

THE INFLUENCE OF GEOLOGICAL HISTORY ON COAL MINE GAS DISTRIBUTION IN THE RUHR DISTRICT - A CHALLENGE FOR FUTURE RESEARCH AND RECOVERY

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(10 figures)

Abstract. Methane emissions to the atmosphere induced by German hard coal mining in the Ruhr mining district reach nearly 700 Mill. m³ of methane per year. Energetic utilization of this methane is environmentally friendly and an interesting completion to coal mining.

Practical experiences with the utilization of coal mine methane (CMM) from abandoned mines showed that the produced gas is highly variable in quantity and quality. Although there is a lot of information about most of the influencing factors to the whole system, their mutual interaction still is hardly understood.

The pre-mining gas distribution in the coal bearing strata of the Ruhr district is rather irregular due to the geological evolution of the basin. The models of “dynamic adsorption” and “fossil migration” explain this situation and may also help to better understand the recent gas dynamics induced by the mining activity.

During the transformation of organic matter into hard coal by basin subsidence a large volume of 50-100,000 km³ gas was formed. Most but not all of this gas escaped into the atmosphere. Gas migration in the rocks and storage capacity in the organic matter or coal are controlled by temperature and pressure conditions, which changed considerably in the geological history of the basin. Due to the large adsorptive storage capacity of coal, gas contents of more than 10 m³ per ton of coal still can be found in several parts of the Ruhr basin. In combination with data of the geological coal resources the remaining gas potential can be calculated. A considerable gas resource still exists.

The utilization of CMM on the local energy market has been stimulated by German legislation. Today, the extraction of the dangerous coal mine gas from still working and abandoned mines pays off and leads to an additional energy recovery, which simultaneously reduces the greenhouse effect of methane otherwise vented to the atmosphere.

Keywords: Coal mine methane, Ruhr district, methane generation, burial history.

1. Introduction

Methane emissions to the atmosphere induced by German hard coal mining reached about 1.4 Bill. m³ per year in the past. Per year and restricted to the Ruhr mining district, 698 Mill. m³ of methane are expected to be emitted in the near future (Meiners, 2001, Thielemann, 2000). From this quantity a considerable part of nearly 200 Mill. m³ may be attributed to the abandoned mines. Further decrease of active mining will increase this proportion. Methane is a greenhouse gas. In the past, most of the mine gas was vented into the atmosphere, accelerating the greenhouse effect. Utilization of the gas as an additional energy resource can slow down the rise of this effect. Hence, in April 2000 the German government installed market regulations, the so-called renewable energies act. Presently, the utilization of mine gas is profitable in

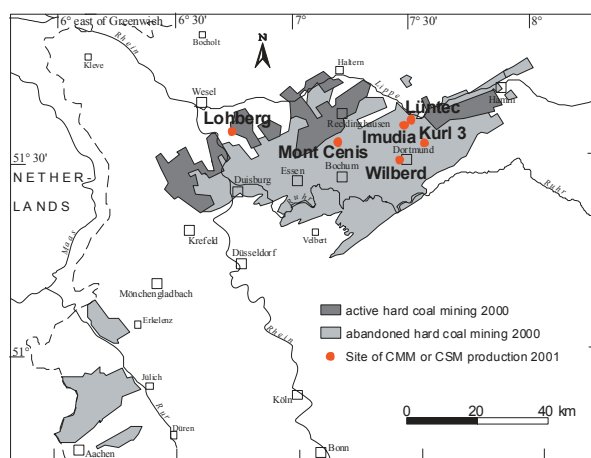


Figure 1. Mining situation in the Ruhr District and coal gas utilization sites in 2001.

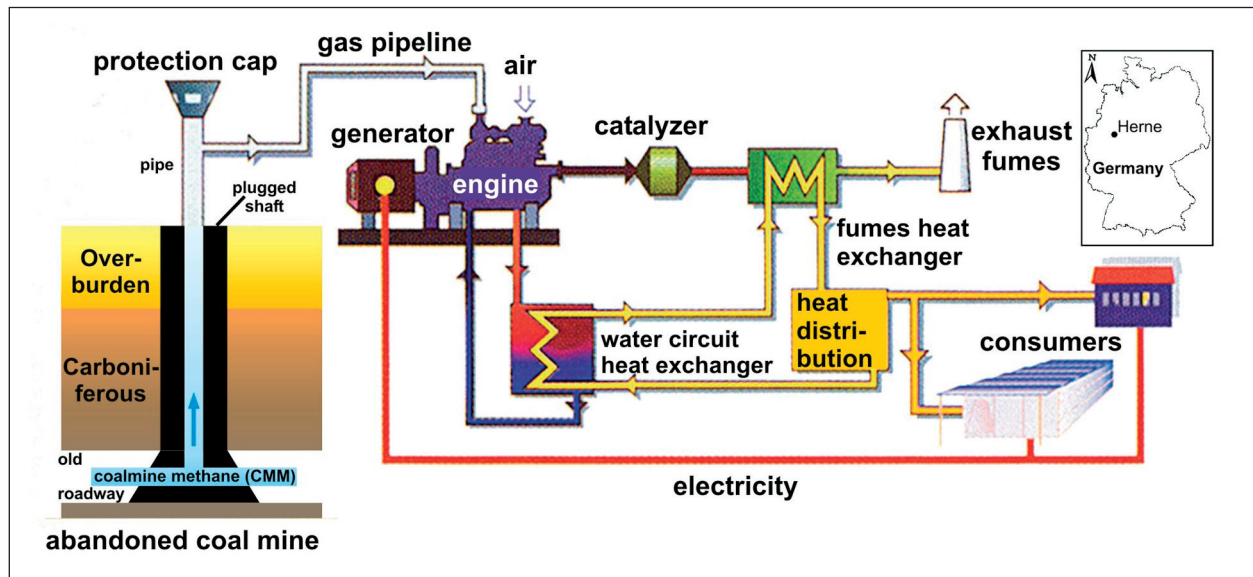


Figure 2. Electricity and heat production from CMM in Mont Ceniz, Herne/Germany. Sketch modified after Stadtwerke Herne (unpublished).

