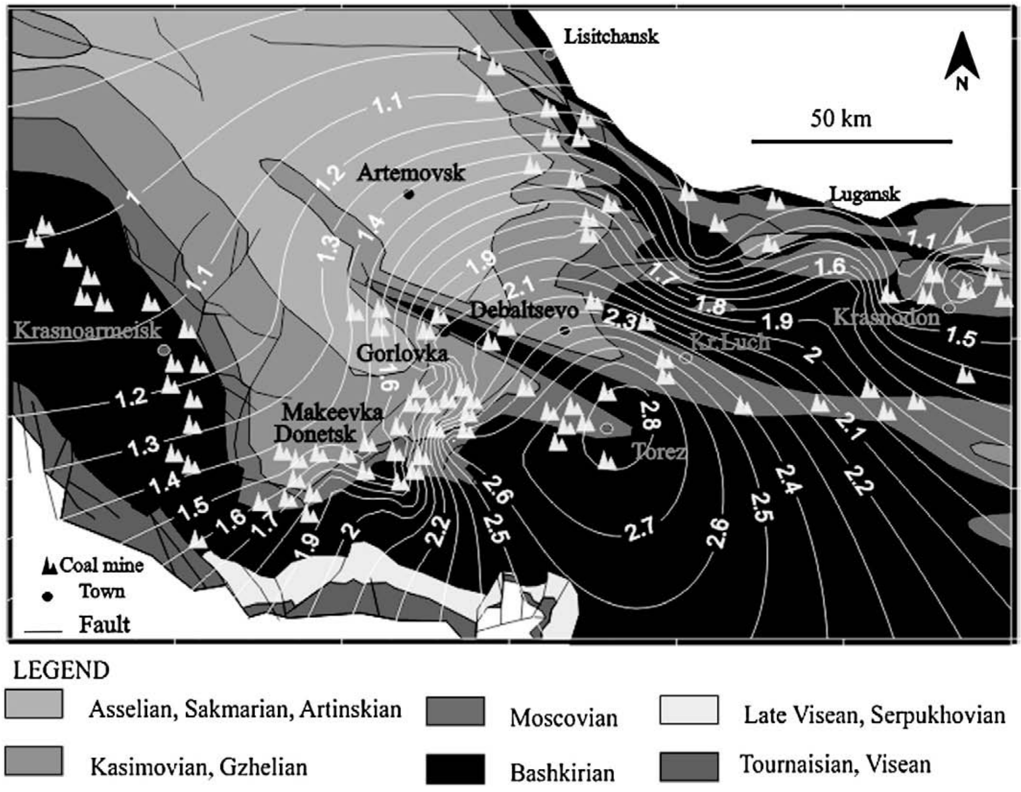

Fig. 2. Map showing the vitrinite reflectance (%R_r) distribution in the Donets Basin for an altitude of −300 m.

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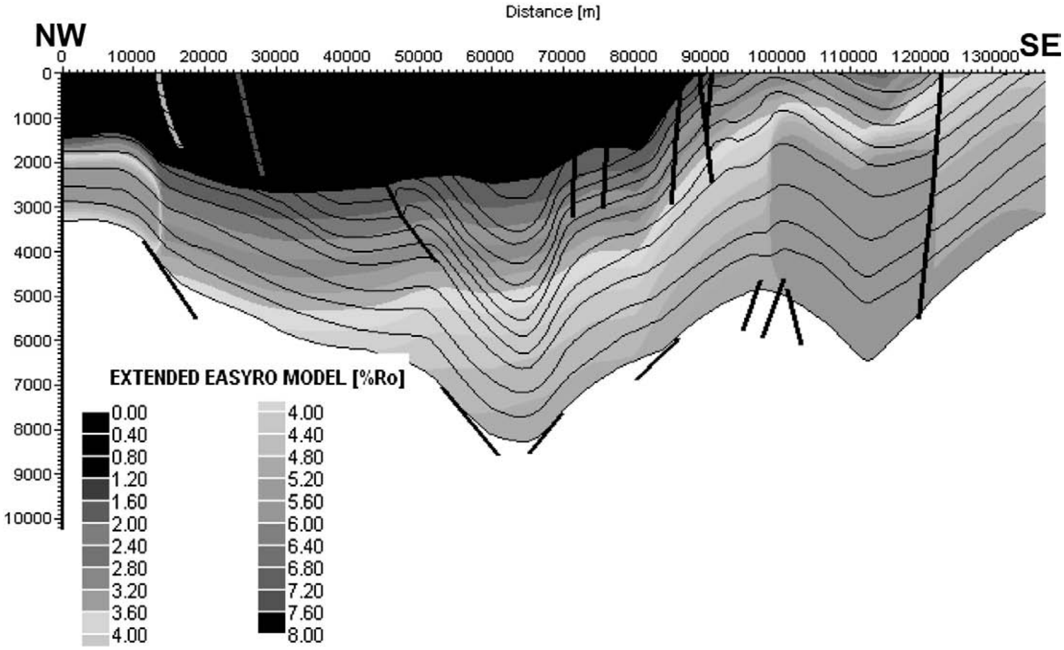

Fig. 3. The vitrinite reflectances in the section 1.

