

Burial history and thermal evolution of Westphalian coal-bearing strata in the Campine Basin (NE Belgium)

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Abstract

A 1D-modelling program has been applied to reconstruct the burial and thermal histories of two exploration boreholes, KB172 and KB174, located in the Campine Basin. The results show differences in geological histories. The coalification of the Westphalian A and B strata in KB174 (0.66–0.98% R_o) was pre-Permian. Calculated maximum temperatures, based on borehole data and vitrinite reflectance, regional thicknesses and a heat flow of 84 mW/m² during the Late Westphalian, range from 110 °C at the top to 175 °C at the bottom of the Westphalian cored in this borehole. The high coalification (0.85–1.30% R_o) of the Westphalian C and D strata in KB172 could be the result of the deposition of ~2500 m of Upper Permian to Middle Jurassic sediments in combination with elevated heat flows (71–80 mW/m²). Two coalification periods, i.e. Late Westphalian and Middle Jurassic, are suggested for this borehole. The simulated maximum temperatures range from 130 °C at the top to 175 °C at the bottom of the investigated Westphalian C and D. The differences in the burial and thermal histories of both boreholes can be related to the activity of the transversal Donderslag Fault, a major structural element in the Campine coalfield, and the Roer Valley Graben.

Introduction

The Campine coalfield forms part of the Variscan Fore-deep Basin. Between 1979 and 1988 an exploration campaign was conducted to assess the coal reserves north of the mining district. Boreholes KB172 and KB174 are exploration wells drilled by the Belgian Geological Survey in 1984 and 1985 respectively. KB172 provides a cored section of about 750 m Westphalian C and D strata. Westphalian A and B strata, attaining 650 m in thickness, are present in KB174.

The aim of this study is to report on the reconstructed burial and thermal histories of both wells. To model burial histories, data from both wells and, as far as necessary, from adjacent boreholes were used. Burial and thermal histories have been simulated using the PDI-1DTM version 2.2 basin-modelling software package (IES 1991). In these simulations, vitrinite reflectance (R_o) was calculated according to the method developed

by Sweeney & Burnham (1990). All models were calibrated by comparing the calculated with the measured R_o data (Langenaeker 1992).

Recently, comparable studies were carried out on Upper Carboniferous coal-bearing strata in the former mining district of South Limburg, the Netherlands, by Veld et al. (1996), and in well Floverich 2E-1 of the Aachen-Erkelenz coal district, Germany, by Bükér et al. (1996). According to the models of these authors, present-day coalification patterns in the Upper Carboniferous were established in Late Westphalian to Early Permian times. Furthermore, these researchers suggest that either the Variscan nappes extended much further to the north than at present, or alternatively, that a molasse basin developed in front of the Variscan orogen during the Late Westphalian D and Stephanian. Subsequently, the strata deposited in this basin were completely eroded.