Germany (Preusse, 2002). Thus, in the areas of active and abandoned mines in the Ruhr district the recovery and utilization of mine gas has become an important goal (Kunz, 2003; Woersdoerfer, 2002). Figure 1 shows the mining situation and coal gas utilization sites in 2001. Figure 2 presents a sketch of one of the production sites. Until now, CSM- and CMM-exploration licences for more than 40 areas have been granted to different companies and institutions.

Mine gas is given different terms depending on its origin. Gas from abandoned mines is called coalmine methane (CMM) whereas gas from active collieries is named coal seam methane (CSM). The CSM from active mines drives normal gas engines, as the gas quality (i. e. methane concentration) is rather stable with time. The utilization of CMM from abandoned mines is more complicated. The first practical experiences unravelled that methane concentration and gas production were too variable for a continuous electricity production by conventional gas engines. The machines had to be adapted to the CMM characteristics. Till present, plausible and proved explanations for the variable gas quality and gas flow of CMM are scarce.

There are three different groups of factors, which influence the CMM production. The pressure and dynamics of the gas, the geometry and geotechnical state of the old mine roads, shafts and works and the geological and geomechanical situation of the coal deposit. Although a lot of information about most of these factors is usually available, reliable information about their interaction is still rare. Due to the limited number of practical cases of CMM recovery these uncertainties cannot be reduced quickly. However, a consideration of both the gas origin and the gas reserves left in the worked coal mines may help solving this problem and minimize

technical and financial risks in CMM production.

This paper wants to introduce new geoscientific findings into the actual CMM considerations, which are dominated by geotechnical aspects. Moreover the presented model of degasification in geological times is a first complex approach to explain the irregular gas distribution in the Ruhr Carboniferous. In this sense it may be used also as a methodic aspect for future investigations of the artificially induced recent gas dynamics.

2. Gas potential

From the first tests of CMM recovery from old shafts it is well established that the extracted gas volume often exceeds by far the possible free space of the old mine works. The coal seams in the neighbourhood of the

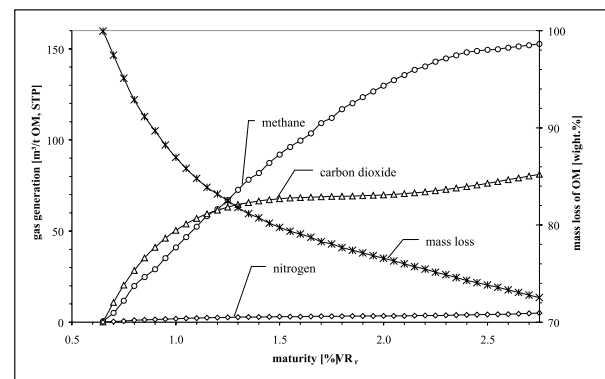


Figure 3. Mass-balanced cumulative generation of methane, carbon dioxide and nitrogen as well as corresponding mass loss of organic matter in the maturity interval of 0.65 to 2.75 %VR_r (= vitrinite reflectance), after Gaschnitz, 2001.

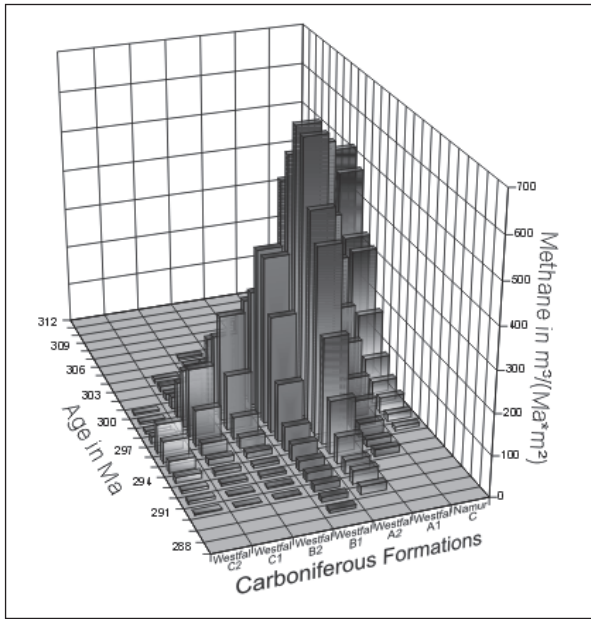


Figure 4. Permocarbiniferous methane generation in the Ruhr basin, calculated per Ma, per area and for a generalized stratigraphic column of the coal-bearing strata, after Thielemann (2000).

mine works therefore should be integrated into the estimation of the recoverable CMM potential. A first approach of the determination of the geological gas content before mining is given below:

As shown by Hinderfeld et al. (1993) and Kunz (1999) the original geological (pre-mining) gas distribution in the coal bearing strata of the Ruhr district is rather irregular.

