CO_2 INJECTION IN AND CH_4 PRODUCTION FROM COAL SEAMS: LABORATORY EXPERIMENTS AND IMAGE ANALYSIS FOR SIMULATIONS.

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Summary

A co-operation between various Dutch research groups and Novem[1] is concentrating on global CO_2 sequestration concepts, surface infrastructures, subsurface geo-information and geo-technical aspects. Among others reduction of CO_2-emissions in a cost-effective way by CH_4 production and CO_2-sequestration is one of the topics. Delft University of Technology - Department of Applied Earth Sciences is focusing on the technical, environmental and economical aspects of the geo-infra structure. Scaled in-situ laboratory experiments on the reservoir properties of coal are carried out in an experimental high P,T device developed for this purpose. The coal cleats, as the major transport system, are characterized by Image Analysis. In this paper the results of the relations between coal, its cleat systems, permeability, stress adjustment and CH_4/CO_2- replacement are presented. In the following phase the experimental results and known geo-parameters are combined and used for simulations at cleat scale and field scale, to assess the capacity of CH_4 production and storage of CO_2. In the experimental high P,T device coal reservoir parameters for a coalbed methane simulator are measured under in-situ conditions up to a depth of about 700m. CH_4/CO_2-displacement experiments on large coal samples are completed at different injection rates, temperatures, pressures and wettabilities. Together with the image analysis results on the spatial dimensions of various cleat systems in slabs and drilling cuttings, the data is used in two simulators. At cleat matrix scale and at field scale, CH_4/CO_2-displacement under dry and wet conditions are estimated. These results are, among others, used for the calculation of sweep efficiencies and improvement of a cost effective CO_2-storage.

Introduction

Reduction of carbon-dioxide emissions in a cost-effective way by CO_2-sequestration in and CH_4 production from Carboniferous coal seams has a growing interest. A co-operation between a number of Dutch research groups, consisting of Delft University of Technology - Department of Applied Earth Sciences (DUT), TNO-NITG[2], Utrecht State University - STS[3], ECN[4] and NOVEM are concentrating on

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[1] Netherlands Agency for Energy and Environment

[2] Netherlands Institute for Applied Earth Sciences

global CO_2 concepts, surface infrastructures, subsurface geo-information and geo-technical aspects. DUT is focusing on the technical, environmental and economical aspects of the geo-infra structure. Geological inventories show that the sub-surface could hold considerable amounts of economic methane gas (Wolf, 1997, Hamelinck et al. 2001).

For that reason the emphasis is laid on CO_2 Enhanced Coalbed Methane (ECBM), particularly for the Dutch and Belgian Carboniferous of the Campina Basin and the adjacent Northwest European areas. Using information of research institutes and oil/mining-companies, coal is considered as a tight gas reservoir in which the behavior of methane, carbondioxide and water are associated with stress, pore pressure and coal permeability (Gunther et al., 1996). This data comprise information on regional depths, geo-temperatures and -pressures, and permeabilities. US methane production shows that coalbed-methane production is already technically feasible up to a depth of about 1600 m. At greater depth very low permeabilities and plasticity of coal create serious production and injection problems. The CBM project in Peer-Belgium validates the first thought for shallow Campina coals. At differential pressures up to 40 bar the coal permeability reaches the mD range (Wenselaer et al., 1996, Wolf et al. 2000). With respect to injection and production rates at field scale one has to understand that the process of exchanging CO_2 for CH_4+H_2O is a process of many years. It includes phenomena like sorption, diffusion and Darcy flow, which are needed for a maximum CO_2-injection with a maximum replacement of methane and water.

This knowledge is used as the basis for laboratory experiments on ECBM production (Wolf et al., 1999, 2000), which are carried out in an experimental HPT device developed for this purpose. Large-scale "in-situ like" tests are accomplished to characterize coal compaction and sorption behavior. At various stress levels and pore pressures methane and water saturated coals are flushed with carbondioxide. In addition the cleat systems of the coal samples are characterized by image analysis to derive a fracture pattern. This can be used as input for a fracture flow model since they are the major transport system (Wolf et al. 2001). Knowing these parameters, it is possible to describe a coal seam as a reservoir consisting of different series of "matrix" pores and "cleat" parallel plates. The modeling work is done at two levels of magnification:

- At sub-cleat or matrix scale, in which the essence of modeling is concentrated on the coal matrix. Sorption and diffusion behaviors are the dominating forces for exchange and replacement.
- At seam or field scale. Here stress related permeability and cleat configurations are the most important variable quantities (Hamelinck et al. 2001, Wolf et al. 2000). The applied reservoir conditions are adapted to the experimental data and the geo-environmental settings of shallow Carboniferous of the Southern and eastern part of Netherlands. Lateral continuity at m to km scale and cleat spacing and angle at seam scale vary regionally and are related to the tectonical and burial history (Pattison et al. 1996). Up to now these discontinuities are not considered in the simulations.

