Geological Quarterly, 2010, **54** (2): 241–256

Hydrocarbon generation and expulsion modelling of the lower Paleozoic source rocks in the Polish part of the Baltic region

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Kosakowski P., Wróbel M. and Poprawa P. (2010) – Hydrocarbon generation and expulsion modelling of the lower Paleozoic source rocks in the Polish part of the Baltic region. Geol. Quart., **54** (2): 241–256. Warszawa.

The burial history, thermal maturity, and timing of hydrocarbon generation of four source rock successions were modelled: the Middle Cambrian, the Upper Cambrian–Tremadocian, the Upper Ordovician (Caradocian) and the lower Silurian (Llandovery and Wenlock). The 1-D modelling was carried out in profiles of eight boreholes throughout the western Baltic region. Four selected boreholes are located offshore: A8-1/83, A23-1/88, B6-1/82 and B4-2A/02, and four onshore: Białogóra 3, Dębki 3, Łeba 8 and Żarnowiec IG 1. The thermal maturity of source rocks is the highest in the deeper buried western part of the basin and decreases from the west to the east and north-east towards the basin margins. The lower Paleozoic source rocks contain oil-prone Type-II kerogen. The modelling indicated that the onset of petroleum generation from the lower Paleozoic source rocks occurred from the Early Devonian through the early Carboniferous period. The peak of hydrocarbon generation took place from the Late Devonian to the Tournaisian. The majority of hydrocarbons generated were expelled during the latest Early Devonian and Carboniferous, and oil has not been expelled from source rock only in the eastern offshore part of the basin.

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(received: December 12, 2009; accepted: April 4, 2010).

Key words: Baltic region, Nothern Poland, lower Paleozoic, source rocks, 1-D modelling.

INTRODUCTION

The aim of this paper is to show processes of generation and expulsion of hydrocarbons from lower Paleozoic source rocks in the Polish part of the Baltic region. Lithostratigraphic sections of boreholes from the offshore Baltic region: A8-1/83, A23-1/88, B6-1/82, B4-2A/02 and onshore: Białogóra 3, Dębki 3, Łeba 8 and Żarnowiec IG 1 were used for modelling these processes (Fig. 1 and Tables 1–3).

The modelling incorporated results of burial and thermal history reconstructions for the boreholes, with restoration of thickness of eroded sediments and heat flow changes in time being of particular importance for the current study with burial and thermal history constrained, the following basic generation conditions were established for the individual boreholes with the use of 1-D numerical modelling:

- time and depth identification of organic matter thermal maturity intervals;
- position of generation phases and transformation degree of kerogen;
- amount of generated and expelled hydrocarbon mass.

MODELLING PROCEDURE

1-D modelling of selected boreholes was performed using *BasinMod*™ software (BMRM 1-D, 2006). The modelling approach adopted in the software requires input data which describe the present-day geological situation as a result of past events. On this basis the geological history is simulated from the oldest event to the most recent one (Nikishin *et al.*, 1996; Poprawa *et al.*, 1999, 2010; Pokorski, 2010). Rock properties – density, porosity, permeability and thermal conductivity are modelled along with their thermal history. *BasinMod*™ software provides an extended database of various lithological types defined by the physical properties mentioned above

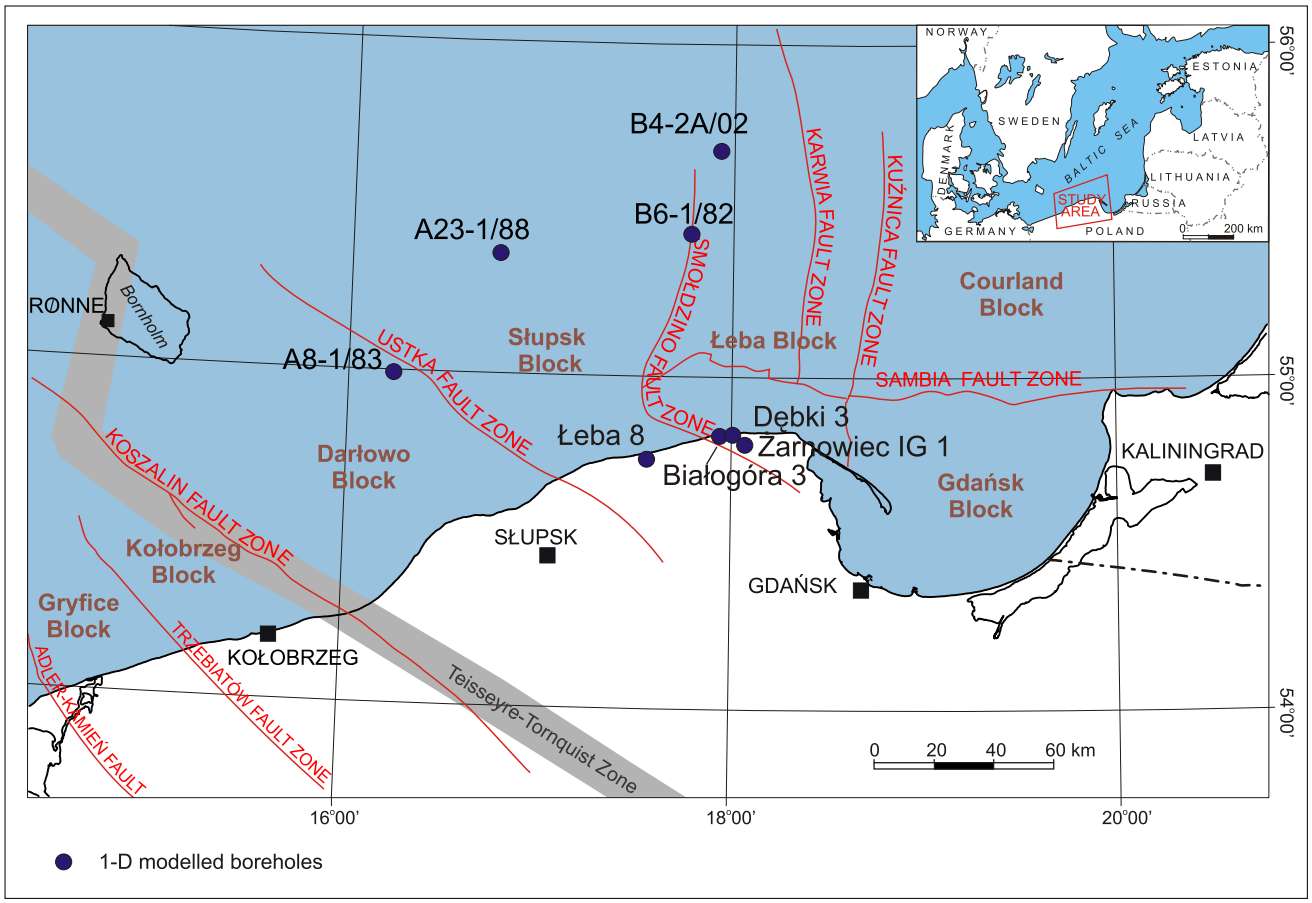

Fig. 1. Sketch tectonic map of the Polish part of the Baltic region and location of 1-D modelled boreholes

Fault system after Pokorski (2010)

(BMRM 1-D, 2006). The details of principles of the modelling technique are given in Welte *et al.* (1997). Thermal evolution is simulated on the basis of boundary assignments applied to certain time steps. Assigned parameters are heat flow densities in mW/m^2 and surface temperatures in °C. Heat flow and surface temperature assignment for the past stages of basin history can only be estimated based on the general tectonic setting and evolution of the region investigated (Besse and Courtillot, 1991; van der Voo, 1993; Yalcin *et al.*, 1997; Allen and Allen, 2005; Golonka, 2009). To determine the magnitude of burial and erosion Rock-Eval T_{max} temperature and reflectance of vitrinite-like macerals (R_o) data (Więcław *et al.*, 2010*a*) were used. Estimation of eroded thicknesses has to be accompanied by testing various palaeo-heat flow models (Poprawa *et al.*, 1999, 2010). The thermal maturity of organic matter was calculated by the EASY%R_o method (Sweeney and Burnham, 1990). Generation and expulsion of hydrocarbons were calculated by LLNL model (Ungerer *et al.*, 1988; Forbes *et al.*, 1991; BMRM 1-D, 2006) and the use of kinetic parameters E_a = 57.5 (kcal/mol) and A_0 = 2.508E + 28 (1/m.y.) for Cambrian source rock, and E_a = 61.9 (kcal/mol) and A_0 = 7.073E + 29 (1/m.y.) for Ordovician source rock, calculated by Więcław *et al.* (2010*b*).

MODELLING OF THE MATURATION HISTORY OF THE LOWER PALEOZOIC SOURCE ROCKS

Thermal analysis of organic matter in the lower Paleozoic strata in the study area was made specifically for each of the source intervals determined, i.e. Middle Cambrian, upper Cambrian–Tremadocian, Upper Ordovician (Caradocian) and lower Silurian (Llandovery and Wenlock).

