Coal Geology of the Donets Basin (Ukraine/Russia): An Overview

V. A. Privalov, R. F. Sachsenhofer, E. A. Panova and V. A. Antsiferov

The Donets Basin (Ukraine/Russia) contains one of the major coal fields in the world with proven reserves in the order of 60 Gt. The Carboniferous basin fill hosts about 130 seams, each with a thickness over 0.45 m. Coal rank ranges from subbituminous to anthracite. The thickness of coal seams currently mined is in the range of 0.6 to 2.5 m. Production during 2001 was 83.4 mio. t. in the Ukrainian and 6.5 mio. t. in the Russian part of the basin. Coal seams usually have high ash yields (12–18 %) and high sulphur contents (2.5–3.5 %), but these data vary significantly depending on peat facies. Coal mines in the Donets Basin are among the gasiest in the world. The average methane content of coal is 14.7 m³/t, but numerous seams have significantly higher gas content. The high methane content presents a severe mine safety problem. On the other hand, it represents also a high potential for coal bed methane projects. Coal and gas outbursts constitute another major mining hazard and account for many fatalities.

Kohlengeologie des Donets-Beckens (Ukraine/Russland): Eine Übersicht. Das Donets-Becken (Ukraine/Russland) beinhaltet eine der größten Kohlenlagerstätten der Erde mit nachgewiesenen Vorräten von ca. 60 Gt. Die karbone Beckenfüllung beinhaltet ca. 130 Flöze mit einer Mächtigkeit über 45 cm. Der Inkohlungsgrad reicht vom Glanzbraunkohlen- bis zum Anthrazitstadium. Die Mächtigkeit der heute abgebauten Flöze schwankt zwischen 0,6 und 2,5 m. Im ukrainischen Teil des Beckens wurde 2001 83,4 Mio. t Kohle gefördert, im russischen Teil 6,5 Mio. t. Die Flöze sind meist asche- (12–18 %) und schwefelreich (2,5–3,5 %). Abhängig vom Ablagerungsmilieu schwanken die Gehalte jedoch beträchtlich. Die Kohlenbergwerke im Donets Becken gehören zu den weltweit gasreichsten. Der durchschnittliche Methangehalt der Kohle beträgt 14,7 m³/t, der Gasgehalt zahlreicher Flöze ist jedoch deutlich höher. Die hohen Methangehalte stellen ein großes Sicherheitsproblem dar. Gleichzeitig zeigen sie auch ein hohes Potenzial für Flözgasprojekte. Häufige Kohle- und Gasausbrüche stellen eine weitere Gefahr dar und sind mit die Ursache für viele Unglücke.

The Donets Basin (Donbas) is located mainly in the Ukraine with the eastern part of the basin extending into Russia (Fig. 1). The basin covers an area of 60000 km² and contains one of the major coal fields in the world with proven reserves in the order of 60 Gt (Zhykalyak and Privalov, 2002; Nazarova et al., 2003).

The Carboniferous basin fill hosts about 130 seams, each with a thickness over 0.45 m. Coal rank ranges from subbituminous (Glanzbraunkohle) to anthracite (Levenshtein et al., 1991 a). The thickness of coal seams currently mined is in the range of 0.6 to 2.5 m. In 1991, before the collapse of the Soviet Union, there were about 300 operating underground mines (Marshall et al., 1996).

The average methane content of coal is 14.7 m³/t coal (Marshall et al., 1996), but numerous seams have significantly higher gas content, presenting a high potential for coal mine methane projects (e.g. Triplett et al., 2001). On the other hand, the high methane content presents a severe mine safety problem. Actually, coal mines in the Donets Basin are among the most dangerous in the world.

Although the Donets Basin hosts significant amounts of coal and gas, its geology and mining industry are poorly known in middle and western European countries. Main aim of the present contribution is to fill this gap.

1. Basin Evolution and Basin Structure

The Donets Basin forms part of the Pripyat-Dniepr-Donets-Karpinsky Basin (Fig. 1), a Late Devonian rift structure located on the southern part of the Eastern European craton (Stovba and Stephenson, 1999; Stephenson et al., 2001). Some important aspects of the evolution of the basin are summarized in Fig. 2.

Total thickness of Devonian pre- and syn-rift rocks is 750 m at the margins of the Donets Basin, but up to 6 km along the basin axis (Maystrenko et al., 2003). Major post-rift subsidence occurred during the Permo-Carboniferous. The Carboniferous sequence, up to 14 km thick, is subdivided into lithostratigraphic units named suites A (C_1^1), B (C_1^2), C (C_1^3), to P (C_3^3) (Lutugin and Stepanov, 1913). The coal-bearing succession consists of elementary sequences, composed of fluvial sandstone, coal, marine limestone or claystone, and deltaic claystone and siltstone (Shirokov, 1963; Shulga, 1981). The sequences are controlled by sea level variations due to glaciations on the Gondwana supercontinent (Izart et al., 2003). The percentage of continental deposits is higher in the