Comprehensive explanations of the gas generation and distribution in geological times have been given by Gaschnitz (2001) and Thielemann (2000). Their models of “dynamic adsorption” and “fossil migration” may also help to better understand the recent processes of gas dynamics induced by mining activity.

During the transformation of organic matter into hard coal by basin subsidence at the end of the Carboniferous a large volume of 50-100,000 km³ gas developed in the area of the Ruhr district (fig. 3 - 5). The major portion of this gas escaped into the atmosphere at different geological stages of crustal uplift and subsidence. Therefore today the coal seams are undersaturated with respect to gas: The recent (hydrostatic) pressure and temperature conditions would allow bigger volumes of coal gases to be stored. Nevertheless, some gas is still left mainly in the coal seams, due to its special molecular structure and its large adsorptive storage capacity for gas (Scheidt & Littke, 1989).

Gas contents of 0 up to more than 10 m³ per ton of coal are found in different parts of the Ruhr district. Combining the irregular gas distribution with coal resources data (= sum of all coal in place) the gas potential can be estimated. This calculation considers that one third of the organic matter in the coal bearing strata is dispersely distributed.

The coal resources data are based upon a comprehensive assessment of the German hard coal deposits by means of a detailed mathematic-geometric 3D model (Juch et al., 1994, Juch, 1997). From these data in the Ruhr district 85 Bill. tons (85 × 10⁹ tons) of coal are calculated to have remained in place in the zone of actual and former mining despite the extraction of 12 Bill. (12 × 10⁹)

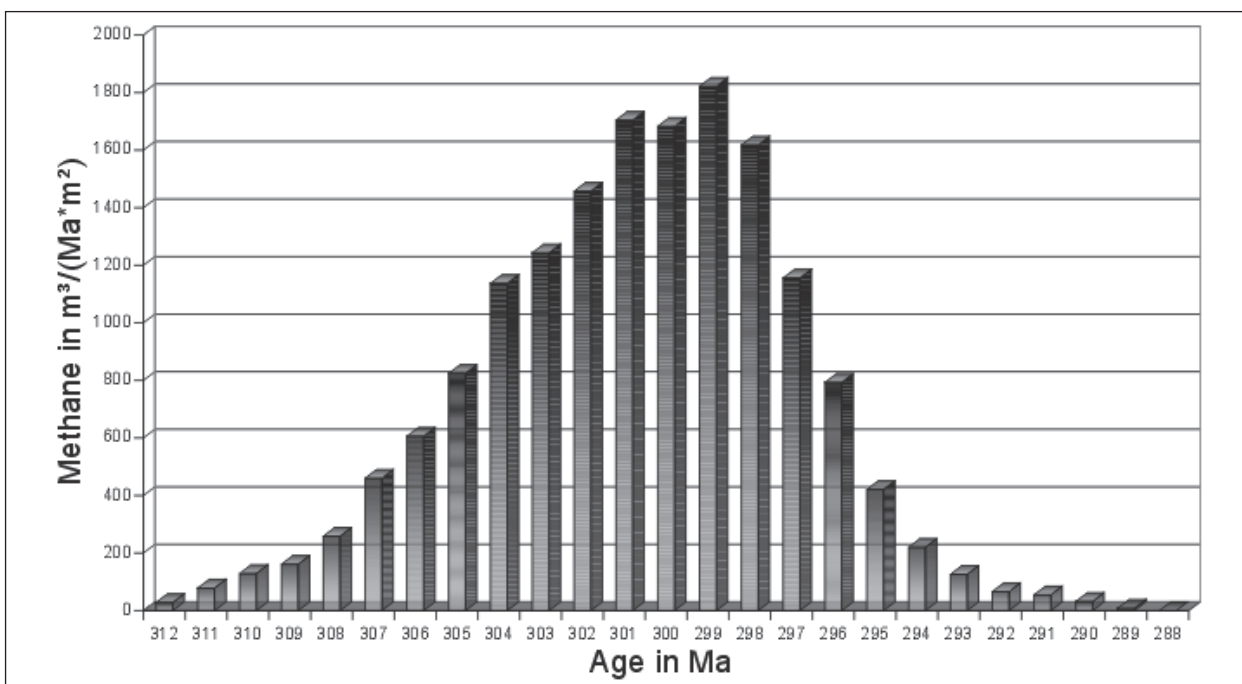


Figure 5. Partial sums per Ma and per area of thermogenic methane generation in the Ruhr basin, time span 312 to 288 Ma ago, after Thielemann, 2000.

