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INFLUENCE OF GEOLOGIC AND ECONOMIC PARAMETERS ON THE (E)CBM-DEVELOPMENT IN THE CAMPINE BASIN (BELGIUM)

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Abstract. The Belgian Campine Basin is part of a large paralic north-western coal basin of Carboniferous age, which also extends northwards and eastwards into the Netherlands and Germany. The Westphalian coal-bearing deposits are disconformably covered by Late Palaeozoic or Mesozoic strata and generally show a moderate dip to the north or north-east. An important transpressional fault zone of Palaeozoic age divides the basin into western and eastern sub-basins. During the Carboniferous, syntectonic differences in palaeo-subsidence caused remarkable differences in the burial history and sedimentological styles of these sub-basins and consequently, in their peat and final coal formation, its setting and CBM-potential.

Large coal reserves still remain in the Campine basin at relatively shallow depths (above 1500 m). Based on the distribution of these coal reserves and their actual rank, an overall CBM-content for the complete basin, as well as for specific anomalous zones within the basin, has been calculated by using an empirically determined (mining) rank / gas relationship. In this manner, six (6) areas have been established in which the gas concentration is significantly (5 times) above a set general threshold value. Together they represent a significant, minimal producible (E)nhanced CBM "target-volume" of about 53 x 10^9 m^3 of methane.

The various target areas demand different approaches in any (E)CBM development. In the southern parts of both sub-basins, the remaining changes in porosity/permeability and stress conditions of the rocks, caused by the former mining activities, have to be included into the (E)CBM-development schemes. More towards the north and north-east, any use of preserved coal mining influences is simply not possible. Here, both the sedimentological and structural setting of coals will determine the predominant geologic (E)CBM-development factors.

Possibilities for ECBM-production by CO_2, N_2 or even "raw" flue gases are largely present within or very close to the most prolific CBM-areas. Gas-pipelines and other infrastructure needed for (E)CBM-development are present in the basin, too. The basin is situated within a low to moderately populated part of the country, which is actually rapidly economically expanding. This certifies a steadily increasing gas-consumer market in the next decades.

Key words: coal basins, coalbed methane, Carboniferous.

GEOLOGICAL SETTING OF THE CAMPINE BASIN

The Campine Basin is situated to the north of the lower Palaeozoic rocks of the London–Brabant Massif (Cambrium to Silurian age). At this actual southern edge of the basin, clastic rocks of the Middle and Late Devonian (Givetian, Famenian) overly the older, Caledonian deformed basement. The former are covered by Lower Carboniferous dolostones and limestones (Tournasian to Viséan) and Upper Carboniferous clastic sediments (Namurian and Westphalian A to D; Fig. 1). In the north-eastern part of the basin, post Carboniferous sediments (Permian to Jurassic) disconformably cover these Westphalian strata in a roughly onlapping wedge (Fig. 2). Both this north-eastern succession and the Palaeozoic sediments in the other parts of the basin are covered again by deposits of Upper Cretaceous and Cenozoic age, in a disconformed way.

Within the basin, the actual main faults have a NNW to SSE or NW to SE direction. These predominantly normal faults and the intersecting, NE-directed smaller faults, divide the basin into long-stretched fault blocks, actually tilted towards the N and NE. This tilting was caused by the uplift of the Brabant Massif during the Kimmerian orogeny.

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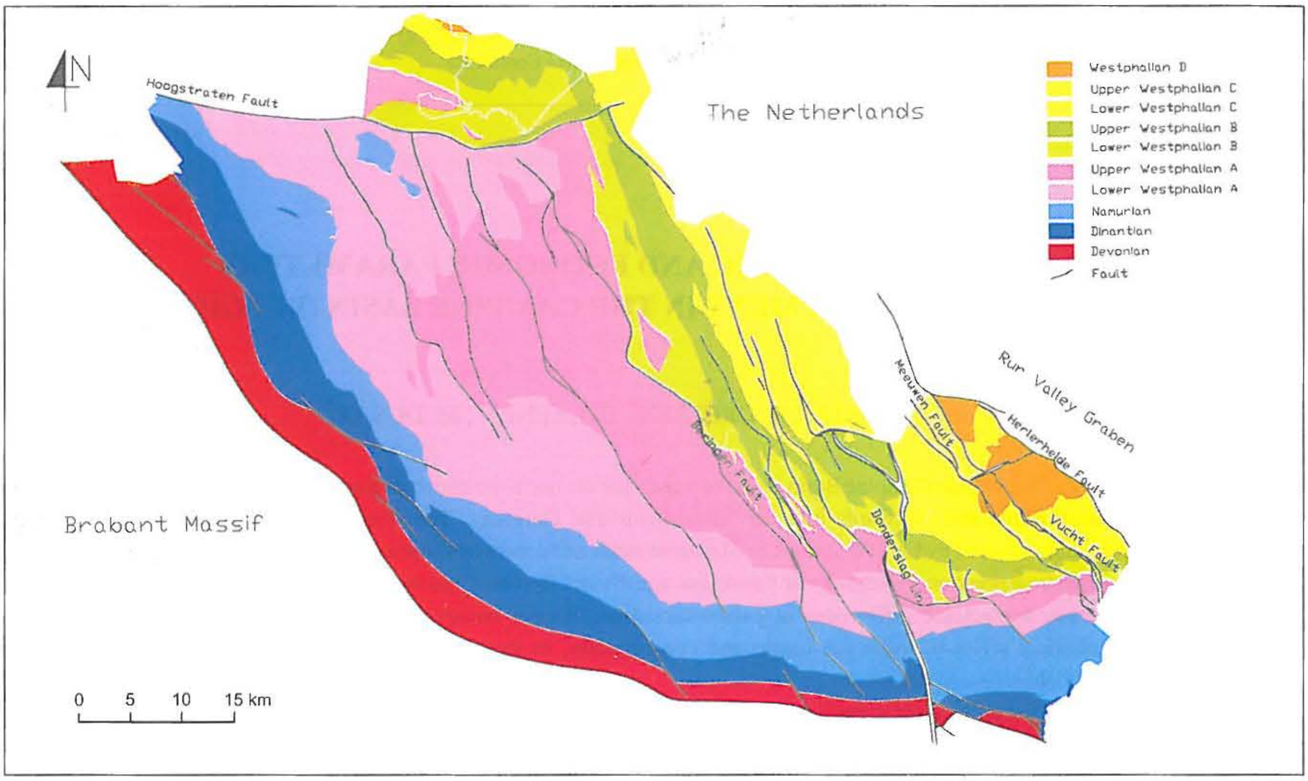