Samples

Origin

Two northwest European mines, i.e. the Beringen mine located in the Campina - Belgium (K-series) and the German mine “Anlage Westfalen” situated in the Ruhr district (Karl-series), are providing the coal samples. Both seams are of Carboniferous - Westphalian age but from different tectonic areas. The Belgian coal originates from the North flank of the London-Brabant Massif, the German coal from the Variscan Front. The burial history of the latter shows serious tectonic effects by Variscan folding, i.e. intensive quadrangular cleat systems. Petrographic data of both coal types can be found at the end of this in table 1.

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[3] Dept. of Science, Technology and Society

[4] Netherlands Energy Center - Petten

Compaction behaviour

Stepwise increase and decrease of stress, creep effects and hysteresis, on the cylindrical coal samples give the volumetric change in cleat porosity. The K-series show a dual porosity system of almost perpendicular face and butt cleats and matrix porosity (Wolf 1999, 2001). Two pore-related stress regimes are observed (figure 8), first the cleat system rapidly closes (pressures up to 0.4 MPa), and thereafter the slow compaction of the coal matrix (up to 11 MPa) follows. The rapid cleat closure in the low stress regime gives a comparable rapid permeability reduction. The initial permeability of about 30 mD reduces swiftly to 1 mD and finally about 0.05 mD. The permeability decreased by a factor 600 during the experiment. The German Karl-type coal shows, due to its tectonic burial history, a less distinct cleat system in quadrangle or rhomboidal shaped matrix blocks. Due to this poor geometry the coal is more resistant to the first phase of compaction and permits less cleat closure and porosity reduction. The original higher permeability of the German coal (75 mD) remains relatively high. The permeability of the Karl-series was decreased by a factor of 75.

Cleat systems

Polished pieces of both types are scanned with blue-violet light, which visualizes the major crack pattern (figure 1). By image analysis the fluorescing fractures are enhanced to an arrangement of lines (skeletonizing). This illustrative but inaccurate pattern is used to find the general cleat orientations and cleat distances. Small cleats at sub-millimeter scale are not recognized due to their pixel resolution or absence of fluorescing dye so the images are also manually enhanced on their orientation and length. The dominant cleat angle for the Karl samples is 70° and for the K-series about 90° (figure 2). The data show a main fracture system on cm scale and indications for cleats at mm-scale.

Environment of interest

The geo-environmental properties for the entire simulations are expected to be: a maximum depth of 1500 meter, with a related temperature of 55°C, lithostatic- and hydrostatic (pore) pressure of respectively 35 MPa and 16 MPa and a net multi-seam thickness of 7 m. A maximum methane content of 20 m^3/ton and a water saturation varying from nearly dry to fully saturated are assumed.

Equipment and procedures

In succession long term high P,T experiments are performed on different coal samples in a high-pressure device. The results are, with a continuous upgrade, already presented (Wolf 1998,1999 and 2000), and used as the sample source for cleat spacing and particle data. Then image analysis equipment is used to measure the particles and calculate their specific spatial characteristics.

The high pressure device and procedure

The device

The high-pressure reactor in which the coal is placed has a maximum annular isotropic pressure of 11 MPa (figure 3). This isotropic stress is put on an inner cylinder of synthetic rubber, which contains the specimen. The sample or sample pieces are about 250 mm in length and 72 mm in diameter. The size stands sure for the presence of a representative cleat system in the sample. During the experiments displacement transducers measure volumetric changes of the sample. A gas booster injects various gases and water into the coal at known rates and pressures. After leaving the coal, the produced fluid and gases are analyzed by a gas chromatograph, which gives the composition of the components. The experiments usually take two to six weeks and provide information on sorption and in-situ related permeabilities of the available cleat system. In extreme cases testing times of 10 weeks are reached (figure 4).

Procedures

The tests start with a complex procedure of mounting a sample tube in the high-pressure reactor, followed by testing of the entire tubing system for leaks (figure 4). The sample is connected with a vacuum pump, for at least 24 hours to 1 week, in order to eliminate gas and water or moisture. Then the coal is filled with methane in cycles. After each injection cycle the methane is allowed to adsorb in the coal matrix until equilibrium is reached. To meet sub-surface conditions, the difference between the annular pressure and the pore pressure is usually kept at ratios in between 2:1 up to 5:3. The injected methane is counted by a mass flow meter till the necessary pore pressure is arrived. Then, if needed, water is injected and both, the tubing system and the pump are brought to the same pressure and temperature conditions as the methane filled sample. More methane will adsorb and again time is needed for this methane to reach a new equilibrium pressure. At the same time the sample and vessel are brought to the desired temperature. In the following injection cycle the pump is filled with CO_2 and injection starts. The gas analyzer determines the relative amount of methane, carbondioxide and nitrogen (for annular leak detection) in the product gas. The water is separated and weight is measured. During the tests the recorded data serve as an iterative feedback in order to rule out their influence in the interpretation afterwards (figure 4).

The Image analysis equipment

The setup

The image analysis equipment consists of two digital image-processing systems and peripheral apparature:

1. A Leica - Quantimet Q570 hardware system with a control PC, color camera, stereo microscope and a computer controlled stage and,
2. Leica Qwin, an image-processing program, running on a Windows based PC.