modelling. Fig. 4 shows the zones of maturity in the section 1, immature zone in the west to gas zone in the east and in the sections 3 and 4 that are located here and there the Zasyadko coal mine chosen for their proneness to outbursts. A great part of these transverse sections 3 and 4 shows gas zone, except the North and South syncline (Fig. 1) that presents immature zone and the main anticline overmature zone. Fig. 5 demonstrates that the generation of methane at 500 m was: (1) low (10–20 m^3 CH_4/ton of coal) in the north-western part, (2) middle (40–100 m^3 CH_4/ton of coal) in the western part (near Krasnoarmeisk), North and South syncline and main anticline, and (3) higher than 100 m^3 CH_4/ton of coal in the eastern and south-eastern parts of the Donets Basin. The calculation was made under a temperature of 30 °C corresponding to the temperature at this depth and with an average TOC equal to 82% for Donets coals and density of methane equal to 0.6457 at this temperature. These values that are obtained by modelling are equivalent to the methane volumes measured by pyrolysis by Alsaab et al. (2008a) on Donets coals at the same vitrinite reflectances.

The map of methane adsorption capacity (m^3/ton of coal, Fig. 6) is based on adsorption data from 58 coal samples (Krivitskaya et al., 1985). Langmuir sorption isotherms were built for diverse coals under pressure between 0.1 and 5 MPa and temperature equal to 30 °C. Its shows low adsorption capacities (10 m^3/ton) in the Krasnoarmeisk, Lisitchansk and Lugansk areas, intermediate capacities (5–25 m^3/ton) in the Donetsk, Makeevka and Krasnodon areas and high capacities (>30 m^3/ton) in the Torez and Krasniy Lutch areas (Fig. 6). The porosity measured by Krivitskaya et al. (1985) in Donets coals exhibits values from 7 to 20% below $\%R_r = 1$, from 6 to 8% between $\%R_r = 1$ and 3, and from 10 to 13% for $\%R_r$ above 3 in anthracites. This change of porosity is similar to Fig. 1 of Rodriguez and Lemos de Sousa (2002). The decreasing of porosity values for $R_r = 1–3$ is related to the generation of bitumen that stay in pores and also to the pressure effect (porosity decreasing), then the increasing of porosity for $R_r > 3$ is related to the cracking of bitumen into gas that escaped and/or adsorbed in micropores. The capacity of methane adsorption in coal decreases upon $\%R_r$ of 3–3.5 due to the disappearing of micropores and the generation of vacuoles (Huang, 1999; Alsaab et al., 2007b). Thus if we go far, till $\%R_r$ of 4 the adsorption capacity will decrease too.

The map of present-day methane content in coals (m^3/ton of coal; Fig. 7) was constructed using 100 data points from Antsiferov et al. (2004) by the desorption canister method. A relationship between desorbed methane and vitrinite reflectance was established after these data for $\%R_r$ from 0.6 to 2.0:

$$\left[\mathrm{CH_4}\,(\text{in m}^3/\text{ton of coal}) = 6.89 \times (\%R_r) + 2.07\right] \qquad (1)$$

For the highest values of vitrinite reflectance corresponding to the anthracite the methane content was equal to 0 in the Torez area because methane is replaced by endogenic CO_2 in this sector (Privalov et al., 2004a).

This map shows that the methane contents are nil in the Torez area and present a maximum of 17 m^3/ton near Donetsk close to faults, in the main anticline (M, Fig. 1, Gorlovka) and South and North synclines (S and N, Fig. 1) located South and North of this anticline and also in the Krasnodon area.

Another map of present-day methane content in coal mines (m^3/ton of mined coal, Fig. 8) was constructed using 101 data points from Brizhanyev and Panov (1990) and Triplett et al. (2001). Methane contents have been estimated considering the volume and composition of the ventilation stream in the mine, and the average tons of mined coal (tons/hour). Fig. 8 shows that methane contents are 5–10 m^3/ton in the Lisitchansk and Lugansk areas, 20–40 m^3/ton in the Krasnoarmeisk area, 20–60 m^3/ton in the Donetsk-Makeevka area, and higher than 90 m^3/ton in the Krasnodon area. These values are over-estimated if we compared with data obtained with desorption canister method (Fig. 7) because this methane is probably not stored only in coals, but also in sandstones and faults. But this method is interesting because it allows the mapping of the areas with the maximum risk of outburst. Surprisingly, very low methane contents (0–5 m^3/ton) are measured in the Torez and Krasniy Lutch areas in ventilation stream and with desorption method (Privalov et al., 2004a).

As we can notice in comparing the previous maps, in the central part of Donbas the methane generation potential (~150 m^3/ton of coal, Fig. 5) is significantly higher than the maximum adsorption capacity (30 m^3/ton of coal, Fig. 6). Thus, large amounts of methane must have escaped from coal seams during evolution of the Donets Basin. Basin modelling suggested than most of the generated gas was