With the thermal conditions adopted for the generation modelling (see Poprawa *et al.*, 2010), as well as the magnitude of the Early Devonian erosion of 100 m and post-Westphalian of 1100–1900 m (Tables 1–3), the Middle Cambrian source rocks – the *Eccaparadoxides oelandicus* and the lowermost part of the *Paradoxides paradoxissimus* Zone (see Modliński and Podhalańska, 2010) reached an early stage of thermal maturity (0.5–0.7% R_o) at the turn of the Silurian and Devonian (Fig. 2). That maturity stage has been developed successively later in time from the vicinity of the Teisseyre-Tornquist Zone in the west towards the central part of the Baltic region (Kanev *et al.*, 1994; Karnkowski, 2003; Zdanaviciute and Lazauskiene, 2004; Poprawa and Grotek, 2005; Grotek, 2006; Więcław *et al.*, 2010*a*). In the Darłowo and Słupsk blocks, the Middle Cambrian source rocks exceeded the maturity threshold condi-

Table 1

Parameters for burial history reconstruction on the Darłowo and Słupsk blocks (western part of the Baltic region)

Stratigraphy	Age [Ma]	Darłowo Block						Słupsk Block									
		A8-1/83						A23-1/88						Łeba 8			
		Top depth	Deposition/Erosion	Generalized litology [%]				Top depth	Deposition/Erosion	Generalized litology [%]				Top depth	Deposition/Erosion	Generalized litology [%]			
		[m]		ss	sil	sh	carb	[m]		ss	sil	sh	carb	[m]		ss	sil	sh	carb
Sea water	0.1													-					
Quaternary	2.6	88		50	30	20		92.3		50	30	20		91		80	10	10	
Neogene	23		n.d.						n.d.						n.d.				
Paleogene	40		n.d.						n.d.					91					
Erosion	65.5		-200						-300						-450				
U. Cretaceous	99.6		200	10	10	20	60		300	10	10	20	60	122	450	60	40		
L. Cretaceous	145.5		n.d.						n.d.						n.d.				
U. Jurassic	161.2		n.d.						n.d.						n.d.				
M. Jurassic	175		n.d.						n.d.					171		35	65		
L. Jurassic	190		n.d.						n.d.						n.d.				
U. Triassic	203		n.d.						n.d.						n.d.				
M. Triassic	245		n.d.						n.d.						n.d.				
Erosion	245		-200						-200						-100				
L. Triasssic	251		200	40	40	20			200	40	40	20		302		85	10	5	
U. Permian	258		n.d.						n.d.					488				2	98*
L. Permian	299		n.d.						n.d.						n.d.				
Erosion	326.4		-1400						-1800						-1400				
L. Carboniferous	359.2		100	10	5	60	25		100	10	5	60	25		100				
U. Devonian	385.3		800	20		20	60		900	25		25	50		100				
M. Devonian	397.5		100	10	10	20	60		200	50	35	5	10		800				
L. Devonian	416		n.d.						-100						200				
U. Silurian (Pridoli)	418.7		300		35	65	5		500		35	65	5	714.5	300			95	5
U. Silurian (Ludlow)	421.3	111	100		45	50	5	130	200	10	65	20	5	990.5			13	85	2
L. Silurian (Wenlock)	428.2	1530			10	90		1055			45	45	10	2429.5				95	5
L. Silurian (Llandovery)	443.7	1707				100		1195			30	70		2586				90	10
U. Ordovician (Ashgillian)	450	1786		10	40	50		1233				50	50	2646			20	50	30
U. Ordovician (Caradocian)	460.9	1805.5				90	10	1245				90	10	2654				95	5
M. Ordovician (Llanvirnian)	467		n.d.					1281.5				20	80	2695.5			30		70
E. Ordovician (Arenigian)	478.6	1866.5		10		85	5	1289			90	10		2702		5	15	55	25
U. Cambrian–Tremadocian	501	1927		10		90		1304.5		5		85	10	2726#		15	5	40	40
M. Cambrian	513	1945.5		40	35	25		1315.6		40	35	25		2747		40	30	30	
E. Cambrian	542	2105		60	30	10								3059		70	20	10	
Ediacaran–L. Cambrian	590	2183		70	30	10		1492		50	40	10		3198		70	20	10	

L. – Lower, M. – Middle, U. – Upper, ss – sandstones, sil – silstones, sh – shales, carb – carbonates, # – only U. Cambrian, * – 70% of evaporates and 30% of carbonates, n.d. – no deposition

Table 2

Parameters for burial history reconstruction in offshore part of the Łeba Block (western part of the Baltic region)

Stratigraphy	Age [Ma]	Łeba Block										
		B6-1/82						B4-2A/02				
		Top depth	Deposition/ Erosion	Generalized litology [%]				Top depth	Deposition/ Erosion	Generalized litology [%]		
		[m]		ss	sil	sh	carb	[m]		ss	sil	sh	carb
Sea water	0.1												
Quaternary	2.6	99.6		50	30	20		89.7		50	30	20	
Neogene	50		n.d.						n.d.				
Paleogene	40		n.d.						n.d.				
Erosion	65.5		-300						-300				
U. Cretaceous	99.6		300						300				
L. Cretaceous	145.5		n.d.						n.d.				
U. Jurassic	161.2		n.d.						n.d.				
M. Jurassic	175		n.d.						n.d.				
L. Jurassic	190		n.d.						n.d.				
U. Triassic	203		n.d.						n.d.				
M. Triassic	245		n.d.						n.d.				
Erosion	245		-300						-200				
L. Triasssic	251		300						200				
U. Permian	258		n.d.						n.d.				
L. Permian	299		n.d.						n.d.				
Erosion	326.4		-1450						-1400				
L. Carboniferous	359.2		200						200				
U. Devonian	385.3		800						700				
M. Devonian	397.5		100						100				
L. Devonian	416		-100						-100				
U. Silurian (Pridoli)	418.7	127	450		35	60	5	114.7	500	35	60	5	
U. Silurian (Ludlow)	421.3	994		10	65	20	5	310		10	65	20	5
L. Silurian (Wenlock)	428.2	1144			45	45	10	837			45	45	10
L. Silurian (Llandovery)	443.7	1276.5			30	70		979			30	70	
U. Ordovician (Ashgillian)	450	1337				50	50	1036				50	50
U. Ordovician (Caradocian)	460.9	1341				90	10	1048.5				90	10
M. Ordovician (Llanvirnian)	467	1337			15	45	40	1072			15	45	40
E. Ordovician (Arenigian)	478.6	1386.5			100			1087.5			100		
U. Cambrian–Tremadocian	501	1410		5		90	5	1112		5		90	5
M. Cambrian	513	1436.5		40	35	25		1125.5		40	35	25	
L. Cambrian	542	1666		50	40	10							
Ediacaran–L. Cambrian	590	1791.5		60	40								

Abbreviations as in Table 1

tions for hydrocarbon generation of 0.5% R_o as early as the Ludlow (Fig. 3). The eastern limit of the early stage of thermal maturity was reached in the Łeba Block in the time interval between the end of the Ludlow and the beginning of the Lochkovian (Fig. 4). The Middle Cambrian source rocks successively reached the main phase of the "oil window" (0.7 to 1.0% R_o) around the Pridoli–Lochkovian boundary, as observed in offshore boreholes of the Darłowo and Słupsk blocks, and on the onshore Łeba Block (Figs. 3 and 4). The offshore boreholes of the Łeba Block reached the main maturity phase in the Emsian (B6-1/82 borehole) or even Tournaisian (B4-2A/02 borehole) (Figs. 2 and 4). The late stage of thermal maturity in the "oil window" stage (1.0 to 1.3% R_o) was reached in a considerable part of the offshore area. In boreholes of the Darłowo and Słupsk blocks the source rocks reached this stage in the Early Devonian (Emsian – Łeba 8 borehole) to early Carboniferous interval (Tournaisian – A8-1/83 borehole) (Figs. 2 and 3). On the Łeba Block the source rock reached the late stage of thermal maturity only in part of the sections analysed. This phase was not reached by the Middle Cambrian in the offshore boreholes on the Łeba Block (B6-1/82 and B4-2A/02 boreholes; Figs. 2 and 4). At this stage maturity was

Parameters for burial history reconstruction in onshore part of the Łeba Block (western part of the Baltic region)