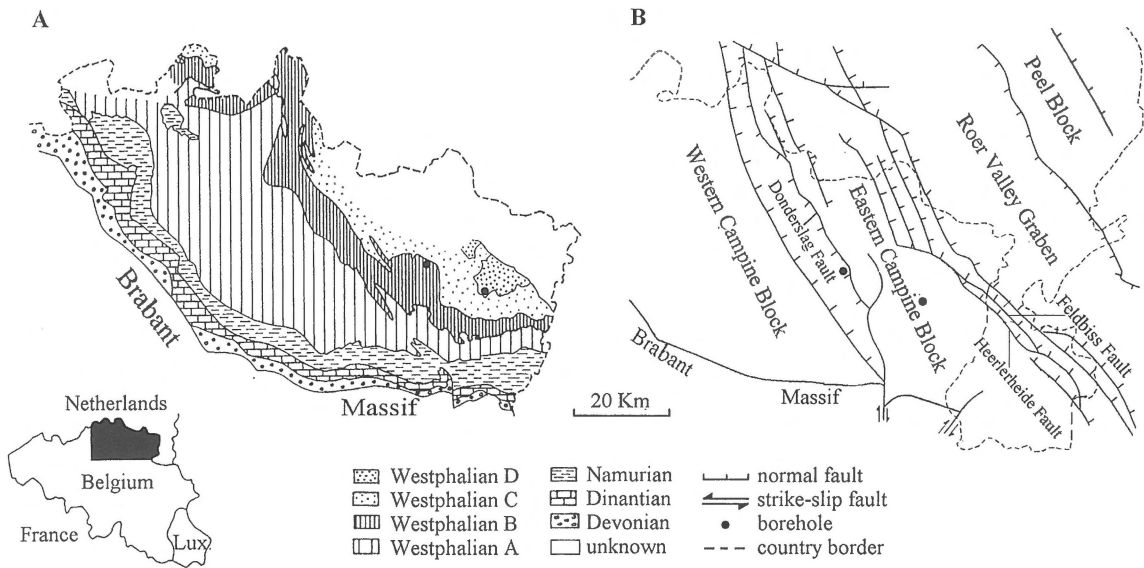


Figure 1. Subcrop map of Upper Paleozoic at base Permian (A) and structural map (B) of the area studied, indicating the locations (●) of boreholes KB172 (Gruitrode-Ophoverdeheide) and KB174 (Hechtel-Hoef) east and west of Donderslag Fault respectively. (after Langenaeker & Dusar 1992; Geluk et al. 1994).

Geological setting

Structural framework

The Campine Basin is located to the northeast of the Caledonian Anglo-Brabant Massif. Its northern boundary is formed by the Heerlerheide-Feldbiss Fault system which marks the southern limit of the Roer Valley Graben, the western branch of the Lower Rhine rift (Figure 1). The present structural picture of the basin basically shows monoclinaly dipping Carboniferous strata, thickening to the northeast towards the Roer Valley Graben (Figure 1A), and covered by a Mesozoic and Cenozoic overburden. NW-SE striking normal faults parallel to the Roer Valley Graben dominate (Figure 1B). Rossa (1987) showed that Asturian (Late Carboniferous) and Cimmerian (Middle to Late Jurassic) movements along these faults generally followed the same strike direction. According to Bouckaert & Dusar (1987) some Asturian strike-slip faults were inherited from the Caledonian basement. The Eastern and Western Blocks of the Campine Basin, separated by the transversal Donderslag Fault, are marked by differences in coal-seam distribution and rank. The differences in coal-seam distribution correspond to synsedimentary tectonic activity along this fault that controlled subsidence and thus coal content (Dusar 1989). Vitrinite reflectance data from well KB174 (0.66–0.98%

R_o), located in the Western Block, display a minimal coalification for Westphalian A and B strata. Well KB172, located in the Eastern Block, on the contrary shows the highest R_o values (0.85–1.30% R_o) measured for Westphalian C and D strata in the Campine Basin (Langenaeker 1992). Vitrinite-reflectance data of Permian sediments are only available for KB172 (internal documents Belgian Geological Survey).

The deformation of Carboniferous sediments started during the Asturian tectonic phase at the end of the Westphalian. The driving force of this deformation was the northward movement of the Variscan orogenic front. The deformation was limited to block faulting and tilting of the strata, partly along strike-slip faults (Bouckaert & Dusar 1987). After the Variscan orogeny, regional subsidence prevailed from the Late Permian to Early Jurassic. Subsidence of the future Roer Valley Graben area continued until the Middle Jurassic and appears to have included the Eastern Campine Block (Zijerveld 1992; Geluk et al. 1994). Cimmerian tectonic activity initiated the break-up of the Permo-Triassic basin into smaller depocentres such as the Roer Valley Graben (Geluk 1990). A third tectonic phase, marked by inversion movements during Late Cretaceous time, caused gradual uplift and erosion of the Cimmerian downthrown blocks. From Late Oligocene times onward the final phase of differential subsidence occurred. Reactivation of normal faults compensated

Table 1. Input data for well KB174 (Hechtel-Hoef). Parameters in boxes were modified according to different simulations. A thickness of '-9999m' marks the total erosion of deposits of an earlier event; SWI-temp are sediment-water-interface temperatures. The lithology W-CBA consists of 52% siltstone, 26% sandstone, 16% shale and 6% coal.