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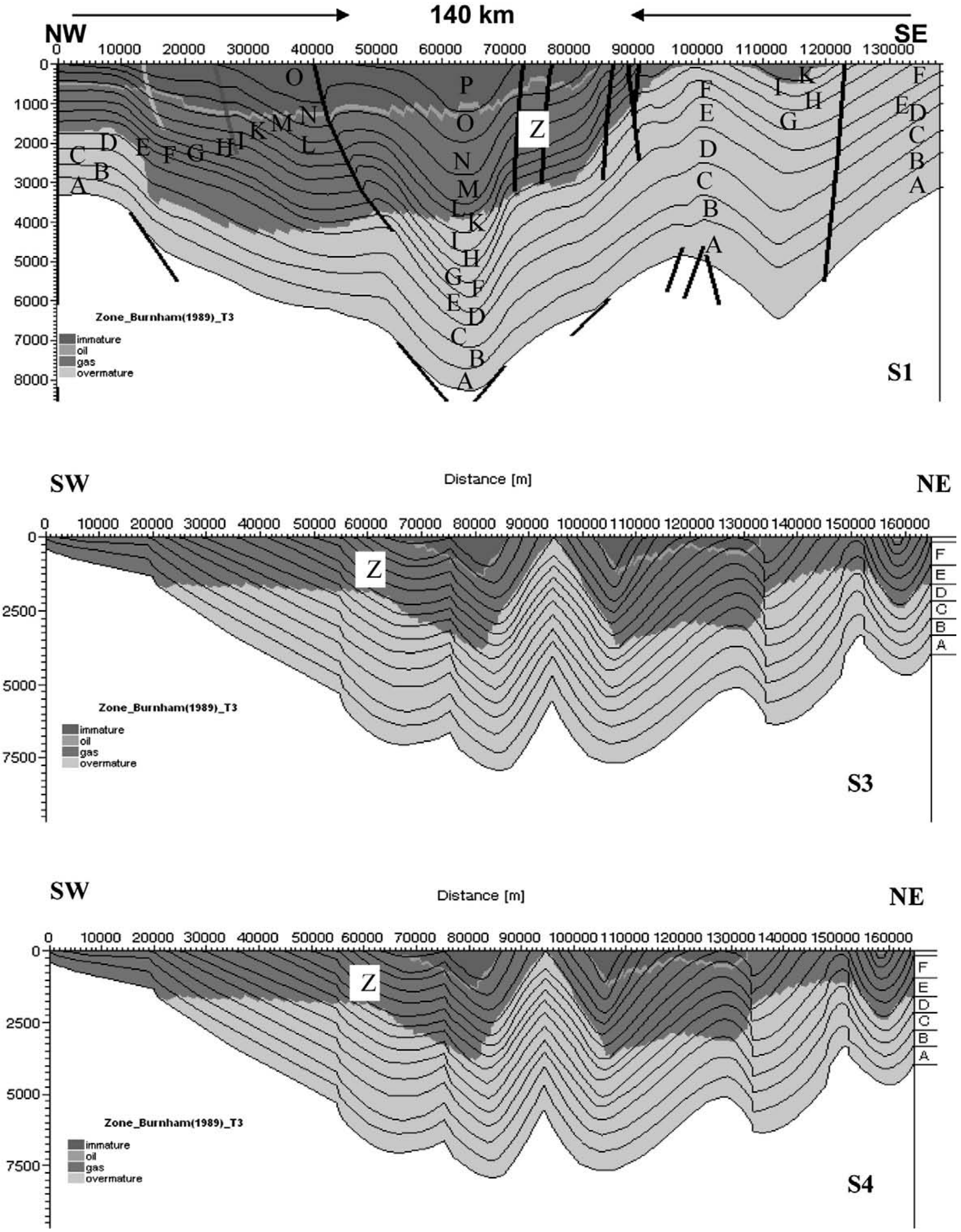

Fig. 4. Zones of OM maturity in the sections 1, 3 and 4. A: Tournaisian and Early Viséan, B: Late Viséan, C and D: Serpukhovian, E, F, G, H and I: Bashkirian, K, L and M: Moscovian, N and O: Kasimovian P: Gzhelian and Z: location of the projection of the Zasyadko coal mine.

lost during the late Permian and Cretaceous uplifts and during the Cretaceous and Tertiary erosional phases (Privalov et al., 2004a; Alsaab et al., 2008b).

Present-day methane contents measured by canister are slightly lower than adsorption capacities in the Krasnoarmeisk, Donetsk-Makeevka and Krasnodon areas (Figs. 7 and 8). In the anthracite zone with the better generative zone of methane (Torez and Krasniy Lutch areas), the present-day methane contents are close to zero. Additional tectonic data are needed to explain the distribution and/or redistribution of methane in Donbas.

4.2. Methane migration and distribution

The geological map of Donets Basin (Fig. 1) exhibits (1) a dextral shear belt consisting of NW–SE and NE–SW trending faults near Donetsk (DF in the SE part), and (2) a dextral shear belt consisting of W–E faults near Krasnodon (K in the eastern part of Donets Basin). It is very important to note that both shear belts formed during the Cimmerian and Alpine deformational stages (Privalov et al., 1998; Privalov, 1998), which post-dated gas generation. Therefore, it is likely that these faults played a significant role in gas redistribution and