Stratigraphy	Age [Ma]	Łeba Block															
		Białogóra 3						Dębki 3						Żarnowiec IG 1					
		Top depth	Deposition/ Erosion	Generalized litology [%]				Top depth	Deposition/ Erosion	Generalized litology [%]				Top depth	Deposition/ Erosion	Generalized litology [%]			
			[m]	ss	sil	sh	carb		[m]	ss	sil	sh	carb		[m]	ss	sil	sh	carb
Sea water	0.1													-					
Quaternary	2.6	0		80	10	10		0		80	10	10		0		80	10	10	
Neogene	50		n.d.						n.d.						n.d.				
Paleogene	40													90					
Erosion	65.5		-300						-300						-300				
U. Cretaceous	99.6	53	300	60	40			97	300	60	40			111	300	60	40		
L. Cretaceous	145.5		n.d.						n.d.						n.d.				
U. Jurassic	161.2																		
M. Jurassic	175	139		35	65			162.5		35	65			165		35	65		
L. Jurassic	190		n.d.					205							n.d.				
U. Triassic	203													198		85	10	5	
M. Triassic	245	197					100								-100				
L. Triasssic	251	310		60	35	5		284.5		60	35	5		320		60	35	5	
U. Permian	258	555				5	95*	556.5				5	95*	574				5	95*
L. Permian	299	782.5		100					n.d.						n.d.				
Erosion	326.4		-1500						-1600						-2000				
L. Carboniferous	359.2		200						300						300				
U. Devonian	385.3		800						900						1000				
M. Devonian	397.5		200						200						200				
L. Devonian	416		n.d.						n.d.						n.d.				
U. Silurian (Pridoli)	418.7	784	300			90	10	792.5	200			90	10	829.2	500			90	10
U. Silurian (Ludlow)	421.3	1150			15	85		1950			15	85		1315			15	85	
L. Silurian (Wenlock)	428.2	2362				95	5	2415				95	5	2420				95	5
L. Silurian (Llandovery)	443.7	2541				90	10	2542				90	10	2582				90	10
U. Ordovician (Ashgillian)	450	2605			20	45	35	2605			20	45	35	2645			20	45	35
U. Ordovician (Caradocian)	460.9	2617.5				95	5	2613.5				95	5	2655.3				95	5
M. Ordovician (Llanvirnian)	467	2652.5			30		70	2648			30		70	2687.5			30		70
E. Ordovician (Arenigian)	478.6	2660		5	15	55	25	2659.5		5	15	55	25	2697		5	15	55	25
E. Ordovician (Tremadocian)	488.3		n.d.						n.d.						n.d.				
U. Cambrian	501	2680		15	5	40	40	2677.5		15	5	40	40	2721.8		15	5	40	40
M. Cambrian	513	2694		40	30	30		2689.5		40	30	30		2731.4		40	30	30	
L. Cambrian	542													3005		70	20	10	
Ediacaran–L. Cambrian	590													3201.1		70	20	10	

Abbreviations as in Table 1

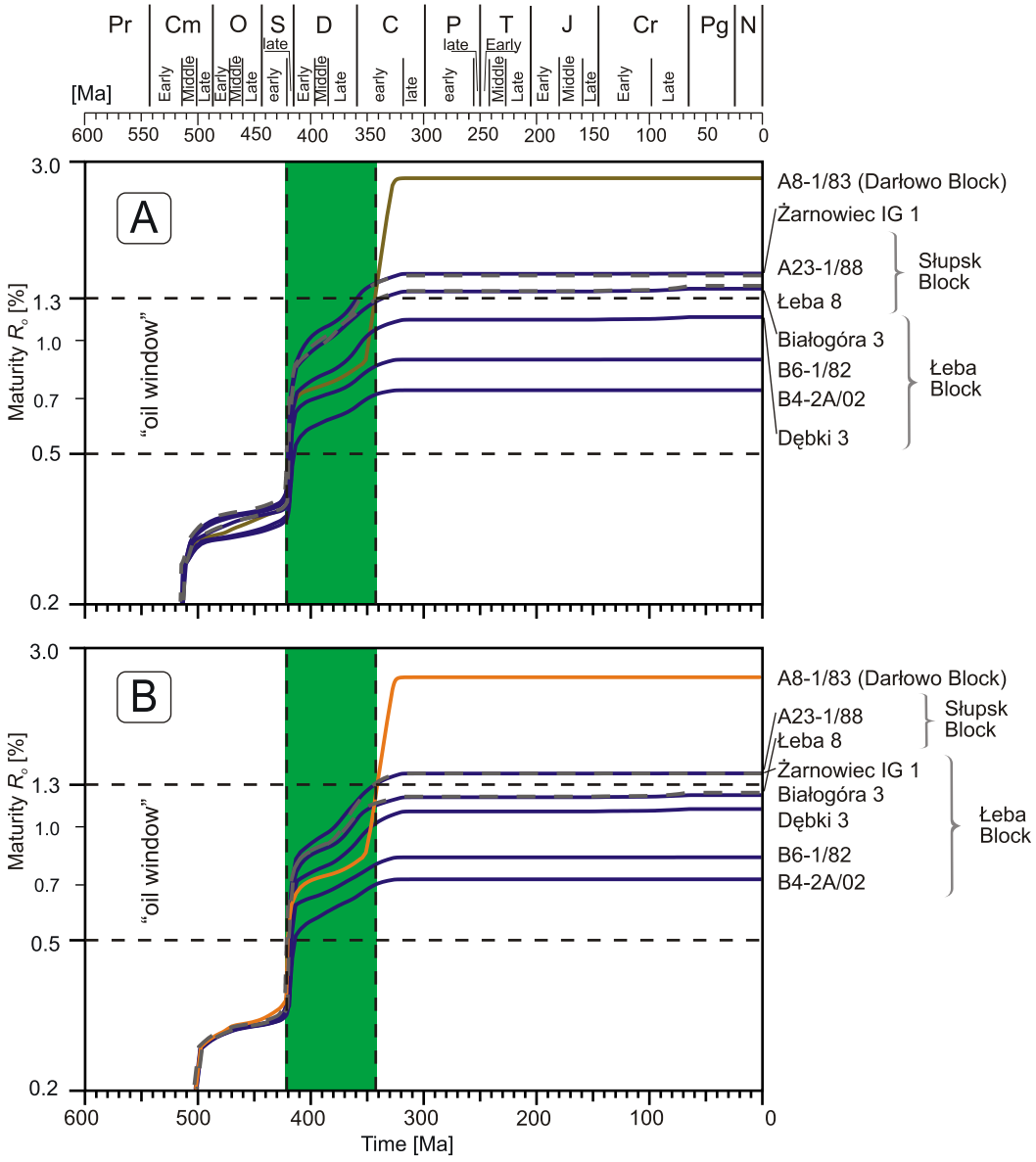

Fig. 2. Maturity evolution curves for: A – Middle Cambrian and B – Upper Cambrian–Lower Ordovician (Tremadocian) source rocks of lower Paleozoic strata in profiles of the boreholes analysed

Pr – Precambrian, Cm – Cambrian, O – Ordovician, S – Silurian, D – Devonian, C – Carboniferous, P – Permian, T – Triassic, J – Jurassic, Cr – Cretaceous, Pg – Paleogene, N – Neogene

reached in a broad depth interval from *ca*. 2500 m (A23-1/88 borehole) to more than 3500 m (Dębki 3 borehole). Source rocks in boreholes on the Darłowo and Słupsk blocks (A8-1/83 and A23-1/88 boreholes) and some boreholes on the Łeba Block (Białogóra 3 and Żarnowiec IG 1 boreholes) reached the maturity stage of the "gas window" (1.3 to 2.6% R_o) during the Tournaisian and Visean, at a depth of burial of 3000–4000 m (Figs. 2–4).

The Upper Cambrian–Tremadocian (in onshore sections only the Upper Cambrian) source rocks reached the early stage of thermal maturity in the same stratigraphic interval as did the Middle Cambrian source rocks, i.e. around the Silurian–Devonian boundary (Fig. 2). This is a result of a significant rate of deposition of the Silurian strata and relatively small thickness of the Middle and Upper Cambrian strata. The main and late stages of the "oil window" were reached during a similar burial time (Figs. 2–4). One of the exceptions is the A23-1/88 borehole, where the late stage of the "oil window" of the Middle Cambrian source rocks developed at the beginning of the Frasnian, and for the Upper Cambrian ones during the Famennian (Fig. 2). Also in B6-1/82, the Łeba 8 and Żarnowiec IG 1 boreholes, the Upper Cambrian source rocks entered the stage *ca*. 15–25 m.y. later compared to the Middle Cambrian rocks (Figs. 2–4). Apart from offshore A8-1/83

