Geological Quarterly, 1999, 43 (3): 297–312

# Origin and thermal maturity of the organic matter in the Lower Palaeozoic rocks of the Pomeranian Caledonides and their foreland (northern Poland)

Izabella GROTEK

Grotek I. (1999) — Origin and thermal maturity of the organic matter in the Lower Palaeozoic rocks of the Pomeranian Caledonides and their foreland (northern Poland). Geol. Quart., 43 (3): 297–312. Warszawa.

The clayey-muddy complex of the Ordovician and Silurian age in the Pomeranian Caledonides belt as well as the Cambrian, Ordovician and Silurian rocks at its foreland (the East European Craton) contain the same genetical type of the organic matter dominated by the syngenetic sapropelic material (oil-prone). The intensity and character of the thermal alterations in both stable organic matter mobile components show distinct analogies despite the different tectonic involvement of both regions. The reflectivity index of the vitrinite-like minerals shows an increase with a burial depth of the successive members of the Lower Palaeozoic. The local increase in thermal alteration of the organic matter is related to the zones of the increased tectonic activity. Assuming that the maximum burial depth of the studied sediments corresponds to their present depth, it can be concluded that the thermal palaeogradient for the Early Palaeozoic in the Pomeranian region was higher than the present-day one. The range of maximum palaeotemperatures which influenced the Lower Palaeozoic complex is very wide ranging from about 70 to 200°C in the Caledonian zone. The analysed deposits do not show a good quality as potential source rocks for hydrocarbon generation. Their low generation potential is probably caused by an earlier generation of a part of hydrocarbons.

*Izabella Grotek, Polish Geological Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland* *(received: October 8, 1998; accepted: January 21, 1999).*

Key words: Pomeranian Caledonides, Lower Palaeozoic, thermal maturity, organic matter, vitrinite reflectivity, hydrocarbons.

## INTRODUCTION

The aim of the present study is the determination of possible variability of both an origin and a level of thermal alterations of the organic matter present in the Lower Palaeozoic deposits in the area to a different degree affected by tectonic activity — the zone of the Pomeranian Caledonides and their foreland in the East European Craton (EEC).

Results of the petrological studies together with the data from the basic geochemical analyses of the dispersed organic matter from the Lower Palaeozoic deposits from twelve boreholes are here presented. The study area is located in northern Poland and situated south-west and north-east from the Teisseyre-Tornquist tectonic zone.

Southwestern part of this area corresponds to the Pomeranian segment of the folded Caledonian belt (comp. R. Dadlez *et al.*, 1994). The northeastern area, located within the East European Craton, represents the foreland of that belt. The present study refers to two lower-order units of the East European Craton: western and central part of the Peribaltic Syneclise as well as the Łeba Elevation (Fig. 1).

Owing to the conducted analyses it was possible to evaluate the genetic type of the primary organic matter by means of determination of the qualitative and quantitative composition of both stable organic matter and mobile compounds as well as by evaluation of a degree of their thermal maturity.

The reflectivity index $R_o$ of some syngenetic organic compounds represents the main parameter for a determination of a thermal maturity of an organic matter. It plays a significant role in a reconstruction of a thermal history of sediment packages and determination of petroleum source rocks (P. Robert, 1985; E. Stach *et al.*, 1982; M. Teichmüller, 1986). Vitrinite is the main component which records thermal effects. However, in the Lower Palaeozoic deposits it either occurs in traces or is totally absent. In such cases the solid bitumen (H. Jacob, 1985) plays the role of the "palaeothermometer" together with the vitrinite-like macerals which

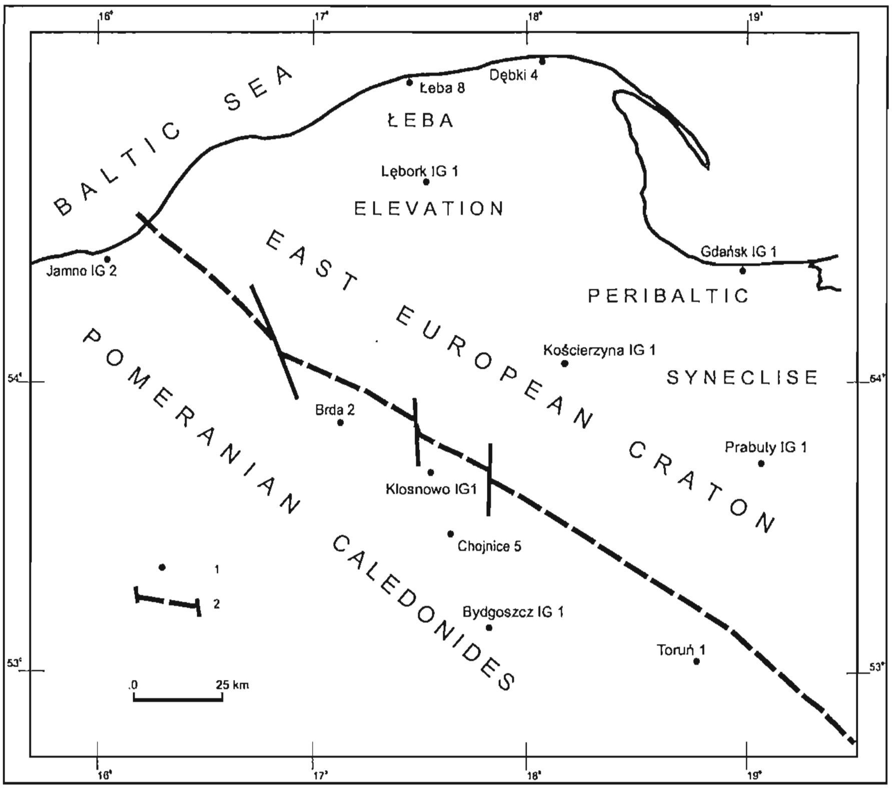



Fig. 1. Location map of the study area

1 — boreholes studied; 2 — Teisseyre-Tornquist tectonic zone (after W. Pożaryski, 1987)

display optical features similar to vitrinite (B. Buchardt, M. D. Lewan, 1990).

The vitrinite-like macerals studied in the present paper are mostly represented by differently coalified graptolite remains. With the increase in a degree of alteration, their optical features change similarly to those of vitrinite and solid bitumen (L. M. Link *et al.*, 1990).

The present study was conducted within the framework of the KBN research grant no. 9T 12 B 02611.

## METHODS

The microscopic studies were conducted on polished samples of clastic rocks (mudstones and claystones, sporadically sandstones) in both white and blue (395–440 nm) light using the *Zeiss Polarisation Axioskop Microscope.*

In the descriptions of petrological components of a dispersed organic matter the nomenclature and classification adopted in 1971 by the International Committee on Coal Petrology (ICCP) was used. Measurements of reflectivity were done according to the Polish Standards (PN-79/G-04525) in a monochromatic light (wave length of 546 nm) using a diaphragm with a diameter 0.16 mm. The optical glass standards with the reflectivity of 1.413 and 1.66%, respectively, were used for comparisons.

The results of the microscopic analyses conducted by the author in the Polish Caledonides area within the research grant no. 9T 12 B 02611 were used in the present paper together with the archival data from the area of the East European Craton (I. Grotek, E. Klimuszko, 1994, 1998). The data from E. Swadowska's studies of the Cambrian and Ordovician deposits from the EEC were also taken into account (M. Nehring-Lefeld *et al.*, 1997; E. Swadowska, M. Sikorska, 1977).

Geochemical analyses were performed in the years 1996–1998 in the Central Laboratory of the Polish Geological Institute. They were done on the disintegrated rock material using the method of the coulometric titration in the Strohleim's apparatus. The percentage of the total organic carbon (TOC) was determined. Bitumen extraction was performed using Soxlet's apparatus with chloroform as the organic solvent. IR absorption studies were performed on the bitumen extracts in order to determine the degree of a bitumen alteration (B. Gondek, 1980). Analyses were conducted in the frequency range 700 to 3600 $cm^{-1}$ using prisms of Kbr, NaCl and LiF.

Fractionation of bitumens after extraction was performed by a columnar chromatography method. Using glass columns filled with absorbents such as $SiO_2$ and $Al_2O_3$ and applying

Table 1

**Microscopical analysis of organic matter from Pomeranian Caledonides area**

| Wells | Depth [m] | Age | Lithology | Contents of organic matter [%] | | | | | $R_o$ [%] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | vitrinite-like | inertinite | liptinite | sapropelic matrix | solid bitumen | |
| Brda 2 | 2944.3 | $O_2$ | claystone | 10 | – | 5 | 45 | 40 | 0.91 |
| | 2727.9 | | siltstone | 30 | – | 5 | 30 | 35 | 0.86 |
| | 2602.8 | | claystone | 20 | – | 10 | 40 | 30 | 0.84 |
| Chojnice 5 | 5008.2 | $O_3$ | claystone | 10 | 5 | – | 50 | 35 | 1.80 |
| | 4897.3 | $O_2$ | claystone | 10 | – | – | 50 | 40 | 1.78 |
| | 4704.2 | $O_2$ | siltstone | 20 | – | – | 50 | 30 | 1.72 |
| Jamno IG 2 | 2600.0 | $O_3$ | shale | 10 | – | 10 | 50 | 30 | 0.81 |
| | 2519.0 | | | 25 | – | 5 | 40 | 30 | 0.78 |
| | 2453.5 | | | 20 | – | 5 | 35 | 40 | 0.75 |
| | 2391.5 | | | 10 | – | 20 | 40 | 30 | 0.75 |
| | 2220.5 | | | 20 | – | 10 | 30 | 40 | 0.73 |
| Klosnowo IG 1 | 2456.0 | $S_2$ | claystone | 10 | – | 40 | 30 | 20 | 0.65 |
| | 2443.0 | | | 20 | 5 | 45 | 20 | 10 | 0.63 |
| Bydgoszcz IG 1 | 5611.5 | $S_3$ | shale | 30 | 5 | – | 40 | 25 | 2.70 |
| | 5606.0 | | | 20 | – | – | 50 | 30 | 2.73 |
| Toruń 1 | 5115.0 | $S_1$ | claystone | 30 | – | – | 45 | 25 | 2.10 |
| | 4721.3 | $S_3$ | | 25 | 5 | – | 40 | 30 | 1.92 |
| | 4457.8 | $S_3$ | | 30 | 5 | – | 30 | 35 | 1.79 |

adequate eluats. The fraction of the saturated hydrocarbons was obtained using hexane as the eluat, while the aromatic hydrocarbons were eluated with benzene.