The color camera gives an image, which is sent to the Quantimet 570. The Quantimet creates binary images of 512 x 512 pixels of the cuttings. These images are sent to the Qwin image analysis system, where each piece is characterized on its spatial values. Combined use of laboratory outcomes and image analysis provides the data used for cleat spacing characterization.

The procedure

The particles are carefully crushed samples from the same coal blocks as the previous mentioned cylindrical cores. The coal breaks according to zones of weakness, which in general correspond with orientations of the bedding and cleat configuration. The particles range in size from centimeters to tenths of a millimeter. To get a representative aggregate and avoid 2D-3D problems on cleat/bedding orientations, about thousand coal particles are taken per sample series.

Random amounts of particles are taken for analysis on a computer-controlled stage under a microscope and scanned (figure 5, left). Since the particles range from mm to cm scale (max. 40 mm) two magnifications are chosen, in order to get a better accuracy at pixel level. The acquired images are 8 bit gray scale images with a view field of 512 by 512 pixels of black coal silhouettes against a white background. The accuracy is depending on the viewfield size and the related pixel length, i.e. for the low and high magnification respectively 46.3 mm/0.0905 mm and 10.8 mm/0.0210 mm. The -Quantimet 570- scanned images are stored for processing.

A program written in the programming language Quips of the PC based image analysis software Qwin (figure 5, right) splits the multi-particle images of randomly orientated coal particles up into single-particle images. For each particle spatial characteristics, such as area, perimeter, particle face angles, length and breadth are measured. Particles smaller than a certain area are selected in the high magnification and particles larger than a certain area are selected in the low magnification. In agreement with the mentioned range the minimum particle size is 30×30 pixels ($0.36\ mm^2$), the maximum size about 450×450 pixels.

After admittance a rotation program rotates single particles, in single particle images (figure 6). It extracts the outline of the particle, which is built up of line segments and measures lengths and orientations as the base information for the definition of cleat angles and widths. In addition the breadth, the area and perimeter of the particle are added and written to a spread sheet program via a DDE-link.

This dataset is used for the geometrical filter; the rotation data is sorted per angle to obtain the cleat angle and cleat length. For all angles these maximum values are stored in histograms. For each measured particle the two or three maximum length values give the sorted cleat angles to find the cumulative spread in angles. The unbiased 3D-presentation of the grains, the inclusion of small grains and the presence of not representative low angular particles cause a diffusion in data. Hence a geometrical filter consisting of 2 parameters, was introduced to look at the relation between the shape of the coal particle and its cleat angle:

1. Particles with minimum area/perimeter ratios (round grains) are neglected (low angularity bias).
2. The grains normally have more or less rhomboidal shapes. By quadrangle definition, parallelograms at angles from 30° to 90° are used to define area/perimeter ratios or geometrical factors (0.61 - 0.88).

All grains are measured and plotted in distribution graphs of the cleat angles of the coal particles that fall within a certain range of geometrical filter (table 3). For each parallelogram angle the optimum cleat angle is determined by the frequency distribution.

Experimental results of the flushing tests

Standardisation of the experiments

The Langmuir curves, obtained by filling the samples with methane at different pressures, show that the coal can hold about 22 m^3 methane per ton of coal and the double amount of carbondioxide. The storage of the latter is the most important, so five different flushing experiments are compared:

- a water free coal with a CO_2-gas and a CO_2-liquid flushing (figure 7 a,b, table 2)
- a water saturated coal with a CO_2-gas and CO_2-liquid replacement (figure 7 a,b, table 2)
- a water saturated coal with supercritical CO_2 replacement (figure 7 c, table 2)

The CO_2-injection rate on all experiments is about 9.4×10^{-6}mole/hr. However, the pore pressures vary, because CO_2 is injected as a gas, a liquid or super critically. Consequently the injection rate in l/hr differs significantly. For comparison, gas production and displaced volumes are normalized to atmospheric conditions.

Experimental results and discussion

The flushing experiments are summarized in the figures 7 and table 2. Here the most important flushing results are discussed and, when realistic, related to field scale occurrences.

- Dry coals rapidly swap CH_4 for CO_2. High sweep efficiency is established without difficulty when on field scale the water is pumped away (figure 7a).
- The CH_4/CO_2-production outlines from a dry coal with liquid phase and gas phase CO_2 look very similar. The displacement volume show that a flush zone of CH_4-saturated coal changed to CO_2-saturated coal will be small.
- In all water-wet systems, the major part of the water is rapidly removed from the cleat system. In water saturated coals water seriously obstructs the CO_2 in reaching the matrix pores (figure 7b). Initially the cleat system is swept clean of methane and water. Several times the pore volume is needed to replace CH_4 for a part of the CO_2. For this reason, at field scale a transition zone from a CH_4-saturated to a CO_2-saturated coal will be large.
- Super critical CO_2 in water saturated coals display also a fast CO_2 breakthrough. However the replacement takes more time and at higher exchange rates. After the maximum CO_2-breakthrough of

92 vol.% production of methane is slowly recovering. It results in a higher sweep efficiency of methane and water and an improved CO_2-storage capacity (figure 7c).