Fig. 1. Campine basin: Palaeozoic subcrop (after Langeneaker, 1998)

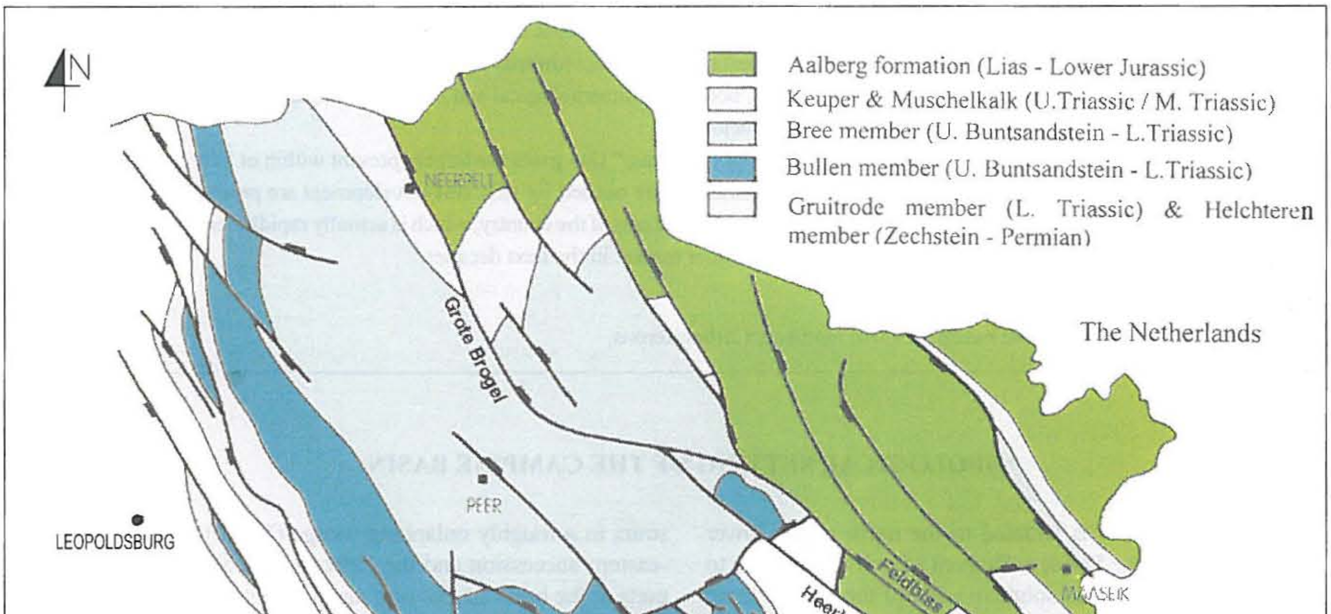

Fig. 2. Pre-Cretaceous subcrop map of post Carboniferous sediments in the northeastern part of the Campine basin (after Langeneaker, 1998)

In this way, a series of (N)NW striking, stepping fault blocks, causes not only the Carboniferous subcrop deepen quickly towards the north and north-east, but is also responsible for the remainder of younger strata deepening in this direction (Wenselaers *et al*., 1996). Therefore, the coal bearing (till 5%) Westphalian sediments of the basin also generally display a gentle monoclinal dip (5 to 10°) towards the north and north-east.

The conspicuous N–S striking Donderslag fault zone divides the Belgian part of the Campine Basin. This fault zone has certainly been active during the Carboniferous time. It has an important (dextral) strike-slip component next to its wrenching appearance (Dusar, Langenaeker, 1992; Wenselaers *et al*., 1996). The Donderslag fault zone is not known to have been active or reactivated during the post Palaeozoic times (Langenaeker, 1998).

The resulting western and eastern Carboniferous sub-basins, each show a different geological history, mainly induced by differences in subsidence. The coalification in the eastern sub-basin is much higher than in the western one (Helsen, Langeneaker, 1999), as is the thickness of many stratigraphic intervals (up to 20%; Laenen, 1999). The fault zone divides also the overall strike-direction of the stratigraphic horizons as well as the directions of the major faults in the basin. The above implies that the actual main NNW and NW striking faults in the Campine basin were already present during the Carboniferous.