The saturated hydrocarbons were further chromatographically analysed by means of a gas chromatography with a flame-ionisation detector — *Hewlett-Packard GG/FID-(589011)*.

## GEOLOGICAL SETTING

The studies were performed on the organic matter dispersed in the clayey-muddy and, sporadically, sandy deposits of the Cambrian, Ordovician and Silurian age from the western and central parts of the Peribaltic Syneclise and in the Łeba Elevation as well as of the Ordovician and Silurian rocks from the Koszalin–Chojnice–Toruń zone (the Pomeranian Caledonides).

The Peribaltic Syneclise represents a depression in the crystalline basement filled with the Palaeozoic epicontinental deposits including the Cambrian, Ordovician, Silurian and Permian. The sedimentary complex comprising from the Cambrian up to the Quaternary rests almost horizontally on the crystalline basement in the western part of the syneclise and in the Łeba Elevation. Its total thickness ranges from 3500 to over 5000 m in the studied area. In the western part of the syneclise the strongly tectonised Ordovician and Silurian deposits were reached at significant depths. These deformations can be interpreted either as overthrusts onto the EEC or as the expression of the tectonic activity in the dislocation zone labelled the Koszalin–Chojnice–Toruń zone (J. Znosko, 1965).

The analysed Lower and Middle Cambrian deposits represent a clastic shelf facies association with a predominance of sandstones intercalated with the claystones and mudstones. In the area of the EEC the Upper Cambrian deposits have been almost totally eroded. In the Ordovician and Silurian the sedimentation was dominated by the clayey lithofacies with graptolites. The distinct increase in its thickness is clearly visible south and south-east of the Łeba Elevation.

At the end of the Silurian the flysch sedimentation started in the investigated area of the Peribaltic Syneclise (K. Jaworowski, 1971). In the latest Silurian the Teisseyre-Tornquist Zone formed the eastern boundary of the intensive Caledonian deformations (J. Znosko, 1987). In the area situated south-west of that zone (Koszalin–Chojnice area) the Ordovician deposits (Llandeilo to Caradoc, other members not recognized) are developed as rather monotonous series, composed mostly of clayey shales and mudstones with sandy, dolomitic and sideritic intercalations. Sporadically there occur tuffitic packages (Brda 2) with thicknesses exceeding 5 m. The Silurian deposits are developed as graptolitic shales. The Upper Silurian deposits contain interlayers and intercalations of mudstones with a pyroclastic material.

It is impossible to constrain the thickness of the Lower Palaeozoic deposits in the Caledonides zone due to a fragmentary core sampling and strong tectonic involvement.

Table 2

**Microscopical analysis of organic matter from East European Craton area**

| Wells | Depth [m] | Age | Lithology | Contents of organic matter [%] | | | | | $R_o$ [m] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | vitrinite-like | inertinite | liptinite | sapropelic matrix | solid bitumen | |
| Gdańsk IG 1 | 3457.0 | $Cm_1$ | claystone | – | 5 | – | 70 | 25 | 1.50 |
| | 3353.3 | $Cm_1$ | claystone | 10 | – | 5 | 70 | 15 | 1.46 |
| | 3301.3 | $Cm_1$ | siltstone | 10 | – | – | 90 | – | 0.97 |
| | 3242.4 | $Cm_2$ | claystone | – | 5 | – | 80 | 15 | 1.53 |
| | 3189.0 | $Cm_2$ | claystone | – | 5 | – | 60 | 35 | 1.40 |
| | 3157.0 | $Cm_2$ | claystone | – | 10 | – | 70 | 20 | 1.23 |
| Dębki 4 | 2699.0 | $Cm_2$ | claystone | 20 | – | – | 60 | 20 | 1.15 |
| | 2668.0 | $Cm_3$ | | 10 | – | 15 | 40 | 35 | 1.12 |
| Łeba 8 | 2958.0 | $Cm_2$ | sandstone | 20 | – | – | 60 | 20 | 1.32 |
| | 2782.5 | $Cm_2$ | sandstone | 30 | – | – | 50 | 20 | 1.23 |
| | 2735.4 | $Cm_3$ | claystone | 20 | – | – | 50 | 30 | 1.22 |
| Kościerzyna IG 1 | 4751.2 | $Cm_1$ | claystone | – | – | – | 70 | 30 | 1.72 |
| | 4505.0 | $Cm_2$ | claystone | – | – | – | 85 | 15 | 1.70 |
| | 4426.0 | $Cm_2$ | siltstone | – | – | – | 75 | 25 | 1.68 |
| Prabuty IG 1 | 3591.4 | $Cm_2$ | claystone | 15 | – | – | 75 | 10 | 1.49 |
| | 3414.5 | | | 20 | – | – | 60 | 20 | 1.43 |
| Gdańsk IG 1 | 3120.0 | $O_1$ | siltstone | 5 | 10 | – | 65 | 20 | 1.30 |
| | 3099.2 | $O_3$ | claystone | 10 | – | 10 | 60 | 20 | 1.27 |
| Łeba 8 | 2708.0 | $O_2$ | claystone | 20 | – | 15 | 35 | 30 | 1.17 |
| Lębork IG 1 | 3268.5 | $O_3$ | siltstone | 20 | 10 | – | 40 | 30 | 2.30 |
| Gdańsk IG 1 | 3069.0 | $S_1$ | claystone | 20 | – | 10 | 50 | 20 | 1.18 |
| | 3042.0 | $S_2$ | claystone | 10 | 5 | 15 | 50 | 20 | 1.06 |
| | 2928.0 | $S_2$ | siltstone | 10 | – | 20 | 60 | 10 | 1.02 |
| | 2360.0 | $S_3$ | siltstone | 10 | – | 20 | 50 | 20 | 0.72 |
| Kościerzyna IG 1 | 4372.0 | $S_1$ | claystone | – | – | – | 70 | 30 | 1.83 |
| | 4301.0 | $S_2$ | claystone | 15 | – | – | 55 | 30 | 1.86 |
| | 4289.2 | $S_2$ | claystone | 20 | – | – | 60 | 20 | 1.83 |
| | 4237.5 | $S_2$ | claystone | 10 | – | – | 50 | 40 | 1.81 |
| | 2760.3 | $S_2$ | siltstone | 10 | – | – | 80 | 10 | 1.27 |
| | 2350.7 | $S_2$ | claystone | 10 | 10 | – | 60 | 20 | 1.04 |
| Lębork IG 1 | 3219.5 | $S_2$ | shale | 20 | – | – | 40 | 40 | 2.10 |
| | 3171.5 | | claystone | 30 | – | – | 40 | 30 | 1.89 |
| | 1975.0 | | shale | 40 | 10 | – | 30 | 20 | 0.88 |
| | 1092.0 | | claystone | 10 | – | 50 | 20 | 20 | 0.82 |
| Łeba 8 | 2496.0 | $S_2$ | claystone | 30 | – | 10 | 40 | 20 | 1.10 |
| | 2321.5 | $S_3$ | | 10 | 5 | 20 | 45 | 20 | 1.05 |
| | 1991.4 | $S_3$ | | – | – | 20 | 50 | 30 | 1.02 |
| | 1290.0 | $S_3$ | | 20 | 10 | 15 | 40 | 30 | 0.94 |
| | 754.0 | $S_3$ | | 20 | – | 10 | 40 | 30 | 0.93 |
| Prabuty IG 1 | 3337.0 | $S_1$ | claystone | 20 | – | – | 60 | 20 | 1.41 |
| | 3282.0 | $S_2$ | shale | 35 | 5 | – | 40 | 20 | 1.37 |
| | 3189.0 | $S_3$ | claystone | 30 | 10 | – | 30 | 20 | 1.35 |
| | 2527.0 | $S_3$ | claystone | 90 | – | – | 10 | – | 1.02 |