In essence, in water free coals both the gas phase and liquid CO_2 are able to replace methane from the matrix with high sweep efficiency. In water saturated coals water acts as a barrier and the sweep efficiency is low for both gas phase and liquid CO_2. However, super critical CO_2 initially acts like liquid CO_2, but after an apparent breakthrough it slowly improves in replacement of water and methane. High sweep efficiencies are realizable.

Conclusions on the experimental results

So far experiments are accomplished under ideal conditions, i.e. a constant and slow injection, dry or fresh water saturated. Various sources report a change in wettability of coal with higher pressure and phase change of CO_2. Some types of coal are reported to transfer from water wet, as was the case in this research, to CO_2 wet (Chi et al. 1987). This is very important for CO_2 diffusion into water wet matrix and consequently for the CO_2\water exchange. It has to be investigated in a new series of experiments.

Image analysis results

Spatial characteristics of particles

For both coal series a summary of the parallelogram angle and the total number of accepted coal particles per cleat distribution histograms is presented (table 3). Some of the distributions of the cleat angle, within the ranges of the geometrical factor, for sample Karl are plotted in figure 12.

From the observations in the frequency figures and table 3 it is concluded that the Karl-series consist of coal particles with shapes resembling parallelograms of 60 to 70° for butt and face cleats and 80 to 90° for angles with the bedding plane.

- For the K-series is concluded that the coal samples give particles with parallelograms of about 90°, but also a considerable amount of particles with angles of 70° and 80°. The parallelogram results of 90° coincide with the cleat angle of 90° in the polished pieces. The cleat angles perpendicular to the bedding plane probably range between 70° and 90°.
- The cleat length of a particle is defined as the longest overlap of the particle outline with the grid lines, measured by the rotation program. The cleat length distribution for all the particles is measured without using a geometrical filter. For the Karl series the cleat lengths range from 1.5 mm to 4.5 mm and the modal cleat length is 2 mm. The K-series have a spreading of cleat length from 2 mm to 7.5 mm and a mode of 2.5 mm. These values are to be used as input parameters for a fracture grid in a simulation.

Cleat dimensions

Stress dependency of cleat widths is needed for fracture flow model. De Haan (1999), Bertheux (2000) and Wolf et al. (1999) describe the flow through a single fracture as the flow between two plates with a specified thickness (b). If the direction of the flow is the x-axis with the velocity of flow as a function of the distance y from that axis, the volume passing through the fracture is depending on the pressure gradient in the x-direction and the cleat length. Combining this fact with Darcy's Law for an amount of fluid passing through the unit area (K), the cleat width (b) is proportionally related to the permeability and the cleat length L is inversely related to the permeability. When the average image analysis cleat length L of the Karl series ($L = 2\times10^{-3}$ m) and K-series ($L = 2.5\times10^{-3}$ m) are related to experimentally measured -stress related- permeability, the theoretical cleat opening is known (figure 8). At increasing stresses up to 0.5 MPa a rapid decrease of cleat aperture is observed. At higher stresses the cleat openings are reducing at a slower rate.

Conclusions on the image analysis results

- It is possible to quantify the cleat angles of the coal particles using a geometrical filter, which uses the relation between the cleat angle, the areas and shapes of equal sided parallelograms. The results present the cleat angles of the specific shapes and of area-angle related shapes of different particles. The modal distribution values of cleat angles, derived by image analysis, for K-series (70°) and Karl-series (90°), coincide with the results on polished slabs. The slabs only give results on the cleat angles parallel to the bedding plane. The image analysis method also quantifies the cleat angle perpendicular to the bedding plane.
- The method also gives the cleat length distribution for the coal particles: 2.5 mm and 2 mm as modes for respectively the K-series and the Karl-series. The outcomes in cleat spacing distribution and cleat angle distribution are implemented in currently used and revised empirical stress/permeability relations. By applying a model for fluid flow through fractures and experimentally measured permeabilities as a function of the effective stress, it is possible to reconstruct cleat-opening distributions as a function of stress.
- This method can be used to optimize the permeability stress relations from wells, by using the drilling cuttings and cores, if available.

Translation of experimental results to simulations

The previous mentioned outcomes of the flushing experiments and image analysis can be used as input parameters for reservoir calculations. The existing reservoir simulators are to a certain extent suitable for the simulation of the laboratory test. They are not able to handle all the processes in the coal cleats and matrix, i.e. Darcy flow, diffusion and differential sorption behavior of multi-phase CO_2, CH_4 and water. Therefore, the reproduced in-situ coal-reservoir parameters are used in seam models at two scales in order to reproduce findings of laboratory and field experiments.

Cleat scale simulation

On the interactive behavior between the matrix and cleats is studied with respect to the cleat dimension and water saturation on the diffusion and sorption of CO_2 and CH_4 in the macerals of the coal matrix. This information will be used as input parameters for upscaling to a multi-cleat/matrix system (seam) model (figure 9).