Sedimentological evidence indicates a diachronous shift in the Westphalian sediments, from marine influenced depositional settings in the Late Namurian–Early Westphalian (coastal marshes), to more fluviatile influenced continental settings (back-swamps, fluvial plains and “hinterland” facies) during the Late Westphalian. Besides a gradually shifting palaeo-climate, synsedimentary tectonics (a. o. the Donderslag fault zone) have been responsible for the observed changes in the architecture of the palaeo-fluviatile environment, and consequently, in the geometry and properties of the palaeo-peat deposits (Dreesen *et al*., 1995). This also affected the maceral composition, and geochemistry of the resulting coal beds. Hence, the activity of the Donderslag fault zone has been of significant influence on the overall methane generation in the basin, as well as on the remaining CBM-potential of the coals. It also separates the former western and eastern coal mining districts of the basin.

COAL RESERVES

Although the southern, shallower part of the Campine basin has been intensively mined for coal during the major part of the 20th century, large coal reserves (both geologic and mining reserves) still remain present; occurring both at relatively shallow (till –1500 m) and at deeper levels.

To perform the basic calculations for the assessment of the coal bed methane (CBM) potential of the basin, the geological coal reserves of the basin have been calculated. Hereto, the basin has been subdivided into major fault block areas and all coal beds have been taken into account (minimum coal thickness till 1 cm!). The coal bearing stratigraphic intervals were subdivided into smaller vertical sequences of 100 m or less. Subsequently, their coal contents (Fig. 3) were added and contoured. Dip corrections were made to control the real thickness.

By using stratigraphic maps and exploration or subsurface borehole information, the results were checked, partly corrected and stored into a data-base. Each coal was attributed to a certain coal rank.

Although the majority of well-data is situated in and around the former mining areas, sufficient exploration wells information for a balanced evaluation exists throughout most other parts of the basin. Only in two occasions information had to be extrapolated to areas lacking direct data. The whole procedure has been carried out for depths of 1500 m as well as 2000 m. In this paper, only the figures to 1500 m are presented.

Based on the above procedure, a geological coal reserve has been calculated at about 39.3 billion tons. After a certain cut-off and a correction for former coal mining, still over 37.5 billion tons of geological coal reserves remain.

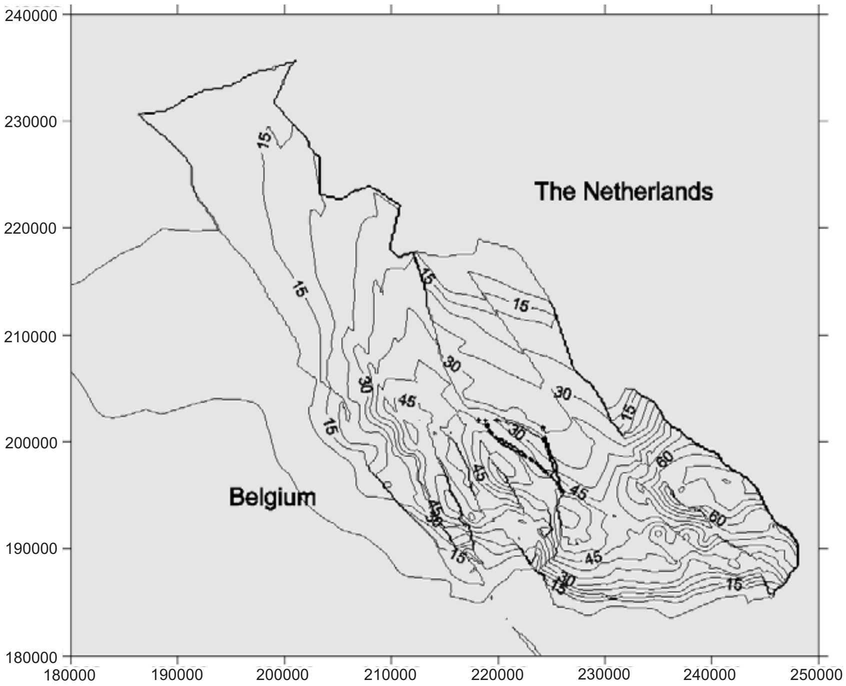

Fig. 3. Campine Basin; coal concentration map; coal concentration is given in million tons per km^2; contour spacing — every 5 million tons per km^2

With respect to any remaining mining reserves, one third of this amount must be discarded at once. Of the remaining 26 billion tons, only one third may tentatively represent any real mining reserves. To a depth of 1500 m, however, this still gives about 8.5 billion tons of mineable coal reserves for the whole basin: about 5 billion tons in the western, and ca. 3 billion tons in the eastern sub-basin. In our calculations of coal bed methane reserves, corrections have been made for both the mined coal and the resulting gas losses.

ECBM-RESERVES IN THE CAMPINE BASIN

Gas-rank relationship used

To calculate the coal bed methane "gas-in-place" content of the Campine basin, an empirical relationship between the remaining gas-content of the coals and the rank of the coals has been used. This relationship (Fig. 4) was established for coal-gas emission purposes in the former Dutch State Mines in the eastern, Dutch part of the Campine basin (south Limburg). It appeared well applicable in the Belgian parts of the basin, too (Vandeloise, 1971).