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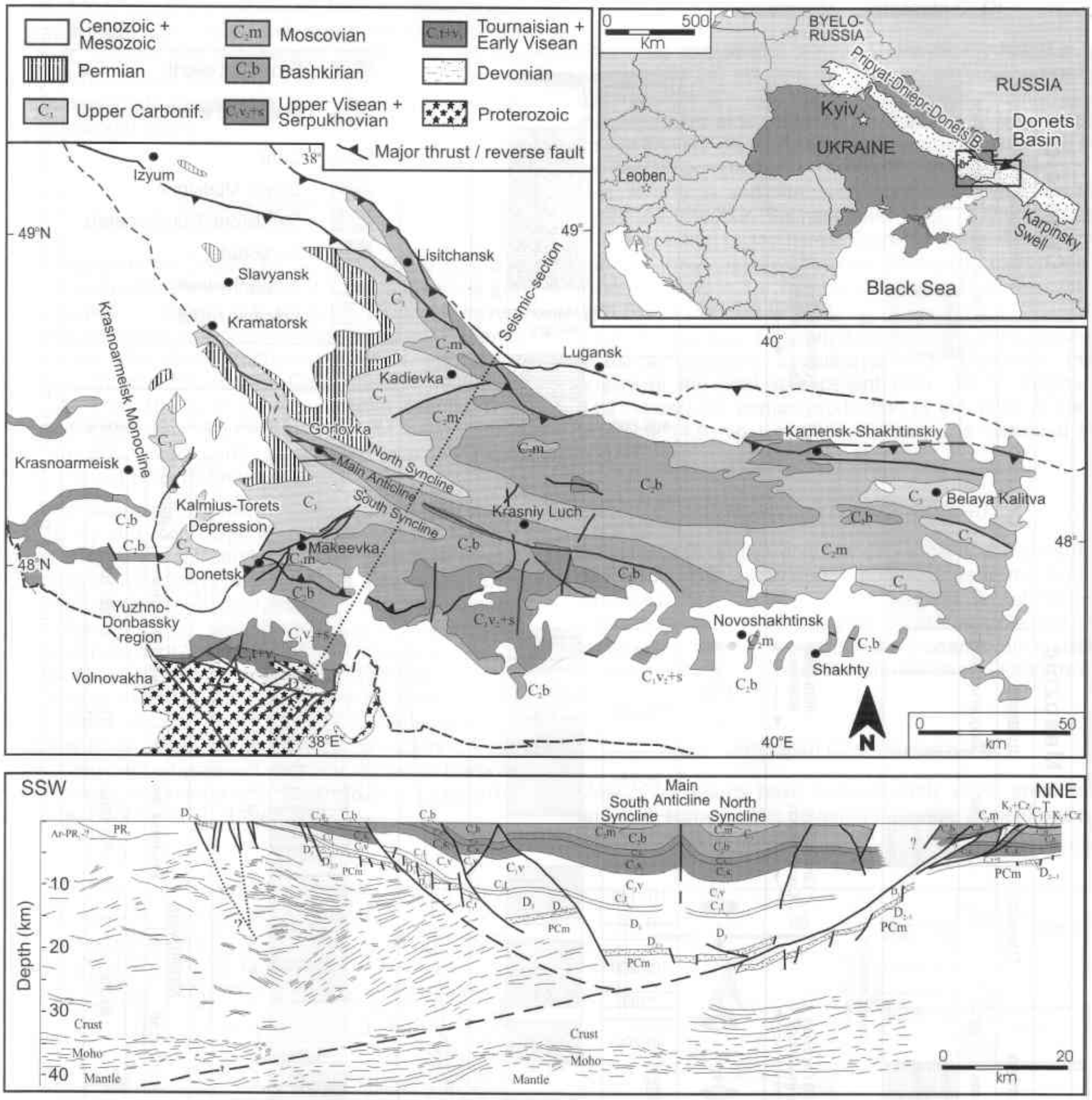

Fig. 1. Geologic sketch map of the Donets Basin (modified after Popov, 1963). Geological cross-section after Maystrenko et al. (2003) and Saintot et al. (2003)

western part than in the eastern part of the Donets Basin. With the exception of the carbonate suite A (C_1^1) of Turnaisian to early Visean age, coal seams and intercalations of coal are present throughout the Carboniferous succession. However, lower Serpukhovian (suite C) and Moscovian successions (suites K to M) are especially rich in coal (Levenshtein et al., 1991 b).

Permian rocks are preserved along the western and northern basin margins, where they are represented by a sandstone-mudstone series with limestone interbeds (Nesterenko, 1978). Thick evaporites hosting economic salt and gypsum deposits occur in Asselian and Sakmarian levels. Only relatively thin sediments were deposited during the Mesozoic and Cenozoic.

Important information on the deep structure of the Donbas Foldbelt, which is the inverted part of the Dniepr-Donets Basin, is provided by the "DOBRE" reflection line (Maystrenko et al., 2003; Fig. 1). The structure of the central basin is dominated by WNW-ESE trending folds (Fig. 1). These folds are fairly tight and in some places overturned. The Main (Gorlovka) Anticline is the largest and most pervasive fold in this zone. It is an almost symmetric structure with steeply dipping limbs (60°–80°), complicated by faults as (oblique) thrusts, as oblique normal and strike-slip faults developed at its hinge, in which dextral movement has been recognised (Saintot et al., 2003). The Main Anticline is bordered by two gentle synclines (North and South Syncline) and anticlines (Fig. 1). Major thrusts occur along the northern margin of the basin. Minor folds, reversed faults and rotated fault blocks prevail along the southern boundary of the basin. The age of the compressional structures is a matter of controversy. Following traditional ideas Popov (1963), Nagorny and Nagorny (1976), Privalov et al.