Field scale simulations

At seam scale, among others, the well configuration, drilling pattern, injection and production rates of CO_2 and CH_4, in-situ pressures, stimulation value (skin), etc. are needed to get a view on the multi-component fluid/gas flow patterns (figure 10 and 11). These simulations are essential to approximate and calculate production and storage, economics and studies on environmental impact and safety. Up to now the sorption of gas on the surface of the coal is modeled as gas dissolved in immobile oil [Seidle & Arri, 1990]. To perform enhanced recovery of CH_4 by injection of CO_2 and/or N_2 a 3-D multi-phase reservoir simulator (STARS) is used (figure 11). Its advantage is a multi-component gas feature with the capability to represent binary gas sorption on coal. Both simulators are using porosity, relative permeability, sorption and diffusion and saturation constants from the laboratory experiments.

Conclusive remarks

The results of the laboratory experiments are successfully used in cleat scale models and field scale models. The answers of the latter are used in feasibility studies on implementations in geological and infrastructural settings as available in the Dutch situation. New equipment is constructed to perform experiments up to a depth of at least 1.5 km. In addition new micro-models and macro-models are to be developed to evaluate, as extremes, dry and fully water saturated coals at greater depths.

Acknowledgements

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Tables and Figures

Table 1: Characteristics of the Belgian and German coal used in the experiments Revised after Wolf et al., 2000)

Coal type		Belgian (K-series)		German (Karl-series)	
Depth (m), age		770 m, Westphalian B		900 m, Westphalian A	
Proximate & ultimate analyses		Original	Dry	Original	dry
Moisture (weight %)		4.28	-	1.82	-
Ash (weight %)		3.55	3.70	5.90	6.00
Volatile matter (weight %)		28.87	30.20	29.30	29.80
Carbon (C, weight %)		71.10	74.3	79.60	81.00
Hydrogen (H, weight %)		4.82	5.00	4.75	4.80
Oxygen (o, weight %)		14.20	14.90	5.82	6.00
Nitrogen (N, weight %)		1.27	1.30	1.44	1.50
Sulphur (S, weight %)		0.72	0.80	0.67	0.70
Maceral analysis	K-series	Karl	Rock Eval.	K-series	Karl
Vitrin. refl. (%Rr)	0.78	1.15	Tmax (°C)	434	463
Vitrinite (%)	37.8	87.2	S1	1.6	1.8
Liptinite (%)	18.0	0.8	S2	145.9	127.5
Inertinite (%)	44.0	9.0	S3	8.0	0.6
Minerals (%)	0.2	3.0	TOC	76.0	52.5
			Hydrog. index	192.0	242.0
			Oxygen index	10.0	1.0

Table 2: *Results at 90 % CO_2 (revised after Wolf, 2000)*	Time (sec)	Displaced (pore) volume (mole/mole)	Methane sweep efficiency (ratio)
A: Dry coal, CO_2-gas	7.5×10^5	1.65	0.52
B: Water saturated coal, CO_2-gas	7.5×10^5	0.55	0.26
C: Dry coal, CO_2-liquid	2.07×10^6	4.9	0.48
D: Water wet coal, CO_2-liquid	8.06×10^5	3.0	0.32
E: Water wet coal, CO_2-super critical*	1.9×10^6	3.5	> 0.40*
*After reaching a maximum of 92 vol.% of CO_2, the methane content slowly increased again after a DV of ~ 4.			

Table 3: *The total of particles for each parallelogram angle configuration*

Parallelogram configuration	Number of Coal Particles	
	K-series	Karl-series
Parallelogram 30°	22	8
Parallelogram 40°	33	23
Parallelogram 50°	83	40
Parallelogram 60°	178	109
Parallelogram 70°	145	231
Parallelogram 80°	250	299
Parallelogram 90°	302	209
Geometrical factor < 0.61	9	14
Geometrical factor > 0.88	56	80
Total number of particles	1078	1013

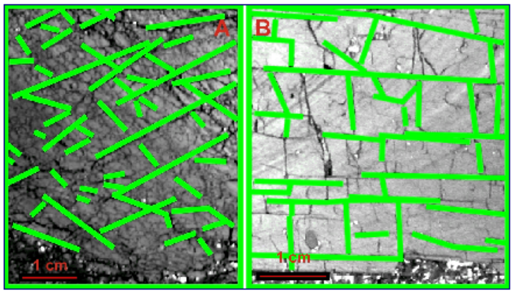

Figure 1: Images from two polished sections with superposed orientations of the main cleats, as used for cleat characterization.

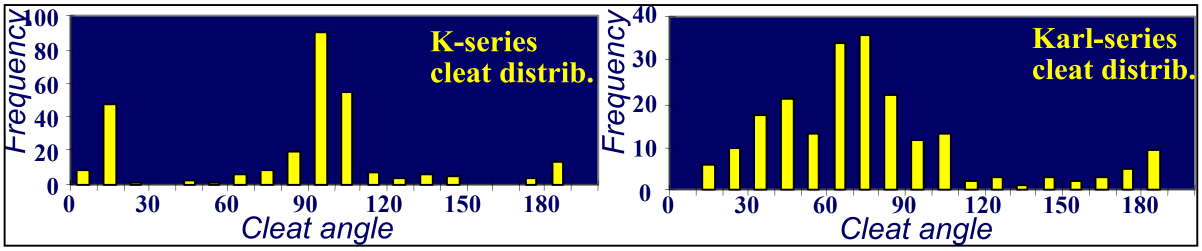

Figure 2: Cleat angle distribution of polished pieces of the K-series and Karl-series. Fluorescence binary pictures are analyzed with image analysis (revised after Wolf et al. 2001).