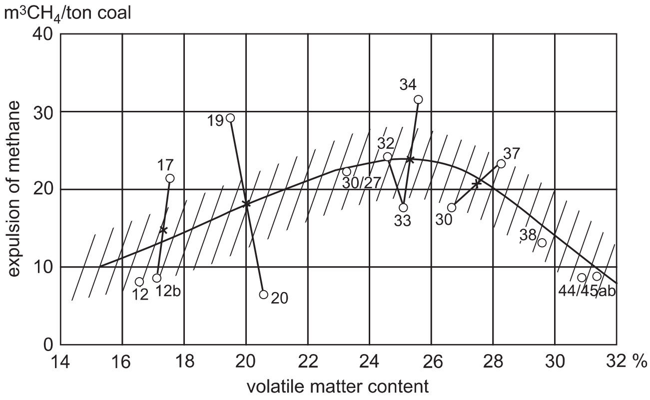

Fig. 4. Relation between gas content and coalification (after Stuffken, 1957, 1960)

Coals of the former Belgian and Dutch mining areas have reached their maximum coalification during the later phases of the Carboniferous period (Stuffken, 1957; Krans *et al*., 1986; Fermont *et al*., 1994). Although some debate still exists whether this holds for the entire basin (Langenaeker, 1998; Van Keer, 1999), any possible effects of recoalification have not been taken into consideration.

In fact, the Stuffken relationship describes how the rank of coals — and to a minor extent at shallow depth, the dip of the coal seams — determines the remaining gas content of the seams in the basin, within the zone of degassed Carboniferous strata, below its subcrop. At low to moderate dips and normal stratigraphic successions, this degassed zone roughly extends to a maximum of ca. 600 m (Stuffken, 1957; Teichmüller *et al*., 1970; Von Treskow, 1985). The remaining gas content is largely a function of changes in the remaining overall coal porosity at increasing ranks, so is their related permeability (Stuffken, 1957; Figs. 5a, b) and the overlying, remaining Carboniferous strata.

The maximum gas content is found around the boundary between medium volatile and low volatile ranked coals ("Fettkohle"). For larger depths, the flanks of the Stuffken curve will flatten out, as less gas escaped during uplift due to larger remaining pressures (the coals having remained within the flatter realm of the Langmuir isotherm). The latter will especially affect the curve part of the higher rank coals (low volatile to anthracite; "Esskohl" to "Anthrazit"). The same phenomenon has been established earlier in English coal fields (Williams *et al*., 1944).

Geohistoric burial conditions and so the depth extensions of these depletion zones (if any!) and their related gas–rank relationships, will vary for each basin or even for different parts within the same basin. For instance, application of the Stuffken relationship is not very valid in the easternmost part of the former Dutch mining district, where various Carboniferous folding phases have occurred. In the northern parts of the Campine basin, its full applicability is also doubtful, as it probably leads here to underrated gas values.

It is clear that our application of the Stuffken relationship gives at best a reasonable approximation of the coal bed methane reserves of the Campine basin. The estimates are likely to be under validated in the northern and north-eastern parts of the basin, whereas they appear to be fairly reliable in the southern parts (notably in and around the former mining districts).

Differences in maceral components of coal are also known to influence both its porosity and cleat formation, as well as its adsorption capacities. For the Westphalian A, B, and Lower C coals, of which the overall maceral compositions generally show identical changes through time in the entire basin, those differences have been averaged out by the number of measurements. Any changes in gas contents due to temperature differences and/or water saturation conditions have, as yet, not been taken into account.

CBM reserves "in-place"

Using all available data, contour maps have been made of the coal "in-place" concentrations (10^6 tons/km^2; Fig. 3) of which the amount of "in-place" coal reserves (in 10^9 tons) was calculated for the basin (Table 1). Also the coals were labelled with their corresponding rank. After corrections (e.g. for contouring and boundary effects), the Stuffken-relation was applied in order to get the corresponding gas values. Next, gas concentration contour maps were generated with these data

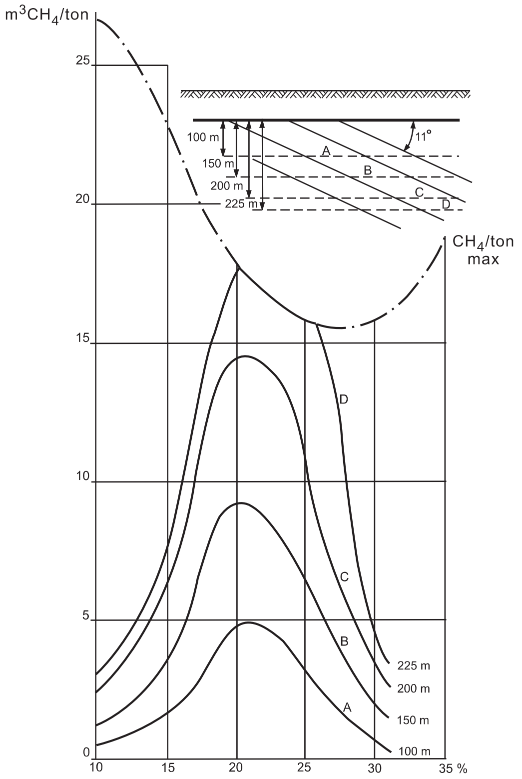

Fig. 5a. Coalgas content in relation to depth and coal rank at a stratigraphic dip of 11° (after Arets *et al.*, 1962)