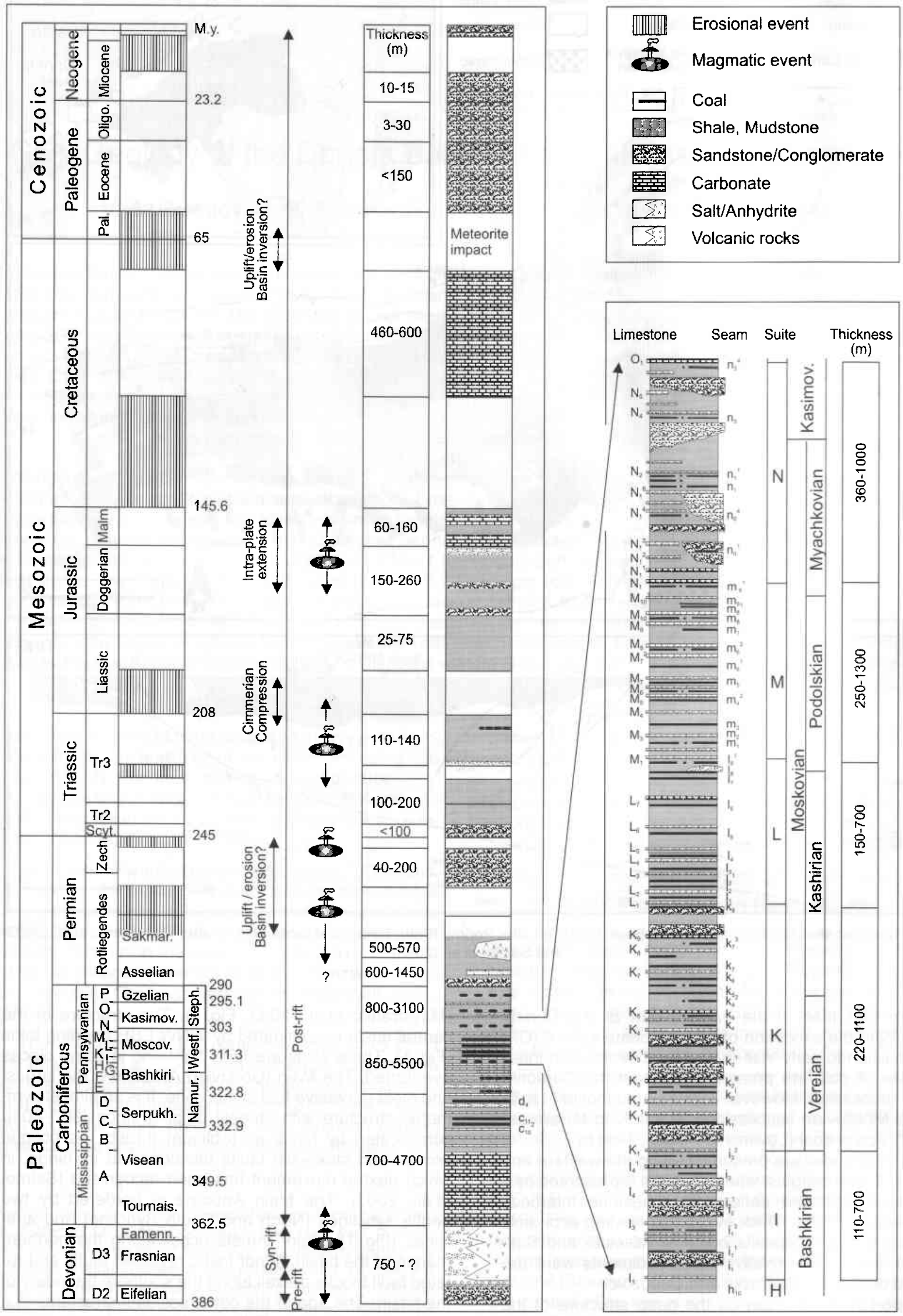

Fig. 2. Chrono- and lithostratigraphy of the Donets Basin. Major magmatic and tectonic events are shown (Sterlin et al., 1963; Belokon, 1971; Einor, 1996; Privalov et al., 1998; Stovba and Stephenson, 1999). A detailed stratigraphic column is provided for the Moscovian sequence

(1998, 2002) assume a dominantly Permian (Hercynian) age with local Cimmerian and Alpine reactivations. In contrast, Stovba and Stephenson (1999) and Saintot et al. (2003) favour a Permian transtensional phase and a dominantly late Cretaceous (Alpine) age for the main compressional event.

2. Coal Seams

Coal seams in the Donets Basin are typically thin, but have a wide lateral distribution. 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. Seams in excess of two meters are rare. In most regions the Carboniferous sequence contains from 10–14 to 30–40 workable seams. This number decreases from the western towards the northern and eastern parts of the basin. Total coal thickness is about 60 m (Ritenberg, 1972).

Coal seams usually have moderately high ash yields (12–18 %) and high sulphur contents (2.5–3.5 %), but these data vary significantly depending on peat facies. Volcanogenic tonsteins occur in many seams and form important marker horizons (e.g. Fig. 4). Other mineral consitutents include siderite nodules and authigenic quartz (Zaritsky, 1972; 1985; Sachsenhofer et al., 2003). Donets coals are known to be rich in hazardeous trace elements such as Hg, As, Cd, Pb, and Zn (Panov et al., 1999; Kizilshtein and Kholodkov, 1999). Especially high contents occur along the Main Anticline, where an epigenetic Hg-deposit (see also Fig. 5B) hosted in Carboniferous rocks was mined near Gorlovka (e.g. Lazarenko, 1975; de Boorder et al., 1996).

2.1 Serpukhovian Coal (Suite C, D)

Economic coal seams of suite C are mainly found in a narrow, NW-SE trending zone along the southwestern basin margin (Shulga, 1981). The coal accumulated in a roughly 10 km wide shore-zone dissected by several NE trending rivers discharging into a nearby shallow sea in the central Donets Basin. The coal is rich in inertinite and liptinite (Fig. 3) and often very poor in ash and low to moderate in sulfur. Sachsenhofer et al. (2003) discuss an origin within raised mires. Currently these seams are mined in the Zapadniy (Western) Donbassky region near Pavlograd and in the Yuzhniy (Southern) Donbassky region SW of Donetsk (Fig. 3).

Coal from suite D (seam d_4) is mined in a single mine (Krasnoarmeiskaya Zapadnaya # 1). However, the quality of the coal is excellent (ash: 4.7 %; sulphur: 0.62 %) and the annual production of this mine is considerable (4.9 mio. t in 2003, 5.7 mio. t is expected in 2004)!

2.2 Bashkirian Coal (Suites E–I)

Suites E to G contain only few economic coal seams (f_1, g_2), which were excavated in some mines in the Krasnoarmeisk and Donetsk regions during Soviet times. Coals from suite H and I are more important. Centers of coal mining are the Donetsk area (12 seams within suite H) and the Russian part of the Donets Basin (4 seams in suite I; Fig. 3).

2.3 Moscovian Coal (Suites K–N)

Moscovian seams have a significantly wider areal extent, with some seams covering the entire Donets Basin.