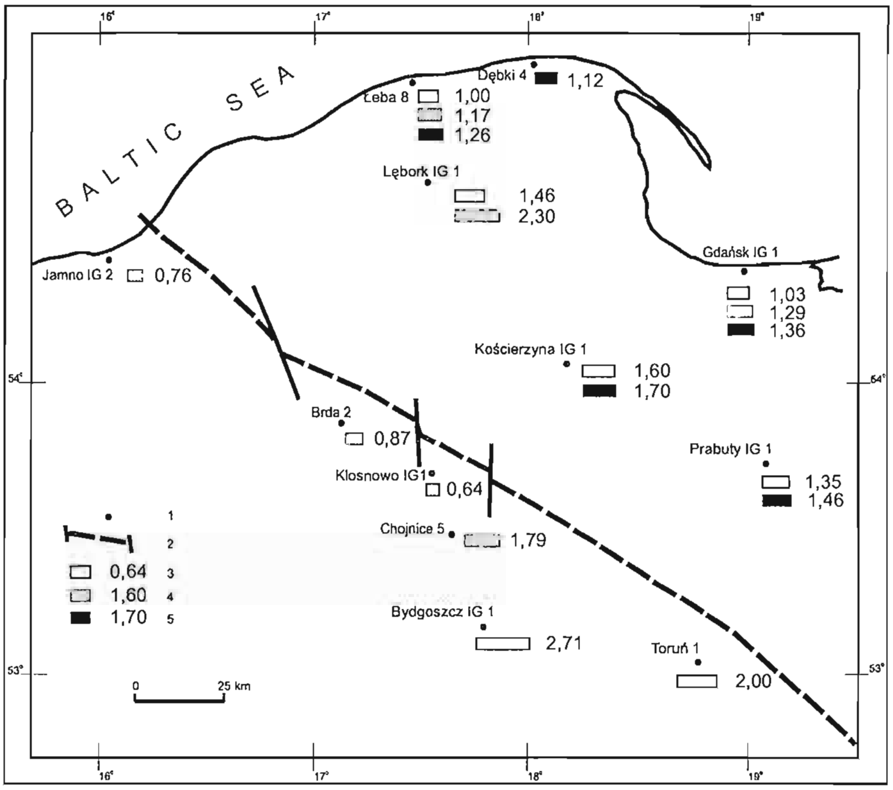



Fig. 2. Map of thermal maturity of the organic matter in the Lower Palaeozoic

1 — boreholes; 2 — Teisseyre-Tornquist tectonic zone (after W. Pożaryski, 1987); mean value of the reflectivity index of solid bitumen and vitrinite-like organic matter (% $R_o$): 3 — in Silurian deposits, 4 — in Ordovician deposits, 5 — in Cambrian deposits

## GENETIC CHARACTERISTICS OF ORGANIC MATTER AND BITUMENS

### CAMBRIAN

The Cambrian deposits in the Pomeranian region were drilled in the area of the East European Craton. Data shown in the present paper were obtained from analyses of these deposits in the following boreholes: Gdańsk IG 1, Kościerzyna IG 1 (Lower to Middle Cambrian), Dęblin, Łeba 8 (Middle to Upper Cambrian). The Cambrian claystones and mudstones in the central and western parts of the Peribaltic Syneclise contain rare and strongly dispersed organic matter and a low content of the total organic carbon (0.1–0.3%). The organic matter forms a sapropelic matrix with an insignificant admixture of the material displaying the optical features characteristic for vitrinite (Tab. 2).

The vitrinite-like macerals form single or double bands with the thickness of about 2–10 μm often disrupted. The character of their occurrence suggests their origin as the vitrinised organic remains, most probably of algae (Pl. I, Fig. 2).

The amorphous solid bitumen usually co-occurs with the sapropelic ground-mass. It displays a form of sloccullic aggregations, sometimes of delicate seams with the thickness of 1–5 μm (Pl. I, Fig. 1a). Locally (Gdańsk IG 1) it is accompanied by liptodetrinite which shows an intensive fluorescence ranging from yellow-orange to brownish (Pl. I, Fig. 1b).

The epigenetic bitumens are present in numerous Upper and Middle Cambrian samples. Their occurrence is mostly connected with the sandy intercalations where they form the mass saturating a matrix of quartz grains (Pl. I, Fig. 3).

The maturity of the extracted bitumens is variable (grade III–IV) pointing to a presence of several hydrocarbon generations (syn- and epigenetic ones).

The geochemical analyses of a relatively poor content of mobile compounds (0.001–0.15%) has confirmed the oil-prone sapropelic type of the organic matter. In the nearly whole Cambrian complex the predominance of saturated hydrocarbons over aromatic ones together with a high percentage of high molecular compounds can be observed (resins, asphaltenes; Tab. 4, Fig. 4).

### ORDOVICIAN

The Middle and Upper Ordovician deposits from the Pomeranian Caledonides (south-west of the Teisseyre-Torn-

Table 3

**Geochemical analysis of organic matter from Pomeranian Caledonides area**

| Wells | Depth intervals [m] | Age | Samples [n] | Bitumens [%] min–max (average) | TOC [%] min–max (average) | $nC_{max}$ | Hydrocarbons [%] | | Metamorphism degree of bitumens |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | saturated | aromatic | |
| Brda 2 | 2576.5–3000.0 | $O_2$ | 6 | 0.011–0.03 (0.017) | 0.2–0.6 (0.4) | 16–18 | 23–26 | 12–16 | III, II |
| Chojnice 5 | 4897.3–5050.5 | $O_2$ | 19 | 0.005–0.009 (0.007) | 0.2–0.3 (0.2) | 17–20 | 25–20 | 4–17 | III |
| Jamno IG 2 | 2110.5–2600.0 | $O_2$ | 9 | 0.04–0.2 (0.06) | 0.2–0.6 (0.35) | 17–23 | 33–61 | 4–16 | I, II, III |
| Klosnowo IG 1 | 2435.0–2498.0 | $S_2$ | 6 | 0.01–0.33 (0.13) | 0.1–2.0 (0.7) | 17 | 34–51 | 6–17 | III, II |
| Bydgoszcz IG 1 | 5600.0–5616.0 | $S_3$ | 4 | 0.001–0.008 (0.006) | 0.21–1.0 (0.3) | 17–21 | 6–11 | 8–12 | V |
| Toruń 1 | 4726.0–5049.6 | $S_3$ | 6 | 0.007–0.015 (0.01) | 0.27–0.5 (0.38) | 16–19 | 15–35 | 12–28 | IV, V |

quist Zone) are represented by mudstones, claystones and shales in the boreholes Brda 2, Chojnice 5 and Jamno IG 2.

These deposits are relatively poor in an organic matter (0.2–0.6% TOC; Tab. 1). The organic mineral association forms streaks and nested concentrations. In the rocks richer in organics it forms the sapropelic ground-mass with small grains (5–10 μm) and laminae of solid bitumen, clasts of liptodetrinite and macerals displaying optical features of vitrinite. The latter are often anisotropic (Pl. II, V). The vitrinite-like macerals form individual or double bands with a thickness 2–5 μm and alongated grains with a diameter 5–50 μm (Pl. II, Fig. 5). The rocks are sometimes enriched in liptinitic material which intensively fluoresces orange and yellow-orange (Pl. II, Fig. 6).

The geochemical analyses of bitumens extracted from the Ordovician deposits (concentrations 0.005–0.26%) have shown the predominance of saturated hydrocarbons over aromatic ones, the feature being strongest in the borehole Jamno IG 2. The distribution of n-alkanes is characterised by short chain molecules $nC_{17}$–$nC_{20}$, with a maximum $nC_{21}$–$nC_{23}$ in the borehole Jamno IG 2 (Tab. 3). Most of the analysed samples is characterised by a considerable proportion of the high molecular compounds (Fig. 5). The thermal alteration degree of the hydrocarbons is high with the most altered compounds (grade I) related to horizons with an increased bitumens content and, at the same time, a low concentration of the organic carbon. It suggests that these compounds are of epigenetic origin (B. P. Tissot, D. M. Welte, 1978). However, the majority of the extracted hydrocarbon compounds is syngenetic with the sediment.

In the area of the East European Craton the Lower to Upper Ordovician deposits in the boreholes Gdańsk IG 1, Kościerzyna IG 1, Łeba 8 and Lębork IG 1 are represented by the clayey rocks enriched in organic matter as compared with the earlier discussed area (maximum 2.6% TOC). The composition and form of the occurrence are analogous as in the area of the Caledonides (Tab. 2; Pl. II, Fig. 1a). The following types of the material can be distinguished owing to fluorescence observations: yellow streaks of alginite and yellow-orange liptodetrinite (Pl. II, Fig. 1b).

The form of the occurrence of vitrinite-like macerals suggests that these are generally variably coalified organic remains syngenetic with the sediments (Pl. II, Fig. 2), occasionally redeposited (Pl. II, Fig. 3). They often show a distinct anisotropy.

The geochemical analyses of the bitumens extracted from the Ordovician rocks in the EEC area also show analogies with the Caledonides zone (Tab. 4). The thermal maturity varies within a very wide range (grade II–V; Tab. 4) pointing to a presence of syngenetic and epigenetic hydrocarbons of at least two generations. Only in the deposits from the Kościerzyna IG 1 borehole the occurrence of weakly altered compounds was observed, which most probably represent relics of the earlier generated hydrocarbons.

## SILURIAN

The shales and claystones of the Middle and Upper Silurian, studied in the area of the Pomeranian Caledonides in the boreholes Bydgoszcz IG 1, Klosnowo IG 1 and Toruń 1, contain variable amounts of organic matter (0.1–2% TOC) and bitumens (0.001–0.33%). A distinct enrichment both in the stable organic matter and mobile compounds in the deposits studied in the borehole Klosnowo IG 1 may be observed. The quantitative composition as well as the alteration character of the organic compounds in the studied boreholes displays significant differences (Tab. 1, 3).

The petrological studies of the Upper Silurian shales in the borehole Bydgoszcz IG 1 showed a high content of the sapropelic mineral-organic association which forms laminae and lenticular concentrations. This association co-occurs with the amorphous bitumen developed similarly to that found in the older deposits (Pl. III, Fig. 5).