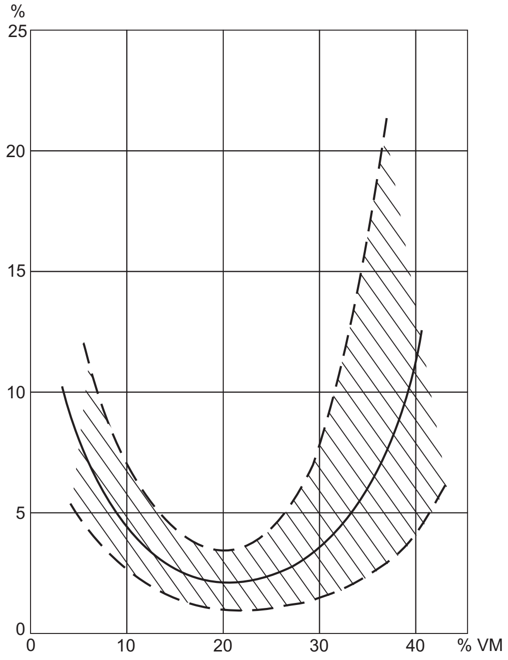

Fig. 5b. Porosity/rank relation of English coals (after King,Wilkins, 1944)

Table 1

Average "in-place" CBM-reserves based on the 50- and 250-gas concentration contours (lower and upper gas threshold values)

Gas concentration contour [10^6 CH_4/km^2]	50-contour	250-contour
Campine basin, total "gas-in-place" [10^9 m^3 CH_4]	291	132
Western sub-basin, "gas-in-place" [10^9 m^3 CH_4)	174	45
Eastern sub-basin, "gas-in-place" [10^9 m^3 CH_4]	117	87

5-coal concentration contour [10^6 ton "coal-in-place"/km^2]	Total "coal-in-place" [10^9 ton]	Average gas concentration [m^3 CH_4/ton coal]
Campine basin	37.5	7.8
Western sub-basin	21.2	8.2
Eastern sub-basin	16.2	7.2

The average gas concentrations are given with respect to the calculated "coal-in-place" values above the lower coal threshold of 5 million tons/km^2. Both the lower gas concentration threshold contour and the lower coal concentration threshold contour roughly encompass identical surface areas.

sets (in 10^6 m^3 CH_4/km^2; Fig. 6), and the volumetric amounts of "gas-in-place" calculated (in 10^9 m^3).

For our basin-wide reserve calculations, we have taken the gas concentration contour of 50 million m^3 CH_4/km^2 as our threshold value. So the relatively low gas containing areas within the 0 and 50 contour lines (near the basin edges) have not been taken into account.

The course of the 50 million m^3 CH_4/km^2 contour line coincides roughly with the coal concentration contour line of 5 million tons/km^2. In this way, about one third of the Carboniferous basin surface was directly eliminated from any reserve calculations. The use of the 5 million ton coal/km^2 contour line reduced the total available geological "in-place" coal reserves from 39.3 to 38.8 billion tons. Corrections for former mining reduced this even further, to 37.5 billion tons.

In this manner, we have calculated an overall CBM "in place" reserve at 291 billion m^3, and an average CBM-concentration of almost 7.8 m^3 CH_4 / ton coal in these remaining two thirds of the basin surface (Table 1).

For the most prolific areas in the basin, the CBM "in-place" content has also been calculated inside the six (6) areas within the 250 million m^3 CH_4/km^2 contour lines (5 x our general threshold value). The total prospective gas "in-place" amounts to ca. 132 billion m^3, of which about 45 billion m^3 are situated in the western basin (2 larger target zones; Fig. 6) and ca. 87 billion m^3 in the eastern sub-basin (4 larger target zones; Fig. 6; Van Tongeren *et al.*, 2000a). The average "in-place" CBM--concentration per ton coal has been calculated for these areas as well (Table 2).