Event no	Event name	End (Ma)	Start (Ma)	Thickness (m)	Lithology	Recent porosity (%)	Water depth (m)	SWI-temp (°C)	Heat flow (mW/m ²)
43	Quaternary	0.0	2.0	5	SANDcongl	35	0	8	63
42	Pliocene	2.0	5.0	59	SAND	39	10	16	63
41	Miocene	5.0	23.0	58	SAND	39	10	16	63
40	Oligocene	23.0	38.0	193	SHALE&SILT	30	15	22	63
39	Eocene	38.0	56.0	13	SHALE	26	0	21	63
38	Paleocene	56.0	65.0	175	SHALEsilt	26	5	21	63
37	Maastricht	65.0	74.0	122	CHALK	44	10	21	63
36	Camp-Sant	74.0	87.0	85	SANDshaly	27	15	23	63
35	Erosion-28	87.0	125.0	-469	SANDcongl	25	0	24	63
34	Erosion-29	125.0	135.0	-9999	LIMESTONE	33	0	26	63
33	Erosion-30	135.0	145.0	-9999	SHALEcalc	23	0	25	63
32	Erosion-31	145.0	178.0	-9999	SHALE	33	0	22	63
31	Lias	178.0	208.0	400	SHALE	27	65	20	63
30	Rhae-Keup	208.0	231.0	103	SHALEcalc	17	5	25	63
29	Muschelk	231.0	243.0	85	LIMESTONE	24	5	27	63
28	Buntsand	243.0	245.0	560	SANDcongl	10	5	26	63
27	Zechstein	245.0	256.0	28	SILTshaly	13	15	25	63
26	Erosion-7	256.0	268.0	-148	W-CBA	21	0	24	63
25	Erosion-8	270.0	273.0	-9999	W-CBA	21	0	24	63
24	Erosion-9	273.0	276.0	-9999	W-CBA	21	0	24	63
23	Erosion-10	276.0	279.0	-9999	W-CBA	21	0	24	63
22	Erosion-11	279.0	282.0	-9999	W-CBA	21	0	24	63
21	Erosion-12	282.0	285.0	-9999	W-CBA	21	0	24	63
20	Erosion-13	285.0	289.7	-9999	SANDSTONE	21	0	24	63
19	Erosion-14	289.7	294.4	-9999	SANDSTONE	21	0	24	63
18	Erosion-15	294.4	299.2	-9999	SANDSTONE	18	0	24	63
17	Erosion-16	299.2	304.0	-9999	SANDSTONE	18	0	24	84
	Erosion			-9999	SANDSTONE	18	0	24	71
	Stephanian			600	SANDSTONE	18	5	24	71
16	Westph-D	304.0	305.0	150	SANDSTONE	14	5	25	84
15	Westph-D	305.0	306.0	150	SANDSTONE	14	5	25	84
14	Westph-D	306.0	307.0	150	SANDSTONE	14	5	25	84
13	Westph-D	307.0	308.0	150	SANDSTONE	14	5	25	84
12	Westph-C	308.0	308.6	150	W-CBA	5	3	25	63
11	Westph-C	308.6	309.2	150	W-CBA	5	3	25	63
10	Westph-C	309.2	309.8	150	W-CBA	5	3	25	63
9	Westph-C	309.8	310.4	150	W-CBA	5	3	25	63
8	Westph-C	310.4	311.0	150	W-CBA	5	3	25	63
7	Westph-B	311.0	311.5	165	W-CBA	5	5	26	63
6	Westph-B	311.5	312.0	165	W-CBA	8	5	26	63
5	Westph-B	312.0	312.5	165	W-CBA	8	5	26	63
4	Westph-B	312.5	313.0	165	W-CBA	8	5	26	63
3	Westph-A	313.0	313.8	230	W-CBA	7	5	26	63
2	Westph-A	313.8	314.0	230	W-CBA	7	5	26	63
1	Westph-A	314.0	315.0	540	W-CBA	6	5	26	63

for the Late Cretaceous inversion and made the Roer Valley Graben subside along the Feldbiss Fault (Geluk et al. 1994).

Conceptual model

Before starting the simulation of burial and thermal histories it is important to build up the conceptual model, which defines the relationship between the geology and the data used for modelling (Welte & Yüklér 1981). The procedure followed is based on Wygrala (1989). The first step is to construct geochronological units, further called 'events'. Each event is characterized by the type of geological process, e.g. sedimentation, non-deposition or erosion. The timescale of Harland et al. (1990) was used for the Late Carboniferous, and that of Harland et al. (1982) for the post-Paleozoic.

The conceptual model is based on the assumption of a pre-Permian coalification of Westphalian sediments. For well KB172 a post-Permian secondary coalification was suggested by Duser et al. (1987). In the Campine Basin, Westphalian A and B strata, compacted to 1650 m (Delmer 1963), are overlain by 700 to 875 m of Westphalian C (Dreesen et al. 1995) and approximately 600 m Westphalian D (Bless et al. 1977). According to Fermont et al. (1994) and Caers et al. (1996) the maximum burial depth of the Westphalian A and B was effectively reached at the end of the Late Carboniferous subsidence period. Erosion of Westphalian strata, associated with the Asturian uplift, occurred after Westphalian D times and before Zechstein deposition (Tys 1980). Zechstein deposits discordantly overlie the Upper Carboniferous, attaining a thickness of only 22 m in KB172 and 28 m in KB174. During Triassic times, 560 m Buntsandstein, 85 m Muschelkalk, 86 m Keuper and at least 17 m Rhaetian could have been deposited (Tys 1980). For Lower Jurassic deposits a thickness of 400 m was estimated (Mucchez et al. 1992). During this Early Mesozoic burial phase, the maximum burial depth of the Westphalian C and D strata in KB172 was reached. After the Cimmerian uplift and erosion in Jurassic times, deposition of Late Cretaceous (starting with Santonian), Tertiary and Quaternary sediments took place. Thickness data of these sediments are provided by Duser et al. (1987; in press).