The liptodetrinite plays a significant role in the composition of the organic matter in the Middle Silurian claystones from the borehole Klosnowo IG 1. Well-preserved sporinite, coutinite and alginite (tasmanite) can also be observed. These macerals fluoresce intensively yellow and yellow-orange (Pl. III, Fig. 6) while the bitumens forming impregnations and streaks vary from yellow to orange-brown (Pl. III, Fig. 6). The

Table 4

**Geochemical analysis of organic matter from East European Craton area**

| Wells | Depth intervals [m] | Age | Samples [*n*] | Bitumens [%] min–max (average) | TOC [%] min–max (average) | $nC_{max}$ | Hydrocarbons [%] | | Metamorphism degree of bitumens |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | saturated | aromatic | |
| Gdańsk IG 1 | 3297.0–3485.0 | $Cm_1$ | 21 | 0.006–0.19 (0.01) | 0.1–0.3 (0.2) | 17–20 | 17–43 [37] | 7–25 [37] | IV, V, III |
| | 3142.0–3264.0 | $Cm_2$ | 15 | 0.006–0.114 (0.01) | 0.2–0.5 (0.3) | 18–20 | 11–58 | 7–65 | III, IV |
| Kościerzyna IG 1 | 4751.2–4824.0 | $Cm_1$ | 10 | 0.003–0.007 (0.005) | 0.1–0.2 (0.1) | 17–19 | 23–35 | 1–6 | III, IV, V |
| | 4426.0–4747.0 | $Cm_2$ | 18 | 0.001–0.02 (0.004) | 0.2–0.9 (0.6) | 17–19, 24 | 25–46 | 1–17 | IV, V, III |
| Gdańsk IG 1 | 3120.0–3134.0 | $O_1$ | 3 | 0.003–0.005 (0.004) | 0.1–0.2 (0.15) | 17, 18 | 22–24 | 5–8 | IV |
| | 3115.0–3119.0 | $O_2$ | 3 | 0.004–0.006 (0.005) | 0.1–0.2 (0.1) | 17–19 | 12–15 | 5–9 | IV |
| | 3096.0–3110.0 | $O_3$ | 7 | 0.007–0.28 (0.11) | 0.2–2.6 (0.8) | 17–19 | 7–75 | 1–15 | I–III |
| Kościerzyna IG 1 | 4408.0–4409.0 | $O_2$ | 2 | 0.005–0.015 (0.08) | 0.1–0.6 (0.4) | 18 | 27–30 | 3–11 | IV |
| | 4397.0–4399.2 | $O_3$ | 4 | 0.002–0.008 (0.005) | 0.5–0.7 (0.6) | 18, 19 | 21–67 | 5–14 | IV |
| Lębork IG 1 | 3268.5–3310.0 | $O_3$ | 6 | 0.002–0.014 (0.008) | 0.4–1.9 (0.85) | 17, 19 | 10–32 | 5–18 | III, IV, V |
| Gdańsk IG 1 | 3069.0–3086.0 | $S_1$ | 4 | 0.006–0.085 (0.007) | 0.1–0.4 (0.3) | 19, 25 | 10–64 | 9–19 | I–IV |
| | 2865.0–3042.0 | $S_2$ | 10 | 0.01–0.18 (0.12) | 0.5–1.4 (0.8) | 17 | 60–67 | 10–14 | I–III |
| | 1653.0–2796.0 | $S_3$ | 14 | 0.001–0.072 (0.04) | 0.1–0.6 (0.35) | 18 | 2–49 | 5–17 | III, IV |
| Kościerzyna IG 1 | 4327.0–4372.1 | $S_1$ | 3 | 0.003–0.01 (0.004) | 0.6–2.2 (1.0) | 18, 19, 23 | 25–64 | 12–26 | IV |
| | 4236.5–4309.0 | $S_2$ | 6 | 0.004–0.01 (0.007) | 0.5–1.1 (0.75) | 17–21 | 26–31 | 18–27 | III, IV |
| | 2103.5–4182.0 | $S_2$ | 24 | 0.003–0.03 (0.01) | 0.1–0.6 (0.4) | 19, 20, 21 | 17–60 | 1–13 | III, IV |
| Lębork IG 1 | 3248.5–3267.5 | $S_1$ | 2 | 0.003–0.006 (0.004) | 0.51–1.06 (0.6) | 17–20 | 19–38 | 7–16 | II–IV |
| | 3108.7–3228.3 | $S_2$ | 3 | 0.001–0.003 (0.002) | 0.62–1.15 (1.0) | 17–19 | 23–42 | 3–19 | III, IV |
| | 1030.6–3080.7 | $S_2$ | 11 | 0.0001–0.086 (0.04) | 0.2–1.27 (0.74) | 17 | 25–49 | 8–22 | III–V |

sapropelic matrix is less abundant forming lenticular and nested concentrations with small sloccullic aggregations of bitumens.

The composition of the Silurian organic matter is complemented by the macerals showing vitrinite-like and inertnite-like optical features (Tab. 1). The vitrinite-like macerals display a variable form of the occurrence. They occur in bands reaching thickness of 50 μm and length up to 2 cm. They represent vitrinised organic remains both syngenetic with the sediment and redeposited (Pl. III, Fig. 7).

The geochemical analysis of mobile compounds extracted from the Silurian shales in the borehole Bydgoszcz IG 1 shows no analogy to the bitumen extracts from the other boreholes (Tab. 3, Fig. 6). These compounds are very poor in hydrocarbons, both saturated and aromatic, displaying, however, a slight predominance of the latter over the former. The degree of alteration is very low (grade V) and points to the relic structures left after generation of a majority of hydrocarbon compounds. N-alkanes of the $nC_{17}$–$nC_{25}$ group (Tab. 3) reach the maximum content.

In turn, mobile compounds from the claystones in the borehole Klosnowo IG 1 are considerably altered (grade II–III) and show the features characteristic for a majority of the analysed syngenetic and epigenetic bitumen extracts of the Lower Palaeozoic.

The Silurian complex in the East European Craton, built of shales and clayey-muddy deposits, was observed in the following boreholes: Gdańsk IG 1, Kościerzyna IG 1, Lębork IG 1, Łeba 8 and Prabuty IG 1. The content of the organic matter is relatively high (max. 2.2% TOC). Petrographically the composition is dominated by the sapropelic matrix (80%), enclosing organic and mineral components of different size. In the rocks poorer in organics, the mineral-organic association forms laminae and lenticular or nested concentrations (Pl. III, Fig. 2). It is accompanied by amorphous solid bitumen (40%) occurring mostly as small bands or thin laminae and lenses reaching 50 μm in lenght (Pl. III, Fig. 1). Locally, in the borehole Gdańsk IG 1, a distinct percentage of the macerals corresponds to liptinite developed analogically to that in the Klosnowo area. Its fluorescence is intensive — yellow-orange (tasmanite, sporinite) and orange-brown (liptodetrinite) (Pl. III, Fig. 3).

Additional components of the described organic matter are macerals displaying optical features of vitrinite and inertite showing diverse forms of occurrence. Most common are bands up to 70 μm in thickness and up to 2 cm in lenght. These are vitrinised organic remains, mostly of graptolites, syngenetic with the sediment (Pl. III, Fig. 4).

The top of the Silurian deposits is characterised by an increase of the content of the vitrinite-like organic matter *in situ* showing a distinct anisotropy. Abundant bitumens also have been noticed in the Upper Silurian deposits (Gdańsk IG 1) where they form local streaks along the fractures and show a variable fluorescence from yellow to orange-brown.

Bitumens extracted from the Silurian complex have a distinctly lower percentage of high molecular compounds (resins, asphaltenes) than the older ones (Fig. 6). Also the n-alkane distribution is variable. The maximum is reached by $nC_{17}$ up to $nC_{20}$ with a local predominance of long-chain hydrocarbons, such as $nC_{21}$–$nC_{25}$ (Gdańsk IG 1, Kościerzyna

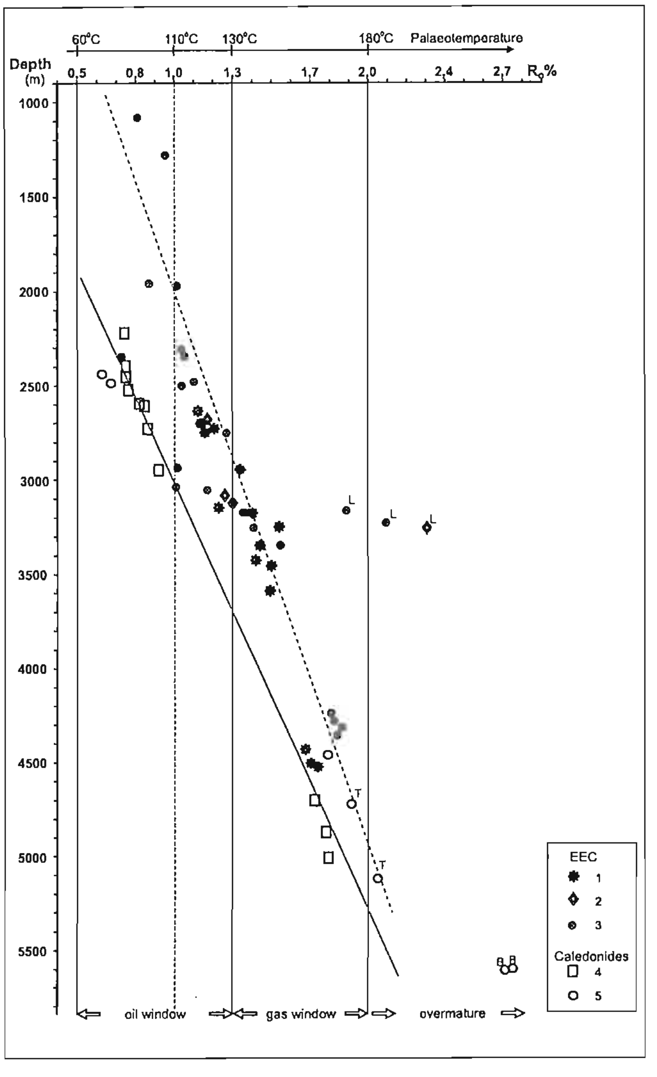



Fig. 3. Depth distribution of the reflectivity index of solid bitumen and vitrinite-like organic matter

1–3 — East European Craton: 1 — Cambrian, 2 — Ordovician, 3 — Silurian; 4, 5 — area of Pomeranian Caledonides: 4 — Ordovician, 5 — Silurian; abbreviated borehole names: B — Bydgoszcz IG 1, L — Lębork IG 1, T — Toruń 1

IG 1). This fact points to the influx of the terrigenous organic matter to the depositional environment (Tab. 3). The maturity of the extracted bitumens varies in a very wide range between grade I and V, most commonly in the range from II to IV grade. This points to the presence of mobile compounds of both syngenetic and epigenetic hydrocarbons.