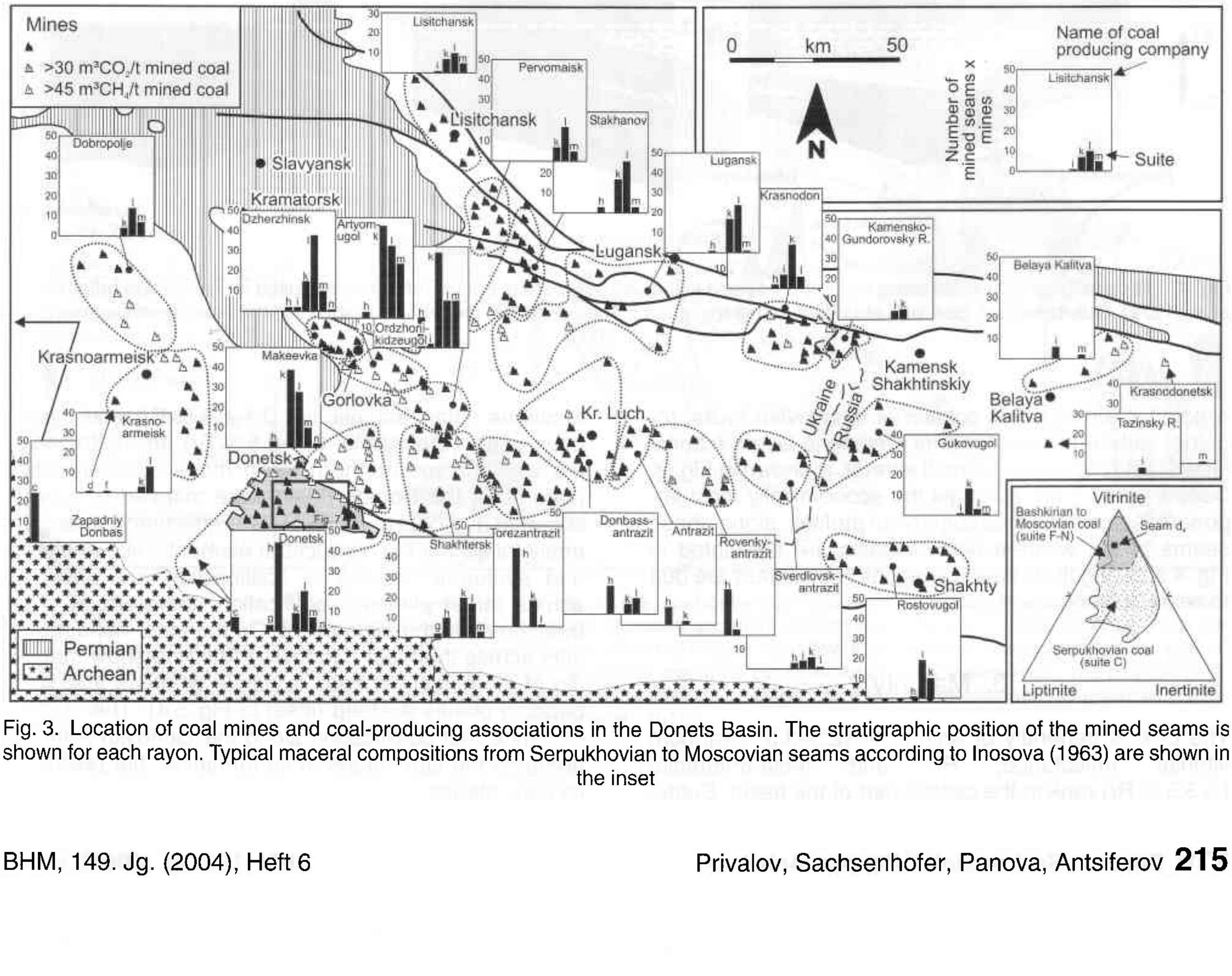

Fig. 3. Location of coal mines and coal-producing associations in the Donets Basin. The stratigraphic position of the mined seams is shown for each rayon. Typical maceral compositions from Serpukhovian to Moscovian seams according to Inosova (1963) are shown in the inset

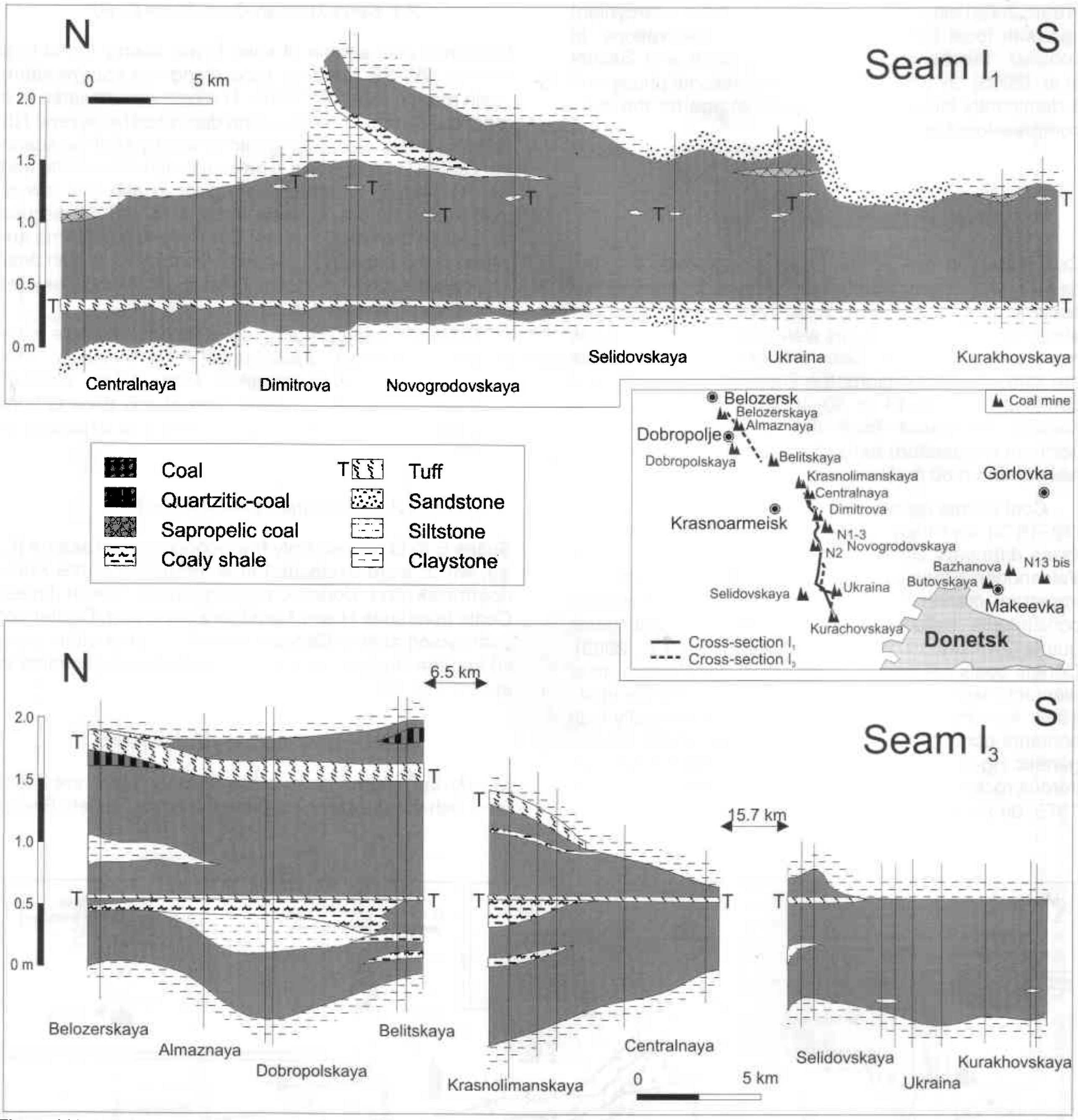

Fig. 4. Lithostratigraphic profiles along the l_1 and l_3 seams in the western Donets Basin. Tuff layers are used for correlation (after Uziyuk et al., 1972). Quartzitic coal: coal with abundant authigenic quartz. The position of the profiles is shown in the inset (from Sachsenhofer et al., 2003)

A detailed stratigraphic column of Moscovian rocks, together with a number code for limestone layers (capital letters) and coal seams (small letters), is shown in Fig. 2. Seams l_1 and l_3 are amongst the economically most important seams. Lithostratigraphic profiles along these seams in the western Donets Basin are presented in Fig. 4 showing that lateral variations in thickness are due to seam splitting and erosion.

3. Maturity

The coal is generally of anthracite (2.5–3.5 % random vitrinite reflectance; Rr) and meta-anthracite (> 3.5 % Rr) rank in the central part of the basin. Subbituminous (Glanzbraunkohle: 0.4–0.6 % Rr) and bituminous coals (Steinkohle: 0.6–2.5 % Rr) are restricted to the western and northern basin margins. Coalification patterns in the Donets Basin were mapped by Levenshtein et al. (1991 b; Fig. 5 A). Iso-reflectance lines generally follow the main structural elements, like antiforms and synforms. Breaks in coalification are observed across thrust planes. Coalification, therefore, is older than the main thrusting event. On the other hand, transects across the Main (Gorlovka) Anticline show that the dip of iso-reflectivity lines is gentle whereas the dip of bedding planes is steep (inset in Fig. 5 A). This is clear evidence that coalification along the Gorlovka Anticline predates the late stages of its formation, but postdates its early stages.