In the modelling, lithologies predefined by the IES (1991) software program were used. Only for the coal-bearing strata a special lithology, (W-CBA in Tables 1 and 2), consisting of 52% siltstone, 26% sandstone, 16% shale and 6% coal was defined. IES default petro-

physical data are listed in Table 3. Present porosity data for the Westphalian and Buntsandstein were derived from point-counting results (Mucchez et al. 1992; Van Keer et al. in press) and from porosity measurements (internal documents Belgian Geological Survey). The input data sets for wells KB172 and KB174 are listed in Tables 1 and 2.

The maturation of organic matter through time was calculated according to the Easy-R_o model (Sweeney & Burnham 1990). The established models were calibrated by comparing calculated with measured vitrinite-reflectance profiles (Langenaeker 1992). As long as no sufficient match between calculated and measured maturity parameters is achieved, the input data set or the conceptual model has to be adapted within geologically reasonable limits.

Simulations

The first simulation run based on an average continental heat flow of 63 mW/m² (Kertz 1969) for all events, resulted for both wells in calculated R_o values which are lower than the measured data (Figure 2: 172-1; Figure 3: 174-1).

KB 172

The extremely poor fit given by the first simulation run could not be compensated by higher heat flows (up to 125 mW/m²) during the entire geological history (Figure 2: 172-2). To achieve a better match of calculated and measured vitrinite reflectance, all further simulations were based on the addition of extra sediments. Two additional models have been developed. The first of these is based on simulations carried out by Bükér et al. (1996) and Veld et al. (1996) who assumed additional strata of Westphalian D and Stephanian age to reconstruct burial and thermal histories of Carboniferous sediments in the Aachen-Erkelenz coal district (Germany) and in wells located in South Limburg (the Netherlands). If we assume a continuous sedimentation throughout the Carboniferous until the end of the Stephanian, a fairly good fit is obtained by adding between 1350 and 3000 m of Stephanian sediments in combination with elevated heat flows (e.g. 80 mW/m² during the Stephanian; Figure 2: 172-3).

Bükér et al. (1996) also assumed erosion of a 700 m thick Asturian thrust sheet. Extra loading by northward tectonic thrusting, however, cannot be invoked to explain east-west variations in coal rank for the

Table 2. Input data for well KB172 (Gruitrode-Ophovenderheide). For explanations see Table 1.