## THERMAL MATURITY OF THE ORGANIC MATTER

A level of maturity based on the $R_o$ index (P. Robert, 1985) points to a variable stage of thermal alteration — from the early phase of oil generation to the late phase of gas generation. Maturity level generally increases with a depth of deposits, whereas regional patterns are less distinct (Figs. 2, 3).

The range of the maximum palaeotemperatures interpreted according to J. Hood *et al.* (1975) and A. Karweil (1975 in: P. Robert, 1985) is rather wide and corresponds to the interval between 70 and about 200°C. The Cambrian deposits are in the main phase of gas generation (1.22–1.72% $R_o$) at the depth interval 2735–4751 m. The process of their maturition occurred in the palaeotemperature interval 120–170°C.

The Ordovician organic matter in the area of the Pomeranian Caledonides shows maturity corresponding to the main phase of oil generation (0.73–0.91% $R_o$) in the area Jamno IG 2–Brda 2 (depth 2220.5–2944.3 m) and to the main phase of gas generation (1.78–1.8% $R_o$) in the area of the Chojnice 5 borehole (depth 4897.3–5000.2 m). The maximum palaeotemperatures correspond to 70 and 170°C, respectively. In the area of the East European Craton within the depth interval of 2708.0–3268.5 m the alteration degree of the organic matter changes from 1.12 (Łeba 8) to 2.30% $R_o$ (Lębork IG 1) which points to the early and late phases of gas generation at maximum temperatures 110–190°C.

The Silurian deposits in the area of the Pomeranian Caledonides have a variable maturity similarly as in the case of the Ordovician rocks. In the Klosnowo IG 1 area, where they occur at the depth of about 2400 m, the organic matter is in the early phase of oil generation (0.63–0.65% $R_o$) corresponding to the maximum palaeotemperatures not exceeding 70°C. In the Bydgoszcz–Toruń zone, with considerable burial depths (4400–5600 m) the organic matter shows the features of the overheating (Bydgoszcz IG 1 — 2.7% $R_o$) which suggests temperatures about 170–200°C.

The complex of the Silurian deposits in the East European Craton displays variable levels of thermal alteration. The $R_o$ values vary between 0.72 and 2.1% with the depth interval 2360–4301 m. This points to the main phase of oil generation (Gdańsk IG 1) as well as the main and late phases of gas generation (Kościerzyna IG 1, Lębork IG 1) under variable palaeotemperature conditons (70–180°C).

## INTERPRETATION OF THE RESULTS

The thermal maturity of the organic matter which is reflected by the vitrinite reflectivity index is dependent on two factors, namely on time and geologically controlled temperatures. The latter factor is the most significant according to the majority of researchers (P. Robert, 1985).

The dependence of a vitrinite reflectivity on the wall-rock temperatures suggests that higher reflectivity of the vitrinite-like matter should be expected in samples from greater depths in the studied boreholes. This rule is not always confirmed in the analysed material although most of the measurements follows the pattern of the increasing $R_o$ with depth (Fig. 3). It should be stressed that the Ordovician and Silurian deposits in the marginal zone of the Pomeranian Caledonides (the Jamno–Klosnowo zone) are at the lower alteration stage than

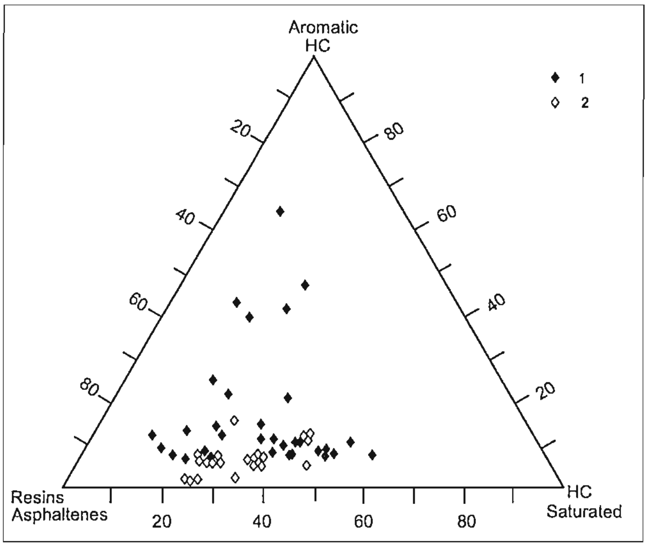



Fig. 4

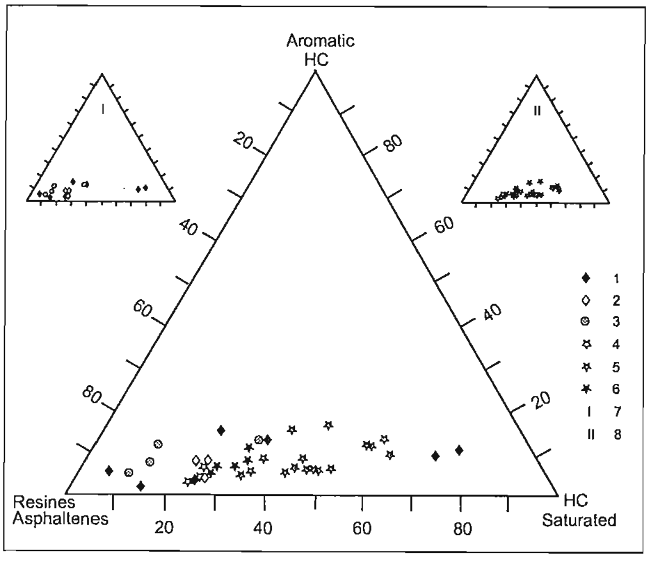



Fig. 5

Fig. 4. Diagram of group composition of bitumens in the Cambrian deposits

Boreholes: 1 — Gdańsk IG 1; 2 — Kościerzyna IG 1

Fig. 5. Diagram of group composition of bitumens in the Ordovician deposits

Boreholes: 1 — Gdańsk IG 1; 2 — Kościerzyna IG 1; 3 — Lębork IG 1; 4 — Brda 2; 5 — Chojnice 5; 6 — Jamno IG 2; 7 — Pomeranian Caledonides; 8 — East European Craton

those in the EEC area located at similar depths at present. Deeper buried deposits (> 3500 m) of both zones show similar metamorphism. The samples from the Upper Ordovician and the base of the Middle Silurian in the borehole Lębork IG 1 (the EEC area) as well as from the Upper Silurian in the boreholes Bydgoszcz IG 1 and Toruń 1 (the Caledonides area — Fig. 3) do not follow the above scheme.

The local overheating due to the fault zone representing a migration path for ascending hot fluids may be the cause of the increased reflectivity. The overheating phenomenon might be also caused by extremely deep burial in the Early Palaeozoic as well as by rejuvenation of older tectonic zones during the younger tectonic movements (Variscan, Cimmerian or Laramide) which are responsible for the present tectonic structural pattern of the Pomeranian area.

The subsidence curves for the Lower Palaeozoic on the EEC area (M. Sikorska, J. Pacześna, 1997; M. Sikorska, 1998; P. Poprawa, unpubl.) point to a maximum burial in the order of the present-day burial depths of the sediments under discussion. The most distinct differences occur in the area of northern Poland close to the Teisseyre-Tornquist Zone. In the studied boreholes they do not exceed, however, 800 m. Northwards (Gdańsk IG 1, Łeba 8) the burial curves show similar to the present or even shallower occurrence of the Lower Palaeozoic deposits during the presumed maximum Silurian–Devonian subsidence.

The high maturity of the Upper Ordovician and near the top of the Middle Silurian in the Lębork IG 1 borehole (2.10–2.30% $R_0$ at the depth 3200 m) is caused both by the palaeothermal gradient higher than the present one value of 4°C/100 m (M. Karwasiecka, 1994) and by the Caledonian tectonics which resulted in numerous block structures in the Łeba Elevation zone. It should be added that the Lębork region lies in the area of the positive thermal anomaly of the Łeba Block, confirmed by the gravimetric measurements (M. Karwasiecka, *op. cit*).

In the area of the Pomeranian Caledonides the maximum burial depths of the Ordovician deposits in the borehole Chojnice 5 (H. Merta, unpubl.) generally correspond to the present burial depth. There exists no data on the maximum subsidence of the strongly altered Silurian deposits in the boreholes Bydgoszcz IG 1 and Toruń 1 (2.7–2.1% $R_0$, temperatures of about 180–200°C). Assuming the thermal palaeogradient about 3.6°C/100 m (M. Karwasiecka, 1994) the maximum burial of the Silurian deposits in this region could have been also similar to the present one.