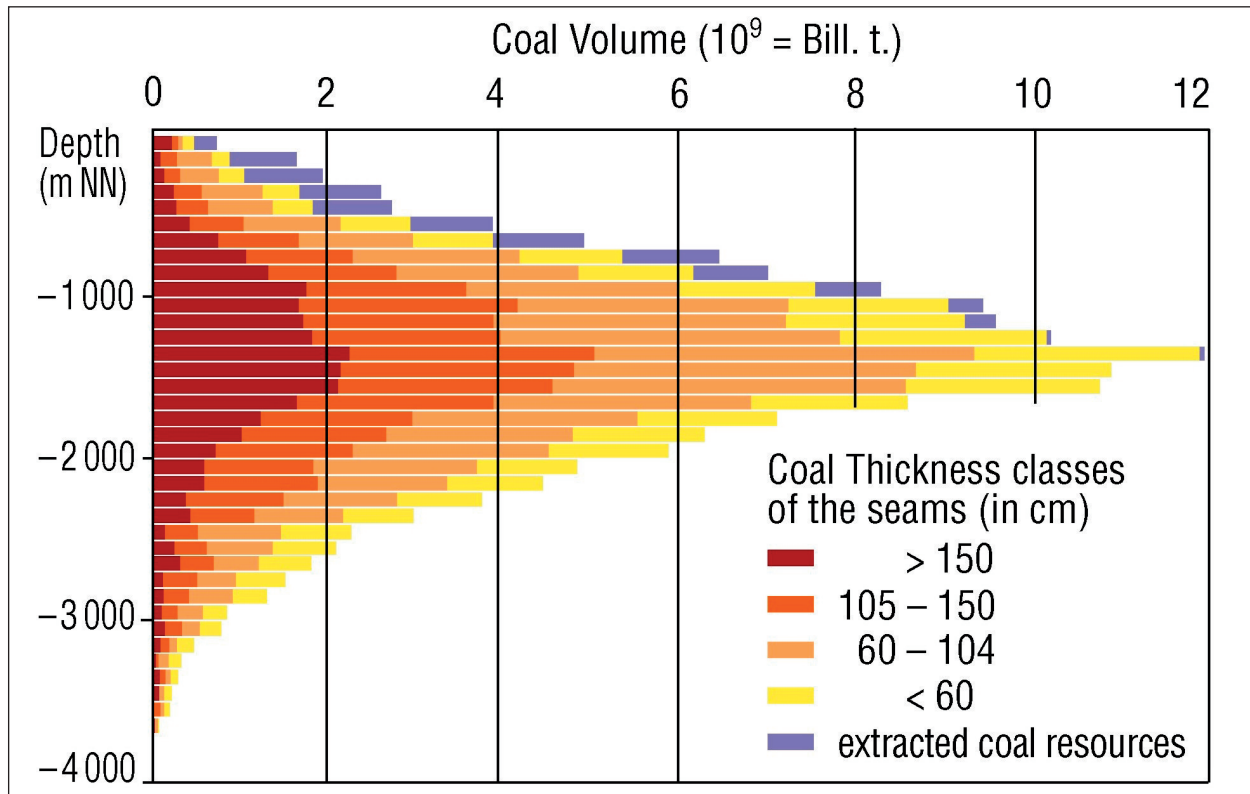


Figure 6. Coal volumes in the mining and exploration zone of the Ruhr district, total 204 Bill. t.. To avoid misinterpretations of this figure: from this large coal in place resources only a small portion of ca. 5 Bill. t can be assigned as mineable under current conditions!

tons of coal during the last centuries. Considering also the “exploration zone” this figure doubles (fig. 6). Considering a primary gas content before mining with values of 5 – 10 m³ / t (e.g. Kunz, 1999, or Gaschnitz, 2001) the estimation of the total gas potential in the Ruhr district reveals a gas volume of 500 to 1,000 km³ (Juch, 1996, Juch et al., 2001). Only 1 % of the gas volume originally generated during the Variscan basin subsidence has been conserved. The gas loss during mining does not exceed 100 Bill. m³ or 10 – 20 % of the pre-mining gas volume. These figures clearly show the dependence of the present day gas distribution in the Ruhr district on gas dynamics and degasification.

3. Gas desorption and distribution

In the Ruhr district the coalification of organic matter largely remained unchanged after the first (and deepest) basin subsidence in late Carboniferous and early Permian times. A post kinematic coalification and gas generation as supposed for the eastern Ruhr district (Lommerzheim, 1988, 1991) can be excluded (Thielemann, 2000; Thielemann et al., 2001; Juch, 2002). Hence, gas generated during this early phase has predominantly been stored by adsorption in coal seams or on disperse organic matter in the adjacent strata. Small parts of the gas have been stored in macropores or cleats and fissures in seams and

surrounding rocks. The parameters to control the storage capacity of organic matter are pressure, temperature, moisture content as well as maceral composition, coal maturity, gas composition and ash content.

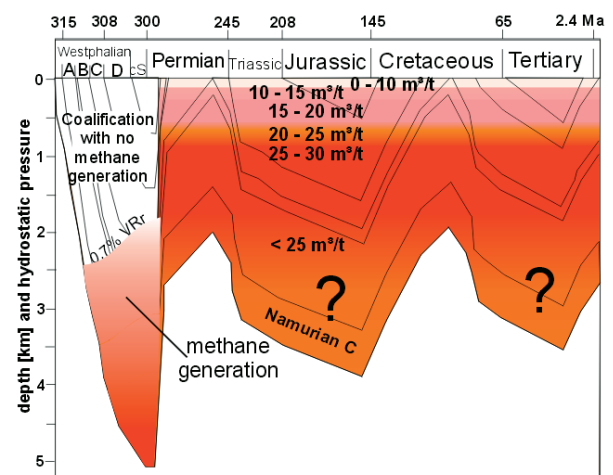


Figure 7. Methane generation and depth-related changes in maximum methane adsorption capacity (dry, vitrinite-rich coals) at hydrostatic pressure in the Ruhr basin. All data are plotted into the burial history of the rocks (Thielemann, 2000). Highest adsorption capacities occur between 800 and 1,500 m depth. Adsorption data are after Gaschnitz, 2001. As laboratory data of adsorption capacities below 2 km depth do not exist, adsorption capacities are indicated with a question mark at those depths.