Event no	Event name	End (Ma)	Start (Ma)	Thickness (m)	Lithology	Recent porosity (%)	Water depth (m)	SWI-temp (°C)	Heat flow (mW/m ²)
38	Quaternary	0.0	2.0	9	SANDcongl	35	0	8	63
37	Plioc-Mioc	2.0	23.0	151	SAND	39	10	16	63
36	Oligocene	23.0	38.0	142	SHAL&SILT	30	15	19	63
35	Hiatus	38.0	56.0	0	SHALE	31	0	22	63
34	Paleocene	56.0	65.0	155	SHALEsilt	26	5	21	63
33	Maastricht	65.0	74.0	114	CHALK	44	10	21	63
32	Camp-Sant	74.0	87.0	108	SANDshaly	27	15	23	63
31	Erosion-16	87.0	111.0	-430	SANDcongl	25	0	24	63
30	Erosion-17	111.0	121.0	-9999	LIMESTONE	33	0	26	63
29	Erosion-18	121.0	131.0	-9999	SHALEcalc	23	0	25	63
28	Erosion-19	131.0	145.0	-9999	SHALE	33	0	22	63
27	Erosion-20	145.0	148.0	-9999	LIME&SHALE	33	0	22	63
26	Erosion-21	148.0	151.0	-9999	LIME&SHALE	33	0	22	63
25	Erosion-22	151.0	154.0	-9999	LIME&SHALE	33	0	22	63
24	Erosion-23	154.0	157.0	-9999	LIME&SHALE	33	0	22	74
23	Dogger	157.0	162.2.	350	LIME&SHALE	20	65	22	74
22	Dogger	162.2.	167.5	350	LIME&SHALE	20	65	20	74
21	Dogger	167.5	172.7	350	LIME&SHALE	20	65	20	74
20	Dogger	172.7	178.0	350	LIME&SHALE	20	65	20	74
19	Lias	178.0	208.0	400	SHALE	27	65	20	63
18	Rhae-Keup	208.0	231.0	103	SHALEcalc	17	5	25	63
17	Muschelk	231.0	243.0	85	LIMESTONE	24	5	27	63
16	Buntsand	243.0	245.0	560	SANDcongl	10	5	26	63
15	Zechstein	245.0	256.0	22	SILTshaly	13	15	25	63
14	Erosion-9	256.0	272.0	-45	SANDSTONE	20	0	23	63
13	Erosion-10	272.0	288.0	-9999	SANDSTONE	20	0	23	63
12	Erosion-11	288.0	304.0	-9999	SANDSTONE	20	0	23	63
	Erosion			-9999	SANDSTONE	17	0	24	84
	Stephanian			1350	SANDSTONE	17	5	25	84
11	Westph-D	304.0	305.0	150	SANDSTONE	14	5	25	84
10	Westph-D	305.0	306.0	150	SANDSTONE	14	5	25	84
9	Westph-D	306.0	307.0	150	SANDSTONE	14	5	25	84
8	Westph-D	307.0	308.0	150	SANDSTONE	14	5	25	84
7	Westph-C	308.0	308.4	100	W-CBA	5	3	25	63
6	Westph-C	308.4	308.8	100	W-CBA	5	3	25	63
5	Westph-C	308.8	309.2	100	W-CBA	5	3	26	63
4	Westph-C	309.2	309.6	100	W-CBA	5	3	26	63
3	Westph-C	309.6	310.0	100	W-CBA	5	3	26	63
2	Westph-C	310.0	310.4	100	W-CBA	5	3	26	63
1	Westph-C	310.4	311.0	150	W-CBA	5	3	26	63

same stratigraphical intervals of the Westphalian in the Campine Basin (Legraye 1930). Therefore, the presence of allochthonous sediments has not been taken into account. The fourth simulation (Figure 2: 172–4) assumes accelerated subsidence of the Eastern

Campine Block up to Middle Jurassic times in relation to rifting in the Roer Valley Graben. Deposition of 1400 m of Dogger sediments and heat flows ranging from 71 to 80 mW/m² provide good fits.

Table 3. Petrophysical properties of lithologies used by the IES-simulation software (IES 1991). The lithology W-CBA consists of 52% siltstone, 26% sandstone, 16% shale and 6% coal.

Lithology	Initial porosity (%)	Density (kg/m ³)	Compressibility (m ² /kP)		Thermal conductivity (J/m ² sec ^o C)		Heat capacity (cal/g ^o C)		Permeability (−5 = 10 ^{−5} md) at porosity of	
			min.	max.	20° C	100° C	20° C	100° C	5%	75%
CHALK	65	2700	65	700	2.85	2.51	0.197	0.226	−1.00	3.00
LIMESTONE	42	2710	25	300	2.83	2.56	0.195	0.223	−4.00	13.00
SANDSTONE	42	2660	10	500	3.12	2.64	0.178	0.209	−2.00	0.00
SANDcongl	35	2663	10	330	2.93	2.63	0.184	0.217	−3.50	0.00
SANDshaly	48	2666	10	1400	2.78	2.37	0.190	0.226	−4.00	0.00
SHALE	65	2680	10	60000	1.98	1.91	0.213	0.258	−5.50	−1.00
SHALEcalc	52	2688	10	5000	2.22	2.09	0.208	0.248	−2.50	8.50
SHALEsilt	62	2677	10	250000	2.05	1.94	0.210	0.254	−5.35	−0.70
SHALE&SILT	59	2674	10	13000	2.09	1.97	0.207	0.251	−5.25	−0.50
SILTshaly	58	2675	10	15000	2.09	1.98	0.203	0.245	−5.15	−0.30
W-CBA	54	2610	10	5000	2.26	2.21	0.197	0.236	−4.36	−0.21