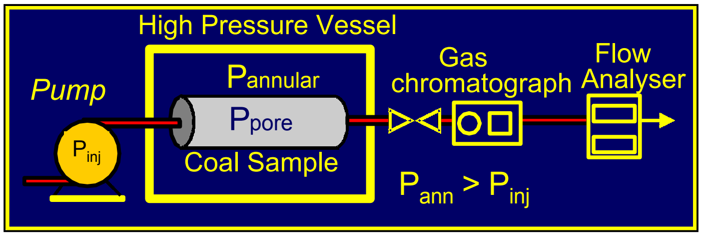

Figure 3: Scheme of the high P,T equipment, as used for the CO_2-flushing experiments

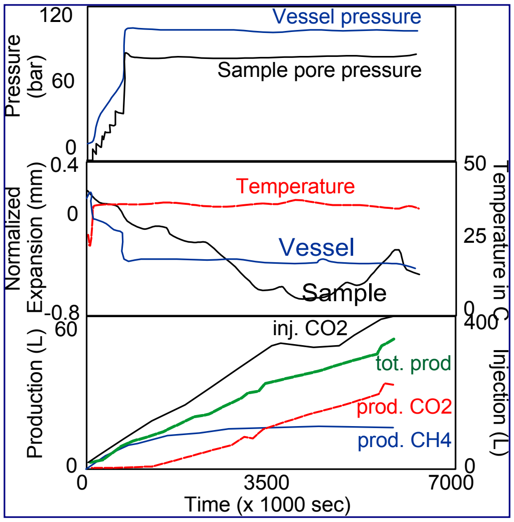

Figure 4: Example of a CO_2-storage experiment. Pressures, temperatures, coal sample compaction and injection/production are visualized versus time.

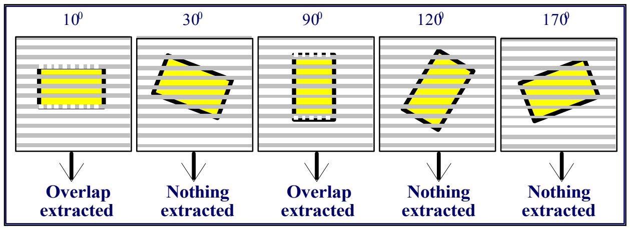

Figure 6: Working of the Qwin rotation program. Some examples of the 10° stepwise rotation of a particle, and the scanning of the particle faces.

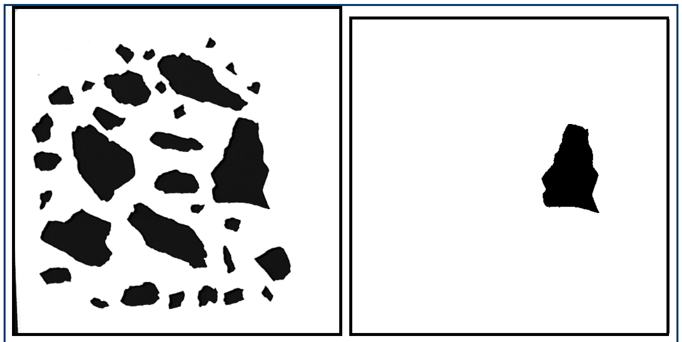

Figure 5: Scanned coal particles. Left: Q570 binary map of one batch of random grains. Right: One particle as separated for spatial characterization with Qwin.

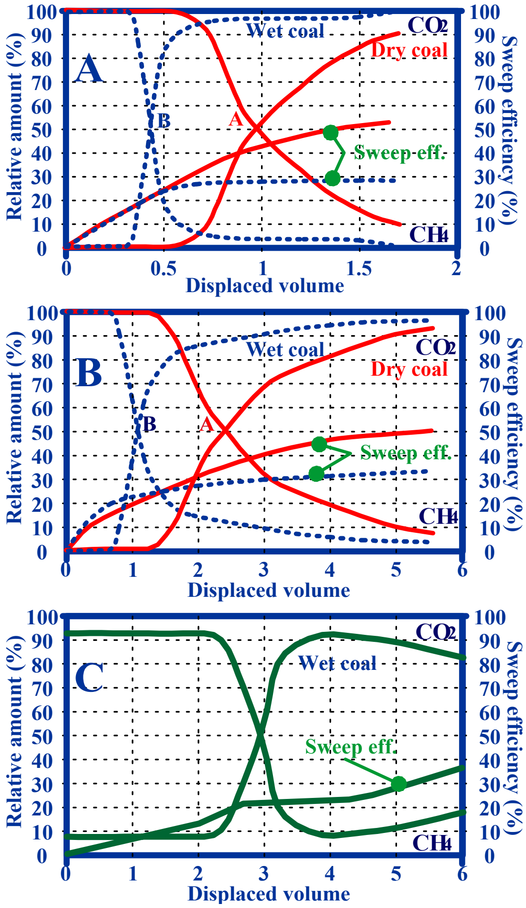

Figure 7: CO_2 flushing experiments. Displaced volumes and sweep efficiencies of CH_4 and liquid CO_2 in dry (A) and water saturated (B) coal. (C) shows super critical CO_2 and water saturated coal (Revised after Wolf et al. 2000).