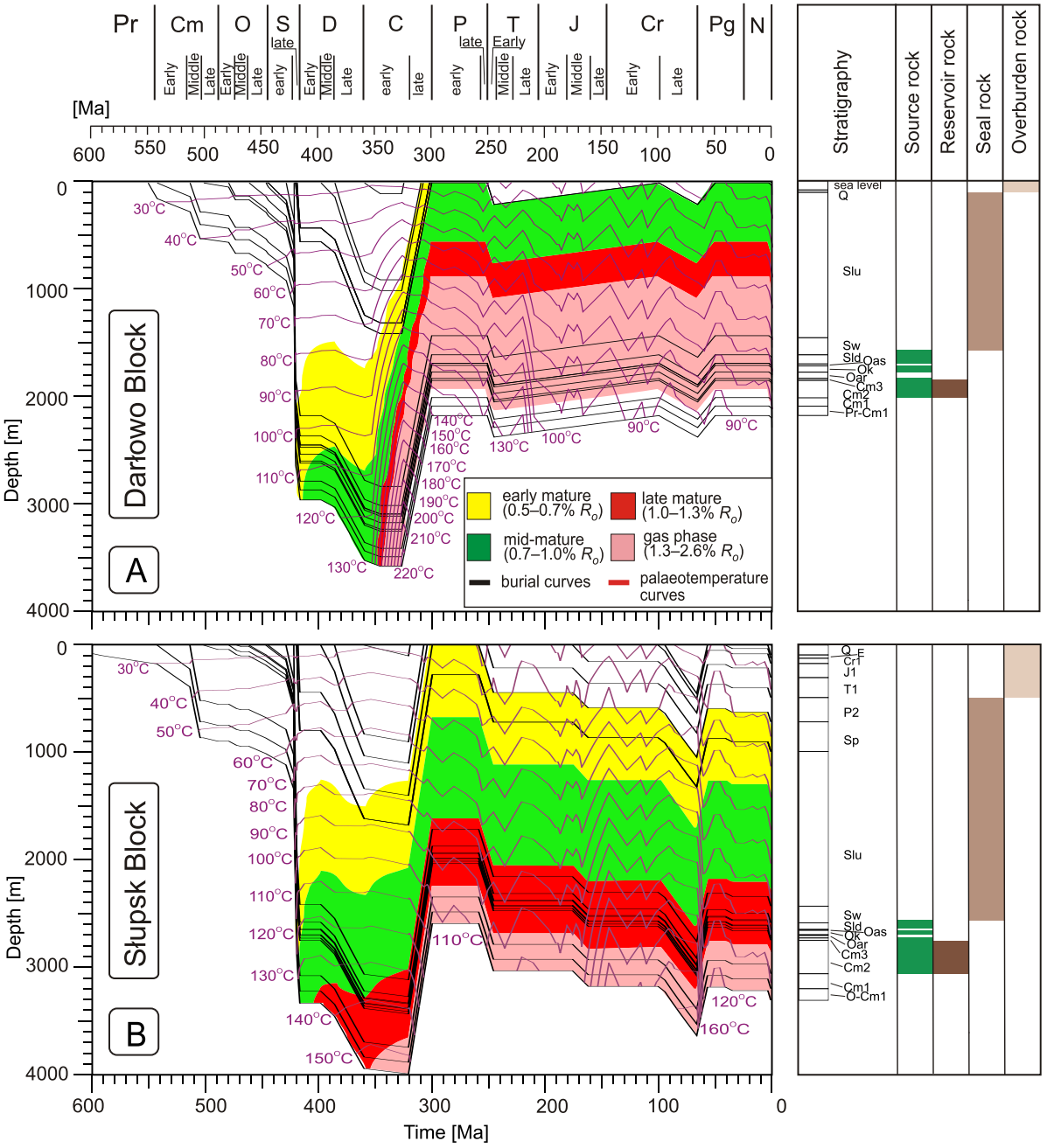

Fig. 3. Burial history curves for selected lithostratigraphic successions with thermal maturity zones in: A – borehole A8-1/83 on the Darłowo Block and B – the Łeba 8 borehole on the Słupsk Block

Cm1 – Lower Cambrian, Cm2 – Middle Cambrian, Cm3 – upper Cambrian, Oar – Ordovician (Arenigian), Ok – Ordovician (Caradocian), Oas – Ordovician (Ashgillian), Sp – Silurian (Pridoli), Slu – Silurian (Ludlow), Sw – Silurian (Wenlock), Sld – Silurian (Llandovery), P2 – upper Permian, T1 – Lower Triassic, J1 – Lower Jurassic, Cr1 – Lower Cretaceous, E – Eocene, Q – Quaternary; other abbreviations as in Figure 2

borehole and onshore Żarnowiec IG 1 borehole, the Upper Cambrian–Tremadocian source rocks did not reach the "gas window" stage (Fig. 4). Post-Westphalian erosion interrupted the burial process, and subsequent limited Mesozoic burial did not allow increase of kerogen maturity of the lower Paleozoic strata (Figs. 2–4).

The thermal maturity history of the Caradocian and lower Silurian source rocks was similar to that of the Cambrian and Lower Ordovician source rocks (Fig. 5). The observed few million years delay in time in entering individual maturation zones is a result of different position in the section. In the Łeba 8 and Żarnowiec IG 1 boreholes only, this delay of dozens million of years is referred to higher stages of kerogen transformation (Figs. 3 and 4).

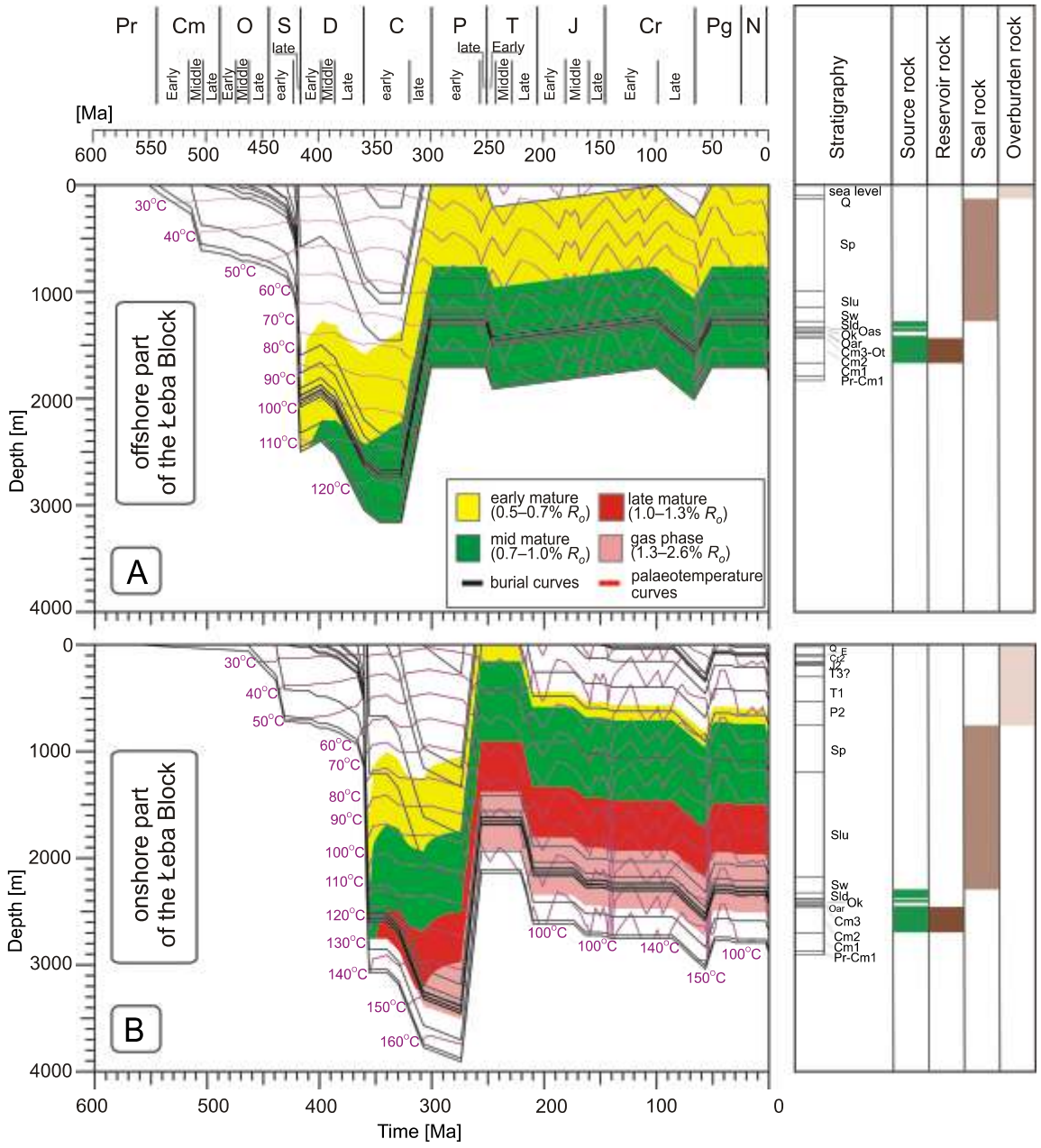

Fig. 4. Burial history curves for selected lithostratigraphic successions with thermal maturity zones in A – borehole B6-1/82 on the offshore part and B – the Żarnowiec IG 1 borehole on the onshore part of the Łeba Block