The region Chojnice–Bydgoszcz–Toruń lies at present in the zone of the moderately low temperatures (M. Karwasiecka, *op. cit.*).

Thermal maturity in the Mesozoic deposits is low but increases towards SW. The deposits are mainly immature and weakly altered. They fall into the early phase of the oil window (0.45–0.65% $R_0$ — I. Grotek *et al.*, 1996).

The maximum palaeotemperature values of about 50–70°C can be interpreted for the Mesozoic deposits in a large part of the Pomeranian region.

It can be presumed in view of the obtained data that the extremely high palaeotemperatures (120–200°C) both in the East European Craton and in the Caledonides zone were

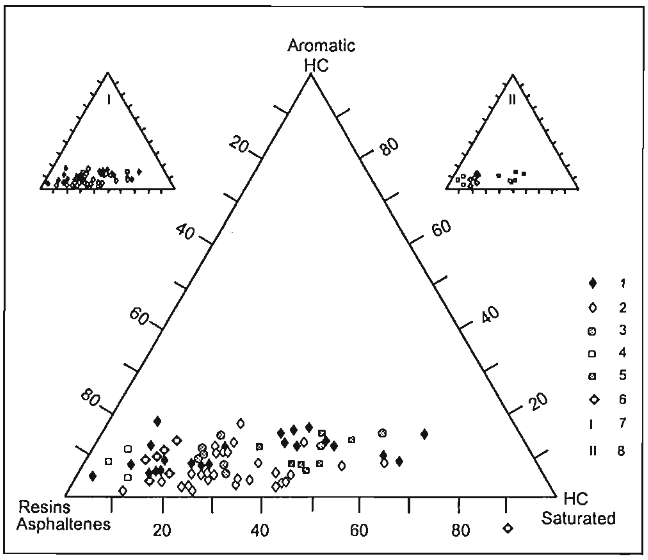



Fig. 6. Diagram of group composition of bitumens in the Silurian deposits

Boreholes: 1 — Gdańsk IG 1; 2 — Kościerzyna IG 1; 3 — Lębork IG 1; 4 — Bydgoszcz IG 1; 5 — Klosnowo IG 1; 6 — Toruń 1; other explanations in Fig. 5

related to the Caledonian deformation front and, additionally, to the influence of the later Permian volcanic activity.

## CONCLUSIONS

The clayey-muddy complex of the Ordovician and Silurian age in the Pomeranian Caledonides belt as well as the Cambrian, Ordovician and Silurian rocks at its foreland (the East European Craton) contain the same genetical type of the organic matter dominated by the syngenetic sapropelic material (oil-prone). The intensity and character of the thermal alterations in both stable organic matter mobile components show distinct analogies despite the different tectonic involvement of both regions.

The reflectivity index of the vitrinite-like minerals shows an increase with the burial depth of the successive members of the Lower Palaeozoic. The local increase in thermal alteration of the organic matter is related to the zones of the increased tectonic activity. Assuming that the maximum burial depth of the studied sediments corresponds to their present depth, it can be concluded that the thermal palaeogradient for the Early Palaeozoic in the Pomeranian region was higher than the present-day one.

The range of maximum palaeotemperatures which influenced the Lower Palaeozoic complex is very wide ranging from about 70 to 200°C in the Caledonian zone. The reflectivity index varies from 0.63 (depth 2443 m, Silurian, Klosnowo IG 1) to 2.73% (depth 5611 m, Silurian, Bydgoszcz IG 1) as well as from 0.82 (depth 1092 m, Silurian, Lębork IG 1) to 2.3% (depth 3268 m, Ordovician, Lębork IG 1) in the area of the East European Craton.

The analysed deposits do not show a good quality as potential source rocks for hydrocarbon generation. Their low generation potential is probably caused by an earlier generation of a part of hydrocarbons. Most of the studied deposits occur in the accumulation phase.

In the area of the Pomeranian Caledonides only some Caradoc shales in the Jamno IG 1 borehole as well as the Wenlock claystones in the Klosnowo IG 1 show features of poor- to medium-quality source rocks.

In the East European Craton individual horizons of the Middle Cambrian and Upper Ordovician claystones and clayey deposits of the Lladovery and Wenlock age in the boreholes Gdańsk IG 1 and Kościerzyna IG 1 as well as top Ludlow claystones in Lębork IG 1 may be regarded as poor to medium source-rocks for a hydrocarbon generation.

## REFERENCES


BUCHARDT B., LEWAN M. D. (1990) — Reflectance of vitrinite-like macerals as a thermal maturity index for Cambrian–Ordovician alum shale, southern Scandinavia. Am. Ass. Petrol. Geol. Bull., **74** (4): 394–406.

DADLEZ R., KOWALCZEWSKI Z., ZNOSKO J. (1994) — Some key of the pre-Permian tectonics of Poland. Geol. Quart., **38** (2): 169–190.

GONDEK B. (1980) — Geochemistry of n-alkanes occurring in the sediments of the Polish Lowlands (in Polish with English summary). Pr. Inst. Geol., **97**.

GROTEK I., KLIMUSZKO E. (1994) — Warunki generowania, migracji i akumulacji węglowodorów. In: Budowa geologiczna kompleksu staropaleozoicznego w strefie Slupsk–Władysławowo (ed. Z. Modliński). Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

GROTEK I., KLIMUSZKO E., SWADOWSKA E. (1996) — Geochemia węglowodorów oraz diageneza materii organicznej na tle ewolucji basenu permsko-mezozoicznego. Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

GROTEK I., KLIMUSZKO E. (1998) — Charakterystyka geochemiczna materii organicznej. In: Rola regionalnych stref dyslokacyjnych w procesie tworzenia się złóż węglowodorów na bloku Łeby (ed. K. Leszczyński). Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

HOOD A., GUTJAHR C. C. M., HEACOCK R. L. (1975) — Organic metamorphism and the generation of petroleum. Am. Ass. Petrol. Geol. Bull., 59: 986–996.

JACKOB H. (1985) — Disperse solid bitumens as an indicator for migration and maturity in prospecting for oil and gas. In: Erdole und Kohle, Erdgas und Petrochemie: 38–365.

JAWOROWSKI K. (1971) – Sedimentary structures of the Upper Silurian siltstones in the Polish Lowland. Acta Geol. Pol., **21** (4).

KARWASIECKA M. (1994) — Opracowanie cieplnego pola Ziemi na obszarze Polski. Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

LINK C. M., BUSTIN R. M., GOODARZI F. (1990) — Petrology of graptolites and their utility as indices of thermal maturity in Lower Paleozoic strata in northern Yukon, Canada. Intern. J. Coal Geol., **15**: 115–135.

NEHRING-LEFELD M., MODLIŃSKI Z., SWADOWSKA E. (1997) — Thermal evolution of the Ordovician in the western margin of the East-European Platform: CAI and $R_o$ data. Geol. Quart., **41** (2): 129–138.

POŻARYSKI W. (1987) — Tectonics. Sub-Permian Paleozoic complex (in Polish). In: Geological structure of the Pomeranian Swell and its basement (ed. A. Raczyńska). Pr. Inst. Geol., **119**: 174–186.

ROBERT P. (1985) — Organic metamorphism and geothermal history. Elf-Aquitae and D. Reidel Publishing Company. Dordrecht. Holland.

SWADOWSKA E., SIKORSKA M. (1998) — Burial history of Cambrian rocks of the Polish part of the East European Platform as based on reflectance of vitrinite-like macerals (in Polish with English summary). Prz. Geol., **46** (8/1): 699–706.

SIKORSKA M., PACZEŚNA J. (1997) — Quartz cementation in Cambrian sandstones on the background of their burial history. (Polish part of the East European Craton). Geol. Quart., 41 (3): 265–272.

SIKORSKA M. (1998) — Role of diagenesis in forming of pore space in Cambrian sandstones of the Polish part of the East-European Platform (in Polish with English summary). Pr. Państw. Inst. Geol., **164**.

STACH E., MACKOWSKY M. T., TEICHMÜLLER M. R., TAYLOR G. H., CHANDRA D. (1982) — Stach's Texbook of Coal Petrology. 2nd ed.

TISSOT B. P., WELTE D. M. (1978) — Petroleum formation and occurrence. Springer Verlang. Berlin, New York

TEICHMÜLLER M. (1986) — Organic petrology of source rock. Org. Geochem., **10**.

ZNOSKO J. (1965) — The problem of Caledonides and the border of Pre-Cambrian Platform in Poland (in Polish with English summary). Biul. Inst. Geol., **188**: 5–72.

ZNOSKO J. (1987) — The Tectonic Map of SW Border of the East-European Platform (IGCP no. 86) — remarks and impressions (in Polish with English summary). Prz. Geol., **35** (1): 3–7.

# PRZEMIANY MATERII ORGANICZNEJ W OSADACH DOLNOPALEOZOICZNYCH — KALEDONIDY POMORSKIE I ICH PRZEDPOLE


Streszczenie

Badania petrograficzne i geochemiczne wykonane zostały na materii organicznej rozproszonej w utworach starszego paleozoiku po obu stronach strefy tektonicznej Teisseyre'a-Tornquista. Objęły one swym zasięgiem osady ordowiku i syluru pomorskiej części pasma kaledonidów oraz kambru, ordowiku i syluru na ich przedpolu, na obszarze kratonu wschodnioeuropejskiego.