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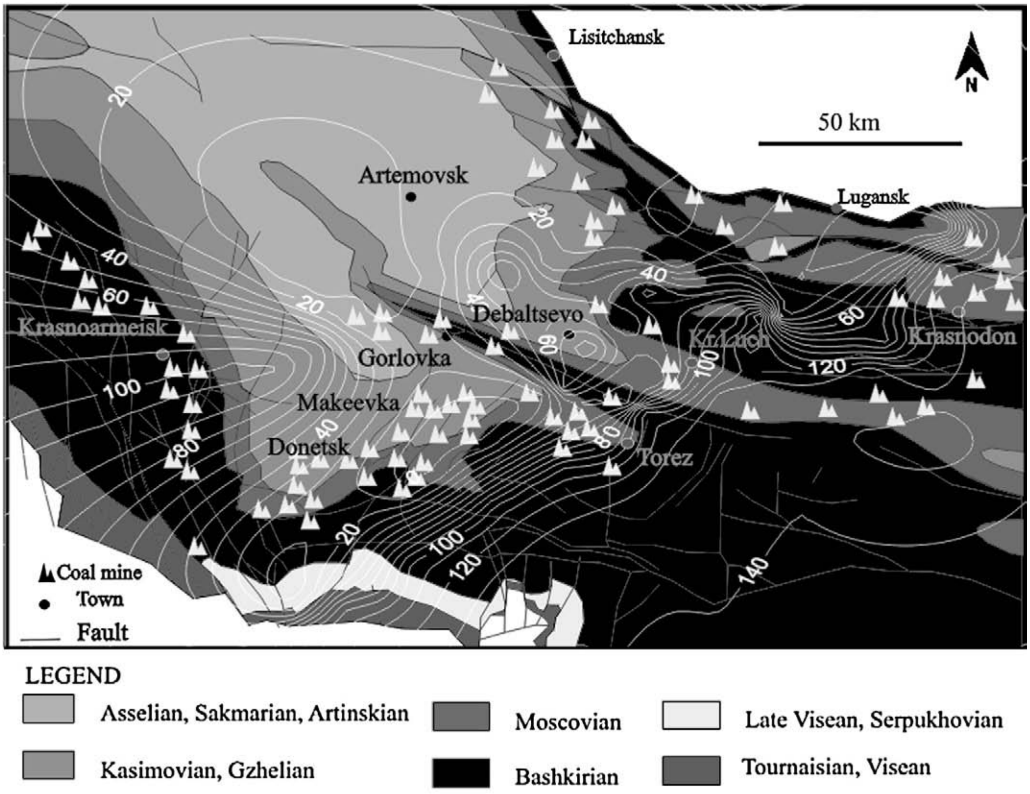

Fig. 5. Map showing methane generation (m^3/ton of coal) from 2D basin modelling in the Donets Basin for an altitude of −300 m.

concentration in the Donets Basin by providing effective migration pathways. Reconstructing the history of Donbas by 1D and 2D modelling, Alsaab et al. (2008b) suggested that the main phases of hydrocarbons generation occurred mainly during the Carboniferous and early Permian subsidence phases. Three pulses of hydrocarbon expulsion have also been predicted in the Donets Basin (Alsaab et al.,

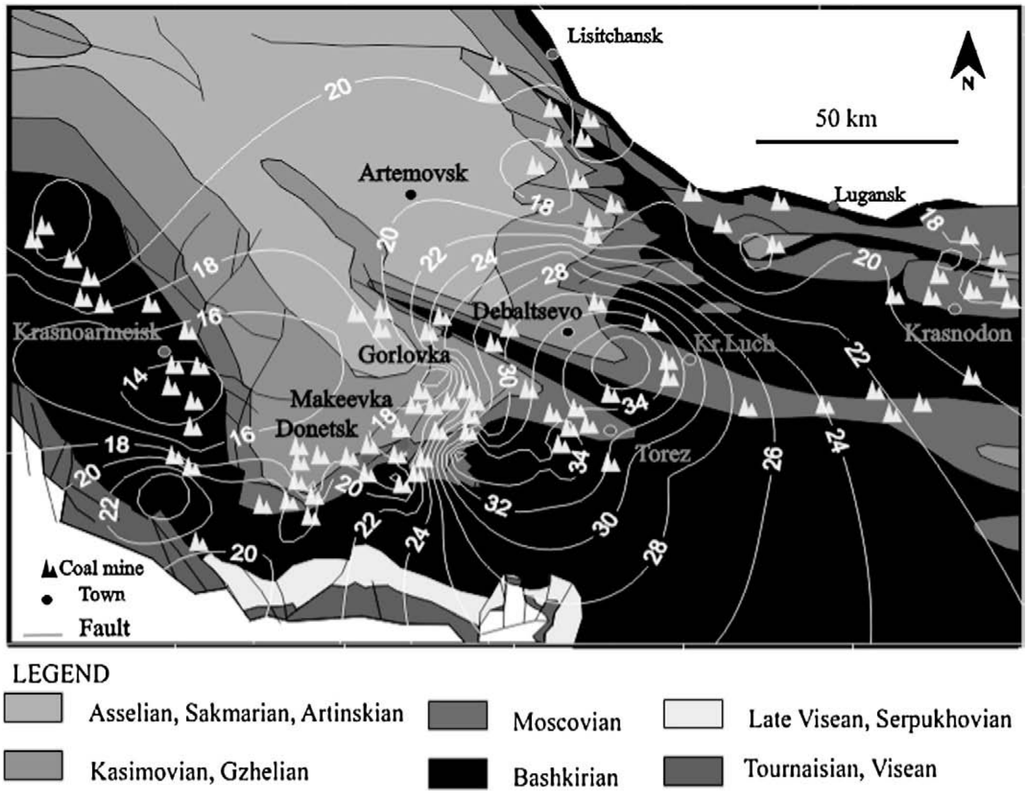

Fig. 6. Map showing the adsorption capacity of coal seams (m^3/ton of coal) for the Donets Basin for an altitude of −300 m.