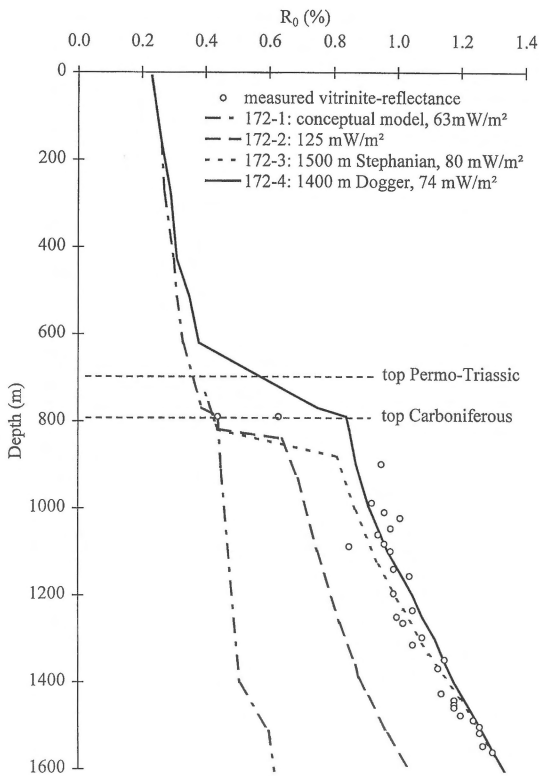


Figure 2. KB172: Comparison of measured (○) versus calculated vitrinite reflectance based on simulation runs 172–1 to 172–4.

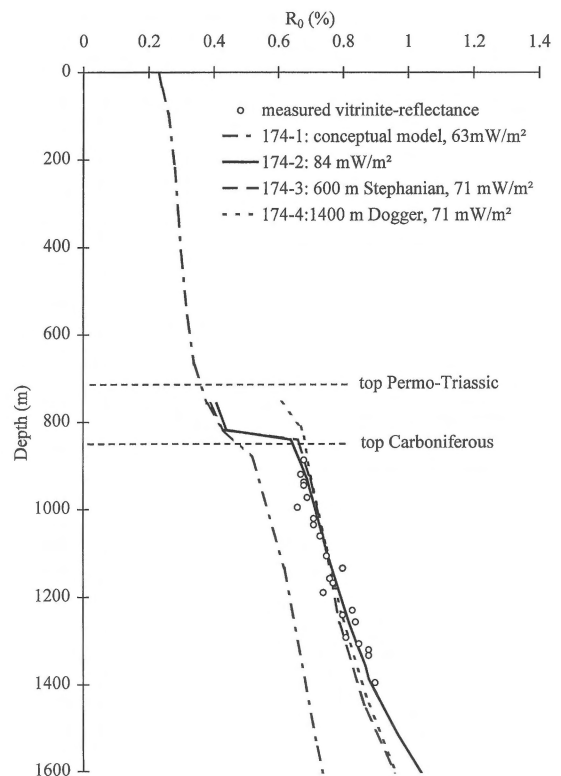


Figure 3. KB174: Comparison of measured (○) versus calculated vitrinite reflectance based on simulation runs 174–1 to 174–4.

KB 174

The Carboniferous geotectonic setting of the Campine Basin corresponds to a back-arc underlain by continen-

tal crust (Leeder 1987). Reported heat flow values in such areas vary between 63 and 125 mW/m² (Brooks et al. 1984; Allen & Allen 1990). The second simulation

for KB174 (Figure 3: 174–2) is based on a heat flow of 84 mW/m^2 during maximum burial in Westphalian D time. This model leads to a close fit between calculated and measured vitrinite reflectance. In order to evaluate whether Stephanian strata could have been deposited in the area, the best fit was obtained by adding 600 m of sediments of this age and by assuming a heat flow of 71 mW/m^2 (Figure 3: 174–3). This third simulation did not result in a better match than the second one. Extra Dogger sediments (1400 m) also produce reasonable results. However, the calculated vitrinite reflectance tends to be too high in the upper part of the measured section or too low in the lower part (Figure 3: 174–4).

Discussion

Burial history

The best fit between measured and calculated vitrinite reflectance for KB174 is given by a 'standard' burial in combination with a heat flow of 84 mW/m^2 during maximum burial (Figure 3: 174–2). Simulations carried out for KB172 show that additional sediment input in combination with elevated heat flows is required to explain the high coalification gradient measured in this borehole. Figure 2 shows that the best fit is obtained by adding 1400 m of Dogger sediments in combination with a heat flow of 74 mW/m^2 during maximum burial. Reasonable results can also be obtained by adding Stephanian strata in combination with a higher heat flow during Stephanian time. However, Stephanian strata are not present in Belgium and they have never been indicated on paleogeographic reconstructions (e.g. Ziegler 1990). Vitrinite-reflectance data of Zechstein strata in KB172 show two populations. The first population is characterized by a mean reflectance of $R_o = 0.44\%$ ($n = 6$), while the second population has a mean value of $R_o = 0.63\%$ ($n = 16$; Belgian Geological Survey, unpublished). If the first population represents the coalification of Permian sediments, and the second population vitrinite grains reworked from the Westphalian, then the model based on additional Stephanian strata should be preferred.