Mimo że materia organiczna jest czułym wskaźnikiem zmian fizykochemicznych, szczególnie termicznych, zachodzących w osadzie w czasie jego dia- i katagenezy, nie stwierdzono wyraźnych różnic w charakterze jej przemian na obu obszarach. Świadczy to o podobnym wpływie procesów tektonicznych związanych zarówno z kaledonidami, jak i młodszymi ruchami diastroficznymi na brzeżną strefę kaledonidów pomorskich oraz na ich przedpole na obszarze kratonu wschodnioeuropejskiego.

Typ genetyczny materii organicznej zawartej w skałach starszego paleozoiku na całym obszarze badań jest reprezentowany przez syngenetyczny materiał sapropelowy *oil-prone*. Zawartość materiału humusowego, głównie redeponowanego, wzrasta dopiero w osadach sylurskich. W całym profilu badanych osadów występują epigenetyczne węglowodory impregnujące skały, wypełniające przestrzenie porowe lub mikroszczeliny spękań.

W kompleksie utworów starszego paleozoiku materia organiczna stała oraz związki labilne występują w zmiennej ilości, przy maksymalnej koncentracji nie przekraczającej 2,6% TOC oraz 0,33% bituminów. Poziomy macierzyste o zawartości powyżej 0,5% $C_{org.}$ występują najliczniej na obszarze kratonu wschodnioeuropejskiego w iłowcach środkowego kambru, górnego ordowiku oraz lokalnie w całym profilu syluru. W brzeżnej strefie kaledonidów pomorskich jedynie pojedyncze poziomy łupków karadoku z otworu Jamno IG 2 oraz wenloku z otworu Klosnowo IG 1 wykazują cechy słabych skał macierzystych dla generacji ropy. Potencjał generacyjny poziomów potencjalnie macierzystych jest najprawdopodobniej obniżony przez wcześniejsze wygenerowanie części węglowodorów.

Określone na podstawie wartości wskaźnika $R_o$ stadia generacji węglowodorów, w rejonie położonym na południowy zachód od strefy Teisseyre'a-Tornquista (kaledonidy pomorskie), zmieniają się od wczesnej fazy generacji ropy po późną fazę generacji gazów (0,63–2,73% $R_o$), wskazując na paleotemperatury w zakresie 70–200°C. Na północny wschód od strefy T-T (kraton wschodnioeuropejski) stopień dojrzałości materii organicznej odpowiada głównej fazie generacji ropy po fazę generacji gazów (0,82–2,3% $R_o$), przy maksymalnych paleotemperaturach oddziałujących na osady kambru –syluru, rzędu 80–190°C. Stopień dojrzałości termicznej syngenetycznych bituminitów oraz macerałów witrynitopodobnych wzrasta generalnie z głębokością pogrążenia osadów. Wydaje się, iż najsilniejszy wpływ na charakter przemian materii organicznej miały warunki termiczne związane z maksymalnym pogrążeniem oraz wielkością paleogradientu termicznego. Lokalne anomalie termiczne związane są ze strefami tektonicznymi oraz działalnością wulkaniczną.


## EXPLANATIONS OF PLATES

### PLATE I

Fig. 1a. Sapropelic material with fine slocculfic aggregations and laminae of solid bitumen
Lower Cambrian claystone, Gdańsk IG 1, 3353.3 m, $R_o$ = 1.46%; polished sample, white light, dry objective

Fig. 1b. Same object in fluorescence with liptodetrinite showing distinct yellow-orange colours
Blue light; immersion oil objective

Fig. 2. Graptolite remains in sapropelic material
Lower Cambrian claystone, Kościerzyna IG 1, 4751.2 m, $R_o$ = 1.72%; polished sample, white light, dry objective

Fig. 3. Bituminous impregnations (orange-brownish) in sandy bed
Middle Cambrian, Kościerzyna IG 1, 4426.0 m, $R_o$ = 1.68%; polished sample, blue light, immersion oil objective

### PLATE II

Fig. 1a. Sapropelic material in streaks and nested aggregates
Upper Ordovician claystone, Gdańsk IG 1, 3099.2 m, $R_o$ = 1.27%; polished sample, white light, immersion oil objective

Fig. 1b. Same in fluorescence. Against the background of black sapropelic material visible are yellow fluorescing streaks of degraded alginite and yellow-orange liptodetrinite
Blue light, immersion oil objective

Fig. 2. Laminae and lenses of vitrinite-like macerals *in situ*
Lower Ordovician mudstone, Gdańsk IG 1, 3120.0 m, $R_o$ = 1.30%; polished sample, white light, immersion oil objective

Fig. 3. Vitrinite-like macerals, mostly redeposited, in clay-sapropelic mass
Upper Ordovician mudstone, Lębork IG 1, 3268.5 m, $R_o$ = 2.30%; polished sample, white light, immersion oil objective

Fig. 4. Anisotropic organic vitrinite-like remnants in clay-sapropelic mass
Upper Ordovician claystone, Chojnice 5, 4897.3 m, $R_o$ = 1.78%; polished sample, white light, immersion oil objective

Fig. 5. Anisotropic fragments of graptolites in sapropelic mass
Upper Ordovician claystone, Chojnice 5, 5000.8 m, $R_o$ = 1.80%; polished sample, white light, immersion oil objective

Fig. 6. Bitumens impregnating a carbonate interlayer fluorescing brown
Middle Ordovician, Brda 2, 2602.8 m, $R_o$ = 0.84%; polished sample, blue-violet light, dry objective

Fig. 7. Liptodetrinite fluorescing orange-brown
Upper Ordovician sapropelic shale, Jamno IG 2, 2600.0 m, $R_o$ = 0.81%; polished sample, blue light, immersion oil objective

PLATE III

Fig. 1. Lens of solid bitumen in sapropelic mass
Silurian (Wenlock) claystone, Kościerzyna IG 1, 4301.0 m, $R_o$ = 1.86%; polished sample, white light, immersion oil objective

Fig. 2. Fine lenses and sloccullic aggregates of solid bitumen in clayey-sapropelic mass
Silurian claystone (Ludlow), Lębork IG 1, 1092.0 m, $R_o$ = 0.82%; polished sample, white light, immersion oil objective

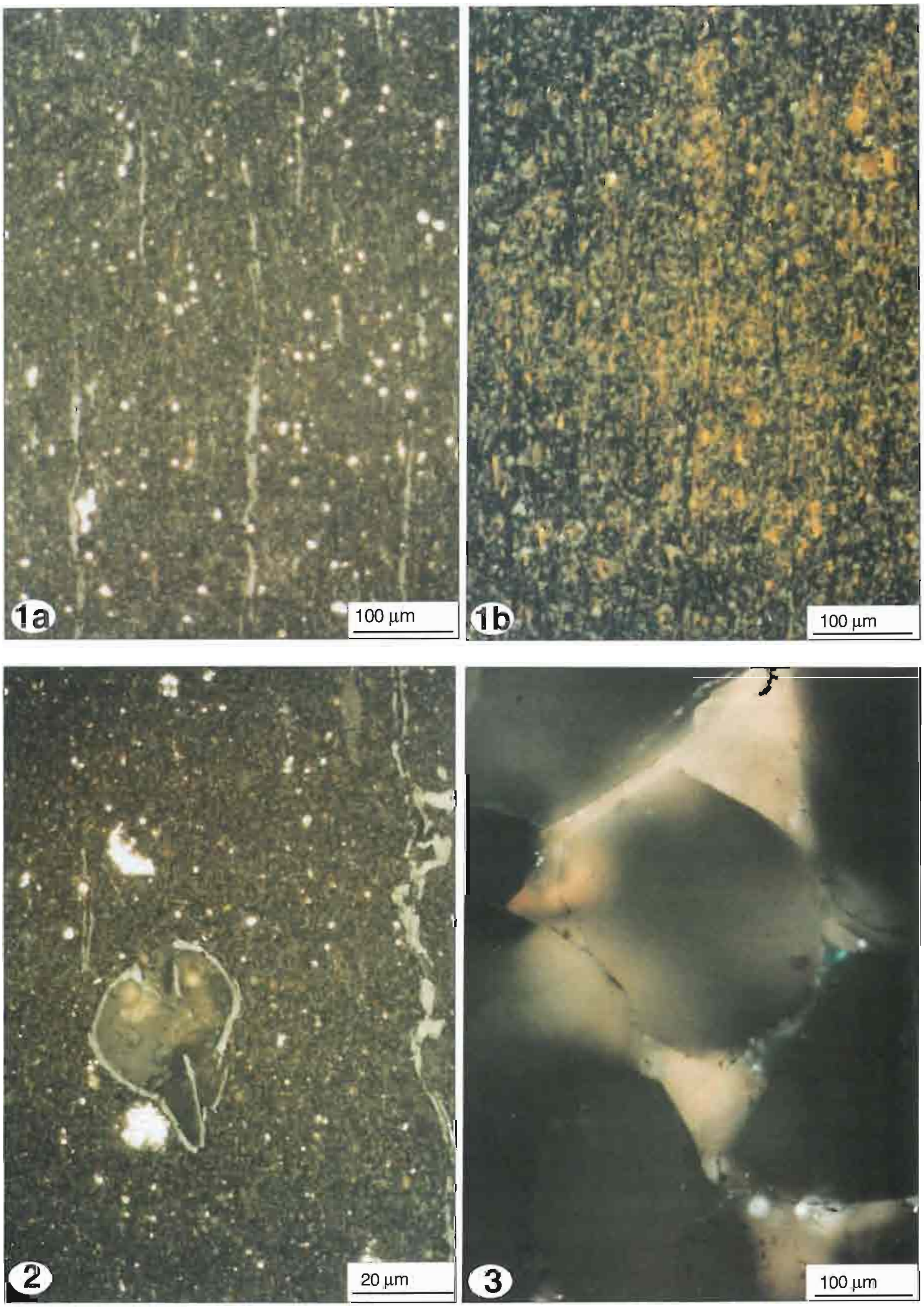
Fig. 3. Streaks of degraded alginite fluorescing yellow and orange, and liptodetrinite
Silurian mudstone (Siedlec), Gdańsk IG 1, 2360.0 m, $R_o$ = 0.72%; polished sample, blue light, immersion oil objective