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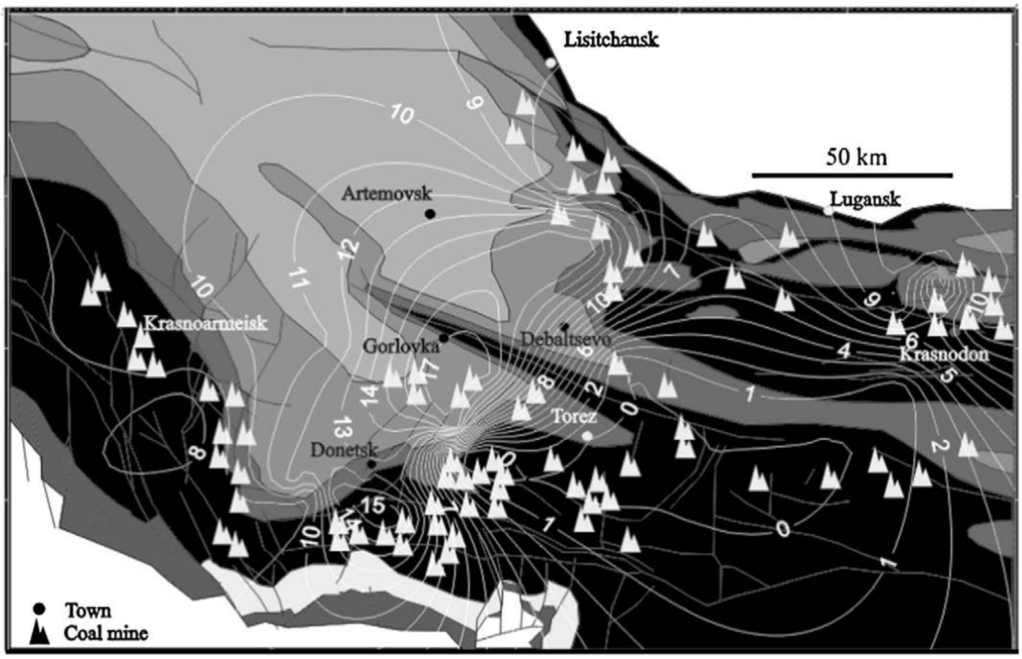

Fig. 7. Map showing the present-day methane content measured by the desorption canister method in coal mines (m^3/ton of coal) in the Donets Basin for an altitude of −300 m.

2008b). Their migration and entrapment likely occurred at times of basin inversion (late Permian and late Cretaceous) and during the tectonic reactivation of Donbas at Cimmerian and Alpine times (Privalov et al., 2003, 2004a,b; Alsaab et al., 2007a). This observation can help to understand, in part, the migration and the present distribution of the methane in the basin. For example, in the Donetsk-Makeevka area whereas methane content measured by ventilation stream is close to 60 m^3/ton (Fig. 8), gas migrated along faults and gas accumulations were focused on structural flexures and in the hanging walls of reversed faults (Privalov et al., 1998). Gas migrated and accumulated also along W–E faults near Krasnodon.

The Central and SE parts of Donbas (anthracite zones) correspond to a Permian uplift with vertical movements up to 10 km (Privalov et al., 1998). The Rovenki pull-apart basin near Torez (Fig. 1) formed during the Carboniferous time and transformed into a push-up during the Permian uplift (Privalov et al., 1998). This initiated the migration of deep mantle-derived CO_2, which replaced the thermogenic methane generated during Permian (Brizhanev and Kraschenko, 1975; Brizhanyev and