From laboratory experiments it is well known that increasing pressure promotes adsorption of gas until the amount of stored gas asymptotically approaches the maximum capacity of the coal. This capacity is not exceeded even at significantly higher pressure. Increasing temperature on the other hand progressively obstructs adsorption of gas on organic matter and tends to reduce the adsorption capacity of coal (Gaschnitz 2001). As a consequence, the parallel increase of pressure and temperature along the geological depth trends ($\approx 30\text{ }^{\circ}\text{C}/\text{km}$, $\approx 10\text{ MPa}/\text{km}$) results in two competing factors controlling adsorption of gas.

At shallow depth adsorption is primarily controlled by reservoir pressure and gas storage capacity increases rapidly (at a given maturity and petrographic composition of organic matter). Towards greater depth reservoir temperature more and more dominates (and obstructs) the adsorption process while the depth dependent increase of pressure only marginally increases the amount of adsorbable gas.

Hence, in a static situation the gas adsorption capacity of coal increases at shallow depth, reaches a maximum at about 500 to 700 m and decreases towards greater depth. In the dynamic process of basin evolution with successive phases of uplift and subsidence the adsorp-

tion capacity within a coal seam changes as a function of (mostly) tectonically induced reservoir pressure and temperature variations (Gaschnitz 2001, fig. 7). A drop of adsorption capacity below the previously stored gas content liberates gas and initiates upward migration. As adsorption capacities in some shallower seams are higher, they provide means to capture upward migrating gas from underlying coal bearing strata.

As reservoir pressure and temperature are competing factors controlling the adsorption of gas at different depth levels tectonic phases of subsidence induce contemporaneously pressure controlled increase of adsorption capacity at shallow depth and temperature related desorption and gas migration at greater depth. In contrast, phases of uplift increase the adsorption capacity of deep coal seams due to decreasing reservoir temperatures while coal seams close to the surface loose most of their adsorption capacity due to the pressure drop during uplift. Gas stored in these coal seams is vented into the atmosphere. The succession of phases of uplift and subsidence as seen in the geological history of the Ruhr Basin (Litke et. al. 1994, 2000) resulted in a stepwise pumping effect where gas generated from deeper strata has eventually been adsorbed in coal seams further up in the section, below the unconformity or even within the Cretaceous overburden (Gaschnitz, 2001).