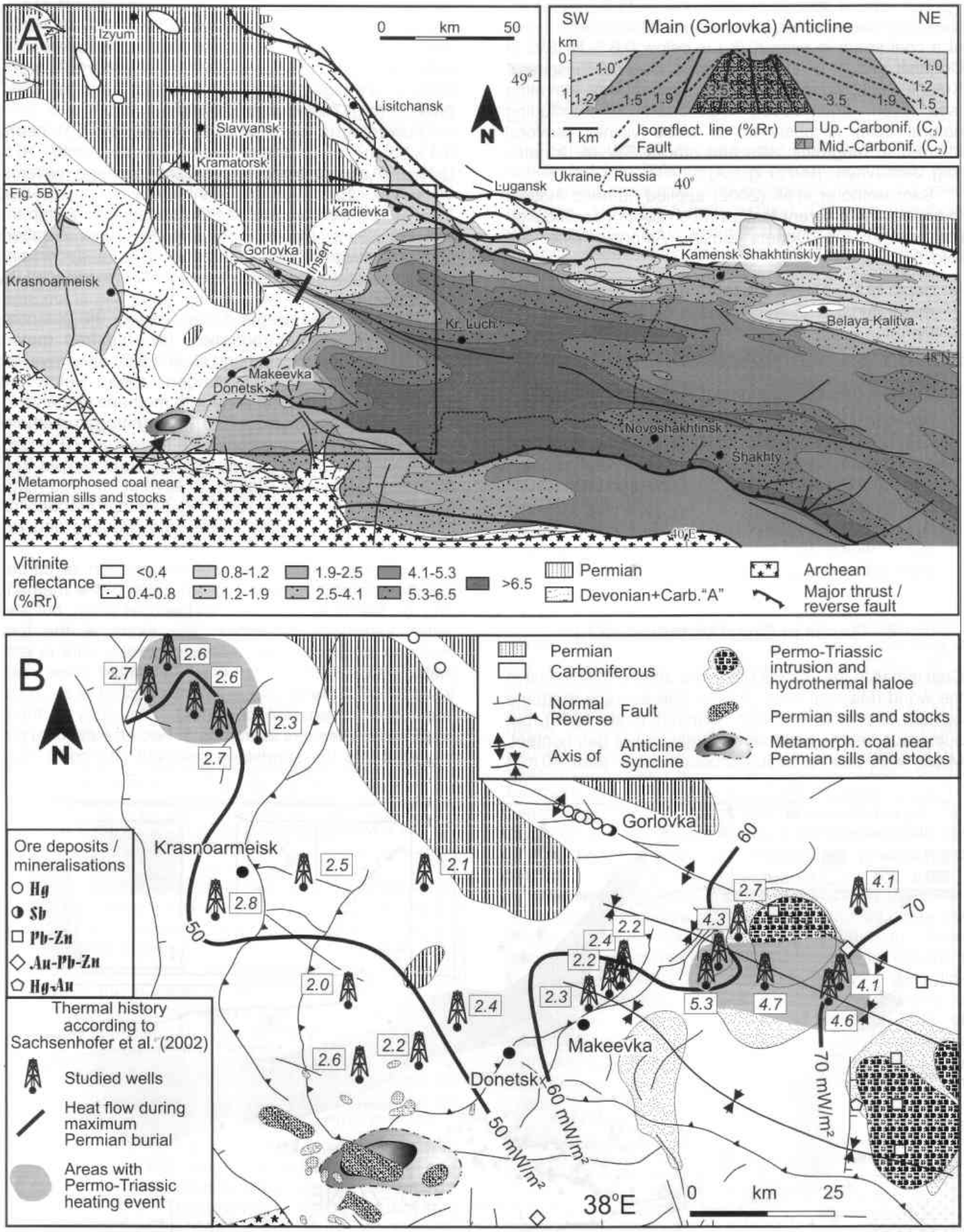

Fig. 5. (A) Coalification map of the Donets Basin at the top of the Carboniferous sequence (modified after Levenshtein et al., 1991a). (B) Some aspects of the thermal history of the basin are indicated according to Sachsenhofer et al. (2002). Isolines show the heat flow distribution during maximum Permian burial. Areas with a Permo-Triassic heat flow event north of Krasnoarmeisk and east of Donetsk are highlighted by grey shading. Numbers in boxes indicate the amount of post-Carboniferous erosion in km. The position of intrusive bodies (Aleksandrov et al., 1996) is indicated together with the location of epigenetic mineral deposits and occurrences (Lazarenko et al., 1975)

The rank of specific stratigraphic units increases towards the basin center. For example, vitrinite reflectance of a coal seam in suite K (k_5) is below 0.6 % Rr SW of Donetsk and N of Lugansk, but above 6.0 % Rr near Krasnij Luch, despite a similar present-day elevation (sea level). Anomalously high coalification including natural coke is observed in close vicinity (several metres) to magmatic sills and stocks SW of Donetsk (e.g. Jernovaya, 1997; Fig. 5 A).

Sachsenhofer et al. (2002) applied numeric models to assess the different factors which control coalification patterns in the Donets Basin. Among these are (Fig. 5 B):

- depth of Carboniferous rocks during maximum (Permian) burial,
- Permian uplift
- lateral heat flow variations during maximum burial.

The resulting coalificaton pattern was overprinted by:

- Permian (~275 Ma) sills and stocks, which coked seams SW of Donetsk. However, the amount of heat transported by the magmatic rocks was not high enough to cause regional heat flow and coalification anomalies.
- A late Permian/early Triassic (~250 Ma) heating event, which was most probably caused by magmatic intrusions (Spiegel et al., 2004).

4. Gases in Coal (Methane, CO_2)

Coal mines in the Donets Basin are among the gasiest in the world (Marshall et al., 1996). The average methane content of coal is 14.7 m^3/t (Marshall et al., 1996), but numerous seams have significantly higher gas content. Mines with seams, which produce more than 40 m^3/t mined coal are highlighted in Figs. 3 and 6. Some seams in some mines even contain more than 100 m^3/t mined coal. The high methane content presents a severe mine safety problem in this area. On the other hand, it represents also a high potential for coal bed methane (CBM) projects (e.g. Triplett et al., 2001).

According to Marshall et al. (1996), in 1991 nearly 3.4×10^9 m^3 of methane were liberated with 16 % (539×10^6 m^3) captured by methane drainage systems. Only 170×10^6 m^3 of this methane were used, thus 3.2×10^9 m^3 were vented to the atmosphere. Within the last ten years, the relation between these numbers changed insignificantly, but because of a decreasing coal production, the total amounts were reduced by roughly 50 %.