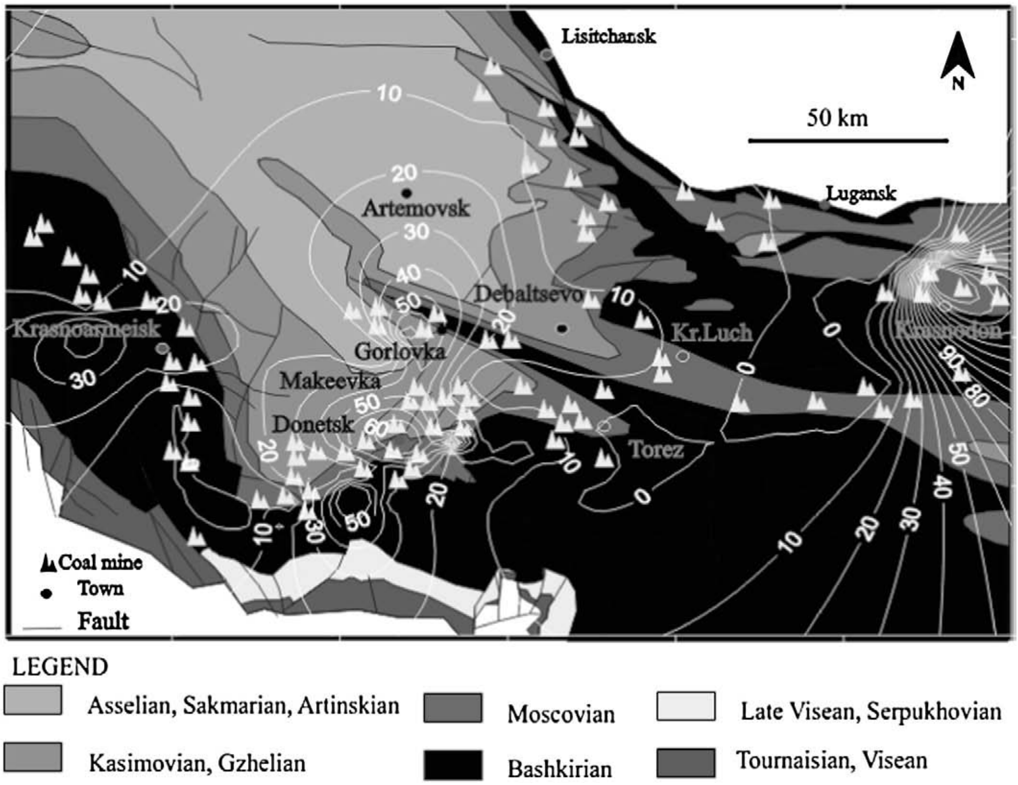

Fig. 8. Map showing the present-day methane content measured by the ventilation method in coal mines (m^3/ton of mined coal) in the Donets Basin for an altitude of −300 m.

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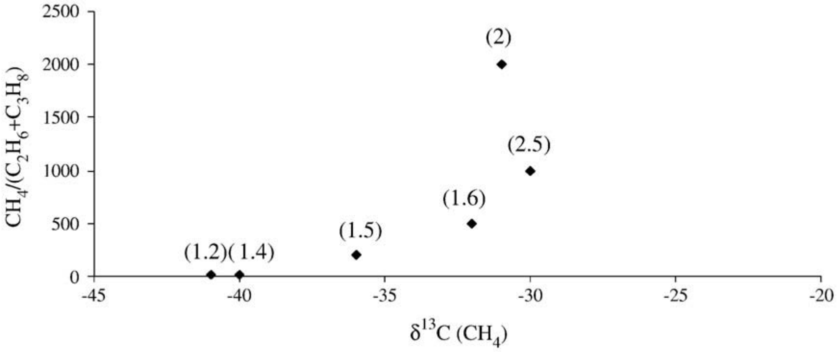

Fig. 9. Bernard diagram, $CH_4/(C_2H_6+C_3H_8)$ vs. $\delta^{13}C$ (CH_4) per mil, for coalbed gases from the wells Sch-1027 and S-1379 (Privalov et al., 2004a, modified) with %R_r between brackets.

Galazov, 1987). Privalov et al. (1998) and Privalov et al. (2004a) found out that the anthracite zones contain mainly endogenic CO_2 (migrated from deep mantle) and methane contents are close to zero (Figs. 7 and 8). Data of $\delta^{13}C$ (CO_2) and $\delta^{13}C$ (CH_4) from the Donets Basin were published by Voitov et al. (1987), Belokon (1987) and Privalov et al. (2004a). Values of $\delta^{13}C$ (CO_2) in the Donets Basin range from −29.7 to −2.7‰ and in the CO_2 Zone (SE Donets Basin) from −8.5 to −2.7‰. Values of $\delta^{13}C$ (CH_4) in the Donets Basin range from −75 to −22‰ (average −34). They range from −42 (at 1%R_r) to −30‰ (at 2.5%R_r) in the wells Sch-1027 and S-1379 located between Donetsk and Krasniy Lutch (Fig. 9, Privalov et al., 2004a). The comparison of $\delta^{13}C$ data from Donets Basin with data from the Lower Silesian Basin in Poland (Kotarba and Rice, 2001), shows that the origin of CO_2 in the CO_2 Zone is abiogenic and endogenic, and that CO_2 (from −20 to −10) and CH_4 (from −50 to −22) are thermogenic in the rest of the Donets Basin. Most probably CO_2 migrated from deep (mantle?) sources or magma chambers during inversion of the Rovenki pull-apart basin. Because the sorptive capacity of coal for CO_2 is 2–3 times greater than that for methane (Styles, 1995), the endogenic CO_2 was able to replace the thermogenic methane generated during (Permo-Carboniferous) coalification (Brizhanev and Kraschenko, 1975; Brizhanyev and Galazov, 1987).

The regional richness in methane content (~20–40 m^3/ton, Fig. 8) in the Krasnoarmeisk area may be related to thermal effects caused by hidden Permo-Triassic magmatic intrusions and the additional pulsations of HCs generation in this area (Sachsenhofer et al., 2002; Spiegel et al., 2004; Alsaab et al., 2008b). Privalov et al. (2004b) explained the elevated methane concentrations in the Krasnoarmeisk area as the result of entrapment in local dilatational domains (tension cracks on synclines and thrusts). Similarly, Alsaab et al. (2008b) showed a peak of hydrocarbon generation in the E and SE parts of Donbas because of a late Permian magmatic event. Additionally, in the Krasnoarmeisk and Donetsk areas the Mesozoic cover eroded only during the Cenozoic (Sachsenhofer et al., 2002; Privalov et al., 1998). For this reason, in these areas methane was preserved in coal seams or clastic reservoirs under an impermeable Permian to Jurassic argillaceous cover. In contrast, in the Torez area erosion of the upper part of the Carboniferous series and oxidation of coals prevailed from upper Permian to Jurassic and even later. Therefore, in this area the methane loss in the atmosphere occurred from Permian to Jurassic times and probably even in the Tertiary (Privalov, 2002). A more precise map of the distribution of methane in reservoir rocks in Donbas based on a modelling was published by Alsaab et al. (2008b). This map showed trends similar to present-day methane contents measured in coal mines, and provided additional data about methane trapping in the North Syncline (Fig. 1), where the Permian rocks form seals and where published data are very poor.