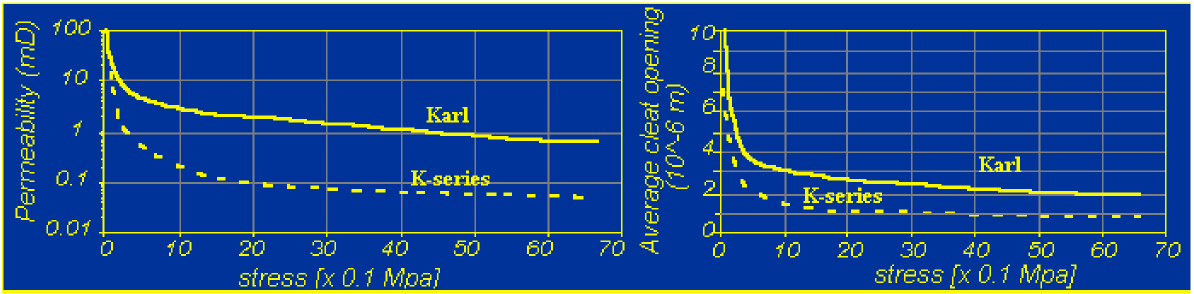

Figure 8: Effective stress versus average permeability (left) and calculated average cleat opening (right) for the K-series and Karl series. (Revised after Wolf et al. 2001)

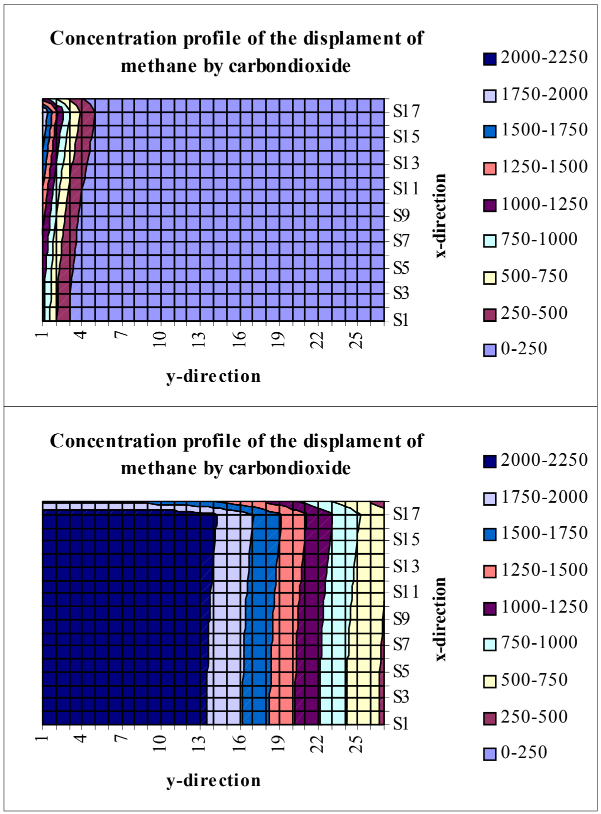

Figure 9: Sweep efficiency in one cleat and matrix. Top: Time: 1.07 [hour]; recovery: 3.80 [%]; CH_4 produced: 0.24 [mole]; CO_2 stored: 0.32 [mole]; ddx 0.0001 [m]; phi 0.03 [-]; v-inj: 0.0005 [m/s]. Bottom: Time: 16.54 [hour]; recovery: 75.97 [%]; CH_4 produced: 4.08 [mole]; CO_2 stored: 4.75 [mole]; ddx 0.0001 [m]; phi 0.07 [-]; v-inj: 0.0005 [m/s].Revised after Bertheux, 2000.