There is a clear depth dependency of the gas composition. Within the uppermost few hundred meters methane is often missing and N_2 and CO_2 are prevailing (gas weathering or "CO_2-nitrogen" zone). Below this zone follows a transition zone with methane contents increasing downwards from 0 to 70 % (nitrogen-methane zone) and the methane zone with more than 70 % CH_4. The thickness of the gas weathering zone ranges from 50 m (e.g. Makeevka region), to several hundred meter (Brizhanyev and Panov, 1990; Fig. 6) and is probably related to the present day stress field (Panova and Privalov, 2001; Privalov, 2003).

The isotopic and chemical composition of carbon clearly indicates the thermogenic origin of the methane (Fig. 6). Methane occurs within the coal seam, but also within sandstone reservoirs. For example, the total methane resource within sandstone reservoirs is estimated 12.9×10^9 m^3 in the Zasyadko mine and 9.1×10^9 m^3 in the Glubokaya mine (Tripplet et al., 2001, see Fig. 6 for position of mines). The study of these sandstone reservoirs is important, because the coal gas migrated into the sandstone reservoir can come back

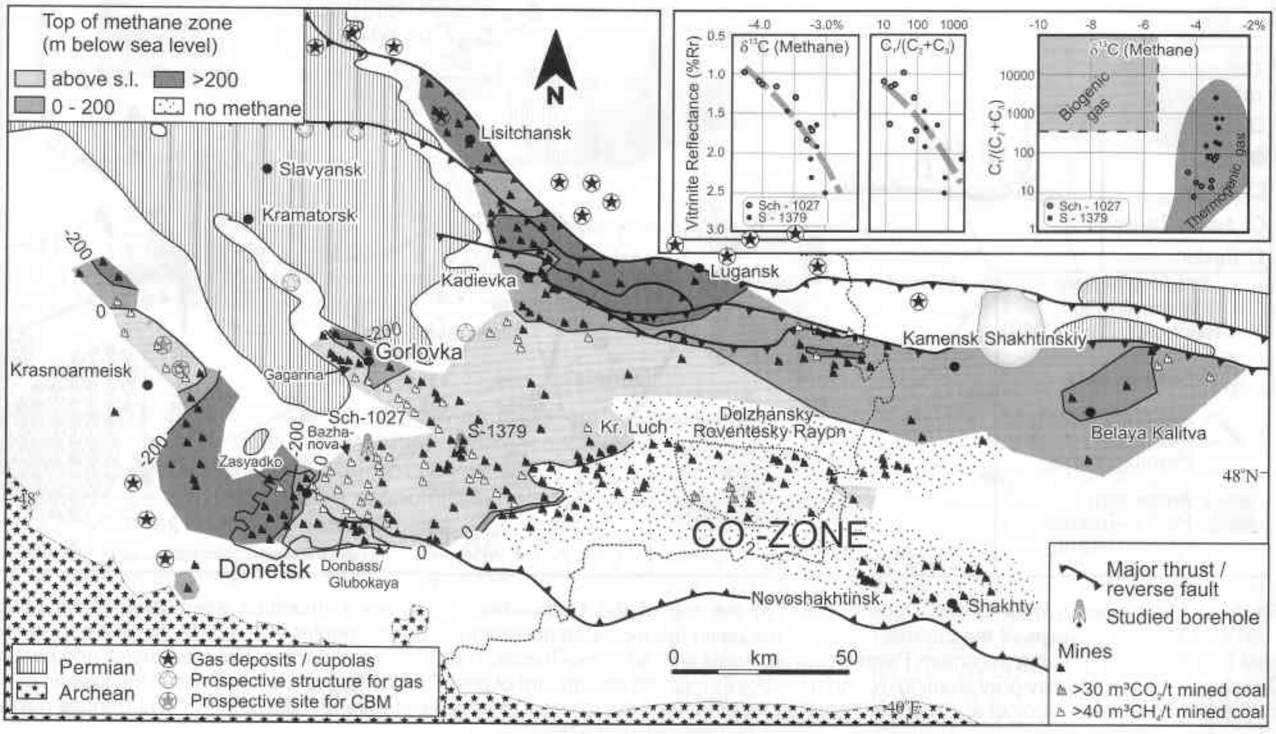

Fig. 6. Top of the methane zone in different parts of the Donets Basin (according to data from Brizhanyev and Panov, 1990). Data on CO_2 contents according to Brizhanyev and Kraschenko (1975). The position of potential CBM sites (Prikhodchenko and Prikhodchenko, 2001) and gas-bearing cupolas is shown. The inset shows isotope data of coal-bed methane from two wells (after Privalov et al., 2004)

into coal galleries during exploitation by fractures and faults.

Some domal structures along the northern marginal fault of the Donets Basin and in the southern Krasnoarmeisk and Yuzhno-Donbassky regions host conventional gas deposits (Fig. 6). Some of these are or were exploited (Brizhanyev and Galazov, 1987; Ulmishek et al., 1994).

There are large areas with high rank coals within the Donets Basin where no methane, but significant amounts of CO_2 occur (Fig. 6). In the Dolzhansky-Rovenetsky region the CO_2 content in some mines is up to 35 m^3/t mined coal. CO_2 constitutes a significant mine safety problem within these mines. Perhaps the lack of methane is due to demethanization during major Cretaceous uplift developed mainly along the southern-eastern margin of the basin and the occupation of the free space by CO_2 (Privalov, 2002).

5. Coal Mining in the Donets Basin

Table 1 gives an overview on some milestones of early coal exploration and extraction in the Donets Basin.

Table 1. *Some milestones of early coal exploration and extraction in the Donets Basin*

1722	Peter I the Great signs an order for expedition to Don, Voronezh regions for coal exploration
1723	Expedition, drilling of 100–130 m deep boreholes
1724	Extraction of coal near Bakhmut
1796	1st coal mine (Lisitchya Guly), 39 m deep
1806	Foundation of Lisitchansk "Steiger" school (4 years of education)
1836	Foundation of Kapitalnaya mine in the Lisitchansk region
1866	Dagmara mine in the Lisitchansk region reaches a depth of 128 m
1868	Kotchegarka mine in Gorlovka town (closed in 2000)
1892–94	Expeditions for mapping the Donets Basin in the scale of 1 : 42000 (F. N. Tchernishev, L. I. Lutugin, N. N. Yakovlev, P. I. Stepanov, A. A. Gapeev). N. I. Lebedev suggested the term "suite".

In 1991 202 coal mines were active in the Ukrainian part of the Donets Basin. This number decreased till 2002 to 161. In the mid-1990s, coal production dropped from 164.8 Mt (1990) to 71.7 Mt (1996), before inching back to 83.4 Mt in 2001. In the Russian part of the Donets Basin the number of mines decreased from 67 (1990) to 18, which produced 5.4 Mt of coal during 2002 (Nazarova et al., 2003). 93 % of the mined coal in the Russian part is anthracite.

Depending on coal rank the coal either is used for electric power generation or is processed into coke for the iron and steel industry.