Ot – Ordovician (Tremadocian), T3 – Upper Triassic, J2 – Middle Jurassic, Cr2 – Upper Cretaceous; other abbreviations as in Figures 2 and 3

MODELLING OF HYDROCARBON GENERATION

Modelling of hydrocarbon generation from the Middle Cambrian source rocks revealed that they reached the entire generation range from the early to the late stage. In the Darłowo Block, in borehole A8-1/83, the Middle Cambrian source rocks reached the early phase (10–25% of generation potential) during the Famennian, at a burial depth below 3100 m and at temperatures above 120°C (Figs. 6 and 7). The main phase (25–65% of generation potential) was reached at the beginning of the Tournaisian, and the final phase (65–90% of generation potential) at its end (Fig. 6). The Middle Cambrian levels on the Darłowo Block, in the zone of borehole A8-1/83 depleted its generation potential around the Tournaisian–Visean boundary reaching 10% of transformation (Fig. 6). On the Słupsk Block (A23-1/88 and Łeba 8 boreholes) the source rocks reached the early stage of maturity at the beginning of the Devonian at a burial depth of 2400–3100 m and temperatures over 120°C

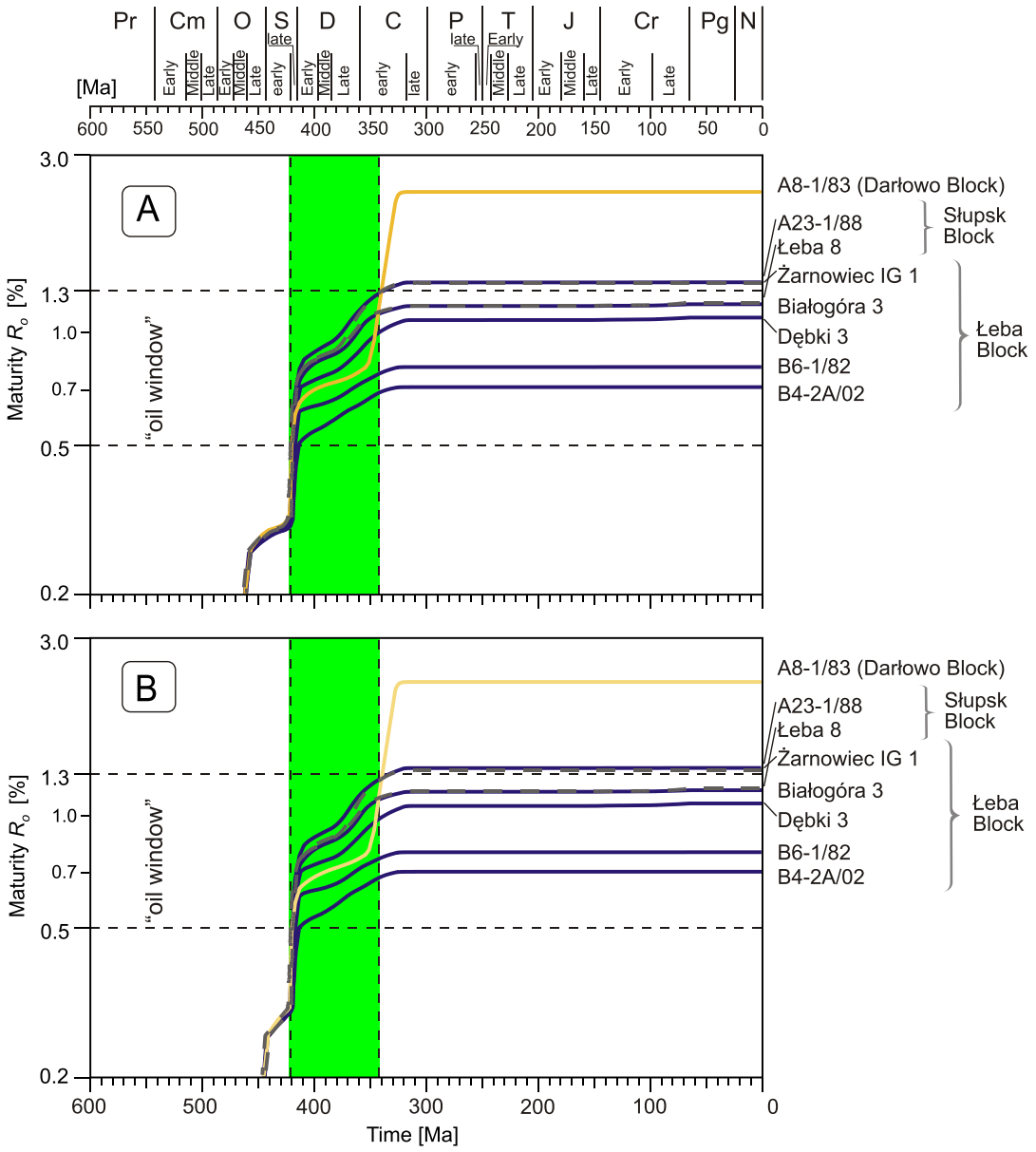

Fig. 5. Maturity evolution curves for: A – Upper Ordovician (Caradocian) and B – lower Silurian (Llandovery/Wenlock) source rocks of lower Paleozoic strata in profiles of the boreholes analysed

Abbreviations as in Figure 2

(Figs. 6 and 8). The main and late stages were reached during the Pragian, at a depth interval of 2400–3100 m and temperatures over 140°C, exhausting their generation potential around the Devonian–Carboniferous boundary (Fig. 7). On the Łeba Block the development of generation stages varied considerably in kinetic modelling. In the model assumed (Więcław *et al.*, 2010*b*), for the offshore part of the Łeba Block, the Middle Cambrian source rocks reached the initial stage of hydrocarbon generation, or even entered the main stage, in the case of borehole B6-1/82, during the Tournaisian and Visean (Figs. 6 and 8). In the onshore part the source rocks reached the entire generation potential from the early to the main stage, and locally even the late stage. In that area, in the Białogóra 3 and Dębki 3 boreholes, the early stage was reached in the Lochkovian and Eifelian at temperatures over 120°C and burial depths of *ca*. 2700 and 3000 m, respectively. The main stage of hydrocarbon generation took place in the Pragian and Famennian, and the late stage in the Eifelian and Tournaisian (Fig. 6). The degree of kerogen transformation obtained during kinetic transformations was complete in both boreholes. As far as kinetic transformations go, a slightly different history of hydrocarbon generation was observed in the Żarnowiec IG 1 borehole. This was a result of considerably higher degree of kerogen transformation in the Middle Cambrian strata compared to that in the Białogóra 3 and Dębki 3 boreholes. In the Żarnowiec IG 1 borehole the early stage was reached at the be-