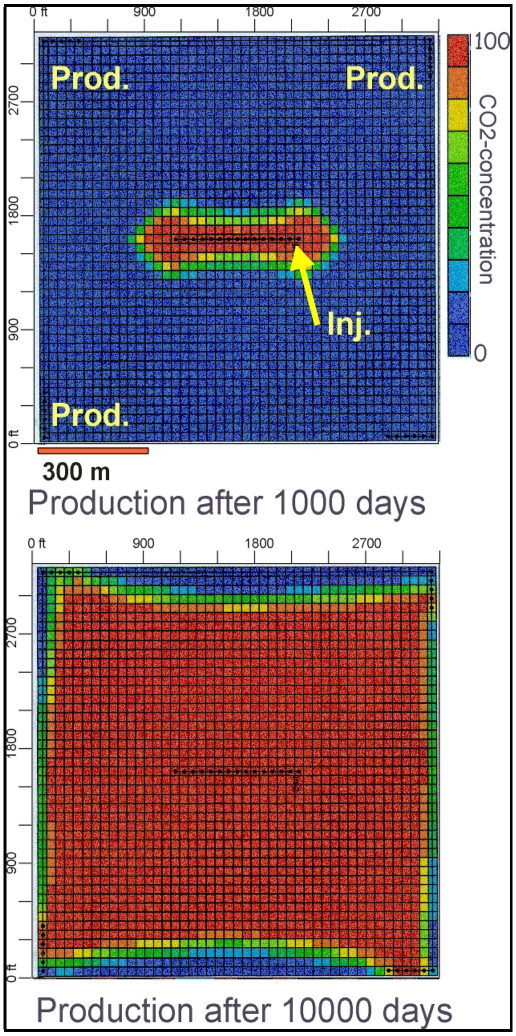

Figure 10: General concept for modelling enhanced production of coalbed methane and water by carbondioxide injection (Revised after Wolf et al., 2000).

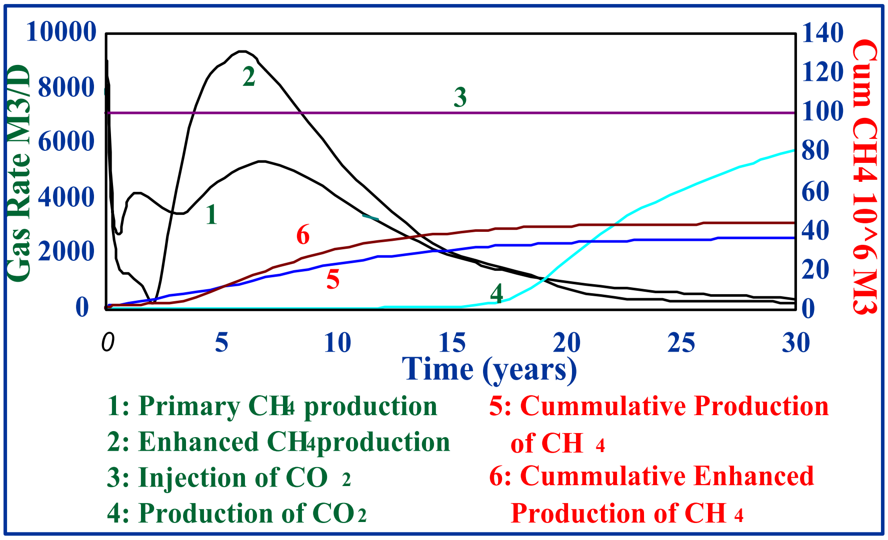

Figure 11: STARS field scale-modeling results on CO_2-ECBM with the production of water, CH_4 and CO_2. Well distance and depth 1 km; permeability 2 mD; in-seam horizontal injection and production wells, 311 m and 100 m (revised after Wolf et al., 2000).

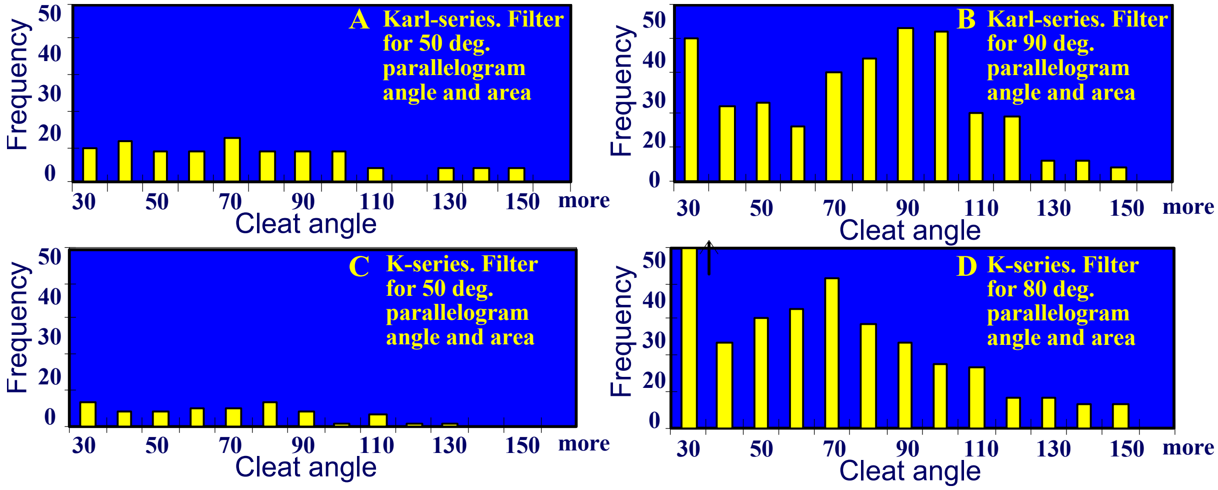

Figure 12: Examples of frequency distributions of particle cleat angles related to geometrical factors of the area and perimeter of angle specific parallelograms. Low correlations are found in figure A and C. High correlations (many particles) are found for B and D (revised after Wolf et al. 2001).

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