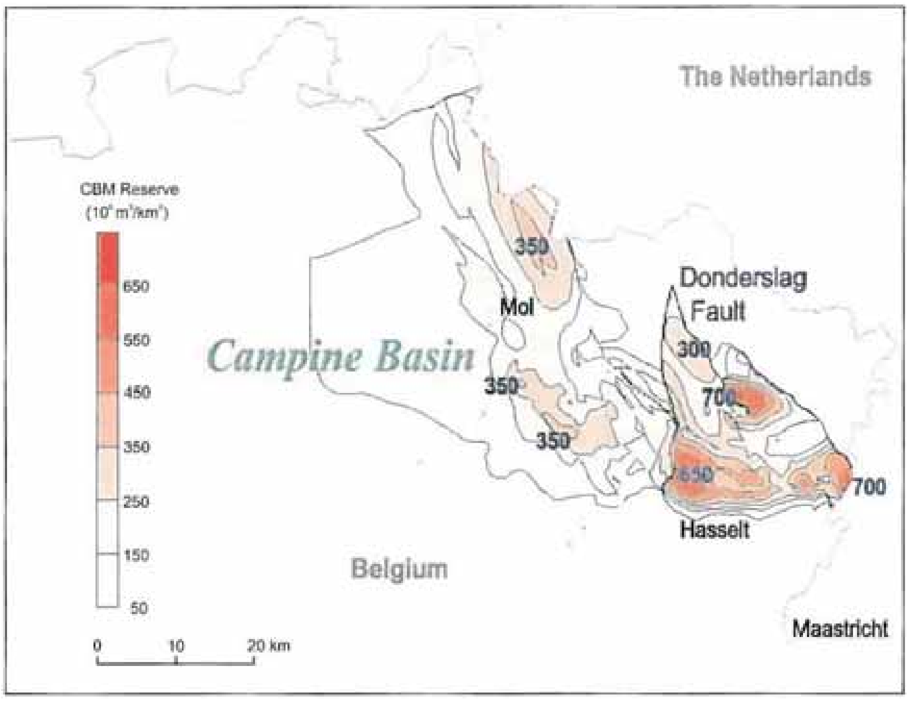

Fig. 6. Coalbed methane concentrations in the Campine basin, according to the application of the "Stuffken-relation" between coal rank and gas content. Gas concentration contours are in million m^3/km^2. Contour spacing is every 50 million m^3/km^2. Peaks of gas concentration values of the target zones are indicated in blue

Table 2

CBM "gas-in-place" reserves in the six target areas with raised gas contents in the western and eastern sub-basins of the Campine basin

250-gas concentration contour	Gas-in-place [10^9 m^3 CH_4]	Surface [km^2]	Average gas concentration [10^6 m^3 CH_4/km^2]
Anomaly West-1 north	27.7	90	308
Anomaly West-2 central	17.2	58	302
Anomaly East-1 north	19.2	47	408
Anomaly East-4 north	8.2	29	283
Anomaly East-2 south	43.9	114	385
Anomaly East-3 south	15.9	41	388

Producible ECBM-reserves

In our actual opinion, one third of the calculated "gas-in-place" is situated in coals which do not allow for any gas production. They are either isolated, too thin, or located too close to faults or to permeable overburden to be of any gas-prospective value. Of the remaining coals, we estimate that 60% could be successfully gas producing, provided that this happens by enhancing production techniques with injections of CO^2, N_2, and/or flue gases.

This still means a likely producible CBM-reserve of ca. 53 billion m^3 for the six "sweet spots" in the Campine basin, which represents about 5 times the actual yearly gas consumption of Flanders.

If by using enhancing production techniques, 90% of the "gas-in-place" could be produced, these reserves would increase to a total of about 79 billion m^3 (Van Tongeren *et al.*, 2000a).

Moreover, the simultaneous sequestration of CO_2 in coals will be an additional environmental bonus.

CO_2 SEQUESTRATION

At a 2:1 exchange ratio for methane replacement by CO_2 (Gunter *et al.*, 1996) and a 60% methane recovery only, the minimum geological CO_2 sequestration capacity within the six target zones is about 106 billion m^3, or ca. 208 million tons (at standard conditions of 0°C and 1 atm). Moreover, if by the use of CO_2-stripping, an enhanced CBM-recovery of 90% might be reached, the CO_2 sequestration capacity by exchange would increase to about 312 million tons.

However, as most coal seams in the Campine basin are under saturated in methane, (estimated at 20%), there will be an additional storage capacity of about 86 million tons CO_2. This would mean, a total minimum CO_2 sequestration possibility of almost 400 million tons of CO_2 (under standard conditions) in the CBM-target zones of the Campine basin exists. As CO_2 will be in supercritical condition at depths larger than about 800 m, the coals might well provide an even larger storage potential (Van Tongeren *et al*., 2000a).

USE OF FORMER COAL MINES

Residual volumes

Within the southern parts of the Campine basin, an extensive subsurface network of high permeable conducts exists in conjunction with a fractured reservoirs of mined out strata. Of the former conducts (>1000 km of concrete lined stone drifts and blind shafts; Fig. 7), many might still be relatively undamaged and open.

The fractured reservoir consists of both the residual voids and the porosity in the former coal production areas, and of the fractured rocks between the mined seams. Based on literature data and unpublished information by consulted mining experts, we calculated an average effective porosity (including both human-induced and intrinsic porosity volumes) of about 8.5% for the caved areas (goaf, gob), and about 5,5% for the back-filled zones of the former mining panels. The intrinsic porosity of the average rock itself has been established in many cases and it usually varies between 0.5 and 1%. Of the conductive, former mine infrastructure, we have estimated a minimum value of 25% only, to have still remained open and intact.

Based on the extrapolation of the values found for the Beringen coal mine (residual porosity volume: at least 5million m^3) to all former coal mines in the (southern) Campine basin, they are likely to possess a total residual pore-volume of at least 35.5 million m^3 (Van Tongeren *et al*., 2000b). Calculations based on certain other literature data (e.g. Vansteelandt, 1993) lead even to a total residual pore-volume of ca. 60 million m^3 for all former Campine coal mines.

Differences in ECBM-development

These residual volumes may be used in different ways, varying from storage of chemical wastes and other industrial residues, to methane storage under low to medium pressure conditions. Many impermeable, thick clay layers and some aquifers are present in the overburden (thickness 270 to >600 m). In some cases, even relatively small amounts of CO_2 may be stored and/or sequestrated in selected and separated parts (with or without remaining coal). The latter might be specifically considered with regard to any ECBM-production in, and near these former mining areas. Their CO_2 storage capacity might even reach over 45 million tons (Dreesen *et al*., 2000).