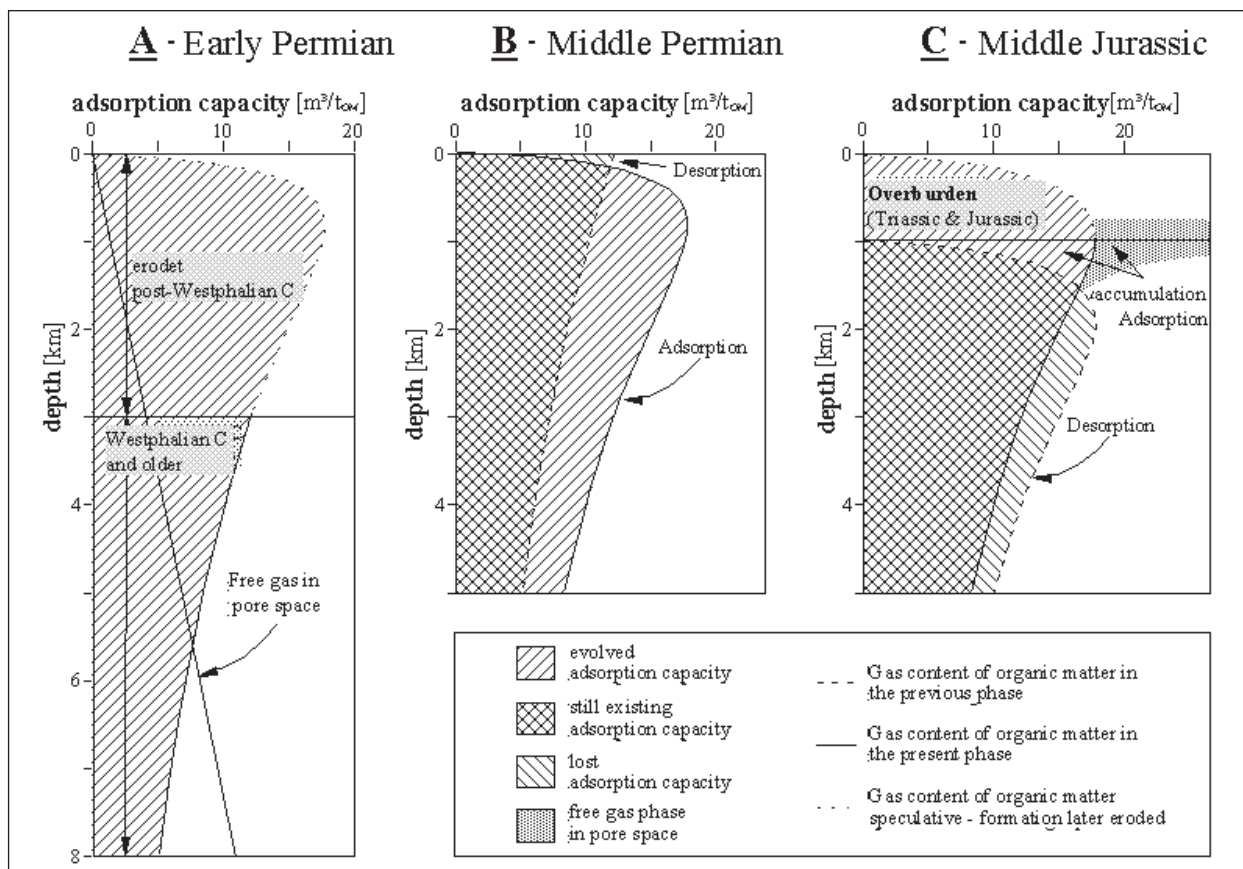


Figure 8. Reconstruction of adsorption capacities of the Upper Carboniferous coal-bearing strata during basin subsidence. Time span here: Carboniferous to Jurassic. Given are a medium maturity of 1,55 % VR_I and a complete water saturation of the organic material, after Gaschnitz, 2001.

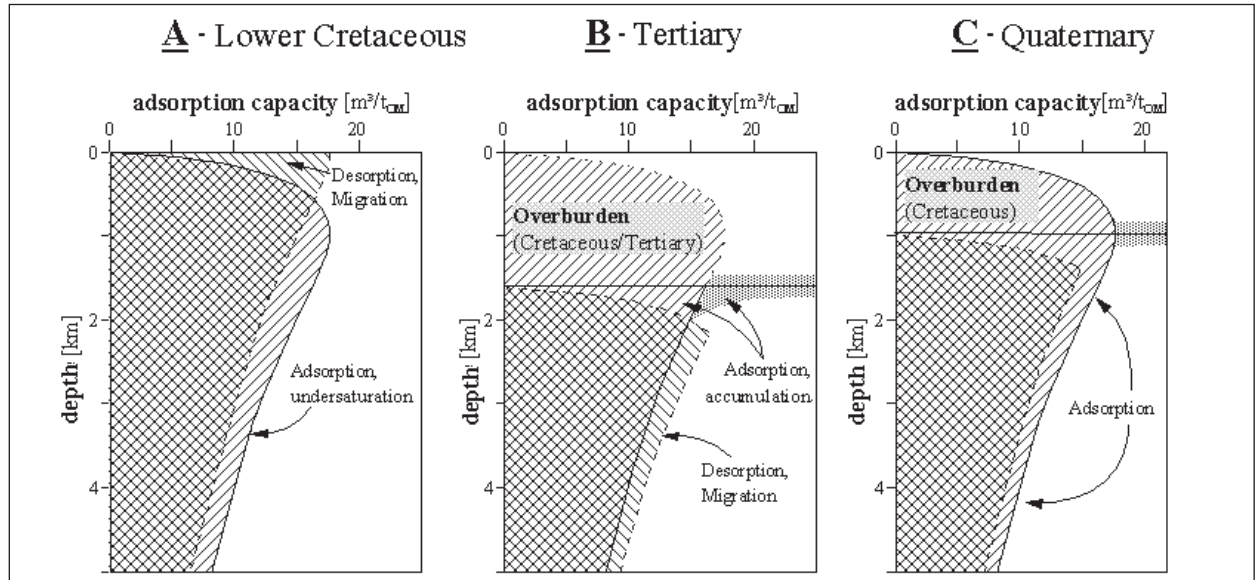


Figure 9. Reconstruction of adsorption capacities of the Upper Carboniferous coal-bearing strata during basin subsidence. Time span here: Upper part of Lower Cretaceous to Quaternary. Given are a medium maturity of 1,55 % VR_R and a complete water saturation of the organic material, after Gaschnitz, 2001.