Several authors, e.g. Tys (1980) and Dusar et al. (1987), however, indicated differences in the geological histories of the various tectonic blocks in the Campine Basin. Furthermore, Figure 4 illustrates different coalification histories of the wells KB172 and KB174. The R_o profile of KB174 shows a less intense coalification than that of KB172. This indicates differ-

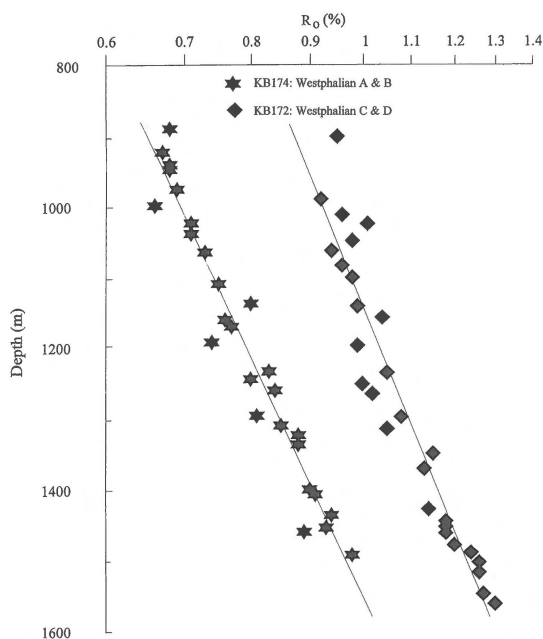


Figure 4. Measured vitrinite reflectance (% R_o) for wells KB172 and KB174.

ent burial histories. The younger Westphalian C and D sediments of KB172 exhibit a higher coalification than the older Westphalian A and B sediments of KB174. Taking into account the modelling results, the geological setting and the coalification data, we suggest that the strata in KB172 underwent a similar burial history until the Late Westphalian as the sediments in KB174, but that they had a different evolution during the Mesozoic. The simulated burial and thermal histories clearly illustrate these differences (Figures 5, 6).

Because the physical properties of the assumed eroded Jurassic sediments are unknown, sensitivity analyses concerning different rock types are necessary. Ziegler (1990) indicated the deposition of limestone and shale during Bathonian and Bajocian times north of the Brabant Massif. Simulation runs were carried out for lithological compositions ranging between limestone and shale. All of them lead to a good fit between the measured and calculated vitrinite-reflectance profiles. Thus, no conclusion concerning the presence of particular rock types can be made.

In general, the Westphalian of the Campine Basin is characterized by three major periods of subsidence interrupted by the Asturian and Cimmerian uplifts. The first rapid burial occurred during Late Carboniferous times. The maximum depth of the Westphalian A and B in KB174 was already reached during this period

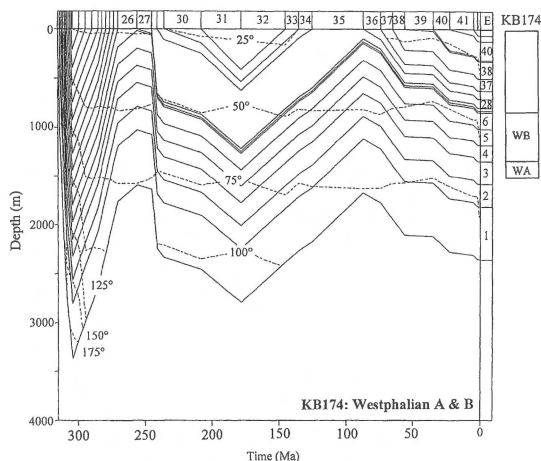


Figure 5. Burial history of Westphalian A (WA) and B (WB) strata in borehole KB174 obtained from borehole data and regional thickness values. Dashed curves are iso-temperature lines ($^{\circ}\text{C}$) considering a heat flow of 84 mW/m^2 during Late Westphalian D and of 63 mW/m^2 during Mesozoic and Cenozoic times (run 174–2). ‘E’ are event numbers given by Table 1.