Without considering any sorption effects of the remaining coal, the storage possibilities of low to medium pressurised methane have been estimated to vary between 0.5 and 1 billion m^3 (Van Tongeren *et al*., 2000b). Here, the areas of tensional release and related porosity increase will be used to

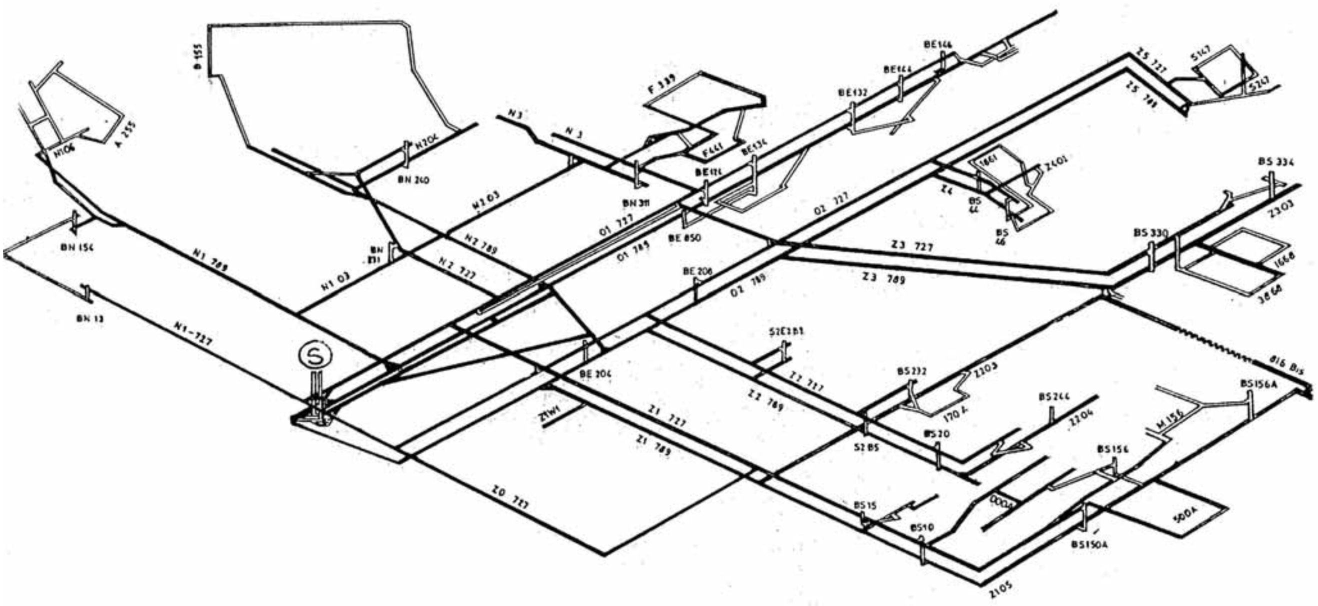

Fig. 7. Infrastructural scheme (aeration system) of the former Beringen coal mine in the western Campine sub-basin (S — location of main shaft)

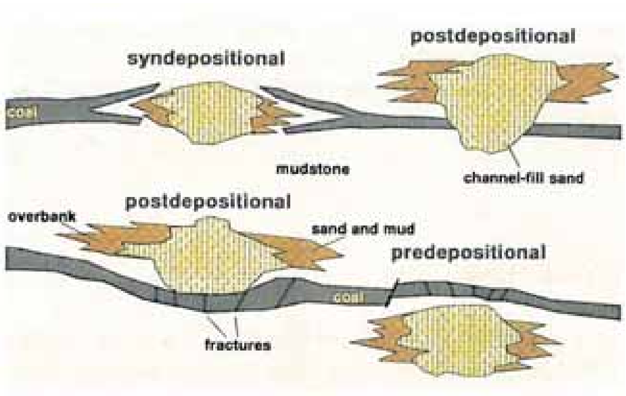

Fig. 8. Enhanced fracture development at differential compaction in specific settings of channel sands coal seams

facilitate both propellant injection and migration (e.g. CO_2, N_2, flue gases) as well as enhanced CH_4-expulsion. Anticipated advantages in production time and the possible reduction of some production costs are likely to render more economic any future development of the many ECBM-targets in these areas.

Economic development of (E)CBM in the northern target areas will be more difficult. The greater depths will increase not only the compressive stresses on the coals — and so reduce their permeability — but also the overall development costs: especially drilling and well-stimulation costs. Closer well-spacing will be required here, as well. Therefore, any economic target development in these northern zones must start by investigating the possible presence of particular geologic conditions by which (E)CBM-production might be optimised. This might involve an additional search for certain structural settings of the coals (anticlines, intra-formational cut-off up-dip slopes, etc.) and/or for areas with enhanced cleat/fracture formation and stress shielding strata (coals in, or under competent rock layers; Fig. 8). In this way, enhanced fracture development may be expected at differential compaction settings involving channel sands and coal seams. Sandstone bodies overlain by coal provide also interesting permeability pathways for CO_2 injection at ECBM-production schemes.