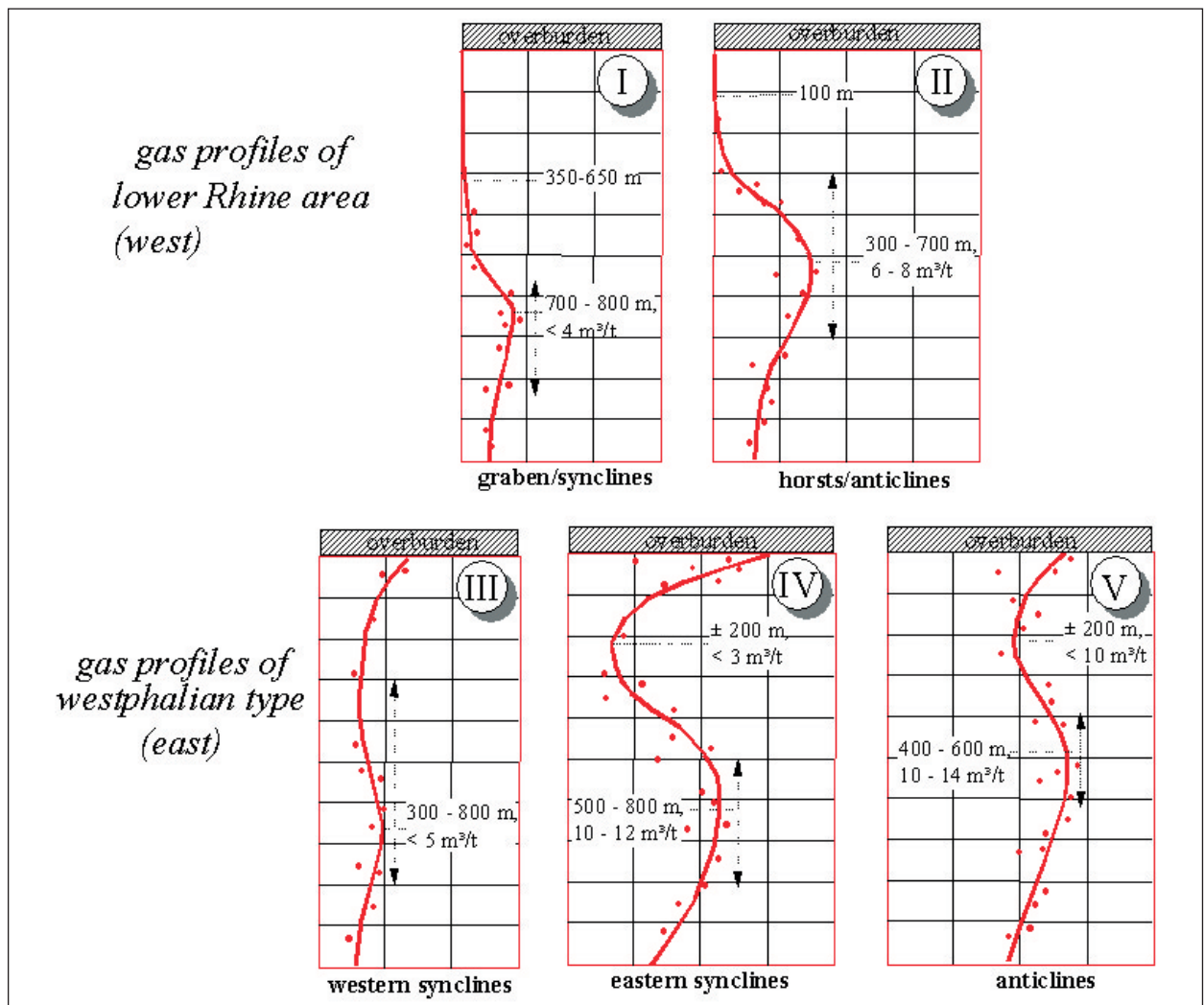


Figure 10. Westphalian and Lower Rhine gas profiles with depth in Upper Carboniferous rocks and their variability with regional and structural positions, after Gaschnitz, 2001.

During the first (Carboniferous) subsidence rising pressure allowed the gas adsorption capacities to increase. The gas was stored within pore space of the yet unconsolidated sandstone formations while adsorption of gas on organic matter was negligible due to high reservoir temperatures ($>180\text{ }^{\circ}\text{C}$). Tectonic activities at the end of the Variscan orogeny generated numerous migration pathways. Most of the gas was released from the coals and migrated along the fissure planes where traces of methane were fixed in fluid inclusions of ore minerals (Jochum, 1999). The gas escaped into the atmosphere, stimulated by pressure decrease and erosion.

After the Variscan orogeny gas desorption took place at very shallow depth during the uplift in the first half of the Permian about 270 Ma ago (fig. 8). Due to cooling accompanied with this uplift the adsorption capacities of coal at greater depth ($> \approx 300\text{ m}$) increased so that gas left in the pore spaces or migrating upward from deeper coal seams was trapped by adsorption in the coal seams and onto the dispersed organic matter. With the onset of the second subsidence phase in the Ruhr Basin ($\approx 250\text{ Ma}$) a new adsorption-desorption phase began: Coal seams at greater depth lost some of their adsorption capacity (due to the temperature increase) and the liberated coal seam gas migrated upward. At shallow depth the adsorption capacity increased because here reservoir pressure was the dominating control. Gas passing by from underlying coal seams was trapped in this strata.

The deposition and erosion of potentially thick Jurassic and Cretaceous strata and the respective subsidence and uplift movements of the Palaeozoic strata resulted in two more cycles of adsorption and desorption as described by the dynamic adsorption model (Gaschnitz, 2001). Also, younger rocks of Jurassic and Lower Cretaceous age probably acted temporarily or locally as a gas lid on top of the Carboniferous. In Upper Cretaceous and Tertiary times, repeated subsidence and uplift led to multiple adsorption and desorption processes within the coal bearing strata (fig. 9). One result is a remarkable gas accumulation in the top Carboniferous of the Eastern Ruhr basin, below a cover of a few hundred meters of Upper Cretaceous marine rocks.

Generally speaking, in the eastern part of the Ruhr district the gas content in the coal is higher than in the western part of the Ruhr basin (Kunz, 1999; Gaschnitz, 2001). Maximum values of up to $15\text{ m}^3/\text{t}$ can be found at structural highs (anticlines, horsts) and 300 to 800 m below the Post-Carboniferous overburden. This corresponds to absolute depths of 1000 to 1400 m, which is the zone of highest adsorption capacities (Gaschnitz, 2001). Normally the methane contents of the gas reach around 90 Vol.-%.