(Figure 5). A second burial phase took place between the Late Permian and Middle Jurassic during which time Westphalian C and D strata in KB172 could have reached their maximum depth (Figure 6). Subsequently, ~ 1000 and ~ 2400 m have been eroded in the areas west and east of the Donderslag Fault respectively, as a result of the Cimmerian phase. After this uplift, deposition of Late Cretaceous, Tertiary and Quaternary sediments occurred during successive subsidence pulses.

The deposition of > 1000 m of Dogger sediments assumed for KB172 can be related to differential subsidence of the Roer Valley Graben. The wells Oisterwijk-1 and Werkendam-2, located in the central and north-western parts of the Roer Valley Graben respectively, give evidence for the deposition of at least 450 to 700 m of Dogger sediments (Van Adrichem Bogaert & Kouwe 1994). Moreover, the top of these sediments is erosional, indicating that thicker strata have been present. Bordering highs, including the area of the Western Campine Block, were areas of non-deposition or incipient erosion because of vertical oscillations. However, it should be noticed that a convective heat flow, which cannot be simulated in 1D-modelling, could lead to a reduction of the required thickness of Dogger strata.

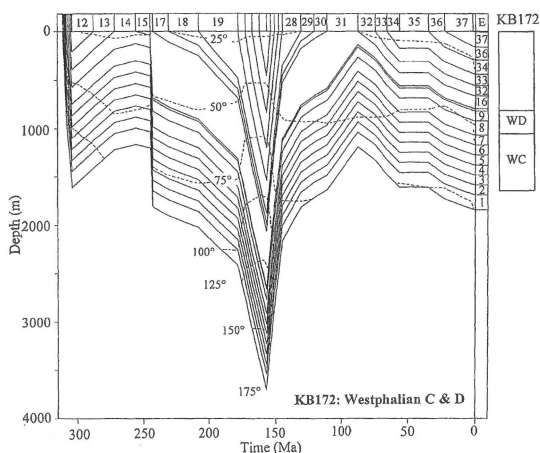


Figure 6. Burial history of Westphalian C (WC) and D (WD) strata in borehole KB172 obtained by adding 1400 m of Dogger limestone and shales and taking into account a heat flow of 74 mW/m^2 during Dogger time. Dashed curves are iso-temperature lines ($^{\circ}\text{C}$) taking into account a heat flow of 84 mW/m^2 for Late Westphalian, 74 mW/m^2 for the Dogger and 63 mW/m^2 for the rest of the Mesozoic and Cenozoic (run 172–4). ‘E’ are event numbers given by Table 2.

Thermal evolution

The reconstructed burial histories of both wells as shown in Figures 5 and 6, indicate two periods during which higher heat flows may have occurred. The preferred model of KB174 gives a Late Carboniferous heat flow of 84 mW/m^2 . This value is in accordance with simulation results given by Ritter (1986) and Bükér et al. (1995; 1996), but exceeds the heat flows calculated by Fermont et al. (1994) for borehole KB206, and by Veld et al. (1996) for South Limburg. Fermont et al. (1994) already mentioned considerable variations in heat flows over small distances. The reconstructed burial history of KB172 indicates a second, Dogger heating stage with heat flows between 71 and 80 mW/m^2 . The higher thermal input into the sedimentary sequence is probably related to North Sea rifting.

The thermal modelling indicates that the tops of the Westphalian B in KB174 and of the Westphalian D in KB172 reached temperatures of at least 110 and $50 \text{ }^{\circ}\text{C}$, respectively, during the Late Westphalian (Figures 5, 6). The Westphalian in KB172 has been subjected to temperatures $> 130 \text{ }^{\circ}\text{C}$ during Dogger times.

Conclusion

The reconstructed burial history of the KB174 borehole is in agreement with the generally accepted geological history of the Campine Basin, in which maximum burial took place at the end of the Carboniferous.

Deposition of 1400 m of Dogger sediments in combination with an elevated heat flow during maximum burial, explains the higher coalification in the KB172 borehole. According to our simulation results two periods of higher heat flow occurred. Our model shows a Westphalian heat flow of 84 mW/m² which is comparable to reported values of the Northwest German Basin. Well KB172 indicates a heat flow between 71 and 80 mW/m² during Dogger times which can be related to North Sea rifting. Simulated maximum temperatures for the tops and the bottoms of the investigated intervals range from 110 to 175 °C for the Westphalian A and B in KB174 and from 130 to 175 °C for the Westphalian C and D in KB172. The difference in the burial and thermal histories of both wells is thought to be related to the tectonic activity of the Roer Valley Graben and to movements along the Donderslag Fault, which separates the Eastern from the Western Campine Block.

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