The decline in coal production during the 1990s was caused mainly by the collapse of domestic demand and the closing of heavy industry since Ukraine became independent in 1991. Ukrainian coal mining industry has employed around 450000 people, suffers now from labour strikes, hazardeous working conditions, inefficiency and still low productivity (Table 2), consumer nonpayments, unpaid wages, huge debts, and outmoded equipment. Main reason for the latter was the investment policy of the former Soviet Union: Coal mining operations were planned to be reduced in the Donets Basin, because it was possible to develop coal fields in the eastern regions of Russia containing cheaper coal.

Table 2. *Productivity index 1996–1998*

	1996	1997	1998
Average per worker (t/month)	15.8	18.2	19.8
Face productivity (t/day)	244	289	312
For mechanized faces (t/day)	357	421	463

The geological resources are significant. They are subdivided into balance sheet resources, outside balance sheet resources and prognostic resources (see Fettweis, 1979 for further details). Different threshold values are used for different coal types to be included as balance sheet resources (Table 3). Data on balance sheet resouces are presented in Table 4.

Table 3. *Threshold values for balance sheet resources*

	Thickness	Ash yield	Sulphur
Coking coal	> 0.55 m	< 40 %	< 4.5 %
Energetic coal	> 0.60 m	< 35 %	
Antracite	> 0.60 m	< 35 %	

Table 4. *Data on balance sheet resources in the Donets Basin*

Balance sheet resources	Whole Donbas (Pogrebnov, 1980)	Ukrainian part (Zhykalyak, Privalov, 2002)	Russian part (Nazarova et al., 2003)
A + B + C 1	54.9×10^9 t		6.5×10^9 t
A + B + C 1 + C 2		52×10^9 t	9.4×10^9 t

Coal mines in the Donets Basin are generally deep. Mines in the Ukrainian part of the basin are operating at 220 to 1380 m depth. The average depth is 720 m. 53 % of the mined coal are from depths less than 600 m, 28 % are from 600 to 900 m, and 16 % from 900 to 1200 m depth. Ten mines are more than 1200 m deep; their percentage in coal production is ~ 3 % (Zhykalyak and Privalov, 2002). Nearly 40 % of all mines have been active for more than 50 years, and 15 % for more than 70 years. Over 35 % of the mines have a productive capacity of only 300000 t per year, which is lower than the annual production of one modern longwall mining system.

The applied mining method depends on the thickness and the dip angle of the seams. All mines utilize the longwall retreat system with caving method. Face lengths vary between 125 to 150 m in steeply (35–70 °) dipping seams and 120 to 250 m in gently (1–35 °) dipping seams. Coal extraction is highly mechanized in mines with gently dipping seams, whereas 70 % of steeply dipping coal (e.g. along the Main Anticline) is extracted with pick hammers. A high percentage of very thin seams is exploited in areas with a steep dip (Table 5).

Table 5. *Distribution of faces in seams with different thickness in areas with steeply and gently dipping seams*

	Steeply dipping seams (35–70 °)	Gently dipping seams (1–35 °)
Seam thickness	Distribution of faces	Distribution of faces
< 0.7 m	33.8 %	8.2 %
0.7–1.2 m	47.5 %	58.8 %
> 1.2 m	18.7 %	33.0 %

Ukraine's coal mines are very dangerous. 3458 coal miners died during the years 1991 to 2000, whereas 295 miners were killed in 2001. Poor working conditions and lack of capital investment are blamed for the frequent accidents. A breakdown of the causes of fatal accidents shows that methane explosions, outbursts, rock falling, and the collapsing of objects from the roof constitute the major parts of the causes of fatal accidents (Table 6).

Table 6. *Causes of fatal accidents in Ukrainian coal mines during the time-span 1991–2000 and during the year 2001*

Causes	1991–2000	2001
Methane explosion	16.8 %	28 %
Sudden coal and gas outbursts, rock falling, collapsing of objects from the roof	25.9 %	24 %
Transport	21.3 %	12 %
On surface		10 %
Cardiovascular	7.7 %	10 %
Personal falls	5.9 %	
Mechanical and technical devices	9.2 %	6 %
Electricity	4.2 %	3 %
Shaft crashes		2 %
Other	9 %	6 %

Instantaneous outbursts of coal and methane in underground mines occur frequently in the Donets Basin. The precise mechanisms of outbursts are still unresolved (e.g. Beamish and Crosdale, 1998) but are related to stress, gas content and physico-mechanical properties of the coal. Factors such as geological features (e.g. small scale faults and local minor folds) and mining methods also have to be considered (Zabigailo et al., 1980, 1994; Privalov, 1985). Smaller events are often unrelated to geological structures, whereas larger events tend to locate along geological discontinuities at some distance in the hangingwall or footwall. Countermeasures include preventive explosions in order to provoke outbursts and the usage of remote-controlled vehicles in dangerous zone.

Nearly two third of all (instantaneous and provoked) coal and gas outbursts occur within the Donetsk area (Petukhov et al., 1989). Figure 7 shows the location of ourbursts related to the h_8 seam together with sections along faults with small displacements (Privalov, 1985; 1988). Sketches of selected coal and gas outbursts in the h_8 (Donetsk area) and the m_3 seams (Makeevka area) are presented in Fig. 8. The largest outburst involving 14000 t of coal and 250000 m³ of methane occurred 1969 in the Gagarin mine (Artyomugol) (Beamish and Crosdale, 1998).