Within the Ruhr basin one observes both, regional and local trends in gas content. Two regional patterns can be distinguished, a Westphalian and a Lower Rhine type of gas profile. The Westphalian gas profile is typical of the eastern Ruhr basin, east of the Blumenthal fault. It

is characterized by gas accumulations at the top of the Carboniferous, 100 to 200 m below a Mesozoic caprock. Gas contents vary between 3 and $14\text{ m}^3/\text{t}$. The Lower Rhine gas profile shows lesser gas content. Gas contents generally range between 0 and $8\text{ m}^3/\text{t}$ and reach only locally up to $14\text{ m}^3/\text{t}$. There are no gas accumulations below the Permian and Mesozoic caprocks (fig. 10).

The two regional trends are overprinted by local ones, which are mainly influenced by medium scale tectonics. Higher gas contents are found in tectonic highs (anticlines, horsts). Also, a higher density of faults negatively affects the gas contents. This is especially typical in the western basin (Lower Rhine type of gas profiles). In contrast, some faults in the eastern Ruhr Basin are very gassy and have been responsible for dangerous gas outbursts during coal mining activities in the past.

The eastern Ruhr basin generally contains more gas than the western part of the basin. Reasons for this are: In the eastern basin the subsidence in Upper Cretaceous and Tertiary times was probably deeper than the older subsidence in late Permian and Triassic times (compare fig. 7). In the western basin the situation was reverse with a shallower subsidence in Cretaceous and Tertiary times. Additionally, the permeabilities of the caprocks locally are lower in the western than in the eastern basin (Thielemann, 2000, Thielemann et al., 2001), favouring a gas accumulation in the east. The caprocks in the western basin also show more variable facies and stronger fault tectonics than in the east. High gas contents in the western basin are restricted to horst areas, which are affected only by small scale tectonics.

4. Geotechnical application

The above description of geological processes and the quantification of gas contents are rather generalized and in parts still uncertain. The transfer of these data to one specific reservoir situation has to take the local geological situation into account. On the one hand, depth and orientation of coal seams as most important gas reservoir varies with the structure of the rocks. On the other hand, the above described regional gas dynamic processes were driven in detail by the non-uniform local geotectonical development. Finally, coal mining generated an irregular network of gas permeabilities of different size, which in every single case needs to be analysed individually.

In general, the local spatial orientation of reservoir parameters (pressure, temperature) around mining areas is quite well known. In many cases this includes the pre- and post-mining gas contents. A sound knowledge exists too about degasification processes accompanied by coal mining. For instance, in the hanging wall direction of mine works the gas contents in the coals are reduced up till 200 m above the worked coal seam. Gas contents gradually drop down to $0\text{ m}^3/\text{t}$ towards the (former) mining level.

Recent knowledge only allows a rough estimation of the recoverable part of the gas potential described above. One should consider only the sectors of the active and closed mines with greater gas occurrences during mining below depths of 600 m and the present day gas viability above the rising water levels: Former coal resources calculations reveal in these parts of the deposit a remaining coal volume of approximately 30 Bill. t (fig. 6). Assuming a primary mean gas content of 7 m³/t and subtracting the gas losses by mining of 100 Bill. m³, an accessible potential of 100 Bill. m³ recoverable gas results. As this calculation does not consider the local variations of the geological and technical parameters, it only indicates the dimension of the gas reserve to be expected. This volume makes only a small portion of the total gas in place still stored in the coal bearing strata of the Ruhr district.

Considering the recovery of this gas only a few findings have been obtained about the mid term and long term gas dynamics after the mining activities have been stopped. These post-mining gas dynamics are mainly controlled by the geometry of the goaf. Gas permeabilities of collapsed longwall mining areas including old mine roads and goafs are highly variable. Of similar importance is the level of mine waters and its changes. With time both, volume and orientation of natural and man-made fissure planes within the mined rock sequence and caprock become increasingly important. All these mid to long term gas dynamics are superimposed by steady changes in atmospheric pressure.

For future predictions of the recovery potential extensive investigations to and experiences with gas dynamics in abandoned mines are still needed. Especially our knowledge of flow resistance is limited and insufficient, but these data are decisive to the direction and size of gas flows. In the Ruhr basin there is much information about reservoir geology and pit geometry. Hence, the development and application of appropriate models will be based on a number of well known parameters. By this way also the calculation of gas dynamics on a regional and local scale should be a solvable problem.

Similar conditions are found in other European hard coal mining districts. Long-time experience with mine degasification exists in the Northern France hard coal district. The geological gas potential of the Donets basin (Ukraine) may be of a dimension which is more than 30 times larger than that of the Ruhr mining district (Marshall et al., 1996).

Furthermore, a successful CMM recovery may also stimulate geotechnical inventions to master the so far unsolved problem of the coal bed methane (CBM) recovery in nearly all coal deposits of Europe.

5. Conclusion

Despite a complicated geological and mining history a considerable methane potential was left in the Carbon-

iferous rocks of the Ruhr basin. Its irregular distribution is mainly controlled by the gas loss with time as a result of different geological processes. As the gas normally is fixed to the coal surface, mainly by molecular bonds, gas migration and extraction is facilitated by mine roads, works, and old goafs. The opening of tectonic structures, joints and cleats during coal mining leads to additional and favourable gas passages. Today, the extraction of dangerous coal mine gas from active and abandoned mines leads to an additional energy recovery, which simultaneously reduces the greenhouse effect to the atmosphere.

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