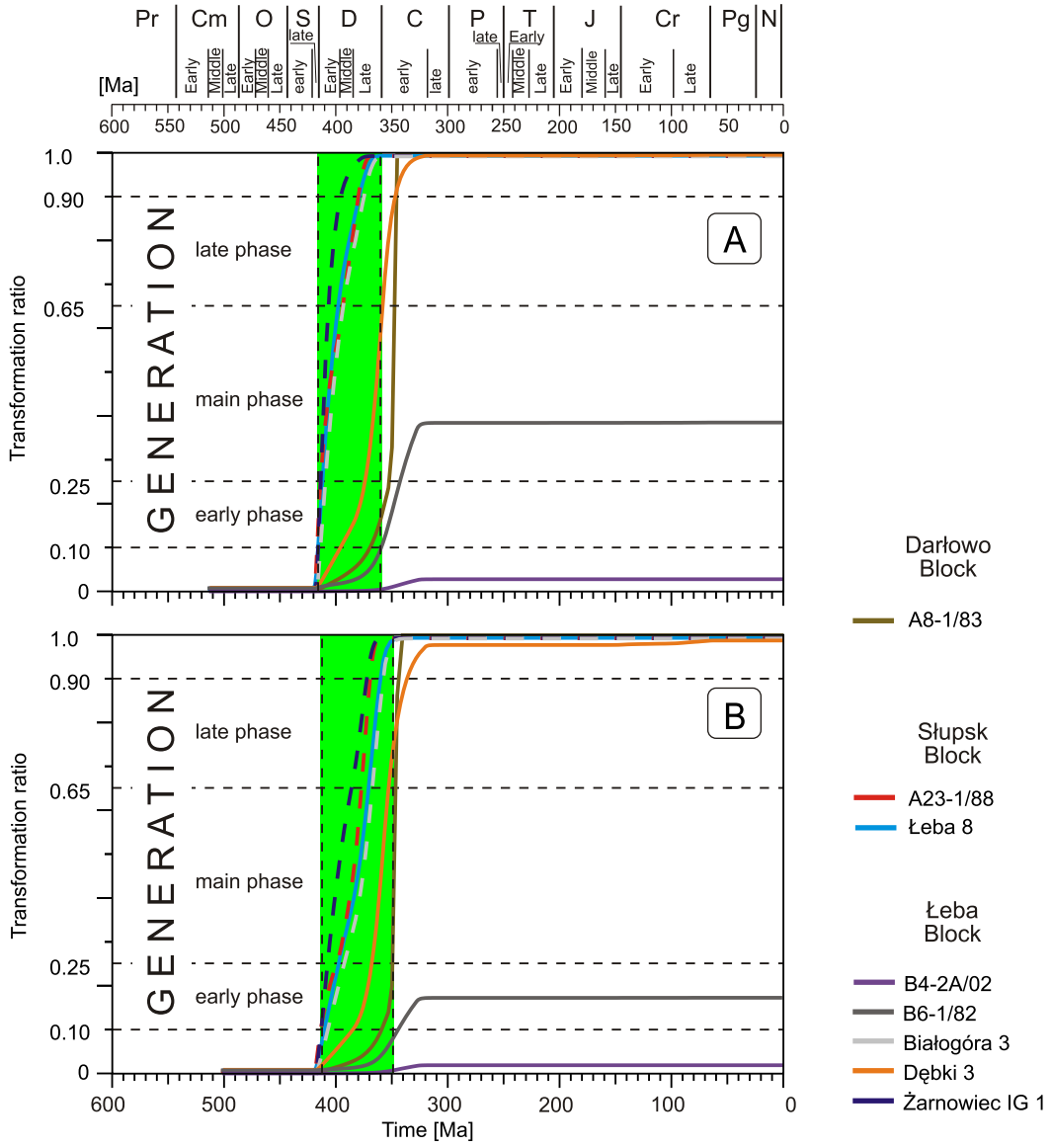

Fig. 6. Transformation ratio of kerogen in: A – Middle Cambrian and B – Upper Cambrian–Lower Ordovician (Tremadocian) source rocks of lower Paleozoic strata in profiles of the boreholes analysed

Abbreviations as in Figure 2

ginning of the Lochkovian below 3200 m and at temperatures over 130°C (Fig. 8). The main stage was reached around the Lochkovian–Pragian boundary, and the late stage in the Pragian. Kinetic transformations resulted in complete transformation of the Middle Cambrian kerogen in the Żarnowiec IG 1 borehole (Fig. 6).

Successive generation stages of the Upper Cambrian–Tremadocian source rocks were obtained in similar time-depth intervals to those in the Middle Cambrian (Fig. 6). The source rocks on the Darłowo Block reached the early stage of hydrocarbon generation around the Devonian–Carboniferous boundary and became completely depleted of its generation potential by the end of the Tournaisian (Figs. 6 and 7). The Upper Cambrian–Tremadocian source rocks on the Słupsk Block reached the early stage in the Pragian and the main stage in the Emsian (Figs. 6 and 7). The late stage of hydrocarbon generation was reached on this tectonic block within a broad time interval of the Late Devonian (Fig. 6). On the offshore part of the Łeba Block in B6-1/82 borehole the generation reached only the early phase in the Lochkovian at a depth of 2750 m and at temperatures over 120°C (Fig. 8). On the onshore area of the Łeba Block the early stage of hydrocarbon generation was entered by the Upper Cambrian source rocks in the Żarnowiec IG 1 borehole during the Lochkovian, in the Białogóra 3 borehole in the Emsian and in the Dębki 3 borehole in the Frasnian (Figs. 6 and 8). In the Żarnowiec IG 1 borehole the main generation stage was reached in the Emsian, and the late stage in the Frasnian at depths of

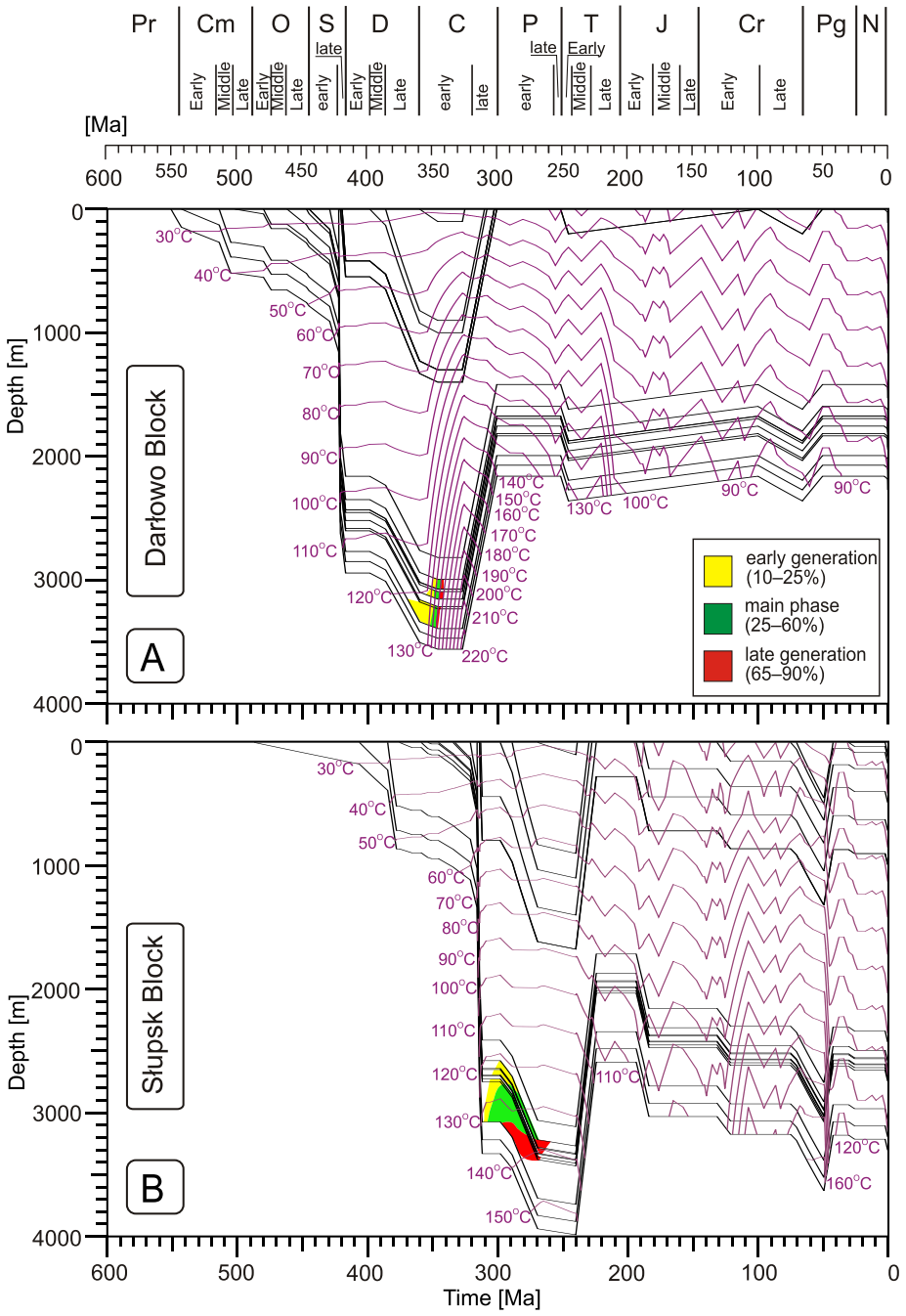

Fig. 7. Burial history curves for lower Paleozoic source rocks with generation stages in: A – borehole A8-1/83 on the Darłowo Block and B – the Łeba 8 boreholes on the Słupsk Block

Abbreviations as in Figure 2

2900–3500 m and temperatures of 130–140°C (Fig. 8). In the Dębki 3 and Białogóra 3 boreholes the main stage was initiated in the Eifelian, and continued throughout the Famennian. At the beginning of the Tournaisian the source rocks entered the late stage, which was reached in the depth interval of 3100–3400 m and a temperature of 130°C. In all the boreholes analysed, i.e. the Żarnowiec IG 1, Białogóra 3 and Dębki 3 boreholes, kerogen transformation was completed in the early Carboniferous (Fig. 6).

The other Caradocian and lower Silurian (Llandovery) source levels determined entered stages of hydrocarbon generation at a similar time, and the degree of kerogen transformation was as for the Upper Cambrian–Tremadocian source rocks (Figs. 7–9).