As a consequence, three principal factors have influenced the migration and accumulation of methane in the Donets Basin: 1) faults that played the role of migration pathways, 2) a replacement of thermogenic methane by endogenic CO_2 in the central and SE parts of the basin, and 3) the occurrence of magmatic events in some areas in this basin. Finally, in Donbas the areas with the highest methane potential and the maximum risk of outburst are not the areas with anthracites that produced the highest volume of methane, but the areas with volatile bituminous coals where an impermeable cover preserved the accumulated gas until the Cenozoic and where dextral shear belts facilitated its migration.

5. Applications on the methane exploitation and forecast of gas outbursts in coal mines of Donbas

Previous gas exploration was carried out from Lisitchansk to Lugansk (Fig. 1) in the northern margin of the Donbas discovering fifteen gas deposits in Carboniferous reservoirs of dome-type from 1958 to 1987

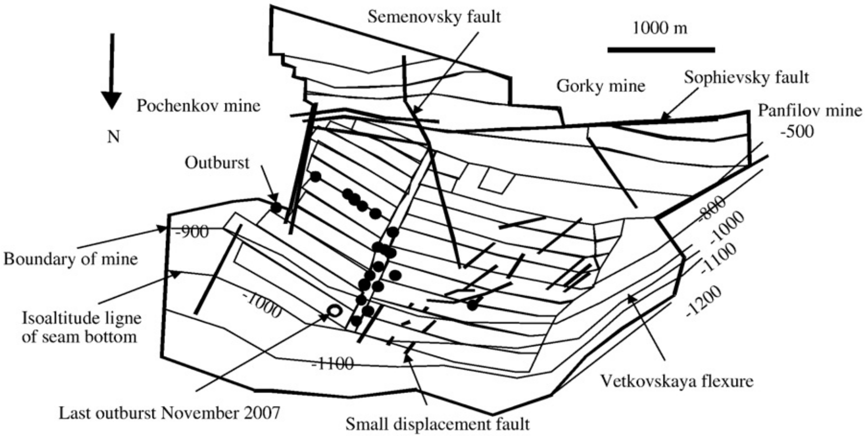

Fig. 10. Map of the coal seam l1 in the Zasyadko coal mine.

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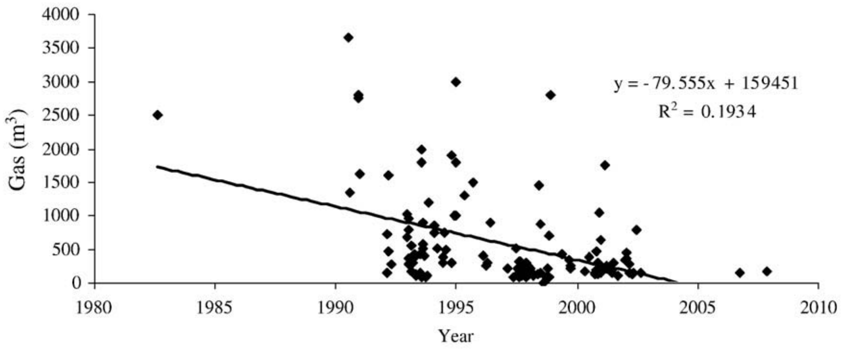

Fig. 11. The volume of gas (m^3) produced by outbursts from the Zasyadko coal mine.

with gas flow up to 5726 m^3/day. The map of volume of methane measured from the desorption method by canister (Fig. 6) allows to delimit the zones where methane could be exploited for coal bed methane in the sector without coal mines in the North syncline and between Donetsk and Gorlovka or for coal mining methane in coal mines between Donetsk and Gorlovka and close to Krasnodon. These sectors correspond also to the zones of high methane generation obtained by our modelling (Fig. 5).

On 200 coal mines in Donbas, 75% present high risk of outbursts and 35% explosion. The outburst-prone coals are found in coal mines where volumes of gas measured from the desorption method by canister (Fig. 7) and the ventilation method (Fig. 8) are high. The quantity of gas adsorbed in coals and the presence of fractures are two conditions to release outbursts (Hyman, 1987). Two types of coal, bright, vitrinite-rich and dull, inertinite-rich are cited as outburst-prone coals (Beanish and Crosdale, 1998). The reflectance of vitrinite of coals in Zasyadko coal mines is close to 1 and the coal is vitrinite-rich (Izart et al., 2006). These maps are useful for the forecast of outbursts in Donbas. The zone at 60 m^3 methane/ton of mined coal on the map (Fig. 7) corresponds to the Zasyadko coal mine that is located close to Donetsk city between the Donets-Kadievka fault and the sections 1 and 3 (Fig. 1). This coal mine is very dangerous because of coal and gas outbursts: 142 from 1972 to the last in November 2007 with 101 coal miners died. These outbursts affected the four coal seams exploited in this mine: k_8 (27%), l_1 (65%), l_4 (1%) and m_3 (7%). The map of l_1 coal seam (Fig. 10) exhibits that these outbursts (circles) are located all along this NNE–SSW gallery of mine in connection with panels of exploitation, inside panels and along small-displacement faults and flexures (knee-shaped folds). 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 with a vertical or stratigraphic displacement less than few decimetres or metres. However, most of them are concentrated within strike–slip zones with clear patterns of Riedel (R_1 and R_2), Y and P shears (Privalov, 1990).