SOCIO-ECONOMIC CONDITIONS

For a starting ECBM-industry, only a limited annual capacity of CO_2 can be handled. An ECBM-gas field of about 7 km^2 and comprising 22 wells might roughly require the injection of only 129,000 tons of CO_2 per year, at a 90% methane recovery and a 2:1 CO_2/CH_4 exchange rate (according to averaged Black Warrior data; Van Tongeren *et al*., 2000a). As the CO_2 will certainly occupy all available spaces in coals, this figure is likely to be even higher. However, increased pressures, water saturation and temperature conditions will probably have a decreasing counter effect.

CO_2 producers in the range of 100,000 to 200,000 tons are present in, or very near the target areas of the Campine basin. Also larger CO_2-producers are present here. One of these (a Dutch petro-chemical industry, a.o. a producer of fertiliser) is located near the town Geleen, just across the Belgian–Dutch border and exactly within an anomalous target zone of the basin (Fig. 9). Another Belgian producer of fertilisers is present close to the edge of the basin, near the Antwerp harbour, at a distance of 60 to 90 km of the prime ECBM-target zones. Additional important CO_2 producers and users of CH_4 are the various petro-chemical industries and electricity producers in and around the basin.

Except for the fertiliser producing industries, which have some separated CO_2 on site, all CO_2 is produced as unseparated flue gases.

Nitrogen, another interesting propellant, can be produced on site from air, by cryogen separation, or at certain production localities.

Next to the presence of a perfect road system, important waterways and railway connections, a major natural gas-transportation system of pipelines crosses the Campine basin and Belgium (Fig. 9). These gas transportation pipelines run from the Netherlands to France, Germany, and Luxembourg, and beyond. Major branches of this system, both within and just around the basin area, lead to industrial facilities and cities. Subsidiary pipelines go even to the above mentioned Dutch petro-chemical industry at Geleen.

Actually, the Belgian economy is rapidly growing. This growth will probably continue in the following years and will lead to a steady increase of energy demand, and consequently to a larger gas demand. Moreover, the relatively high oil prices in combination with a steadily growing concern about the environmental impacts of increased fossil energy consumption, will increase the demand for cleaner fuels — notably gas — even further. A regional well-developed ECBM-industry would be, therefore, of economic as well as of strategic importance.

Also in social respects, e.g. population density and distribution, demographic development and considerations, with regard to sustainable employment, development of a regional ECBM-industry would be advantageous (Van Tongeren *et al*., 2000a).

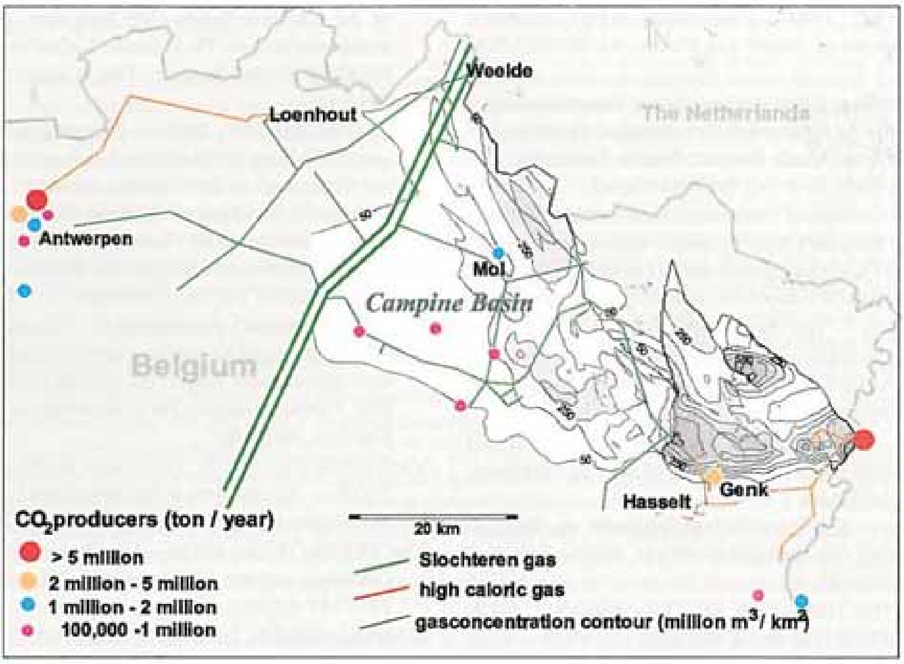

Fig. 9. Location of some important CO_2-producers and gas pipeline infrastructure in relation to the CBM concentrations in the Campine basin

CONCLUSIONS

The Campine basin still possesses large coal reserves and at least six target areas with an increased CBM concentration. In combination with CO_2 sequestration an / or the use of other propellant gases, the estimated producible CBM-reserves in these areas vary between 53 and 79 billion m^3.

Initial development of these reserves will vary from target to target. In the southern regions of the basin, it will certainly involve the use of the induced changes in the general stress pattern(s) by the former mining activities. In the north, an initial development will necessitate the search for geologic traps and/or particular coal settings. CO_2 sequestration possibilities in conjunction with the CBM development are important: under certain conditions even up to 400 million tons of CO_2 might be sequestrated.

Within the Campine basin, CBM-reserves, producers of propellants (notably CO_2), technical infrastructure as well as an (expanding) market for the produced methane are all present or are very near. This certainly warrants further ECBM development activities.

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