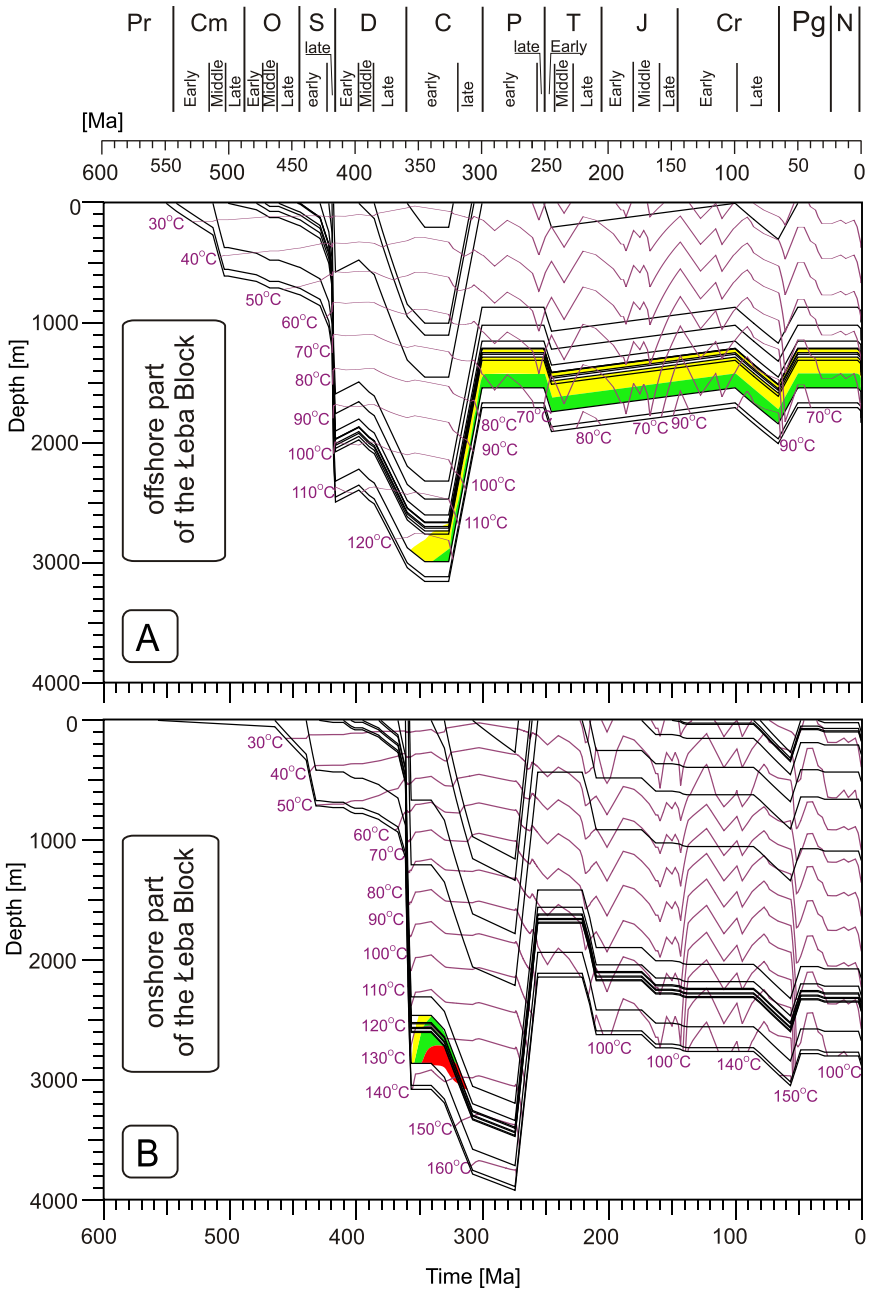

Fig. 8. Burial history curves for lower Paleozoic source rocks with generation stage in: A – borehole B6-1/82 on the offshore part and B – the Żarnowiec IG 1 borehole on the onshore part of the Łeba Block

Abbreviations as in Figures 2 and 7

AMOUNT OF HYDROCARBON GENERATION AND EXPULSION

1-D modelling allowed calculation of the amount of hydrocarbon generation and expulsion potential from the lower Paleozoic source rocks. The differences in the degree of transformation of kerogen observed in kinetic studies between individual tectonic blocks in the western part of the Baltic region also impacted on the generated hydrocarbon masses.

On the Darłowo and Słupsk blocks where the transformation ratio of kerogen was the highest, the generation potential varies considerably. From the Middle Cambrian, Caradocian and lower Silurian source rocks, only a small amount of hydrocarbons have been generated, usually below 10×10^{-3} m^3 HC/m^3 s.r. (source rock). In the Łeba 8 borehole only approximately 25×10^{-3} m^3

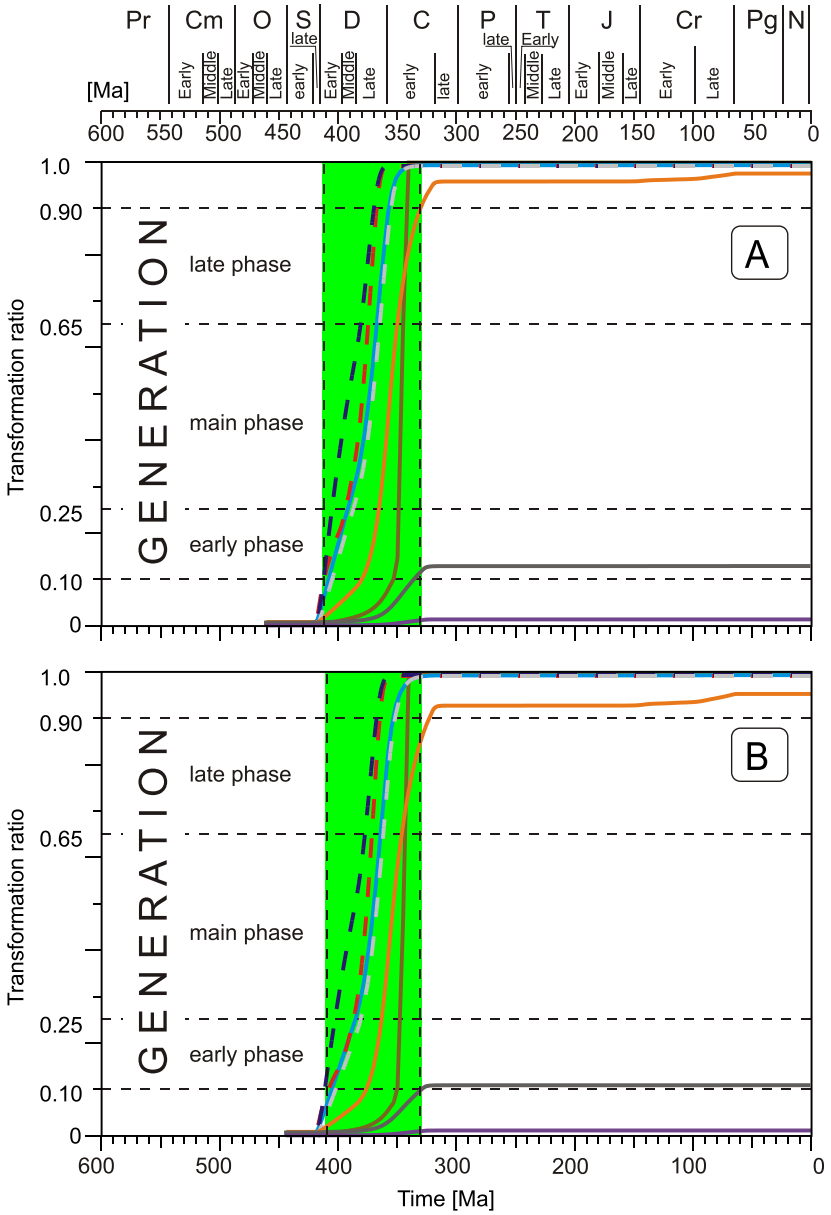

Fig. 9. Transformation ratio of kerogen in: A – Upper Ordovician (Caradocian) and B – lower Silurian (Llandovery/Wenlock) source rocks in lower Paleozoic strata in profiles of the boreholes analysed

For abbreviations see Figure 2

HC/m^3 s.r. was generated from the Caradocian deposits (Fig. 10). The Upper Cambrian–Tremadocian source rocks have generated considerably more hydrocarbons, up to 130×10^{-3} m^3 HC/m^3 s.r. (A23-1/88 borehole).

Some quantity of hydrocarbons has been expelled. On the Darłowo Block the transformation ratio of kerogen and the mass of generated hydrocarbons enabled expulsion of hydrocarbons solely from the Upper Cambrian–Tremadocian source rocks. The quantity of expelled hydrocarbons was approximately 105×10^{-3} m^3 HC/m^3 s.r., i.e. about 90% of the mass of generated hydrocarbons.

On the Słupsk Block the amount of expelled hydrocarbons from the the Upper Cambrian–Tremadocian source rocks was from 100 to about 120×10^{-3} m^3 HC/m^3 s.r. Locally, the hydrocarbons generated from the Caradocian source rocks have also been expelled in quantities of *ca.* 50% of generated hydrocarbons (Fig. 10).