Diverse types of outburst were proposed by German mining engineers cited by Noack (1998): 1) outburst of gas and coal, 2) outburst of gas and rock, 3) heavy floor or roof gas emissions without discharge of coal or rock, and 4) other sudden liberation of larger amounts of gas (fissure gas, sliding of coal, boundary case linked with microtectonic fault, gas collected in old mines, occurring in faces at the starting phase of production). And Ukrainian mining engineers used the following classification of outbursts: 1) Coal-and-gas instant non-forecasted outburst, 2) Coal injection with high gas flux, 3) Instant Coal injection with high gas flux provoked by dynamic collapses of roof or bottom, 4) Coal-and-gas outburst provoked by "tremor" explosion, 5) Coal-and-gas outburst during opening work, and 6) Gas flux followed by his explosion. The Ukrainian type of outbursts 4 is the more frequent (86%), the type 3 (11%) and other types (3%) in the Zasyadko coal mine. K_8 coal seam presents only type 4 and l_1 coal seam especially type 4, but also type 3. Most of the type 4 outbursts have seismic nature; however, gas content of coal seam and sandstone is also important. 90% or even more are coincided with small-displacement faults, flexures or folds. The seismic activity along faults seems the main factor of genesis of outbursts in this coal mine. The degazeification by boreholes before coal exploitation and the ventilation seem also insufficient.

The volume of gases (m^3) produced during outbursts in Zasyadko change from 100 to 3650 m^3 (Fig. 11) with higher volumes in l_1 coal seam. The equation showing a decrease of gas during the last years with a low correlation coefficient R^2, so this trend is uncertain. The tonnage of extracted coal close to 2–3 million tons by year in the period 1990–2007 remains stable. The number of outbursts is higher from 400 to 1200 m depth of exploitation and from 15 to 35 m^3 gas/

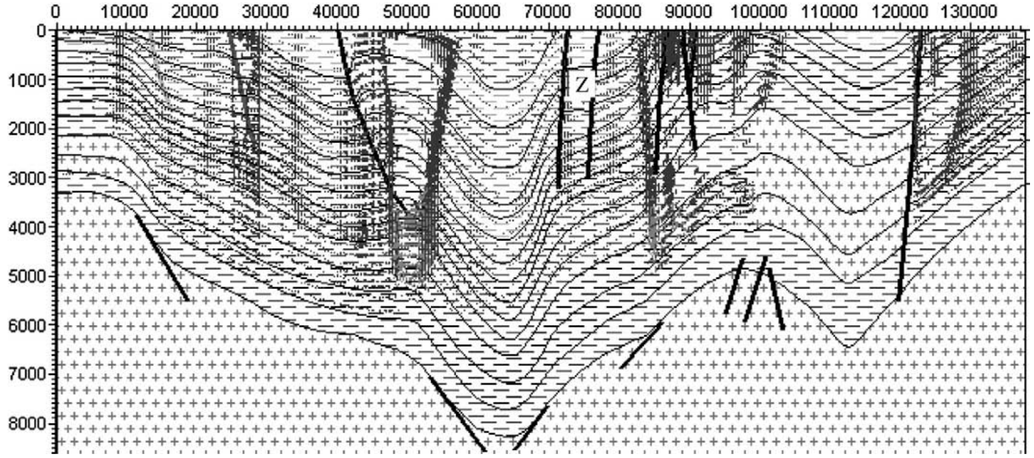

Fig. 12. Recent gas migration (shaded zone) in the section 1 with location of the projection of the Zasyadko coal mine (Z).

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ton of mined coal. The Zasyadko coal mine is located in a gas zone that is shown by the map of volume of gas from the ventilation method (zone at 60 m^3/ton of mined coal, Fig. 8) and the maturity of organic matter in sections 1, 3 and 4 (Fig. 4) and in a complex faulted zone, the Donetsk-Kadievka fault, that is actually yet a path for gas migration (Fig. 12) as the modelling of the section 1 (Alsaab et al., 2008b) proved. The migration study and the geological structures allow us to define the types of outbursts and take needed requests to avoid them.

6. Conclusion

Maps were constructed showing the amounts of methane generated and the adsorption capacity of coal at an altitude of −300 m. Two other maps displayed the present-day methane contents based on desorbed methane by canister and ventilation gas composition. A comparison of these maps indicates that three principal factors influenced the methane migration and accumulation in the Donets Basin: 1) faults that acted as migration pathways, 2) a replacement of thermogenic methane by endogenic CO_2 proved by $\delta^{13}C$ data in the central and SE parts, and 3) the occurrence of magmatic events in some areas in this basin. Finally, in Donbas, the areas with the highest methane potential and the maximum risk of outburst are not the areas with anthracite coal that produced the highest volume of methane, but areas with volatile bituminous coals, where an impermeable cover preserved the accumulated gas until the Cenozoic in North and South synclines located North and South of the main anticline (Gorlovka) and where dextral shear belts facilitated its migration (faults near Donetsk and Krasnodon).

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