Fig. 4. Graptolites in sapropelic-clayey mass
Silurian mudstone (Ludlow), Kościerzyna IG 1, 2350.7 m, $R_o$ = 1.04%; polished sample, white light, immersion oil objective

Fig. 5. Vitrinite-like macerals in sapropelic mass
Upper Silurian claystone, Bydgoszcz IG 1, 5606.0 m, $R_o$ = 2.73%; polished sample, white light, immersion oil objective

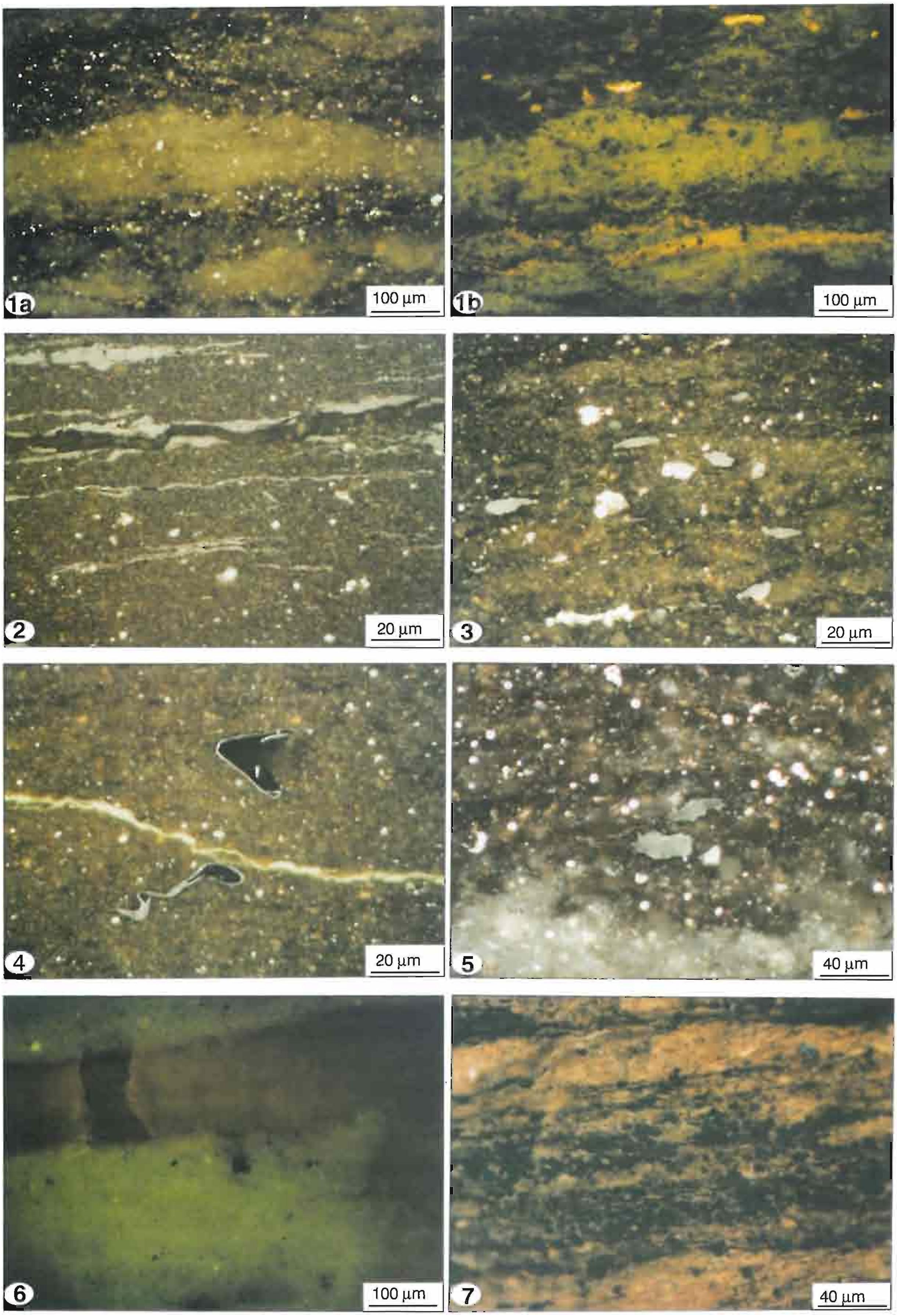
Fig. 6. Liptodetrinite and streaks of degraded alginite fluorescing yellow-orange and orange
Silurian claystone (Wenlock), Klosnowo IG 1, 2443.0 m, $R_o$ = 0.63%; polished sample, blue light, immersion oil objective

Fig. 7. Lens of solid bitumen (dark grey) and graptolite fragments
Silurian claystone (Wenlock), Klosnowo IG 1, 2456.0 m, $R_o$ = 0.65%; polished sample, white light, immersion oil objective

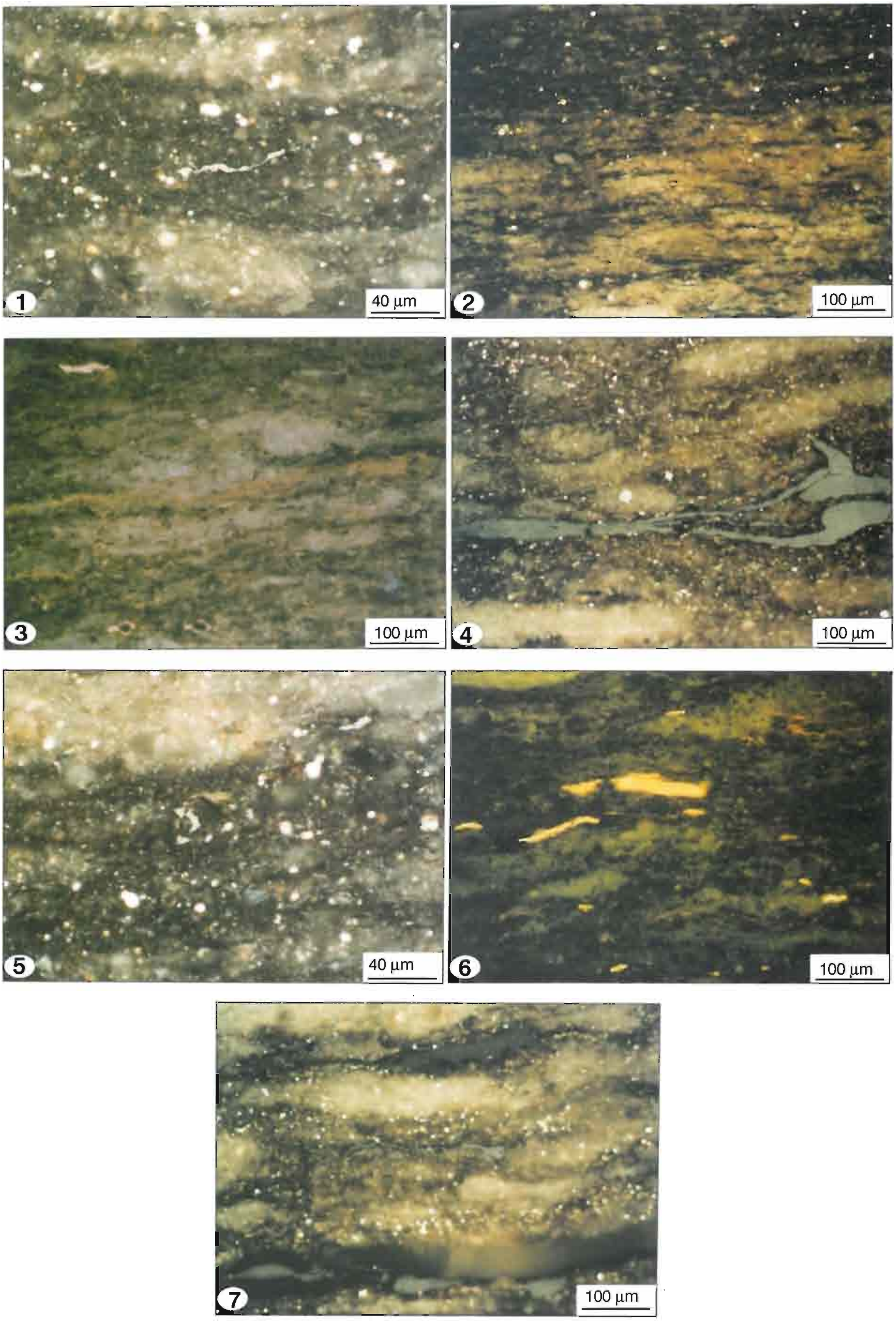



Izabella GROTEK — Origin and thermal maturity of the organic matter in the Lower Palaeozoic rocks of the Pomeranian Caledonides and their foreland (northern Poland)

Geol. Quart., 1999, **43** (3)




Izabella GROTEK — Origin and thermal maturity of the organic matter in the Lower Palaeozoic rocks of the Pomeranian Caledonides and their foreland (northern Poland)




Izabella GROTEK — Origin and thermal maturity of the organic matter in the Lower Palaeozoic rocks of the Pomeranian Caledonides and their foreland (northern Poland)