On the Łeba Block there are considerable differences between the offshore and onshore areas. In the B4-2A/02 and B6-1/82 boreholes the mass of hydrocarbons generated from the lower Paleozoic source rocks was insignificant. In the Up-

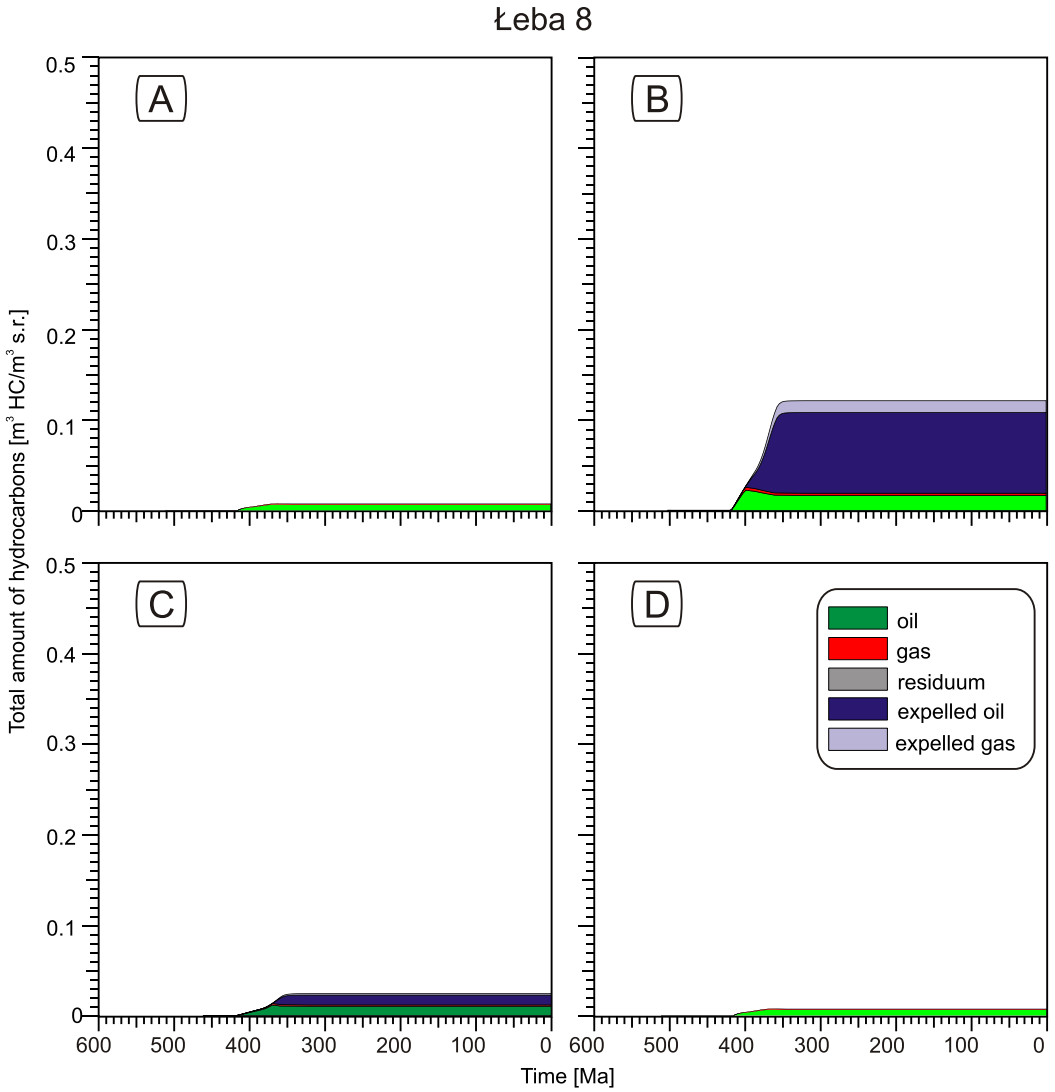

Fig. 10. Total amount of hydrocarbons generated in the profile of the Łeba 8 borehole from lower Paleozoic source rocks: A – Middle Cambrian, B – Upper Cambrian–Lower Ordovician (Tremadocian), C – Upper Ordovician (Caradocian), D – Silurian (Landovery)

s.r. – source rock

per Cambrian–Tremadocian source levels in borehole B6-1/82 this comprised only *ca.* 35×10^{-3} m^3 HC/m^3 s.r.

In the onshore area the amount of generation potential of the Middle Cambrian strata varied from approximately 5×10^{-3} to *ca.* 12×10^{-3} m^3 HC/m^3 s.r., in the Upper Cambrian from 96 $\times 10^{-3}$ to *ca.* 120 $\times 10^{-3}$ m^3 HC/m^3 s.r., in the Ordovician (Caradocian) from about 13×10^{-3} to *ca.* 35×10^{-3} m^3 HC/m^3 s.r., and in the Silurian (Llandovery–Wenlock) 10–12 $\times 10^{-3}$ m^3 HC/m^3 s.r.

On the offshore part of the Łeba Block the transformation of kerogen enabled the process of expulsion only in part of the area. The quantity of hydrocarbons expelled from the Upper Cambrian–Tremadocian source rocks was approximately 20 $\times 10^{-3}$ m^3 HC/m^3 s.r., i.e. about 50% of the mass of the hydrocarbons generated. On the onshore part of the Łeba Block the amount of expulsion from the Upper Cambrian was from 80 $\times 10^{-3}$ to about 100×10^{-3} m^3 HC/m^3 s.r. Locally hydrocarbon expulsion is observed also from the Caradocian source rocks.

CONCLUSIONS

Analysis of the lower Paleozoic successions in the western part of the Baltic region revealed that the threshold criteria of the generation process – 0.5% R_o, was higher and the generation process in the "oil window" started at over 0.8% R_o of kerogen maturity and lasted to *ca* 1.1% R_o.

The kinetic modelling revealed that:

– The Middle Cambrian source rocks reached the complete generation interval from the early to the late stage. The early stage was reached by the source rocks from the beginning of

the Devonian to the beginning of the Carboniferous. On the Darłowo and Słupsk blocks the source rocks reached the generation interval in the Devonian. The main and final generation stages were reached on the Darłowo Block during the Tournaisian and on the Słupsk Block during the Pragian. In both blocks, the Middle Cambrian source levels reached a complete level of transformation. On the Łeba Block there were lateral changes in development of the generation stages. On the offshore part of the Łeba Block the Middle Cambrian source rocks reached the initial stage of hydrocarbon generation or even entered the main stage in borehole B6-1/82, from the Tournaisian to the Visean. On the onshore part the source horizons reached the entire generation potential from the early to the main stage, locally even the late stage. The early stage was reached at the beginning of the Devonian, in the Lochkovian and Eifelian. The main stage of hydrocarbon generation was during the Pragian and Famennian. Locally, from the Eifelian to the Tournaisian the main stage of hydrocarbon generation was also initiated.

– In the case of the Upper Cambrian–Tremadocian source rocks, the specific generation stages were reached in similar time-depth intervals as for the Middle Cambrian ones. On the Darłowo Block the source rocks reached the early stage of hydrocarbon generation around the Devonian–Carboniferous boundary, totally depleting its generation potential by the end of the Tournaisian. On the Słupsk Block the Upper Cambrian and Tremadocian source rocks reached the early generation stage during Pragian, and the main stage during the Emsian. The late stage of hydrocarbon generation in that tectonic block was reached during the Famennian. On the Łeba Block the Upper Cambrian source rocks reached the early stage of hydrocarbon generation in a broad time interval from the Lochkovian (the Żarnowiec IG 1 borehole), through the Eifelian (the Białogóra 3 borehole) to the Famennian (the Dębki 3 borehole). The main generation stage was also reached gradually from the Emsian to the beginning of the Tournaisian. The late stage of generation was initiated at the beginning of the Famennian and lasted to the end of the Visean. On the onshore Łeba Block the level of kerogen transformation obtained was complete and reached in the early Carboniferous. On the offshore part of this block kerogen transformation is much lower, not exceeding 25%.

– In the Caradocian and Llandovery source rocks, the observed time of entering specific stages of hydrocarbon generation and the level of kerogen transformation were similar to those of the Upper Cambrian–Tremadocian source rocks. The entire process of hydrocarbon generation in given temperature conditions lasted from the Pragian to the beginning of the late Carboniferous.

Acknowledgments. The research was undertaken as part of a project of the Ministry of the Environment (No. 182/2005/Wn-06/FG-sm-tx/D). The authors thank A. Shogenova from the Tallinn and S. Golonka from the AGH University of the Science and Technology in Kraków, for very constructive remarks and comments that greatly improved of the original manuscript.

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