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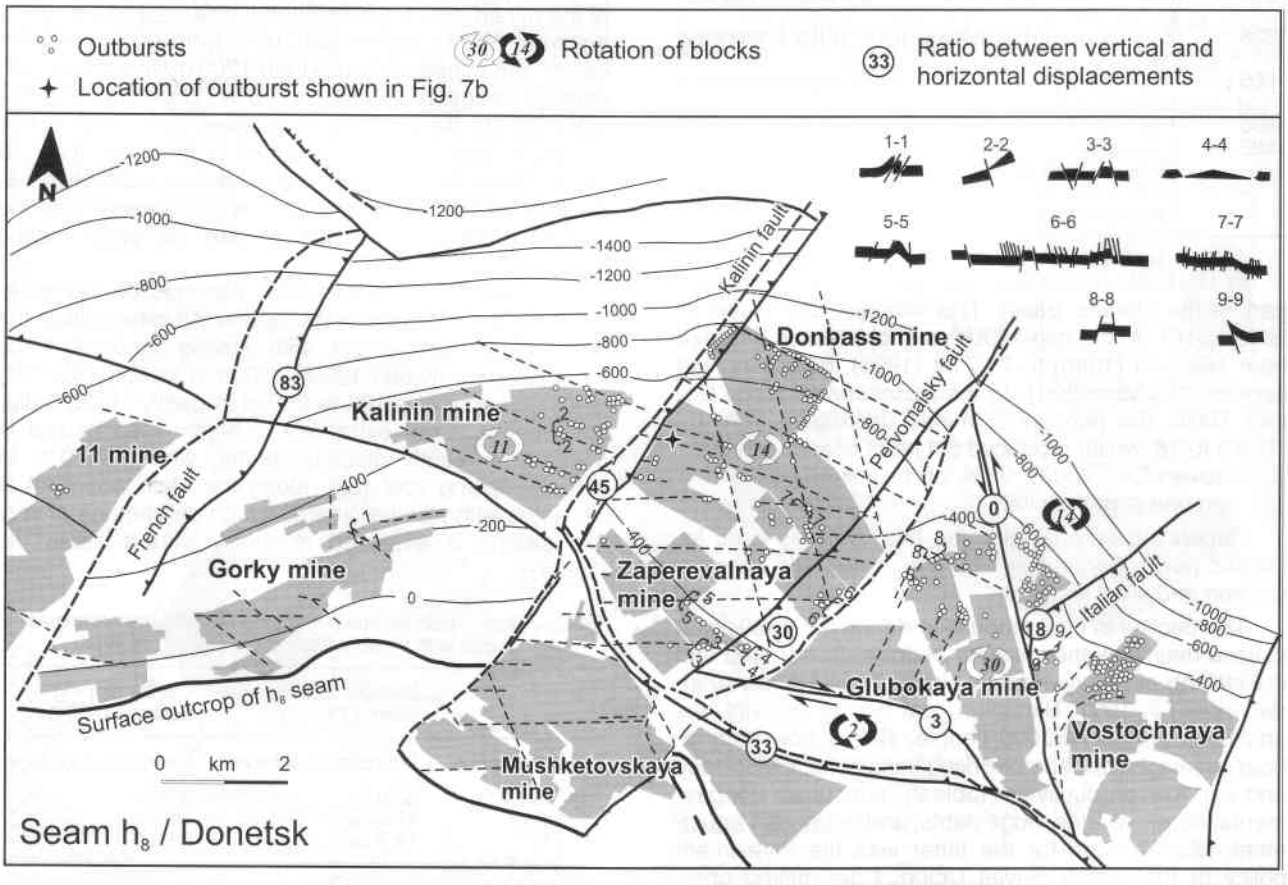

Fig. 7. Underground plan of the h_8 seam in the Donetsk area (see Fig. 3 for location of map) with location of coal and gas outbursts. The lines of intersection of faults with the seam are shown for the hangingwall (solid line) and for the footwall (stippled line) (after Privalov, 1985; 1988). Fault zones with small displacements (see insert) occur within the large tectonic blocks bounded by regional faults

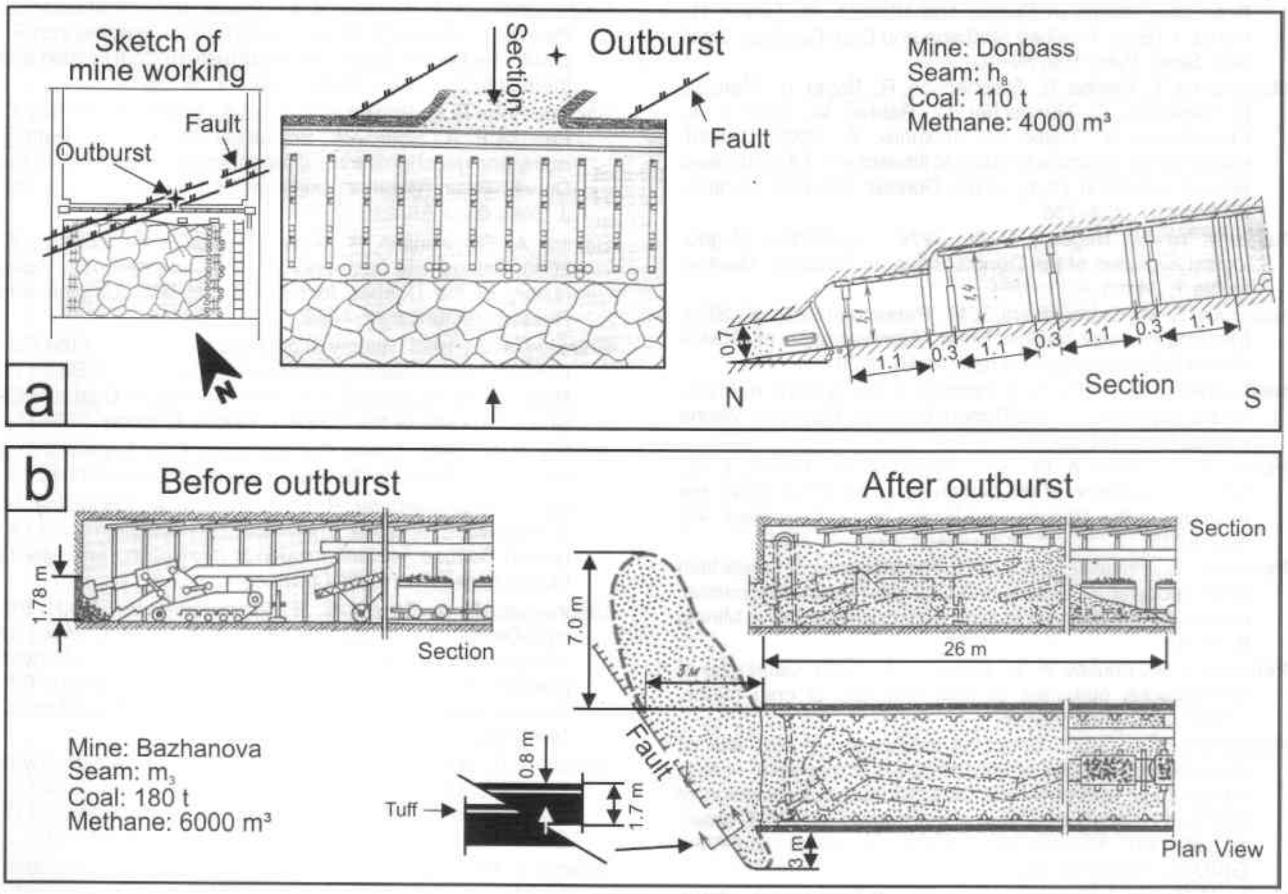

Fig. 8. a) View of a coal and gas outburst in the h_8 seam the Donbass mine (28. 12. 1980; Petukhov et al., 1989). The location of the outburst is indicated in Fig. 7. The outburst occurred in a zone with high pressures caused by a coal pillar in the overlying h_{10} seam and was related to a set of minor faults b) Sketch of a coal and gas outburst in the Bazhanova mine (12. 2. 1987; Petukhov et al., 1989). The outburst was related with a reverse fault displacing the m_3 seam. See Fig. 6 for location of Bazhanova mine

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